Frequency Based Cellular Microgrid Control
Demand Side Management and Supply Side Management using Grid Frequency in a Cellular Microgrid

Thijs Vral
FREQUENCY BASED
CELLULAR MICROGRID CONTROL

DEMAND SIDE MANAGEMENT AND
SUPPLY SIDE MANAGEMENT USING
GRID FREQUENCY IN A CELLULAR MICROGRID

by

Thijs Vral

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Abstract

In the world as we know it, huge transitions are ongoing. By now, everyone has heard the words Global Warming and seen news articles and documentaries about the dangers of climate change. Multiple approaches have been described to tackle these problems, of which one is switching to a fully renewable energy supply. This means switching to a situation where the energy resources will be of a decentralized kind. More importantly, the energy resources of tomorrow will not be as controllable as they are today.

Establishing this transaction is not an easy job, turning towards distributed renewable energy sources as main energy supplier brings along a lot of new challenges. The introduction of cellular microgrids can offer tools to facilitate this. On top of that, it can offer benefits in terms of increasing the electrification rate in currently non-electrified regions.

These cellular microgrids exist of islanded systems: small cells with respective loads, energy suppliers and buffers, that can be interconnected in order to support each other. One drawback of current solutions is that they rely on dedicated communication equipment, in order to reach the required operations. Introducing the necessity of communication tools has a negative impact on the system costs, complexity and reliability.

For this, a proposal for the concept of a microgrid was made, enabling the microgrid to have a modular structure, thus to work satisfactorily both when working independently and when interconnected with other cells. On top of that, the grid is flexible both in terms of types of end-users and energy resources, and it grants a means of demand and supply side management. This ensures that a microgrid powered by uncontrollable renewable resources operates in a stable and satisfactory way on the longer term. This is fulfilled while omitting the need for dedicated communication equipment.

In order to allow an exchange of information between actors, local grid parameters are used: the grid voltage and frequency. To achieve this, droop speed control is applied, though its static nature is adapted in order to make it represent the actual state of the microgrid. This way, a modular grid is established, to which different actors contribute according to their capabilities and setpoints.

After designing the control strategy, first and foremost its stability is tested and improved. Subsequently, the controller is implemented and tested using advanced simulation software. The results show that the proposed strategy is effectively able to fulfil the requirements: it is possible to interface multiple inverter-based microgrids, without the need of adding dedicated communication equipment, and give the microgrids the decision over power sharing, load shedding and renewable energy curtailment, depending on their state of energy and power.

Keywords: Cellular Microgrid, Islanding, Demand Side Management, Supply Side Management, Battery Storage, Distributed Renewable Energy Sources, Droop Control
ACKNOWLEDGEMENTS

After about nine months of work, I can honestly say that I am delighted that I am writing these words. The graduation project is finished, and very soon I should be an engineer from TU Delft. Of course, I was not alone during this process, therefore I would like to use this page to thank some people.

I would like to thank my supervisors from TU Delft, Pavol Bauer and Laura Ramirez, for introducing me to the CSGriP project, and subsequently guiding me throughout the thesis and the graduation process. My daily supervisor, Seyedmahdi Izadkhast, has proven to be a very helpful person throughout the thesis. I remind the hours of discussions in his office, trying to find solutions to the ever arising problems. The work would have been less complete if not for Mahdi. Furthermore, I want to thank Jose Rueda Torres for his willingness to complete the thesis committee.

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A special word can be placed for my colleague and friend Nikos Bilidis, with whom I cooperated intensively throughout the thesis process, given the common ground of our projects. Throughout the year, by means of long discussions that sometimes took us really far, I learned a lot from the collaboration. Also other students and friends, to mention Antía, Ivan and Behzad, helped me a lot throughout the process, not only on scientific grounds, but also in offering me a listening ear whenever needed.

Building further on this, I would like to finalize this letter with expressing my greatest gratitude to my family, and all my friends from Delft and Belgium, for the nice times and for the never-ceasing support.

Thijs Vral
Delft, September 2016
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# Acronyms, Abbreviations and Symbols

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<td>AC</td>
<td>Alternating Current</td>
</tr>
<tr>
<td>Bb</td>
<td>backbone</td>
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<tr>
<td>BESS</td>
<td>Battery Energy Storage System</td>
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<tr>
<td>CSGriP</td>
<td>Cellular Smart Grid Platform</td>
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<tr>
<td>CSI</td>
<td>Current Source Inverter</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>DoD</td>
<td>Depth of Discharge</td>
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<tr>
<td>DRES</td>
<td>Distributed Renewable Energy Source</td>
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<td>DSM</td>
<td>Demand Side Management</td>
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<tr>
<td>EV</td>
<td>Electrical Vehicle</td>
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<td>ICT</td>
<td>Information Communication Technology</td>
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<td>µG</td>
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The PEM can be calculated by diving the average output of renewable energy by the average demand. A PEM of 100% means that the average demand is equal to the average output of renewable energy.

**Reactive Power**
The imaginary component of the apparent power at fundamental frequency, expressed in volt-ampere reactive (var).

**Renewable Energy Ratio**
Represents the mix between the average wind power and the average solar power and is always equal to 100%. If the average wind power in a system is 3 times the average solar power, the RER is 75% wind and 25% solar energy.

**Static Inverter**
An electronic device or circuitry that changes direct current to alternating current. The inverter does not produce any power; the power is provided by a source of direct current, which can be a battery system or a renewable power generator. Static inverters do not use moving parts in the conversion process, hence are inertialess.

**Synthetic Inertia**
A replication of the effect of inertia of a synchronous machine. Using synthetic or emulated inertia, the system will behave as if actual inertia is present.
1

AN INTRODUCTION TO THE PROJECT

The White Rabbit put on his spectacles. ‘Where shall I begin, please your Majesty?’ he asked. ‘Begin at the beginning,’ the King said gravely, ‘and go on till you come to the end: then stop.’

Lewis Carroll
Alice’s Adventures in Wonderland

1.1. MOTIVATION AND EXISTING PROBLEMS

The world, more specifically the world of power and energy, is facing huge transitions these days. Where yesterday’s grid was all about centralized, big and controllable power plants, the grid is facing a shift from centralization to decentralization, from few big to many small sources, and most impactful from controllable and regulated sources such as thermal power plants towards uncontrollable sources like wind turbines and photovoltaic panels which generate power only when the external and uncontrolled source, respectively wind or sun, is present. For instance, in Germany, the goal has been set to scale up the power generated by means of renewable sources to 35% by 2020 and even to 80% by 2050 [1].

This transition is taking place because the world is becoming aware of the fact that burning fossil fuels is causing an unavoidable and undesirable greenhouse effect, and on top of that they are not an infinite source of energy. The awareness of this problem started forming back in 1992, when the “United Nations Framework – Convention on Climate Change” was signed by 189 members of the United Nations [2]. The bottom line of the treaty is:

“(…) stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system (…) ”

More recently, the Paris Agreement COP21 has set an international, legally binding action plan to limit global warming below 2°C [3]. To reach the goals set by this climate deal, governments, cities, regions and local authorities have the obligation to scale up efforts to reduce emissions using the best available science and technology.

Next to the dangers of global warming, also the finiteness of fossil fuels should be of concern. We might not have fossil fuels forever, it is not a renewable source of energy, and it might be a good idea to prepare for the moment when we run out of them. And even if we do not run out, we can still ask ourselves the question whether we waited to end the Stone Age until we ran out of stones.
In order to solve these problems, we should work at two solutions simultaneously: the demand of energy should be reduced, and the energy should be yielded from sustainable and renewable sources as much as possible. These point also lay at the basis of a concept named Trias Energetica [4].

This concept breaks the solution to the energy problem apart into three parts, where every former step is prioritized over the next. The Trias Energetica is depicted in Figure 1.1. In descending priority, the three steps that have to be taken are (i) reduce the energy demand, (ii) generate the reduced energy from sustainable sources and (iii) generate the rest of the energy demand as sustainable as possible. If every prior step has been executed effectively, the next step should be easier to achieve.

The work of this thesis mainly aims at the second step, by trying to offer a solution of easier interfacing Distributed Renewable Energy Sources (DRESs) with end-users.

A solution for these problems seems to be clear: the application of DRESs. However, running a grid on solely DRESs, without taking any measures, will lead to unsatisfactory grid behaviour. For instance, if the end-users would be able to consume electricity only at the moments that the sun is shining, or when the wind is blowing, a very poor customer satisfaction could be expected.

It seems that the transition from the old way of doing things to the new way demands some huge adaptations from the grid: business as usual is not going to grant sufficient tools to battle the upcoming problems. These problems are mainly caused by the fact that, as mentioned before, the renewable energy sources are uncontrollable and hence do not necessarily deliver power at the moments when energy is needed. This problem could be solved in different ways, for instance by extremely over-dimensioning the renewable sources and curtail them when they are producing more power than needed, by trying to shift the load curve in order to match the generation curve [5], or by trying to buffer the energy by means of a Battery Energy Storage System (BESS), interfaced by means of a Smart Grid (SG), to be used later as desired [6, 7].

It is important to realize that a BESS will contribute a lot to the investment costs of the system [8]. This means that an economic trade-off will always be aimed for, exchanging the ability to cover all load power for less investment costs. This means that it could become unavoidable that a part of the loads will have to be shed. If this is done in an unthoughtful way, the power delivery to crucial power consumers such as hospitals or telecom towers can be put at risk [9].

In order to prevent situations like this to happen, it seems viable to install a central control unit, sending commands and setpoints using a dedicated communication network to all the devices connected to the grid, and for instance shedding unimportant loads for the sake of crucial ones [10].

However, adding dedicated communication in the form of Information Communication Technology (ICT)
equipment is expected to add to the costs of the ultimate system, and could eventually lead to a lower availability of the system [11]. This because, if the operation of the grid depends on two systems, both the electrical grid and the ICT network, a higher chance of failure could be expected [12].

A proposal that omits the necessity of applying communication equipment into a SG running on DRESs has been defined [13–15]. The main idea is that the grid frequency will be used as the main means of communication. This way, all devices connected to the grid should be able to read the grid frequency, that mirrors the State of Energy and Power (SEP) of the grid, and react according to predefined rules.

The basis of the idea is twofold: firstly, by applying a deviation of grid frequency from its nominal value, introduced by events or states of the grid, the SEP of the grid can be interpreted by only monitoring this grid frequency; and secondly, by using this always present variable, the usage of other communication tools, such as ICT equipment, can be avoided, avoiding extra costs and increasing the reliability of the system.

The modularity of the system is guaranteed by the application of droop speed control [16]. This means of grid forming offers the possibility of sharing active and reactive power among different power sources by actively influencing the grid frequency and voltage, this way ensuring a decentralized control approach for cellular microgrids (μGs).

In order to ensure preference-based load shedding, power consumers would be separated based on priorities. When the grid is approaching a state of overconsumption, devices can detect this because of a decreasing grid frequency, and in turn the lowest priority loads will disconnect by application of Demand Side Management (DSM) [17].

Similarly, when for instance the batteries are getting fully charged and the renewable energy sources are generating too much power, the grid frequency would exceed 50 Hz, and the Supply Side Management (SSM) scheme will react by scaling down the power generated by the DRESs [18].

This behaviour can be achieved by influencing the location of the frequency droop curve, reflecting the SEP of the grid. Thus, without the need of communication equipment, the requirements for keeping critical loads online for the longest time possible can be reached.

1.2. Research Goals

The main goal of this thesis is to enable μGs via advanced controllers to have a modular structure, to be flexible in terms of linked energy consumers and resources, and to offer the possibility of prioritized DSM, while avoiding the need of employing a dedicated communication network.

The research goals can be divided into two goals: inverter control strategy and demand and supply side management. The ultimate goal shall be that the μG is able to use a BESS at its component of main importance.

1. Inverter control: The first part of the research is realizing a controller that complies with the following requirements:

   - **Battery Energy Storage System:** A μG shall be able to use a BESS as its main component.
   - **ICT-less:** The controller shall be able to operate without the necessity of ICT equipment.
   - **Grid frequency based:** Following on the previous requirement, another means of communication has to be found, for which the choice fell on the grid frequency.
   - **Standalone operation:** A cell shall be able to operate in standalone conditions, so disconnected from the public grid or from any other cells.
   - **Multiple cell operation:** Multiple cells shall be able to cooperate in case they are connected to a common backbone (Bb), allowing a cellular nature.
   - **Independent from used loads:** The controller should not limit which type of loads can be used on the grid, this means no limits are made for capacitive, inductive or resistive loads, nor for loads with rotating inertia.
2. Demand and supply side management: After the inverter control has been designed, the next step is to expand the capabilities of the µG by implementing the possibility of an autonomous DSM and SSM. The result of this control shall be that the grid frequency varies according to the SEP of the grid, and the connected load and sources react to this by respectively shedding or curtailing the power demand or supply.

1.2.1. Research Questions
These two identifiable goals of the project are clearly reflected in the research questions:

1. How should a µG be implemented, in order give a cell the capability of influencing the grid frequency for the sake of control, hereby capable of working in both islanded and interconnected mode?
   (a) What are the potential drawbacks of the ICT-less structure?
   (b) How can the system be implemented in a way that it can work both independently and interconnected with other cells?
   (c) How will active and reactive power be shared among different cells?
   (d) How can the system's stability be guaranteed?
   (e) Can multiple cells with a different interest in setting the frequency work together?

2. Can DSM and SSM be performed on a cellular µG, energized by a BESS, only using frequency as an input signal?
   (a) Is the controller capable of changing the frequency as a function of its SEP?
   (b) Can the loads and power sources effectively change their behaviour according to the frequency?
   (c) Do the DSM and SSM reach their initial goals, preserving a longer stability of the grid?

1.3. Methodology
In order to investigate the dynamic stability of the proposed method, the development of a base model has to be performed first. This base model shall offer all the required characteristics, being the independence of dedicated communication equipment, a modular approach, inherent load shedding and DRES curtailing capabilities… Furthermore, the model shall be designed with a philosophy of easily allowing extension, and be prepared for certain tasks that will be needed to be implemented in the future, such as the intentional coupling and disconnecting of multiple cells initialized by the controller.

Subsequently, to keep the grid in a stable and satisfactory state, measures will be designed and tested in order to interact with loads and sources. It is known that extensive use will be made of uncontrollable DRESs, thus the situation where loads cannot be fed because of a lack of energy can occur, and similarly it is possible that not all the energy from the DRESs is usable. These situations will be tackled by the application of respectively DSM and SSM.

After the design of the desired control organs, advanced simulation software will be applied to test them in an extensive range of applications and situations, in order to see their behaviour and robustness. It will be evaluated whether the main controller is able to allow a modular design, thus work both in stand-alone and interconnected mode without adaptations, whether active and reactive power are effectively shared, and whether no other instabilities arise. Most importantly, it will be checked whether the SEP of the cells is adequately mirrored by the grid frequency.

The reaction of the loads and DRESs will be dependent on the grid frequency, in a way that helps the grid. This means that loads should switch off if the grid runs into a state of being under-energized, and DRESs will limit their power output if the grid cannot handle the power injection. Hereby the priority of loads shall be respected, as well as defined limits in the State of Charge (SoC) of the BESS.
The progress of developing both the inverter controller and the DSM and SSM controllers is expected to proceed hand in hand. The controller for the inverter has to be developed in a way that it favours the performance of the DSM and SSM, and also the DSM and SSM should not subvert the stability of the rest of the grid. However, the explanation of how both controllers are developed will be separated for the sake of keeping the overview.

### 1.4. Contributions of the Thesis

In literature, many control mechanisms for $\mu$Gs have been proposed. Many of these proposals use either ICT equipment in order to sustain a stable working point, or use a static droop characteristic. However, the possibility of changing the droop curve to represent the SEP of the grid has not been investigated.

This thesis will prove the concept of dynamically changing droop curves, by showing that multiple $\mu$Gs are able to connect and share active and reactive power only using the frequency and voltage at their terminal. Furthermore, the thesis will show that, using these droop curves dependent on the SEP, DSM and SSM can be applied satisfactorily.

Summarizing, the main contributions of the thesis will be:

- Provide a working control strategy that includes the listed requirements
- Proof that the SEP of a cell can be applied to reach certain behaviours of connected devices.
- Show that multiple cells can work both independently and interconnected, sharing power according to their SEP.
- Show that multiple cells with a different SEP can help each other out, hereby avoiding load shedding or DRES curtailment.

### 1.5. Alfen BV

The work has been performed in collaboration with Alfen BV. Alfen is a company established in 1937, so having 80 years of experience, is located in Almere, with a branch in Ghent, and is currently the market leader in the Netherlands in the field of transformer substations and switch gear, having 80% of the market share and selling around 1000 transformer stations per year. Next to this business, Alfen aims at penetrating the field of charging points for electric vehicles, having realized more than 10,000 charging points to date. Lately, Alfen also started entering the field of Smart Grids, aiming at a preparation of the electricity distribution for the future, and an increase in worldwide electrification rate.

Alfen is a part of the TBI-group since 1971, which is a well-known construction and installation company in the Netherlands. Since 2014, two thirds of the shares have been bought by Infestos, an investment organization, which focusses on sustainable investments.

Alfen developed a broad variety of solutions for medium voltage network connections, electrical vehicle charging poles. Their products include:

- Transformer stations
  - Compact stations
  - Accessible stations
  - Built-in stations
- Solutions for rail systems
- Junction boxes
- A range of products for energy distribution
- ICU Charging Equipment: electrical vehicle charging
• SOPRA / CSGriP: autonomous energy grids

The company has approximately 180 employees working, who develop, design, produce and assemble all products in-house, and also realize turnkey solutions for professionals.

1.6. Organization of the Document

The structure of the document will be as follows: Chapter 2 deals with the previously done work in this field, both in the general literature, §2.1, and in the field of preceding work to this thesis, §2.2.

The relevance of this is as follows: this thesis can contribute to the behaviour of $\mu$Gs in any fashion, but initially started with the intention of helping in the development of this CSGriP project. Thus, firstly all the concepts needed to understand the further development of the thesis will be explained, and a relevant literature review will be provided, and next the foundations of this will be applied to the exact case.

Chapter 3 will show how the development of the controller in the modelling software has taken place. Then, in order to run simulations that are relevant and that allow on drawing conclusions, Chapter 4 is needed to investigate the system stability, and subsequently Chapter 5 will explain the chosen parameters and case studies.

After the relevant parameters and case studies have been defined, the results of the work will be presented in Chapter 6.

Finally, the outcome will be commented upon, in Chapter 7, and Chapter 8 will draw the conclusions, present work that has not been performed but nevertheless would be interesting, and briefly discuss other relevant work that was carried out simultaneously with this thesis.

An explanation of the source of used consumer data is presented in Appendix A, and subsequently a paper that was written within the margins of the project is attached to the document, see Appendix B for this.
2

BACKGROUND REVIEW ON CELLULAR MICROGRIDS

If I have seen further it is by standing on the shoulders of Giants.

Sir I. Newton

2.1. SCIENTIFIC LITERATURE: A REVIEW

This section gives an overview of the state of the art in the field of relevant topics concerning μGs. It should be noticed that the project itself aims to be innovative, so it is expected that the literature will not take all the aspects into account. In terms hardware, all components that will be applied in the these well-known technologies. The reader with background knowledge is free to skip these general parts, as they might be perceived as very basic knowledge. The main contributions of the thesis, as well as of the project as a whole, will be situated in the development of the controller.

2.1.1. INTRODUCTION

If the main subject of the project should be cracked down to one word, the word of choice would be microgrid. The purpose of the project is in fact to design a μG that is independent from ICT equipment, a μG that can perform DSM and SSM, a μG with cellular capabilities etc.

In fact, a μG is the evolution of simple distribution networks, the next big thing [19, 20]. μGs can be considered to be superior over the current distribution network. This because the μG has a certain intelligence, which facilitates certain measures that are hard or even impossible to achieve in the dumb distribution network.

For instance: μGs are able to accommodate a much higher density of DRES, including wind turbines, photovoltaic (PV) panels, diesel generators etc. Furthermore, the possibility to connect and disconnect the μG from the higher network can be provided, by means of a switch. Devices to store energy can be available, in the form of flywheel storage or BESS. The μG will be monitored by a certain management software, either standardized or tailored. To finalize, controllable end-users are expected to be important actors of the μG.

Using a μG has multiple benefits over the use of the current distribution network. Some problems that are expected to be solved by applying μGs are listed as follows [19]:

• Currently, costs of installing more infrastructure for transmission and distribution of power are increasing, because in some areas this infrastructure is hard to install due to environmental parameters. Here,
installing µGs on a local scale can have huge benefits

- Integration of DRESs: in the current situation, grid stability can be affected by a high penetration of renewables, due to their intermittent nature, if installed in high numbers.
- More control for end user can be present, for instance dynamic price schemes can be implemented in order to give end users decision in when power is consumed. This can also have positive effect on grid stability, because the grid will be unburdened at peak moments.

### 2.1.2. Microgrids in the Smart Grid Concept

“Going forward, we want to support microgrids. We don't see distributed generation as a threat.”

(Joseph M. Rigby, Pepco)

**Smart Grid**
The main grid was designed more than 100 years ago to fit the needs of that time. Large, centralized power plants were used to supply the rather straightforwardly predictable energy demand of the end-users. The power balance, which is the constraint saying that the power input shall match the power output at any time, was guaranteed using the economically most profitable power plant, to make sure the costs were minimized.

However, the environmental movement came in play, and old, dirty and big power plants cleared off in favour of new, green, distributed energy generating units, such as PV panels, wind turbines etc. This shift added extra uncertainty to the grid: instead of a predictable load-only curve, the predictions now also have to cope with less-predictable weather circumstances. In case of wind energy generation, determining the wind speed profile is rather precise, so this energy can be taken into account. On the other hand, when talking about solar panels, only one cloud in the sky can already alter the output drastically, making these devices very unpredictable.

Nothing changed in the laws of physics: the power input into the grid still has to match the power output at any moment in time. This means that when for instance an unpredicted cloud covers a solar field, the drop in power injection has to be covered instantaneously by another power generator. Nowadays this happens by using fast-starting turbojet engines, that consume kerosene for generating this power. This approach could mean that the installation of uncontrolled renewable energy sources could increases the amount of fossil fuels that are consumed at the end of the year.

The intermittent behaviour of renewable energy sources asks for new methods to reach this crucial power balance. Among others, some of these approaches are the installation of batteries in order to compensate sags in power supply, and the application of DSM which arranges the demand as a function of electricity supply. This is where SGs first come into play: these new tools are not easily implementable in the current grid, but ask for new measures in order for them to work as expected from them.

A SG is not a product, it is a concept bundling tools that are needed in the grid of the future. SGs can be seen as the power grid of the future, where the main difference with the current grid will be a shift from one-way towards two-way power and information flow. Currently, data about consumption flows from end-user to power plant, and power flows from the plant back to the user. In the SG, information will be exchanged between the power producing unit and the end-user, and also end-users can produce their own power and send it back to the grid if they do not need it or store it in their batteries.

A short comparison between the existing grid and the smart grid can be made, as summarized in Table 2.1.

**Microgrid**
Currently, µGs are a very popular area of research [19]. µGs are seen as an ideal means of increasing the development and adoption of SGs. It can be said that SGs focus on large improvements of the system as a whole, hereby using µGs as potential building blocks to achieve this goal. Since the adoption of improvements
Table 2.1: A comparison between the current grid and the smart grid

<table>
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<tr>
<th>Existing Grid</th>
<th>Smart Grid</th>
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<tbody>
<tr>
<td>Electromechanical</td>
<td>Digital</td>
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<tr>
<td>One-way communication</td>
<td>Two-way communication</td>
</tr>
<tr>
<td>Centralized generation</td>
<td>Distributed generation</td>
</tr>
<tr>
<td>Few sensors</td>
<td>Sensors throughout</td>
</tr>
<tr>
<td>Manual monitoring</td>
<td>Self-monitoring</td>
</tr>
<tr>
<td>Manual restoration</td>
<td>Self-healing</td>
</tr>
<tr>
<td>Failures and blackouts</td>
<td>Adaptive and islanding</td>
</tr>
<tr>
<td>Limited control</td>
<td>Pervasive control</td>
</tr>
<tr>
<td>Few customer choices</td>
<td>Many customer choices</td>
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</tbody>
</table>

To the public grid is a process that is expected to evolve slowly, the transition from the current grid to a SG will develop through a system of interconnected smart µGs [6, 21, 22].

A µG is, as the name suggests, an energy system on a limited scale, typically consisting of DRES and a range of loads. The grid has capabilities to operate in islanded or grid-connected mode, e.g. respectively decoupled from or connected to the main grid. The µG will operate as an autonomous grid, even when grid-connected, thus can be controlled to act as a constant load on the main grid.

µGs are able to provide small communities, e.g. residential, industrial, rural, public or military facilities, with electricity around the clock. Using a range of power sources and energy storage devices, power can be delivered to the end-users even when the wind stops blowing, the sun is not shining or preferences limit the use of a diesel generator.

Islanded operation of µGs has been defined in the IEEE Standard 1547.4-2011: IEEE Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems. The standard defines certain conditions to which a grid has to comply before it can be called an intentional island in the power system that contains distributed resources. These are, not very surprisingly, electric power systems that (i) have DRESs and loads, (ii) possess of the ability to disconnect from and connect to the main grid, (iii) include the local electric power system and (iv) are intentionally planned to be islanded.

In general, the µG is defined as “an integrated energy system consisting of distributed energy resource and multiple electrical loads operating as a single, autonomous grid either in parallel to or islanded from the existing utility power grid” [23].

When compared to SGs, similar behaviours of a µG are that it will also aim at meeting the demand as good as possible, hereby using more DRESs, improving the economical exploitation of the grid while also increasing the efficiency of the power usage. As already mentioned, µGs can be a small part of a larger SG, optimizing the behaviour of the latter on a local scale.

One unique characteristic a µG possesses is the possibility of supplying its loads even if the main grid is unavailable. This interesting feature is called the islanding mode. At the moment the main grid would go down, the µG is able to maintain the grid voltage and frequency using energy from the DRESs and storage devices. This is an attractive behaviour, since certain costs can be identified because of power outages:

- Industrial customer: probably large costs due to loss of production, maybe cleaning or repairing needed for sensitive equipment.
- Hospital: patients subject to potential life-threatening situations.
- Residential customer: can face a certain degree of discomfort.
The institutions that have the biggest risk in case of power outages, like these hospitals or data centres, will protect themselves against any casualties by the application of backup power generators, e.g. diesel generators. These cannot be called a good choice, being inefficient, environmentally unfriendly, and costly. The security of supply could be a subject of doubt, since in remote areas transport routes could be cut off. Finally, one characteristic of a diesel generator is that it takes a certain time before a cold generator reached its full power output.

Researchers have shown that a huge increase in reliability is possible in case hybrid μGs are applied [24]. In this case, the possibility of going into islanding mode will prevent any catastrophic results due to grid faults, outages or decreased power quality [25, 26].

It is important to realize that a μG is not just a glorified backup system. Next to the possibility of applying it as a backup system, a μG can do more, like performing real-time control in order to make the generation and storage match the consumption. Furthermore, an economical aspect can be coupled as well, for instance by delivering power to the mains at moments the electricity costs are high, and take power from the grid at low prices. As mentioned, a regime independent from the main grid also lies within the possibilities.

Remote Islanding Mode According to an estimate from the World Bank, made in 2010, 1.6 billion people did not have access to electricity [27]. In 2013, still an estimate of 1.2 billion people, or 17% of the world population, was living in an non-electrified region [28].

Most of these people live in remote and hardly accessible areas, often characterized by rough terrain and a low population density. Electricity lines would have to be very long and installed in harsh conditions in order to connect these people to the mains. It is also acknowledged that electricity is one of the drivers for a region to gain economic growth, and to combat underdevelopment. This is a situation for which the μG is a perfect solution.

2.1.3. Power Electronics

The project will make excessive use of the application of power electronic devices. These devices prove very useful for the project, because of the need to interface multiple power sources of different nature. Adequately applying power electronics will enable an interface between Alternating Current (AC) and Direct Current (DC) sources, thus facilitate a power flow from DRESs to the end-users or the BESS in case of abundance, and from the BESS to a multitude of loads.

Ways of Implementation

The way these interfaces are implemented and controlled depends on the desired operation. For instance, the requirements for the way DRESs interact with the grid will differ from the way a BESS has to behave. This is, DRESs will only inject power into an already electrified grid, hereby taking over the grid voltage and frequency that is seen by the device. On the other hand, in a grid supplied by batteries only, the inverter belonging to the BESS has to actively provide the grid parameters.

From this, it is clear that two main methods of implementing a power electronic device are around: the grid-forming and the grid-feeding scheme [29–31]. A third group can be isolated, this is the grid-supporting inverter, offering characteristics of both types.

Grid-Forming Mode A grid-forming inverter can be seen as an ideal AC source: the voltage amplitude and grid frequency can be set by using a proper control loop, and the inverter is connected to the grid through a small series impedance.

Another name for this device is Voltage Source Inverter (VSI). This means that from a grid point of view, the inverter is really an ideal voltage source, emitting power with a certain given frequency and voltage. This also means that the inverter is unable to influence its output power, as this is then a variable which depends on the loads connected to the grid.
Since the VSI has got a very small output impedance, the AC bus voltage and frequency can be expected to be well regulated. As a drawback, a very accurate synchronization mechanism is needed in case multiple VSIs are supplying the same grid: small irregularities will lead to big power flows between devices. This need of communication equipment can be seen as a disadvantage. As an example for a grid-forming inverter, we can name a standby uninterruptible power supply: a device with integrated battery which will take over the power supply to a certain area in case the main source of power would fail.

An inverter operating in grid-forming mode can be represented as an ideal source of AC voltage, as long as its limits and power ratings are not exceeded [30, 32–34]. Because of this latter requirement, the performance of power sharing is very important in case multiple inverters feed the same grid, not to exceed the limits of one of the actors.

**Grid-Feeding Mode** An inverter modelled according to the grid-feeding scheme always needs to see an already energized grid, before power can be injected into this grid. This means that a generator or a grid-forming device of any kind needs to be present in order to be able to work. The most basic representation of a device like this would be a current source, connected to the grid, with a high impedance in parallel.

The so-called Current Source Inverter (CSI) gives setpoints for active and reactive power, and the other grid parameters are used as is. This means that the grid-feeding inverter will not aim to influence the grid voltage or frequency. The devices are unable to operate in island mode, without a device being present that dictates the voltage amplitude and frequency of the network. However, if the network is connected to the main grid or supported by one VSI as grid-forming device, multiple CSIs are perfectly able to work together. In fact, most of the DRESs as we know them today are interfaced with the grid using the grid-feeding implementation. Here, we can think of PV panels or wind turbines.

**Grid-Supporting Mode** As can be seen from the previous analysis, certain drawbacks exist for both devices: if it is required to form a μG, the limitation that exists is that the network has to be fed by one and only one grid-forming device, and the rest of the devices need to be modelled in a grid-feeding way. In order to get more flexible requirements, the grid-supporting scheme should be applied.

In fact, a grid-supporting device is a mix between both previously mentioned inverters. It can be implemented either as an AC controlled current source in parallel with a shunt impedance, or an AC voltage source connected to the grid by means of a series link impedance. The inverter is able to change its output parameters according to what the network requires, thus the required behaviour is really the participation in the regulation of the grid voltage and frequency.

When implemented as a current source, the inverter is able to support the main grid in case of certain occurrences, e.g. facilitating a low-voltage ride through or fault ride through for mega wind turbines. This is not the aim of the project.

If a grid-supporting inverter is modelled as being a voltage source with an output impedance, it will emulate the behaviour of an AC voltage source. In fact, it can be compared with this of a synchronous generator. The link impedance can be connected either physically, or be modelled as a virtual component in the current control loop. The device is able to work both in islanded as well as grid-connected mode, without the need of changing any parameters in the control scheme, and multiple devices can power the same grid.

**Components**

Next to the way the controller will be implemented, it can be useful to take a moment and discuss the components that will be used as interface between different power sources and users. The main component will be the Pulse Width Modulation (PWM) inverter. This is an inverter that can work either in bidirectional or unidirectional mode, which means that respectively the inverter is able to transport power both from the AC to the DC side and vice-versa, or only from one side to the other. For the sake of being able to recharge the batteries, it is obvious that for the BESS a bidirectional device will be needed.
Figure 2.1 shows a schematic representation of a PWM inverter [35]. The most basic form of a three-phase PWM inverter comes with six bidirectional switches, as can be seen on the drawing, that all have turn-off capability. Figure 2.2 shows how the output voltage and current are created [36]. By consecutively switching on and off the right switches, the magnitude of the current is influenced, in order to create AC starting from a DC source.

Figure 2.1: Equivalent model of a PWM inverter [35]: The figure shows what a PWM inverter looks like in a schematic representation. A basic three-phase PWM inverter needs six switches with turn-off capability. The bidirectional PWM inverter is able to invert DC to AC and vice versa.

Figure 2.2: Waveform of output voltage and current [36]: The figure shows clearly how the current through an inductor can grow by manipulating the voltage, which is done by means of properly turning the switches on and off.

The output waveform depends on the switching technique that is used. Three common techniques exist: no modulation, rectangular modulation and sinusoidal modulation. The magnitude of the voltage output can be calculated as:

\[ U_{AC} = K_0 \cdot P_m \cdot U_{DC}, \]

where \( K_0 \) depends on the type of modulation that is applied, and \( P_m \) is the modulation factor.

For sinusoidal modulation, where the amount of harmonics in the output signal is acceptable, and which can be called the standard modulation technique in power applications, the constant \( K_0 \) is calculated by:

\[ K_0 = \frac{\sqrt{3}}{2\sqrt{2}}. \]

For the DRESs, such as PV panels or wind turbines, a similar device will be used, though a unidirectional structure will suffice. This because no power needs to flow from the grid back to the renewable power source.
2.1.4. Prospection of the Controller

When it comes to controlling μGs, there are two main possibilities in architecture of the control organism: either the grid is controlled in a distributed way, or a central controller is applied [10]. Sometimes both architectures are combined, depending on the parameters that are subject to optimization. The main requirement of a μG formed by inverters is the fact that the inverters need to provide grid-forming capabilities [30].

Centralized Control

It seems that a lot of concepts make use of a central controller that makes the decisions and communicates with all the actors on the grid [37–40].

High-bandwidth communication is not always needed: in order to optimize the decentralized power sharing, low bandwidth communication [41] or wireless technology [42] seems to be sufficient, even power line communication in the form of injecting a sinusoidal signal of a specific frequency into the grid can be applied [43], circumventing the need of a dedicated communication network.

Furthermore, it seems that some distributed control approaches still rely on some communication equipment, often limited to a slow communication link between neighbouring actors [44, 45]. Even though each actor of the grid has the ability of making decisions, the behaviour will still be determined by iterative data exchange among agents.

Decentralized Control

Methods are on hand that remove the need of a centralized controller, hence dedicated communication signals. The advantages of this lay in the fact that no communication equipment is needed for a satisfactory behaviour of the grid. Some advantages can be listed.

- In terms of costs, the system will probably be cheaper since less complex components are to be applied.
- The architecture of the overall grid will be less complex to understand and to maintain.
- A higher availability can be expected, in the sense that a system which has to rely on two separate networks to work, here the electrical network and the communication network has a bigger chance to fail than a network with only one critical link.
- The grid is of a modular kind, to which plug & play devices can be coupled, offering an extendible layout.

With decentralized control the aim is to use readily available parameters on an AC-grid, i.e. the grid frequency and voltage. By influencing these signals in a smart way, the need of dedicated communication equipment can be avoided.

Some issues should be adequately addressed by the decentralized controller in order to make it stable [46]:

1. Global stability of the system should be reached by the decentralized controller using local parameters.
2. The total load should be shared in a good way among the inverters.
3. Any oscillations between output filters of different inverters should be damped out.
4. No DC voltage offset should be present on the grid.

The application of using active power – frequency (P/f) and reactive power – voltage (Q/U) droop schemes, which will be explained further in § 2.1.5, has been a field of research for a long time [16, 47–50] and is currently still being applied, tested and improved [51–54]. From this work, it turns out that the application of this way of control successfully bypasses the need of external communication signals; the network frequency can successfully serve as an implicit signal for communication [55].

The droop control concept makes a static inverter, from the point of view of the grid, behave in a similar way like a synchronous generator does, by introducing a negative relationship between active power and grid
frequency: if one goes up, the other goes down.

It is clear that some work has already been performed in the field of distributed µG control, making it possible to implement a µG avoiding the use of central control organs and their needed communication signals.

**Comparison Centralized and Distributed Control**

It can be argued that a decentralized control approach, like the one that is proposed in this project, has got many benefits over a situation where the controller is a central device and all the actors on the grid act like slaves of this master controller. The main drawback in this second technique, where one controller needs to collect all the data, make decisions and sends control setpoints back, is the necessity of communication signals, increasing the costs and the tendency of failure of the system. Further drawbacks of this approach can be listed.

- If the controller or one of its components fails, the whole system fails. If redundancy needs to be achieved, the total costs of the system are expected to increase drastically.
- The hardware applied needs to perform very well, and the communication system needs to have high speed- and low-latency properties. Those requirements further increase the costs.
- If the central controller requires maintenance, this has an impact on the system as a whole.

On the other side, if one controller takes all the relevant decisions, we can expect that the whole system will work at a working point closer to the optimum point, so the behaviour will be closer to the economical situation [39, 56].

It has been shown that both central and distributed control methods are possible choices for controlling a µG. A division is distinguishable between control methods that need, sometimes limited, communication between multiple inverters feeding the same grid, and other methods where no communication is needed, and only the grid voltage and frequency suffice to reach a satisfactory behaviour of the grid. It may be clear that a system where an advanced communication interface is available will have a superior performance — this is, if the communication equipment is available.

In what follows, the consideration is made to see which one of these possibilities is more favourable.

To start, some characteristics of both methods can be listed:

- **Control decisions occur at local level:**
  - Controllers use locally available info of voltage and frequency.
  - Loads control their own shedding.
  - DRES controller makes curtailing decisions.

- **Central controller is applied:**
  - Forecasting of load demand is possible.
  - Forecasting of weather, thus of DRES production is possible.
  - Dispatching can occur in an economically optimal way.
  - Black start capabilities are easier to implement.

As can be seen from this list of characteristics, both approaches seem to be viable choices. However, if we look further, there are more benefits to a decentralized approach [16, 57]:

- A less complex controller is needed per device.
- If one device fails, this does not result in a catastrophic situation.
• A decentralized system is easily scalable and expandable.
• Upgrades are easily implemented.
• No need of communication redundancy.
• Each node acts autonomously but still closely together with the other subsystems.

Of course, as we are not living in an ideal world, these benefits are sometimes nullified by certain drawbacks, including:

• No possibility of implementing a secondary controller, which means sustained deviations in frequency and voltage from the nominal value.
• Sharing of active and reactive power might not be perfectly balanced.
• The components have to deal with control tasks.

For the sake of this project, making a decision between using a centralized or decentralized approach can be made purely using the project description, clearly describing that the system must be able to work without any means of external communication equipment [11], only the available signals, thus grid frequency and voltage, are allowed to be used. This requirement rules out the possibility of using a centralized approach, as in this concept the central controller needs to communicate setpoints to the actors.

2.1.5. P/f AND Q/V Droop Schemes
In the previous section, some ideas are presented that can help to succeed at the objective which states that, if it is possible, no communication equipment should be used in the network. However, the terms and concepts that have been used can sound confusing or blurry, thus they might not be very clear to a reader who might be new to this subject. Therefore, in what follows, the background of these concepts will be explained in greater detail.

Rotating Generators
In order to understand the behaviour of droop curves as grid-forming control method for static inverters, the basics of droop speed control should be explained from a historical and mechanical point of view. Let us start with an infinitely strong public grid, with well-defined values for frequency and voltage, and we want to attach a power generating device to this grid in order to inject power into the grid. If now the frequency setpoint of this generator deviates even slightly from the grid frequency, due to always-present imperfections in the production process, measurement errors, or drift of components, the prime mover controller will either completely turn off the generator by closing the fuel supply, trying to decrease the grid frequency, or inject maximum power into the grid, aiming to push the grid frequency up.

No stable working point can be achieved, as can be seen on Figure 2.3. In both situations, the generator safety breakers should trip in order to protect the device. A similar reaction between the automatic voltage regulation and the reactive power will be seen. It can be concluded that the generator works unsatisfactorily when connected in isochronous mode to a strong grid.

A different means of control is needed when a generator has to be able to inject power into a powerful grid satisfactorily. This is done by application of the droop speed control: this method consists of changing the power output ($\Delta P$) of the generator if a deviation in frequency ($\Delta f$) is noticed. The way a stable working point between an infinitely strong grid and a generator is found can be seen in Figure 2.4. The droop value $K_p$, defining the ratio of frequency change to output power change, is fixed mostly somewhere between 3 and 5% [58].

It can be seen as the opposite of the gain of the controller, as such that a small droop value introduces a very big power deviation when a small frequency deviation occurs. Thus, a droop coefficient that is too small could lead the system into instabilities [59].
2. Background Review on Cellular Microgrids

Figure 2.3: Isochronous generator trying to supply a powerful grid: It is clear that a stable working point between a generator controlled in an isochronous way and the public grid does not exist.

Figure 2.4: Necessity of droop speed control for a generator supplying a powerful grid: It is clear that a single, stable working point exists for the power injected by a generator into the grid, if this generator is controlled by means of a droop curve.

Figure 2.5: Droop speed control for two parallel generators: Both generators will change their output power, in order to find a working point where they can work together in a stable way, on the point where the frequency setpoint of both devices is the same.
Power Dependency of Frequency  It is clear that a strong correlation exists between the active power consumed from the grid and its frequency. These two variables are interconnected in both directions: (i) if the power consumed from the grid increases but the injected power stagnates, then the frequency will start to decrease, and (ii) if the generator tries to introduce a higher frequency to the grid, then in fact the power injection will increase, in turn effectively increasing the grid frequency. This can be seen on Figure 2.6 [60].

Figure 2.6: Frequency dependency on the active power [60]: It is clear how the active power injected into and used from the grid have their influence on the grid frequency: in case the injected power would surpass the consumed power, the grid frequency would increase.

In the current grid, measures are used in order to keep the grid frequency within predefined limits. This because the grid frequency can be seen as an indicator of the overall power balance on the network. If the balance is broken, this is noticed in a deviation of the frequency. As a first measure, there is the proactive step, consisting of the prediction of parameters, which is possible within very close margins [61]. This way, before the consumption actually takes place, the supply side already knows with high precision how big the consumption will be.

This proactive control is not entirely correct. Therefore, a reactive control scheme has to be present, which consists of the primary, secondary and tertiary frequency control. The concept is very straightforward: when the frequency deviates from a predefined setpoint, the control mechanisms will try to restore the grid frequency back to the normal value.

As soon as a big load is connected or disconnected from the network, this will be noticed in the grid frequency, as is clear from the Swing Equation, shown in Equation (2.1). A sudden increase in load will cause a rise in the burden of the generator, causing the rotational speed to decrease. This will be seen by the primary controller, which will increase the output power.

\[ P_a = P_m - P_e = J \frac{d^2\delta}{dt^2} \]  

where \( P_a \), \( P_m \) and \( P_e \) are respectively the accelerating, mechanical and electrical power, \( J \) is the total moment of inertia of the system, and \( \delta \) is the angular position of the rotor with respect to the synchronous frame.

This primary control will be the first one to react on this frequency drop by applying the concept of droop speed control, increasing the power output as a reaction to a decreased grid frequency. The purpose of the primary control mechanism is to stabilize the grid frequency and prevent further deviations. The reaction is a purely proportional signal, increasing the power generation from the generators and stopping the frequency
from diverging, but it is not capable of restoring the initial setpoint.

This is where the slower, secondary control comes into play. This controller also includes an integrating function, which means that its setpoint will actually be reached at the end of the control action. Thus, the secondary controller will start to work after the primary controller finished its job, by changing the generator output power slightly higher or lower than the power demand, this way slowly driving the grid frequency back to the setpoint.

The tertiary control is a slow control mechanism, used to reallocate the power increases or decreases per generation unit which happened by means of the primary and secondary control. This reallocation aims at achieving the economic optimum working point of the system as a whole.

Summarizing, the primary control is there to deliver reserve power opposed to any frequency change; secondary control will deliver reserve power bringing back the frequency and re-allocating load flows; and the tertiary controller will slowly, sometimes manually initiated, change the unit commitment to restore the secondary control reserve, cope with eventual congestion, and restore the frequency in case the secondary control turns out to be insufficient.

**Emulated Inertia**

A static power generating device, such as a power electronics inverter, does not dispose of inertia, which could be problematic in a future grid where a lot of rotating synchronous machines are replaced by static power electronics.

This could mean that a small disturbance on the grid will quickly lead to large frequency deviations, in their turn leading to an unstable grid, if the control is performed badly. Also the other advantage achieved by applying droop speed control, which is the automatic sharing of power among the generators according to their capabilities, will be decreased.

It can be understood that other measures could be needed when a grid supplied only by static generators is used. One of these measures is found in emulated inertia. This virtual inertia, which is in fact an energy buffer performing short-term energy storage, will stabilize the grid when combined with an adequate control mechanism [62, 63]. The implementation of virtual inertia can remove the limits on the amount of allowable DRES penetration in the grid.

**Static Generators**

Now that the basic working principles of the droop concept are revised, a step can be made towards the implementation of this droop control in static generators. Maybe the most evident way of doing this would be to exactly mimic the rotating generators, thus using the active power as a function of the frequency. However, since the static generators will be controlled as being VSIs, and more specific as a grid-supporting inverter as explained in §2.1.3, the power supplied is fixed by the load on the grid, and cannot be controlled by the inverters themselves.

On top of that, if a generator is feeding an inertialess grid, it is simply impossible to inject more or less power than what the loads are consuming. This is because the basic law of power balance needs to be observed: the injected power shall equal the consumed power at any time. And, unlike on a system with rotating inertia which can take or supply this difference by accelerating or decelerating the rotating mass, a static system is unable to supply or absorb the missing power. Therefore, in a static system where the power consumption is dictated by the connected loads, frequency deviations cannot be introduced by changing the injected power.

Because of this, it is proposed to turn the behaviour around, thus to control the grid frequency as a function of the power. This will be done by measuring the power flow from the inverter and subsequently calculating the frequency output according to the drooping behaviour [16]. Similarly, the reactive power output is measured and used to adjust the voltage setpoint. This behaviour is shown in Equations (2.2) and (2.4). This method is viable for inverters that are controlled as VSIs, since the control scheme for these inverters asks for a voltage and frequency setpoint. This in contrast with a CSI, where the control scheme asks for P and Q setpoints.
\[ f_i = f_{0,i} - K_{p,i} \cdot p_i \]  
\[ K_{p,i} = \frac{f_{\text{max}} - f_{\text{min}}}{p_{0,i}} \]

where \( p_i \) is active power output of inverter \( i \), \( f \) is the actual grid frequency at which the system currently operates, \( p_{0,i} \) the rated power output of the inverter and \( f_{\text{min}} \) and \( f_{\text{max}} \) are respectively minimum and maximum allowable frequency. \( K_{p,i} \) is the gain of the droop curve of the \( i \)-th inverter.

Similar formulas can be acquired for the voltage depending on the reactive power:

\[ U_i = U_{0,i} - K_{q,i} \cdot q_i \]  
\[ K_{q,i} = \frac{U_{\text{max}} - U_{\text{min}}}{q_{0,i}} \]

In its concepts, the voltage drooping is perfectly equal to the concept of the active power droop. In practice, however, the droop behaviour will be influenced by the voltage drop over line impedance, which does not happen with the frequency droop. This can have an influence on the effectiveness of reactive power sharing.

An inverter that is grid-connected cannot impose the grid voltage or frequency, as the main grid is supposed to be an infinitely strong source, fixing these variables. In this case, an inverter behaving according to the droop curves will inject active power according to:

\[ P = \frac{f_0 - f_g}{K_P} \]

and reactive power will follow

\[ Q = \frac{U_0 - U_g}{K_Q} \]

where \( f_g \) and \( U_g \) are the grid frequency and voltage, \( f_0 \) and \( U_0 \) the zero-power frequency and voltage of the droop curves, and \( K_P \) and \( K_Q \) the absolute droop coefficients.

Now, if multiple VSIs are feeding the same \( \mu G \), without a main grid, then the voltage and frequency can be said to be variable, and will depend on the interactions between the inverters. Then, \( \Delta f \) and \( \Delta U \), respectively the deviation of the nominal frequency and voltage, will be calculated by:

\[ \Delta f = K_{p,i} \cdot \Delta P_i \]

and

\[ \Delta U = K_{q,i} \cdot \Delta Q_i \]

where \( \Delta P \) and \( \Delta Q \) are the active and reactive power variations, and \( K_{p,i} \) and \( K_{q,i} \) the absolute droop coefficients for active and reactive power of the \( i \)-th inverter.

In order achieve power sharing among different inverters, based on their power rating, the droop values should be chosen according to Equation (2.6) [64].

\[ K_{p,i} P_i = K_{p,j} P_j \]  
for all \( i, j = 1, \ldots, n \)

where \( P_i \) is the absolute power rating of the \( i \)-th inverter, \( K_{p,i} \) is the absolute and \( K_P \) the relative droop coefficient.
A similar behaviour can be deduced for the reactive droop coefficient. Construing this equation tells us that the relative value for the droop shall be equal for all devices, in order to achieve satisfactory power sharing among devices of different power ratings. For this reason, from now on the droop coefficients will be called $K_p$ and $K_q$ instead of $K_P$ and $K_Q$, pointing at their relative definition.

It is possible to reach power sharing using the voltage phase shift $\delta$ instead of the grid frequency [65]. The reason for that can be found in the fact that the actual drooping behaviour really works by means of influencing this voltage phase angle, as will be explained in what follows. Thus by directly influencing this, rather than indirectly by means of the droop value, lower steady-state frequency deviations will be seen. However, since doing so would rule out the possibility of communicating the SEP through the grid frequency, this idea is omitted.

