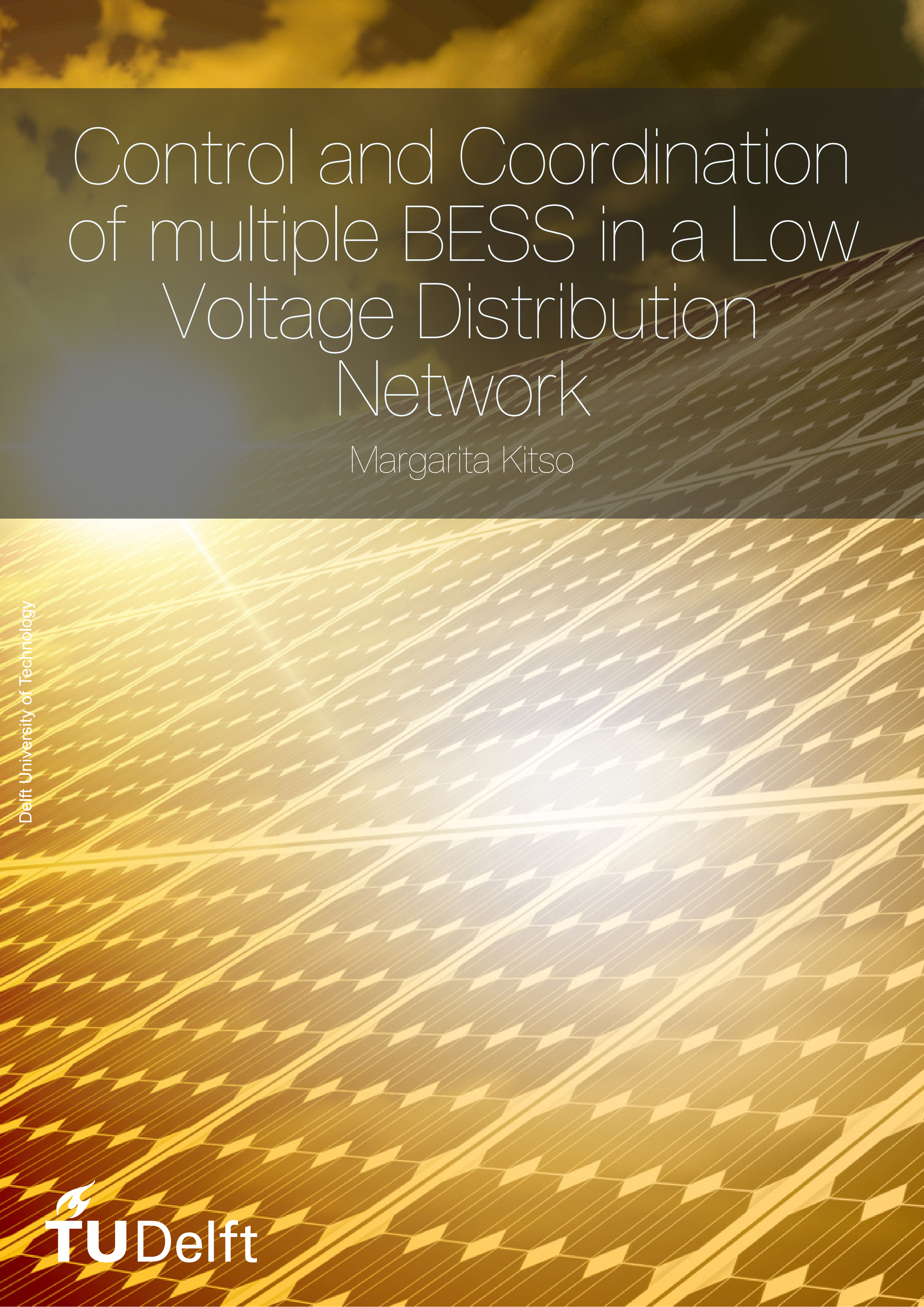

# Control and Coordination of multiple BESS in a Low Voltage Distribution Network

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# Control and Coordination of multiple BESS in a Low Voltage Distribution Network

by

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Cover: Power Technology, Here comes the sun: space-based solar power is on the horizon

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# Acknowledgements

*My interest in sustainability and facilitating the energy transition has driven me to pursue a MSc degree in Sustainable Energy Technology. This research study aims to achieve my goal of a sustainable future by mitigating the negative impacts that Photovoltaic Units have on electricity networks through the use of multiple BESS. The number of BESS increases, as renewable energy technologies become more predominant in the electricity sector, altering the energy infrastructure. This research is intended to assist the progress of the energy transition.*

*Firstly, I would like to thank my family for their encouragement and support throughout my studies; my parents are my role models who inspired me to pursue my dreams and believed in me. Secondly, I would like to thank my supervisor, Laura Ramirez Elizondo, for her guidance throughout this research study, as well as Marco Stecca for being present and assisting me with all my questions and difficulties in this journey. Finally, I would like to thank my friends for being there for me through my successes and difficult times.*

*Margarita Kitso*
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# Abstract