Sensitivity analyses were performed on the mathematical side [66, 67], proving the effective functioning of the system on both idealized and lossy networks, and providing ranges for values for both active and reactive power droop constant [55].

Active and Reactive Power Flow

By mimicking this way of parallel operation for synchronous generators supplying one bus, a good decentralized behaviour can be obtained for static inverters. Due to the lack of inertia and stability in a low-voltage $\mu$G supplied by static inverters, and due to the differences in cable parameters, when compared to the big main grid, the stability of these systems is of great importance and should be investigated. Some problems in this sense can be defined [68, 69]:

- On the high voltage network, the line impedance $Z$ is predominantly inductive. This means that the line reactance $X$ is dominant over the line resistance $R$, and the so-called $R/X$ ratio of the line is small. However, in a low-voltage $\mu$G, due to small cable sections, the behaviour of the network will be mainly resistive, leading to a coupling between real and reactive power.

- Due to unequal voltage drops because of unequally distributed line impedances, the performance of reactive power control drops even further.

The problems could be partially or even fully solved in case the grid impedance would be mainly inductive, cutting down the $R/X$ ratio of the network between two sources. This can be achieved by implementing a virtual impedance in the controller [70, 71], thus virtually decreasing the $R/X$ ratio in order to reach a similar behaviour as the conventional power system, leading to a decoupling of active and reactive power. It is seen that the virtual impedance is able to decouple the active and reactive power, by simulating the behaviour of a mainly inductive grid, even with mainly resistive line parameters. No inductor needs to be physically connected for this, as the step merely consists of a change in the controller.

The power and frequency droop control method is based on the real and reactive power flow between two power sources with an impedance $Z$ in between, with $Z = R + X j$, which will be quickly reviewed.

If $E$ is the voltage of the main grid and $V$ the voltage of an inverter, then the power flow between those two power sources can be described [48, 72, 73]:

\[
P + jQ = S = EI = E \left(\frac{E - V}{Z}\right) = E^2 \frac{e^{j\phi}}{Z} - EV \frac{e^{j(\phi + \delta)}}{Z} \tag{2.8}
\]

where $E$ and $V$ are the magnitudes of the voltages, $\delta$ is the phase angle difference and $Z$ is the line impedance.

From this, it follows:
Figure 2.7: Power flow through a line: Transporting the amount of apparent power $S$ through the cable with an impedance $Z$ will cause a voltage drop which can be calculated.

$$S = \frac{E^2}{Z} \cos\phi - \frac{EV}{Z} \cos(\phi + \delta) + j \left( \frac{E^2}{Z} \sin\phi - \frac{EV}{Z} \sin(\phi + \delta) \right)$$  \hspace{1cm} (2.9)$$

and thus:

$$P = \frac{E^2}{Z} \cos\phi - \frac{EV}{Z} \cos(\phi + \delta)$$  \hspace{1cm} (2.10)$$

$$Q = \frac{E^2}{Z} \sin\phi - \frac{EV}{Z} \sin(\phi + \delta)$$  \hspace{1cm} (2.11)$$

Knowing that

$$Z = R + jX$$

and using

$$\cos\phi = \frac{R}{Z}$$

$$\sin\phi = \frac{X}{Z}$$

and the sum and difference formulas for sine and cosine, Equations (2.10) and (2.11) yield:

$$P = \frac{E}{R^2 + X^2} (R(E - V \cos\delta) + XV \sin\delta)$$  \hspace{1cm} (2.12)$$

$$Q = \frac{E}{R^2 + X^2} (-RV \sin\delta + X(E - V \cos\delta))$$  \hspace{1cm} (2.13)$$

where $P$ and $Q$ are respectively the active and reactive power that flows in the lines.

**Influence of Line Impedance**

The derived formulas for active and reactive power flow between two sources can be simplified, according to the situation which is dealt with. This will be done for the high voltage grid, with a very low R/X ratio, and a low voltage grid, where the opposite holds true.

**High Voltage Grid**

Analysing Equations (2.12) and (2.13) leads us to some interesting insights. It is known that on high voltage lines, the line reactance $X$ is bigger than the line resistance $R$. In fact, the latter may be neglected, as seen in Figure 2.8 (plotted using data from [74]), and doing so yields Equations (2.14) and (2.15).

Furthermore, the phase angle difference $\delta$ is typically a small value, allowing to the assumption that $\sin\delta \approx \delta$ and $\cos\delta \approx 1$. In this case, the flow of real power will be proportional to the phase angle difference $\delta$ only, and the flow of reactive power will depend on the difference in voltage magnitudes, as shown in Equations (2.16) and (2.17). This leads to the possibility of influencing the active power flow by varying the phase angle, or in practice the output frequency, and similarly, the reactive power flow is influenced by varying
the magnitude of the output voltage. This is a concept which holds true in both islanding and grid-connected applications.

\[
P = \frac{E \cdot V}{X_{\text{line}}} \cdot \sin \delta \quad (2.14)
\]
\[
Q = \frac{V^2}{X_{\text{line}}} - \frac{E \cdot V}{X_{\text{line}}} \cdot \cos \delta \quad (2.15)
\]
\[
\delta \approx \frac{X_{\text{line}} \cdot P}{E \cdot V} \quad (2.16)
\]
\[
E - V \approx \frac{X_{\text{line}} \cdot Q}{E} \quad (2.17)
\]

Figure 2.8: R/X ratio with increasing cable section: From this plot, the change in the cable resistance-to-reactance ratio is immediately clear. From literature dealing with power sharing between sources, it is known that a smaller R/X ratio leads to a better sharing of active and reactive power when droop control is applied.

**Low Voltage Grid** The problem with low voltage \( \mu Gs \), like the one discussed in this thesis, is the fact that they have different line properties: the line resistance is not negligible and can in fact be more important than the line reactance, because the lines short and have low sections, thus are not inductive. The R/X ratio for cables with different sections is shown in Figure 2.8. This characteristic of cables applied in \( \mu Gs \) implies that the real and reactive power flows will not be decoupled inherently. When taking this further, and assuming that the lines are only resistive, the following behaviour is obtained:

\[
P = \frac{E}{R_{\text{line}}} (E - V \cdot \cos \delta) \quad (2.18)
\]
\[
Q = \frac{E \cdot V}{R_{\text{line}}} \cdot \sin \delta \quad (2.19)
\]

Again, it can be said that \( \sin \delta \approx \delta \) and \( \cos \delta \approx 1 \).

\[
E - V \approx \frac{R_{\text{line}} \cdot P}{E} \quad (2.20)
\]
\[
\delta = -\frac{R_{\text{line}} \cdot Q}{E \cdot V} \quad (2.21)
\]
According to Equations (2.18) and (2.19), it can be argued that a so-called opposite droop scheme is required in case of a highly resistive grid, where the voltage depends on the active power, and the frequency is a function of reactive power. However, a system with this opposite droop behaviour loses its compatibility with the higher grid and with standard generators [75]. Therefore, this is not the most favourable solution.

It is seen that the conventional droop curves, thus the ones that were used throughout the whole section, can be applied by using a workaround [75]. Bypassing this problem can be done by connecting an inductor to the inverter, making the behaviour of the grid, as seen by the inverter, predominantly inductive. This will probably be included in the end project as a LCL-filter will be needed at the output of the inverter.

A solution can also be offered using software, where a virtual output inductor would be implemented into the controller. This way, an inductive impedance can be added to the grid, without the need of physically connecting a passive component. This is done by using the line current for calculating the voltage drop over the virtual inductor $V_L$, and subtracting this value from the reference value for the voltage. Hence, the final inverter reference voltage is obtained, and from the point of view from the inverter, the grid has an inductive behaviour.

If this inductance is implemented successfully, the real and reactive power flows will be decoupled, resulting in a satisfactory behaviour of the P-f and Q-V methods. This will also make the system inherently compatible with rotating machines that apply these droop curves, consequently with the main grid.

It is possible that the reactive power will never be shared perfectly, due to ever-present voltage drops over the resistance of the lines, influencing the reactive voltage sharing scheme [76]. It can however be expected that a grid where the reactive power is being shared satisfactory, though not perfect, already meets the expectations. Some drawbacks are unavoidable with using a system where ICT equipment is avoided, so concessions have to be accepted.

**Dynamic Behaviour**

As mentioned earlier in this section, the generally applied, well-known behaviour of the droop curves is turned around in this work. Current applications of drooping behaviour rely on a grid inertia in order to work: when the frequency deviates, the power input is increased or decreased, and the grid inertia respectively absorbs this power and accelerates, or supplies some power and decelerates.

However, in this project, grid inertia might not be present. Thus, increasing the injected power for the sake of increasing the rotational speed of the grid inertia cannot be done. On top of this, if the inverters are controlled as being VSIs, the required input signals to the inverters are the grid voltage and frequency, and not the power. So there is a fundamental clash between the common approach and the one needed in this work.

As explained before, this clash is solved by turning around the droop behaviour: since the power supplied by VSIs is dictated by the load on the grid, this power is measured and the output frequency is adapted. It is clear that on a grid with only one inverter, this method can be applied. However, one might expect problems in case this same approach is applied for multiple VSIs powering one load: at the moment one of the inverters would like to change its output frequency, we have a situation where we interconnect multiple sources with a different output frequency, which leads to problems on the grid. Huge currents will flow in the grid because of big values for $\delta$, as can be noticed from Equation (2.14).

However, this will not happen in this system. The reason for this is simply that all inverters are equipped with the drooping behaviour. This can be explained as follows: let us take a grid supplied by two inverters. They are interconnected, synchronized, and sharing one load. As long as the frequency output of both sources stays the same, the phase angle difference $\delta = \Delta \theta$ will not change, thus no changes in the system take place.

The phase angle $\theta$ is calculated by means of integrating the frequency ($\omega$, in rad/s). Still knowing that $f = f_0 - K_p \cdot p$, and $\omega = 2\pi f$, we can write:

$$\theta = \omega \cdot t = \int K_p \cdot p \cdot dt$$
and
\[ \theta_1 = \theta_2, \]
thus
\[ \delta = \text{constant}. \]

However, at a certain moment in time, Inverter I increases its zero-power frequency setpoint \( f_0 \), for whichever reason. The result of this change is that the output frequency of the first inverter increases.

This leads to an increase in the angle \( \delta \) between the vectors of both voltage sources, equal to the integral over time of the frequency difference of both inverters:
\[ \delta = \int (\omega_1 - \omega_2) \cdot dt. \]

This increase in \( \delta \) leads to an increase in power flowing from Inverter I to Inverter II. From Inverter II’s point of view, this means that less power needs to be supplied, thus following the droop curve to the left, the output frequency of Inverter II increases. This stops \( \delta \) from rising, moreover, \( \delta \) will drop again.

The interaction between both inverters leads to a new, stable setpoint where both inverters share power according to their needs. In the above case, by increasing the zero-power frequency, Inverter I will end up supplying more power than before the disturbance took place.

**Stability**

An analysis can be made of the dynamic stability of the system. However, before moving into the field of control engineering, where the droop coefficient can be optimized, it can be useful to think about the consequences of applying a big or a small droop value.

As was explained earlier, in a common system with rotating devices, the change in power \( \Delta P \) depends on the change in grid frequency \( \Delta f \). In case a small droop coefficient is applied in a system like this, we will notice a big reaction of the power to small deviations of the grid frequency. Thus, a small droop value means that the gain of the system is big, and taking this too far will lead the system into unstable behaviour, due to too direct reactions.

On the other hand, there is the system described in this work, where the output power is measured and used to calculate the frequency deviations. In this case, the behaviour is turned around: a small droop value means that a big change in power leads to a small reaction of the frequency, and similarly, a steep droop curve will introduce a very powerful reaction of the frequency when small changes in the output power are seen.

In this case a big droop value introduces a big gain: small changes in power lead to big reactions of the frequency, thus big deviations in \( \delta \). Consequently, other inverters connected to the grid will know an equally strong reaction to the change in output power they see, introduced by the change of \( \delta \). This means that a small change can lead to a cascade of big reactions, possibly putting the stability of the grid at risk.

It can be understood that stability analysis is a very important issue for these \( \mu \)Gs. In previous works, complete state-space models have been developed, being capable of judging a system on its small-scale stability with changing parameters [23, 77, 78]. This makes it easy to predict how a system will react to specific values for parameters. However, with a big number of inverters and loads connected to the system, and because also for instance cable dynamics have to be taken into account, these systems become very complex. Reduced models can be produced, for instance by ignoring the dynamics of the voltage and current controller of the inverters [79], though with a doubtful prediction of system stability in case of dealing with fast systems, which a \( \mu \)G based on power electronics definitely is [80].

Stability of the system can also be investigated by means of dynamic phasor modelling, yielding a system that is simple and effective [80]. This means can take into account also the dynamics of all the elements without drastically adding to the complexity of the system as a whole.

Because of the fact that the system stability is an important concept, it will be discussed more thoroughly throughout Chapter 4.
2.1.6. Power Quality

Power Quality (PQ), sometimes also referred to as Electric Power Quality, concerns all the rules and regulations that have been defined in order to keep the waveform of the voltage on the power bus near sinusoidal, at rated magnitude and frequency [81, 82]. It defines the quality of the electric power that is being distributed to the end-users, which is important because with a lack of PQ, loads can be expected to malfunction or even fail to work.

One of the important parameters defining the PQ is the continuity of service, which basically means how long the power is available within the predefined minimum and maximum values. It is expected that, if the μG discussed throughout this thesis is implemented, this aspect can be improved since the concept will have a positive impact on the system availability.

EN 50160

The well-known standard EN 50160, defining the European Grid Code, sets certain rules for the power quality to which the European Grid has to comply [83]. EN 50160 can be seen as a referee, keeping an eye on the interactions between the grid operators, the end-users and the manufacturers of devices.

EN 50160 specifies the grid parameters, and to which extent they can deviate from the nominal values. For instance, the maximum allowable frequency deviation is set to ±1%, or an interval of 49.5 – 50.5 Hz, for 99.5% of the time [84]. For the other 0.5%, or about 44 hours per year, the allowable frequency interval is 47 – 52 Hz, or +4% to −6%. In the Netherlands, the grid regulations have been adapted before adoption, which results an interval of 50 Hz ±1% for 99.9% of the time, and 50 Hz +2% / −4% for the rest of the year [85].

Some parameters concerning the grid voltage have been specified as well. Of these, the most important ones are nicely presented in Figure 2.9 [83].

Remarks

It can be seen that the requirements for the PQ are very strict, and it could be argued that they are in fact maybe too strict. As an example, the limit for the flicker severity points at a philosophy where the main sources of light are still incandescent light bulbs. Flicker concerns a quick variation of the grid voltage, which can be noticed in a flickering behaviour of these lights. This can be perceived as annoying by people, therefore the flicker severity was limited. However, in case the main sources of lighting become energy saving bulbs, flicker is of no concern anymore.

Also, the strict frequency limits are expected to be prone for an update. These frequency limits still come from the time when powering the grid was a matter of centralized power plants, and keeping the frequency within these limits was easier and more important than what it is today, considering the growing implementation of DRESs.

We can see that the current grid standards will probably hold the proposed μG from being allowed to be installed into the grid, since deliberate frequency deviations for the sake of active power control and similarly voltage deviations for reactive power control might push the grid characteristics out of the bands defined by the standard.

2.1.7. Distributed Energy Resources

Distributed energy resources, and if possible distributed renewable energy sources, should be the main suppliers of the energy used in the μG. DRESs include, but are not limited to, solar panels, wind turbines, geothermal energy, hydroelectric, biomass etc. In the current grid, DRESs only account for a small part of the total energy supply, which explains why they do not have a huge impact on the grid behaviour; the main dynamics of the grid are still determined by the central power plants, which consists of big turbines rotating in a synchronous way, providing thousands of kilograms of rotating steel to support the grid stability.

If now the sun is shining and suddenly drops away, this change in energy injected into the grid is not noticeable if the penetration of solar energy into the grid is not immense, therefore no stability issues arise.
However, at the moment these PV panels become the main supplier of power, the stability of the grid is endangered when, for instance, unpredictable and inevitable clouds pass by and no rotating inertia is present to cover this sudden dip in power. This makes a grid that mainly relies on volatile and unreliable DRESs unstable by nature. Measures have to be taken in order to run a grid on solely DRESs.

One of these measures is the installation of a buffer into the grid, which can be a BESS, as will be mentioned in \S\ 2.1.10. This will, when the output power of the DRESs suddenly drops, fill the gap between the required and available power, but also when the load would suddenly drop, the BESS is able to consume remnant power.

Another adjustment to be made is the act of \textit{curtailing} the energy from DRESs, often addressed as SSM, as will be mentioned in \S\ 2.1.9. Power curtailment is a measure that is needed to keep a grid with mainly uncontrollable power sources stable, by limiting the power produced by the DRESs at moments the power cannot be consumed by the loads nor stored in the batteries.

Digression on the mentioned problems will not be done in this section, here merely a short introduction is presented of the distributed power sources that will be applied in the work: solar panels and wind turbines. In order to reach a system with more freedom or security of supply, it can be appropriate to expand the number and type of distributed energy sources, as doing so is expected to rule out any intermittent behaviour of one of the sources.

As an example, using a hybrid of solar and wind energy will already ensure a certain degree of levelling the injected power, since wind energy is also available during the night. It can be understood that a more diverse

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure29.png}
\caption{Important voltage parameters of the EN 50160 standard: The grid voltage has to comply to certain characteristics, in terms of variations, dips, quick changes etc. These are nicely depicted on the figure.}
\end{figure}
mix of sources will result in a levelling that is taken much further. Adding a controllable device, for instance a diesel generator, offers tools to take the security of supply way beyond what can be done with using renewable sources. This is, however, not studied in the thesis.

Solar Energy

One of the first sources of renewable power that will probably be thought comes from solar panels, also called PV panels. It is probably common knowledge that a PV panel is able to generate power when illuminated by the sun, or by any other light source. A deep analysis of the physics of semiconductors that lie behind this behaviour would lead us too far from the goal of the thesis, but a quick explanation of the components and general behaviour of a PV power plant can be discussed.

As stated, a solar panel will generate power when illuminated. This power comes available in the form of a DC voltage and current, thus PV panels cannot be directly implemented into the grid. Measures are needed, which come in the form of an inverter, interfacing the DC voltage coming out of the PV panels with the AC voltage on the grid.

In general, the voltage and current magnitudes generated by one single panel would prove insufficient for a practical case. Therefore, a typical PV system will consist of multiple panels, arranged in multiple parallel strings of PV panels, as depicted in Figure 2.10. This way, an adequate voltage and current can be generated, enabling the inverter to inject the generated power into the grid. As mentioned before, in § 2.1.3, the inverter will be controlled as a CSI, thus feeding the grid and not forming it.

Other required elements in the PV system are DC cabling and a mounting system.

Figure 2.10: Schematic layout of a PV plant: The figure shows the components of main importance of a solar plant. The plant generally consists of solar panels connected in series or parallel and an inverter to interface the DC side with the AC side.

The main responsibility of the PV inverter is to yield the maximum power that is available at every moment, in case no limitations are dictated by the SSM scheme. Yielding the maximum power from a PV panel is less straightforward than it sounds, since the PV panels have non-linear I-V characteristics. Figure 2.11 shows how the inverter has to be capable to set the right voltage at the terminals of the panel which allows the PV panel to work in its optimum point, the so-called maximum power point.

Wind Energy

The second source of power that is considered throughout this thesis is wind energy. Wind turbines are aerodynamic apparatus that are able to convert the kinetic energy stored in the wind to electrical energy. It will not be explained how the exact forces are formed rotating this rotor, only the basic behaviour will be discussed. For this, a simple, schematic representation is presented in Figure 2.12.
As can be seen, the wind causes the rotor to start rotating. Then, the rotational speed can be increased using a gearbox, in order to closer match the optimum point of the generator. Subsequently, the AC voltage with variable frequency generated by this electric generator is rectified and again inverted, using a current sourced type of inverter, and fed into the grid.

Because of this way of interfacing where the power is being rectified and inverted again, from the grid's point of view the system behaves as a static generator. Therefore, no inertia is introduced to the grid by implementing a wind turbine like this.

Other ways of implementation exist, for instance a reference to the doubly-fed induction generator can be made, where inertia will be introduced. It can be interesting to investigate the way a device like this will interact with the $\mu G$, though this will not be discussed in this thesis.

Building upon this, similar dynamics could be introduced by implementing a diesel generator, which is another type of a distributed energy source. However, as mentioned this will also not be a part of the research.
### 2.1.8. Demand Side Management

DSM is a concept that aims at using the loads connected to the grid for stabilizing the grid behaviour. This can mean that for instance load is disconnected at the moment the SoC of the connected BESS runs low, or when an event happens on the grid which suddenly cancels out a considerable part of power generation. On the other side, loads can be connected and encouraged to consume power at moments when renewable energy is abundant and batteries are charged.

DSM comprises a range of measures that all focus on changing the behaviour of the end-user in order to stabilize or unburden the public grid, by modifying or reducing the end-users’ energy demand [17]. It is referred to as the next evolution in SGs, and could imply a social benefit of $59 billion (~ €54.5bn) per year [90].

In accordance with the philosophy of the project, the DSM should be modelled in a way no communication equipment is needed for its successful functioning; it should be merely based on the grid frequency.

### Introduction

In the µG concept, renewable energy sources will be excessively used. This means that an uncontrollable power source will be used to deliver a product that is expected to be available at all times: electricity. Without the application of certain workarounds, it can be expected that a city cannot run solely using PV panels. Doing this would result in a city where nobody can use electricity while the sun is not shining, so during the night or a cloudy day, because then none or not enough power is generated. Also, during a nice summer day, the energy produced should be consumed right away, this because a disturbance in the balance between momentarily power consumption and production results in an unstable grid.

In other words, power produced has to be consumed at the same time, and similarly power consumed has to be produced at the same time. In order to fulfil this constraint in a grid supported by uncontrolled sources, some measures are needed. The first solution to this issue will be installing buffer capacity, to store the renewable generated power when it exceeds the demand, and supply the power demand at the moments it exceeds generation.

A system only taking battery storage into account will need huge oversizing, both in terms of buffer capacity and renewable power sources. When optimizing the economical side of the system, an oversized system is not the best option. Other options can be thought of, including the use of a diesel generator that will be switched on when the batteries and renewable sources cannot secure the energy demanded by the loads, in combination with the application of renewable power curtailment, which ramps down the power output when it is not needed. Another solution is the application of DSM.

DSM programs usually comprise two focus points, which are “energy efficiency” and “demand response”. In this work, the main subject will be the latter, so the means of DSM under investigation is changing the actual consumption pattern of the end-users by the application of load shifting. This behaviour is twofold: when the available power on the grid is less than the power demand, the DSM will introduce a decrease in power demand, which should result in a stable grid. On the contrary, if the power generated by the renewable resources tends to increase and get bigger than the power consumed, DSM will lead to an increase in demanded power, this by, for instance, starting up certain power consumers for which the consumption of energy can be shifted in time.

One example of a consumer like this is the water pump of an irrigation tower: since the water tower acts as a buffering mechanism, the water pump can be prevented to consume power for certain hours. Only when the water level in the tower would reach a critical level, the water pump cannot be prevented from pumping the water up to a higher level. But in normal operation, this water pump offers an excellent means of consuming power only at the moment when it needs to be consumed.

Cooling devices can be expected to offer similar capabilities, as well as devices with inherent energy storage, for instance thermostatic controlled loads, air conditioning systems or heat pumps, and appliances with an integrated battery [91–94].
By changing the amount of power consumption by the end-users in times of over- or underproduction of power, the grid can be stabilized without needing buffering mechanisms at best, or at least allowing the buffer to be reduced in size.

The other branch of DSM, this is the energy efficiency and conservation, focusses on the decrease of energy demand only, by for instance motivating end-users to consume less power by changing the set point of the thermostat, or replace old, inefficient devices by new, energy efficient models. Real-time access to information provided by a smart grid, by means of in-home displays on which consumers get direct feedback of their power saving efforts, can lower the energy usage by up to 18% [90].

Six ingredients that are needed for a successful implementation of DSM can be identified. These are:

1. **Rates**: Momentary energy tariffs should reflect the actual generation cost.

2. **Incentives**: Compensations for participating customers should be present.

3. **Access to information**: Customers having access to real-time information have been shown to decrease their energy consumption.

4. **Utility controls**: Shifting loads like air conditioners away from critical peak periods.

5. **Education, marketing**: Convince customers from the benefits of DSM.

6. **Customer insight and verification**: Verify results, collect feedback, introduce optimization.

For this work, it will be considered that these ingredients are readily present, thus that DSM by application of load shedding, thus the active disconnection of certain load groups depending on the SEP of the grid, is possible.

**Load Shifting**

Before diving into what load shedding profiles are exactly and how they work, the concept of load shifting is quickly touched. The idea itself is rather straightforward: when dealing with energy sources that cannot be controlled, such as DRESs, but the loads can be manipulated to a certain extent, the moment of using these loads should be optimized to match the generation profile as closely as possible.

As an example, a case of Belgium can be discussed. Since this country relies on nuclear energy which does not have the capability of ramping up or down the output power too quickly, during the night a lot of power is available. For this reason, the government decided to install a considerable amount of lampposts throughout the country, lighting highways, in order to use energy during the night, and install special pricing schemes where the energy is cheaper during certain hours of the night.

On the other hand, in the modern grid where solar plants could be a main source of energy, it would be ignorant to keep these pricing schemes and facilities which encourage nightly usage of energy: this would be energy that has to be yielded during the day, stored in batteries and supplied during night. It would be more efficient to use the energy right away and avoid the electrochemical conversion of battery storage.

The discussion shows the importance of optimizing the load consumption according to the power generation, in case the latter cannot be managed. Load shifting can do so, by actively enabling and disabling certain loads, to optimize the energy usage during abundance. As mentioned, a water tower can consume energy when it is available, and use the water in the buffer while energy is scarce. Another example would be an electrical vehicle, like a car or scooter. In this case, the DSM would be addressed as **Vehicle-to-grid**, or V2G.


2.1. Scientific Literature: A Review

**Load Shedding**

After talking about load shifting, a second DSM step can be discussed: load shedding, which means that loads are actively turned off when the supply of power cannot be guaranteed, or if certain priority preferences require so.

When talking about load shedding in a developed country, in a situation where the μG is usually connected to the main grid and will only disconnect when this is required, three different scenarios can be defined [95]:

1. The μG is being supplied by the public grid, and a major event occurs in this public grid putting its stability under pressure.

2. The μG is connected to the public grid, and the event occurs in the μG itself.

3. The μG is in islanded state at the moment an event occurs.

It can be argued that it would be desirable to disconnect the μG from the public grid at the moment an event occurred in the latter. However, if the μG is injecting power into the main grid, coming from the DRES, it might be undesirable to disconnect the μG, since this will burden the public grid even further. On the other hand, if the main grid loses stability and blacks out, we will want to disconnect the μG from the main grid in order to guarantee a continuous power supply to the end-users. In the second case, it can be expected that the power levels with which the μG copes will be considerably lower than the ones that the public grid usually deals with, thus no reaction should be foreseen. The third case, which can occur if the μG is in islanding state and e.g. the SoC reaches a critical limit, load shedding will be unavoidable.

One thing that has to be taken into account is that people living in developed countries, thus who are used to the availability of electricity at any time of the day, are probably not willing to give up this comfort and have their power shed often.

**Load Shedding Profiles**  
The load controller is this part of the controller logic that will take care of the load shedding situations. According to the requirements, the controller has to be able to function with merely one control input available, this being the grid frequency. Furthermore, it should be the aim to develop a controller that is able to control a big amount of different load types. For instance, there are loads that are able to modulate their power demand, which means that they can change the load demand continuously. This can be applied over either a part or the full load range. Next to this, certain loads will not be able to modulate the demand, hence will have an on/off behaviour. Furthermore, it can be expected that certain loads will always require a minimal power flow, which can be due to a control or protection system. The shape of some different load profiles is shown in Figure 2.13.

**Standard Load Shedding Scheme**  
To implement a cell into the public grid, it can be expected that certain regulations and standards will have to be met. Because of this, the Under-frequency Load-shedding (UFLS) scheme as it exists today [96] should be considered. The UFLS is currently the most commonly used scheme of system protection, and was generally accepted after the occurrence of the Great North-East Blackout of 1965 [97]. By implementing this standard, the μG becomes compatible with the main grid, which would be a requirement for implementing the microgrid into the existing main grid.

The conventional UFLS has been originally designed to offer a means of keeping the demand and supply of the public grid balanced after a major event happened, like a big power generator that suddenly stops injecting power, or the protection device of a major power line that trips. This philosophy is not the same as the one that lies at the basis of the design of DSM in this thesis: where the UFLS is designed to provide a means of restoring the grid frequency after a major, unexpected incident, the DSM scheme should offer a means of keeping the most important loads that are being supplied by the μG on-line at the expense of shedding some loads of lesser importance. Also, where the UFLS deals with very small allowable deviations in frequency, the DSM scheme in this work is expected to function by the grace of frequency deviations that reach the magnitude of some hertz.
As an example, Figure 2.14 shows the frequency response of the grid after the 2006 European blackout [98]. This major blackout, which occurred on November 4, 2006, affected more than 15 million clients, cutting off their power for about 2 hours. The figure shows how the frequency deviation as a response to this event, caused by a planned disconnection of a major power line because a tall ship needed to pass through safely, does not exceed a $\Delta f$ of more than 1 Hz at any moment. This shows a completely different philosophy than the one applied in this thesis: where on the current grid any deviation of the 50 Hz value points at imbalances and potentially dangerous situations, the thesis employs the frequency deviations in order to prevent these situations.

Additionally, the source of the frequency deviations is different for both cases. In the public grid, frequency deviations emerge from a difference in power that is being injected into and consumed from the grid, which results in filling this gap in power with rotational inertia stored in the generation devices. Unavoidably, by supplying this rotational energy, the rotating devices slow down, showing that a problem is present on the grid. However, in a $\mu$G that is fed by static generation devices, no intrinsic frequency deviations occur due to power jump, but as explained in §2.1.4, the grid frequency will depend on the power supplied by the inverter in order to give multiple inverters the possibility of feeding a common grid without the need for communication equipment.

Even if the frequency deviations are the offspring of different phenomenons, and even if the reasoning behind the implementation of the UFLS in the main grid is different from this of implementing DSM in our $\mu$G, an analysis of how the UFLS exactly works can provide some useful insights. On top of that, if the cells need to be implemented into the main grid, as mentioned certain standards need to be complied to.

The UFLS is a standard concerning load shedding in the current grid, fixing the desired load shedding according to the measured grid frequency [99]. It has to be noted that the regulation in which the UFLS is
described does not specify the exact values, but merely gives suggestions concerning steps in load shedding and frequency deviations. This can be seen from Table 2.2, an interpretation of the standard [60], and Figure 2.15 [100], another interpretation of the requirements.

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Required action</th>
</tr>
</thead>
<tbody>
<tr>
<td>49.8</td>
<td>Activate all reserves in generation units</td>
</tr>
<tr>
<td>49.0</td>
<td>10 - 15% load shedding</td>
</tr>
<tr>
<td>48.7</td>
<td>Additional 10 - 15% shedding</td>
</tr>
<tr>
<td>48.4</td>
<td>Additional 10 - 15% shedding</td>
</tr>
<tr>
<td>47.5</td>
<td>All units go to island mode</td>
</tr>
</tbody>
</table>

By comparing these different implementation schemes of load shedding, some differences can be seen and interesting remarks can be made. The implementation shown in the table incorporates the activation of all reserve units. It is clear that in the developed grid, emphasis is put on a continuous supply of loads, thus on the highest achievable quality of service. This is understandable by considering what was mentioned earlier, namely that customers in developed countries are used to an ever-present energy supply and would not accept frequent load shedding.

Another interesting feature can be noticed in Table 2.2. We see that at the moment the low value of 47.5 Hz is reached, all units are required to enter a state of islanding. At that moment, a situation in which every cell should take care only for itself is reached. This can have advantages in case the cell which belongs to a critical load, e.g. a hospital, is designed in a way that it can cope with more extreme situations. In this case, it cannot be allowed that this cell supplies power to other loads through the backbone, hereby increasing the risk of a critical state of under power for the critical load in the near future. This is an interesting insight that can prove useful in the further design of the DSM scheme.

From the figure, we can see that different means of load shedding can be chosen. The lower line, Curve A, shows a so-called late load shedding scheme, where the steps increase with decreasing frequency. This type can be less favourable, since it defers the reaction of the loads until very critical situations, making a full system
collapse more prone to happen. As an advantage, however, it can be mentioned that less users will experience any drawbacks from the shedding in case of a less significant disturbance of the grid.

The second implementation, Curve B, follows a behaviour where the amount of load shed has a linear dependency on the severity of the frequency dip.

Curve C is a so-called early scheme, where the first steps of load shedding are bigger in size than the last steps. This scheme will react very strong on any irregularities, thus is the best reaction in order to avoid bigger fluctuations. However, as a drawback we can see that small frequency disturbances will immediately lead to plenty affected customers. Another danger is the potential risk of overcompensation, hereby again limiting the system stability.

Proposals can be made to introduce a load shedding profile that is dependent on different parameters, in order to choose the optimum amount of load being shed for every situation [101]. However, the drawback of methods like this would be that a certain amount of data gathering and central decision-making is needed, which does not comply with the basic requirements set in the project.

The ENTSO-E, or the European Network of Transmission System Operators, has tried to benchmark the response of a multitude of load shedding reactions [99]. From this, the first conclusion is that load shedding should be seen as a last resort, thus all possible measures should have been taken before UFLS is made use of. The size of the load shedding steps should not exceed 10%, in order to avoid overcompensation. A permitted area can be defined, which guarantees the best response. The area is shown in Figure 2.16, and some similarities can be seen between this figure and Figure 2.15.

At least six steps should be present, where the application of more steps leads to a system which approaches the linear theoretical response more closely. Due to practical considerations, the maximum number of steps will be limited to ten. Optimally, the range of UFLS is located between 49.0 and 48.0 Hz. These borders are selected depending on different actors in the grid, which might influence the stability of the grid as a whole.

Disconnection and Restoration  Two more considerations have to be made, namely the dynamic behaviour of both disconnection and restoration of loads. The first applies to situations where a transient causes the frequency to deviate for a short time, for instance because of a temporary change on the grid, or while two cells are in the transition state of synchronizing in order to interconnect. In this case, we do not want any loads to disconnect, since a transient probably does not point at a situation that asks for a change in load shedding.
By means of simulations, the ENTSO-E compared 16 different ways of implementing the UFLS into the grid. From the results, certain boundary conditions have been designed, which give the most favourable reaction in case load shedding is needed.

This can be solved by implementing an *intentional time delay* before the load is shed, and *filter* the output of the frequency measurement device, in order to rule out any short spikes.

Furthermore, the decision has to be made how the loads will reconnect to a grid with restored characteristics. One of the dangers is to connect loads too soon or in too big numbers at the same time, as this can result in an oscillatory on-off behaviour. This can be explained as follows: consider a load restoration scheme where the effect of the restoration causes the frequency to surpass a shedding threshold again. Thus, by restoring the load, the shedding controller is triggered again, causing the load to shed. This will result in an increase in frequency, which in its turn could trigger the restoration scheme again. It is clear that these kinds of oscillations are far from desirable.

It is understood that the restoration of load needs to be designed carefully. In order to do so, two main criteria can be determined [102]:

1. **Restoration frequency setpoints**: This encompasses the choice of the frequency where the load restoration is initialized.

2. **Size of restoration steps**: The steps with which the load is restored must be chosen as such that the new operating point does not cross a new shedding step.

If the steps in which load shedding occurs are very small, ideally according to a continuous profile, the mode of shedding – restoration is called *continuum*. This seems like an ideal technique, however the restoring scheme is not desirable in case of a grid with rotating devices that aims at going back to 50 Hz: if the load restores with increasing frequency, the grid is immediately burdened as it slowly recovers.

Therefore, discrete load restoration seems the better choice in this case. This would mean that the load waits until the system is recovered to a certain extent before switching on again. As an example, we can put that the second priority group of loads that have been shed will be allowed to come back on the line only at the moment the grid is recovered well enough to be in the region of shedding for the first load group, e.g. when
using data from Table 2.2, the second group will reconnect at the moment the grid surpasses the boundary of 49 Hz again. Similarly, the first group of loads will reconnect at 49.8 Hz.

Load restoration in small steps in order not to slow down rotating generators is not a requirement in this project, since the grid is supplied by static devices that will not experience a drop in speed because of load jumps directly. On the other hand, the drooping scheme does introduce this frequency jump depending on the output power of the inverter, though the magnitude of the deviations will not change depending on the size of the restoration steps: the ultimate change in frequency is the same for 10 steps of 1% and 1 step of 10% restoration. Of course, this guarantee can only be made in case the total load does not surpass the nominal rating capabilities of the inverter; this is a design requirement that is expected to be fulfilled.

Therefore, as mentioned above, the load restoration should occur in steps, and leave a deadband that is big enough not to trigger shedding again immediately after restoration. The size of this deadband can be calculated, or at least estimated, if we know the droop coefficient applied in the controller: a step in load power leads to a step in inverter power, which leads to a perfectly known frequency increase. Using this information, it can be guaranteed that the reconnection of a group of loads with a known power demand will not trigger a new step in load shedding.

2.1.9. Supply Side Management
The power balance on the grid can, and should, be stabilized by affecting the power generation side. The way to reach this control mechanism is the application of SSM, which can be said to be similar to DSM, though working the other way around.

Linked to this project, the SSM scheme will try to control the power output of the DRESs at the moment a state of overpow is upcoming, thus a bigger amount of power is flowing into the grid than what the grid can handle at that moment. The SSM scheme will then limit the injected power.

Introduction
To start, it should be noticed that the term SSM covers a lot more than what will be discussed here. The application of SSM goes through the whole supply chain, covering generation, transmission and distribution of energy, which spans from preparation and distribution of fuel over the generation of electricity to the successful delivery of this electricity [18]. This section will only consider the generation of electricity, particularly by means of controlling the power output from DRESs.

The act of curtailment points at a situation where the full potential power of the DRES is not being harvested, in order to maintain or return to grid stability. Because of the limited scale at which DRESs are still applied these days, most of the times curtailing is not yet needed and the maximum available energy can be harvested at all times. However, in for instance the German grid, due to the large penetration of DRESs, stability issues can occur when the energy output is high and the consumption is low. Also specific regions in the Netherlands experience problems due to a sudden and huge increase in installed solar panels [103].

The way curtailing works is quite straightforward: at moments the power injection into the grid gets too high, the grid frequency will increase. This happens because an increase in power injection leads to a decrease in opposing torque seen by the generators, ramping up their rotational speed, as explained in § 2.1.5. Thus, by monitoring the grid frequency, this regime of over generation can be recognized. As a reaction, DRESs cut down the power they inject into the grid, following predefined requirements, in order to decrease the power injected into the grid, thus offering a means of regaining grid stability.

The implementation of SSM is of great importance, and should be well considered, since it holds one of the crucial keys that can decide between a stable or unstable network. As an example, applied to the main grid, it can be mentioned that end 2014 in Europe almost 90,000 MWp of PV power was installed [104]. Knowing that currently the largest power producing source in the world, the Three Gorges Dam in China, has a power production capability of 18,200 MW, and that this is equivalent to about ten nuclear power plants, this huge
number can be put into perspective [105]. If the SSM scheme would merely be based on an on-off reaction, then every time it comes into action an equivalent power production capability of about 5 times the size of the biggest plant in the world would be connected to or coupled from the grid. Huge problems will follow. Therefore, it is important to consider the design of the SSM scheme very carefully.

Currently Applied Standard

For reasons mentioned above, a regulation has been designed by the German association VDE\(^1\), which copes with preventing stability issues due to an overproduction of renewable energy sources.

In Germany, one of Europe’s leaders in terms of DRES penetration, this grid standard *VDE-AR-N 4105* is to be followed [106, 107]. This standard aims at limiting the output power of DRES according to a predefined curtailing curve, as depicted in Figure 2.17. As can be noticed, at the moment the limit 50.2 Hz is crossed, the inverter ramps down the power output of the DRESs at a rate of \(-40\%/\text{Hz}\). Hereby, the power output at the moment when curtailing started is taken as reference power. If the frequency drops again while the curtailing scheme is active, the inverter is allowed to increase the power accordingly.

The standard ends with a drastic step: as soon as a grid frequency of 51.5 Hz is reached, a step from 48% directly to zero is dictated. This can be understood from the conventional grid point of view: if ever 51.5 Hz would be reached on the main grid, this shows that a huge problem is occurring on the grid. The inverter will then be allowed to reconnect to the grid only if the frequency fell between acceptable limits again, lower than 50.05 Hz yet higher than 47.5 Hz, for at least 60 seconds, while the grid voltage should be within a toleration as well.

![Figure 2.17: Characteristic of the VDE-AR-N 4105:](image)

The output power of DRESs has to be curtailed according to the sensed grid frequency. Starting at 50.2 Hz, the output power follows a linear drop of 40% per Hz, until the clamped output power reaches a value of 40% of the original value, then the output drops to zero.

Other Services

SSM can present a number of auxiliary services to the grid. As an example, low-voltage ride through could be seen as a feature provided by SSM, because distributed energy sources are controlled in a way that helps stabilizing the grid. Low-voltage ride through ensures that these distributed sources stay connected to the grid in case of e.g. a voltage dip, which then can prevent a more severe blackout.

Another service has been investigated by the National Renewable Energy Laboratory is the application of intermittent and uncertain wind energy for grid stabilizing [108]. This illogical behaviour can be reached by

\(^1\)Ger. *Verband der Elektrotechnik, Elektronik und Informationstechnik*, Association for Electrical, Electronic & Information Technologies
adjusting the generator’s active power output in order to assist in balancing demand and supply on the grid, instead of aiming at a 100% energy yield. The study shows positive results in terms of the overall stability of the system, economic benefits can be reached, without any considerable drawbacks to the structure of the turbines.

It should be clear that SSM does not only incorporate the act of curtailing renewable sources, but can offer a lot more interesting features to the grid.

2.1.10. Energy Storage
As explained, in order to exploit a standalone grid, an energy storage system has to be considered. Most of the times, BESSs are used as a means of stabilizing the grid, improving the reaction of the grid on load changes or other impacts [109]. Next to this, the application of BESSs makes the implementation of DRESs more straightforward, since the moment of production and consumption don’t necessarily have to match in a BESS backed system. The different parts of a BESS are usually the batteries, a control and power conditioning system and some protection devices.

A huge number of applications for which BESS can help the system, support and improve the grid, increased DRES penetration, etc. can be thought of. These include, but are not necessarily limited to [7]:

1. Frequency regulation: helping to keep the grid frequency within limits.
2. var support: tuning of the power factor.
3. Voltage support: helping to keep the utility voltage within limits.
4. DRES output shifting: storage of DRES output for usage when needed.
5. DRES output levelling: output ramp-rate management.
6. Peak shaving: dispatched buffer usage for grid support.
7. Intentional islanding: give the grid a tool for working independently from the public grid.

This thesis should mainly take into account the last item mentioned, so usage of buffer capacity to enable intentional islanding of the grid. Furthermore, also frequency regulation, but then with variable frequency setpoints, can be one of the objectives, as well as DRES output levelling.

Even though all these applications are very useful and clearly advantageous in the grid, it can be seen that only few of them are exploited nowadays. The reason for that is twofold: on one hand, the conventional power system is designed in a way that the generation can easily react to changes in the demand, and it is very strong because of many interconnections. Since the grid is already foreseen to battle possible stability problems, it is economically not interesting to implement another system doing the same. On the other hand, a chicken and egg situation can be recognised in the implementation of BESS into the public grid. Since practical experience is not available, the technology is still expensive, tools can be unavailable, and costs are not optimized yet. But, because of this, gaining practical experience fails to happen, this way not solving the existing issues [110].

Batteries
A number of energy buffering technologies exist. The main technology which can be thought of is probably batteries. A battery is in fact made of cells, these are anodes and cathodes, which generate a potential difference because of a chemical redox reaction [111]. Increased demands of voltage or current capacities can be attained by stacking respectively in series or parallel circuits.

Some terminology is needed to understand certain specifications of batteries [112]. Battery capacity is normally expressed in the unit Ampere-hours [Ah], expressing the amount of current the battery is able to deliver in the duration of one hour. The same value can be expressed in Watt-hours, or [Wh], calculated by multiplying the capacity in Ah with the average terminal voltage. The rated power will be expressed in watts
A battery also has a so-called C-rating. This number, in which C stands for capacity, expresses how fast a battery can be charged or discharged. If a battery is rated with $x\text{C}$, this means that the battery can be discharged with a current that is $x$ times the current capacity for one hour. For instance, if the battery has a current rating of 100 Ah and a C-rate of 2, the battery is fit to supply 200 A, and will be drained in half an hour.

Other very relevant battery properties are efficiency, allowable operation temperature, allowable Depth of Discharge (DoD), the rate of self-discharge, the cycle life, which is the number of cycles for which the battery keeps certain properties, and the energy density, which is the usable energy per unit of mass.

A broad range of battery technologies are currently available, or under development [110]. A detailed survey of all existing technologies would lead us too far, but some major technologies can be mentioned. The discussion will be limited to Lead-acid (Pb) and Lithium-ion (Li-ion) batteries.

Probably one of the most used and well-known battery technologies is the Pb type. In this battery, the positive electrode is made of lead dioxide, and the negative electrode is sponge lead. The battery has the advantage of being a very mature battery type, being discovered more than a century ago.

Pb batteries designed for stationary energy storage should be capable of lasting for about 200 – 300 cycles at 80% DoD, reaching efficiencies of 72 – 78% [110]. A lower DoD will lead to a bigger cycle life, though more capacity needs to be provided for the same usable battery capacity.

Li-ion batteries are made of the combination of a lithiated metal oxide with graphitic carbon. The batteries have a claimed efficiency of nearly 100%, and a lifetime of more than 3000 cycles with 80% DoD, but are far more expensive than Pb batteries [110]. They have a low rate of self-discharge, making them ideal in terms of long-term energy storage.

**Considerations**

From an economical point of view, storage components are the main cost drivers for all PV hybrid systems [94]. This means that the consideration of which technology to use is a very important one. From the above discussion, it is clear that battery systems are currently the most used way of energy storage on this scale. Flow batteries will probably need some time more to become proven technology. Both flywheel storage and supercapacitors are energy sources that should be used for intermediate energy storage only, and will be less optimal for supplying energy on the longer run.

In this work, the most common mean of energy storage will be applied, thus battery storage. The main choice to be made is whether to choose Li-ion batteries or Pb-batteries. Because of the big economic impact of the batteries, especially the lifetime and the required battery capacity will play a role, which have their effect both in terms of initial costs and total cost of ownership [94].

In terms of lifetime, lead acid batteries can have a lifetime of 4 to 8 years, whereas Li-ion batteries claim to reach lifetimes of +20 years. Furthermore, whereas the usable DoD of a lead acid battery is limited to about 20 to 30%, a Li-ion battery can be discharged for 65 up to 80%, which means that three to four times less capacity is required for the same amount of energy storage. These characteristics make sure that higher initial investment can be justified.

More benefits of making a decision in favour of the Li-ion technology can be listed [94]:

- They offer a modular, redundant and extendible solution.
- Similar technology as the one used in Electric Vehicles.
- They have a high reliability.
- Long lifetime of 20 years-plus, even with DoD up to 80%.
- High safety standards.
- Cost effective:
– Initial investment: 3 – 4 times less capacity required.
– Total cost of ownership: 3 – 5 times longer lifetime.

2.1.11. Gaps in the Literature

The discussion has made clear that a big share of work concerning the control of \( \mu G \)s has already been performed; both centralized and decentralized control have been studied and clearly described, and benefits and drawbacks for both methods have been defined.

However, the possibility of using the readily-available grid parameters, the frequency and voltage, for controlling complete behaviour of a \( \mu G \) interfaced with DRESs has not been investigated. If these parameters are applied, then the aim is always to minimize the deviations from the nominal values at all costs. No research on a grid that aims at optimizing its behaviour actively using those parameters and hereby avoiding the necessity of introducing dedicated communication equipment could be found. Frequency deviations, for instance, are currently seen as a problem, pointing at the disability of the grid forming devices to supply the needed power adequately.

However, it can be expected that if these imperfections are embraced, and in fact intentionally introduced into the network, certain grid behaviours can hit the scene. This way, end-users can actually read the SEP of the grid as a whole by reading its frequency, and interact on this. All the factors of the grid that influence the current grid reliability, like the SoC of the battery systems, the amount of cells connected to the Bb, the amount of power that is supplied by the inverters … will mutually boil down to one grid frequency, defining the state of the grid. Subsequently, the introduced schemes for DSM and SSM can read this grid frequency and this way help in improving the reliability of the grid even further.

The main aim of the thesis is to check whether using these grid parameters as a means of controlling the grid is feasible, and if it leads to a satisfactory behaviour of a potential DSM and SSM scheme. This controller has to be designed.
2.2. A Short History of SOPRA and CSGriP

In this section, the background of two projects, the Sustainable Off-grid Power plant for Rural Applications (SOPRA) and the Cellular Smart Grid Platform (CSGriP) will be explained. SOPRA and CSGriP can be seen as the bigger picture, the case study on which the outcome of this thesis can be applied.

From the literature review, some gaps in the state of the art could be defined. In this chapter, the proposals that shall fill these gaps and the already defined solutions will be presented.

"The act of Demand and Supply Side Management occur by means of the grid frequency. That is the crux of CSGriP"  
(E. Raaijen)

2.2.1. Introductory

The research is done within the margins of a bigger project, SOPRA, and its successor CSGriP, of which a schematic depiction can be seen in Figure 2.18. One of the goals of CSGriP is developing and testing a platform that is capable of working in a grid-connected mode as well as islanding, where it is able to behave fully self-supporting and regulating. In SOPRA, it was found that the grid frequency could be used as the main information carrier [11].

The reasoning behind this concept is a very straightforward one: continuity of electrical power to ensure a better consumer experience. It is expected that in a future grid, elements will be present making this grid a SG. But, currently a lot of smart grid approaches rely heavily on ICT equipment in order to work [10].

![Figure 2.18: Schematic representation of CSGriP system](image)

This is a good approach as long as the ICT equipment does not fail, but can be seen as a risky situation, in which a so-called deadlock could happen if the ICT equipment fails, but the ICT equipment is needed in order to restore the power on the grid. For this reason, CSGriP can be seen as a back-up system for these smart grids. Whenever the main grid, or the medium voltage backbone, is down, which would cause an outage of the ICT equipment, the CSGriP-network can decouple from this main grid and continue operation independently.

This is schematically depicted on Figure 2.19. This decoupling of the public grid will include a certain loss of performance, but not a loss of functioning. This means that the PQ might go down, as seen in a variable frequency, or some selected devices will not be allowed to consume power anymore due to load shedding, but that at least the basic functionalities of the electricity grid will still be present. This in contrast with a grid where no CSGriP is available, where all functionality is lost at the moment the Bb drops away.
Some aspects CSGriP should develop, which will make it superior when compared to SOPRA, are that so-called *prosumers* can easily connect to the CSGriP-based grid, for whom CSGriP will foresee in an optimal amount of storage capacity. “Prosumer” is a term invented to address customers who do not only *consume*, but also *produce* and sell energy.

When the energy produced by these prosumers is insufficient, a solution in the shape of a cogeneration or combined heat and power plant, or a (bio-)diesel generator will be present to keep the µG online, or the possibility of connecting the µG to a stronger, higher grid could be present. This grid could also operate as a Bb, hereby offering the possibility of eliminating discrepancies in generation and consumption of energy between different cells by providing the possibility of interconnecting multiple cells. Prosumers can also evolve into *prostumers*, which are end-users who consume, produce and *store* energy.

### 2.2.2. Main Requirements

In the Project Description [11], some outlines for the project have been recorded. The most important ones will be briefly presented here. These requirements can be recognized as being the basics of the project.

From the Project Description, the following passages can be found:

*Development and testing of a new technology, called Cellular Smart Grids Platform – CSGriP, to realize a local, intrinsic stable, self-sufficient, and self-regulating energy grid (level of a neighbourhood, a village or an industrial plant), including the technology to interconnect these cells using a MV or HV grid, this for eventual energy sharing and buffering.*

*Using advanced power electronics, an intelligent electrical cellular network will be created, tested, analyzed and validated. A control system will be developed, allowing an efficient exchange of energy between cells or between a cell and the backbone. A cellular network exists of the CSGriP system, coupled to the backbone (the MV grid) on one side, and to storage and a variety of energy generators and users, like PV, wind turbines, µCHPs, fuel cells, biofuel-CHPs, heat pumps, electrical vehicles (…)*

*(…) One example is a communication standard which regulates how one CSGriP base station will communicate with the base station of another cell on the backbone. Advantage of the CSGriP concept is the redundancy of communication from a cell to individual consumers / prosumers and their appliances. This will have a great impact on the number of needed standards and communication protocols needed for cooperation, and makes the basic functionalities of the system insensitive for loss of ICT equipment.*

The selected requirements are:

- The concept is to develop a µG that does *not depend on external communication equipment* in order to keep operating.
• No external communication shall be necessary for operation; the grid will remain stability using the ever available frequency and voltage signals.

• The microgrid shall be cellular, so a plug & play nature has to be present without adaptations to the grid.

**Unconstrained of ICT Equipment**

ICT equipment is considered to be unneeded in the CSGriP-concept, so the cellular grid shall behave as an intrinsically stable system. In the future, when more and more energy will be generated in a sustainable and decentralized way, and where the grid will strongly depend on ICT to perform power and energy balancing, a failure of this ICT would lead to a failure of the whole grid, which in turn could lead to an increased failure rate of ICT equipment, this way possibly leading to an avalanche.

Working this way, however, will have consequences on the PQ of the grid: the frequency and voltage are expected to fluctuate around the nominal value with a bigger range than the current situation. In order to avoid this, a double approach can be adopted: at the moment everything works fine, ICT can be available, activating the controllers that shift the grid parameters back to their nominal value. However, it should be clear that this behaviour is merely complimentary, the main requirement remains *a system that is able to work without this extra layer of communication.*

**Frequency Based Communication**

The main aspect allowing the operation independent of ICT equipment should be a grid frequency that can vary within a predefined range, depending on the status of the grid. This will give new opportunities for balancing of demand and supply of power, which might allow the installation of a smaller buffer. Energy will be used at the moments when it is produced, and renewable sources will not produce energy when it would make the grid unstable. Also a dynamic kind of pricing can be coupled to this behaviour, awarding end-users that are using energy at moments of abundance and saving energy in times of energy scarcity.

Furthermore, devices that work with a certain buffering mechanism, such as a water tower or Electrical Vehicles (EVs), can benefit from this dynamical way of pricing, by only consuming when energy is abundant. An EV can react not only using an on-off control, but also by means of a modular control, where the charging current is ramped up or down smoothly according to the status of the grid. Other big loads, such as heat pumps, can follow the same regime.

The question that can be asked is whether or not it is possible to change the grid frequency to one’s liking. Nowadays, frequency deviations are seen as unwanted events that have to be eliminated as fast as possible. Frequency deviations are result of big events on the grid, such as huge load changes, short circuits etc.

It is clear from § 2.1.6 that in the current situation, a lot of emphasis is put on keeping the grid frequency within a very narrow band. Grid codes have been developed in a time this steady frequency was much-needed. The reason for this is as follows: in a grid formed by generation devices with inertia, an increase or decrease in frequency alerts to an abundance or deficit of power input, respectively. The Automatic Generation Control needs to see this frequency deviation, and then adjusts the power input to the generators, in order for them to follow changes in load demand. Since these generators are synchronised to the main grid, they need a stable reference value in order to react to changes in the grid the same way.

Next to this, in the past, some loads were frequency dependent. For instance, electric clocks driven by a synchronous motor were used, which means the grid frequency needs to be of a very reliable kind because it had to represent the time. A synchronous motor will follow the grid frequency at all times, and if the frequency would vary, the speed of every motor will change with it.

Some loads have a relationship between frequency and power, which is not necessarily linear. As an example: for a fan the torque is proportional to the speed, making the power demand proportional to the square of the speed. Small deviations in frequency will result in large deviations in power demanded. It can be expected that this behaviour can cause oscillations on the grid, as an increase in frequency will result in
an increase in power demand. This will result in a decrease in frequency, which will again cause a decrease in power demanded. If the allowable frequency band were to be too big, this behaviour could take place *ad infinitum*.

These days, however, most electric motors are interfaced with the mains by means of a drive, a power electronic device capable of creating any desired frequency starting from the grid frequency. This means that the frequency a motor sees is fully decoupled from the frequency at which the grid operates.

The question is whether in a system that is not supplied by rotating generators this narrow frequency band is still necessary. If only electric clocks are the problem, and these are the only devices preventing the grid standards to change, it is probably safe to argue that the standards can become less strict. If, however, the standards are not allowed to change, the maximum available bandwidth for frequency based communication in CSGriP would be limited to a mere 1 Hz, which might turn out to be insufficient.

One problem is that a change in mentality of grid users will be needed. Currently, frequency deviations are seen as something bad, and it will take time to get used to the fact that a changing frequency is actually useful and helps in stabilizing the grid. Most of today’s used equipment connected to the grid by means of an adapter is able to operate on a broad range of frequencies, very often the allowable frequency even reaches 60 Hz.\(^2\) So on the technical side, no drawbacks of a changing frequency are expected.

**Modularity**

Another important feature of a CSGriP-cell should be the fact that it is fully modular and flexible, a cell has to be able to work on its own, but also in grid connected mode, or coupled together with other cells. Furthermore, an important characteristic would be the benefits in terms of customer privacy, because the customer is able to make decisions within his own walls, only by receiving information via the grid frequency. This way, no private customer information has to be collected, and people will not experience a *Big Brother*-feeling. This increased level of privacy will probably have a positive influence on the acceptance rate of end-users towards CSGriP.

The consumer will not see any differences between nowadays grid and a cellular smart grid, which will also lead to a better acceptance rate. Only when the consumer decides to give in some quality for the sake of lower costs, differences will be noticeable. But likewise, the consumer should be able to make his own choices.

### 2.2.3. Application Goal

The application of CSGriP can be divided into two main fields: on the one side, there are currently electrified regions, like the western world where there is in fact no need of battery backup. In these regions, main groups of users include households, industry and critical customers like hospitals.

On the other hand, there are currently non or poorly electrified regions where a CSGriP-cell would have a huge impact. Also here, the same three types of customers can be recognized.

**Developed Area**

In the Western world, there is currently no distinct case for a system like CSGriP. All the houses are connected to a very strong and reliable electricity grid. To give an example, figures of the reliability of the Dutch public grid show that in 2014, the grid was unavailable for 20 minutes in total [113]. This boils down to a reliability of 99.996%. It is clear that for people who are dealing with a grid like this, storage *in situ* is not needed. Installing a CSGriP-cell would in many cases cause an economic disadvantage without real advantages; the necessity of such device can only be justified in specific cases, very critical processes like data centres.

Some interesting cases, of course, exist. One example that can be given is a project where a cell was installed next to a fast charge station for electrical vehicles. The situation was as follows: at that location, the installed grid capacity was not sufficient for the deployment of the fast charging station. Some characteristics of a

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\(^2\)This can be verified by the reader, for instance by looking at the voltage requirements for the power supply unit of a notebook.
fast charging station are: peak power demand is short and high, while average power demand is rather low. However, in order to deliver the peak power demand, grid investments would be needed. In order to avoid an excessive investment, it was opted to install a cell with a relatively limited battery capacity of 90 kWh that supplies the peak demand, while the main grid still takes the base demand into account. This resulted in an investment that was 4 to 5 times lower than sizing up the grid connection at that location. This way, the system can operate as an actor for performing peak shaving, load shifting and energy trade, this way offering economic viability. However, the possibility of doing so is not discussed in this thesis.

For now, it is considered that a µG has been implemented into the main grid, its existence being justifiable. Then, an analysis can be made of what will happen in case the main grid trips and the µG has to switch to islanding mode.

It is important to realize that the requirement of having an ICT-less grid is not an uncompromising one. It will be seen throughout the thesis that having an ICT-less structure in fact has a big impact on the PQ of the grid, for instance the grid frequency deviations can take big values, for the sake of reaching communication without dedicated equipment. The requirements set for the project can be understood as being in case of emergency. This means that it is perfectly possible that in normal situations the grid will use ICT equipment, providing the end users with a high PQ and a behaviour of the grid that they expect. Only in case an emergency situation would take place, limiting or completely ruling out the possibility of using dedicated communication equipment, the CSGriP can go into its communication-less operation and sustain the grid, at the price of a lower PQ, but this where a grid without these capabilities would have failed.

A potential procedure can be described as follows:

1. Normal mode; grid connected.
2. Problems occur on the main grid, µG has to decide to go into islanding mode or not.
3. In case µG enters islanding mode.
   (a) ICT equipment available: use it, supply power with high PQ
   (b) No ICT available: enter droop mode, control by means of grid voltage and frequency

It is clear that the discussions in this thesis will only focus on Step 3b, thus the main grid is unavailable and the µG is required to omit any possible communication equipment.

The topology that comes to mind when thinking about the implementation of CSGriP in a developed situation is shown in Figure 2.20.

The first choice that has to be made, as seen on the figure, is whether a cell is capable of fully decoupling the end-user from the main grid. In case the back-to-back sequence of inverters is present, then the choice can be made of supplying the loads directly using the main grid, or opening the switch between both inverters and actually supplying the grid voltage by means of the inverter. If this approach is adopted, then no transient period is needed at the moment the grid would fail, since the power is already being supplied by means of the inverters. On the other hand, implementing the system like this will have consequences in terms of initial investment and grid losses.

The smart meter that is shown can decide on connecting or disconnecting the end-user from the grid, by reading the grid frequency and following certain predefined requirements. More advanced, the smart meter can differentiate between loads of high and low priority, first switching off the latter group.

Multiple locations where the cell should be implemented can be defined. Judging from the figure, there is Level 1, that is the end-user level, where a battery system might be present; then Level 2 is a cell at
Figure 2.20: Potential implementations of CSGriP in the main grid: The figure shows how CSGriP can be implemented at different locations of the main grid: from the high voltage to the end-user level, each implementation bringing along certain advantages and drawbacks.
neighbourhood scale; Level 3 would mean a cell implemented in the MV distribution grid; and finally Level 4 shows a cell that is located on the HV backbone of the grid.

It can be desirable to limit any exchange of power between different levels, where only in extreme situations power flow over these borders would be allowed. However, it could be that cells will achieve a better performance when this overflow of power would be allowed.

The BESS can be installed at multiple places, as seen on the figure. It can be expected that a battery which is located higher in the grid will relatively need a smaller amount of energy storage since individual differences in load consumption and power injection are ruled out. However, installing the batteries near the end-users can prove beneficial in terms of limiting current flows over the low voltage network.

**Developing Area**

For end-users living in areas where heavy load shedding is applied and all energy comes from big polluting diesel generators, or where the general electrification rate is extremely low, reasons for installing a SOPRA-like system are abundant. An estimation shows that more than 95% of the people living in Burundi, Chad or Liberia do not have access to electricity [114]. One can think about the increase in peoples comfort and welfare, if electrification is spread. Also, energy security is affected, because the village will be less dependent on the import of diesel if renewable energy sources are used. Furthermore, the positive effect on the environment which occurs when switching from fossil fuels to renewable energies is a big plus.

In this case, there is no main grid that has to be dealt with, thus obviously there is no initial condition in which the main grid is present. In this case, one cell will always work on its own, supplying a number of loads and receiving power from its DRESs, or multiple cells that are located close to each other can be interconnected by means of a Bb.

The possible topology is shown in Figure 2.21. On this figure, three cells that are presumably located close to each other are presented, equipped with the possibility of making an interconnection to the Bb, and without a grid connection. The figure shows clearly how, by opening the right switches, the controller can decide to either run the cell in a stand-alone mode, dealing with its proper DRESs and loads, or close the switches and reach a state where sharing of load power and DRES injection can be interchanged.

The figure also shows the possible back-to-back structure of two inverters, which can be used to decouple the $\mu$G from the Bb in terms of voltage and frequency. A choice that can be made, for instance, is to keep the frequency on the Bb at a stable 50 Hz, and only tuning the grid frequency of the $\mu$G. However, by doing so the possibility of sharing power with a cell at low SEP is lost.

![Figure 2.21: Three CSGriP cells with the possibility of interconnecting](image)

A potential implementation of CSGriP in a developing country, where no main grid is present. The cells can be provided with the possibility of connecting to a Bb structure, which can result in a stronger grid because individual weaknesses can be ruled out.

Here, the choice that needs to be made is whether the priority is given to make the cells predominantly behave individually or supporting one another. This means, should different cells that have the possibility of
making an interconnection do this, or not? Some advantages and disadvantages of both control means can be mentioned.

• If a cell operates individually, and an event occurs which could potentially endanger the system’s continuous operation, it could take a long time before other cells react and help the cell out.

• A cell that is designed to operate individually will need a bigger buffer and a bigger amount of DRESs, since it has to deal with a bigger degree of uncertainty than cells that are usually interconnected. For these, it can be expected that temporary changes in load consumption or power supply will be averaged out.

• If a cell has been designed with a big buffer, because it is constructed to supply a crucial load, it would be undesirable if this cell supports loads of lower importance, hereby endangering its own load.

It can be expected that the ultimate answer to this question will have to be tailored for every situation that is considered. Some examples can be given:

• In case a second cell is installed in the grid because the capacity in terms of power or energy from the first cell did not suffice any longer, it can be expected that these two cells will work closely together, thus will be interconnected whenever possible.

• If for instance a village with a hospital is equipped with a μG, it can be opted to install two separate cells, one for the village and one for the hospital, if this increases the availability of power for the hospital, or to connect the hospital to both the grid of the village and its proper grid. In this case, both grids would probably be used in a separated way most of the time.

• If a village has a large geographical spread, it can also be advantageous to install multiple cells in order to minimize grid losses. Calculations or simulations can show what would be the optimal solution in this case, interconnecting or working separately.

2.2.4. Expected Outcome CSGriP Project
The expected outcome of the project as a whole, thus the bigger picture than the thesis, is defined as follows:

• Development of the theoretical CSGriP-concept with all prerequisites foreseen, this is:
  – Definition and application of the usable frequency bands
  – Physical structure of a CSGriP-cell
  – Optimal way of exploiting and monitoring of the network
  – Optimization of local buffering size

• Development of a tool for further analysis of the CSGriP-network, including means for optimization, economical and technical analysis, etc.

• Simulations and measurements at location

• Insight in influence of a grid using dynamic frequency on other networks

• Market research to gain insight in customer acceptance rates

• Development of business models

• Knowledge distribution
2.2.5. Preceding Work Controller

Prior to this thesis, some research has already been carried out concerning CSGriP, in fact more specifically on its predecessor SOPRA. Among other things, basic work concerning control of the grid has been developed. The main ideas will be explained in this section, and also used in the further work.

The existing concept is based on droop speed control [14]. Loads are divided into different priority groups, these are high priority, e.g. hospitals and telecom towers, or loads that should never be allowed to be disconnected. Next, there are medium priority loads, which are loads that can be disconnected but should be connected as often as possible, and finally there is the section of low priority loads, that will be the loads that can be disconnected first. The division between different groups can be based on importance of the load, as mentioned, but also for instance on a pricing scheme: customers can decide to pay more for their connection if this ensures them a lower probability of disconnection.

The overall concept is shown in Figure 2.22 [115]. On this schematic, we can see how the main source of energy is supposed to be PV panels. Their inverted power is directly injected into the grid, either to supply load demand or to charge the batteries.

As explained, the battery inverter takes care of the grid forming task, utilizing the droop control that is being calculated by a controller.

As a reaction of this droop control, a variable frequency can be seen by the loads. These then, by means of smart meters, can be connected and disconnected according to certain predefined requirements.

![Flow diagram of a complete µG system](image)

Figure 2.22: Flow diagram of a complete µG system: DRESs are the main energy sources of the microgrid, while an energy storage device is supposed to be the main energy carrier, or buffer. A grid forming inverter supplies the loads with power. The loads have a smart meter that will switch them on or off, or decrease the power demand, according to the grid frequency.

In order to achieve this, the allowed grid frequency is divided into different zones, or areas. For each and every new area that is reached, the next group of loads will be connected or disconnected. The frequency zones that are applied are given in Table 2.3. It is clear that fixed definitions are applied in this concept, where a certain value for the grid frequency always points at one state of the grid, and where the controller aims to set the frequency value that is defined by its proper SEP.
Table 2.3: Proposal for states and their frequency band

<table>
<thead>
<tr>
<th>State</th>
<th>Frequency band</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Surplus (ES)</td>
<td>50.2 – 52.0 Hz</td>
</tr>
<tr>
<td>Battery Charging (BC)</td>
<td>50.0 – 50.2 Hz</td>
</tr>
<tr>
<td>Battery Discharging (BD)</td>
<td>49.8 – 50.0 Hz</td>
</tr>
<tr>
<td>Energy Limitation 1 (EL1)</td>
<td>49.6 – 49.8 Hz</td>
</tr>
<tr>
<td>Energy Limitation 2 (EL2)</td>
<td>49.4 – 49.6 Hz</td>
</tr>
<tr>
<td>Energy Limitation 3 (EL3)</td>
<td>49.2 – 49.4 Hz</td>
</tr>
<tr>
<td>Energy Limitation 4 (EL4)</td>
<td>47.2 – 49.2 Hz</td>
</tr>
</tbody>
</table>

This approach, however, has not been dynamically tested, and thus its dynamic performance is uncertain. A quick reflection tells us that problems can arise in case multiple cells with different SEP are interconnected: in case the frequency setpoint is defined in this fixed way, the system is in a potential treat of entering a situation where no stable steady-state working point can be found.

Assume a situation in which one cell wants to set a lower grid frequency because its batteries are running low, but another, connected cell is having a lot of power input of its renewable energy sources, and thus wants to increase the frequency. This will result in interconnected generators with a different droop curve. It will have to be determined whether the droop curves will be successful at finding a working point within the limits.

It can be understood that different situations can be distinguished, this where one cell is in charge of its own network, or when multiple cells are feeding the same network, or when the network is connected to the public grid. All these situations have to lead to a desirable behaviour, and testing this is one of the aims of this thesis.

2.2.6. Gaps in the Preceding Work

So far, all the results have been defined on conceptual grounds, thus no verifications of any kind have been executed. The droop concept with variable frequency setpoint, for instance, is a nice idea, though some fundamental remarks can be placed next to it.

The next step of the project is the actual verification of the applicability of the whole concept, in order to check whether all the concepts can be combined into a working project. This will have to be performed simultaneously with the design of a controller, since no such design has been presented before. Thus, developing and testing a control structure that allows a $\mu$G to work according to the predefined requirements is the most important step.

After this controller has been designed, it is important to verify the applicability of further features, for instance the schemes for DSM and SSM.

2.3. Summary of the Chapter

The chapter consists of a review of scientific literature, in order to define which research has been done prior to this thesis, and subsequently an introduction to the CSGriP project was provided, which is actually the framework within this thesis takes place.

The scientific literature has pointed out that a lot of the concepts that will be applied for the thesis, for instance droop control, are well-established. However, applying these schemes for the sake of communication-less control seems to be a subject that has not been researched yet.

The aim of the thesis focusses on the first item of the prospected outcomes of the CSGriP project, this is find an optimal way of exploiting the network. This will be done by developing and optimizing a revolutionary implementation of a $\mu$G controlled by means of a varying grid frequency, with added features of DSM and SSM. This way, the network can be exploited in a stable way without being dependent of ICT equipment.
The following chapter will discuss how, using the insights attained from the literature review and previous work, the \( \mu G \) controller has been developed.
Throughout this chapter, the implementation of the relevant controllers will be cracked down and discussed. While providing a working controller, the parameters and setpoints will not be substantiated here. This will be done in great detail in Chapter 5.

3.1. INTRODUCTION
The goal of the development of the model is to create a tool that gives the possibility of simulating the behaviour one or more μGs in a dynamic way. The stability has to be checked, for different events, like connecting and disconnecting loads, curtailing and shedding of respectively renewable sources and loads, making and maintaining an interconnection with another cell, etc. All these events have to be introduced by using the available grid parameters only, so no communication between the cells is allowed other than the grid frequency and voltage.

As was explained throughout Chapter 2, voltage and frequency droop control will be applied in order to reach this independence from communication equipment. This droop control will allow multiple inverters to share power according to their power rating.

However, since no controllable power sources are to be implemented, one requirement of the controller is to enable cells to share power according to their SEP. This requirement will result in a droop curve that can vary in accordance to this SEP, resulting in the required behaviour. The control strategy will be discussed throughout § 3.2.

In order to see the reactions of the controller, a model is presented that incorporates all the components that a grid would consist of, such as power consuming devices, uncontrolled power producing devices, an energy buffer, cables etc. Their characteristics will be discussed when relevant.

Because of the fact that the grid consists of non-controllable power producers only, it cannot be expected that the energy buffer will always be able to supply power to all the loads, as the buffer cannot be seen as a source of energy. For this reason, a proposal is made in which the load reacts to the SEP of the cells, communicated through the grid frequency. Similarly, the DRESs will not always be allowed to inject all the power into the grid.
as the energy buffer has got a finite storage capability. The moment at which the sources should curtail their energy output can be read from the grid frequency as well. Loads and DRESs will be discussed in § 3.3 and 3.4, respectively.

During the modelling phase, excessive use is made of the software DlgsiLent® PowerFactory [116]. The main reasoning about why was opted for using PowerFactory, and not for instance the in the world of research more common MATLAB®, or other known tools like Gaia LV Network Design from Phase to Phase, can be quickly repeated:

- Focussed on Power System Analysis: less broad but more powerful.
- More stable for extended simulations.
- More and better libraries, with models and controllers available.
- Freedom to program not yet existing controllers.
- Compatible with other partners in the CSGriP project.

3.2. Grid Forming Controller
The BESS is probably one of the most important, if not the most important component of the µG; the grid forming device. The whole system consists of batteries, an inverter and control logic. The batteries are the actual energy carriers, while the inverter acts as an interface between the µG running on AC and the battery DC voltage. The controller aims at regulating the whole system, and make it work satisfactorily.

In times of energy abundance, when more is produced by the DRESs than what is consumed by the loads, this energy will be stored in the battery, for later use when the DRESs cannot feed the loads anymore. The importance of this step is clear, because in order to guarantee a continuous availability of energy backed by sources that only work for a part of the time, installing an energy buffering device is inevitable. The controller of this device is a very important one, since it is the control logic of this object that decides on the whole behaviour of the grid. At the end, it is this controller that will be responsible whether the µG is able to meet the expectations, or not.

3.2.1. Modelling
Before a controller can be tested in the simulation software, the physical layer needs to be defined. Subsequently, the controller will interact with this physical system, making it behave in a way that is required to end up with a satisfactory user experience.

Static Generator: Limitations
The most simple device that can be used as grid forming component, if the ideal AC voltage source is left out of scope, is the static generator, of which the representation in the software is shown in Figure 3.1. It comes with different options: it can be modelled as a battery, PV inverter, Fuel Cell etc. The RMS model of the Static Generator can work in two ways, either modelled as a CSI or a VSI. As explained in § 2.1.3, the difference between these two models is the way the generator reacts to the grid, given that a grid is present.

For the CSI, a main grid has to be present and the generator will sense the voltage and frequency of the grid, while injecting active and reactive power according to the setpoints. This way, the CSI will not try to improve the PQ of the grid, but just use it as is.

For the second option, modelling the inverter as a VSI, a grid is not necessary. Moreover, if the grid would be present, it can cause problems if the controller is not adequately built. This is because a VSI tries to introduce a voltage and frequency to the grid that is then already present, and the presence of two master components on one grid can result in an unstable behaviour.
3.2. Grid Forming Controller

Figure 3.1: Representation of a Static Generator in PowerFactory: The depiction of the device shows how the model consists of a voltage source with inbuilt inverter. This makes that all internal processes are unclear, thus everything that happens between voltage source and inverter is located in a black box.

It may be clear, and was already stressed multiple times, that for the purpose of CSGriP a voltage sourced inverter is the needed system, since it cannot be guaranteed that a grid will always be present. However, since no communication is allowable, a workaround will have to be present, solving the problem of the presence of multiple masters on one grid. It will not be possible to send a signal to certain inverters to switch to the current sourced mode, due to the restriction on using communication equipment, so multiple VSIs should, and will, end up feeding the same grid at moments multiple cells are present on the same backbone.

One problem that is faced with the model of a Static Generator is the fact that it works like a black box that supplies a certain voltage at a given frequency. No information about what happens inside the block is known. However, for the control of a CSGriP cell, it is important to know for instance what the current drawn from the batteries is, in order to have information about the state of charge of the batteries. This is information that is not available from the model, thus makes its behaviour unsatisfactory.

For this reason, another device will have to be used, giving better performance and more possibilities.

PWM Converter: The Better Choice?
The inbuilt model of a PWM inverter in PowerFactory is shown in Figure 3.2. It is modelled as a well-known three phase inverter circuit with switches that have the turn-off capability. What makes this model advantageous over the model of the Static Generator is the fact that here the black box way of working is omitted: a voltage source, representing a battery, has to be manually connected to the input terminal of the inverter, which gives the user the possibility of knowing for instance the actual SoC of the batteries, because the output current can be measured. Furthermore, the dependency of the battery output voltage as a function of SoC can be simulated this way, and the used battery model can be chosen by the user.

An important scheme of the PWM controller is the one that is shown in Figure 3.3. On this figure, the available
Figure 3.2: Representation of a PWM Inverter in PowerFactory: On the figure, we see a PWM inverter connected to a DC-voltage source which acts as battery on the DC-side, and connected to the AC-side of the system on the other side.

inputs and outputs of the model in case of performing an RMS-simulation are shown. Of course, not all the inputs are needed. Only some should be used, depending on the purpose of the model, and the way the inverter should be modelled, as VSI or CSI. The available combinations of inputs can be listed:

- **Pmr, Pmi**: In this mode, the real and imaginary part of the pulse width modulation index have to be supplied to the inverter. A reference system is needed, e.g. a reference machine or an external network; the inverter works as a CSI.

- **Pmd, Pmq, cosref, sinref**: Here, the modulation factors according to a d-q reference-system are supplied. In fact, the provided signals boil down to the values of the previous possibility, thus here again, a grid has to be present since the inverter will act like a CSI.

- **id_ref, iq_ref, cosref, sinref**: Reference values for the d- and q-axis current are given, just like the goniometric values of the reference angle. Here an internal current controller in the PWM is necessary, and a CSI behaviour is seen.

- **Pm_in, dphiu**: Here, the magnitude and phase of the PWM modulation factor are to be given. Because of the specification of the phase, which is given in reference to the global reference frame, the signals are exactly the same as Pmr and Pmi.

- **Pm_in, f0 (F0Hz)**: In this mode, Pm_in means the magnitude of the modulation index, where f0 is the frequency in per unit (F0Hz is the frequency in Hertz). The inverter will act as a VSI.

For simulating a CSGriP-cell, the implementation using f0 and Pm_in is the desirable one, since in this implementation no reference grid is needed thus the inverter acts as a VSI. Because of the fact that both signals of interest for applying the voltage and frequency droop are directly affected by this implementation, the control structure can be expected to be easily implementable into the software.
3.2. GRID FORMING CONTROLLER

3.2.1. AVAILABLE IN- AND OUTPUTS OF A PWM INVERTER IN POWERFACTORY

An inverter can be considered as an ideal source of voltage and frequency, so whichever voltage or frequency is asked from the inverter will be delivered, of course within the limits of what is possible.

3.2.2. STORAGE SYSTEM

The energy storage cell is the device that takes the task of buffering, by storing energy at the moments it is abundant and releasing it again when there is a lack. For this, batteries are used, interfaced to the grid by means of a bidirectional inverter. This inverter is in fact probably the most important device on the μG, because it is this exact component that takes care of forming the grid voltage and frequency, thus this is the device to which the voltage and frequency controllers discussed in the previous section will supply their setpoints.

Because of this important task, the battery system will always be connected to the grid; even at moments when the load consumption would be perfectly covered by the power injected from the renewable sources, the battery system stays online. This because otherwise no stable grid behaviour could be guaranteed, since the inverters of the DRESs are controlled as CSI, thus no grid forming element would be present on the grid.

3.2.2. BATTERY MODEL

A model is developed in order to attain a satisfactory behaviour of the actual batteries. Many ways of implementing a battery have been described, each of them more complex and detailed than the previous one [117–119]. Because a battery is in fact a very complicated electrochemical device, multiple physical processes have to be taken along if its behaviour needs to be known exactly, and in case they have an influence, certain battery behaviours have to be taken into account.

For the research carried out here, however, this exact behaviour is of no interest. The only feature that is needed is a battery that can charge and discharge, hereby giving a representative value of its SoC, and supplying a reliable output voltage. For this, an ideal battery is modelled, represented by means of an integrator, coupled to the grid through an internal resistance. The integrator receives the amount of current that is being supplied or received by the battery system, and using this information the current state of charge of the battery in Ah is easily derivable.

Explaining what the internal resistance of a battery is, is easiest done by showing it in a schematic. This is plotted in Figure 3.4. Here, a schematic of a battery is represented by the series coupling of a voltage source and an internal resistance between terminals X and Y.
The voltage source, represented by $V_{\text{open}}$, cannot be seen as a constant voltage source. On the contrary, the open clamp voltage of a battery will depend on the state of the battery: a higher SoC leads to a higher open clamp voltage. This will be shown in Figure 5.5 on p. 94.

Next to the battery output voltage depending on the SoC, it will also depend on the current flowing out of the battery, because this current introduces an internal voltage drop over $r$. This means that, as the discharge current becomes bigger, the output voltage of the battery will proportionally decrease, and the other way around, as the charging current increases, the negative voltage drop, or increase in battery voltage, increases. This requires the battery management system to charge the battery with a bigger voltage than the open clamp voltage at zero current, which will increase the losses, since all the power that is burnt over the internal resistance accounts as a loss. Similarly, with the same charge or discharge current, a battery with bigger internal resistance has more losses. The resistance will generally be different for a charging or discharging battery, and can depend on the SoC [112], but for the sake of simplicity, this behaviour is omitted in the thesis and a constant internal resistance is assumed.

![Figure 3.4: Schematic representation internal resistance of a battery.](image)

It has been mentioned that the output voltage of a battery depends on its SoC. For this reason, a small control step is added, which will read the current SoC of the cell, compare this value with a lookup table and respond with the output voltage that belongs to this value for SoC. Subsequently, using the current that is being supplied by the device, the voltage drop over this internal resistance can be calculated, and depending on the direction of the current this drop is added to or subtracted from the cell output voltage. Then, using this cell voltage, and having information about the number of cells that are connected in series, the battery bank has an actual output voltage.

### 3.2.3. Overall Controller

The main challenge is to develop a controller ensuring a stable behaviour of the $\mu$G, both when in islanded mode and when interconnected with other $\mu$Gs, and enabling DSM and SSM. Active and reactive power sharing need to be effective, without the need for communication, nor the need for one master as grid forming element and multiple slaves as grid feeding elements.

The reason for this last requirement is that the grid is built in a modular way, where cells can connect to and disconnect from each other depending on their SEP, or other requirements like the priority of the loads they are feeding. This means that it cannot be known which devices will be connected to the Bb at every moment. Since no communication among different cells is allowed, this would mean that it cannot be guaranteed that at every moment one and only one master will be forming the grid.

It can be expected that a controller built this way will interact with any main grid in a desirable way, since the grid will act as a very powerful cell from the other cell's point of view.
Finally, allowing curtailment of the renewable input sources and shedding of the loads by means of the grid frequency is also an important characteristic the controller should have, in order to allow the µG to stay in a stable state for as long as possible. This means that the grid frequency will depend, in the most easy implementation, on the SoC. In case the controller is taken further, other factors such as prediction of future load profiles and DRES input power shall be taken into account in the process of setting the grid frequency. This would then avoid the initialisation of load shedding or power curtailment in case predictions of e.g. renewable energy production foresee that shedding is unnecessary at this moment.

The first requirement is reaching an acceptable sharing of both active and reactive power without sending P and Q setpoints to different inverters. In the nowadays existing public grid, sharing of active and reactive power is achieved by using respectively a frequency and a voltage droop characteristic. In the high voltage grid the impedance of the lines is mainly inductive, which results in a decoupling of active and reactive power according to these formulas. However, the line impedance of a µG is mainly resistive, which results in a big value for the R/X ratio thus coupling of P and Q. This will have as a result that the active and reactive power sharing will be less performing than the same approach on a mainly inductive network. Simulations will have to give an answer to whether the behaviour is within acceptable limits. Also, some workarounds have been presented which that be validated.

**Control Proposal**

The lay-out of the cellular microgrid, as proposed in the text, is depicted in Figure 3.5. It consists of two inverters, each powering their proper load and having the possibility of interconnecting through the Bb. For the sake of clarity, DRESs are not represented on the figure. From the figure, it might seem like the inverter cannot control its switches to connect to or disconnect from the Bb, though this is a matter of representation and is not the actual case. It can be assumed that every cell has the possibility of discriminating its total power supply from the power supplied from or to the Bb, and can also control the transfer switches to adapt its interaction with the Bb.

The virtual control layer is depicted in Figure 3.6. The controller uses a number of measurements to reach two single setpoints, being \( f_{set} \) and \( u_{set} \), respectively the setpoints for frequency and voltage. These signals are given to the inverter control, that using the actual values of the grid parameters \( f_{grid} \) and \( u_{grid} \) employs a closed loop controller for direct and quadrature voltage and current to generate the actual inverter setpoints, for instance the switching decisions for the PWM switches. This is not described in this thesis.

The block *Proposed controller* is where the main focus lies. This controller consists of two parts of importance, which are the *active power – voltage* and the *reactive power – frequency* controllers, respectively depicted in Figures 3.7 and 3.8, and respectively explained in § 3.2.4 and 3.2.5.

### 3.2.4. Frequency Controller

The way the active power – frequency droop scheme works has been explained in § 2.1.5. Shortly summarizing, because of the fact that the inverters are implemented as VSIs, the power is dictated by the load. Because of this, when the load power increases, the power injected by the inverters increases. Following the droop curve, a change in power output results in a change in frequency output, which has an influence on the angle \( \delta \), which is the angle between the voltages of multiple sources. This \( \delta \) has an influence on the power exchange between these sources, in turn influencing the output power of the individual inverters, which then influences the frequency output again, resulting in a change of \( \delta \). Overall, the dynamics of this control mechanism enable the system to find a stable working point where the active power is shared between the sources.

Bear in mind that, while this is an approach which works when two cells have successfully synchronized and are interconnected, one should never connect two sources of different frequency to each other. This would result in huge power flows between the devices because of the enormous values the difference in voltage phase \( \delta \) will take. However, as soon as two devices are interconnected, as soon as one of the devices tries to generate a different grid frequency and the angle \( \delta \) changes, this will immediately result in a change of the power flow,
Figure 3.5: Depiction of the cellular microgrid: Two microgrids with the possibility of interconnecting are depicted, each with their proper load and energy buffer. It is clear how the cells are capable of measuring the power output of the inverter, by measuring the direct and quadrature voltage ($u^*_d$ and $u^*_q$) and current ($i^*_d$ and $i^*_q$) output and calculating the active and relative power, here represented in relative values $p_{inv}$ and $q_{inv}$. The powers going to or coming from the Bb, $p_{Bb}$ and $q_{Bb}$, are calculated the same way.

Figure 3.6: Virtual layer of inverter controller: Using measurements, the proposed controller offers a frequency and voltage setpoint $f_{set}$ and $u_{set}$ to the internal controllers of the inverter, that then establish these grid parameters.
3.2. Grid Forming Controller

Figure 3.7: Active power - frequency controller: The considerations that are taken in order to reach a frequency setpoint $f_{set}$ are depicted. Using the SoC, a frequency setpoint $f_{base}$ is calculated. This then is influenced with respect to limiting a cell from the $Bb$, $\Delta f_{dSoC}$, an overloading prevention $\Delta f_{ol}$, and a damping step $\Delta f_{dp}$, resulting in the zero-power frequency $f_0$. Then, using droop, $f_{set}$ is obtained.

Figure 3.8: Reactive power - voltage controller: In order to find the voltage setpoint $u_{set}$, first the expected voltage drop over the lines is calculated using the measured values for the current $i_d$ and $i_q$, and subsequently this $\Delta u$ is added to the nominal voltage $u_{base}$ in order to calculate the starting point for the droop controller, $u_0$. Using the reactive power the inverter supplies, $q_{inv}$, the $u_{set}$ is obtained.
which in its turn, according to the droop characteristic, leads to a new output frequency.

A schematic of the droop behaviour is shown in Figure 3.9. The most simple way of implementing the controller is by using a fixed point for $f_0$ and $K_p$, so the output frequency is a function of output power solely. However, the aim is to get a dependency of the frequency on for instance the SoC of the batteries, because as mentioned before the SEP of a cell is one of the important parameters. For reaching this dynamic behaviour, three approaches can be followed: dependency on SEP can be reached by changing $f_0$, $K$, or both. These three schemes can be compared to each other.

![Figure 3.9: Control behaviour using a droop curve: The droop curve works as depicted: as soon as the measured power increases, the frequency setpoint moves along the line and the output frequency decreases.](image)

**Fixed or Variable $f_0$ and $K$?**

From Figure 3.7, it became clear how the input of the active power – frequency droop block consists of two variables: $f_0$ and $p$. This means that the droop coefficient $K_p$ is assumed to be a constant, pre-programmed into the controller. The reason for this should be justified.

Like every linear curve, the droop curve consists of two variables: the slope, which is $K_p$ in this case, and the section point with the $y$-axis: $f_0$. It is clear that both variables can be changed in order to reach the behaviour that is wished for, namely a frequency which depends on the SEP of the grid, and a sharing of power according to each cell’s capabilities.

To start, a system with constant $f_0$ and a $K$ dependent on the SoC is considered. Figure 3.10 shows the progress of the droop curves of two cells. From this graph, it is immediately clear that all inverters will always be required to work in the same mode: either all connected inverters are supplying power, or all inverters are charging their BESS. This can be advantageous, because this way we can be sure that a situation where one battery is pumping power into another one will never occur.

However, this method has a big flaw: there is a clash of interests between the deviation of the frequency depending on the SoC, depending on whether the devices are charging or discharging. It is easy to understand that we want the cell with the lower SoC to receive more power in case we deal with a surplus of power, and to supply less power in case power needs to be delivered to the loads. On Figure 3.11 we can see that the device with the droop curve that is located “above” the other curves will supply most power in case of discharging, and receive least power in case of charging. This means that this curve should belong to the cell with the higher SoC.

From the curves depicted in Figure 3.10 it is clear that there is no uniform definition of the $K$ factor in terms of the relative SoC. In the discharging regime, so positive power, the inverter with the smallest absolute value for $K$, depicted by the less steep curve, supplies more power, which is desirable if its SEP is stronger. However, it will be also this inverter with the smaller $K$ factor that will take the bigger share of power in the charging regime, thus the inverter with the higher SoC charges more, which is off course undesirable. When turning this
3.2. Grid Forming Controller

Figure 3.10: Two droop curves with different droop factor $K$: Sharing of power is reached by a dynamic $K$ factor. In this scheme, all connected generators will supply or receive power with the same sign, either all batteries are being charged or all batteries are being discharged.

behaviour around, the cell with the biggest absolute value for $K$, thus the cell which has the steepest curve, will supply less power when discharging, but also receive less power when charging.

It is clear that no definition of the $K$ factor can be linked to the SoC, because the reaction of the SoC should be different depending on the direction of the power flow at any moment.

Secondly, we can take a look into a system with a fixed drooping value and a variable zero-power frequency $f_0$. As mentioned above, one requirement would be that the curve of the cell with the largest SoC would always lie above the cell with a smaller SoC. This is easily done, by choosing a frequency setpoint that is straightforward proportionate to the SoC.

The third scheme that can be developed is this where both $f_0$ and $K$ are varying. It is clear that, if the values are chosen correctly, it can be guaranteed that the curve of the stronger cell will be located above the others at all times, thus helping more in the supply of power and claiming less when a power surplus is present. However, guaranteeing this could require a communication signal between both cells, in order to synchronize multiple controllers. This is a requirement that is not desired.

Decision Analysing the above discussion leads to the conclusion that it is desirable if there is a fixed relation between the SoC and zero-power frequency setpoint exists. Therefore, the control scheme with a varying $f_0$ and a fixed $K$ is chosen. It is important to choose the value for the droop very carefully, in order to reach a grid that works stable at any time. This will be discussed thoroughly in Chapter 4.

If the BESS of multiple interconnected cells has the same SoC, it can be beneficial that the cell with the biggest battery capacity provides more power than a smaller one, in order to reach an even discharge rate. However, it is possible that the battery with the biggest capacity is installed in the presence of the most critical load, thus it should be avoided to use this battery for the sake of supplying less important loads.

Furthermore, a certain mechanism has to be built into the controller which prevents fast and sudden changes of the frequency. If the $\mu G$ is compared with the current public grid, we can expect that a certain amount of damping is inevitable in order to sustain the grid in a stable working condition. In the public grid, this damping is provided by the rotational inertia. In the $\mu G$, however, having the obligation of adding inertia in the form of rotating mass is not allowed, as this would imply adding certain requirements to the grid that are undesirable. One of the base requirements of CSGriP is the necessity of being able to run all kinds of loads, so the possibility of having a grid running solely loads without inertia exists. So, an alternative for avoiding these sudden jumps needs to be found.
Figure 3.11: Result of one droop curve that is always above the other: From this picture, it is clear that a cell with a "higher" droop curve will supply more power in case of load demand, and receive less power in case the devices receive power.

This alternative exists, and can be found in the virtual inertia. This consists of an extra parameter in the control loops, preventing quick and sudden changes in the frequency. If suddenly power is added to or subtracted from the grid, an inertialess system will follow these changes in demand very dynamically, but this can lead the grid into instability. With this extra control scheme, which can be implemented in different ways, the quick changes are prevented and the grid works more stable.

Summarizing, the frequency behaviour of the inverter depends on three variables: $f_0$ and $K$ of the droop curve, and $P$ delivered by the inverter. By using a function dependent on the SoC, the location of $f_0$ is calculated. Then, by taking $K$ as a constant, and measuring the power delivered by the inverter, the active frequency is calculated according to

$$f_{set} = f_0 + K_p \cdot p.$$ 

One might think that it is problematic when two inverters are interconnected and working at a different frequency setpoint. In fact, having two inverters in parallel working at a different frequency setpoint is problematic. However, this exact problem is solved by applying the droop curve. The formula for active power flow is given in § 2.1.4, where we saw that the active power flow depends on the phase angle between the voltages. If both inverters would try to make a different frequency, this would cause a huge power flow from one to the other. This shifts the set point for frequency up or down, in turn allowing both inverters to find their common frequency and power setpoint at which the power sharing will be according to the requirements set by the controller.

**Calculation of $f_0$**

As mentioned, the zero-power frequency $f_0$ depends on the SoC. However, in order to reach a desirable behaviour at all times, more dependencies can be necessary. Using the derivative of the power, the SoC and the dSoC, $f_0$ will be calculated, which acts as an input for the droop characteristic.
State of Charge  A change in SoC should yield a change in frequency output. This way, if the state of charge is higher or lower, more or less curtailment or shedding will occur, respectively. Also, if multiple cells are interconnected, the one with the lowest SoC will be less burdened. It is desired that in normal operations, so when no drastic actions are required, the desired frequency is close to 50 Hz. Only when the SoC reaches critical values, both in terms of over- or undercharging, the frequency deviation becomes significant in order to cope with this situation. This behaviour is depicted on Figure 3.12. The exact values for $f_{\text{min, max}}, \text{SoC}_{\text{min, max}}, x_{1,2}$ and $y_{1,2}$ will be defined in a later stage.

From the figure, it is clear that the value for frequency that will be chosen based on the SoC has a high value, around 1 p.u. or 50 Hz at all times.

Figure 3.12: Frequency dependency on state of charge: The graph shows how the frequency output of a controller changes depending on the SoC measured from the batteries.

Derivative of Power  The term for the derivative of the power is used to add damping to the grid. The aim of this term is to make sure no sudden changes in the frequency can occur, by opposing sudden deviations. If an unforeseen change in power takes place on the grid, the frequency setpoint is instantaneously altered in order to stabilize the output frequency, which will then change more slowly.

The value for this term of the frequency is a low value. In case no power changes happen, the value is 0, and only at given moments, this term will take a value which then will be added to the frequency setpoint based on the SoC.

Input:

\[
\begin{align*}
  t = t_0 : P &= P_0 & \rightarrow f_{t_0} &= f_0 - K_P \cdot P_0 \\
  t = t_1 : P &= P_0 + \Delta P & \rightarrow f_{t_1} &= f_0 - K_P \cdot (P_0 + \Delta P) + x
\end{align*}
\]

Wish:

\[
\begin{align*}
  f_1 &= f_0 & \rightarrow \text{calculate } x \text{ with } x = K_d \cdot \frac{\Delta P}{\Delta t}
\end{align*}
\]

\[
\begin{align*}
  0 &= f_0 - K_P \cdot P - f_0 + K_P \cdot (P_0 + \Delta P) - x \\
  x &= K_P \cdot (P_0 + \Delta P) - K_P \cdot P_0 \\
  x &= K_P \cdot P_0 \\
  K_d \cdot \frac{\Delta P}{\Delta t} &= K_P \cdot \Delta P \\
  K_d &= K_P \cdot \Delta t
\end{align*}
\] (3.1)
**Derivative of State of Charge** Another dependency of the frequency can be the derivative of the state of charge. The first reason for this is the fact that this term can prevent e.g. Battery I being charged while Battery II is discharged. If this would happen, energy is wasted, as both the charging as the discharging process obviously do not occur with unity efficiency [120]. This is where the dSoC-term would play its role, by normalizing the setpoint for \( f_0 \) in function of the rate of change of the SoC, the no-power frequencies of the different cells are closer to each other, so less energy will be poured over from one battery to another.

Secondly, this derivative acts as a feed forward, so any upcoming problems in terms of e.g. load support can be predicted before they actually happen. Moreover, assume a situation where multiple cells are interconnected and sharing load. Let us say that one of the cells is equipped with a bigger battery than the other one. In this case, the factor resulting from dSoC will make sure that this cell with a bigger battery (given that all the other parameters are the same) takes the biggest share in power into account. The term for dSoC will aim at normalizing the derivative of the state of charge for all batteries, in order to reach an even support.

This procedure, however, holds a potential drawback: if the DRES of Cell I are producing a lot of power, then it is desired that Battery I is charged accordingly. However, if this battery sees this big rate of change, it will try to fight the reason of this, thus potentially limit the power output of the DRES when this is actually not needed. Thinking about this, application of a frequency setpoint dependent on the dSoC can result in more curtailed DRES power, thus also a potential increase in eventual diesel consumption. A solution consists of measuring the power that enters the cell through the Bb.

**No Charging from Backbone** As mentioned, the influence of the dSoC-term can be limited to those moments when power comes from the Bb. This way, we are sure the power of the DRES within the cell is used for charging the battery of this cell first. The procedure will be as follows: if a cell is charging at a rate higher than a predefined speed (e.g. a C-rate of 0.5), it will be checked where the power comes from. If the power comes from the proper DRES, so within the cell borders, there is no problem. However, if it turns out that there is power flowing from the Bb into the cell, the cell will limit the charging rate by gradually increasing the zero-power frequency setpoint \( f_0 \). This because it is unknown where that power comes from, so it can potentially be coming from another BESS, causing one battery to discharge into another battery.