*The decarbonization of the electricity sector, the reduction of greenhouse emissions, the climate change and the energy transition has led to an increase in the integration of renewable energy technologies. Many countries around the world have set the goal of having a carbon-free energy sector by 2050. Renewable energy technologies are being used to accomplish this goal. As a result, countries are planning to incorporate more renewable technologies into their energy sectors while decommissioning conventional fossil-fuel plants.*

*The rapidly growing number of renewable energy technologies has started changing the infrastructure of the conventional energy sector, which was based on one-directional power flow. Bidirectional flows are created in the network with the integration of renewable technologies. The electricity network and system operators face many new challenges created due to renewable energy sources. Renewable energy sources are characterized by an intermittent and stochastic character which affects the power production from renewable energy technologies. As a consequence, the power production from a Photovoltaic (PV) unit is determined by solar irradiation. Thus, the produced energy may pose challenges to the grid when it is higher than demand since the excess power is injected into the grid and it causes overvoltage problems.*

*Battery energy storage systems (BESS) can contribute in facing the problems created by renewable energy technologies. They offer environmental benefits, they contribute to the integration of renewable technologies and they enhance grid's reliability. These factors have as a result an increase in the integration of batteries in the electricity network. This research has as a goal to develop a control and coordination method for multiple BESS in a low voltage distribution network in order to address overvoltage and undervoltage issues caused by high penetration of PV units. There are many control strategies used in order to control the increasing number of batteries so that normal operation of the energy system is sustained. The main control strategies are centralized control, decentralized control and distributed control.*

*In this thesis study, a coordination control strategy of multiple BESS was developed to address the network's voltage violation issues caused by the high penetration of PV units. The coordination control strategy is based on a consensus algorithm that determines each battery's contribution to the network. The goal of this control strategy is to maintain the voltage within the limits. When a battery is not available due to a state of charge limit violation or maintenance, the amount of power that this battery would contribute under normal operation is distributed equally from the neighboring batteries until the battery becomes available again. This control strategy is a combination of distributed control, as it entails communication between neighboring batteries which share information together, and local control. The developed coordination control strategy is compared to a decentralized control strategy, which is widely used in distribution networks in order to control the contribution of batteries. Moreover, one of the batteries is emulated in the laboratory in order to examine the behavior and contribution of the battery, with the coordination control strategy implemented, in real-time application in comparison to the simulation.*

*The findings of this thesis study contribute to the research of mitigating voltage limit violations caused by renewable energy technologies by demonstrating the effectiveness and benefits of the proposed control and by providing a comparison of the proposed control to a decentralized control strategy, commonly used in distribution networks for controlling the contribution of BESS, for voltage regulation. Furthermore, the laboratory results contribute in the potential implementation of the proposed control in real distribution networks.*

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# Abbreviations

| Abbreviation | Definition |
|---|---|
| AC | Alternating Current |
| BESS | Battery Energy Storage System/s |
| CIGRE | Council on Large Electric Systems |
| COP | Conference of the Parties |
| DC | Direct Current |
| EU | European Union |
| $G_{\text{ov}}$ | Gain overvoltage |
| $G_{\text{un}}$ | Gain undervoltage |
| IEA | International Energy Agency |
| LV | Low Voltage |
| m | Droop coefficient |
| MPC | Model Predictive Control |
| n | number of neighboring batteries |
| Ploadmax | Maximum power of Load |
| PnomBat | Nominal power of the Battery |
| Ppvmax | Maximum power of PV unit |
| Pref | Reference Power |
| PV | Photovoltaic |
| RES | Renewable Energy Sources |
| SoC | State of Charge |
| Ts | Sample time in MATLAB/Simulink |
| $u_{\text{i}}$ | Utilization factor |
| $u_{\text{leader}}$ | Leader utilization factor |
| Vlimit | Voltage limit |
| Vn | Voltage of the bus |

# 1

# Introduction

## 1.1. *Motivation*

One of the primary goals set by European countries in the EU Energy Roadmap 2050 and during the COP26 climate change conference is to achieve carbon-neutral energy production by 2050. As a result of this goal, investments in renewable energy technologies are being made in order to meet demand and accelerate the energy transition. This will transform the electricity sector, which has previously relied primarily on conventional-fossil-fuel plants [11].

According to the IEA, renewable energy capacity is expected to increase by 60% by 2026 when compared to renewable energy capacity installed in 2020. Solar power is one of the renewable energy sources that has grown in popularity over the years. More specifically, the installed capacity of PV units has been increasing [12]. During 2019 to 2020 the installed capacity worldwide increased by 18% [13]. Moreover, globally an increase of 9% is expected every year for PV units installation until 2050 [14].

The figure 1.1 depicts the estimated increase in PV unit installation from 2022 to 2030 based on [2]. The projected installed capacity from 2022 to 2030 is divided into PV Untis on the utility scale, PV Untis on the commercial scale, and PV Untis on the residential scale.

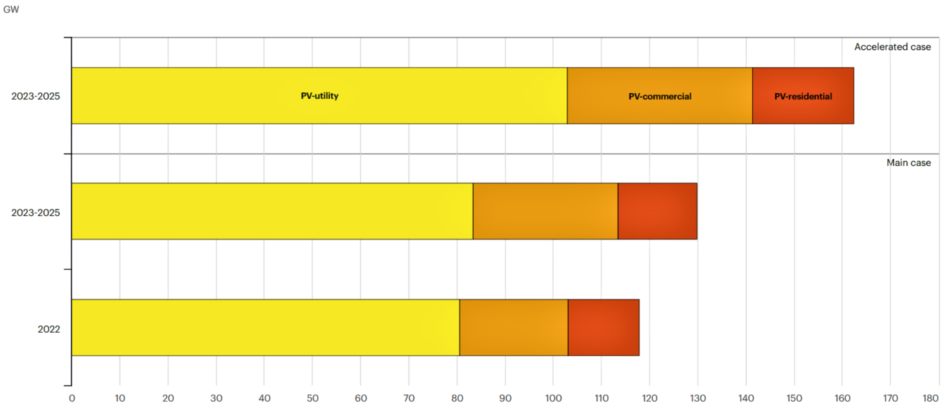


**Figure 1.1:** Average global annual capacity of PV units 2023-2025 [1].

The stochastic nature of renewable energy sources, on the other hand, has an impact on power generation from renewable technologies. Their production is dependent on the availability of energy sources; for example, changes in the irradiance that reaches the PV units will result in a change in the PV unit's power output. The main issues caused by the integration of renewable sources are voltage magnitude deviations, such as overvoltage when demand exceeds supply, the impact on power quality, and all of this may affect network stability. The problem of supply and demand mismatch is responsible for these problems and a lot of research has been done on how to cover the demand when the production is low and what should be done when the production is higher than the demand [15–17]. One of the solutions used to handle with these problems are storage units. Storage untis are being used in order to improve the security of supply.

Storage technologies are used to store excess power generated by renewable sources and deliver it to the grid when demand is high. Storage technologies can be classified according to their maximum rating power, discharge times, energy density, lifetime, and efficiency. Based on these characteristics a decision can be made on the most efficient choice based on the application needed. Batteries, hydro-plants, hydrogen storage units, supercapacitors, and flywheels are the most well-known storage technologies. Batteries are one of the most popular storage technologies for low voltage distribution systems.

The figure 1.2 depicts the increase in BESS installed capacity from 2015 to 2030. According to [18], installed capacity is expected to increase more than sixfold by 2030, compared to installed capacity in 2020. This highlights the critical role of Battery Energy Storage Systems (BESS) in the energy sector's transition to carbon-neutral electricity production [18].

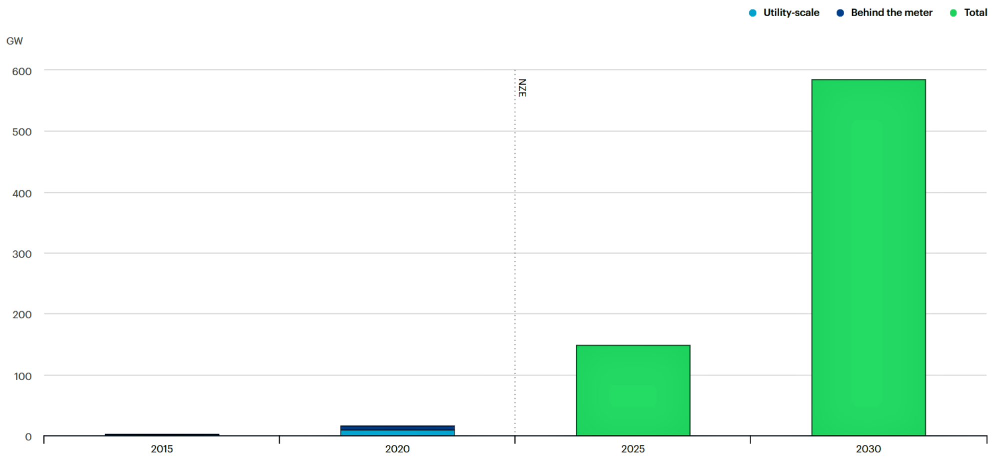


**Figure 1.2:** Total installed BESS capacity in the Net Zero Scenario (2015-2030) [2].

Batteries are frequently used in conjunction with PV units to address the aforementioned issues. Excess power generated by PV units is stored in batteries and used to power loads when demand is high but production is low. Furthermore, the price of BESS has decreased by 70% between 2015 and 2018 and continues to fall, making them an attractive proposition when combined with the integration of renewable technologies, particularly PV Untis [18].

This increasing number of batteries must be properly controlled in order to effectively regulate voltage instabilities caused by demand and supply mismatches. Many aggregation and control techniques have been developed so that the integration of BESS can facilitate the further penetration of PV units in order to meet countries' goals for energy sector decarbonizarion.