In fact, the step is comparable with the dSoC one, since the speed of charging will be known by means of the derivative of the state of charge. The main difference lies in the fact that this step will only work if power comes in through the backbone, and there will not be a fixed dependency on dSoC. The frequency dependency is variable by the application of an integrating step.

A potential drawback here is that e.g. Cell II can be curtailing power from its DRESs while Cell I is limiting the rate of charging. This can be solved by requiring that the limiting scheme only functions at frequencies below 50.2 Hz. Furthermore, a distribution of power depending on the size of the BESSs is not reached. Benefits and drawbacks of both dependencies of dSoC are listed in Table 3.1, where ✓ represents an advantage and ✗ a disadvantage.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>dSOC</th>
<th>No charge Bb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potential curtailing own DRES</td>
<td>✗</td>
<td>✓</td>
</tr>
<tr>
<td>Potential curtailing other DRES</td>
<td>✗</td>
<td>✓</td>
</tr>
<tr>
<td>Normalize contribution according to size battery</td>
<td>✓</td>
<td>✗</td>
</tr>
</tbody>
</table>

Looking at Table 3.1, we can see that the second approach has a potential benefit over the first approach. Also, it can be argued that the potential drawback of this method, being the normalization of the contribution depending on the battery size, is not an issue, since every battery should be sized according to the limits and boundaries of its proper cell, without taking into account other cells. So the contribution of Cell I in delivering
power to the loads which belong to Cell II might be dispensable and even undesirable. Therefore, the second approach is preferred.

The value of this term will, similarly to the value of frequency depending on the derivative of the power, be 0 in normal operation and only add or subtract to the frequency setpoint at certain given moments.

**Overload-limiting step** A frequency influencing parameter is needed in order to keep the inverters from being overloaded. This step will be discussed in great detail in § 4.3.

### 3.2.5 Voltage Controller

As discussed earlier, the inverter module does not only require a value for frequency, but also the grid voltage that has to be produced has to be known. In fact, the inverter is not interested in the real value for the voltage, though in the modulation index, which is in fact the ratio between AC and DC voltage magnitude, and can be repeated:

\[ P_m = \frac{U_{AC}}{K_0 U_{DC}}, \]

in which:

\[ K_0 = \frac{\sqrt{3}}{2\sqrt{2}}. \]

In this formula, \( U_{DC} \) will depend on the SoC of the batteries, and \( U_{AC} \) is dependent on the requirements as set by the voltage controller.

One of the responsibilities of the voltage magnitude at the terminal of the inverter is providing the possibility of reactive power sharing between different inverters. But, as known from the basic requirements for PQ, the voltage at the load terminals should not cross certain borders, e.g. the terminal voltage needs to lie within \( \pm 10\% \) of the nominal voltage at all times. This means that the unavoidable voltage drop because of a current running through a resistor, as defined by Ohm's Law, has to be compensated for.

It seems that the voltage setpoint will depend on two measurements, both the reactive power and the value of the current supplied by the inverter. From this voltage setpoint, using the DC voltage at the terminal that depends on the SoC and the current coming from the batteries, the modulation factor is calculated.

The first dependency is easy to understand: knowing the grid impedance, or at least an approximation, and the current supplied by the inverter, the voltage drop over the impedance is easily calculated by means of Ohm's well-known Law,

\[ \Delta U = Z \cdot I. \]

This calculated value for \( \Delta U \) will be added to the voltage setpoint, thus if a current is supplied by the inverter its voltage setpoint will increase, in order to supply the correct value for the potential.

Secondly, the potential difference between multiple sources interacts with their reactive power supply, as was proven in § 2.1.5. This means that, similar to the dependency of \( f \) to \( P \), \( U \) depends on \( Q \), specifically according to

\[ U = U_0 + K_q \cdot q. \]

It was mentioned how the effectiveness of \( Q \) sharing largely depends on the output impedance of the inverter. This because, with an increase of resistivity in this output impedance, the voltage drops more for the same output current, obviously having its influence on the \( Q \) sharing scheme.

However, in order to filter out high-frequency harmonics that are ever-present in the output of a PWM inverter, an LCL-filter is applied at its output. This filter introduces an inductive behaviour, in combination with a well-known impedance. Consequently, this element is expected to improve the reactive power sharing scheme while facilitating the compensation for the voltage drop over the lines.
Overall, the final voltage magnitude is calculated by adding the terms that were calculated for the compensation of the voltage drop and the one for the droop characteristic to the base value of 400 V. This ultimate voltage is then divided by the voltage that is received by the battery bank and by the modulation constant, yielding a value for the desired modulation index, which is fed to the inverter. The desired voltage is consequently attained.

3.3. Energy Consumers
On the grid, obviously some energy consuming devices are present. These can be seen as the components of main importance of the grid, since they are what the whole grid is about: try to supply power to these consumers when they require it, and try to succeed at this as long as possible in case of a low power inflow from the DRESs, hereby potentially differentiating between load priorities.

3.3.1. Load Modelling
The influence of the energy consuming devices, in general the load, should not be underestimated when considering the overall grid behaviour. Implementing the load differently can result in a difference in grid behaviour. One easily understandable example is how an engine will interact with the grid: in case the device is directly coupled to the grid, without an interfacing drive, a rotating inertia is added to the grid. This will have as result that frequency deviations cannot take place instantaneously: first the engine needs to accelerate or decelerate, hereby respectively consuming or injecting power from or into the grid.

On the other hand, a conventional incandescent light bulb does not have this frequency behaviour, and will act as a constant impedance load to the grid. Another type of load, for instance a drive, will try to preserve the power that it draws from the grid. This means that with a decrease in grid voltage, the current will increase to keep the power output the same.

It is clear that load modelling is not a straightforward process, not only due to the fact that a number of different load types exist, but is also a result of the large number of loads a grid holds. So even if the behaviour of each and every single load is perfectly described, still implementing all these loads individually would be a inconvenient task.

For these reasons, two broad categories of loads have been defined in literature [121]. These are Static loads and Dynamic loads.

Of these types, only static loads will be considered in this thesis. The static load can have three different behaviours, which are:

- Constant Power;
- Constant Current;
- Constant Impedance.

The so-called exponential load model is capable of simulating the behaviour of these three types of static load [74]. This model is built up by expressing the load characteristics as a function of grid voltage and frequency at the terminal, hereby taking the reaction of active and reactive power separately. The equations for active and reactive power are given.

\[
P = P_0 \left( \frac{V}{V_0} \right)^a
\]

\[
Q = Q_0 \left( \frac{V}{V_0} \right)^b
\]
where \( P, Q \) are the active and reactive power, with \( P_0 \) and \( Q_0 \) their setpoints in case of nominal grid voltage \( V_0 \), and \( a, b \) are the exponents characterizing the loads, following Table 3.2.

<table>
<thead>
<tr>
<th>Value for ( a, b )</th>
<th>Load type</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Constant Power</td>
</tr>
<tr>
<td>1</td>
<td>Constant Current</td>
</tr>
<tr>
<td>2</td>
<td>Constant Impedance</td>
</tr>
</tbody>
</table>

This constant load model is the one present in DIgSILENT PowerFactory [122], named the General Load. Therefore, the explanation of other implementations for loads, like the so-called ZIP model [74], can be omitted. Also, for the sake of simplicity, dynamic loads are omitted. This can be a nice recommendation for future work.

The choice is made to model all load as being constant power loads, since their change in behaviour with a change in grid voltage is the most challenging one from the controller’s point of view.

The load model in PowerFactory asks for two inputs: the active and reactive power that needs to be consumed momentarily, thus respectively \( P_0 \) and \( Q_0 \) from Equations (3.2) and (3.3). Upon receiving these setpoints, the amount of power is effectively consumed. The VSIs follow and supply the power that is needed for the loads, after what the CSIs have already covered.

The amount of active power consumption will be discussed in Chapter 5, both for a grid in a developed country like the Netherlands, and a grid in a developing country like Burundi. The reactive power consumed by the loads is calculated by means of a small calculation, where the arbitrary choice is made to make the loads consume with a power factor of 0.95. Since harmonic currents are omitted in the simulations, the power factor equals the \( \cos \phi \) in every case, thus the reactive power consumption is easily calculated by dividing the active power by this value for \( \cos \phi \), 0.95, and subsequently multiplying it with \( \sin \phi \), calculated as \( \sin(\arccos \phi) \).

### 3.3.2. Load Shedding

Since the delivery of power occurs by means of uncontrolled DRESs, buffered by a battery system, it cannot be expected that energy will always be available. Of course, both the battery system and the DRESs can be heavily oversized, in order to be able to supply the loads even in case of multiple days of low energy yield, or a controlled energy source such as a diesel generator can be installed, but in case we ignore these two solutions and consider a normal-sized grid without diesel generator, it can be understood that load shedding might prove necessary at certain moments in time.

The concept of load shedding has been discussed in §2.1.8, thus will not be reviewed in this section. What will be quickly presented here is how the load shedding will be implemented into the simulations.

The response of load will be according to the different profiles as sketched in Figure 2.13 shown on p. 32 for the developing case, and according to the requirements set by UFLS as discussed in §2.1.8 for a \( \mu \)G implemented in a developed situation. Which loads will disconnect at which specific frequency is something that will be discussed further, in Chapter 5.

The way of implementing this load shedding is done in a relatively straightforward manner: a shedding factor is defined, which equals 1 at any moment when no load shedding is required, and 0 when the complete load should be disconnected. Subsequently, the load power is multiplied with this factor, yielding the load power that can be consumed at any moment. This value is passed to the load element in MW units, as defined by the requirements of the General Load. This is depicted in Figure 3.13. The shedding decision block gets \( P_{\text{load}} \), the actual load power, and the current grid frequency as an input. Then, using different parameters, a decision
is made on whether the load should be shed or not, resulting in $P_{\text{shed}}$, the power after shedding. Using the power factor, this results in an actual setpoint for the load consumption, both active ($P_{\text{set}}$) and reactive ($Q_{\text{set}}$).

It is clear that this consists a very simplified approach, where any irregularities such as tardiness of load reaction or customers by whom the necessity of load shedding is ignored are not taken into account. However, it is expected that in case a project is effectively implemented, and load shedding is required in this project, the way of the implementation of this feature will be done effectively, hereby justifying this simplified way of implementation.

![Diagram of load controller implementation](image)

**Figure 3.13: Implementation of the load controller:** By using the grid frequency and knowing the exact location of the shedding curve, the amount of load after shedding is calculated. Subsequently, using a predefined value for the power factor, the ultimate $P$ and $Q$ are calculated and fed to the load block.

### 3.4. Distributed Renewable Energy Sources

DRESs will be the main — if not only — source of energy in the µG. Their interaction with the grid is important to see how the overall grid responds in a static and dynamic way. As it is commonly done, the DRESs will be implementing as CSI.

Two types of DRESs will be considered in the simulations, these are solar panels and wind turbines. The choice has been made to use small-scale wind turbines only, interfaced to the AC grid by means of an inverter, first rectifying the AC voltage supplied by the wind turbine and subsequently inverting it again to meet the grid requirements. This means that, from the grid’s point of view, there is no real difference in the way the solar panels and wind turbines behave.

#### 3.4.1. DRES Modelling

In the software, a model for static generator is present, which can represent any kind of non-rotating generator, among which PV generators and wind turbines [123]. Indeed, a wind turbine is a rotating device in se, but because of the AC-DC-AC conversion it behaves as a static device, thus it is allowed to implement it like this.

The model can be implemented in a number of ways. For instance, for the PV panels, it can be opted to supply solar irradiation to the model, together with the panel type and the plant size, which will then yield the PV production. Another way of implementing this device is by simply telling it the amount of current produced, thus the conversion of irradiation to power output has been already executed. For the wind turbine, a similar decision exists.

Since the data that was available for use in the project was delivered in the form of power produced, it has been opted to use the second way of implementation. For this, the power output has to be transformed to direct and quadrature current, and this in the per unit representation. Since $\cos \varphi = 1$ was chosen, $i_d$ is easily calculated by dividing the power by the voltage at the generator terminal, and $i_q = 0$ at all times. The static generator behaves as a CSI.

For reasons that will be explained further in Chapter 5, the developed grid will include both a wind turbine
and a solar park, while the developing situation will only incorporate solar panels.

### 3.4.2. DRES Curtailing

Similar like the way the load should react to the frequency, also a reaction of the DRESs when the grid frequency deviates too much from the nominal setpoint is expected. This behaviour has been clearly explained throughout § 2.1.9.

Shortly summarizing, if it is chosen to implement the German grid standard VDE-AR-N 4105 (see Figure 2.17 on p. 37), then starting at 50.2 Hz the PV output power ramps down following a rate of 40% per Hz, after which a step to 0 power output is taken in case 51.5 Hz would be reached.

Other frequency-dependent reactions can be thought of, of which one will be explained further in § 5.1.2.

The exact dynamics of the SSM are of low importance for the implementation of this curtailing, since implementing another SSM scheme merely consists of including different equations in the relevant block; at the moment the specific scheme is known and the grid frequency can be measured, the rest is clear-cut.

In order to reach the act of curtailing, the same method as the one explained for the DSM scheme has been used: depending on the chosen standard, and taking into account the grid frequency and the current curtailment state, a factor can be calculated that expresses the amount of allowable residual power output. Subsequently, the input power is multiplied with this power, yielding the power that can be produced by the DRES. This power is then converted into $i_d$, which is supplied to the Static Generator. This is depicted in Figure 3.14. The potential amount of DRES production, $P_{DRES}$, is fed into the curtailing block, along with the frequency. Using the standard and the state, this power can be curtailed or not, resulting in $P_{curt}$, the power after curtailment. Subsequently, the current setpoints for the CSI have to be known, which can be done using the grid voltage $U_{clamps}$, resulting in the current setpoints $i_d, set$ and $i_q, set$, fed to the static generator block.

![Figure 3.14: Implementation of the DRES controller](image)

The potential power production is known. This power is curtailed, taking into account the grid frequency and the applied standard. Subsequently, the amount of curtailed power $P_{curt}$ is converted to the direct and quadrature current, which are fed into the static generator block.

### 3.5. Summary of the Chapter

Firstly, the way how the BESS is implemented and controlled has been explained. The implementation has been done by connecting a DC voltage source, modelled as a battery, to a PWM inverter. The control of this inverter occurs by implementing the drooping behaviour for active and reactive power, with some extra parameters that influence, like the actual SoC.

After this, the implementation of the energy consumers has been discussed, hereby showing how the loads are represented and react to changing parameters on the grid, and also how the DSM controller works.

Finally, the DRESs has been shown: a model exists in the simulation software, which could be easily used for simulating power injection from renewable sources. The devices are interfaced by means of a controller that takes care of the SSM.

*The following chapter will discuss the stability frame of the just-defined controller.*
STABILITY OF THE SYSTEM

We cannot solve our problems with the same thinking we used when we created them.

A. Einstein

When it comes to $\mu$Gs fed by static devices only, it is a fact that no inertia is present in the system. This can be seen as a drawback, as inertia has the inherent, very desirable characteristic of introducing a natural damping to the system. Some inherent characteristics of a system fed by synchronous machines can be listed [124]:

- Speed of variations of grid frequency is limited by the machine inertia.
- Grid frequency and active power are inherently linked, this is, if the mechanical power stays constant, the grid frequency will drop with an increase in output power.
- Due to the presence of a synchronizing torque component, devices that are initially interconnected will remain in synchronism.

Due to the absence of these natural characteristics in a system supplied by static power inverters, these operating conditions need to be introduced by the control system of the inverter, as was discussed in § 2.1.4. It is important that system stability can be guaranteed, both the small-signal stability, which concerns the ability of the controller to keep the devices synchronised after disturbances, and steady-state stability which will take care of a satisfactory operation of the system over longer periods of time, for instance finding a stable working point within the rating limits.

4.1 SMALL-SIGNAL STABILITY

The first field that should be analysed is the small-signal stability of the system. This concerns the power system's response to any small perturbations, where the synchronization between multiple voltage sources should not be lost. If disturbances are adequately damped out over time, thus oscillations are suppressed, then the power system is said to be stable. On the other hand, if the magnitude of oscillations would rise over time, or stay constant, then we can conclude that the power system is unstable. This is represented in Figure 4.1.

The presence of rotational inertia in the system offers a means of dynamic damping to the system, as the inertia cannot accelerate and decelerate instantaneously. So even if the system controllers would try to drastically increase and decrease the speed of the system in an oscillatory manner, this could not possibly be followed by the power system. This unlike the static inverters which this thesis deals with, where any changes in e.g. output frequency can be followed right away.
As discussed earlier in §2.1.4, the active power output of the system is looped back into the controller, passed through a gain and then used to adapt the system frequency. The graphical representation of the droop curve is recited in Figure 4.2. It is important to realize that the droop curve always follows a negative slope, thus $K_P$ is always a negative number, since introducing a positive droop scheme introduces more drawbacks than advantages [16]. For instance, compatibility with the higher located power network would be lost, because the virtual link between output power and grid frequency is turned around in case of a positive $K_P$.

Control theory teaches us that a large gain in the feedback loop can vitiate the system stability. Analysing the behaviour of the system, it seems that a high droop value corresponds with a high value for gain: if the power deviations are considerable, with a big droop value the frequency deviation will be big as well.\(^1\) Thus, an increase in power output of one inverter can lead to a powerful reaction of the frequency output, which will have a big influence on the voltage angle $\delta$. In turn, this leads to a considerable rearrangement in output power of different inverters, triggering more and stronger reactions of the output frequency.\(^2\) This behaviour can come to be an unstable oscillatory reaction, which should be avoided at all costs.

### 4.1.1. SMALL SIGNAL MODEL

Unlike for synchronous machines, the analysis of the small-signal stability for inverter based $\mu$Gs is a relatively new field of interest. Due to the above-mentioned reasons, care has to be taken that the network is not forced into stability because of the absence of physical inertia. The system dynamics that have to be taken into account are the inverter itself, with all its relevant power controllers, the loads connected to the network, and surprisingly the network characteristics. These are negligible in case of a system using synchronous machines, due to the large time constants that are present there, but can have their influence in combination with static devices with low time constants. Some work has been done when it comes to this field [55, 67, 77, 124, 125].\(^3\)

\(^1\)For the sake of clarity: if throughout this chapter the term bigger droop is used, this means that the absolute value of the droop variable is bigger, thus the droop curve follows a steeper trend. In the case discussed here, this means a system with a bigger gain.

\(^2\)As explained throughout §2.1.5, this is the opposite of what is being observed in the current application of droop control: a mechanical system, where frequency deviations cause power deviations. In this case, a low value for the droop coefficient $K_P$ leads to a strong power alteration, which involves a high gain is reached with a low droop.

\(^3\)Due to time restrictions, the analysis has not been performed for the system described in this thesis. It has been opted to adopt and utilize analyses that have been performed on a similar system [77]. This means that the results discussed in this section need to be
4.1 Small-signal Stability

Our system comes with an outer power loop, based on droop control to share the active and reactive power. This outer loop is used to obtain the voltage magnitude and grid frequency. The setpoints for these are presented to a voltage and current controller included in the inverter, managing the switching process of the PWM inverter. This switching can be neglected due to the high dynamics, commonly in the order of above 4 kHz. The system can include a filter at the output in order to remove high frequency disturbances in the output voltage, or a virtual inductance.

In order to analyse system stability, the eigenvalue analysis is a commonly used tool [126]. This comprises of deriving the state-space model of the complete grid, which then can be used to analyse the dynamics of the system. By doing so, it can be guaranteed that the system will remain in stability under all circumstances with a certain frequency gain, or droop value, and also the value for the gain can be optimized.

**Power Control**

The power controller is the system that mimics the governor of any synchronous generator, where the behaviour of a decreasing grid frequency and voltage with an increase of respectively active and reactive power is set. Firstly, the active and reactive power coming from the inverters must be known. It is known that active and reactive power are calculated according to

\[
\tilde{p} = v_d i_d + v_q i_q \\
\tilde{q} = v_d i_q - v_q i_d
\]

These instantaneous values for power are then passed through a low-pass filter in order to obtain the RMS values of these signals:

\[
P = \frac{\omega_c}{s + \omega_c} \tilde{p} \\
Q = \frac{\omega_c}{s + \omega_c} \tilde{q}
\]

where \(\omega_c\) is the cut-off frequency of the filter.

Then, according to the active droop scheme, the output frequency can be calculated. Similarly, reactive power is shared by means of the voltage droop.
State-space representation. A state-space model for the power controller can be obtained. The inverter-controller system has two outputs, namely the grid frequency $\omega_o = 2\pi f_o$ and $U_{o,dq}$. The model looks like Equations (4.1) and (4.2).

$$
\begin{align*}
\dot{\Delta \delta} & = \Delta P \cdot \Delta \delta + B_P \cdot \Delta i_{od} \\
\Delta P & = A_P \cdot \Delta \delta + B_P \cdot \Delta v_{odq} \\
\dot{\Delta \omega_o} & = C_P \cdot \Delta \delta + D_P \cdot \Delta i_{odq} \\
\dot{\Delta v^*_o} & = \Delta P \cdot \Delta Q + D_P \cdot \Delta i_{odq}
\end{align*}
$$

In which:

$$
A_P = \begin{bmatrix} 0 & -K_p & 0 \\ 0 & -\omega_c & 0 \\ 0 & 0 & -\omega_c \end{bmatrix}
$$

$$
B_P = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \omega_c I_{od} & \omega_c I_{od} & \omega_c V_{od} & \omega_c V_{od} \\ 0 & 0 & \omega_c I_{od} & -\omega_c I_{od} & -\omega_c V_{od} & -\omega_c V_{od} \end{bmatrix}
$$

$$
C_P = \begin{bmatrix} 0 & -K_p & 0 \\ 0 & 0 & -K_q \\ 0 & 0 & 0 \end{bmatrix}
$$

$$
D_P = [0]
$$

where $i_o$ is the output current of the inverter, $i_l$ represents the output current after the filter, $v^*_o$ is the voltage setpoint, $v_o$ is the actual voltage and $\Delta i_{ldq} = \begin{bmatrix} \Delta i_{ld} \\ \Delta i_{lq} \end{bmatrix}$.

Rest of the System

In a similar way, the rest of the system that consists of the voltage controller, the current controller, the output filter and coupling inductance, the network and the loads, can be expressed in a state-space system. From these equations, the system can be deducted as follows:

$$
\begin{align*}
\dot{\Delta x_{INV}} & = A_{mg} \cdot \Delta x_{INV} \\
\Delta i_{line,DQ} & = A_{mg} \cdot \Delta i_{line,DQ} \\
\Delta I_{load,DQ} & = A_{mg} \cdot \Delta I_{load,DQ}
\end{align*}
$$

where $\Delta x_{INV}$ is the representation of $n$ inverters with their respective controllers, that can be defined as follows: $\Delta x_{inv,1}$ $\Delta x_{inv,2}$ $\ldots$ $\Delta x_{inv,n}$ $\Delta I_{line,DQ}$ is the model for the network, and $\Delta I_{load,DQ}$ represents all the loads on the network. $A_{mg}$ is the complete system state matrix.

As was mentioned in § 2.1.5, a state-space system like this, taking into account a big number of loads and sources, will result in a very complex approach.

4.1.2. Eigenvalue Analysis

The field of eigenvalue analysis is well-established in the world of power system stability [121]. It has proven to be a very useful tool to determine the stability of a system, by revealing the way a system responds to any disturbances, in terms of oscillatory behaviour and effective damping of transient signals.
By representing the eigenvalue spectrum of a system, it can quickly be determined how the transient behaviour of the system will be. For instance, if a system has eigenvalues with a big imaginary value and a small (negative) real value, it can be expected that oscillations will damp out slowly. On the other hand, a system without any imaginary component will not show any oscillatory output. A positive real value alerts to a system with positive damping, which is in fact a never-ending increase in the output signal, thus an unstable system. This and that are graphically represented in Figure 4.3.

![Figure 4.3: Stability of the system according to the eigenvalues](image)

From the eigenvalue spectrum, the stability and transient behaviour of a system can be quickly determined. Positive real values lead to instability, and an imaginary term shows oscillations.

### 4.1.3. Discussion and Reservations

From analysing the system's state space model, interesting conclusions can be drawn. As expected, the stability of the system is put under pressure when increasing the droop value: a very low value for the droop, say 0.05%, leads to a system that is safely in the stable region, but upon increasing this gain, the eigenvalues slowly move towards the unstable region. Instability is reached at a droop of 0.6%. In order to keep a certain safety margin, it is recommended to keep the droop value below 0.5%. A similar analysis of the reactive droop factor shows that the stability will be guaranteed for values up to 8%.

A trade-off exists between the effectiveness of active and reactive power sharing and system stability: the higher the droop, the better the ultimate sharing will be, though potentially at the price of system stability.

As mentioned, the analysis in this discussion was adopted from a similar system that has been performed in the past. This means that the state-space model discussed in this section is not the exact model of the system discussed in the thesis. In the absence of better, this model is used for the simulations.

Due to the fact that the magnitude of the droop coefficient is very limited, some problems can be expected. The first problem is a potential risk of overloading the inverters on the long term, because a small gain means that the inverter power needs to increase a lot for a small difference in output frequency. This will be discussed in the following section. Another problem can be found in active power sharing among different inverters: it is known that the risk of decreasing the droop coefficient leads to a poor sharing of active power. Especially in combination with the variable zero-power frequency setpoint which is considered in this thesis, the performance of active power sharing could be jeopardized because of the small value for droop. This will
be verified in the simulations, in Chapter 6.

4.2. Steady-state Stability

Next to the dynamic stability, which was analysed in the previous section, another factor of importance is the ability of the system to find a stable long-term working point at all times. This means that the inverters should not be overloaded for too long, which can be accomplished by considering the location of the working points in case two or more inverters are interconnected, or by taking the sufficiency of sharing active and reactive power into account.

If power is shared less effectively, it is clear that overloading of one of the components is more prone to happen. This makes a system with a low droop coefficient vulnerable for overloading. Of course, the assumption is made that the amount of nominal inverter power on the grid was designed with the load power in mind, thus that the grid is well-designed.

Overloading of one of the components will only occur in the first moments after different cells have interconnected. This because this is the moment at which the SoC of the cells can have the biggest difference. When multiple cells have been interconnected for a certain time, because of the way the controller works, the SoCs are equalized and the danger of overloading disappears.

4.2.1. Working Point

In order to understand how the place where the working point is situated can cause problems, first it needs to be understood how this working point is settled. As explained, a working point between two inverters will be reached due to an interaction between voltage angle $\delta$ and the power output of the inverter: by moving along the droop curve, two inverters will change their frequency output until they reach a common frequency with a difference $\delta$ that allows them to share the power in accordance with all the prerequisites.

It is easy to predict where this working point will be located, if the droop value and point of zero-power frequency of all inverters are known. As an example, the deduction will be done for two inverters, as this is easier to grasp, but it is understood that the same rules will apply for a system with $n$ inverters.

In fact, the working point of two inverters can be emanated using two boundary conditions: firstly the frequency of both systems need to be the same, and secondly the total power supplied by the inverters needs to equal the power demanded by the loads. The working point of both inverters can be found by solving the system shown in Equation (4.3).

\[
\begin{align*}
    f_i &= f_0,i - K_{p,i} \cdot p_i \\
    \text{With: } &\left\{ \begin{array}{l}
        f_1 \equiv f_2 \equiv f_n \\
        p_1 + p_2 + \cdots + p_n \equiv p_{\text{load}}
    \end{array} \right.
\end{align*}
\]

(4.3)

In this system, the setpoints for $f_{0,i}$ and $K_{p,i}$ are known.

The working point can also be found in a graphical way, by plotting the droop curves and sharing the active power that needs to be delivered among the inverters, with the boundary condition that the output frequency needs to be the same. Where this approach is still doable for finding the point among two inverters, it will clearly have shortcomings for finding the working point of more devices.

From Figure 4.2 on p. 75, it can be understood that a bigger droop value will result in larger deviations from the nominal frequency value $\Delta f$ for the same change in power $\Delta P_{\text{inv}}$. This means that it will be harder to keep the grid within the limits defined by the EN 50160 [84], which is an argument in favour of choosing a low value for droop, on top of the dynamic stability requirements discussed earlier. On the other hand, no droop means an isochronous system, which was explained in Figure 2.3 on p. 16: a behaviour where no working point can be found.

Taking this a bit further shows us that even a system with drooping behaviour has a risk of not successfully finding a long-term stable working point, if the values of the zero-power frequency setpoint $f_0$ are far away
from each other and the droop curves are not steep enough. Figure 4.4 shows this: even if both inverters are set up with a droop, they are unable to find a common frequency point without violating the limitations in output power.

As a result of this, even if an inverter can be overloaded for a short time [128], it is unacceptable to run a system like this, since overloading the inverter for too long can jeopardize the continuity of power supply to the system, the lifetime of the components, the safety of operation or have any other possible drawbacks.

It is clear that, after an analysis of the small-signal stability which was performed in the previous section, taking a closer look into the steady-state stability cannot be omitted from the research.

![Figure 4.4: Two inverters unable to find a common frequency setpoint](image)

---

### 4.2.2. Analysis of Droop Value

As explained in § 3.2.4, the setpoint of the zero-power frequency $f_0$ mainly depends on the SoC of the battery in order to obtain a satisfactory long-term behaviour in terms of power sharing etc. This means that the choice for the frequency at minimum and maximum state of charge sets the minimum allowable droop value for which the inverters can still find a working point. When compared to the dynamic stability, which is negatively influenced by a higher gain thus a higher droop, the long-term stability will benefit from selecting a higher value for droop.

Figure 4.5 shows a system with the high droop coefficient of 4% and a zero-power frequency setpoint $f_0$ of respectively 47 Hz for the minimum SoC and 52 Hz at maximum. The figure shows that even if the inverters work up to 120% $p_{nom}$, no stable working point is obtainable when a cell with a battery at critically low SoC is connected to a cell with a battery at very high SoC. This cannot be accepted, as it shall not be a requirement in the project not to interconnect cells like this.

The possibilities to solve this problem are either (i) that the inverter should be allowed to supply even more power, (ii) the difference between the frequency setpoint for minimum and maximum SoC should be limited or (iii) the value of the droop coefficient has to increase even further.

The first solution obviously is limited in how much overloading of an inverter is possible without jeopardizing its lifetime. An example of a commercial inverter has got overloading capabilities which are limited in how long they can persist, e.g. 1.3 p.u. for at most 30 min., 1.5 p.u. for 5 min. and even more than 2 p.u. for some seconds [128]. However, since the amount of time for which the overloading will be present cannot be safeguarded, this possibility should not be overly used. Moreover, charging the battery with a power of more than 1 p.u. will have consequences in terms of efficiency and battery lifetime. For these reasons, until further notice the inverters are limited to work at 1 p.u.
The second solution will result in a system where there is a less distinct difference between cells with a high or a low charge state of the batteries, and also limits the overall working frame of frequency of the system. If it would be allowed to use the whole range of 47 to 52 Hz, then this means that a frame of 5 Hz is available in which the actions of DSM and SSM can take place. If, however, the difference in frequency at minimum and maximum SoC is decreased, then in turn the frame for DSM and SSM is limited, leading to a lower freedom and a more nervous reaction of DSM and SSM since the critical borders will be located closer to each other.

The third solution will, as already mentioned, result in a system with larger deviations of the frequency depending on the power output of the inverter, even if the power output of the cell does not change too much. Not only will this lead to a more aggressive reaction of the DSM and SSM schemes, and bigger deviations from the nominal grid frequency during normal operation of the grid, it will also have consequences on the dynamic stability of the controller, as deduced earlier. The droop coefficient cannot be too large not to intervene with the small-signal stability.

The two depictions plotted in Figure 4.6 show how the long-term stability region of the system changes with a change in $\Delta f_0$, where respectively a frequency difference between the states minimal and maximal SoC of 1 and 5 Hz are considered. It is clear that the first figure has a bigger long-term stability region, and also that the stability becomes more attainable as the droop value $K_p$ and the allowable overload of the inverter $p$ grow.

One of the important considerations that has to be made is whether the frequency deviations introduced by the power supplied by the inverters will not trigger load shedding or renewable energy curtailment even in a normal situation. This can be seen as follows: if an inverter is connected to a battery with a normal value for the SoC, we do not want this to eventuate into DRES curtailment nor shedding of precious loads. However, as dictated by the droop reaction, we do expect a frequency deviation depending on the power that is being supplied or received. This demonstrates that it is very important that the location of the frequency setpoints depending on the SoC, the schemes for both DSM and SSM, and the value for droop are chosen together, within the available leeway.

A bigger droop coefficient makes the act of DSM and SSM more prone to be initialized during a normal SEP.

Analysing the previous discussion leads to the following proposed means of decision making:

Step 1: Define the maximum working boundaries of the inverters
4.2. Steady-state Stability

Figure 4.6: Graphical representation of stable regions in a system with $\Delta f_0 = 1$ Hz and $\Delta f_0 = 5$ Hz: A situation where a low difference between the frequency setpoint for minimum and maximum SoC is chosen yields a situation that is stable at small values for $K_p$, without requirements of overloading the inverters. A bigger chosen difference yields a system that has a smaller stability region.

Step 2: Choose the change in $f_0$ if the SoC goes from minimum to maximum

Step 3: Define the bands in which DSM and SSM will be active

Step 4: Define the minimum overlap in frequency that is required (i.e. frequency margin)

Step 5: Calculate the droop value which satisfies these choices

Overloading the Inverters

It is possible that the inverters will need a certain rate of oversizing, as a measure to absorb any long-term increase in power consumption, which is prone to happen, and in order to cope with the power flow from DRESs at moments of high yield and low load. Furthermore, the amount of time for how long an inverter can be in the overloading region is limited. It can be expected that, at least in the discharging region, the nominal power will not easily be reached. On these grounds, the assumption that the inverters will have to deal with a power output which will always be lower than 1 p.u. is made, thus the maximum working boundaries of the inverters are set to 100%.

Usable Frequency Band

As stated in the EN 50160, the lower and upper limit for the grid frequency are defined as 47 and 52 Hz, respectively. However, as was shown in Figure 4.6, a $\Delta f_0$ of 5 Hz in combination with a $P_{\text{max}}$ of 1 p.u. leads to a system which needs at least 5% droop in order to function in a stable way. This means that the deviation in frequency between 0 and 1 p.u. power output equals

$$\Delta f = k_p \cdot P \cdot f_{\text{base}} = -0.05 \cdot 1 \cdot 50 = -2.5 \text{ Hz}$$

which is a big deviation. A system with a frequency band of 4 Hz, e.g. from 48 to 52 Hz, finds itself at the border of stability with a droop value of 4%. This could lead us to the decision of taking a frequency window of 3 Hz. However, choosing this will lead to the issue of where to place this window, e.g. from 49 to 52 Hz, or from 48 to 51 Hz?

Both ranges have a drawback in respectively applicability of DSM and SSM. This can be seen as follows: if the grid frequency is clamped at 51 Hz, then the curtailing curve for renewable energy sources cannot be applied, since it takes a maximum frequency of 51.5 Hz into account (see § 2.1.9). Also, according to the UFLS the frequency needs to be allowed to drop until 48 Hz at least, discussed in § 2.1.8.

It has to be guaranteed that a battery that reached the maximum SoC that is allowed by the system design will not be charged further, even if the maximum SoC is not 100%. This means that the point where the DRES curtailment reaches a complete curtailing of the power has to coincide with the zero-power frequency which is set at maximum SoC. Along with this, if the minimum grid frequency is set to be 49 Hz, then there is only a window of 1 Hz in which the DSM needs to take place, which might turn out to be a task that is not so trivial, taking into account limits for accuracy of frequency measurements etc.
For these reasons, it can be chosen to use a frequency band of 48 to 51.5 Hz, thus a $\Delta f$ of 3.5 Hz.

Since the battery is expected to charge, or at most deliver only very limited power to crucial loads, at the moment that the frequency setpoint reaches 48 Hz, it can be seen that the power will not go into high positive values thus the frequency will not be reduced much further. Similarly, if the SoC is high and the frequency setpoint is 51.5 Hz, then no danger of surpassing 52 Hz exists, since the inverter will not charge the BESS any further, thus no big frequency increase because of the drooping behaviour will be experienced. This is important in order to stay within the limits as set by EN 50160, being 47 to 52 Hz.

**Implementation of DSM and SSM**

The next decision that has to be made is the bands in which DSM and SSM will take place. As mentioned earlier in the discussion, the SSM should work according to the predefined standard VDE-AR-N 4105, which has a curtailting behaviour starting at 50.2 Hz and stops at 51.5 Hz. Starting at this 50.2 Hz, the power output of the DRESs is curtailed at a speed of $-40\% P_{in}$ per Hz until the output power is limited to 48% at 51.5 Hz. When 51.5 Hz is reached, the PV plant is required to decouple from the grid, until the grid frequency is below 50.05 Hz for at least 60 seconds. Using this standard, we want to make sure that the DRES power is fully curtailed at the moment the inverter reaches maximum SoC, in order to avoid overcharging, as mentioned earlier.

On the other side of the spectrum, at the moment the zero-power frequency is set to by 48 Hz, there is still one hertz margin until the minimum allowable grid frequency is reached. It is expected that at the moment the frequency drops this low, all the loads that are not extremely important will have been shed, thus the consumption at this point will be rather low. The frequency band for DSM is chosen to be 48 – 49.8 Hz, thus this is the window in which the load shedding can be implemented.

**Margin for Long-term Stability**

As can be expected, designing the system to have one exact common point of frequencies at extreme situations might not be the most robust choice; a certain margin or overlap is desirable. This is in fact an arbitrary value, where a bigger value leads to a more robust system but with all the aforementioned drawbacks that come with increasing $\Delta f$. For this work, the choice of frequency margin is 0.2 Hz, which means that an inverter with a minimum SoC and maximum power demand has a frequency setpoint that is 0.2 Hz higher than an inverter with maximum SoC and maximum power supply. This should lead to a stable system with some room for errors.

**Calculation of Droop Coefficient**

After choosing (i) the working boundaries of the inverters to be 1 p.u., (ii) a zero-power frequency range of 48 – 51.5 Hz, (iii) the windows for DSM (48 – 49.8 Hz) and SSM (50.2 – 51.5 Hz) and (iv) a frequency margin of 0.2 Hz, using

$$f_{p_{\text{max,SoC_{max}}}} - f_{p_{\text{min,SoC_{min}}}} \leq f_{\text{margin}}$$

the minimal needed droop coefficient can be calculated:

$$\left(f_{0,\text{SOC_{max}}} + p_{\text{max}} \cdot K_p \cdot f_{\text{base}} \right) - \left(f_{0,\text{SOC_{min}}} + p_{\text{min}} \cdot K_p \cdot f_{\text{base}} \right) \leq f_{\text{margin}}$$

$$\left(51.5 + 1 \cdot k_p \cdot 50 \right) - \left(48 + (-1) \cdot k_p \cdot 50 \right) \leq -0.2$$

$$k_p \leq -0.037$$

It turns out that, given the selected parameters, a droop of at least 3.7% results in a long-term stable behaviour of the system. This is a problem, since the small-signal stability cannot be guaranteed for a droop of more than 0.6%, as was seen in § 4.1. Thus, another solution will have to be found in order to make the system behave correctly both in the transient and in the long-term world.
4.3. Small-signal Stability vs. Steady-state Stability

A solution has to be found for solving the huge differences in interest between § 4.1 and 4.2. As seen from the first section, the droop coefficient should be limited to at most 0.6% in order to keep the system dynamically stable, but the second section shows that a much bigger droop coefficient is required if we want the system to work satisfactorily in the longer run, complying to the requirements that were set.

4.3.1. Solution Clash Stability

By analysing the behaviour of two inverters that are initially working in stand-alone mode and then get the signal to interconnect, a possible solution for the problems can be found, as will be discussed here.

It is known that multiple inverters that want to interconnect have to satisfy certain essential conditions, of which one reads that the output frequency of both devices shall be (nearly) identical [129]. The word nearly points at the necessity of always having a small difference, such that the difference in voltage angles can shrink to zero.

For the system under scope, this implies that if two inverter systems want to interconnect, at least one of them will have to adapt the location of its droop curve, in order to reach the frequency at which the other one is currently working.

For the sake of this analysis, the assumption is made that Inverter I is initially powering a certain grid with some loads connected to it, and Inverter II is disconnected from this grid and is not supplying any local loads. At a given moment in time, Inverter II gets the signal to interconnect with Inverter I, irrespective of where this signal came from. For the analysis, the SoC of Inverter I is in a very healthy condition, while Inverter II has a critically low SoC. For the time it takes to synchronize and connect Inverter II to Inverter I, it can be assumed that neither the SoC of the battery connected to the inverters nor the power consumed by the loads varies.

Assuming that the act of synchronizing the inverters has successfully been performed, thus the controller of the second inverter was able to fulfill all requirements by changing the location of the droop curves. Exactly at the moment that the connection has been established, we can be sure that the frequency of both inverters is equal, and the second inverter will not supply any substantial amount of power to the grid. This moment is plotted in Figure 4.7.

![Figure 4.7: Two inverters right after the moment of successful synchronisation](image)

Figure 4.7: Two inverters right after the moment of successful synchronisation: On the figure, we can see how Inverter I is supplying the power that is demanded by the loads. Inverter II just finished the synchronisation phase, and has an output frequency equal to this of Inverter I without supplying any power.

Now, the critical moment for the long-term stability commences: if all boundary limits, e.g. prohibiting a cell to charge from the Bb, are omitted for the analysis, and the setpoint for $f_0$ is a function of the SoC only, then Inverter II will want to move its setpoint for $f_0$ down, in accordance with the SoC. If now the deviation of $f_0$ which is required by the SoC of Inverter II deviates too much from $f_0$ of Inverter I, and the droop coefficient is too small, the problem discussed above can occur: in order to find a point where the output frequency of both
inverters is the same, they might be obliged to surpass their power limits. In this case, a solid operation of the system is no longer maintained.

However, a solution exists: if the dependency of \( f_0 \) to the SoC is not fixed, but can vary with respect to how much the inverter is currently loaded, it can be guaranteed that the long-term stability is never threatened even with a very low droop coefficient. Thus, by making \( f_0 \) dynamically dependent on both the SoC and the power in- or output of the inverter, the problems mentioned above can be solved. The final situation might look something like Figure 4.8.

![Figure 4.8: Two inverters after being interconnected](image)

It has to be clearly mentioned that charging the BESS which belongs to Inverter II by using power coming from the battery of Inverter I will probably not be acceptable. This is because both the act of charging a battery and this of drawing power from it include certain losses, thus energy is lost without using it. Both from an economical and an energetic point of view, this would probably be a remarkable thing to do, unless some specific circumstances are in play [130].

Suppose that both Inverter I and Inverter II would have DRESs locally connected. In case the BESS which belongs to Inverter I is fully charged, the BESS of Inverter II is almost depleted, and the DRESs of both systems are injecting a lot of power, it can be seen that the power limit of Inverter II could be endangered. So, even if the specific situation which was drafted in this example was not realistic, the general ideas are.

### 4.3.2. Practical Implementation

The control step was not implemented into the model exactly like described, because including the synchronization mechanism to interconnect multiple inverters is out of the scope of the thesis. As will be mentioned in the section that talks about other theses written for the same project (§ 8.3), this has been taken care of in another project.

Because the act of synchronization was left out of scope, the transition during which the connection takes place is not considered. The initial time of the simulations will be after the moment the cells are successfully interconnected, as shown on Figure 4.9.

For the sake of this work, the implementation of the dynamic scheme is slightly altered: initially, the setpoint of \( f_0 \) is directly determined by the SoC only, so it is possible that initially the inverters will be overloaded. Then, a control step will come into play, monitoring the output power of the inverters. If it is noticed that the inverter is currently being overloaded, so \( p > 1 \ p.u. \) or \( p < -1 \ p.u. \), the value for \( f_0 \) will be slowly altered in the right direction, by passing the value of the power through an integrator. Thus, the output power will be shifted
towards $\pm 1 \ p.u.$ with a speed that depends on the amount of overloading.

In a next phase, when it is noticed that $p \ll \pm 1 \ p.u.$, the value of $f_0$ will be slowly moved back to the value which would be set when only taking the SoC into account, by checking whether the output of the integrator is zero or not.

By using this workaround, the clash between the necessity of a small gain for the small-signal stability and a large gain for the steady-state stability is solved. The chosen parameters are depicted in Table 4.1.

### 4.4. Selected Parameters

Using 0.3% as droop coefficient, and combining it with what was calculated in Equation (3.1) on p. 65, the coefficient for the derivative action of the power can be calculated to be $-3 \times 10^{-6}$, if a $\Delta t$ of 0.001 s is considered.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_p$</td>
<td>0.30%</td>
</tr>
<tr>
<td>$K_q$</td>
<td>2%</td>
</tr>
<tr>
<td>$K_{dp}$</td>
<td>3.00E-6</td>
</tr>
<tr>
<td>$\Delta t_{dp}$</td>
<td>0.001</td>
</tr>
</tbody>
</table>

One problem that can be expected with using a low droop coefficient like this is the fact that active power sharing might not be very good: a similar system with a bigger coefficient for droop will outperform the system with the smaller value for droop. This gain in performance will, however, be at the expense of bigger frequency deviations, and possibly instabilities.

It is expected that this difference in power sharing will not manifest itself as long as the difference in SoC of the different cells is small, thus the droop curves are located close to one another. However, at the moment the droop curves would be located further from each other — because of this difference in SoC — big differences in how much each cell contributes to the power demanded by the loads could be seen.
4.5. **Summary of the Chapter**

The chapter has dealt with the stability margins of the grid, both in terms of small-signal stability and steady-state stability. The difference between those two considerations is the following: the small-signal stability takes into account the reaction of the controller output with changes on the grid, for instance a load jump, while the steady-state stability assumes that a stable working point can always be found and then tests this working point to see whether it does not put the system in an overloaded state.

From the analysis taking into account the small-signal stability of a μG, it seems that a system with a too large value for the droop coefficient, which means a large gain, can enter the unstable region. However, having these small values for this coefficient have a bad influence on the steady-state stability. In fact, it turns out that the latter requires the droop coefficient to be ten times higher than the first analysis.

In order to match these fighting requirements, thus to design a system that is stable both in the dynamic and in the steady-state region, an extra control step was designed. The way this control step is implemented, it checks whether the inverter is currently overloaded. If this is the case, the droop curve is shifted up or down, and the overloading state of the inverter is cleared out.

However, a better means of implementing this step would be if the droop curves do not migrate away from each other before it is sure that the inverters will not be overloaded. This can be implemented in the synchroscope, for instance. The result would be that, after two cells have been interconnected, thus are working at the same frequency, their frequency setpoints do not drift away too quickly, hereby avoiding a state of overloading of the inverters.

*After this interesting discussion concerning the grid stability, the following chapter will discuss other choices that have to be made, like the grid parameters, and the way case studies will be presented.*
In this chapter, the procedure of selecting all relevant parameters and data will be presented. The chapter is split into two parts: (i) Parameters of the Grid and (ii) Case Studies. The first part aims at choosing the simulation parameters in such a way that the simulation results will be as relevant as possible, by mimicking a real situation as good as possible. After selecting these numbers, in order to run significant simulations, the second part will propose proper case studies.

The simulations will focus on two scenarios:

- Developing countries or rural areas: the initial aim of SOPRA was to electrify rural areas, so checking the behaviour of the system in this situation is indispensable.
- Developed countries: CSGriP also takes the developed countries into account, so it will be very interesting to see how the system performs here.

It is important to be conscious of the fact that there is a substantial difference between these two use cases. Where the case in a developing area concentrates on non-electrified regions without constraints, or places with a grid available that is very weak, the implementation of a $\mu$G in a developed area will have to cope with predefined standards and requisites, before it can be allowed to connect to the main grid.

Furthermore, where in the developing case only the aspect of providing a complete autonomous energy solution combined with DRES will be the focus, in a developed country the focus can be on the field of Uninterrupted Power Supply, Primary Control Reserve, maximization of DRES-usage to gain economic benefits etc. The developing case will require the cells to be self-supporting, without help from an eventual main grid, where the developed situation will have to cope with $\mu$Gs implemented into the main, strong grid with a large uptime. This difference will be seen at the end of this chapter, where the case studies are defined (§ 5.4).

To summarize:

- **Developed situation:**
– Top-down approach: infrastructure is readily present.
– Large number of cells implemented into the grid.
– Cells can enable an increased integration of renewable energy sources.
– New services can be offered, like energy trading or the imbalance market.

• Developing situation:
  – Bottom-up approach.
  – Self-supporting cells, have to be independent.
  – If present, the cells have to support a weak grid.

In order to make clear to the reader what is currently being discussed, this chapter will be divided into sections listing the different variables, and every section will be divided into two subsections, the first one discussing the developed situation, and the second one explaining the choices made for a developing situation.

5.1. Selection of Parameters

The parameters of probably main importance when it comes to the dynamic behaviour of the system, being the active and reactive droop coefficients, have been discussed throughout Chapter 4.

As the reader can expect, these are of course not the only parameters with influence on the \( \mu G \). For instance, the initial situation of the grid has to be known. A big difference can be seen between a \( \mu G \) that is installed in a developed country, connected to the main grid, or in a remote area where currently no electricity supply has been installed. When it comes to the long-term performance of the system, the treatment of the BESS becomes very relevant. The applied DoD and the charge rate will have impact on the battery lifetime. The implementation of DSM and SSM schemes will have a considerable influence as well.

5.1.1. Initial Situation

Defining a certain basic situation can prove helpful in order to understand what the grid will look like in both a developed and a developing situation.