## 1.2. *Research question and intended outcomes*

This research focuses on low voltage distribution networks that have a high penetration of PV units. Voltage fluctuations are caused by PV units due to a mismatch between the power produced by the PV unit and the demand. Battery storage systems are integrated into low voltage distribution networks to maintain voltages within acceptable limits.

The main *research question* of the thesis is:

***How can the increasing number of BESS be controlled and coordinated more effectively in order to regulate voltage in a Low Voltage Distribution Network with high PV Unit penetration?***

This needs to be further analysed by answering the following sub-research questions:

- ***What are the benefits that multiple BESS offer to networks?***

To facilitate the penetration of PV units in the energy sector, the problems caused by solar power intermittency must be addressed. BESS can help in this direction, which is one of the reasons for their increased integration in the energy sector. As a result, identifying the benefits that BESS can provide is required before they can be deployed further.

- ***What effect does the proposed BESS coordination control strategy have on the voltage fluctuations caused by high PV Unit penetration?***

To coordinate the growing number of BESS in a low voltage distribution network, a distributed control strategy will be developed. In addition, the developed control will be tested in overvoltage and undervoltage conditions caused by the high penetration of PV units.

- ***Why distributed control of BESS is more effective than decentralized control in distribution networks with high penetration of PV Units?***

Many strategies for controlling BESS have been developed; however, distributed and decentralized control are the two most commonly used control strategies because they are more effective when many BESS are integrated into the system. Identifying and comparing the coordination control strategy with the decentralized control strategy will help towards answering that question.

**The intended thesis outcomes are:**

- *Identification of the benefits that multiple BESS can provide to the network.*

- *Development of a control and coordination strategy for multiple BESS in the network.*

- *Evaluation of the developed strategy in overvoltage and undervoltage mitigation in a Low Voltage Distribution Network with high penetration of Photovoltaic Units.*

Answering the main research question as well as the sub-research questions will assist in achieving the desired thesis outcomes. This research will help to facilitate the integration of multiple BESS in distribution networks with a high penetration of PV units in order to mitigate voltage fluctuation issues caused by the intermittent nature of solar power. Furthermore, the developed control strategy will be compared to the implementation of the decentralized control strategy, supporting research into the most effective methods of controlling the growing number of BESS in the energy sector.

## 1.3. *Methodology*

In order to answer the main research question of the thesis MATLAB/Simulink is used. The methodology used during the thesis is :

- *Literature study on the strategies used for BESS control.*

First a literature study was conducted on the strategies used to control multiple BESS in a low voltage distribution network and the distributed control was chosen. More specifically, the coordination control of multiple BESS is chosen to be tested.

- *Use of MATLAB/Simulink to create the simulation system.*

A simple eight-bus distribution network and the CIGRE low voltage distribution network were modeled in MATLAB/Simulink in order to be used for the implementation of the developed control.

- *Development of the coordination control strategy.*

A control and coordination strategy for multiple BESS was developed in Simulink. The developed control was tested on the simple eight-bus system where three BESS and PV units were integrated. Then, the developed control was tested on the CIGRE low voltage distribution network, where six BESSS and PV units where integrated, in order to evaluate the performance of the coordination strategy when the amount of BESS is higher.

- *Evaluation of the coordination control strategy.*

Real daily mismatch data with values holding the same value for 15 minutes and a sampling time of Ts=5e-05 sec in Simulink were used in order to evaluate the developed strategy for overvoltage and undervoltage mitigation.

- *Comparison of Coordination control strategy and Decentralized control strategy.*

The CIGRE low voltage distribution network was used and a decentralized control was implemented instead of the coordination control so that to evaluate voltage regulation and compare it with the coordination control.

- *Test of the behavior of one BESS in the Laboratory with the coordination control strategy implemented.*

A test will be conducted on the behavior of one of the batteries, with the coordination control strategy implemented, in order to evaluate the real battery performance in comparison to the performance during the simulation. For this purpose the RT-Lab software was used, where the simulation of the CIGRE low voltage distribution network was developed, and laboratory equipment.

## 1.4. *Thesis Outline*

The thesis is divided into six chapters. In each chapter different aspects of the thesis are presented in order to answer the research question and accomplish the intended thesis outcomes. The chapter outline is:

- **Chapter 2** presents the impact of renewable sources and especially PV units on distribution networks, a literature study of the benefits that multiple BESS can provide to the network and a literature review on the control methods used for control of BESS in a low voltage distribution network as well as the intended contributions of the proposed control .

- **Chapter 3** presents the developed coordination control strategy. In this chapter the graph theory used for the consensus algorithm and the consensus algorithm are explained. Moreover, the control implemented on the inverters connected to the BESS is shown.

- **Chapter 4** presents the eight-bus low voltage network and the CIGRE low voltage distribution network used for the simulations. More specifically, specifications of these systems are provided since they are used for the simulation purposes.

- **Chapter 5** presents the case studies created in order to evaluate the performance of the coordination control strategy in overvoltage and undervoltage mitigation. It provides the results of the simulations and the results from the laboratory testing.

- **Chapter 6** includes the conclusions, contributions and the reflection on the results of the thesis. Furthermore, recommendations for future work are given.

# 2

# Benefits of multiple BESS in the network

In this chapter,the impact of renewable technologies on the network are presented in section 2.1, in section 2.2 the benefits of multiple BESS in the network are illustrated. Finally, in section 2.3 a literature review of the control methods used for the integration of BESS in low voltage networks are depicted.

## 2.1. *The impact of renewable technologies on power grids*

The transition to a carbon-free electricity sector has begun, with the primary drivers being climate change, the depletion of fossil fuels, and the growing need for flexibility in the electricity sector. The demand for electricity has been increasing and the use of renewable sources has been rapidly growing [19]. Renewable energy sources have begun to change the energy infrastructure, but conventional power plants are difficult to replace because the electricity sector is established around them. However, renewable energy technologies create problems to the network and their power production may not be able to meet the demand without the use of other supportive technologies such as storage units [20, 21].

Renewable energy sources have a stochastic nature that affects their power production. As a consequence, the availability of sunlight and wind determines the power generated by photovoltaic units and wind turbines. Because solar irradiation and wind speed are constantly changing, the power generated by these renewable technologies is uncontrollable. As a result, the power supplied to the grid by renewable sources may pose difficulties to the electricity grid and system operators. The main challenges raised by renewable technologies are voltage magnitude fluctuations, deterioration of power quality, network instability, and component overheating. Voltage stability is especially important in distribution systems, so voltage fluctuations caused by renewable technologies can adversely impact network reliability [21]. In figure 2.1 the difference in the power produced between a renewable energy technology and a conventional energy source is presented. The production from the conventional plant is depicted on the left side. The right side depicts the power produced by a wind turbine.

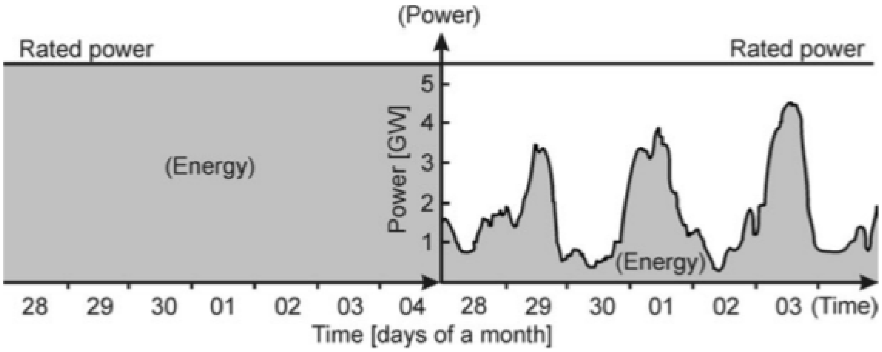


**Figure 2.1:** The difference in the power production between a conventional unit and a wind turbine [3].

Voltage fluctuations are caused by a high production of power generated by renewable sources that is greater than demand, causing a network overload. This problem most of the times is faced with power curtailment which leads in power waste. Moreover, the integration of renewable technologies has transformed the network since bidirectional power flows are created while the system is developed to manage and control one directional power flow. Because conventional protective equipment is designed to handle one directional power flow, this bidirectional power flow necessitates the development of new protection equipment. The existing protective devices in the network jeopardize the system's reliability [21].

Furthermore, it is very common for renewable technologies to be installed near loads, thus sudden changes in their production will affect the voltage of the distribution feeder that is connected to the loads. Apart from the voltage fluctuations caused by the mismatch between production and consumption, power quality is also impacted by variations and distortions that are created in the current and voltage. These distortions are caused by the power electronic devices that renewable technologies have, which may create voltage distortion in combination with harmonics in the current. Harmonics can cause component temperature to rise, the power factor to deteriorate, and the protection devices to malfunction. Furthermore, overproduction of power from a renewable energy source will affect losses; for example, if the production of a wind turbine exceeds the demand due to high wind speeds, the losses will increase [21].

Moreover, the intermittent nature of renewable sources, which results in varying power production, may cause thermal stress on network equipment and components. Thermal stress is a significant factor that influences component lifetime. For instance, transformers and safety equipment require frequent repair and replacement, which raises costs and makes investors hesitant to invest money [21]. In figure 2.2 the main negative impacts that renewable technologies cause to the electricity networks are illustrated.