Multiple use cases can be defined for the project. Depending on the type of customer that is dealt with, some parameters will change, as well as the behaviour and performance that is expected from the \( \mu G \). Also, depending on the location where the \( \mu G \) is installed, a different performance from the main grid can be expected, hereby changing the challenges the cell faces.

Developed Country

For the developed country, the assumption is made that a strong main grid should always be present. Therefore, there would be no reason not to connect the \( \mu G \) to this main grid; preference schemes can be built in, in order to for instance limit power exchange with the grid, if this is required.

In case the main grid would experience problems, it can be opted to disconnect the \( \mu G \) and continue in islanded mode. This way, for the loads connected to the \( \mu G \), no problems arise. At this moment, the \( \mu G \) will work in a similar way like how the grid would behave in a developing situation, where no main grid is present.

However, since it is expected that the moments in which the main grid runs into problems will not be very abundant, so no strong economic case exists for employing the cell like this. However, other economically attractive implementations of a battery system into the main grid exist, and could be considered in order to make installing a \( \mu G \) in the main grid interesting. These ways of implementing the \( \mu G \) into the main grid are out of the scope for this thesis.
Developing Country

In a developing country, the situation can be different: the assumption can be made that no grid or only a very weak, unreliable grid is present. In this case, the cards have been altered for the $\mu$G: in case no grid is present, it makes perfect sense to install a battery in order to supply loads from mainly renewable power.

Depending on the philosophy, multiple cells that are located in the same area could or could not be interconnected. However, for the simulations different cells will always be assumed to be interconnected through the Bb, unless explicitly sated otherwise, for the sake of showing how the cells work together, and because of the unavailability of a controller that can synchronize and interconnect different cells.

5.1.2. Supply Side Management

The background of SSM has been discussed in § 2.1.9 on p. 36. It was seen in this section that certain predefined standards exist, which are not expected to be changed overnight. Thus, especially when it is required that the $\mu$G is compatible with the main grid, the standards have to be followed. For the sake of clarity, the VDE-AR-N 4105 can be explained once more: from the moment the PV inverters sense a frequency of more than 50.2 Hz, the output power is ramped down at a speed of $-40\% / \text{Hz}$, until it reaches 48% at 51.5 Hz. At this moment, the power output drops to zero until the grid frequency has recovered and is stable within an acceptable band of grid frequency and voltage.

Using the droop value that has been defined in the previous section, to be specific $K_p = 0.3\%$, it can be looked into what this frequency deviation of 0.2 Hz means, and whether it is acceptable for the SSM scheme to start curtailing at this moment. If a cell is connected to a battery with normal SoC, the zero-power frequency setpoint $f_0$ can be assumed to be 50 Hz. This means that the start for PV curtailment, at 50.2 Hz, is reached at a power value of

$$\Delta f = K_p \cdot p_{inv} \cdot f_{base} \Leftrightarrow p_{inv} = \frac{\Delta f}{K_p \cdot f_{base}} = \frac{0.2 \text{ Hz}}{0.3\% \cdot 50 \text{ Hz}} = -133\%.$$  

It seems that no curtailing will be initiated for a battery with a normal SoC, which points at the fact that the droop coefficient is definitely not too large when it comes to frequency deviations in normal conditions.

It was explained how a bigger droop coefficient leads to bigger frequency deviations, thus to more curtailing when this would not yet be necessary. As a proof for this, the same deduction can be made for a $\mu$G where a droop coefficient of 4% is used. In this case, with $f_0 = 50 \text{ Hz}$, the border of 50.2 Hz is reached at

$$p_{inv} = \frac{\Delta f}{K_p \cdot f_{base}} = \frac{0.2 \text{ Hz}}{-4\% \cdot 50 \text{ Hz}} = -10\%.$$  

Interpreting this value, it would mean that a battery that is not in the critical state would initialize renewable power curtailment at the moment it is being charged with a rate of merely 10%. It is clear how a big value for the droop coefficient can have a negative influence on the grid performance.

The jump of 48% to 0 PV output certainly holds some drawbacks, since introducing jumps this big can lead to instabilities or oscillatory behaviour. However, this is not the only drawback of the standard curtailing scheme.

Think about a situation where the battery system is almost fully charged, thus the grid frequency is increasing. At a given moment in time, the grid frequency reaches 51.5 Hz, which means that the standard curtailing scheme is required to completely switch off the renewable energy sources, and wait until 50.05 Hz is seen again.

This means that the batteries with a SoC high enough to introduce a high grid frequency will have to feed all the loads that are present on the grid, until the moment the SoC dropped enough to ensure that the grid frequency reaches a low value again. Thus, while the batteries are discharging, the DRES inverters are curtailing renewable energy.
For this reason, the suggestion is made to extend the standard, omitting this jump from 40% to 0, but rather regulating the power down to 0 p.u. in a smooth way, while also allowing the power output to smoothly ramp up again instead of waiting until the frequency reaches 50.05 Hz again. Similar to the standard, the frequency window can be chosen to be 50.2 to 51.5 Hz. The proposal is plotted in Figure 5.1.

Applying this non-standard solution will have clear benefits in case the batteries approach a state of being fully charged. At that moment, it is expected that a balanced grid frequency will be found at which the load power is supplied by the DRESs, leaving the battery with the task to deliver any small power mismatches, this way not requiring it to lose a certain amount of charged energy before the DRESs can reconnect. This means that it is expected that a lot of unneeded power curtailment can be avoided by applying the non-standard scheme.

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![Figure 5.1: Proposal of continuous curtailing scheme: The output power would ramp down from 100% to 0, starting at 50.2 Hz and going to 51.5 Hz. No hysteresis is present, the power output can move up and down along the curve freely over the complete interval.](image)

### 5.1.3. Demand Side Management

The way in which the DSM scheme will react has to be decided upon. As mentioned above, the frequency window in which the actions can take place spans the interval from 48 to 50 Hz. The way DSM will be implemented depends on the situation in which the grid is installed: differences can be seen between a system that is grid connected in a developed country, a cell which supplies a critical process in a manufacturing plant or e.g. in a war zone, or a cell in a developing country where the current situation is either non-electrified or coping with regular brownouts or blackouts.

The controller is designed to be able to control all five types of loads that are shown in Figure 2.13 on p. 32, using four parameters: modulating (yes/no), shedding frequency (Hz), modulation width (Hz) and minimum switch-off power (%). By entering different values for those parameters, all five shown profiles can be obtained.

### Developed Countries

For the load shedding profile in a developed country, the results of the simulations done by ENTSO-E, as discussed in § 2.1.8 will be applied in order to achieve a proper frequency response and comply with the current grid standards, which would be a prerequisite in case the cell needs to be connected to the main grid.

The main criteria can be quickly revised:

- The UFLS acts as a last resort; all possible measures have been taken before the UFLS is activated.
5.1. Selection of Parameters

- The size of the load shedding steps should not exceed 10%.
- The number of shedding steps should be between 6 and 10.
- The used frequency bandwidth ideally located between 49.0 and 48.0 Hz.
- After the last shedding step, still 50% of load is still supplied.

The selected steps for load shedding are depicted in Figure 5.2. The choice has been made to make the first steps big in terms of frequency (0.2 Hz) and small in terms of power shedding (-5%), and the last steps are smaller, at 0.1 Hz, and shed more power (10%). It is clear how in total 8 steps are taken, none of them exceeding 10% load decrease. Implementing the scheme like this will result in less affected loads in case the critical state of the grid is only temporarily, and corresponds to a so-called late scheme.

The every load step will come back online at the moment the threshold of the previous shedding step is crossed. This means that, if Step I occurs at 49 Hz and Step II at 48.9 Hz, and the grid is recovering, then the loads that were shed in Step II will reconnect at a frequency of 49 Hz.

This means that at 48 Hz, the load power will still equal 50% of the initial power, but the SoC of the battery system reached a very critical zone here. The reason for this 50% is that it is expected that this situation will never occur on the main grid, at which the ULFS is mainly aimed, and discomfort or potential dangerous situations need to be avoided, thus never 100% of the load should be shed.

![Figure 5.2: Implementation of developed load shedding scheme](image-url)

One thing that could be said for the \( \mu \)G is that the batteries can act as energy storage devices, though not as energy sources. This means that if the risk is taken of supplying a load with batteries, it has to be considered that a potential situation can exist where the load can no longer be supplied by the power stored in the BESS. For this reason, the border of 50% load shedding is kept, in order to keep half of the loads present on the grid online for as long as possible.

In case the \( \mu \)G design has been well-considered, hence enough DRESs and battery energy are present, this approach can be expected to suffice, certainly when combined with the knowledge that the main grid is a very reliable machine that is not expected to be unavailable for very long.

In a further stage of the project, the first step which is mentioned in this Table 2.2 on p. 33 should be taken into account as well: this is if controllable power sources, such as a bio-diesel generator, are present on the grid they should be activated at the moment the load shedding scheme starts. This way, load shedding might be avoidable, leading to a higher quality of service that can be offered to the customers.
Developing Countries

Similarly as for developed countries, also here some load shedding steps have to be defined, but differently to that case, in the developing countries the shedding profiles can be developed starting from tabula rasa, as no standards have to be included in an off-grid solution.

It is opted to make four energy limitation bands, each of them with a lower frequency range, as shown in Table 5.1. They will be applied with decreasing priority of the loads, where Budget customers are the ones with the lowest priority, and a Critical customer might be a local hospital with the highest priority of power supply. In between there is a profile called Comfort.

This will be explained in greater detail in §5.2.2, but in brief it boils down to Budget I and Budget II users that are the majority of the villagers, with few resources. Their power consuming devices are split into two groups, being luxury products like smartphones in the first group, and essential devices like lighting equipment in the second. Comfort customers hold villagers with more purchasing power, non-critical parts of a hospital, a military facility etc. Finally, the Critical users are a hospital and a telecom tower, facilities that should be supplied at all times.

Table 5.1: Division of loads in developing countries into four states of energy limitations

<table>
<thead>
<tr>
<th>Shedding Profile</th>
<th>Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Budget I</td>
<td>49.5</td>
</tr>
<tr>
<td>Budget II</td>
<td>49</td>
</tr>
<tr>
<td>Comfort</td>
<td>48.7</td>
</tr>
<tr>
<td>Critical</td>
<td>48</td>
</tr>
</tbody>
</table>

Having only four bands will affect more customers than it should do, due to a strong reaction per step, thus this scheme is undeniably destined for being optimized in future work. For this reason also, the profiles allowing power modulation that were developed for load shedding will be applied.

The reactions of the different load groups are plotted in Figure 5.3. The first step of the load shedding for Budget customers can consist of some more luxurious goods, thus can be switched off with a step reaction. This group of loads is called Budget I. The second step will consist of more important loads, like lighting equipment, for which a modulating scheme can be developed, which will turn off lights one by one depending on the SEP, or apply light dimmers, though eventually going to zero power: Budget II.

Next, in the profile for the Comfort loads, among others a military facility is placed. Thus it can be expected that certain small power users will never be allowed to switch off in this profile, arbitrarily chosen to be 10%. This leads to a shedding scheme with a modulating behaviour though a minimal residual power demand. A bit of overlap with the shedding of Budget loads is provided, as it can expected that the marginal cost of shedding loads for Budget customers will increase with an increased level of shedding.

Finally, the Critical customers should not be switched off at any cost, so will only experience a power outage at the moment the battery system reached its minimal SoC. As mentioned above, the zero-power frequency for minimum SoC will be located at 48 Hz, so as plotted in Figure 5.3 this is the moment where the critical loads stop consuming power. This same step at 48 Hz can be seen in the profile for shedding Comfort customers.

As mentioned in §2.1.8, one idea can be to introduce a frequency setpoint in which all cells, given that a number of cells is connected to the Bb, enter the islanded state. This way, it can be avoided that a μG powering a critical load with high availability requirements endangers the power supply to this critical load by supporting other, less critical cells for too long.

5.1.4. Battery Parameters

Next to the fact that the batteries need to be sized in terms of required power and energy content, which will be discussed further in §5.2.4, choosing other parameters in unavoidable. Among these parameters,
5.1. Selection of Parameters

Figure 5.3: Load shedding schemes for developing grid: The schemes show how the load will be shed at which frequency signal.

concepts like the acceptable DoD, the voltage profile as a function of SoC, the internal resistance etc. are covered. Other parameters, like for instance the requirements in ambient temperature to keep the batteries in a good condition, are ignored in this discussion.

For the simulations, a model was built which needs these parameters in order to work properly. If chosen well, these parameters together will yield a behaviour mimicking a real battery. The value of the parameters will, among other things, depend on the battery technology, as was discussed in § 2.1.10. For this project, the Li-ion technology is supposed to be the most favourable technology.

Depth of Discharge

Next to these internal battery parameters, other control choices are important. For instance, the applied DoD of the battery will have huge impact on the expected lifetime. The trade-off is as such that a higher DoD will lead to a lower lifetime, but a lower DoD leads to a bigger number of cells required in order to achieve the same usable energy content, thus a higher oversizing. Lifetime and sizing of the batteries are, economically speaking, very important parameters due to the price of batteries.

Another important choice is where to put this usable band: is it better to use the SoC-range at the lower SoCs, or will the battery lifetime be longer if the DoD is placed at the high side.

It is very important to keep the BESS in the best condition as possible. From data and recommendations from different manufacturers, the optimum DoD turns out to be 80%, the charge and discharge rate of shall not exceed 1 C, and the best results are obtained if the region of the maximum SoC is avoided.\(^1\)

Because of this, if for instance 1 MWh of battery capacity is needed, the battery will have to be oversized with a factor 1/0.8, leading to an installed battery capacity of 1.25 MWh that will be used in the range 0 – 80%. The used DoD is shown in Figure 5.4.

Next to the advantages in lifetime, not using the battery until the highest SoC has another advantage, which can easily be understood using a little thought experiment:

In this situation, the cell is working in islanding mode, on a day with an abundance of renewable energy. The batteries are fully charged, and the grid frequency raised in order to curtail enough energy from the DRESs. If, at this moment, the cell wants to connect to the mains, and the SoC would be as high as 100%, problems

\(^1\)Confidential information obtained from two different major battery manufacturers.
could appear due to overcharging: in order to connect two generators, some requirements have to be fulfilled, among others the frequency.

The frequency of the main grid can be considered to be a fixed 50 Hz. This means that the frequency of the microgrid will have to be reduced to 50 Hz, which will result in an interruption of the curtailing behaviour. This means that the DRESs will start to produce energy again after a certain amount of time (as discussed in §2.1.9), possibly leading to a dangerous overcharging of the batteries. However, if the batteries are normally clamped at 80%, there will be some room for charging a bit further in case the above mentioned situation occurs. It will have to be economically investigated whether the loss of lifetime justifies this action.

**Voltage Curve**

The voltage at the output of a battery varies with a changing SoC. This means that, with a change in SoC, the input voltage to the DC terminal of the inverter will vary, which means that the modulation factor has to change in order to end up with the same AC voltage amplitude.

The variation of the voltage with respect to the SoC, applied in this thesis, is shown in Figure 5.5.

**Internal Resistance**

The physical meaning of the internal resistance of a battery was explained in §3.2.2. There, however, no value for the resistance was defined, as this is really a grid parameter of interest.

It is clear that the internal resistance of a cell decides on its charging and discharging efficiency. As a realistic value for the internal resistance per cell, a value close to $7\, m\Omega$ can be seen at high SoC and $12\, m\Omega$ for a battery with a low SoC [131]. For this work, taking into account that the battery will be used in the lower regions for SoC, a value of $9\, m\Omega$ is selected as overall internal resistance per cell. The way cells will be connected in series and parallel in order to form the battery pack will result in the overall resistance of the pack.
5.1.5. Other Parameters

The two biggest choices in parameters that had to be defined, namely droop coefficient and battery properties, have been reviewed. This leaves us to some other, mainly arbitrary choices for control parameters, which will be tackled here.

No charging from Backbone

As was discussed in § 3.2.4, a small control step will be implemented that aims at limiting charging the cell battery if the cell senses a power inflow from the backbone, since it cannot be known whether this power comes from the DRESs of another cell, or from its BESS. It is very undesirable to charge a battery using energy coming from another battery, since by doing this energy is lost without any noteworthy advantages.

The control step works by measuring the derivative of the SoC. If this derivative surpasses a certain value, e.g. a charge rate of 0.01 C, the controller will check how the power flows are located. This is possible without using external communication devices if the power from the DRESs and the power from the Bb penetrate the cell through different injection points. If the cell notices a power flow from the backbone to the cell, it will react by slightly increasing the frequency setpoint \( f_0 \). For this, an integrator with an anti-wind-up protection and a large time constant is used. This way, the frequency setpoint gradually increases until it reaches the maximum allowed deviation, as long as there is power coming from the backbone and as long as the rate of change in SoC exceeds the set limit.

Reactive Power Sharing

As pointed out before, the effectiveness of the reactive power sharing scheme based on voltage drooping depends not only on the choice for droop coefficient \( K_q \), but also on the characteristics of the lines between the power sources. If the lines have a relatively large resistance \( R \) compared to the reactance \( X \), which is the case in low voltage networks, then a change in active power will lead to a change in voltage drop along the line, thus interfering with the reactive power control, and vice-versa. This can be solved by changing the R/X-ratio as seen by the inverter, either by \((i)\) introducing a passive component to the grid, e.g. an inductor or a transformer that inherently have a small value for R/X, or \((ii)\) by introducing a virtual inductor, mimicking this passive component. Typical values for the R/X ratio for the three different voltage levels are shown in Table 5.2 [75].

While the second option definitely seems the most promising one, attempts to implement this control loop failed during the implementation phase. For this reason, it is opted to connect the inverter to the bus of the cell by means of a short and very inductive line. In a next phase, it is important that a solution is found for this, so that it is no longer required to connect this reactance as a physical element, hence to succeed in implementing this virtual component into the controller. Similarly, the probable implementation of a filter at the output of the inverter needs to be taken into account as well.

### Table 5.2: Comparison of typical values for \( R' \) and \( X' \) for different voltage levels

<table>
<thead>
<tr>
<th>Type of Line</th>
<th>( R' (\Omega/km) )</th>
<th>( X' (\Omega/km) )</th>
<th>( \frac{R'}{X'} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>LV line</td>
<td>0.642</td>
<td>0.083</td>
<td>7.7</td>
</tr>
<tr>
<td>MV line</td>
<td>0.161</td>
<td>0.19</td>
<td>0.85</td>
</tr>
<tr>
<td>HV line</td>
<td>0.06</td>
<td>0.191</td>
<td>0.31</td>
</tr>
</tbody>
</table>

Based on Table 5.2, it is decided that an R/X ratio of less than 1/3 can be considered desirable. Therefore, reaching this value will be aimed at, at the moment the cable sizes etc. are discussed (§ 5.2.3).

Virtual Inertia

As has been mentioned in § 2.1.10, an energy storage device can double as a source of virtual inertia on an inertialess grid. Multiple ways of implementing a virtual inertia exist, of which there are for instance a control step that limits the rate of change of frequency, or a first-order filter at the output of the controller [63].
For this work, in a first stage the virtual inertia is omitted, but as will be noticed during the Case Studies, in particular § 6.5, a small analysis will be done, taking into account the most fundamental implementation of a virtual inertia: the first-order filter limiting the rate of change of the frequency setpoint entering the inverter.

5.2. Sizing of Components
The selection process of the relevant values and sizing for the components will be tackled throughout this section. Contrary to the previous section, in which mainly software-choices were made, e.g. parameter settings for controllers, this section makes the choices for the hardware, thus the effective sizing will be carried out. Under this, we can understand power ratings, cable lengths, and so further.

For the sake of clarity, the chosen parameters will consistently be presented in Table 5.6 on p. 110, distinguishing the chosen parameters for a developed country, the Netherlands, from these for a developing country, Burundi. The word chosen is emphasized, since no optimum exists, selecting parameters will always be a trade-off in terms of costs, self-sufficiency, impact on the environment, minimal load shedding . . .

Besides, the aim of this thesis is not to demonstrate or define what the optimal parameters are for the grid, but merely to demonstrate that the concepts work in a realistic situation. Therefore, no claims are made that the sizing of components carried out in this chapter yields an optimal system.

5.2.1. Per Unit System
For the sake of generality, the parameters will be mainly expressed in the per unit system (p.u.). This means that certain base values have to be chosen, e.g. the base power and the grid voltage. Taking into account the fact that the grid will be a three phase system, the base power is specified as the total apparent grid power, and the voltage is the line-to-line value. Also a power factor, or for this case a $\cos \phi$ has to be defined, here arbitrarily chosen to be 0.95. Using these values, the rest of the needed values can be expressed in a per unit system, making the case study easily scalable.

As base values are chosen:

\[
S_{\text{base}} = 40 \text{ kVA} \\
U_{\text{base}} = 400 \text{ V} \\
\cos \phi = 0.95
\]

From these values, we can easily yield:

\[
I_{\text{base}} = \frac{S_{\text{base}}}{\sqrt{3} \cdot V_{\text{base}}} = \frac{40 \cdot 10^3}{\sqrt{3} \cdot 400} = 57.7 \text{ A} \\
Z_{\text{base}} = \frac{U_{\text{base}}^2}{S_{\text{base}}} = \frac{400^2}{40 \cdot 10^3} = 4 \Omega \\
P_{\text{base}} = S_{\text{base}} \cdot \cos \phi = 40 \cdot 10^3 \cdot 0.95 = 38 \text{ kW} \\
Q_{\text{base}} = S_{\text{base}} \cdot \sin \phi = 40 \cdot 10^3 \cdot \sin(\cos^{-1}(0.95)) = 12.5 \text{ kvar}
\]

Now, to explain how the p.u. system works, an easy example works best. Start with a load with an apparent power $S = 20 \text{ kVA}$. Then, the p.u. value of this load can be easily calculated as $\frac{20 \text{ kVA}}{40 \text{ kVA}} = 0.5 \text{ p.u.}$ And if a line with an impedance $Z = 8 \Omega$ is used, then the per unit value for the impedance of this line equals $\frac{8 \Omega}{4 \Omega} = 2 \text{ p.u.}$.
5.2 Sizing of Components

In the definition of the base values, the symbols P, Q and S are used, which respectively present the active, reactive and apparent power of the system. Their relation can be easily explained, and is shown in Figure 5.6. The active power P is expressed in watt (W) and is the factor that performs the work in the system. The reactive power Q, expressed in volt-ampere reactive (var), does not perform actual work, but nonetheless is needed for the good functioning of the power system. S, the apparent power, is the magnitude of power the system actually has to transport. It is expressed in volt-amperes (VA), since its value is the product of the voltage and current. The ratio between the real and apparent power is called the power factor, and is calculated by means of $\cos \phi = \frac{P}{S}$ in case no harmonics are present in the system.

The mathematical relationship among these variables is expressed as follows:

$$S = P + jQ$$

Figure 5.6: Power Triangle: Apparent power S is built up from the active power P and the reactive power Q. The angle $\phi$ is an important parameter in any power grid, commonly used in the form $\cos \phi$, hereby showing the ratio between active and apparent power.

5.2.2 Loads

The loads are probably the most important group of parameters in this section. The sole purpose of the grid is to supply the loads as effective as possible. The rest of the component parameters will be a trade-off between certain requirements, as some of them counteract each other, but the main influence on the rest of the grid is exercised by the size of the loads.

As soon as the consumption profile and magnitude is known, the size of the components needed to supply this consumption can be determined. The load profiles will be presented, both for a developed area like the Netherlands, and a rural area. It is expected that the profiles will be very different from each other. Furthermore, a selection of load groups has to be made, dividing them into priority groups.

Next to the definition of the load profiles, some attention needs to be spent to size the grid according to future expectations. It is clear that the load profiles will not stay static forever, on the contrary a yearly increase can be expected. This increase will be higher in the case of a developing grid, since we can understand that as soon as the people discover the comfort of electricity, and the local economy starts to flourish because of the new potentials, more electrical appliances will be purchased. In the developed grid, where to date everybody is used to an ever present electricity signal, the yearly load increase will probably be lower.

Developed Areas

As location for the simulations in a developed country, not very surprisingly the Netherlands is chosen. For a country like this, synthetic load profiles are easily attainable [132]. Different load profiles are available, including residential loads with single or double tariff and industrial loads with different ranges in uptime and connection capacity. For now, the choice is made to analyse the performance with a residential dwelling with single tariff connection. The consumption points are normalized, so they all have to be multiplied with the expected yearly consumption of a household in the Netherlands. A recent investigation showed that this yearly consumption amounts approximately 3250 kWh of electricity per year [133]. The consumption profile is then given with a resolution of kilowatt-hour (kWh) per quarter of an hour.

It is important to understand that the load profiles are heavily averaged, thus no decisions can be made on the scale of a single household using this data. The data shall only be used in case enough households are
present on the system, hereby recognizing the averaged data.

The data can easily be calculated to be expressed in the per unit system, by dividing every value by the maximum value of the set. This way, for a summer day in June, the profile shown in Figure 5.7. On this figure, in order to be comparable, the profile for a day in December is plotted as well. It is immediately clear that the consumption during a month in winter time is higher than during a summer month, which is easily explainable by the extra consumption for lighting and heating purposes. This will lead to a seasonal mismatch between production of PV-power and residential consumption.

The energy usage can be expressed in the per unit system by determining the ratio between what the house consumed in a period of time, and how much energy the house would have consumed with a constant load at 1 p.u.

Over one year, the energy consumption in the developed grid amounts to 0.47 p.u. This which means that a house with a constant consumption of 0.47 p.u. of power will have used the same amount of energy at the end of the day as an actual house that has a maximum power consumption of 1 p.u.

It can be assumed that in the developed countries, where the rate of electrification is already about 100% and where there is a strong focus on energy saving, the rate of growth in demand will not be very significant. This means that the power consumption which can be expected in the future will probably not deviate too much from the demand as we see it today. A commonly used number for the growth factor in a developed grid is 0…10% on a 10 to 15 year period [134]. However, it can be assumed that the customer will prefer to assume a smaller projected time frame for sizing the system. For this reason, from the point of view of demand growth, it is opted to choose a growth factor for the consumption on the developed grid of 1.05 p.u. This should lead to a system which is feasible to suffice for a period of at least five years.

![Figure 5.7: Electricity consumption in June and December](image)

Figure 5.7: Electricity consumption in June and December: We can clearly see how the profile changes over the day: from a base load during the night over a local maximum during noon to a peak consumption in the evening. The consumption on a winter day is always higher than this on a summer day. It can be expected that a mismatch exists between this profile and the profile of solar power.

Further research can include simulations with other load profiles, like residential dwellings with a double meter, which then might be equipped with accumulation heating systems, so will consume a big amount of energy during the night. Also, simulations in industrial situations can be executed, where certain preferences might be different. This means that it could be the case that load shedding should never occur, as this can result in high costs for production losses.
5.2. Sizing of Components

Developing Areas

For rural areas, the load profile is expected to have a different shape. However, the same peak in evening demand will be seen, as this is the moment where people need a lot of power for lighting applications. For the rural case, a complete village is taken into account, with some households, a tower for telecommunications, a military facility, schools and a hospital. This because it can be expected that the microgrid will run a whole village in the case of rural areas, and not only households like in the developed case.

Since no actual measured or calculated data for the load profile of a rural area could be obtained, a profile of the load data was estimated, based on discussions with local energy suppliers and customers. In this respect, three load groups can be distinguished:

- **Critical loads**: These are loads, like hospitals and telecom towers, that cannot be switched off at any point of time. They are users with a maximum energy security.

- **Comfort**: Wealthy customers who use power at any moment of the day, for powering more luxurious goods. The maximum power limit for these users is 500 W – 5 kW.

- **Budget**: Customers that use power only during the evening and night. Here, the electricity will mainly replace candles and kerosene, so is used for lighting purposes. The power limit is between 50 and 100 W.
  - **Budget I**: The lower-priority luxury goods that the customers possess, such as smartphones or laptops.
  - **Budget II**: The essential power consumers, for instance lighting equipment.

The obtained load graphs for these customers are plotted in per unit values in Figure 5.8. The consumption profile of these customers is based on an on-site assessment [135], and is further specified in Appendix A. It is clear that the use profile for the hospital and telecom tower follow a rather constant consumption, due to the continuous operation of these facilities. The **Budget** customers on the other hand have a very distinct peak in power consumption after dawn, which stops again at the moment the sun raises. This can be explained by the fact that these people use electricity mainly for lighting purposes.

The load consists of a big range of actors. The **Budget** customers are a cluster of 657 households with, as explained, limited purchasing power. The **Comfort** customers consist of 13 households, primary and secondary schools, a church, a military facility, an orphanage and an office. The **Critical** group holds a telecom tower and a health centre: facilities that should never face load shedding.

![Figure 5.8: Electricity consumption of a village in a developing country](image)

As we can see from Fig. 5.8, the load consumption peaks at around the same moment as it does in a developed country. However, the reason for this similarity is probably different: where in the developed case, this peak
in power is probably due to electrical cooking equipment, in the developing country it is mainly because of lighting equipment for Budget customers.

The electricity consumption in both situation can be compared. As mentioned before, an average value for the yearly consumption of a household in the Netherlands is around 3250 kWh per year, or an average of almost 9 kWh on a daily basis. When this is compared to the village in Burundi, where for the sake of easiness the consumption of the complete village is divided by the number of households, we get a value of around 570 Wh per household per day, or 208 kWh per household per year. This number is a factor 15 lower than the developed countries. Note that in this value, also the consumption of the hospital, schools and so on is included. We can conclude that a big gap exists between the consumption pattern in a developed and a developing country.

This daily energy consumption can be expressed in per unit as well. For the developing case, the value equals to 0.413 p.u.

Figures have shown that a growth of 80% in power consumption can be expected in Sub-Saharan Africa over the next twenty years [136]. It is clear that, if the short term solution of sizing at 1 p.u. would be chosen, the inverter will quickly bump into its limits, thus a new inverter would be necessary. On the other hand, if the inverter would be sized to comply to a load which will be only reached twenty years in the future, then this will lead to a big oversizing costs with very limited cash-flow returns.

For this reason, if the increase in consumption is considered to follow a linear profile, and a time frame of five years is considered, it is opted to choose for a consumption growth factor of 1.2.

5.2.3. Cables and Lines
Cables and overhead lines play an important role in the power system, as these are the actors that have to take care of transporting all the power delivered to the system. Since the cable lengths are expected to be rather short, no problems with reflected signals etc. are expected so detailed modelling can be omitted.

Certain parameters of the cables have to be known for the study, and can have an influence on the dynamic performance of the model. For instance, as explained in § 2.1.5, a bigger $R/X$-ratio will result in a better sharing of reactive power. Furthermore, cables with a bigger section, indicated by a lower resistance, will result in lower grid losses. The parameters of the cables applied mainly depend on the allowable voltage drop, which in its turn depends on the power they have to carry ($\sim I$) and the cable length and section ($\sim Z$), as Ohm’s law prescribes.

In case a limit of 4% voltage drop at the end of the cable is required, then taking into consideration that the maximum current over that line will be 1 p.u. it can be seen that the maximum value for the cable resistance is 0.04 p.u.

Two main types of cables will be distinguished in the model. Firstly, there are the DC-cables that will connect the batteries to the inverter. These are expected to be short, as both devices are located within the same cell, thus of low importance.

The cables coming from the DRES can be either AC or DC, which is a direct consequence of the type and technology of the DRES applied. Depending on the physical location of the DRES, these cable lengths might be chosen to be ignored.

Furthermore, there are the AC cables that connect the cell to the backbone and to the connected loads. These are the components that are expected to have a big influence on the overall system. For the sake of practical considerations, in an actual system these lines will probably be installed as overhead lines.

Finally, the line connecting the cell to the Bb (if any) will probably have a length which is not to be underestimated. This will depend on the physical locations, hence distances between cells.

Developed Areas
For the system layout representing a developed area, a microgrid benchmark is adapted [137], where lengths etc. are readily present. It is shown in Figure 5.9. The cable lengths can be deduced from the amount of poles that are visible, where the pole-to-pole distance equals 35 m. The cable sections that are given for the case are
5.2. Sizing of Components

designed for a peak load of 110 kVA.

The main line has a total length of 315 m. It will be modelled as 4x120 mm² Al XLPE. The line going to Customer I has a length of 30 m and a section of 4x6 mm² Cu. Customer II is connected through a 30 m long line made of 4x50 mm² Al. Customer III is fed through a 30 m long line made of 4x25 mm² Cu. This is also where the wind power flows into the grid. Customer IV is connected by means of a 30 m long 4x16 mm² Cu cable, and finally Customer V is connected through a 30 m long 4x25 mm² Cu cable, along with the solar plant. The Cell has a line of 30 m, which is a 4x25 mm² Cu line.

The specifications of the different customers are shown in Table 5.3. The specifications of the cables are listed in Table 5.4 [138].

<table>
<thead>
<tr>
<th>Customer</th>
<th>Type</th>
<th>Power (kVA)</th>
<th>Extra info</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Single residential customer</td>
<td>5.7</td>
<td>—</td>
</tr>
<tr>
<td>II</td>
<td>Apartment building</td>
<td>57</td>
<td>13 customers</td>
</tr>
<tr>
<td>III</td>
<td>Four residences</td>
<td>25</td>
<td>Wind turbine</td>
</tr>
<tr>
<td>VI</td>
<td>Single residential customer</td>
<td>5.7</td>
<td>PV plant</td>
</tr>
<tr>
<td>V</td>
<td>Apartment building</td>
<td>25</td>
<td>7 customers</td>
</tr>
</tbody>
</table>

Table 5.3: Specifications of the customers in the developed grid

<table>
<thead>
<tr>
<th>R (Ω / km)</th>
<th>X (Ω / km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>XLPE 4x120 mm² Al</td>
<td>0.325</td>
</tr>
<tr>
<td>XLPE 4x50 mm² Al</td>
<td>0.822</td>
</tr>
<tr>
<td>4x25 mm² Cu</td>
<td>0.927</td>
</tr>
<tr>
<td>4x16 mm² Cu</td>
<td>1.47</td>
</tr>
<tr>
<td>4x6 mm² Cu</td>
<td>3.93</td>
</tr>
</tbody>
</table>

Table 5.4: Summary of chosen cables for the developed case

Developing Areas
For the sizing of the cables in a developing area, the cables that will be considered are the ones between the cell and the load, and from the cell to the Bb. The rest of the cables is expected to be of lower importance.

Line to Loads  According to a feasibility study carried out to investigate a total electrification in Nigeria, the averaged length of LV-cable can be estimated at around 24 – 25 m per household [139]. Given the estimation used in the load profile for the developing country to be 670 households, and for now ignoring the other consumers in the village, the amount of cable connecting the households to the point of common coupling can be estimated to be about 16 km. Since this is a very long line length, we can expect that it will not be installed in one part. Instead, the needed cable length is divided into 10 lines, each of them having a length of 1.6 km. On these lines, the loads are grouped along the lines; 10 branches are modelled, each with 160 m in between. The ability of the voltage controller to deliver the proper voltage amplitude to users located far away will have to be checked.

The total load the lines will have to carry is 1 p.u., so around 40 kW. Earlier, the per unit current for this system has been calculated as well, boiling down to around 58 A.

With a maximum allowed voltage drop of 4%, the cable length yields a needed section of 50 mm² [83]. For this, the cable type NYBY 3x50/25 is selected, which is a standard type in PowerFactory. The cable parameters are shown in Table 5.5 [140]. From the inductance L of the line, which is 0.283 mH/km, the cable reactance per
kilometre can easily be calculated as

\[ x_L = 2\pi \cdot f \cdot L = 2\pi \cdot 50 \cdot 0.263 = 0.0826 \Omega/\text{km} \]

**Line to Backbone** An assumption has to be made for the length of the backbone, which is the line length between two inverters. An average distance of 500 m from one cell to the backbone is estimated. If also here the assumption is made that the maximum power the backbone has to transport is 40 kW, the cable can be calculated to need a section of 70 mm².

Again, a cable can be selected, this being the NYBY 3x70/35. For this cable, the parameters are given in Table 5.5, and the line reactance will be 0.0798 \(\Omega/\text{km}\).

<table>
<thead>
<tr>
<th>Table 5.5: Summary of chosen cables for the developing case</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>NYBY 3x70/35</td>
</tr>
<tr>
<td>NYBY 3x50/25</td>
</tr>
</tbody>
</table>

If it is desired to have an R/X-ratio of less than 0.33 between two cells connected through the backbone, taking into account lines of 500 m, then per line this boils down to a reactance of at least 0.4 \(\Omega\), or an inductor with an inductance of at least 1.3 mH with a 50 Hz current. This can be provided by, as mentioned before, a virtual reactance in the control loops, or an output filter. Another practical implementation of the needed inductance...
can be found in a transformer at the output terminal of the inverter, which is a measure that is inevitable in case the DC voltage of the BESS that arrives at the DC clamps of the transformer would not suffice for creating a 400 VAC signal. This last mentioned problem does not occur if the battery output voltage is at least 1.4 times higher than the required AC voltage magnitude \[141\]. This value depends on the inverter technology.

The chosen grid layout is shown in Figure 5.10. The lengths of the cables have been discussed earlier in this section, but for clarity one of the cells has been drawn in detail.

![Figure 5.10: The used grid for a developing country: A three-cell structure without connection to any main grid is assumed. The cells are initially interconnected by means of a backbone, but have the freedom of disconnecting from it and working independent from each other, given that proper control tools are available.](image)

### 5.2.4 Battery Energy Storage System

The BESS has a very important role in the grid: it is the actor that keeps the whole system up and running. The BESS supplies a grid voltage with a certain frequency, and makes sure the grid works satisfactorily within limits. It consists of a source and sink of energy, which is the battery, and an inverter which interfaces the batteries with the rest of the grid. The inverter should be supplied with a battery management system, watching over the state of the batteries and aims to keep them in their optimal condition at any time.

The converter is the component which interfaces the batteries with the grid. It needs to be a device which is able to both rectify and invert a current, respectively when there is an abundance of power on the grid and
power needs to flow to the batteries, and if there is a scarcity and power is needed from the battery bank.

The most straightforward choice as a type of inverter that is capable of performing both actions would be a PWM-converter, which is the one applied in the project. The device is presented in § 2.1.3. Sizing of the inverter might seem like a trivial task: it looks easy to install an inverter which is exactly sized for the load, thus has a power rating of 1 p.u. On the short term, this approach might seem economically viable, however, it can be expected that the power consumption in the network will not stagnate after commissioning the grid, as explained in § 5.2.2.

Furthermore, it has to be taken into account that at moments when the consumption is at its bottom point and the renewable energy sources are pushing a lot of power into the grid, the converter needs to be able to process this power flow in order not to require curtailment at that moment. This last consideration might in a later stage of the sizing process update the requirements of the inverter, and will be discussed in § 5.2.8.

In this discussion, another benefit of the CSGriP project became apparent: the modular structure of the microgrids enables the later installation of extra cells. If, for instance, the growth of the system would turn out to be higher than accounted for, then the way the microgrids cooperate does not interfere with the possibility of installing a second, independent cell.

**Developed Areas**

In the view of optimizing the sizing of certain components of the grid, an optimization tool has been developed by one of the partners of the project [142]. When taking the results of this tool, it can be seen that for the Netherlands the optimal battery size is supposed to be 6.4 kWh when optimized from an economical point of view, thus for overall costs. If the aim of the battery would be achieving a 100% self-sufficiency, the high value of 156.3 kWh per household is calculated, which will result in an economically infeasible system. So, a battery capacity of 6.4 kWh per household is taken into account. It has to be noted that in this case, costs for a diesel generator and fuel were taken into account.

The battery capacity can also be calculated to be expressed similarly to the per unit system. This will be done by expressing the battery size in relation to the averaged daily energy consumption of a household. From § 5.2.2, we know that an average Dutch household consumes an amount of 9 kWh on a daily basis. This means that a battery of 6.4 kWh per household corresponds to a relative battery size of 71%.

**Developing Areas**

A situation where the lowest overall costs per household are achieved makes use of a battery capacity of 0.4 kWh per household for a situation in Burundi. Given a daily consumption of ±570 Wh per household, the battery size can be expressed as 0.7 p.u.

However, if it is supposed that the Burundi village does currently not have access to any kind of main grid, the most important design parameter should be the fact that the grid can run 100% self-sufficient. In this case, the needed battery capacity per household can be calculated to be 0.9 kWh, or 1.6 p.u. The fact that the battery size is bigger than 1 p.u. is because less sunny days need to be covered as well.

**Location of the Batteries**

Knowing the optimal size of the BESS is one thing, but knowing where and how to install this battery is a different kettle of fish. A lot of research has been performed on whether a small battery per household, one big central battery, or anything in between these two extremes is better [143–147].

For this project, since a CSGriP-cell is in basically one big battery, the central approach is used. However, the research shows that scattering the battery systems can have advantages, so it can be considered to decrease the capacity of the central battery and distribute part of the battery capacity to lower levels of the network. This possibility was also shown in Figure 2.20 on p. 46.

**5.2.5. Ratio Solar to Wind Energy**

It is generally known that neither the production of solar energy nor the production of wind energy will perfectly match the consumption profile of a load, which is why a battery system will always be needed in case
of an islanded microgrid only supplied by non-controllable DRESs. One of the reasons for this mismatch are seasonal variations, especially distinct in the European continent. Where wind power has more output during the winter months, solar energy output peaks during the summer. It could be expected that this opposing profile is advantageous if both energy resources are combined in a grid [148]. This would mean that the share of DRESs can be chosen in such a way that the BESS has to supply as little power as possible, thus that the counterbalancing action between solar and wind output is at its optimum.

Previous research in the SOPRA project has investigated this research question, and deducted an ideal Renewable Energy Ratio (RER) of 20% solar energy to 80% wind energy [149, 150]. The best results were obtained in case this is combined with a Potential Energy Mix (PEM) of 140% for a situation in the Netherlands.

For the situation in Burundi, because of the lack of seasonal variances in that region, probably a situation with only solar energy would be a viable one.

5.2.6. PHOTOVOLTAIC ENERGY

One of the most important DRESs is solar energy, or PV. It is known that in the Netherlands, seasonal variations are very common. This can also be distinguished from Figure 5.11, on which an overview of insolation is given for a one year period. It is very clear that in the summer the insolation is higher than in winter time, and that the daily variations can be substantial. However, when looking at Figure 5.12, we can see a much more flattened profile for the available solar power in Burundi. This will be the reason of turning to a RER of 100% sun in an area like this.

![Figure 5.11: Yearly solar insolation for the Netherlands](image)

![Figure 5.12: Yearly solar insolation for Burundi](image)

**Developed Areas**

As mentioned in the previous section, a PEM of 140% can be considered ideal for the Netherlands, of which 20% solar energy. This boils down to a total of 28% solar energy per household. To understand this value, the zero-on-the-meter concept has to be explained, which is the amount of solar energy that exactly the full load on a yearly basis. Thus, at the end of the year, from a grid point of view the dwelling did not consume nor produce any energy.

This means that a PV installation in the Netherlands, that needs a size of 28%, will have to generate

\[
0.28 \cdot 3250 \text{ kWh} = 910 \text{ kWh}
\]

on a yearly basis. Using a common rule of thumb, which states that the capacity factor for a well-placed solar installation in these regions approximates 10.3%, or a generated energy of about 900 kWh per installed kWp on
yearly basis [151], a solar installation with an installed size of approximately 1 kWp per average household is needed.

From Figure 5.9 it is clear that not every house will be provided with solar panels. On the contrary, one PV plant is foreseen in the scheme. This means that this one plant will have to supply the solar energy needed for the whole network, accounting a solar installation which delivers 0.28 p.u. of energy. This is an installation with a power output of about

$$0.28 \cdot \frac{0.47}{0.103} = 1.27 \text{ p.u.}$$

**Developing Areas**

According to the already mentioned Python script written for sizing of the grid [142], for successfully exploiting a standalone microgrid in Burundi, the ideal amount of solar energy is 325%. Knowing that the daily usage in Burundi equals 570 Wh per household per day, the yearly consumption will amount around 208 kWh per annum.

Now, taking into account that the capacity factor for an islanded solar plant equipped with battery storage in Africa amounts approximately 20% [114, 152], or 1.8 kWh per Wp per year, the solar plant in Burundi needs a size of approximately 110 Wp for a zero-on-the-meter scenario. Together with the prerequisite of yielding 325% of solar energy, the needed size becomes 375 Wp per household. This amounts to a power of

$$3.25 \cdot \frac{0.413}{0.2} = 6.7 \text{ p.u.}$$

The other scenario, where no 100% self-sufficiency is achieved though the economics of the system are considered to be of importance, asks for a PV plant with a size of 166%, or 3.4 p.u.

**5.2.7. Wind Energy**

As explained before, it can be beneficial to supplement the renewable energy input from solar with input from wind.

**Developed Areas**

Due to seasonal variations, the solar power profile in the Netherlands does not exactly match this of the load consumption. This can be seen very clearly on Figure 5.13. In winter time, the load profile reaches its peaks, whereas the peaks of the solar input power are reached in the middle of the year, during summer.

For this reason, it is often proposed to supplement the use of solar power with wind power. This because, just like for the solar profile, also the wind output profile follows a certain, though less distinct, seasonal variation, which can be seen by examining Figure 5.14, where we can distinguish a behaviour in which the average wind speeds drop a bit in the summer and increase again around the winter.

Detailed wind speed profiles for regions in the Netherlands exist, as shown in Figure 5.15. The histogram which belongs to this profile is shown in Figure 5.16. If this wind profile is combined with the power curve of a wind turbine, which shows the relation between the wind speed and output power, it is very straightforward to draw the power output of the wind turbine at any moment in time.

Taking into account the 80/20 ratio wind to solar, the wind production needs to amount approximately 112%, which means 3640 kWh should be produced on a yearly basis, or about 10 kWh per day. Calculating with an estimation for the capacity factor of 0.215 for onshore wind power in the Netherlands [153, 154], the installed wind power per household should amount approximately 1.9 kW.

In per unit terms, the installed wind power should amount

$$1.12 \cdot \frac{0.47}{0.215} = 2.45 \text{ p.u.}$$

Similar to the solar installation, this wind park will be modelled as one big plant rather than a small scale wind turbine per household.

---

1. **Wp or Watt peak** shows how much power the PV module would generate under full solar radiation, at standard test conditions. A solar insolation of 1000 W/m² is applied.
5.2. Sizing of Components

Figure 5.13: Plot of solar profile vs. load profile in per unit

Figure 5.14: Plot of solar profile vs. wind profile in per unit
Developing Areas
For reasons mentioned earlier, wind turbines will be omitted in the simulations for Burundi. A country with a position like this of Burundi does not know distinct seasons, as can be clearly seen on the figure of the PV profile, Figure 5.12. Also, variations in night and daytime will not be as big as in a country like the Netherlands. Thus, it can be expected that combining solar with wind energy in order to cancel out seasonal variations is less relevant in an area like this.

5.2.8. INVERTERS
Two types of inverters will be distinguished in the μG. First, there are the ones interfacing the batteries with the grid, which will act as VSIs and thus take the grid forming task. Next to those, there will be the inverters used as an interface between the BESSs and the grid. These inverters do not have to form the grid, thus will be used as grid-feeding CSIs.

Battery Inverter
The inverter has to be able to transport power in two directions, to both charge and discharge the batteries. The direction of the power will depend on multiple parameters, e.g. the SoC of the proper batteries, the SoC of the batteries of connected cells, the amount of load and renewable power injection etc.

The inverter is capable of acting as a VSI, and creates a three phase AC voltage signal that can reach the interval $0 \ldots U_{dc,in}/1.4$. According to manufacturer data, the losses of the inverter will account $\pm 1\text{ kW}$ when
the switching frequency amounts 4 kHz [155]. A lower switching frequency will be beneficial in terms of these losses, but can result in more output noise and a lower PQ.

When it comes to sizing of the inverters, some consideration is needed as well. In § 5.2.2 on p. 97, the oversizing of the inverters due to potential future increase in load consumption has been discussed. However, it is important that the full power output of the DRESs can be handled by the battery inverter as well, to make sure that no problems occur in a situation where the output power of the DRESs is high while the load demand is low. Because of this requirement, the inverter for the developed case should be able to process a wind power of 2.45 p.u. and a solar power of 1.27 p.u. This leads to a required inverter power of about 3.7 p.u. In § 5.2.2, it was calculated that for the developed case, a load growth of about 1.05 p.u. can be expected. This leads us to an inverter size of 3.9 p.u., hereby taking into account that probably the DRESs will be oversized as well.

For the developing case in a 100% self-sufficient scenario, the solar peak power equals 6.7 p.u. This means that, at moments of low load demand and high solar power inflow, the inverter needs to be able to process almost 7 times more power than what the load requires. When this value is combined with the value for load growth, as calculated in § 5.2.2, the needed oversizing of the inverter becomes

\[ 6.7 \cdot 1.2 = 8 \text{ p.u.} \]

The other scenario for the developing case, seen from an economical point of view, shows a solar peak power of 3.4 p.u. This in combination with the projected load growth over a period of five years leads us to a needed inverter size of 4 p.u.

Solar Inverter
The solar inverter does not need to be a type which is able to work in islanding mode, as the inverters which are connected to the BESS take the task of creating the grid voltage into account. The proposed inverter reaches a maximum efficiency of 98.5% and an European efficiency of 98.2% [156].

5.2.9. Summary
An overview of the chosen parameters is presented in Table 5.6. In this table, households is abbreviated as “hh”; “€” points at the economical scenario; and “ss” means the scenario where the grid is 100% self-sufficient.

5.3. Zero-power Frequency
Using the decisions made in this and in the previous chapter it is now possible to define the droop curves. From § 4.2, we know that the zero-power frequency range has been selected to be 48 – 51.5 Hz. Next this, in § 5.1.4, the usable range for SoC of the battery was chosen to be 0 – 80%. This means that these values should be seen as being those where a battery in normal SoC does not yet cause an overreaction by the loads or sources. They will be used as being \( y_1 \) and \( y_2 \) on Figure 3.12 on p. 65, respectively. The values for \( f_{\text{min}} \) and \( f_{\text{max}} \) are 48 and 51.5 Hz.