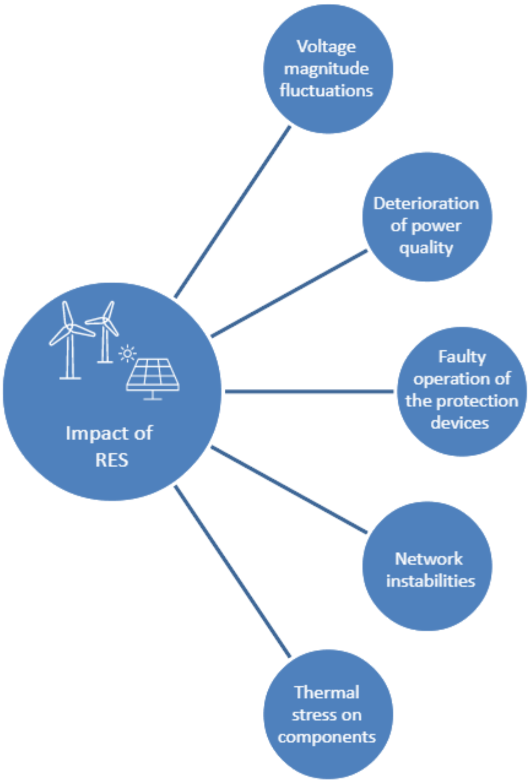


**Figure 2.2:** Impact of RES on distribution networks.

Photovoltaic (PV) units are one of the most widely used and well-known renewable technologies; they have grown rapidly due to their low cost and numerous technical advantages. PV power generation is dependent on solar irradiation, which, like all renewable energy sources, is unpredictable. As a result, power production varies, causing voltage fluctuations and network instabilities. When there is a high penetration of PV units, these issues become more severe, resulting in power quality and voltage issues [19].

According to [19] , Europe has been investing in PV units, with the main goal of 2020 being to produce 84.4 GW of power from PV units. Even though their high penetration can increase the flexibility of the grid and cover the demand, when there is a reverse power flow, so the production of the PV is higher than demand, that excess power is injected into the grid creating an overvoltage in the distribution feeder. This issue is particularly severe in distribution networks with a high penetration of PV Units, as power production varies with solar irradiance, resulting in frequent voltage fluctuations [22].

Furthermore, according to [22], changes in the power produced by PV units are determined by a ramp rate, which it may range from 10% to 20% per second. This causes unprecedented changes in power production, making conventional voltage control strategies ineffective in achieving voltage regulation, resulting in instabilities. As a result, fast-responding devices, such as battery storage units, are required for voltage regulation. Only in this way can a voltage regulation failure be avoided.

Thus, the integration of renewable energy technologies in the energy sector such as the increased penetration of PV units creates network stability problems. This causes increased losses, overvoltage challenges, and thermal stress on the components, transformers, and cables. These lead to technical problems on distribution networks and raise operational costs [22]. All the aforementioned factors highlight the critical need for storage units to mitigate the negative impact that renewable energy technologies may have [21].

## 2.2. *Benefits of multiple BESS in the network*

In recent years, the electricity demand has been increasing significantly and renewable energy sources are being used more and more in order to provide power to loads and cover demand. As a result, renewable energy sources are becoming an important part of the electricity generation [16]. The stochastic character of renewable sources such as wind and solar, has an impact in the power production of renewable energy technologies and that may lead to instabilities in the voltage, may deteriorate the quality of power and affect the reliability of the grid [4]. More specifically when a PV units is operating and the solar irradiation is high during the day, this may lead in an overvoltage, causing problems to the grid. Storage units are being deployed to address these issues by storing the excess power generated.

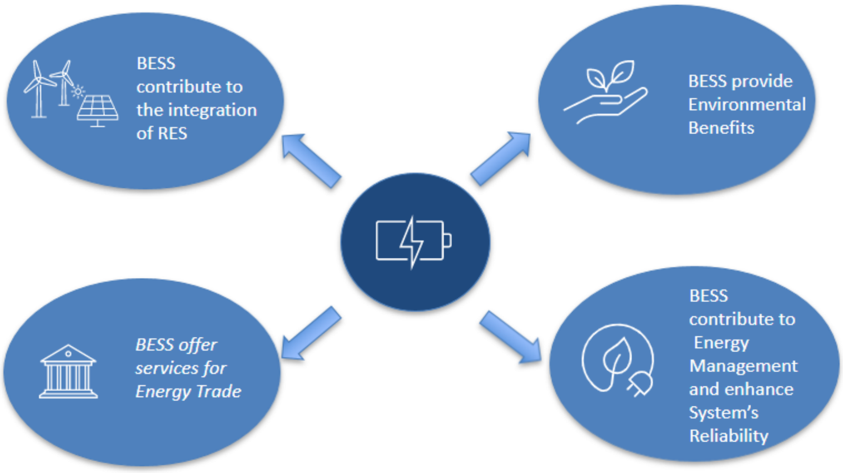


**Figure 2.3:** Contribution of multiple BESS in the energy sector.

### *A. Environmental Benefits of using BESS*

Conventional power plants are responsible for the vast majority of greenhouse gas emissions, making electricity production one of the major sources of pollution [4]. Countries aim to reduce the use of conventional power plants through agreements and internal policies, with the goal of achieving decarbonization. As a result, there is a greater demand for renewable energy technologies and energy storage units.

The decommissioning of conventional power plants, combined with the proliferation of sustainable energy technologies and storage units, is transforming the electricity industry and posing new challenges. The main challenges that network operators face are ensuring that production meets demand and that excess power is stored or exchanged in the electricity market, as well as revenue losses [23].

The use of multiple BESS contributes to the global goal of decarbonization set by many countries. BESS are typically integrated in networks with sustainable energy technologies whose production cannot be controlled due to the stochastic nature of sustainable sources. When it comes to achieving the goal of decarbonization, BESS are used because they provide many technical and financial benefits. In case BESS are integrated without the use of sustainable sources in a network, then they are charged during base load, since during that period the $CO_2$ emission rate is low and they provide power when there is high demand and $CO_2$ emission rate is high [4].

### *B. Contribution of BESS in the integration of Renewable Technologies*

Battery energy storage units are typically used in combination with sustainable energy technologies because they are very flexible, whereas renewable energy sources have no flexibility and are variable. Their cost is constantly decreasing, making them a popular option for energy storage. The goal of having a carbon-free electricity sector by 2050 will further increase their integration [24]. In order to maintain grid stability, multiple BESS are aggregated together. Many BESS are integrated in an electricity grid that uses multiple renewable energy technologies because they improve the efficiency of renewable technologies by minimizing the negative outcomes that the stochastic nature of renewable sources creates, and they provide ancillary services such as voltage regulation.

Battery storage systems are usually paired with PV units because they can store the excess power during the day and offer it to the loads and to the grid during the night. They can replace the need of conventional fossil-fuel plants as they can increase the reliability of supply. Thus, BESS in combination with renewable technologies can be used to replace the need for conventional units during peak events.

Moreover, BESS are used in combination with renewable technologies in micro-grids and they offer the opportunity of islanded operation as well as they are responsible for ensuring stable power supply when power supply in the micro-grid fails to meet demand. Micro-grids with the integration of multiple BESS are becoming an important part of the smart grid development since they facilitate the integration of renewable technologies [25].

### *C. Contribution of BESS to the energy management and system's reliability*

The integration of renewable energy technologies into the electricity network reduces $CO_2$ emissions, however, when production is high and demand is low, the power cannot be inserted into the grid due to overvoltage creation issues. As a result, power is curtailed. BESS can aid in the storage of this power and when multiple BESS are coordinated together then the possibility of a BESS being unavailable due to maintenance or reaching its allowable limits of state of charge is avoided. Energy management service offered by BESS can help in the decupling of generation and consumption. Energy can be produced when prices are lower, stored and distributed when there is need of power to cover the demand. Energy losses are decreased through the use of multiple BESS [4]. Thus, BESS can assist transmission congestion relief and can offer back up power service as well as they can provide to consumers demand side management offering relief to the distribution network congestion.

BESS can also replace Peaker Plants, which are conventional plants (usually Gas Turbines) that can fast provide power to the grid during peak electricity demand. BESS can be deployed as Peaker Plants as they can also very quickly offer power for a short period of time in order to cover the peak demand and they help avoid the emission of green-house gases produced by those plants. Thus, BESS are able to shave peak demand and even totally cover it.

When it comes to large scale BESS they can assist in the electricity network restoration in case a failure occurs in the grid. Frequency deviations from the permitted limits are caused by unbalances between power production and demand. These events can be dealt by BESS, which provide frequency and voltage restoration by charging when production exceeds demand and discharging when consumption exceeds production. BESS contribute in facing events such as high demand on a transmission and distribution lines , which may result in increased thermal stress on network components, such as distribution transformers and cables [26]. The overloading of transformers for a long period of time decreases their lifetime creating the necessity for frequent replacement which leads in more financial expenses. If BESS are integrated at the secondary of a distribution transformer, they will handle the stress created by high production or high demand.

### D. BESS offer services for Energy Trade

Apart from frequency regulation multiple BESS offer also ancillary services such as daily energy cost minimization and energy scheduling. System operators determine the participation of BESS in the energy scheduling and particularly during real-time operation when frequency and voltage deviations occur. This participation in the energy scheduling reduces energy costs because the sources that participated receive compensation based on their contribution and energy market prices [27].

BESS are able to provide demand side management by reducing high demand load and preventing undervoltage incidents in the electricity network [23]. The use of BESS for demand side management has been proven to reduce electricity bills for customers and especially when BESS are combined with PV units, then according to Gangon et al. the decrease reaches a value of 10% [23]. When coordination is achieved between multiple BESS, then the financial benefits for customers and network operators are even more significant [23]. BESS are used in the energy trade management, as they offer the opportunity of energy purchasing during off-peak hours [26]. They provide services to the customers and system operators such as the control of electricity flow and contribution to peak demand, they absorb power during high production and they prevent voltage instabilities.