The values where the battery is seen as being in a critical state are selected to be 30% at one side of the spectrum, and 70% at the other side. The asymmetry can be explained as follows: while the SSM scheme follows one line which can ramp up or down the output power in a continuous manner, the DSM is bound to steps in shedding schemes, discomfort of users, potential economic consequences etc. Therefore, it can be expected that a bigger band is needed for the DSM scheme to work properly. As soon as the battery reaches the 30% limit, the system will start to shut down certain loads, according to the predefined priority groups. Then, a big margin is still available to preserve the loads with high priority as much as possible. With this, the values for \( x_1 \) and \( x_2 \) on the same Figure 3.12 are pinned at 30 and 70%, respectively. \( \text{SoC}_{\text{min}} \) and \( \text{SoC}_{\text{max}} \) will be 0 and 80%. The accompanying scheme is plotted in Figure 5.17, the functions of the three states are given in Equations (5.1) – (5.3).

---

5 The European efficiency is a weighted efficiency, showing the performance of the inverter over a range of power outputs, rather than only the maximum efficiency. Thus the real efficiency over a full day is approximated more closely.
Table 5.6: Chosen parameters – The Netherlands and Burundi

<table>
<thead>
<tr>
<th>Description</th>
<th>Unit</th>
<th>NI</th>
<th>Bi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>kWh/year/hh</td>
<td>3250</td>
<td>208</td>
</tr>
<tr>
<td></td>
<td>kWh/day/hh</td>
<td>8.9</td>
<td>0.57</td>
</tr>
<tr>
<td><strong>Base power</strong></td>
<td>p.u.</td>
<td>0.413</td>
<td>0.47</td>
</tr>
<tr>
<td>Load increase</td>
<td>p.u.</td>
<td>1.05</td>
<td>1.2</td>
</tr>
<tr>
<td>Cables – Bb</td>
<td>Length</td>
<td>m</td>
<td>315</td>
</tr>
<tr>
<td></td>
<td>R &amp; X</td>
<td>Tab. 5.4</td>
<td>Tab. 5.5</td>
</tr>
<tr>
<td>Cables – Loads</td>
<td>Length</td>
<td>km</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>R &amp; X</td>
<td>—</td>
<td>Tab. 5.5</td>
</tr>
<tr>
<td>BESS Inverter</td>
<td>Power (€)</td>
<td>p.u.</td>
<td>3.9</td>
</tr>
<tr>
<td></td>
<td>Power (ss)</td>
<td>p.u.</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Losses</td>
<td>kW</td>
<td>1</td>
</tr>
<tr>
<td>Battery Technology</td>
<td>Li-ion</td>
<td>Li-ion</td>
<td></td>
</tr>
<tr>
<td>Capacity (€)</td>
<td>kWh/hh</td>
<td>6.4</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>p.u.</td>
<td>0.71</td>
<td>0.7</td>
</tr>
<tr>
<td>Capacity (ss)</td>
<td>kWh/hh</td>
<td>—</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>p.u.</td>
<td>—</td>
<td>1.6</td>
</tr>
<tr>
<td>PEM</td>
<td>Zero-on-the-meter (€)</td>
<td>p.u.</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td>Zero-on-the-meter (ss)</td>
<td>p.u.</td>
<td>—</td>
</tr>
<tr>
<td>Solar / Wind</td>
<td>RER % / %</td>
<td>20 / 80</td>
<td>100 / 0</td>
</tr>
<tr>
<td>Solar</td>
<td>Power (€)</td>
<td>kWp/hh</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>p.u.</td>
<td>1.27</td>
<td>3.4</td>
</tr>
<tr>
<td></td>
<td>Power (ss)</td>
<td>kWp/hh</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>p.u.</td>
<td>—</td>
<td>6.7</td>
</tr>
<tr>
<td>Wind</td>
<td>Power</td>
<td>kW/hh</td>
<td>1.9</td>
</tr>
<tr>
<td></td>
<td>p.u.</td>
<td>2.45</td>
<td>—</td>
</tr>
<tr>
<td>DRES Inverter</td>
<td>Efficiency</td>
<td>%</td>
<td>98.5</td>
</tr>
</tbody>
</table>

\[
\begin{align*}
    f_1 &= \frac{1.8}{30} \cdot \text{SoC} + 48, \quad \forall \text{SoC} \in [0,30] \\
    f_2 &= \frac{0.4}{40} \cdot \text{SoC} + 49.5, \quad \forall \text{SoC} \in [30,70] \\
    f_3 &= \frac{1.3}{10} \cdot \text{SoC} + 41.1, \quad \forall \text{SoC} \in [70,80]
\end{align*}
\]  

Furthermore, the final droop curves can be plotted as well, for both extreme cases for the SoC, with a zero-power frequency of 48 and 51.5 Hz, and one for normal SoC. The plot is shown in Figure 5.18. From this figure, it is very clear that the remarks which were given in § 4.3, namely that a small value for droop means that the inverters would be severely overloaded in case cells with a big difference in SoC are interconnected without taking precautions, are justified.

5.4. Case Studies

After the definition of all relevant parameters, it is now time to dive into the real work. A controller has been modelled, and probably at this point the reader is eager to see how the whole controller behaves in relevant
Figure 5.17: Frequency dependency on state of charge, with values filled in: The figure shows how the value for the frequency depending on the SoC will be calculated. It is clear how three different regions can be defined, these are the undercharging, no problem and overcharging region.

Figure 5.18: Final droop curves for low, normal and high SoC: The figure shows where the droop curves will be located in case of a low, normal or high SoC, using the selected droop coefficient of 0.3%. The figure shows also how due to this low droop coefficient no stable working point could be found between e.g. a high and a low charged cell, therefore the extra control step that was explained is necessary.

The first thing that is important to demonstrate is the fact that the proposed control mechanism is able to behave as it should without the application of DSM and SSM. This will be shown both in a case where one cell only is powering the load (Case I), subsequently three cells powering their loads (Case II), interconnected by means of a backbone. The grid layout for this is loosely based on the WSCC 9-Bus System [157], but in order to give every cell full control over working in stand-alone of interconnected mode, the ring structure which is proposed by the WSCC System is replaced by a bus structure.

Next, on the system with only one cell, the action of DSM and SSM will be demonstrated (Case III). A fourth case can be checked, namely how the controller reacts if two cells of different power rating are interconnected. Then, in Case V, it will be checked what the influence is of the implementation of virtual inertia. Thereafter a small sensitivity analysis will be carried out in order to see the influence of a changing droop coefficient.

The parameters that will be used for these cases are not of huge importance, as the cases mainly aim at showing how the control steps work together, while the deducted parameters (e.g. amount of solar power, size of battery etc.) are aimed to reach a satisfactory behaviour in terms of predefined criteria, which can be 100% self-sufficiency, or economically sized.
After these basic behaviours have been demonstrated, two concluding grids will be tested and discussed. The first one will be a microgrid in the developing situation, where three cells are interconnected according to the predefined grid layout (Fig. 5.10 on p. 103), where the controllers for DSM and SSM are active and where the sizing is carried out according to the demands defined by both the self-sustainable and the (somewhat more realistic) economically sized parameters. Subsequently, the same grid will be used, but with two containers that were built with a different philosophy: one economically sized for a village, and one self-sustainable for a hospital. The differences between an interconnected and an islanded situation will be shown.

Here, all the values that were calculated in the per unit system will be converted using the base values that were defined, with a base apparent power of 40 kVA. This yields system values given in Table 5.7, where the calculated parameters were summarized in Table 5.6. One problem is that only one load profile is available. However, in practice it will never happen that three containers see an exactly similar load. Also, it is possible that different cells have a different load profile. Therefore, a random factor between 0.9 and 1.1 will be added, in order to get a certain scatter in load consumption, and the profiles can be shifted a bit in time.

<table>
<thead>
<tr>
<th>Value</th>
<th>Calculation</th>
<th>€</th>
<th>100% ss</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_{max}$ (kVA)</td>
<td>—</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>$P_{max}$ (kW)</td>
<td>$S_{max} \cdot \cos \varphi$</td>
<td>38</td>
<td></td>
</tr>
<tr>
<td>$Q_{max}$ (kvar)</td>
<td>$S_{max} \cdot \sin \varphi$</td>
<td>12.5</td>
<td></td>
</tr>
<tr>
<td>$P_{avg}$ (kW)</td>
<td>$P_{max} \cdot \ p_{base}$</td>
<td>17.9</td>
<td></td>
</tr>
<tr>
<td>$P_{in5yrs}$ (kW)</td>
<td>$P_{avg} \cdot \text{load increase}$</td>
<td>21.4</td>
<td></td>
</tr>
<tr>
<td>$P_{BESS}$ (kW)</td>
<td>$P_{in5yrs} \cdot P_{BESS}$</td>
<td>85.7</td>
<td>171.5</td>
</tr>
<tr>
<td>$E_{BESS}$ (kWh)</td>
<td>$P_{in5yrs} \cdot 24 \cdot e_{BESS}/\text{DoD}$</td>
<td>450</td>
<td>1030</td>
</tr>
<tr>
<td>$P_{PV}$ (kWp)</td>
<td>$P_{in5yrs} \cdot P_{PV}$</td>
<td>72.9</td>
<td>143.6</td>
</tr>
</tbody>
</table>

Finally, for the developed situation, the layout of the grid will look different. Here, too, the initial condition is grid-connected, and only at certain moments the μG has to act on its own, independent from other cells. The grid layout will be based on a predefined microgrid benchmark scheme, as shown in Figure 5.9 on p. 102. The parameters have been discussed throughout this chapter, and are listed in Table 5.8.

<table>
<thead>
<tr>
<th>Value</th>
<th>Calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_{max}$ (kVA)</td>
<td>—</td>
</tr>
<tr>
<td>$P_{max}$ (kW)</td>
<td>$S_{max} \cdot \cos \varphi$</td>
</tr>
<tr>
<td>$Q_{max}$ (kvar)</td>
<td>$S_{max} \cdot \sin \varphi$</td>
</tr>
<tr>
<td>$P_{avg}$ (kW)</td>
<td>$P_{max} \cdot \ p_{base}$</td>
</tr>
<tr>
<td>$P_{in5yrs}$ (kW)</td>
<td>$P_{avg} \cdot \text{load increase}$</td>
</tr>
<tr>
<td>$P_{BESS}$ (kW)</td>
<td>$P_{in5yrs} \cdot P_{BESS}$</td>
</tr>
<tr>
<td>$E_{BESS}$ (kWh)</td>
<td>$P_{in5yrs} \cdot 24 \cdot e_{BESS}/\text{DoD}$</td>
</tr>
<tr>
<td>$P_{PV}$ (kWp)</td>
<td>$P_{in5yrs} \cdot P_{PV}$</td>
</tr>
<tr>
<td>$P_{wind}$ (kW)</td>
<td>$P_{in5yrs} \cdot P_{wind}$</td>
</tr>
</tbody>
</table>

A summary of the case studies is presented in Table 5.9.
Table 5.9: Summary of selected case studies

<table>
<thead>
<tr>
<th>Case</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>One cell, no DSM &amp; SSM</td>
</tr>
<tr>
<td>II</td>
<td>Three cells, no DSM &amp; SSM</td>
</tr>
<tr>
<td>III</td>
<td>One cell, with DSM &amp; SSM</td>
</tr>
<tr>
<td>IV</td>
<td>Different power rating</td>
</tr>
<tr>
<td>V</td>
<td>Virtual inertia</td>
</tr>
<tr>
<td>VI</td>
<td>Sensitivity of $K_p$</td>
</tr>
<tr>
<td>VII</td>
<td>Developing Country: Self-sufficient</td>
</tr>
<tr>
<td>VIII</td>
<td>Developing Country: Economical parameters</td>
</tr>
<tr>
<td>IX</td>
<td>Developing Country: High and low priority load</td>
</tr>
<tr>
<td>X</td>
<td>Developed Country: Initially grid-connected</td>
</tr>
</tbody>
</table>

5.5. Summary of the Chapter

During this chapter, the whole $\mu$G was cracked down to its basic components, describing the behaviour that is expected from every single element and selecting needed values accordingly.

First, some general parameters were discussed, including the exact implementation of both DSM and SSM, some important battery characteristics, and control steps.

After this, the physical components have been discussed, according to predefined requirements. Among other things, some important decisions that were made are for instance the installed PV size, the buffer capacity, line lengths, load profiles etc.

After the discussion concerning parameters, some case studies have been defined, which will aim at effectively showing every control step that is needed in order to reach a desirable behaviour of the $\mu$G, and showing where problems exist in case certain control steps are omitted.

The following chapter will present the results.
SIMULATION RESULTS

Don't tell people your plans.
Show them your results.

In this chapter, the results that are obtained from the simulations are shown, according to the discussion at the end of the previous chapter, in § 5.4. However, next to these specific cases, some other aspects and trade-offs of the grid will be discussed. One of them is the difference between the continuous DRES curtailing scheme and the standardized one.

The goal of this chapter is showing the reader what the model is capable of doing, and to prove that the choices for the control schemes lead to satisfactory results.

6.1. Case I: One Cell, No DSM or SSM

As a first verification of the controller mechanism, this is, to see whether one VSI is able to supply a certain amount of loads, using a certain PV input, a grid with one cell is simulated. A certain, constant amount of renewable power coming from the solar panels is assumed, and the load consumption is based on the consumption that was plotted in the previous chapter (Figure 5.8 on p. 99), and is implemented as being constant power load. The first case will be split into three subcases, where the first one will show a non-critical situation, and the second and third will try to show the necessity of DSM and SSM, respectively.

Since the drooping behaviour is in fact only needed for sharing power among different, interconnected cells, in this case where only one cell is under scope it could be argued that the droop coefficient can be set to zero. While this is in fact true, as doing so would not have any influence on the stability of the system, it is chosen to keep the droop coefficient at the value that is needed for enabling multiple cell behaviour, in order to allow transitions in case a cell would connect to another cell without the possibility of communicating this event.

6.1.1. Case I.1: No DSM or SSM Needed

For the first subcase, the initial SoC of the battery which belongs to the single inverter is chosen to be 50%, so no problems in neither over- nor undercharging will be expected on the short term. The amount of power produced by the PV park is approximately equal to the average power consumed by the load, so the inverter only supplies the difference between these. The relevant sizing and initial conditions are given in Table 6.1. The battery size is expressed in Ah, and for the sake of clarity it can be said that the BESS has an output power in the order of 1 kV. This brings the battery size to about 100 kWh, which is the total size of the battery system. This size in combination with a DoD of 80% gives us a usable energy content of the batteries in the order of 80 kWh. The PV power is set to a constant 45 kW input, while the load varies between 42.5 and 46.5 kW.
Table 6.1: Initial Conditions Case I

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery Capacity</td>
<td>100 Ah</td>
</tr>
<tr>
<td>Initial SoC</td>
<td>50%</td>
</tr>
<tr>
<td>Rated power inverter</td>
<td>60 kW</td>
</tr>
<tr>
<td>Power PV</td>
<td>45 kW</td>
</tr>
</tbody>
</table>

**Observations**

Figure 6.1 shows the power consumed by the loads, and the power supplied by both the inverter and the PV panels. From the figure, it is clear that some unavoidable losses are present in the system, which can be situated in the power lines. The power lost in the battery or in the inverter switches cannot be seen here, since the power that is being measured is the output power of the inverter. From the figure, we see that about 1 kW is lost in the grid.

![Figure 6.1: Case I.1: Power supplied by PV and inverter, and consumed by load](image)

**Figure 6.2:** Figure 6.2 shows how the frequency varies over time. Comparing this to Figure 6.1, it is clear that the grid frequency is inversely proportional to the inverter output, which is because of how the droop curve works. The next figure, that is Figure 6.3, shows an overview of the grid frequency, where it is clear that the borders for DSM and SSM are far from reached.

---

1 The legend of the figures that are presented in this chapter has been generated automatically by the simulation package. The legend is built up of two parts: "Component Name": "Signal/Variable". The components have been named with a number and then a description, in order to differentiate multiple similar components. For instance, 2 PWM will be the PWM inverter of the second cell on the grid. The components 2 Load and 2 PVSys will be the load and the PV system belonging to the this cell. Term stands for terminal, and the word Controller shows a controller setpoint or calculation.
Figure 6.2: Case I.i: Grid frequency. Detailed view of how the grid frequency varies with time. When comparing this figure with Figure 6.1, it is clear that the frequency is inversely proportional to the output power of the inverter, as expected.

Figure 6.3: Case I.i: Grid frequency with borders. Broad view of how the grid frequency deviates, with the limits for a normal situation indicated.
As a start, this first, very basic case study shows the possibility of interfacing a VSI connected to a BESS with a CSI getting power from PV panels and a general, constant power load. Since the amount of PV power closely matches the power consumed by the load, and the battery system was initialized with a SoC of 50%, no states of undercharging or overcharging were expected, and indeed do not occur. This means that the absence of a DSM or SSM scheme goes unnoticed during the course of the simulation.

The grid frequency stays well around 50 Hz at all times, which is due to the combination of a small droop coefficient thus small frequency deviations with power changes, the fact that the battery SoC does not deviate from the middle value too much and the low power that the inverter has to supply. Thus, the starting point of the droop curve is always around 50 Hz, and the setpoint oscillates around this value but stays very closely.

Bigger deviations would be seen if one of those ingredients would be omitted: a big droop coefficient leads to bigger frequency deviations for the same output; an extreme value for SoC leads to a bigger deviation due to the zero-power frequency setpoint; and loading the inverter at 1 p.u. has a different reaction than loading it at only 0.1 p.u.

The next case is this where one single cell is supplying a load, but the load is not equipped with a DSM controller. This means that the load will not react to an eventual state of undercharging of the battery. The initial conditions are the same like the ones for Case I.i, except for the initial SoC of the battery, selected to be 40%, and the PV power is disabled, in order to see the behaviour that we want to show.

Figure 6.4 clearly shows how the PV output power is zero at all times, so all the power that is needed to supply the loads and the grid losses comes from the inverter, thus from the BESS. It can be seen that the simulations are prematurely stopped around $t \approx 3200$ s, because at this moment the SoC of the BESS reaches 0% and no power can be supplied anymore. From Figure 6.6, it is clear that the frequency decreases severely, but as can be seen on Figure 6.4, no reaction of the load is noticed.

As a first interpretation, we can see how the grid frequency severely drops with a SEP that becomes critical. This behaviour is what is expected from the main controller.

The result of the absence of DSM is immediately clear: a continuous power delivery to the most critical loads cannot be guaranteed. There is no division between high or low priority loads; they are all treated equally. This is problematic, as seen from the simulations, since doing so endangers the power supply to the critical loads by draining the batteries faster.

By shedding some loads in due time, based on their priority and the grid frequency, a critical blackout of the whole grid can be avoided or at least postponed.

The third, basic subcase is one where the importance of SSM will be proven. For this case, all initial conditions are again similar to the ones in the two previous cases, except for the load power which is set to be 0 kW, thus no consumption is present on the grid. The PV plant is connected again, injecting 45 kW into the grid. The initial SoC of the BESS is chosen to be 55%.

Figure 6.7 shows how there is no consumption present on the grid, thus all injected PV power is stored in the battery system. The most relevant figure in this case is this of the SoC. Figure 6.8 shows how the small battery is quickly charged to almost 100%, because the PV plant does not stop injecting power. It can be expected that this behaviour will be bad for the battery lifetime, and problems can occur if the battery gets charged up to 100%. For this, the presence of a controller stopping the PV plant from injecting power at the moment this
Figure 6.4: Case I.ii: Power supplied by PV and inverter, and consumed by load: The PV plant is disabled, and the load consumes the same amount of power as in Case I.i. The simulation stops before $t = 1 \text{ h}$ is reached, because the battery is completely drained, as seen on Figure 6.5.

Figure 6.5: Case I.ii: Change of SoC: The battery is completely drained in about 3200 s. At the moment the battery reaches 0%, the simulations stop as no power can be supplied anymore.
Figure 6.6: Case I.ii: Grid frequency. It is clear how the grid frequency reaches extreme values, because the inverter tries to communicate to the loads to limit their consumption power. However, since no DSM is present, no reaction from the loads can be expected.

state of overcharging occurs is very important.

To finalize, the grid frequency can be shown, which can be seen in Figure 6.9. It is clear that in this case, the inverter tries to increase the grid frequency in order to activate the SSM scheme, but to no avail.

The maximum frequency that is being set seems to be 52.11 Hz. This value can be explained as follows: according to the controller settings, the zero-power frequency setpoint can never go beyond 52 Hz, nor below 47 Hz. Thus, at one moment, the frequency which is set according to the SoC surpasses this 52 Hz border, and is clamped over there. Now, according to the droop scheme, knowing that:

\[ p_{inv} \approx \frac{-45 \text{ kW}}{60 \text{ kW}} \approx -0.75 \text{ p.u.} \]

and using a 0.3% droop coefficient, the output frequency becomes:

\[ f = f_0 + K_p \cdot P \cdot f_{base} = 52 + (-0.003 \cdot -0.75 \cdot 50) = 52.112 \text{ Hz}, \]

as can be seen from Figure 6.9. This 52.1 Hz exceeds the upper limit of the frequency that is defined by the grid code, however will not be reached as SSM is implemented into the grid. The SSM is designed to reach full curtailment at 51.5 Hz, thus the grid frequency will not surpass this border under normal circumstances.

**Interpretations**

The simulations made clear that a system where no SSM scheme is present is prone to undesirable behaviour. Nothing limits the amount of power that flows into the grid from the DRESs, and since all the injected energy needs to be used as well in order to keep the power balance, this will lead to complications. In case rotating devices are present, an over-injection of power can result in a runaway, causing the frequency to ever-increase until the protection devices interrupt. If the battery management system is not adjusted to the batteries properly, this situation can cause the batteries to overcharge and considerably reduce the expected lifetime of
Figure 6.7: Case I.iii: Power supplied by PV and inverter, and consumed by load: No load is present on the grid, and the PV plant produces the same amount of power as in Case I.i.

Figure 6.8: Case I.iii: Change of SoC: We can see how the battery almost gets charged completely, in case it is assumed that the battery management system takes all the power from the grid to charge the batteries. It can be expected that charging the BESS this high will have consequences in terms of battery lifetime and the PQ of the grid.
6. Simulation Results

Figure 6.9: Case I.iii: Grid frequency: In this case, the grid frequency reaches very high values in order to activate the SSM. We see that the zero-power frequency setpoint is clamped at 52 Hz.

the BESS. Furthermore, overvoltages can be created by this power surge.

It is clear that a grid where the power injection is not managed properly will work in a very unsatisfactory way. The reactions will lead to a grid that is not able to meet the set requirements for the PQ, which in turn leads to a grid that is possibly exposed to a loss of performance, or lifetime. This shows that the implementation of SSM is inevitable.

6.2. Case II: Three Cells, No DSM or SSM

As mentioned at the end of § 4.3, the fact that the droop coefficient needs to be small leads to the concern that the sharing of active power might not be perfect. It is expected that, in case the interconnected cells have a similar SoC, thus their zero-power frequency setpoints are equivalent, sharing of active power will be good. However, at the moment the SoCs of the cells will deviate more, the effectiveness of sharing active power is expected to decrease.

Two cases will be mentioned: Case II.i, where the cells start at the same SoC, thus the same zero-power frequency setpoint $f_0$; and Case II.ii where the initial SoC of the cells will be different.

Another thing that was mentioned in the same § 4.3 is how the initialization of the grid happens. Figure 4.9 on p. 85 shows very clearly how the initial condition of the simulations assumes initially interconnected cells. Consequently, no transitions of cells connecting to or disconnecting from the Bb will be included.

6.2.1. Case II.i: Three Cells With Equivalent SoC

This first subcase includes three cells where the initial SoC is selected to be identical for each cell. The three batteries, however, will have a different size, in order to see a deviation of the SoC of the three cells over time. Every cell includes a certain amount of load, though no restrictions are set in terms of how much of this load power can be supplied by another cell via the Bb. Relevant choices are depicted in Table 6.2.
### Table 6.2: Initial Conditions Case II

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Cell I</th>
<th>Cell II</th>
<th>Cell III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery Capacity</td>
<td>500 Ah</td>
<td>700 Ah</td>
<td>900 Ah</td>
</tr>
<tr>
<td>Initial SoC</td>
<td>50%</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td>Rated power inverter</td>
<td>60 kW</td>
<td>60 kW</td>
<td>60 kW</td>
</tr>
<tr>
<td>Rated power PV plant</td>
<td>25 kW</td>
<td>0 kW</td>
<td>45 kW</td>
</tr>
<tr>
<td>Length line to Bb</td>
<td>500 m</td>
<td>550 m</td>
<td>600 m</td>
</tr>
</tbody>
</table>

**Observations**

From Figure 6.10, it is clear how the active power is divided among the three cells. Initially, when the $f_0$ setpoints are equal, the act of sharing power is performed perfectly. However, due to the differences in cell capacity, the values for SoC grow apart as can be seen in Figure 6.11, and so does the setpoint for $f_0$ as seen in the same figure. As a result, in order to keep on finding a common point for the frequency from the droop curves, the active power output of the inverters needs to deviate more from each other. This characteristic gets more distinct with a decreasing value for the droop coefficient. It is expected that only at the moment that one of the batteries reaches a critical SoC, such as over- or undercharging, the other systems will unburden this device.

One good point about this reaction is the fact that the biggest share of power is supplied by the battery with the biggest size: as seen from Table 6.2, BESS III has the bigger energy content, and accordingly supplies more power to the grid than Battery I, which is almost half the size.

![Figure 6.10: Case II.i: Active power supplied by the three inverters, with different parameters](image)

As a comparison, the same simulation has been executed with three batteries that were identical both in initial...
Figure 6.11: Case II.1: Change of SoC and the alike change of $f_0$: It is clear that the batteries start at the same SoC, but because of the difference in battery size, as reported in Table 6.2, Battery I drains fastest. This is also expressed in the setpoint $f_0$, plotted on the same figure and following the exact same progress as the SoC. The frequency is expressed in p.u., thus should be multiplied with 50 to get the actual frequency setpoint.

conditions and parameters. The result of the power sharing in this test is plotted in Figure 6.12: clearly with these idealized conditions, the power sharing scheme performs flawlessly, the active power is perfectly shared among the three inverters at all times.

The sharing of reactive power is shown in Figure 6.13. The reactive power is needed for both supplying what the loads need, since every load is consuming power with a $\cos \phi = 0.95$, and supplying the imaginary losses on the grid. As mentioned, the reactive power sharing takes place according to a Q-V droop curve, but its performance is inferior to that of the P-f droop scheme due to the fact that the grid frequency is a global control variable while the grid voltage has a local nature [60].

From the figure, it is indeed clear that even in the first moments of the simulation, where the active power is shared perfectly, the reactive power supplied by equals 11.7 kvar for Inverter III and 16.9 kvar for Inverter II, or 44% more, despite the similar initial conditions.

The grid frequency itself can be shown as well, which is done in Figure 6.14. Here, we can clearly see two things: firstly that the grid frequency stays well within the borders that are considered to be normal working points, and secondly it can be remarked that only one curve is visible on the graph where in fact three different devices are present on the grid. This is of course a requirement for having multiple power sources synchronised to the same grid, but at the same time it is a proof that the droop concept works well.

**Interpretations**

From the simulations, multiple insights can be learned, but the most relevant ones cope with the act of sharing active and reactive power among the different inverters.

It is expected that the reactive power sharing will not be perfect, due to the fact that we are coping with a low voltage grid, which inevitably limits the performance of the reactive power sharing scheme. This was
indeed noticed, the sharing scheme does not perform in an optimal way, leaving a gap of more than 40% between the inverters that supplies least and most reactive power.

From the literature, it is known that active power can be shared optimally if the relative droop coefficients of the different inverters are the same. The simulations, however, show how the sharing of active power deteriorates over time. The explanation for this derogation can be found in the dispersing behaviour of the frequency setpoint $f_0$ over time. As was mentioned in §2.1.11, no prior research took a difference in location of droop curves into account. Thus, if the droop curves are equally placed, active power sharing will be perfect, as was shown in Figure 6.12.

However, the main simulation took three systems with a differently sized battery into account, which means that if all three batteries would supply the same amount of power, the SoC of the smallest system would decrease much faster than this of the biggest system, which might or might not be a desired behaviour. In this simulation, however, it was shown that the system with the biggest battery energy supplies most power, and consequently the smallest battery injects least. Because of this, the SoCs of the batteries stay relatively close to each other, at least closer than they would if the power was shared equally.

As a numerical example, let us ignore the second battery, and see how the final SoC of Batteries I and III would differ in case they provided the same power. Figure 6.11 shows that Battery I loses about 2.6% of SoC over the hour, or about 23.0 Ah is supplied. The SoC of Battery III decreases by about 4.2%, or 20.9 Ah. If both batteries would have supplied the same amount of power, that is $(23.0 + 20.9)/2 = 22.0 \text{ Ah}$, Battery I would have dropped by:

$$\frac{22.0 \text{ Ah}}{900 \text{ Ah}} = 2.4\%,$$
Figure 6.13: Case II.i: Reactive power supplied by the three inverters: From the figure, it is clear that the Q-V droop behaviour performs less in terms of power sharing than the P-f droop scheme. Three identical inverters do not reach reactive power sharing effectively. It is clear that the sharing is not affected by the fact that the SoCs of the batteries grow apart, which was expected from the Q-V droop scheme.

Figure 6.14: Case II.i: Grid frequency: The grid frequency never leaves the zone that is considered to be the normal working point.
and similarly Battery III would have dropped by 4.4%. Ultimately, the difference in SoC between both devices would be 0.4% higher, which might seem a very banal difference but can have its influence in case the grid supplies power for longer than merely one hour.

Concluding, it is seen that multiple cells, with VSIs as interface, are able to supply a common grid without the necessity of communication or grid inertia. The droop theory seems to function, resulting in a perfect sharing of active power in case all cells are identical. Reactive power, as expected, is not shared properly, though as long as inverters are not overloaded, this seems to be a fact that could be ignored.

It has been shown that cells with different characteristics are able to share power as well: a deviation in the location of the droop curves does not imperil the grid stability. Moreover, this shift in droop curves has as an effect that stronger cells, e.g. with higher SoC, account for a bigger share of the active power supply. This is a positive effect of the strategy that calculates the location of $f_0$. However, the reason why one cell might be stronger than another one needs to be taken into consideration: if this cell is designed for a critical load that needs to be able to bridge multiple days without renewable power output, it will be unacceptable that this battery system supplies stored energy to insignificant loads.

This, however, leads to the discussion that a grid with interconnected cells is a stronger grid, where all actors benefit from each other, and it might be unwanted if a cell with critical load only benefits and never shares. The outcome of this discussion will strongly depend on the actual situation of each individual grid.

6.2.2. Case II.11: Three Cells With Different SoC

As a second subcase for Case II, it will be shown how the power output of the cells can vary if the SoC of the interconnected cells deviates remarkably. For this case, Battery I, the smallest battery, is selected to start with a near-critical SoC, chosen to be 20%. All other conditions stay the same. In this case, the importance of the control step do not charge the battery from the backbone will be indicated, as well as the reason why the last step discussed in Chapter 4 is needed: the control step where the droop curve is shifted up- or downwards at the moment the inverter is overloaded.

Observations

In order to understand what happens on the grid, Figure 6.15 shows what the total power flows look like. It is clear that the PV plants are not capable of injecting all the needed power into the grid, so on average about 70 kW needs to come from the inverters, thus the battery systems. We can see how initially the inverters supply more power than what is needed by the load, which can be attributed to losses in the grid due to big power flows and overloaded inverters, as will be discussed in the next paragraph. A snapshot of the distribution of powers is shown in Figure 6.16. It is seen that the numbers do not add up exactly, the result of line losses. The snapshot is taken after 3600 s, so at the end of the simulation.

Figure 6.17 shows the per unit loading of the different devices. It is clearly visible that all the inverters are severely overloaded initially, because of the big difference between the locations of the droop curves combined with a very small value for the droop coefficient. This means that immediate action is required from the controller step preventing an overloading state, in order to make sure that this situation does not last for too long.

In fact, in less than 80 s none of the inverters is overloaded any longer. This control step, as explained, works in a curative way, thus only has an effect at the moment the inverters are already overloaded. In the final system, this controller shall be designed to work in a preventive manner, by only moving the droop curves away from each other at the moment no state of overloading can occur.

From Figure 6.18 we can see how the grid frequency evolves over time. The inverters need to inject or consume a big amount of power in order to find a common setpoint because of the big difference in the location of the
droop curves at the beginning. This is clear by looking at the power demanded and supplied by the inverters, and manifests itself by the low frequency that is set initially. However, by shifting the droop curves according to the different control steps, the grid frequency is quickly normalized and falls within the normal range again.

It can be seen that Inverter I, thus in fact BESS I, receives a lot of active power during the initial state of the simulations. This power is expected to come from both Inverters II and III, as the PV plants do not supply enough power. Of course, it is not possible to include a communication signal from Inverters II and III to Inverter I in order to stop this inverter from charging its battery. Thus Inverter I can only use the information he has, limited to the SoC of its proper battery, the grid frequency and the amount of power coming from the Bb, a value that can be measured locally.

By checking the derivative of the SoC, and checking the power coming from the backbone, the controller can make the decision to limit charging the BESS by moving the droop curve upwards. However, if it would be noticed that the grid frequency is beyond the value where power curtailing starts, it will be decided not to limit the charging rate, because in this case limiting it would introduce even more undesired, and in fact unneeded, curtailing.

The reaction of these both controller steps can be seen on Figure 6.19. On the figure, the calculation of the three \( f_0 \) setpoints is depicted, which is a result of the frequency dependent on the SoC in combination with both steps discussed above. First, the frequency according to the SoC is calculated \((f \text{ fun } \text{ SoC})\), subsequently this frequency is changed with respect to the active power output of the inverter \((f \text{ fun } \text{ SoC and p})\), and after this the step that prevents charging from the backbone can influence the frequency setpoint as well \((f \text{ fun } \text{ SoC, p and CB})\). In what follows, the exact reaction of the controllers will be discussed.

**Inverter I** To start, let us take a look at the controller that belongs to the cell with the critical battery. This concerns the upper graph on Figure 6.19. We can see very clearly a reaction of both the frequency depending
on the power, and the frequency influenced by the act of charging via the backbone. Both reactions start right away, as the inverter is initially in an overloaded state (Figure 6.17), and the battery immediately starts to charge using power coming from the backbone as seen on Figure 6.20.

Because of the interaction of both schemes, and the reaction of Inverters II and III, the state of being overloaded does not last too long, so it can be seen that the curve which depicts \( \text{SoC and } p \) quickly rejoins the curve only taking the \( \text{SoC} \). However, the frequency reaction to charging from the backbone stays present over the whole course of the simulation. At its maximum, the frequency deviation due to this control step equals about 0.0112 p.u., or 0.56 Hz. We can see that, as time passes, the curves slowly move back together. This has two main reasons: firstly, Battery I charges slightly, thus the frequency setpoint depending on the SoC increases, and secondly Batteries II and III discharge slightly, while powering the load, thus their droop curve slowly moves down, towards the droop curve of Inverter I.

**Inverters II and III** The second and third part of Figure 6.19 are very similar to each other. This is because both inverters start at the same SoC and have a similar battery size. It was noticed from Figure 6.17 that the inverters are initially overloaded, thus the controller starts with decreasing the setpoint for \( f_0 \) in order to eliminate this overloaded state. As soon as this state has disappeared, the frequency is not influenced by this step any longer. Furthermore, since the batteries do not charge, there is no need of the control step limiting the act of charging the batteries from the backbone.

**Interpretations**
The simulations made clear that three cells, of which one is in a potentially critical state, are capable of working together and share power according to their respective state. It was observed that Cell I, with a very
Figure 6.17: Case II.ii: Per unit power supplied by the three inverters: It is clear how all inverters are initially overloaded. However, we can observe that the curative controller succeeds at eliminating this overpowered state and drives the inverters to a normal in- or output power.

Figure 6.18: Case II.ii: Grid frequency: Initially, the grid frequency is beyond the limits of what is considered normal, but because of the interaction of control steps, this situation is quickly amended.
low initial SoC, was not driven into this dangerous situation further, but effectively was helped by Cells II and III.

The simulations showed the drawback of a low droop coefficient, as discussed throughout § 4.2, namely that no stable working point can be found within the power limits of the inverters in case the values for \( f_0 \) deviate too much. It was seen that for this reason, initially the inverters were overloaded. However, at the moment the controller notices that the inverter is overloaded, the droop curve is shifted up or down accordingly, in order to eliminate this hazardous state.

The result of this control step is visible on Figure 6.17: until about \( t = 80 \) s, all inverters are overloaded, but the inverter power is quickly moving up or down, going to the direction of a normal magnitude of output power.\(^2\) The deviation of the \( f_0 \) setpoint was shown as well, in Figure 6.19, where the dynamics of the control step that avoids overpowering the inverters are clear.

On top of this, there is a second control step influencing the frequency setpoints, carrying the task of avoiding to charge a battery using power from another battery. This is a situation that can occur if the SoC, thus the \( f_0 \) setpoint of different cells, differs too much. The reaction of this second scheme is also visible on both Figures 6.17 and 6.19: in the power received by Inverter I after \( t = 750 \) s, we see a certain oscillatory behaviour, which is introduced by the no charge from Bb scheme.

This can be understood by knowing how the controller is implemented: namely by using the output of a set-reset (SR) flip-flop circuit that activates an integrating element in order to move the frequency up or down.\(^3\)

\(^2\)In fact, the inverter's apparent power output \( S \) is considered, since the power is mainly dictated by the capabilities of the switches, and these do not differentiate between active and reactive power.

\(^3\)For the sake of completeness, a SR flip-flop is a circuit with two inputs and one output, where the output is affected by the combination of both inputs and the current state: if the S state is high, then the output is high, and if the R state is high, then the output is low. If both S and R inputs are low, the current output state is held, and both inputs are not allowed to be high at the same time.
Implementing a scheme like this has certain benefits: it will prevent a very fast switching between different states, because a deadband exists that has to be crossed to switch the output state. Applied to this case: it is chosen to limit the derivative of the SoC to a certain charge rate, where the arbitrarily chosen upper limit of the C-rate equals 0.02 and the lower limit is 0.005C.

This means that the scheme monitors the charge rate of the batteries, and at the moment the charge rate is above 0.02C, the limiting scheme is activated. Note that the scheme then first checks whether the grid frequency is below 50.2 Hz, the point where PV curtailing starts. If the frequency is higher than this value, then the battery is allowed to charge using power from the backbone, in order to prevent unnecessary DRES curtailment. The scheme then stays active until the charge rate is below 0.005C. Only at the moment when the rate gets above 0.02C again, the scheme is re-activated. This oscillatory behaviour is one potential drawback of the implementation, as it can be clearly seen in the grid frequency (Figure 6.18), where this behaviour should not introduce any load shedding if not necessary.

6.3. CASE III: ONE CELL, WITH DSM AND SSM

In § 6.1, it was discussed how the absence of a DSM or SSM scheme influences the grid behaviour, stability, reliability, lifetime and so forth. This section aims at showing the grid behaviour in case these schemes are present, and how they can help. For this case, the initial conditions will be identical to those used in § 6.1.2 for the case where the battery faces a too low SoC, and the conditions used in § 6.1.3 for the case where the battery is overcharged.

The load is consumed by three identical loads, each of them consuming a constant 15 kW, and each of them equipped with a load shedding profile with different settings. Load I shuts down at 49.5 Hz, and has a stepwise behaviour. Load II has a modulating behaviour, the modulation starts at 49 Hz and stops at 48.5 Hz. The load has 10% residual consumption. The third load starts modulating at 48.5 Hz, and reaches 0 p.u. after
0.5 Hz. This is shown in Table 6.3.

The PV curtailment can follow two settings: the VDE-AR-N 4105 scheme, or the proposed continuous curtailment scheme. Both will be compared in terms of performance.

<table>
<thead>
<tr>
<th>Load</th>
<th>Modulation?</th>
<th>$f_{shed_{deg}}$ (Hz)</th>
<th>Mod. width (Hz)</th>
<th>Residual (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>×</td>
<td>49.5</td>
<td>—</td>
<td>0</td>
</tr>
<tr>
<td>II</td>
<td>✓</td>
<td>49</td>
<td>0.5</td>
<td>10</td>
</tr>
<tr>
<td>III</td>
<td>✓</td>
<td>48.5</td>
<td>0.5</td>
<td>0</td>
</tr>
</tbody>
</table>

### 6.3.1 Case III.1: DSM Scheme Intervenes

As a first subcase for the situation where one cell is equipped with a DSM and SSM scheme, it will be shown how the DSM scheme can prevent, or at least postpone, the battery from being discharged to 0%, by supplying power to certain high-priority loads for a longer time than low-priority loads. This way, these high-priority loads can be spared from potentially catastrophic power outages.

### Observations

The most interesting graph to show in this case is this where the residual power consumed by the loads is depicted. This can be seen in Figure 6.21. On this figure, we see that after about 1000 s, the first load disconnects according to its predefined on-off behaviour. The second load starts modulating at $t = 2160$ s, and reaches 10% load consumption just at the moment the simulation reaches 3600 s. The third load, which then can be seen as the load with the highest priority, does not shed at all, since the frequency limit of this load is only reached at 3600 s, as can be seen on Figure 6.22. This means that, moments after the end of the simulation, a modulating behaviour of these customers would be introduced.

The reaction of the SoC to this shedding is shown in Figure 6.23. It is very clear that the SoC starts to decrease more slowly as more power is being shed, completely within expectations.

One important remark can be made, using Figure 6.22. At the moment the first load sheds with a drastic step of 15 kW, a reaction can be seen in the frequency: it jumps up, gaining about 0.04 Hz in 30 ms, or one and a half period. It is important to consider these load jumps, and build an adequate dead zone into the load shedding controller. If this deadband would be omitted, an oscillatory behaviour of the load could be seen, being very unwanted. In this case, a deadband of 0.3 Hz is included into the controller, which means that the load will come back online at the moment the grid frequency reaches 49.8 Hz.

It can be understood that this deadband is less critical in case the load is modulating, as no load jumps are experienced and a balanced working point can be found smoothly.

### Interpretations

The simulations have shown that the load shedding schemes work as expected: at the predefined frequency setpoints, the according, low-priority loads switch off, effectively unburdening the BESS and preventing loads with a higher priority from facing power outages. It is seen that, in order to prevent the BESS from discharging too quickly and leaving the grid unsupplied, DSM will be unavoidable in any $µG$ that is supplied with uncontrollable power sources, and can still prove helpful in limiting e.g. running costs of a controllable power source in case this latter is present.

The loads can be switched off following a stepwise on/off behaviour, which will mainly be the case for dumb, uncontrolled loads. Other, controlled loads, can offer a modulating scheme to the grid. One can think of the charging of an electric vehicle, where the consumed charging power can move up or down smoothly according to the frequency of the grid. Another group of loads like these can be dimmable lights, given that the dimmer
Figure 6.21: Case III.i: Power consumption by the loads: The figure shows how much power the loads consume over time. All three loads are set to consume a constant 15 kW, but with a decreasing grid frequency, the load shedding scheme can decide to disconnect the load, or decrease the power consumption if possible. It can be seen that around $t = 1000$ s, the first load is disconnected, and around $t = 2160$ s the second load starts modulating.

Figure 6.22: Case III.i: Grid frequency: On this figure, the decrease of the grid frequency over time is depicted. This is caused by the fact that the SoC of the batteries decreases over time, because no PV power is being injected into the grid. At about $t = 800$ s, there is a kink in the line, this is the moment the battery SoC reaches 30% and the setpoint of frequency with respect to SoC starts to have a bigger slope.
does not work based on a potentiometer.

It is clear that a stepwise shedding profile can introduce oscillations or disturbances in the grid, if a big load is disconnected at once. A small spike in the frequency was consequently noticed (see Figure 6.22). This brings along another important requirement of the load shedding scheme, namely the fact that reconnection of the load should be carefully considered. If this small spike in the grid frequency would trigger the reconnection of the just-disconnected load, this would lead to a sudden drop in the grid frequency again, because of the sudden extra load. This would then again trigger the disconnection of this load, and an unstable, oscillatory situation can be created.

Indeed, in case of a load with modulating capabilities, this oscillatory behaviour is of lower concern. This is due to the fact that an oscillatory load shedding scheme will not introduce any sudden steps in power consumed from the grid, hence no stepwise reactions of the grid frequency are expected. In fact, the modulating load will smoothly decrease its power output at the moments the grid frequency decreases, and similarly smoothly consume more power with an increase in grid frequency, never triggering possible instabilities in the grid.

6.3.2. Case III.ii: SSM Scheme Intervenes

Using VDE-AR-N 4105

For this second subcase, as mentioned the same initial conditions are chosen as in the first case. This is: no load, 45 kW of PV power, and an initial SoC of 55%. The SSM scheme is activated, thus we will see a curtailment reaction of the PV plant at the moment the grid frequency surpasses 50.2 Hz. The reaction will take place according to the VDE-AR-N 4105 standard, which has been explained repeatedly throughout the report.

Observations

The relevant observations are depicted in Figure 6.24, showing the grid frequency, Figure 6.25 which shows the SoC and Figure 6.26 where the PV output power is shown. As expected, an increase in SoC leads to an
increase in grid frequency. This, in its turn, leads to a decreased power output of the PV plant, as soon as the grid frequency goes beyond 50.2 Hz, which happens at about \( t = 300 \) s. As can be seen on Figure 6.25, the SoC of the battery is effectively clamped around 80%, in accordance to the requirements set in the previous chapter.

At the moment the curtailing scheme reaches the point where all the renewable power is curtailed, the grid frequency jumps from 51.5 to 51.45 Hz in about 40 ms, or two periods at 50 Hz. From this moment onwards, nothing happens anymore because no load connected to the system and no PV power is injected.

**Figure 6.24: Case III.ii: Grid frequency:** It can be seen that the grid frequency increases drastically. Around \( t = 300 \) s, the grid frequency reaches 50.2 Hz, and the curtailing starts. At the moment the grid frequency reaches 51.5 Hz, the power injected by the PV plant falls to zero, and no further changes are seen on the grid, due to the absence of load.

**Interpretations**

The simulations show that the SSM scheme is able to limit the SoC of the BESS at the predefined value. As seen, the batteries stop charging when they reach about 80% SoC, because at this point, the grid frequency reaches the value at which the PV panels stop injecting power into the grid, 51.5 Hz. In the simulation, no load was present on the grid, so at the moment the PV panels are disconnected, nothing happens on the grid any longer.

Extrapolating the behaviour of the grid in case load would be present, using the knowledge of the implementation of VDE-AR-N 4105, can lead to interesting insights and possible drawbacks of using this standard in the \( \mu \)G.

It is known that the VDE-AR-N 4105 prescribes that the grid frequency should fall below 50.05 Hz for at least 60 s before the PV plant can start injecting power again. In the current grid, this is a well-understandable choice, since the PV panels will only disconnect at 51.5 Hz: a very uncommon and possibly dangerous situation. Having a frequency deviation this big on the interconnected main grid would mean that huge catastrophes are taking place somewhere, and burdening the grid with PV power too soon can cause triggering of the protection devices of a not yet fully recovered grid again.

However, as already explained, these deviations in grid frequency do not need to be problematic in a grid
6.3. Case III: One Cell, with DSM and SSM

Figure 6.25: Case III.ii: Change of SoC: The SoC grows over time due to the big amount of PV power that is being injected. It is clear that the critical situation of a SoC higher than 80% is effectively avoided by the curtailment scheme.

Figure 6.26: Case III.ii: Power injected by the PV plant: We can see how the injected PV power starts to diminish at the moment $f = 50.2$ Hz is reached. When the battery enters the danger zone of overcharging, the frequency ramps up more quickly thus the injected power decreases drastically. At the moment the grid frequency reaches 51.5 Hz, the injected power falls to 0.
where the frequency is used as being the main information carrier. This means that in this situation it can be undesired to prevent the DRESs from injecting any power into the grid for a long time after the frequency deviation was this high for a moment. Yet, when holding on to the standard, as long as the battery has a SoC of above a certain value, this low grid frequency will never be reached, and the VDE-AR-N 4105 scheme will abide in curtailing PV power without mercy.

This means that the battery will need to discharge to a certain extent before the PV panels are allowed to inject power into the grid again, thus battery power will be used while PV power is being curtailed. The question arises how much *unnecessary* PV curtailment will be experienced while battery power, or valuable cycles of the battery lifetime, is being used.

### 6.3.3 Case III.iii: SSM Scheme Intervenes

#### Continuous Curtailing

After discussing how the VDE-AR-N 4105 deals with the curtailing of PV power, it can be interesting to take a non-standard scheme into account. This scheme will have a behaviour as depicted on Figure 5.1, shown on p. 90: the curtailment scheme starts at 50.2 Hz, but goes to 0% power in a smooth way, unlike the profile set by the standard. This profile is expected to have certain benefits over the standard SSM scheme, though it is not expected that this can be implemented into the current grid codes overnight.

**Observations**

As can be expected from a curtailting scheme that follows a continuous gradient, no stepwise reactions are seen. Figure 6.27 shows the grid frequency, which runs towards 51.5 Hz in a smooth way. As discussed previously, the discontinuity around \( t = 1300 \) s is due to the battery entering the critical zone. 51.5 Hz is not yet reached after \( t = 3600 \) s, so the PV plant is expected to still inject a limited amount of power.

Figure 6.28 shows how the PV power smoothly decreases, on its way to but not yet reaching 0 kW. Furthermore, the SoC, depicted on Figure 6.29, shows a smooth change towards 80%. Extrapolating the figure, it seems that the graph shows an asymptotic behaviour towards 80%.

**Interpretations**

When compared to the reactions seen in the previous section, it can be argued that the continuous curtailment scheme acts in a completely different way than VDE-AR-N 4105. One of the first differences is the speed at which the batteries are charged up to their maximum value: while the previous simulations using the VDE standard had the batteries fully charged around \( t = 1500 \) s, the battery connected to a PV plant using the continuous scheme has not yet reached a SoC of 80% after \( t = 3600 \) s, seen on Figure 6.29. This is due to the fact that the VDE standard ramps down the PV power output with a speed of 40% per Hz, while in the proposed standard the power ramps down more quickly, to say 100% over 1.3 Hz, or about 78% per Hz. This can be seen as a disadvantage.

On the other hand, the PV plant is injecting power into the grid until the end of the simulation, and extrapolating the course of the SoC tells us that the value of 80% eventually will be reached.

The positive thing about the continuous curtailment is the fact that no jumps in power injection are experienced; Figure 6.28 shows the injected PV power that smoothly moves towards 0 kW as the SoC increases.

Similar to the previous simulation, no load was present, thus it cannot be seen how the grid will react in case of load being present. However, contrary to a grid with the VDE standard, in this grid with the continuous scheme it is not expected that the load will have to be supplied using power from the battery system as long as the grid frequency did not cross a certain value. Moreover, it is expected that a balance can be found between the grid frequency and the load power, where all load can be supplied using power coming from the PV panels and ideally the batteries do not take part in power delivery.
6.3. Case III: One Cell, with DSM and SSM

Figure 6.27: Case III.iii: Grid frequency: Due to the interaction of the continuous curtailment scheme and the frequency setpoint of the controller, the grid frequency climbs up to 51.5 Hz following an asymptotic path.

Figure 6.28: Case III.iii: Power injected by the PV plant: Unlike the PV reaction which could be seen for the VDE-AR-N 4105 scheme, in this case the PV power does not fall to zero at a certain moment. In fact, the injected power is lowered according to the non-standard graph, charging the battery slowly to its limit value.
Figure 6.29: Case III.iii: Change of SoC: The non-standard scheme is able to limit the SoC, by not charging the battery up to the maximum value. An asymptotic value can be deduced, where probably the battery SoC will eventually reach 80%.

6.3.4. Comparison: VDE-AR-N 4105 vs. Continuous Curtailing

In § 6.3.2 and 6.3.3, the behaviour of two SSM schemes was shown using the same initial conditions as the ones applied in § 6.1. However, one of the choices that was made in this case was not to include load into the grid, in order to see the necessity of SSM more clearly. When it comes to comparing the continuous profile with this defined by VDE, it will be interesting to include some load into the grid, in order to see how much PV power is curtailed after the moment the risk of overcharging the battery has averted. This means that some power needs to be drawn from the grid, to drive the SoC back down after the PV curtailment scheme successfully intervened.

In order to successfully show this behaviour, some adaptations are made to the initial conditions: initially, the battery capacity is reduced by 50%, in order to see changes in SoC at double speed, and secondly a load of 20 kW is connected to the grid at \( t = 30 \) min.

Observations

Figures 6.30 and 6.31 show the powers that are consumed from or injected into the grid for respectively a situation where the standard curtailment scheme, VDE-AR-N 4105, is used, and a situation where the non-standard continuous curtailment scheme is applied. One big difference immediately attracts attention: in the grid where the VDE standard is applied, the PV power stays 0 after \( t = 1100 \) s, while the non-standard scheme enables power injection from the PV plant immediately after the load is connected. The result of this is that, while in case of the VDE standard the battery has to supply all the power consumed by the load, the grid with the non-standard solution quickly finds a balanced situation where the PV plant injects exactly the amount of power that is consumed by the load, as predicted. This leaves the inverter with quasi zero power supplied. The lack of power injection in case of the VDE standard is due to the fact that the grid frequency needs to reach a value below 50.05 Hz for at least 60 s, which clearly does not happen with a value for SoC this high.

The result of this can be seen on Figure 6.32, where the SoC of the batteries in both cases is compared. A first
Figure 6.30: Case III - Comparison: VDE – power supplied by PV and inverter, and consumed by load: In the first half of the graph, no load power is present yet, thus the PV plant charges the battery up to the limit and the curtailing scheme disconnects the PV plant. At the moment the grid is loaded, the PV plant does not inject power into the grid because of the frequency limitations. Thus, all load power is supplied by the inverter.

Figure 6.31: Case III - Comparison: Continuous – power supplied by PV and inverter, and consumed by load: In this case, as soon as the load connects to the grid, the PV plant starts injecting power in order to supply the load power. We can see that by the end of the simulation, all load power is supplied by the PV plant, thus the inverter does not need to address the battery for extra power.
observation, as already seen in the previous sections, is that the battery SoC is effectively clamped before the critical value 80% is reached. A more important observation, however, is the fact that while the battery for the non-standard solution stops discharging at about 75%, the BESS drops drastically in case of applying the VDE standard. Thus, a lot of PV power is curtailed, which has to be supplied by the batteries. This can be called a non-ideal situation.

Finally, Figure 6.33 shows how the grid frequency evolves over time for both situations. As was already deducted above, the grid frequency in case of applying the standard does not reach 50.05 Hz for long enough during the course of the simulation, which is why the VDE standard does not allow any power injection from the PV panels. On the other hand, for the continuous scheme a certain frequency is found at which the power injected by the PV panels exactly equals the power consumed by the loads. This can be called a good reaction, as no more PV power is curtailed than what is needed.

**Interpretations**

From the observations, it is clear that the continuous curtailment scheme has a better reaction than the VDE-AR-N standard, because of the more conservative approach this latter takes. The standard has been designed with the main grid in mind, where a deviation of 1.5 Hz from the nominal frequency points at an emergency situation that has to be cleared completely before injection of power can be considered again. On the other hand, the non-standard solution has been designed with the background of this μG in mind: a grid where frequency deviations can be seen as a normal reaction of occurrences on the grid that are not *per se* disastrous, merely a necessity in the communication-less structure of the grid.

Because of this difference in background and philosophy of both curtailment schemes, it is understandable that the non-standard solution hands the best tools for regulating the injected power according to the needs of
the grid. However, practical considerations arise: before any device can be implemented into the main grid, it has to comply certain standards, e.g. the VDE standard in case DRESs are applied. This means that, even if the non-standard solution would be better, it is not allowed to apply it when interconnection with the main grid is required. On the other hand, in case the \( \mu \)G is implemented in a location without any main grid, or without standards to be followed, it can definitely be considered to implement the non-standard solution in order to yield more renewable power and avoid using the battery system when possible.

### 6.4. Case IV: Two Cells With a Different Power Rating

Until now, if multiple inverters were present on the grid, they always had a similar or identical power rating. However, in a real-life situation it can occur that, for instance, a village is equipped with a big, powerful cell, but after some years of load increase, the one cell does not suffice any longer. In this case, one can opt for installing a second cell next to the first one, which then can take care of the power due to load growth over time. It can be expected that this second cell will have a lower power rating than the first cell, thus the controller needs to be able to deal with a situation like this.

As was mentioned in § 2.1.4, particularly in Equation (2.6) on p. 19, multiple cells of different power rating can reach a satisfactory power sharing in case their relative droop setting is the same. In fact, throughout the whole document so far, it had been opted to express the droop coefficient in the per unit system, since this makes comparison among components of different size easy.

In this case, this claim will be put to the test: a grid is modified to have two cells supplying their own loads, interconnected by means of a backbone. The second inverter has a rating of 10 kW, while the first inverter has got a rating of 60 kW. Also the second load is on average 6 times smaller than the first load. The load is adapted with respect to the simulations which were done before, in the sense that they show a stepped change in power.
consumption, rather than the smooth load changes that took place up till now. Furthermore, the initial SoC for both inverters is set to be identical at 55%, and 25 kW of PV power is present on the grid.

**Observations**

Figure 6.34 is the most relevant image which needs to be discussed for this case. It shows the per unit amount of loading for both inverters. From the figure, it is clear that the per unit power sharing for both devices is near-perfect. The inverters seem to share the power according to their proper rating splendid.

The actual values for the active power can be seen in Figure 6.35. On this figure, the power consumed by Loads I and II has been summed. We can see how Inverter II delivers 6 times less power than Inverter I, leading to a similar active power sharing.

![Figure 6.34: Case IV - Per unit power supplied by inverters of different rating](image)

From the simulations, it is clear that two inverters with a drastically different power rating using the same relative droop coefficient are interconnected by means of a backbone, they are perfectly capable at sharing the power that needs to be supplied.

**Interpretations**

From the simulations, it is clear that two inverters with a different power rating are able to share the power according to their respective ratings. This proves the statement that requires an identical relative droop coefficient for different inverters correct. In the simulation, the battery size was decreased according to the inverter power, and also the load was adapted, which results in a similar SoC throughout the simulations. This implies that the setpoint for the zero-power frequency $f_0$ stays the same for both systems at all times, resulting in a perfect sharing of the power as was discussed in § 6.2.

The fact that differently sized systems can share power effectively is a promising one, as this proves the cellular $\mu$G concept viable. Villages with a certain load consumption can opt to install a properly sized cell, and maybe set up a second, smaller cell in the future in case the consumption tends to exceed the first cell’s capabilities.
6.5. Case V: Virtual Inertia

In §2.1.5, the possibility of adding emulated inertia to the grid was discussed. Doing so is expected to improve the dynamic stability of the grid, as inertia effectively damps the system frequency. The result of this would be that the discussion concerning small-signal stability could become less critical, because the frequency setpoint of the inverters reacts more slowly to changes in output power, also limiting the output power reaction to a changing $\delta$.

Even if studying the presence of adding a virtual inertia to the grid will be omitted in the research, it can be interesting to see how the grid behaves with adding this step into the controller. The easiest way of implementing a virtual inertia into a controller is simply by adding a first-order filter to the output of the frequency calculation [63]. This way, the frequency setpoint the inverter sees is damped. It is known that the transfer function of a first-order filter, written in the Laplace notation, can be written as

$$\frac{Y(s)}{X(s)} = K \cdot \frac{1}{\tau s + 1},$$

and the notation for a rotating mass equals

$$\frac{Y(s)}{X(s)} = \frac{1}{2Hs + D}.$$

This means that the time constant $\tau$ of the first-order filter shall be equal to $2H$, where $H$ is the actual value of inertia. It is opted to choose for a low emulated inertia, e.g. a small diesel gen-set. The value for $H$ for this device with a low value of inertia can be estimated at 1.3 s [158]. Thus, the time constant $\tau$ of the first-order filter is set at 2.6 s.

For this simulation, a grid with two cells is considered. Both cells have the same power rating of 650 kW, a very similar initial SoC of respectively 55% and 55.1%, and an average load of respectively 20 kW and 14 kW.
Cell I is also equipped with 25 kW of solar input. In order to show the reaction to a big load jump, Load I is disconnected from the grid at $t = 1800\,$ s.

**Observations**

Figure 6.36 shows the initial response of the active power output of both inverters. Because of the small difference in initial SoC, we can see a transient while the inverters try to find a common working point. The transient situation seems to damp out within about 15 s.

When comparing the long-term behaviour grid with virtual inertia to a grid without virtual inertia in terms of active power sharing, we do not see any difference. Figure 6.37 shows the results of a grid with emulated inertia and a grid without this inertia. On this figure, only one pair of power output signals can be seen, which proves the fact that the virtual inertia does not have any influence on the power sharing at the moment both inverters are in operation.

The frequency response of a big load jump is shown in Figure 6.38. From this figure, the differences between both situations are very clear: where the grid without inertia can change its frequency momentarily, the frequency for the grid with emulated inertia grows gradually, showing the reaction we would expect from an accelerating rotating inertia.

It is known that a first-order filter will reach 99.3% of its steady-state value within 5 time constants, by $1 - e^{-5} = 0.993$. With $\tau = 2.6\,$ s in this case, and the fact that the steady-state value for frequency is reached in about 13 s, this behaviour is seen on the grid with virtual inertia.

**Interpretations**

It seems that implementing virtual inertia into the grid does not need to be more complicated than simply adding a first-order filter to the output of the controller. Two inverters are able to find a working point with this extra control step implemented, and share power effectively as soon as the initial oscillations have disappeared.
Figure 6.37: Case V: Power supplied by inverters: The figure actually shows the power supplied by the grid with and without virtual inertia. The figure makes clear that for both grids, the power is shared exactly in the same way. Furthermore, the effectiveness of the droop scheme for active power sharing is proven again from this figure, both in the charging and in the discharging phase.

Figure 6.38: Case V: Comparison of frequency response with vs. without virtual inertia: It is immediately clear that the frequency change upon a big load jump is way more aggressive for a grid where no virtual inertia is present.
These initial oscillations take some time to damp out, depending on the magnitude of the virtual inertia.

From the reaction seen in Figure 6.38, we can conclude that adding virtual inertia to the controller smooths out the reactions to any load jumps on the grid. It is expected that a system with a bigger virtual inertia will react in a more stable way to load jumps or other events on the grid, since the reaction of the controllers to these events is smoothed out. In fact, as mentioned in § 4.1, a change in frequency setpoint is caused by a change in output power of the inverter, and as soon as the droop coefficient would be too big, the strong reaction of the output frequency could lead the grid into unstable behaviour because of overcompensation due to a big gain setting. However, this overcompensation would be damped out by the output filter acting as virtual inertia, thus a big gain can result in less stability concerns.

This could lead us to the conclusion that the small-signal stability of the grid is less endangered by bigger values for droop in case a sufficiently big virtual inertia is present, however it is dangerous to prejudge. Analysing a system with a controller equipped with this virtual inertia step, by means of its state-space representation, would close this question.

6.6. Case VI: Impact of Changing Droop Coefficient

As discussed in § 4.1, the droop coefficient should be limited to a maximum value of 0.6% in order to keep the grid within the small-signal stability limits. However, as was mentioned there and already proven in this chapter, a low droop coefficient can lead to an underachievement of the active power sharing.

Figure 6.10 on p. 123 showed us that active power sharing is not effectively reached at the moment the SoC of the cells starts to deviate, which happened because differently sized batteries were applied in the grid. This results in a deviation of $f_0$ over time, decreasing the effectiveness of active power sharing. An advantage of this was the fact that a bigger-sized battery tends to take a bigger part in the power supply.

The active power can be shared perfectly in specific cases, as can be seen from Figures 6.12 and 6.37, respectively on p. 125 and 147. These figures show how the active power sharing is near-perfect in case multiple cells have equivalent initial conditions and size, thus a lasting equivalent setpoint for $f_0$. Also in case of cells with a different sizing but the same relative droop coefficient, which was seen on Figure 6.34 on p. 144, the relative active power sharing can be called perfect.

It is expected that an increase of the droop coefficient will lead to an improved performance of the active power sharing scheme, even if the values for $f_0$ are located further away from one another. This happens because with an increase of steepness of the droop curves, bigger deviations in power lead to bigger deviations in frequency, thus a smaller deviation in power is needed in order to reach the same frequency setpoint for both cells. This will result in a power sharing closer to the ideal case, though with higher deviations from the nominal values.

Despite this advantage, increasing the droop coefficient has to be approached with care, since § 4.1 and a basic understanding of control theory teach us that a bigger gain leads to a system that is potentially unstable. Nevertheless, as was mentioned in the same section, the stability analysis has not been performed on this exact system, but indeed on a similar $\mu$G, so it is not sure whether the limit for $K_p = 0.6\%$ also holds true for this case.

In order to gain more insight in the dynamic stability of the model, a small sensitivity analysis will be carried out, where the droop coefficient will be varied, and the impact of doing so will be scrutinized. A grid with two cells is considered, where the initial values for SoC will be 50 and 70%, respectively. The battery size will be the same for both batteries. No PV power is present, and the loads consume a constant 15 kW. Constant load consumption is considered, which is a tentative choice: load changes or load jumps could lead a system with a big droop curve into dynamic instability. Furthermore, the controller that limits the battery to be charged from the Bb is disabled, in order to see the behaviour based on the frequency setpoint and droop coefficient only.

The value for the droop coefficients that will be compared will be firstly the 0.3% that has been used
throughout this chapter. Subsequently, 4% droop will be set, because this is a commonly used value in mechanical systems [58], and also closely equals the 3.7% that was deduced in § 4.2. For the sake of comparison, a droop value of 2% will be considered as well, an arbitrarily chosen value.

**Observations**

A first, important observation is that a controller using 4% droop does not seem to threaten the system’s stability. This can be due to the fact that there are no load jumps present on the system, so no abrupt changes in output frequency are needed, in turn not straining the system stability.

As expected, the system with the bigger droop coefficient reaches the best active power sharing, as depicted on Figure 6.39. On the figure, we see how the two cells with a different SoC and 4% droop share the power according to the interests: the weakest cell delivers least power, about 12 kW, while the strong cell delivers 18 kW, or 150% more. As a reference, in the system with 2% droop the initial delivered power equals 9 kW and 21 kW respectively, thus the strong cell delivers about 230% more power, but the weaker cell still takes part in the power supply. The image changes for the system with 0.3% droop: here the initial power sharing is very poor, with respectively 55.5 kW delivered by the strong cell and 24.5 kW of power received by the weaker cell, which points at a displacement of energy from BESS I to BESS II, an intolerable situation. This would be intercepted by the control step which prevents the battery from charging over the Bb, but as mentioned this control step was disabled in order to see the reactions according to the droop curves only.

![Figure 6.39: Case VI: Power sharing for three droop values](image)

As expected, a system with a higher value for the droop coefficient has a better performance in terms of power sharing. The figure shows the participation in active power delivery by two interconnected inverters, compared for three different values for $K_p$, which are 0.3%, 2% and 4%.

Another important remark concerns the grid frequency: as can be expected, judging the shape of the droop curves, a system with a bigger droop that delivers the same amount of power will have a bigger frequency deviation. This behaviour can be very clearly seen on Figure 6.40. While the system with the smaller droop coefficient stays neatly above the 49.8 Hz border, the situation in which 2% droop is used crosses 49.8 Hz around $t = 3000 \text{ s}$, and the system with 4% droop never even falls within the border. The decreasing trend is
due to the absence of solar energy, thus the batteries discharge while delivering the needed load power.

![Figure 6.40: Case VI: Comparison of grid frequency for three droop values](image)

**Figure 6.40: Case VI: Comparison of grid frequency for three droop values:** The grid frequency is depicted for three systems with identical initial conditions but a different droop value $K_p$: 0.3%, 2% and 4%. It is clear how the biggest droop curve results in a system with the highest frequency deviations, which might be undesirable.

At the moment the system with 2% droop leaves the normal zone, thus crosses 49.8 Hz, the SoC of the batteries is still 63.5 and 47%. These values for SoC do not yet seem to be critical, thus load shedding should not yet be needed at this moment. Nevertheless, due to the natural behaviour according to a high droop coefficient, the system as a whole senses that a critical situation is reached, and will react accordingly. The same holds for the even higher droop coefficient: we see that the system initializes in this critical zone, but with a battery SoC of respectively 50 and 70%, it can be reasoned that no load shedding should take place. However, due to the high droop coefficient, load shedding could be initiated already, depending on the way the DSM scheme is implemented.

**INTERPRETATIONS**

The first and foremost noticeable reaction of this limited sensitivity analysis is the fact that a bigger droop coefficient does not result in an unstable system. This observation, however, probably needs to be taken with a grain of salt, since a very artificial situation is taken into account, with no changes in load consumption or whatsoever.

As expected from the droop theory, a system with bigger values for the droop coefficients results in a more equalized sharing of active power, even if the $f_0$ setpoints are located far away from each other. The bigger slope of the droop curves means that a similar output frequency can be found with a smaller deviation in output power, leading to a more equal power supplied by the different inverters. However, another expectation has proven correct, namely that steeper droop curves come hand in hand with bigger nominal frequency deviations. As seen from Figure 6.40, while all grids are in a normal operating condition, the grid with 4% droop falls out of the borders of this normal condition while the grid with 0.3% droop is not yet close to the border.
These observations can be explained more schematically using Figure 6.41. On this scheme, we can see two depictions of inverters sharing a similar load. The left case has got a controller with low droop coefficient, while the droop curves for the right case are very steep. The figure shows what the steady-state frequency setpoint will be with this amount of load demand. It is clear that, while the right figure succeeds in sharing the power more equally, it also results in a grid frequency that deviates more from the setpoint.

Extrapolating these insights to a possible situation with more PV power than load, it can be understood that a system with a high droop coefficient will cause the grid frequency to reach higher values, because the zone of the droop curve where power is supplied leads to an increase in grid frequency. Because of this, the PV curtailment scheme could be activated, even if the batteries are not yet critically charged.

Summarizing, it seems that selecting a droop coefficient is not a trivial task; choosing its value incorporates making a trade-off between active power sharing among cells with different conditions and having a satisfactory grid frequency, which means that the grid frequency should not go beyond the borders of normal frequency values if there is no reason to do so. Optimizing to one of these requirements automatically jeopardizes the other one.

 Plenty different inputs need to be taken into account, which are listed in Table 6.4. This trade-off in fact shows the indispensability of the secondary control mechanism in the main grid, that was mentioned in §2.1.5, which was the control step that restores the frequency back to its nominal value after deviations took place, no matter what. In this case, the optimization of the droop coefficient needs to take less influencing parameters into account, as no steady-state deviations from the nominal frequency need to be coped with.

However, in the μG discussed in this thesis, it is impossible to implement this secondary control layer, as this will immediately cancel out all the requirements that were initially set. It is known that in this grid, it is aimed at avoiding the need of using communication equipment by actively changing the grid frequency according to the SEP of the grid. If now the grid frequency would be pushed back to its nominal value after each and every event by means of a secondary frequency controller, this whole communication idea would be overruled and lose its functioning. Because of that, the droop coefficient needs even more consideration here than in the main grid.

6.7. Case VII: Self-sufficient Grid in Burundi

After the different control steps have been discussed and shown in the previous sections, it will be interesting to put all the pieces together and see how the system will behave on the longer run using the parameters discussed in §5.4. Table 6.5 gives an overview of the parameters calculated throughout Chapter 5. The simulations will run for one full day, except for cases where more interesting things can be shown through a longer run.
Table 6.4: Influences by a change in droop coefficient: In the table the symbol ✓ points at an improved behaviour with an increasing droop coefficient, while ✗ will result in a worse performance.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Increasing droop coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power sharing</td>
<td>✓</td>
</tr>
<tr>
<td>Nominal frequency deviations</td>
<td>✗</td>
</tr>
<tr>
<td>Steady-state stability</td>
<td>✓</td>
</tr>
<tr>
<td>Small-scale stability</td>
<td>✗</td>
</tr>
</tbody>
</table>

Table 6.5: Self-sufficient grid in Burundi

<table>
<thead>
<tr>
<th>Value</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_{\text{In5yr}} ) (kW)</td>
<td>21.4</td>
</tr>
<tr>
<td>( P_{\text{BESS}} ) (kW)</td>
<td>172</td>
</tr>
<tr>
<td>( E_{\text{BESS}} ) (kWh)</td>
<td>1030</td>
</tr>
<tr>
<td>( P_{\text{PV}} ) (kWp)</td>
<td>144</td>
</tr>
</tbody>
</table>

The first analysis that will be done uses the values selected for a 100% self-sufficient case. Implications for a grid that aims to be self-sufficient are that oversized battery systems in terms of energy storage are needed in order to bridge days with less solar power, and similarly a large PV plant needs to be installed, which implies an oversized battery inverter in terms of power, in order to yield all daily needed energy in a matter of some hours, while the sun is shining. This is noticeable in the parameters selected for the self-sufficient case.

As discussed, the initial condition of a cellular grid in a developing region can be either an interconnected one, where all cells help each other out, or an individual one where every cell accounts for itself, and the Bb is only addressed in case of emergency situations. For these simulations, the first approach is adopted: all cells are interconnected at all times, thus help each other out whenever needed and possible. This makes the grid stronger as a whole, and will also optimize the amount of renewable power that can be yielded, by redistributing it. It is very important to disable the control step no charge from Bb as soon as the grid frequency reaches 50.2 Hz, since this would mean that PV power is curtailed that could have been used to charge another battery.

6.7.1. Case VII.1: Normal Day

For a first check of the grid behaviour, normal spring day will be considered, where the initial SoC of the batteries is not critical, the sun shines and all components are online. As seen in Figure 5.12 on p. 105, the solar output does not drastically change over the course of a year, so about 1000 W/m² of solar irradiation is expected, hence about 140 kW of output power during the afternoon. As explained, the battery inverter is sized to be able to yield all this power, thus greatly oversized in terms of what the load consumes.

Observations

The initial SoCs of the batteries are arbitrarily chosen to be 48%, 50% and 52% for respectively Battery I, II and III, as can be seen on Figure 6.42. From this figure, it is clear how the SoC of the three batteries equalizes after some hours. The three profiles of solar irradiation have been chosen to be three different days in March, for the sake of some randomness in the simulations. The deviation in solar output power will show what would happen in case one of the cells is equipped with a smaller PV park, or for instance a PV park that is installed in a way that it is covered by shadow for some part of the day, or that sees a less ideal irradiation angle.
6.7. Case VII: Self-sufficient Grid in Burundi

Figure 6.42: Case VII.i: SoC of the three battery systems: At the moment the batteries reach their upper limit, the grid frequency stops the PV inverters from injecting power and the battery systems start to discharge.

The load consumption for the three different loads can be shown, as well as the output power of the three PV plants. This can be seen in Figures 6.43, 6.44 and 6.45. The values on the x and y-axis of the lower figures are exactly the same as the ones that can be read from the bigger figure.

The figures show how the first PV system has a higher power yield in the morning. This is expressed in the SoC of the batteries, where we can see how the first battery charges somewhat faster than the others, until the first critical border of 70% is reached. From this moment onwards, the batteries charge up to 80% following about the same rate.

Figure 6.46 shows the reaction of the grid frequency to this SoC. As expected, the grid frequency increases drastically, in order to initialize the curtailment behaviour of the PV systems. Around 13:30, the critical value of 51.5 Hz is reached, and all PV installations immediately stop producing power. Here again, the already mentioned drawback of the VDE-AR-N 4105 scheme is clear: the PV plants are not allowed to inject any power until 50.05 Hz is reached again, which happens at 20:52, a moment when the sun has already set.

Figure 6.47 clearly shows the p.u. missed solar energy between 13:30 and sunset. The discussed continuous scheme would have used as much of this PV power as possible, as proven in §6.3.3. The benefits discussed in this section were twofold: firstly the batteries were not forced to discharge to a certain extent before the PV plant could inject power again, and on top of that less PV power was curtailed, resulting in a bigger overall yielded energy from the DRESs.

For this case, again the VDE standard and the non-standard continuous curtailment scheme can be compared. This has been done, and as seen on Figure 6.48, this results in a more satisfactory behaviour of the grid: the batteries end the day with a SoC of about 10% higher in case the continuous curtailment scheme is applied. The batteries stay around their maximum SoC for as long as the sun is shining, instead of introducing a fully curtailed state where the batteries have to supply all the power consumed by the loads.

Finally, Figure 6.49 shows the power sharing between the three inverters. At the moment the batteries have the
Figure 6.43: Case VII.i: Power consumed by the loads and injected by the DRES of Cell I: The figure shows the load consumption as expected: both Budget schemes do not use any power during the day, the consumption by the Comfort customers has got a peak during the midday and evening, and the Critical loads consume a quasi constant power throughout the day. The PV energy also runs as expected, with a sunrise around 06:00. Full PV curtailment starts around 13:30, and the PV plant is not allowed to inject any power anymore after this time.

Figure 6.44: Case VII.i: Power consumed by the loads and injected by the DRES of Cell II.

Figure 6.45: Case VII.i: Power consumed by the loads and injected by the DRES of Cell III.
Figure 6.46: Case VII.i: Grid frequency: The grid frequency climbs up to 51.5 Hz, hereby introducing PV curtailment.

Figure 6.47: Case VII.i: Potential PV power and amount lost due to curtailment: The amount of PV power in the black box is power that could have been yielded, but is lost because the PV inverters are not allowed to inject power.
Using the continuous curtailing scheme, the batteries stay at their maximum SoC until the sun sets.

**INTERPRETATIONS**

First and foremost, the simulations have proven that all the control steps can work together satisfactorily. No instabilities of any kind appear in the grid, and all reactions that are seen work as expected.

Next to this, it seems that the batteries for the self-sustainable case are rather well sized. As was seen from Figure 6.42, the SoC at the end of the simulation is approximately the same as the initial SoC, so the amount of power that can be stored in the batteries along with the amount of power injected by the PV park seem to be able to supply all the loads on the grid for a day, without the need of any load shedding. However, it has to be noticed that a sunny day was simulated, thus in case of a cloudy day, this reaction might be different.

No frequency border of any DSM shedding scheme was crossed, thus no load shedding is initialized at any point, which will result in satisfied customers.

It was seen how the PV curtailing scheme fully disconnects the PV plants shortly after midday, so at a moment when still a lot of renewable power can be yielded. However, due to the fact that the curtailing scheme needs to wait until the border of 50.05 Hz is crossed again, all this renewable power is lost here, and the batteries have to supply all the load power during this time. This reaction is then compared with a situation with the non-standard curtailment scheme, and it turns out that at the end of the simulation all the battery systems have a SoC of about 10% higher. It seems that again the continuous curtailment scheme performs in a better way than the VDE standard, though a non-accepted SSM scheme could be impossible to implement in a μG.

From the power sharing of all the cells, it was seen that initially the cell with lower SoC initially supplies the
least amount and the more charged cell supplies most. Due to this, the SoCs of all cells move together, which results in a perfect power sharing. At the moment the sun rises, it is seen how Battery I charges quicker than the other ones, because this is the battery connected to the cell that receives most power from the PV panels. Because no PV curtailment is needed yet, as seen from the grid frequency, Batteries II and III limit their charge rate.

Battery I reaches a SoC of 70% first, around noon. At this moment, its charge rate is limited, and first Batteries II and III charge to reach this 70% as well. At this moment, the batteries are not limited to charge using power coming from the backbone anymore, because the grid frequency already surpassed 50.2 Hz. Limiting these batteries to charge would result in more unneeded power curtailment.

At the moment the maximum SoC is reached, the behaviour is different for the grid using VDE-AR-N 4105 and this using the non-standard scheme: for the first one, the PV power is disconnected and the batteries start to discharge, moving towards the 50.05 Hz border, while in the latter case the batteries keep the SoC of 80% for as long as the PV power is able to supply the load power. It is only at the moment the sun has set that a decrease in SoC of the batteries is seen.

6.7.2. Case VII.ii: Cloudy Day

For the next subcase, the grid behaviour when dealing with a cloudy day will be simulated. For this, the same solar profiles as the ones for Case VI.i are used, though limited to 20% of solar input on the first day. Because the grid is oversized in terms of battery energy, we expect a situation where at least the loads with higher priority stay online.

In order to see the reactions of the grid clearly, the simulations are stretched over two days, where the first day has this limited solar output and the second day has a normal, sunny day with an abundance of solar power.
From Figures 6.50, 6.51 and 6.52, it is clear how the amount of injected PV power does not exceed 30 kW at any moment on the first day. From this low amount of injected PV power, it is expected that the batteries will not be able to reach a safe energy content during of the day, which can lead to a power deficit in the evening and night. On the second day, enough PV power is available to fill this gap again.

We can see how in the night the consumed load power drops for both Comfort and Budget customers, however the Critical processes seem to be supplied at all times.

From the figures, it is clear that indeed a certain amount of load shedding is required: both profiles of budget customers see a decrease in power they can consume, and eventually even the comfort customers are curtailed. The Comfort users are limited in terms of power usage between 22:15 and 08:30. Only at that time the batteries have been charged sufficiently using solar energy to re-enable these users. Around 10:30, all users are back online.

The grid frequency, initializing this load shedding, is depicted in Figure 6.53. On this figure it is clear how first the 49.5 Hz border is crossed, where Budget I loads are shed stepwise. A bit later, 49 Hz is reached, thus the Budget II customers start to shed smoothly. When the grid frequency reaches 48.7 Hz, also the Comfort customers are affected. The critical loads stay online.

At the end of the first day, all batteries have an equal SoC of about 10%, which can be seen on Figure 6.54. At this moment, another 5 to 6 hours have to be bridged before the sun comes up. This leads to a big shedding of the three lower priority load profiles.

From this range of simulations, it is clear that even a grid sized at 100% self-sustainability is unable to feed all the loads in case a bad solar day has taken place. The reason for this can be found in the way the ideal sizes have been calculated; if the wrong assumptions have been made concerning this matter, the grid cannot function properly. Since the values for the ideal sizes of a CSGriP cell have been calculated by a partner in the consortium, no insight in the exact methodologies exists. However, as the main interests of the thesis do not lie in sizing the grid properly, but in handing a tool that can adapt to a multitude of situations, the exact sizing is of no concern for the thesis.

As mentioned, the main aim of the thesis is to develop a controller that can adapt to a broad range of circumstances, in terms of location, loads, different types of DRESs, grid layout etc. The exact grid layout, component ratings and so further will have to be tailored for every project individually.

The simulations clearly show how both Comfort customers and even the Critical customers are affected by power outages after a day with low insolation. The Critical customers are affected during the night between the first and second day, starting around 20:00 and lasting until 8:30 in the morning; evidently, the Budget customers are affected for a longer time.

Multiple solutions for this load shedding can be thought of. Maybe the most obvious workaround would be the installation of a controllable power generating device, like a generator using diesel. This engine can then be turned on at the moment the energy is scarce, and recharge the batteries or directly supply the power demanded by the loads. The choice has to be made whether burning diesel is accepted, and to which extent load shedding can be tolerated. Also, the security of supply of diesel has to be considered, because a generator without fuel will be of no use.

Other possibilities of keeping the light on for at least a longer time are installing more storage capabilities into the grid, in order to store more energy during moments of abundance, increasing the size of the DRES plants, in order to yield more energy even with a lower energy input. It can also be argued that using a distribution of energy sources will result in a higher security of supply. For instance, if next to solar panels also a wind turbine would have been present in this case, then even during a cloudy day there would have been wind power, and also during the night the batteries would not have to supply all the load power.
Figure 6.50: Case VII.ii: Power consumed by the loads and injected by the DRES of Cell I: From the figure, it is immediately clear how low the PV power production is on the first day: the generation stays under 30 kW at its maximal point. Because of this, it can be seen how the Budget I loads disconnect and stay disconnected until the evening of the second day. The Budget II load also first radically reduces in power consumption and finally disconnects around midnight of the first day. At this moment, even the Comfort users are affected, and they come back online during the morning of the second day. The Critical users are not affected.

Figure 6.51: Case VII.ii: Power consumed by the loads and injected by the DRES of Cell II.

Figure 6.52: Case VII.ii: Power consumed by the loads and injected by the DRES of Cell III.
Figure 6.53: Case VII.ii: Grid frequency: The absence of sun on the first day decreases the SoC, thus the grid frequency, drastically.

Figure 6.54: Case VII.ii: SoC of the batteries: During the day of low power inflow, the batteries reach a low SoC. This is clearly solved as soon as a sunny day has passed.
6.8. Case VIII: Economically Sized Grid in Burundi

A solution optimized in terms of economics has been derived. This way of optimizing the grid results in smaller components than the case dealing with self-sufficiency. For instance, the battery capacity that is needed in this case is almost three times smaller, and the PV park is sized about 50% smaller. The parameters are listed in Table 6.6.

<table>
<thead>
<tr>
<th>Table 6.6: Self-sufficient grid in Burundi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
</tr>
<tr>
<td>$P_{\text{in5yrs}}$ (kW)</td>
</tr>
<tr>
<td>$P_{\text{BESS}}$ (kW)</td>
</tr>
<tr>
<td>$E_{\text{BESS}}$ (kWh)</td>
</tr>
<tr>
<td>$P_{\text{PV}}$ (kWp)</td>
</tr>
</tbody>
</table>

These component ratings will probably result in a grid with more load shedding, thus a worse PQ for the end users. However, with a lower investment for the grid, it could be possible that any fines would be paid to the customers when they face load shedding, compensating this loss in comfort.

One day with an abundance of solar power is simulated, and with batteries that are initially charged at 40%, 40% and 45%, respectively.

Observations

Figure 6.55 shows the change of SoC. As expected, overnight the SoC decreases, and it seems that the batteries discharge to about 15%, a rather low value. Figure 6.56 shows the corresponding frequency reaction: the grid frequency drops below 49 Hz during the night, initializing the curtailment of both Budget I and II schemes, as seen on Figure 6.57. Both Comfort and Critical customers receive power at all times.

Figure 6.58 shows the load consumption and PV production for the loads and PV plant connected to Cell I, and as before, Cells II and III have a similar behaviour, seen in Figures 6.59 and 6.60.

Interpretations

From the simulations it became clear that even after a sunny day a continuous power supply cannot be ensured, definitely not for the customers of lower priority. Not enough storage energy is present on the grid, introducing load shedding during the night. Also, it seems that not enough renewable power is yielded throughout the day, since the batteries do not reach their fully charged state after a full day of receiving solar power.

Apart from these deficiencies in terms of how the grid reacts as a whole, using the sizing as adopted from previous work, it can be said that again the controller itself is able to successfully perform according to the predefined requirements using what is available. The grid frequency is adapted according to what is needed, the available solar energy is yielded according to the capabilities of the BESSs, loads of low priority are shed in order to spare loads of higher priority, and the batteries are charged and used in an equal manner.

Here again, installing a controllable source of energy would help in the continuous supply of end-users — in case the installation of such device blends into the underlying philosophy of the project.

6.9. Case IX: Interconnected vs. Individual Behaviour

It can be interesting to compare the behaviour of two cells that are interconnected with this for the same two cells when they are in an individual state. As explained, the choice of which one of these states is the best will probably be a project-specific one: if for instance a second cell is installed in a village because the first cell did not suffice any longer, then it can be expected that they will be interconnected at all times. However, if one cell has been designed to power a critical load, and another cell was designed for less crucial loads, interconnecting them might interfere with the security of supply to this critical load.
Figure 6.55: Case VIII: SoC of the batteries: The batteries follow the same charge and discharge regime, and reach values at which load shedding will have to be initialized.

Figure 6.56: Case VIII: Grid frequency: Due to the fact that the battery SoC drops to near-critical values, the grid frequency drops as well, introducing load shedding.
It is this second scenario that will be looked into throughout this section. For the case, two cells have been designed, where Cell I supplies a village with Budget and Comfort customers, and Cell II was designed for powering a hospital. The ratings of the components used for the village have been based on the economic scenario, while the cell for the hospital is built with self-sufficiency in mind. Relevant parameters are shown in Table 6.7.

The simulations will start with a SoC of 40% and 50% for the cell connected to the village and the hospital, respectively. The simulations run for 48 h, and the first day is one of low solar irradiation (20%), while the second day has an abundance of sun.

<table>
<thead>
<tr>
<th>Value</th>
<th>Village</th>
<th>Hospital</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design</td>
<td>Economical</td>
<td>Self-sufficient</td>
</tr>
<tr>
<td>( P_{\text{in3yr}} ) (kW)</td>
<td>17.8</td>
<td>6</td>
</tr>
<tr>
<td>( P_{\text{BESS}} ) (kW)</td>
<td>71</td>
<td>48</td>
</tr>
<tr>
<td>( E_{\text{BESS}} ) (kWh)</td>
<td>375</td>
<td>290</td>
</tr>
<tr>
<td>( P_{\text{PV}} ) (kWp)</td>
<td>60</td>
<td>40</td>
</tr>
</tbody>
</table>

**Observations**

To start, both cells are interconnected and sharing power according to the predefined control strategy. This means that the cell with the highest SEP will supply more load, and also the cell with a higher power rating will deliver more power, a result of the equal relative droop coefficient.
Figure 6.58: Case VIII: Power consumed by the loads and injected by the DRES of Cell I: The figure shows how the PV plant is able to reach full output power due to the abundance of sun. However, before the sun comes up, the power of Budget I appliances is cut off, and also Budget II customers are required to consume less power starting around 05:00. Due to the fact that the sun is sufficiently present, the Budget customers can consume power again in the night, however around 21:40 Budget I is cut off again, and later in the night also the power that can be consumed by the second Budget group is decreased. Comfort and Critical users do not notice this.

Figure 6.59: Case VIII: Power consumed by the loads and injected by the DRES of Cell II.

Figure 6.60: Case VIII: Power consumed by the loads and injected by the DRES of Cell III.
Figure 6.61 shows the change of SoC of both cells: it is clear how the batteries quickly equalize in terms of SoC, which means that the power delivered by the components indeed matches the SEP of both cells: the cell belonging to the hospital has a smaller BESS and a lower rated inverter, and its SEP moves towards this of the village-cell.

From Figure 6.62, it is clear how the power supplied by the inverters and demanded by their proper loads look. The village has a higher power consumption than the hospital, and it is noticed how the inverter designed for the hospital delivers more load than what is needed from the hospital, hereby supplying power to the village. This is not interrupted by any control step, since the controller of the hospital’s cell does not know where this power goes to, and the batteries of the cell installed in the village do not charge using this received power, thus they do not interrupt it.

Figure 6.63 shows the amount of load that was shed in the grid. It is clear that after the low solar day, a lot of shedding is needed, even the Comfort customers are shed for more than 60%. The Critical load, however, is not shed, but judging from the SoC of the batteries, the limits are in fact not far from being reached, falling below 10%.

Secondly, the same case is simulated, but in a situation where both cells are decoupled from each other. As can be expected, this yields a completely different behaviour, since the µGs have interactions anymore.

If the SoC of both battery systems is compared, it is clear how the Hospital’s cell never really reaches a dangerous situation, having still 30% SoC after a full day of low solar input. This is seen from Figure 6.64. The village, however, reaches a critically low SoC and a big number of loads need to be disconnected, as seen from Figure 6.65.

Because of the fact that no help is received from the second cell, even during the first day Budget I devices have to be disconnected. Because this preserves a bit of energy, during the second day the Comfort customers are affected less, though still significant load shedding is needed, with a ratio up to 50%.

Figure 6.66 shows a completely different image than what Figure 6.62 showed previously. It is seen that the inverter of the hospital now only accounts for the load the hospital consumes, and not the load of the village.
Figure 6.62: Case IX: Power consumed by the loads and delivered by the inverters - Connected: The upper figure shows the inverter and load of the village, while the lower figure shows the values for the hospital. It is clear how the inverter of the hospital delivers more power than needed, helping the cell of the village.

Figure 6.63: Case IX: Shedding factors for Budget, Comfort and Critical users - Connected: Because of the day with low irradiance, a considerable amount of load shedding is needed.
no longer. This is also noticed from Figure 6.64, where it is seen that the SoC of the hospital-battery ends the simulation with a very high value.

**Figure 6.64: Case IX: SoC of both battery systems - Disconnected:** While the SoC of the battery connected to the village reaches dangerously low values, the hospital battery resides in comfortably high regions due to the oversized battery energy and solar power.

**Interpretations**

The simulations showed drastic differences between both cases. This proofs that a very well-thought consideration has to be made in the choice whether or not cells will be interconnected in normal operation. It was seen that a cell that has been designed in a very safe way, thus for supplying its end user as long as possible, can actually jeopardize the operation of its load by helping out less-important loads. If cells are interconnected, the grid as a whole becomes stronger, however on the individual scale one cell can tear down another one.

It is clear that the philosophy of the controller, this is sharing active power according to the SEP and the inverter rating, is not the ideal philosophy in all cases. In this case, for instance, this behaviour can be unwanted, as the reason for installing a cell for the hospital was to have a higher certainty of supplying power to this hospital, not to share power with the village.

One recommendation for future work in this sense can be to include a decision making step in the controller that actually can control the switch to the Bb, and judging on the state of the cell decide to connect or disconnect to the latter.

**6.10. Case X: Microgrid in the Netherlands**

The previous sections have made clear that the grid is able to work satisfactory in a non-electrified, rural region. It is indeed possible to place a $\mu$G, connect some DRESs and loads to it, and make it work according to predefined requirements.

A second possible implementation of the $\mu$G is this were a cell is installed in a readily electrified location. At this moment, the grid will have to blend in, and its main tasks can be expected to become completely different: since the main grid in western countries has a very high availability, the main task of the $\mu$G will not be to guarantee power supply to end-users. On the other hand, the grid could be used for economical purposes, by selling energy at moments it is expensive, and buying it again when it is cheap. Another possibility is a better
Because of the fact that the cell connected to the hospital does not supply power to the village, Budget users are shed earlier.

It is clear how now the cell of the hospital, depicted on the lower half of the figure, only supplies power to what it was initially designed for.
way of interfacing renewable energy sources with the grid, potentially maximizing their energy yield. Furthermore, the cell can be exploited as a peak shaver, in order to avoid, delay or minimize any investments to the grid.

These different tasks will not be discussed in this chapter, as the development of a controller able to perform like this was not the concern of the thesis. On the other hand, it can be argued that if the main grid would stop working at one point, the µG should be able to take over the power supply to the loads, making sure that the end-users are not affected by this power outage in a higher located grid.

It is this task that will be discussed in this last section. For the simulations, a main grid will be present, showing how the non-adapted controller reacts to the presence of a much stronger grid, which in the view of the µG can be described as an infinitely strong cell. The µG will not be able to influence the grid frequency, for instance, but this is not a problem as all the power can be supplied or absorbed by the main grid. It will be shown how the µG, thanks to its drooping behaviour, can be interfaced with the main grid while still working in VSI mode, thus no switch to a CSI controlled inverter is needed.

As mentioned in § 5.2.5, in case of the Netherlands it can be useful to complement solar with wind energy, therefore this will be done throughout the simulations. For the simulations, the production of wind and sun on a day in March are used. The initial SoC of the battery can be 45%. The main grid will be available at the beginning of the simulation, but around 02:00 in the night an event takes place and the main switch of the µG is triggered: the grid goes into islanding mode. The simulations will show whether the µG can successfully supply all loads until the evening, thus whether the end-user notices this change. Reconnection of the grid is not considered since this would need a synchronizing control step, viz. a synchroscope, a feature that is not present in the controller.

The scheme for DSM that will be applied during the simulations was discussed in § 5.1.3, and in order to comply with the grid standards the DRES curtailment scheme will be the standard one of VDE. The grid layout is the one depicted in Figure 5.9 on p. 102. The grid is sized according to the parameters deducted in the previous chapter, shown in Table 6.8.

<table>
<thead>
<tr>
<th>Table 6.8: Absolute Values Netherlands</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
</tr>
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<td>$P_{in5yrs}$ (kW)</td>
</tr>
<tr>
<td>$P_{BESS}$ (kW)</td>
</tr>
<tr>
<td>$E_{BESS}$ (kWh)</td>
</tr>
<tr>
<td>$P_{PV}$ (kWp)</td>
</tr>
<tr>
<td>$P_{wind}$ (kW)</td>
</tr>
</tbody>
</table>

6.10.1. CASE X.1: SUFFICIENT RENEWABLE POWER

The first simulation takes place a sunny and windy day in March. Because of the abundance of input from both renewable energy sources, no problems in supply are expected.

Observations

Initially the µG is connected to the much stronger main grid. This means that the grid frequency is dictated by this main grid, keeping the frequency at 50 Hz. This is seen on Figure 6.67, for the first two hours of the simulation. At this moment, $t = 2$ h, something happens on the main grid and the µG is disconnected promptly, entering the islanding state. From this moment onwards, the grid frequency is governed by the µG itself, thus with a change in SEP a deviation from nominal frequency will be introduced.

The figure shows how from this moment onwards, the grid frequency drops slowly to about 49.8 Hz, before it climbs up again. The reason for this can be found in the SoC, which initially decreases and then from 19:00
onwards increases again, as seen on Figure 6.68. This, in turn, is due to the renewable energy output, that at the beginning is not able to supply all the load power, requiring the BESS to provide the rest of the power, and then increases and charges the battery system. This behaviour is plotted on Figure 6.69, showing the power consumed by the households and supplied by the renewable plants. The power from these DRESs is plotted separately in this figure, too, showing how the wind intensity increases over the day, and the sun clearly follows the well-known daily solar curve.

![Figure 6.67: Case X.i: Grid frequency](image)

It is clear how the grid frequency does not deviate from 50 Hz as long as the main grid is connected. However, at the moment the main grid fails, and the microgrid is responsible for the frequency again, deviations are seen due to changes in SoC and delivered power. The grid frequency never crosses 49 Hz, the point where load shedding is introduced according to UFLS. Due to the fact that the grid frequency does not fall below 49.8 Hz, and consequently stays far away from the 49 Hz where the UFLS scheme starts, the latter is never activated. This can be seen in Figure 6.70, showing the power consumed by the loads, from which it is clear how no load jumps are introduced.

**Interpretations**

The simulations have shown that the controller is able to be interfaced with the main grid without any adaptations. From the figure depicting the SoC, it can be deduced that the battery system tries to reach 50% SoC. This is a value that could be expected by the way the value for $f_0$ is calculated: this setpoint reaches 50 Hz exactly at a SoC of 50%, so as long as the battery system does not reach this value, it will either demand or supply power to reach this state. The $\mu$G interprets the presence of the main grid as being a very strong, other cell, with zero droop and with a SoC that requires it to work at 50 Hz.

This way behaviour is a relic of the controller for non-electrified regions, and it can be discussed whether this is a good or a bad behaviour. Maybe it is desirable that the SoC normalizes to 50% whenever the grid is present, maybe another SoC is preferred, depending on the wishes of the project the answer to this can alter.

The main point of interest is what happens with the $\mu$G after the moment the main grid has been disconnected. The simulations show that the behaviour is as expected: the DRESs are able to supply enough power and the battery covers the rest, the grid frequency is adequately adapted, and the loads consume the power they need.
Figure 6.68: Case X.i: SoC of the battery system: From the figure, we can see how the battery tries to reach 50% while the main grid is available. At the moment the main grid goes offline, the battery starts to receive and supply power according to the balance between load and DRES. The battery never discharges below 30%, so no load shedding seems to be necessary.

Figure 6.69: Case X.i: Power consumed by the load and delivered by solar panels and wind turbine: The consumption from the combined load follows the well-known behaviour as this is known in a developed grid: a base load during the night, a small peak in the morning and a bigger peak in the evening. The DRESs inject power according to how much sun and wind is available, resulting in a rather random power injection.
As expected, all loads follow the same profile. It has to be noticed that the synthetic load profiles use heavily averaged data, so in fact the load consumed by Customer I or Customer IV will not follow this smooth flow. However, together with the apartment block and the other consumers, the load consumption will be averaged out and all together the load profile will match the one depicted here. It is clear that no load jumps are needed because no critical grid frequency is reached.

No load shedding is needed because no critical states are entered. The grid frequency reaches 49.4 Hz at its minimum point, being still far away from the moment where load shedding starts, 49 Hz.

\textbf{6.10.2. Case X.ii: Not Enough Power from DREs}

It is always possible that the grid goes off on a cloudy and non-windy day. In this case, it can be expected that load shedding will be needed in order to not fully drain the batteries. Certain loads will be switched off, irrespective of any possible priority settings, since this is not included in the UFLS. It will furthermore not be commented upon which loads switch off, it is merely assumed that it is possible to switch off 5\% load at the moment this is needed according to the scheme.

For this case, a day with only 70\% of wind and 20\% of sun compared to the previous day is considered. This means that a big part of the power consumed by the loads will have to be supplied by the battery system, which in turn results in a lower running SoC, hence potential load shedding. The initial SoC of the BESS stays the same as the one for the previous subcase, and also the grid parameters do not change.

\textbf{Observations}

Figure 6.71 shows the amount of load demanded by the grid and renewable power supplied by the sources. It is clear that for a big part of the day, the load demand is bigger than the energy supply, leading to a drop in SoC, as seen in Figure 6.72. Because of this radical drop in SoC, reaching a value of less than 5\%, the frequency drops significantly, just not reaching 48.2 Hz, as seen on Figure 6.73. On this figure, the different steps of load shedding are indicated, and it is noticed that 5 steps of load shedding are activated. The fifth step, as mentioned before, introduces 25\% shedding.
Figure 6.71: Case X.ii: Power consumed by the load and delivered by solar panels and wind turbine: The figure makes clear that the amount of power input from the DRESs is in fact smaller than the power that is demanded by the loads. The battery system will have to supply this power and consequently the SoC will decrease.

Figure 6.72: Case X.ii: SoC of the battery system: Initially, as long as the main grid is present, the SoC tries to reach the value of 50%. At the moment the grid trips, the battery system has to supply power to keep the loads running, hereby reaching the critical state of charge of less than 5%. At that moment, enough load has been shed and enough renewable power is injected in order to recharge the battery.
The grid frequency again follows the course of the SoC, indicating that a potentially dangerous situation is upcoming. It takes until around noon before the 49 Hz border is crossed, where the first load is shed. From then until 19:00, 4 more load shedding steps are initialized.

The amount of residual load after shedding is depicted on Figure 6.74. We can see that 45 minutes past noon the first shedding step is activated. If we now refer to Figure 6.71 again, it is clear how at this exact time a small step is visible in the load consumption, pointing at 5% of the total load consumption that is disconnected.

At a certain moment in the evening, the injected power starts to exceed the power demanded, so the batteries are able to recharge. In turn, loads are allowed to reconnect to the grid one by one, as seen on Figure 6.74.

**Interpretations**

From the simulations, and in fact also from some common sense, it is clear that a day on which the power consumed by the load is bigger than the power supplied by the DRESs will trigger the battery to supply more energy and hence potentially drain its charge rate. Because of this, it seemed that the frequency decreased thus low that load shedding was required.

It is known that the load shedding scheme applied in this case, the UFLS, is a scheme that has been developed for application on the main grid, where load powers reach values of multiple GWs and are separated in terms of villages, not households, and the power is supplied by means of centralized, controllable plants. The UFLS is optimized for this situation, by decreasing the load on the grid with 5 - 10% only at crucial moments, when the grid frequency reached 49 Hz: an abnormal situation in the main grid. The abnormality of these situations is also expressed in the end point of the UFLS: at 48 Hz, the last shedding step, still 50% of the load is connected to the grid, which points out the belief that a situation more severe than this will never take place.

In the μG supplied by merely uncontrolled DRESSs, however, the situation looks drastically different. It is hard to disconnect 5% of the load from a μG, since it is not known which load has to shed, according to which priority, there is no certainty that this effectively happens ... It is unclear how the implementation of a 5% load shedding step would be put into practice.

Furthermore, since the grid is supplied by uncontrollable power sources and a battery, the possibility of
Figure 6.74: Case X.ii: Amount of residual load after shedding: The figure shows how much load is still present on the grid after the load shedding has been introduced. We can see that, as implemented, load is shed in steps of 5%, and that at the maximum point about 25% of the load has been disconnected.

running out of power clearly exists. This needs to be addressed by the load shedding scheme, prioritizing loads and shedding the lower priority ones in order to preserve more important loads. Depending on the types of loads that are connected to the grid, probably less than 50% of load will still be connected at the moment the grid is in a critical condition.

The simulations showed how still 75% of load is present at the moment the battery SoC reached less than 10%. The result of this is twofold: on the one hand it means that less users will be affected, which is definitely a big advantage in a developed world. On the other hand, this means that critical loads will run into problems faster, as the battery is drained more quickly and as a result 0% SoC approaches faster. It can be argued that the main grid will probably never be unavailable for this long time (here it is unavailable from 02:00 onwards), so that these problems might never manifest themselves in the real world.

By altering the calculation of the $f_0$ setpoint depending on the SoC, the speed of load shedding can be increased. This would involve a frequency setpoint that drops faster with a decrease in SoC, or has an earlier tipping point. This, in turn, will lead to more affected end-users but a longer security of supply, for those still connected.

Another characteristic that can be changed this way is the SoC that the battery system tries to reach at the moment it is grid connected. Because the grid dictates a frequency of 50 Hz at all times, the battery moves towards the SoC at which it can set this 50 Hz as well, without supplying any power. In the current scheme, this is 50%, but depending on the preferences of the project this value can be something else.

It can be argued that the UFLS scheme is no longer required in the $\mu$G at the moment it has been disconnected from the main grid, since the UFLS is a standard which has to be complied to in order to be allowed to be connected to the grid. However, at the moment the main switch tripped, the $\mu$G is no longer connected to the main grid, but stands on its own. Thus, a certain mechanism could be provided, which activates the UFLS at
the moments the $\mu$G is in grid-connected mode, and the frequency deviations are introduced by the main grid, and activates another shedding scheme when the islanding mode is activated. This proposal will not be investigated further.

Summarizing, the case study has shown that even though the controller works for a grid in a developed region, it is certainly not optimized for it. The $\mu$G can be implemented into the main grid without adaptations, but it is clearly working ideally. A controller that avoids using ICT equipment can effectively keep a $\mu$G running, at least for a certain amount of time, in case the main grid runs into problems, but that certain behaviours and parameters of the grid have to be selected with more care in order to get better results.

Furthermore, as mentioned the $\mu$G could be able to fulfil fruitful tasks in the main grid in case it would be really considered to implement it like this, because the availability of the main grid as we currently know it is thus high that implementing a $\mu$G only for the sake of continuous power supply needs very crucial loads in order to be economically justified. The development of a controller that aims at performing tasks like these is out of the scope for the thesis.

### 6.11. Summary of the Chapter

The chapter gave an overview of the results that have been attained from running the previously defined case studies. The main conclusion can be that the different control steps effectively lead to a desirable grid behaviour, where it was proven that omitting one of the steps leads to certain drawbacks.

A grid where no DSM or SSM are present was shown to lead the battery to a state of minimum or maximum state of charge, without reaction. If however both DSM and SSM are present, reactions of the loads and DRESs are seen, according to what is expected.

Certain drawbacks were defined concerning the use of standards of the current grid, like the UFLS or the VDE-AR-N 4105.

The ultimate simulations, this of the developing grid and the developed grid, showed the expected reactions.

*After a quick discussion of the results obtained in this chapter, the next chapter will discuss the results more deeply and thoroughly.*
**DELIBERATIONS AND RESERVATIONS**

In the last chapter, the results that were obtained from running the simulations have been shown, and every case was accompanied with a discussion. The main points of interests of these passages will be recapped here, matching the outcome of the analysis to the research questions that were defined in § 1.2.1.

These research questions can be quickly reviewed, and the process as a whole will be measured in terms of whether the objectives have been achieved.

1. How should a $\mu$G be implemented, in order give a cell the capability of influencing the grid frequency for the sake of control, hereby capable of working in both islanded and interconnected mode?
   
   (a) What are the potential drawbacks of the ICT-less structure?
   
   (b) How can the system be implemented in a way that it can work both independently and interconnected with other cells?
   
   (c) How will active and reactive power be shared among different cells?
   
   (d) How can the system’s stability be guaranteed?
   
   (e) Can multiple cells with a different interest in setting the frequency work together?

2. Can DSM and SSM be performed on a cellular $\mu$G, energized by a BESS, only using frequency as an input signal?

   (a) Is the controller capable of changing the frequency as a function of its SEP?

   (b) Can the loads and power sources effectively change their behaviour according to the frequency?

   (c) Do the DSM and SSM reach their initial goals, preserving a longer stability of the grid?

7.1. **CONTROLLER OF THE MICROGRID**

The first conclusion that can be drawn is the fact that the ultimate controller is effectively able to run a cell, independent of whether the cell is interconnected with other cells or not. It was also shown that the controller does not have problems with a grid connection. The frequency is indeed a function of the SEP of the grid, and multiple cells are capable of collaborating without the need of explicit communication.

7.1.1. **REPRESENTATION OF THE GRID THROUGH THE FREQUENCY**

It could be seen that the grid frequency effectively changed when needed, i.e. at the moments when the SEP reached critical values. The most clear representation of this behaviour was seen in Case I, § 6.1, where the grid frequency skyrocketed at the moment the SoC reached critical levels and still renewable power was injected into the grid, and the frequency abated drastically when the SoC fell below a certain value and still a big
amount of consumption was present.

The simulations where multiple cells were interconnected showed how also in this case the grid frequency represents the combined SEP of the cells. This behaviour has been shown throughout § 6.2. In case all the cells are in a similar state, the definition of the grid frequency occurs according to what it would be in case these cells would be combined into one large cell. In case the cells are in a drastically different state, for instance one cell is critically undercharged, then also the grid frequency represents what is going on on the grid.

This means that in case both strong and weak cells are powering the same grid, the eventual grid frequency represents the share of strength and weakness present on the grid.

In the mentioned section, also the behaviour of the schemes that prevent a state of overloading of the inverters, or charging one of the batteries from another cell, has been shown. The influence of these schemes on the ultimate grid frequency is considerable, because these schemes actively increase or decrease the grid frequency according to predefined requirements.

The ultimate influence on the state of the grid as seen by the end-users by reading the grid frequency can be minimized by the application of measures like an anticipatory frequency check. The control step that prevents charging from the backbone will first read the grid frequency, and judges whether the grid is allowed to charge from the Bb or not using this frequency. If it is noticed that the grid frequency already surpassed the limit where DRES curtailment starts, then the battery should not be prohibited to use the excess power to charge.

Overall, it can be concluded that the grid frequency effectively represents the SEP of the cells, regardless of the fact that one cell is powering the grid or multiple cells are in charge.

Some drawbacks have to be accepted when dealing with a grid like this. For instance, huge deviations of the nominal frequency can occur, for instance when the batteries reach their upper limit the frequency can climb up to 51.5 Hz, and when the batteries are almost depleted, the frequency drops as low as 48 Hz. It is clear that a grid without ICT equipment is capable of powering end-users, though with a lower PQ than what might be considered as normal today. Thus, if in a situation where the cells are installed the possibility of ICT equipment would exist, it is important th realize that the performance will be better by applying this. Subsequently, the methods proposed throughout this thesis will then be activated at the moment the ICT equipment would drop away, ensuring the grid to stay powered.

7.1.2. Intracellular Behaviour

From the simulations, it became clear that a desirable intracellular behaviour was obtained using the controller. Thus, even without the application of dedicated communication structures, a cellular μG is capable of sharing power.

Multiple cells are capable of working together, feeding one and the same grid. A mutual frequency output is found by using the dynamics of the droop curves: at the moment the power output of one of the inverters changes, its frequency setpoint shifts according to the droop curve, which in turn influences the power that flows between both inverters as seen from the equations describing power exchange between two sources. Because of this, an ultimate common grid frequency is found, which then indeed represents the SEP adequately.

The discussion about whether or not to interconnect multiple cells has been opened. It is seen that if cells have been designed with a different philosophy, interconnecting them could jeopardize the initial goals of the cell.

It was noticed that certain trade-off’s will be needed when deciding upon the ultimate parameters of the grid. For instance a smaller gain value, thus less steep droop curves, leads to a system with lower deviations from the nominal grid values in normal operation, though the performance of the active power sharing between cells is lower. Nonetheless, this can have advantages, because the stronger cell will always supply the biggest part of the power to the loads, and the weakest cell will be supported as much as possible.

However, the question arises until which extent this weaker cell should be supported; it becomes problem-
atic at the moment when the battery system of a weak cell is starting to be charged using energy coming from the BESS of a strong cell.

One of the issues of main importance that still reside is this of the small-signal stability. As mentioned, studies in this field have been carried out, though no analysis has taken place on the grid that was studied for the thesis. Results for a similar grid show how the relative droop coefficient should not surpass a certain value, corresponding to a sufficiently low gain, though a limited set of simulations has shown that even using a higher value for this gain still results in a stable grid response.

The results of this, however, should not be taken without any further thought, this for multiple reasons. For the sake of not triggering any instabilities in the simulations no changes in load consumption or PV injection, gradual nor stepwise, were present. This means that the system stability in fact was never put to the test. Furthermore, it can be that the way of running the simulations, by calculating the RMS values, omits fast switching transients and consequently fails at recognizing instability issues.

Overall, it was seen that multiple cells can work together in a desirable way. Although power sharing is maybe not perfect at all times, and inverters are prone to be overloaded at certain moments, due to a big difference in the spacial location of the droop curves, measures can be taken to solve these problems and make the grid work satisfactorily. A bigger value for the droop coefficient will lead to a better sharing of active power, if desired. A smaller droop value yields a system where the interaction between different cells is even more distinct, as the stronger cell will very clearly supply the biggest share of active power, and the weaker cell will only take a small part, ultimately even receiving power if the limiting step is omitted.

Reactive power, on the other hand, is not shared perfectly, as expected. The reactive power droop curves are influenced by voltage drops along the lines, thus are incapable of reaching the same performance as the active power sharing scheme using the grid frequency, a global variable. On the other hand, it can be argued that as long as the inverters are not overloaded, there is no significant problem in the ineffectiveness of reactive power sharing, as it does not jeopardize the system stability on the longer term in any way.

Furthermore, it was noticed that the system that is supplying the biggest amount of active power was delivering the smallest amount of reactive power. This way an equalizing effect on the apparent power output of all systems can be obtained. The reason for this can be the fact that a bigger active power output points at a bigger current flowing out of the inverter, which results in a bigger voltage drop along the resistive lines, hereby having an influence on the reactive power sharing scheme. Taking this into account, it could maybe be seen as an advantage to not reach perfect reactive power sharing. However, this has not been investigated into detail.

7.2. POTENCY OF DSM AND SSM

The necessity of both DSM and SSM have been clearly demonstrated by means of the simulations where these interventions were not present. This led to a situation where either the battery was fully charged, not taking into account the limits in SoC that are defined in order to achieve a good lifetime, or at the other side batteries that are fully discharged without any reaction from the grid.

At the moments when both DSM and SSM schemes were present, however, the expected reactions are seen. Power coming from distributed sources is effectively curtailed when the state of charge of the battery system reaches critical values, and also certain loads are shed when the SoC drops too low.

One shortcoming of the simulations is the fact that shifting loads have not been included. These loads, in general disposing of an inherent buffering mechanism, should be activated at the moment a state of over-charging is upcoming: this way power curtailment can be limited by using the power for a useful goal.

Two ways of DRES curtailment have been discussed, (i) the standard scheme, called VDE-AR-N 4105, and (ii) a non-standard approach, of which the benefit is that no redundancy is present. It is known that the standard scheme disconnects the DRES from the grid at the moment the grid frequency surpasses a certain value, and
does not allow any further injection of power until the grid frequency dropped below a threshold again. The reason for this is that the scheme originates from the main grid, where frequency deviations mark problems on the grid, and the grid should not be burdened any further by these DRESs.

However, since the rationale of the µG is of a complete different kind, the standard scheme does not behave optimally for this project: since the SoC directly influences the grid frequency, the standard scheme introduces a behaviour where the batteries have to discharge until a certain extent before distributed power is injected again. This means that, for a given amount of time, renewable power is stopped from entering the grid, while power has to be supplied coming from the battery system.

This problem is solved by the application of the non-standard scheme, where no triggering point of completely limiting the power injection exists. A system using this non-standard scheme finally reached a balance between injection of renewable power and load consumption, in case the batteries are nearly full. It can be concluded that this scheme in fact offers a better behaviour, but that probably the standard scheme will have to be followed in case the µG has to be interfaced with the main grid.

When it comes to load shedding, two different approaches have been defined. Firstly, there is the UFLS, a standard scheme that was with the common grid in mind, and secondly the individual reaction of loads has been proposed, like a modulating or a stepwise behaviour, depending on the type of load that is dealt with.

A shortcoming of the UFLS is the fact that it does not take into account the possibility that a grid is being supplied using a battery system solely, so a grid where no power sources can be actively controlled. This can be observed considering the fact that even in the most extreme case of load shedding, still 50% of the loads are connected to the grid. Furthermore, since the scheme was defined for a large grid, where big groups of end-users form clusters, steps in load shedding between 5 and 10% are proposed, which then comes down to tripping certain well-defined switches on the grid, hereby blacking out whole regions.

The way this load shedding in steps of 5 to 10% would be implemented in practice in the µG is unclear. On the contrary, the concept of dividing loads into priority groups and shedding them according to certain physical characteristics, such as the possibility of modulation or the presence of residual power demand after shedding, is tangible and probably easier implementable into a real-life situation.

It can be concluded that both DSM and SSM work effectively, and both schemes only need the grid frequency in order to perform. However, the application of schemes that were designed with the common grid in mind do introduce certain drawbacks or deficiencies into the grid.

The choice whether the standard schemes should be chosen or diverged from will probably be a project-specific one, in which both the end-responsible of the grid and the eventual grid operator should have their say.

### 7.3. Summary of the Chapter

The chapter quickly revised the research questions that were defined for the project, and it was discussed whether they have been answered adequately throughout the thesis process.

It was seen that both questions were positively answered; it is possible to manage a µG solely using readily available grid parameters, thus without using communication equipment. The grid frequency can decently represent the state of the grid, and this can in turn be used to activate certain features in devices connected to the grid, such as DSM and SSM.

Some questions have not been answered, where the ones of main importance are how the dynamic stability of the ultimate system can be ensured, and whether grid standards should be applied with all the associated consequences or these standards should be turned away from. Choosing to turn away from these standards proved to be beneficial, but it is unclear what exactly the requirements would be in a real world situation.

The discussion has lead us to some interesting insights. The most interesting outcomes of the project will be summarized in the next chapter, the Conclusions. Furthermore, some other information about side projects will
be presented, as well as proposed future work to take the results of this thesis further in the future.
CONCLUSIONS & FUTURE WORK

After the discussion that took into account the results obtained from the simulations, finally some conclusions can be drawn. After this has been done, some proposals will be made of which work should follow up this thesis, and it will be quickly mentioned what other work within the CSGriP project has lead to.

8.1. CONCLUSIONS
The main aim of the thesis was the development and verification of a control structure that is capable of performing the requirements as set by the project description.

For this, a controller had to be designed, capable of running a μG in both islanded and interconnected mode, and eventually offering the possibility of connecting to the main grid. No restrictions should be present in terms of which loads can be connected to the μG, or which sources of power should be used. The μG is required to work in a decentralized mode, thus the usage of ICT equipment should be avoided as much as possible. This is, ICT equipment can be present, though should not be necessary to run the grid. In order to reach this, readily available grid parameters, being the frequency and voltage signals, should be deployed to ensure basic communications between components. The concept needs to be modular, so it should be possible to add and subtract cells to ones liking, without having to change any parameters. The controller shall be made with a philosophy that allows the addition of new extensions or features in the future.

In order to ensure a satisfactory behaviour on the long term of a grid only supplied by uncontrolled power sources, DSM and SSM have to be present, introducing the act of load shedding and DRES curtailment.

From the simulations, it is shown that a controller that is able to fulfil all the listed requirements has effectively been developed during the course of the project. The control strategy that ensures this is the droop control, which is a control method that is also employed in the main grid. In essence, it boils down to the fact that the grid frequency or voltage set on the grid depend on respectively the active or reactive power that has to be delivered. By means of dynamic interactions between multiple sources, this scheme is effectively able to reach a stable working point.

On top of this droop control, certain other factors of interest are taken into account. One of them is the SoC of the battery system, a state that clearly has its influence on the upcoming behaviour of the grid. In case the SoC decreases to a certain extent, this is noticed in the grid frequency, alerting the demand side that problems could be upcoming. Similarly, if the batteries are charged completely, the supply side will know because of a drastic frequency increase.

Next to this influence, other frequency-influencing control steps are needed for reaching a satisfactory controller reaction, such as a damping scheme and a step that avoids overloading the inverter.

In terms of load response, two different approaches were discussed. The first approach was based on a standard scheme, the UFLS, which is the currently applied load reaction in the main grid. Shortcomings were noticed,
since the standard has been designed with the main grid in mind, not a \( \mu G \) that is limited in for instance controllable power resources.

Secondly, there were the individual load responses, such as an on/off scheme, or a modulating load reaction. Since the response of these schemes can be tuned to one's liking, according to specified requirements, the response of the grid with this scheme applied can be called superior.

Also for the supply side management, a standard and a non-standard scheme have been discussed. It was clear that the main drawback of the standard scheme lies in the fact that the power source is required to disconnect at the moment a certain grid frequency is surpassed. This leads to a situation where stored energy and valuable battery cycles are being used while the power coming from the DRES is being curtailed.

Better reactions could be seen from using a non-standard scheme, where this requirement of disconnecting the DRES for as long as the grid did not normalize is not present. It was seen that less power curtailment is seen when this scheme is applied.

Connection to the main grid has been discussed, though no economical case exists for the uninterruptible power supply characteristics that were discussed throughout the thesis. It would be interesting to offer lucrative features to the grid by using the battery storage system, for instance black start capability, primary control reserve, or peak shaving. However, since this was out of the scope, a controller for this has not been designed.

Overall, it can be concluded that throughout the thesis, the basic control concepts that were defined have been proven to work, with some necessary adaptations every now and then. It is seen that applying this controller has some drawbacks in the grid performance. As an example, the grid frequency and power coming from the Bb are used in order to determine whether the battery is charging from another battery, or from the DRESs of another cell. This mechanism would perform much better in case an amount of data exchange would be allowed.

It has been mentioned that the grid, in a real life situation, would not be required to work in an ICT-less scheme all the time. The concepts that have been defined throughout the thesis show that a cellular \( \mu G \) is capable of working without ICT equipment, though in case this equipment is available, the overall performance will be better.

### 8.2. Future Work

One part that can be improved is the dynamic stability analysis of the \( \mu G \). In this work, a preliminary study based on previous work has been presented, though it would be interesting to study the exact \( \mu G \) this way. From this analysis, the chosen value for the droop coefficient can be optimized.

Next to this, the presence of virtual inertia on the grid has not been studied thoroughly. From the case studies, it was seen that a small verification of a model with a first order filter, acting as virtual inertia, has been performed, though in order to make real conclusions this needs to be taken further.

Building upon this point, inertia can also be added to the grid by means of a physical device: a synchronous or an induction generator. Of course, more important than adding inertia to the grid, these devices would give the grid operator the possibility of increasing the security of supply to end-users, by using fuel to power the grid in case the battery energy would prove insufficient.

Also the reaction of any dynamic loads, or a wind turbine that is interfaced with the \( \mu G \) not by means of the AC-DC-AC step but in a way that passes on its inertia to the grid, will be interesting to investigate.

Another important improvement to the model will be the inclusion of the synchroscope, as will be discussed in the next section. This addition to the controller would allow cells to switch between stand-alone and interconnected mode, according to predefined requirements. For instance, cells can be required to be islanded when their SoC is non-critical, and make a connection when a critical state is reached. For this, a control logic that makes this decision needs to be developed. The inclusion of this step would then lead to a better
implementation of the control step for limiting overloading of the inverters.

8.3. Concurrent Research
Simultaneously to this thesis, other research was carried out on similar topics, within the CSGriP project. Interesting insights of these research projects can be shared.

As mentioned in the previous section, one of the tasks was to develop a synchroscope, a controller that enables a two cells to make a connection, or to safely disconnect. This is done by matching the grid voltage amplitude, frequency and the phase angle, influencing the setpoints of the controller. The controller has been developed, based on a basic model that was similar to the one used in this thesis, and has to be merged.

Another research topic is the optimal sizing and exploitation of a CSGriP cell. Using the mathematical programming tool GAMS, a method is being developed that enables the optimal control of a CSGriP cell, not only using the SoC of the battery but also taking into account actual prices of power, weather predictions . . . in order to reach an optimal working point, where no load is shed in case the weather forecasts say that there will be an abundance of energy from the DRESs, for instance.

As discussed in this thesis, another side project was the investigation of adding a virtual inertia to the $\mu$G. The outcome of this work shall be introduced in the base model, which then will allow the end-user to increase or decrease the virtual inertia to his likings.

Finally, the possibilities that come when the $\mu$G is connected to the main grid are being studied. This research does not only take into account the uninterruptible power supply characteristics, but tries to optimize the system economics to make the $\mu$G economically viable in a real-world scenario.


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### Table A.1: Consumption of households

<table>
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<tr>
<th></th>
<th>Quantity</th>
<th>Total</th>
<th>Power rating (W)</th>
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<td>2224</td>
<td>10</td>
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<td>Refrigerator</td>
<td>1</td>
<td>13</td>
<td>92</td>
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</table>
Table A.2: Consumption rest of the village

<table>
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<tr>
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<th>Quantity</th>
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<th>Power rating (W)</th>
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<td>15</td>
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<tr>
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<td>120</td>
<td>10</td>
<td>1200</td>
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<tr>
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<td>30</td>
<td>80</td>
<td>2400</td>
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<tr>
<td><strong>Secondary boarding school</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
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<td>9</td>
<td>18</td>
<td>10</td>
<td>180</td>
</tr>
<tr>
<td>Light Kitchen (15 – 22 h)</td>
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<td>2</td>
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<td>20</td>
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<tr>
<td>Light Classroom (19 – 22 h)</td>
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<td>Computer</td>
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<td>480</td>
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<td><strong>Secondary schools</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td><strong>Military Camps/Orphanages</strong></td>
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<tr>
<td>Radio</td>
<td>1</td>
<td>2</td>
<td>60</td>
<td>120</td>
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<td></td>
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<td>Audio System</td>
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<tr>
<td><strong>Telecom Tower</strong></td>
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WRITTEN PAPER
Frequency Based Cellular Microgrid Control
Thijs Vral, Pavol Bauer, Seyedmahdi Izadkhast, Evert Raaijen and René van Wesenbeeck

Abstract—This paper proposes a controller that enables microgrids to have a modular structure, to be flexible in terms of linked energy consumers and resources, and to offer the possibility of prioritized demand side management, while avoiding the need of employing a dedicated communication network. For this, the control strategy applies droop control, combined with a variable frequency setpoint depending on the state of the grid. Furthermore, a strategy for applying demand and supply side management is established, enabling the grid to operate stable using renewable energy resources.

The reactions of the proposed control structure have been studied in a broad range of cases, using simulations performed in DlgSILENT PowerFactory. Results show that the proposed controller has a satisfactory performance, it is able to interface multiple microgrids without the necessity of dedicated communication, and both load shedding and renewable energy curtailment schemes can be initialized, when needed.

Keywords—Cellular Microgrid, Islanding, Demand Side Man-agement, Supply Side Management, Battery Storage, Distributed Renewable Energy Sources, Droop Control

I. INTRODUCTION

TODAY’S world shows many changes and challenges. We are living in a world that is threatened by global warming, and where a clash exist between developed and developing countries. The developed countries, traditionally seen as the authors of global warming, have the means of coping with the results of this global warming, hereby sometimes deserting the developing countries.

Increasing the electrification rate in these regions will result in a better economic situation, which in turn can provide them the means of fighting against potential disastrous effects of global warming.

However, lessons learnt should not be forgotten. In this sense, it would not be a systematic choice if the electrification rate in regions like this is increased by using synchronous generators burning fossil fuels. It can be understood that better solutions should be present.

The solution that comes to mind is the application of distributed renewable energy sources (DRESs). However, running a grid on solely DRESs, without taking any measures, will lead to unsatisfactory grid behaviour. If the end-users would have to wait for a renewable energy source, such as wind or the sun, before they can actually start consuming energy, this would lead to a very poor customer satisfaction. The solution to this, however, speaks for itself: the installation of a buffer, in the form of a battery energy storage system (BESS), interfaced by means of a Smart Grid (SG) [1], [2], [3], [4]. This device then can store energy at moments of abundance, this way making the grid more stable and increasing its reliability [5], [6].

It is a fact that batteries actually contribute to a major part of the costs that come with the installation of a system like this [7]. This means that a trade-off will exist between the installation costs and the security of supply: there will be a tipping point where the price of adding more storage does not outweigh the benefits any longer. This means that, at certain moments, the power delivery to crucial power consumers such as hospitals or telecom towers can be put at risk [8].

In order to prevent a situation like this, it is of great importance that the power delivery to different sources is done in a well-considered way. For this task, the possibility of a central control unit seems viable, which then gives setpoints or commands to the loads and sources, using a dedicated communication network [9]. This way, loads that are considered to have a lower priority can be shed, in order to preserve the security of supply to more important loads.

Introducing a dedicated communication scheme like this, however, would add to the costs of the commissioned system, and can result in a lower availability of the system [10]. This because the energy supply would suddenly depend on the presence of two systems: the electrical grid and the communication network. Therefore, the fail rate can be expected to increase, no matter how reliable both systems are [11].

In this work, a method is proposed that omits this necessity of applying communication equipment into the system. For this, a decentralized controller that implements the frequency and voltage droop schemes in order to manage a microgrid ($\mu$G) is designed. The application of these droop schemes offers the $\mu$G the possibility of being built in a modular way, thus multiple cells can be interconnected to one’s liking [12].

Furthermore, the location of the frequency droop curve will be dependent on the state of energy and power (SEP) of the $\mu$G. This means that at the moment the system enters a critical SEP, the end-users are alerted by means of the always-present grid frequency [10]. Without the presence of a dedicated communication signal, the necessary communications can take place, thus loads of low importance will be shed in order to preserve the power delivery to crucial end-users by the application of demand side management (DSM) [13]. By means of supply side management (SSM), the injection of renewable power can be controlled as well [14].

In the developed world, where currently $\mu$Gs and SGs are seen as a promising technology, it is expected that the dependency on communication equipment will increase in the upcoming years [3], [4]. Therefore, in case the grid would face a total blackout, problems can arise because the need for
electricity for the communication equipment to work would prevent the grid to restore.

If the system can be used successfully without needing dedicated communication, it could be implemented in the main grid of a developed country as well, offering a means to the users connected to the μG to avoid eventual power outages.

It can be expected that the economic case for such systems in the reliable main grid makes it only viable for specific cases. However, at the moment a BESS is implemented into the main grid, a set of opportunities to make it economically interesting come along. For instance, the system can offer primary control reserve to the grid, can act as a means of peak shaving, it can initialize load shifting as seen from the grid’s perspective, energy yield of DRESs can be optimized etc.

The structure of the paper looks as follows: II introduces the considerations that have to be understood for the control strategy, explaining both the grid-forming inverter, the loads and energy resources, and the system stability. Subsequently, III talks about the chosen parameters and modelling assumptions, and introduces the case study that was selected for the paper. IV then shows the simulation results with some considerations, and finally V will conclude the paper.

II. FREQUENCY-BASED CONTROLLER FOR CELLULAR MICROGRIDS

The development of a controller offering the specified characteristics is the first necessary task. The control strategy shall be designed with the philosophy of offering the possibilities to include any possible requirements that can be necessary in a future stage of the project. Subsequently, methods to keep the grid in a stable working behaviour even if the amount of uncontrolled power injection does not match with expectations are designed. The controller is tested using extensive simulations in DIgSILENT PowerFactory.

The section can be divided into two main parts, being (i) the proposed control scheme for the inverter and (ii) the application of DSM and SSM.

A. Proposed Control Scheme for Inverter

The main factors that are included in the control scheme of the inverter are the droop control, which is the step that allows multiple Voltage-source Inverters (VSIs) to be interconnected without requiring explicit communication signals, and the dependency of the frequency setpoint of the grid’s SEP.

1) Voltage-source Inverter: An essential part of a μG is the introduction of a grid voltage with a certain frequency, since these parameters are not offered by a strong main grid in case of an islanded state. Therefore, the inverter needs to be capable of forming the grid [15]. It is important that the grid-forming device is not controlled with fixed setpoints, as this would jeopardize the system stability in case multiple sources are connected to the same bus. The workaround for this is found in the application of droop control.

2) Droop Control: The control part responsible for sharing active and reactive power among different sources is the drooping characteristic [12], [16], [17]. This means that the inverter setpoints, which are the grid frequency and voltage, vary over time, hereby offering a means of active and reactive power sharing. This is known from the real and reactive power flow between two sources connected by means of an impedance, as shown in (1) and (2) [18], [19].

\[
P = \frac{E \cdot V}{X_{line}} \cdot \sin \delta \]  
\[
Q = \frac{V^2}{X_{line}} - \frac{E \cdot V}{X_{line}} \cdot \cos \delta \]  

where \( E \) and \( V \) are the voltage amplitude of both sources, \( X_{line} \) is the line reactance, \( \delta \) is the phase angle between both voltages, and \( P \) and \( Q \) represent respectively active and reactive power flow.

It has to be noted that these formulas hold in case of a system with large time constants, like a grid supplied by synchronous generators. However, in a grid supplied by static generators, thus where the time constants are very small, a better system representation is obtained by taking into account dynamic phasor-based modelling techniques [19].

The equations assume that the line between both sources is predominantly inductive, hereby dropping the term for ohmic resistance and only considering the line reactance X. This is an assumption that is easily justifiable on the main grid, where lines are inductive by nature, and that shows how the active and reactive power control are decoupled by definition.

However, in order to see the same behaviour in a low voltage μG, interventions are needed in order to obtain this grid nature [20], [21]. It can be argued to implement a so-called opposite droop scheme, where the active power depends on the voltage and the reactive power on the grid frequency, though this will restrict the compatibility with synchronous generators, or the main grid [22]. One of the more viable solutions, allowing the application of conventional droop, is the implementation of an inductive element at the clamps of the inverter of the BESS, like a filter, which will at the same time rule out any high-order noise in the output signal. Another means of reaching this grid behaviour is the implementation of a virtual inductance in the controller, mimicking the installation of a physical element [23], [24].

The well-known working principle of the droop curve is depicted in Fig. 1. Because of the fact that the inverters are interfaced as voltage sources, they do not decide upon the active and reactive power output. This is set by the load that is present on the grid, which means that the frequency setpoint of the inverter is calculated by means of:

\[ f_{set} = f_0 + k_p \cdot p. \]

Where \( f_0 \), \( k_p \) and \( p \) are the zero-power frequency, the relative droop coefficient and the per unit power, respectively. \( f_{set} \) is the output frequency.
Note how the droop action in fact is built up only using a proportional controller (P action).

Power sharing according to this scheme occurs by means of the voltage phase angle $\delta$. This in a way that if two sources are interconnected and the consumed power changes, the power flow between both sources is influenced, which has an effect on the output frequency. This way, a mutual and stable grid frequency is achieved.

By means of a voltage droop depending on the reactive power output, a similar behaviour is noticed in terms of Q sharing. However, since the grid voltage is a local parameter, unlike the grid frequency which is the same globally, the reactive power sharing scheme is influenced by voltage drops, jeopardizing its effectiveness [25]. This will, as suggested, be solved by the successful implementation of the reactance.

3) Frequency Setpoint: Next to this droop curve, it is required to have a grid behaviour that depends on the SEP of the different cells, in case multiple cells are interconnected. If two cells with a different power rating are interconnected, it is expected that they will have a power output that reflects this difference in rating. Also, if a cell with a BESS at high state of charge (SoC) is connected to a cell of which the battery system is almost fully drained, a requirement is that the strongest cell delivers most of the consumed power, and the weakest cell receives most power injected by the DRESs.

Another requirement is that no communication towards the end-users is present, thus in case all the cells that are feeding the grid are connected to a highly drained BESS, the loads shall notice this and react according to the shedding requirements. Similarly, in case the SoC of all BESSs is approaching the maximal value, the DRESs shall be warned by this and limit the power injection into the grid.

These requirements are tackled by making the zero-power frequency setpoint ($f_0$), indicated on Fig. 1, a function of the SEP of the cell. This means that a cell with a high SEP will introduce a high $f_0$, and a cell with low SEP introduces a low $f_0$, ultimately leading to the desired characteristics in terms of power sharing and grid frequency.

A general concept of the $f_0$ setpoint as defined by the SoC is shown in Fig. 2. Three regions can be distinguished, these are the undercharging state, a normal area and a state of potential overcharging. If the battery reaches one of its limits, SoC$_{\text{min}}$ or SoC$_{\text{max}}$, then the frequency setpoint is quickly altered in order to limit the load consumption or DRES injection adequately. If this is not the case, the frequency setpoint closely approaches $f_{\text{nom}}$, thus no big deviations from this nominal value are noticed, though still two sources with a different SEP will share power according to their capabilities. The values are chosen using requirements set by the battery manufacturers in terms of depth of discharge, and in correspondence with the schemes for DSM and SSM, setting the minimal and maximal grid frequency.

![Figure 1. Active power - frequency droop with zero-power frequency $f_0$](image)

![Figure 2. Dependency of the $f_0$ setpoint on the SoC of the battery system.](image)

Apart from the frequency dependency on the SoC, other frequency dependencies are needed. These include a dependency that prevents a BESS to charge using power coming from another battery, a step that interferes with overloading of inverters, which will be discussed in § II-C, and a derivative controller (D action), used as a means for damping of the output frequency. This D-action can be combined with the droop characteristic, resulting in a PD droop scheme.

The overall decision making for the frequency depending on the active power is depicted in Fig. 3: $f_0$ depends on the actual value for SoC forming $f_{\text{base}}$ and on the derivative of the SoC in an intervention that prevents a battery from charging power coming from the backbone $p_{\text{BB}}$, forming $\Delta f_{\text{dSoC}}$. Furthermore, the derivative of the power $dp$ has an influence in order to damp the system’s response by means of $\Delta f_{\text{dp}}$, and if the inverter is overloaded, $\Delta f_{\text{ol}}$ stops this. By means of the droop, the frequency setpoint $f_{\text{set}}$ is calculated and provided to the inverter.

Finally, the possibility of easily adding extensions, for instance including a synchroscope using grid frequency which would enable the controller to seamlessly switch between interconnected and islanded mode, has to be present.

B. Load and DRES Response

It can be understood that a reaction of the power consumers is necessary in order to preserve the satisfactory operation of the system in case a state of undercharging is upcoming. Also, as soon as the batteries are threatened to be charged further than what is acceptable, this shall lead to a reaction of the DRESs.

1) Demand Side Management: For reaching the proper reactions of the loads, a division is made, listing the end-users according to their priority. Then, as the SEP of the grid abates,
load power consumption is decreased according to this priority. This way, crucial loads such as hospitals can be safeguarded, at the price of shedding less essential consumers.

2) Supply Side Management: The SSM scheme curtails the power output of the DRESs as a function of the grid frequency, thus with an increment of the SEP. For the main grid, the standard VDE-AR-N 4105 has been defined [26]. In the view of this project, it has an unsatisfactory behaviour, in the sense that the complete power output is curtailed starting at a certain grid frequency, to wait for a low grid frequency to restart. This way, the BESS is obligated to supply an amount of energy, discharging the batteries while renewable energy is being curtailed.

A better response was found in the application of a continuous scheme, depicted in Fig. 4, though this is a non-standard solution.

Figure 4. Scheme for SSM proposed to replace VDE-AR-N 4105

C. Stability Issues

The discussion of the stability of the system can be split up into two main fields. At the one hand, there is the small-signal stability, which answers the question whether the electric system can return to a stable working point after a disturbance, without losing the synchronism among different power sources. On the other hand, steady-state stability can be defined, dealing with the ability of the system to find a working point among different cells without overloading one or another.

Analysis of both states leads to the conclusion that there is a clash between both requirements: while the small-signal stability forces the gain of the power sharing loops, or in fact the droop coefficient $k_p$, to be small [27], [28], the steady-state stability shows that a small value for this droop coefficient leads to a system that cannot find a long-term stable working point. The reason for this is as follows: depending on the value for the droop coefficient, if this value gets too small, the inverters need to supply more power in order to find a common frequency setpoint, given that their value for $f_0$ differs drastically. This can be seen from Fig. 5, where a small difference between the setpoints for $f_0$ of two inverters shows a large stable region. On the other hand shows that a large difference results in a small stable region, only in the range of large droop coefficients.

Figure 5. Two inverters with a $\Delta f_0$ of 1 Hz have a big region in which a stable working point can be found.

In order to solve this conflict, an extra frequency dependency is necessary. The solution is of a curative kind, reallocating the $f_0$ setpoint in order to rule out overloading the inverters. The reason for this curative step is because no synchroscope is included in the current model, thus there is no possibility of connecting or disconnecting cells once the grid has been initialized. Since the inverters are only vulnerable to be overloaded the first moments after a successful connection, this state change cannot be simulated thus a preventive step cannot be implemented.

At the moment this synchroscope is present in the controller, this control step can be changed by a step that limits the separation of droop curves after connection, preventing a state of overloading.
III. PARAMETERS AND CASE STUDIES

A model of one cell was developed, composing of a BESS with the described controller, a photovoltaic plant and a wind turbine with an overlying SSM scheme, and a range of loads equipped with DSM are present. Using this model of one cell, a cellular μG can be built by interconnecting individual cells, also allowing a connection to the main grid. Using this model, the behaviour of the μG as a whole can be studied.

A range of parameters, including controller setpoints and physical characteristics of components, are needed in order to ensure relevant simulation results. Next to this, unit sizes and ratings have to be chosen, depending on the case study, yielding a relevant implemented system.

A. Selection of the Parameters

The setpoints include the values for gain of the P(D) controller for active and reactive power sharing, time constants etc. Physical choices include component efficiencies, load characteristics, line parameters, tolerated depth of discharge (DoD) and charge rate of the BESS, and windows for DSM. Some relevant choices are listed in Tab. I.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>$K_p$</td>
<td>0.3%</td>
</tr>
<tr>
<td>$K_q$</td>
<td>2%</td>
</tr>
<tr>
<td>Battery Technology</td>
<td>Li-ion</td>
</tr>
<tr>
<td>Battery range</td>
<td>0 – 80%</td>
</tr>
<tr>
<td>Frequency range</td>
<td>48 – 52 Hz</td>
</tr>
</tbody>
</table>

Furthermore, some modelling assumptions have been made. These include the behaviour of the load, which is static constant power loads, a PV system that acts as an ideal current source with $\cos \varphi = 1$, and the inclusion of an output impedance for the inverter to make the R/X ratio smaller, aiming at a R/X ratio below 0.3 [29].

B. Selected Case Study

During the verification phase of the controller, a total of ten case studies have been defined and investigated. A summary can be found in Tab. II.

<table>
<thead>
<tr>
<th>Case</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>One cell, no DSM &amp; SSM</td>
</tr>
<tr>
<td>II</td>
<td>Three cells, no DSM &amp; SSM</td>
</tr>
<tr>
<td>III</td>
<td>One cell, with DSM &amp; SSM</td>
</tr>
<tr>
<td>IV</td>
<td>Different power rating</td>
</tr>
<tr>
<td>V</td>
<td>Virtual inertia</td>
</tr>
<tr>
<td>VI</td>
<td>Sensitivity of $K_p$</td>
</tr>
<tr>
<td>VII</td>
<td>Developing Country: Self-sufficient</td>
</tr>
<tr>
<td>VIII</td>
<td>Developing Country: Economical parameters</td>
</tr>
<tr>
<td>IX</td>
<td>Developing Country: High and low priority load</td>
</tr>
<tr>
<td>X</td>
<td>Developed country, initially grid-connected</td>
</tr>
</tbody>
</table>

Of these, one case study will be discussed, a μG in Burundi with sizing optimized in terms of economics (Case VIII). In this grid, three cells are initially interconnected, as shown in Fig. 7. Every cell is connected to a small village, with a total of 670 households. Furthermore, a hospital, a military facility and a telecom tower are located connected to the grid, along with other facilities. The load is divided into four groups, according to their priority: Budget I & II, Comfort and Critical. DSM is performed based on this priority level and the type of consumers in every group. The load reactions are presented in Fig. 8.

The length to the backbone will be around 500 m, and cable sections have been selected in terms of power carrying interests. A battery size of 360 kWh is needed, thus combined with a DoD of 80%, a BESS with 450 kWh is installed. Furthermore, every cell is connected to a PV plant of about 70 kWp. For the simulations, a sunny day is considered.

IV. SIMULATION RESULTS AND DISCUSSION

Fig. 9 shows the load consumption of the four load groups, and the PV power injection of Cell I; similar consumption and injection were present on the other cells.

The flow of the loads can be explained as follows: Both Budget I and Budget II customers represent the majority of the villagers, with limited resources and consequently few power consuming devices. The load is limited to charging of technological devices, like smartphones and laptops, grouped in Budget I, and lighting equipment, accounting for the bulk power use of Budget II. From Fig. 8 it was clear that Budget I will shed sooner than Budget II, which means that first less critical consumers like phone chargers will be disconnected, before putting the villager in the dark.

The Comfort group represents a smaller group of people with more purchasing power, hence more devices that consume electricity. Furthermore, the non-critical parts of the hospital are included in this group of consumers, and so is the military base and other facilities like schools. Fig. 8 showed how these customers have a bigger priority than the Budget customers.

Finally, Critical users include the hospital and the telecom tower. These loads should be preserved as much as possible.

The ability of the voltage controller to keep the load voltage within the $\pm 10\%$ limits, prescribed by the grid standard EN 50160 [30] is checked and confirmed.
Figure 7. Schematic representation of the grid under test, where three cells are initially interconnected through a backbone and are all equipped with proper loads and DRESs.

Figure 8. Reaction of the DSM schemes

One of the purposes of the controller is to reach an acceptable effectiveness of active and reactive power sharing, without the need of setpoints from a central controller. Fig. 10 shows the performance of the active power sharing.

From the simulations, it is clear that both active and reactive power sharing schemes are effectively able to make every inverter account for a proportion of the load. The reactive power sharing follows a flow that is similar to that of the active power sharing, showing the coupling between P and Q, a result of the high ohmic resistance of the low voltage µG. The loads are assumed to be linear, with a constant $\cos \varphi = 0.95$.

The initial difference in active power sharing is due to a different SoC at the beginning of the simulations. The system connected to the BESS with the lower SoC supplies less, as desired. Furthermore, we see that Cell I receives more power during the charging regime, which is caused by better performing DRESs, because for the simulations the performance of the DRESs was altered slightly for the three cells.

Consequently, the BESS of the first cell charges faster, as seen on Fig. 11. Only when it reaches the first limit of a critical SoC, defined at 70%, it stops charging and the power injected by the DRESs is divided among Cells II and III.

Figure 9. Active power consumed by the loads and injected by the DRES of Cell I.

Figure 10. Active power sharing among different cells.

As was prescribed, the grid frequency is an indication of the current SEP of the µG, in order to give end-users information of this SEP without the need of communication. The frequency of the grid is plotted in Fig. 12, and when comparing this to Fig. 11, it is clear that the SEP of the grid is effectively reflected in the frequency. Following from this, we can see that...
at certain moments of the day shedding of load is required. The amount of residual load is plotted in Fig. 13.

During the night the SoC drops, resulting in a required shedding reaction of both Budget I and II. Budget II is shed later and restored earlier, due to its higher priority, and is also shed modularly, which can be reached by e.g. installing a dimmer in the lighting equipment.

Both Comfort and Critical customers do not notice the energy deficit during the night.

It is noticed that the grid frequency exceeds 50.2 Hz during the day. The cause of this is the fact that all batteries reach a high SoC, and as a result DRES curtailing will be activated. The amount of residual PV power is shown in Fig. 14.

V. CONCLUSIONS

The aim of the work was to develop a controller that is capable of managing a μG without the necessity of dedicated communication signals. No restraints should be placed on the allowable range of loads and power sources feeding the grid.

Due to the volatile and uncontrollable nature of renewable energy sources, SSM needs to be performed in an effective way, and also DSM is imperative. The grid must be suited to work in a standalone fashion as well as interconnected with other cells, where both active and reactive power have to be shared according to the capabilities of the individual cells.

The requirements lead to the definition of a controller with droop characteristics, enabling active and reactive power sharing. The SEP of the cell is taken into account by means of a variable grid frequency setpoint, and also any conflicting interests have been solved by influencing this setpoint for \( f_0 \).

A controller and implementation for both DSM and SSM have been proposed, substituting the standard schemes that have been defined for their application on the main grid.

Extensive simulations have shown that the controller is capable of providing the necessary requirements. Multiple cells work together as desired, finding a common frequency setpoint and sharing power according to their respective needs. In case the power inflow from the DRESs increases beyond what the μG can handle, this is seen in an increase of grid frequency,
initiating the curtailment scheme. Similarly, if the cells approach a potential undercharging state, the grid frequency decreases and low-priority loads are shed.

REFERENCES