**Table 2.1:** BESS application on the network.

| ***BESS Application*** | ***Description*** |
|---|---|
| Capacity | BESS can ensure a firm capacity as they will be able to cover demand when production is low. |
| Arbitrage services | BESS can be used to store power when the price in the energy market is low and provide that power when the price is high. |
| Voltage and frequency regulation | BESS can ensure voltage and frequency regulation as they can store excess power that leads to overvoltage and provide power when the demand is high in order to avoid undervoltage. |
| Contingency events | BESS can be used to face contingency events as they offer a fast response. |
| Black start | BESS can help during network failures in order to restore system operation. |

BESS in comparison with other storage units such as flywheels, hydro-plants and compressed air storage has more advantages to use as it is easier to implement in all sites and it is more flexible and easier to install [28]. From the available battery technologies, the Lithium-Ion batteries are the most used ones for frequency and voltage regulation. The main reasons for this are the fast-ramping ability, the high energy density and their constantly decreasing price. Many tests have been conducted in order to provide information regarding the performance of Lithium-Ion batteries under real-time performance in the electricity market. The goal of these tests is to ensure that the batteries can be used commercially and to assess the investment risks [27]. The main characteristics of BESS that make them ideal as storage units and their contribution to the energy sector are shown on table 2.2.

**Table 2.2:** BESS Characteristics and their contribution on the network.

| ***BESS Characteristic*** | ***Contribution*** |
|---|---|
| Fast | BESS are able to deliver and store power very quickly (within seconds) which is of great importance in emergency situations. |
| Flexible | BESS are able to cover the mismatch of demand and supply offering flexibility to the network. Moreover, they can be placed where is needed, providing flexibility in comparison with other storage units such as hurdo-plants that can be installed in specific places. |
| Efficient | BESS have high round trip efficiency reaching 95% witch indicates that BESS are able to provide nearly the same amount of power that they absorb. They have the highest efficiency compared to other storage technologies. For instance, the round trip efficiency of pumped- hydro storage is 79%. |
| Reverse Power | BESS can absorb power when there is excess power produced in the system and provide that power when the demand is higher than supply. |
| Affordable | The price of BESS has been decreasing significantly, between 2015 to 2018 the price has decreased by 70% [18]. |

Moreover, BESS are becoming more and more popular as a storage option as they can minimize the costs regarding higher needs for generation capacity by offering flexibility to the operation of the electricity sector and support during contingency events in the power systems. BESS are considered very beneficial to the energy sector because they offer arbitrage support in the electricity market, they offer grid services to the transmission and distribution system operators as well as to producers and consumers. In figure 2.4 the applications of BESS in the energy sector are summarized.

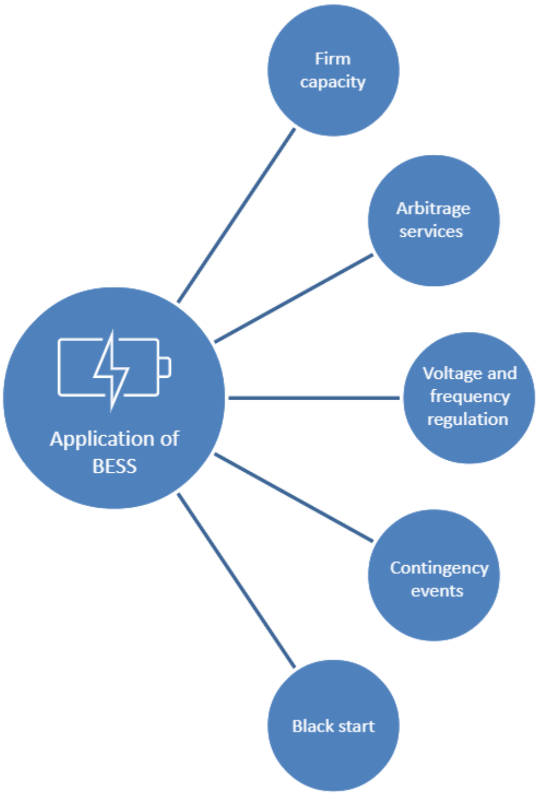


**Figure 2.4:** Application of BESS in the energy sector.

The location of BESS could be either in the transmission network or near loads at the distribution networks. BESS are used to create reserves in order to balance the mismatch between production and demand and assist in dealing with congestion events caused by increased loads or production. When BESS are located near loads in distribution networks, they are considered more beneficial because they offer the same advantages as when they are implemented in the transmission network and are also able to face the power quality problems. As it is difficult to place conventional units near loads to deal with demand increases, BESS are the preferred choice since they can cover the high demand and store the excess power, they do not emit greenhouse gases and do not necessitate large spaces for their implementation. Furthermore, the implementation of BESS in distribution networks helps in minimizing losses of transmission and distribution, as well as they can support the grid during extreme events that may disrupt normal operation and help in avoiding power curtailment from renewable sources connected to distribution networks.

As a consequence, BESS will play a significant role in the energy sector's transition. The primary goal of BESS is to ensure system's stability and operation. BESS offer other services to consumers, to producers and system operators. To producers the main benefits are that they ensure a firm capacity and they avoid power curtailment from renewable generations. To system operators BESS offer arbitrage services, they facilitate network expansion, they reduce the energy prices and minimize forecast energy errors. To consumers BESS facilitate demand side management, they offer back up power and energy arbitrage [4]. In figure 2.5 the benefits offered by BESS to (a) Producers, (b) System Operators, and (c) Consumers are summarised.

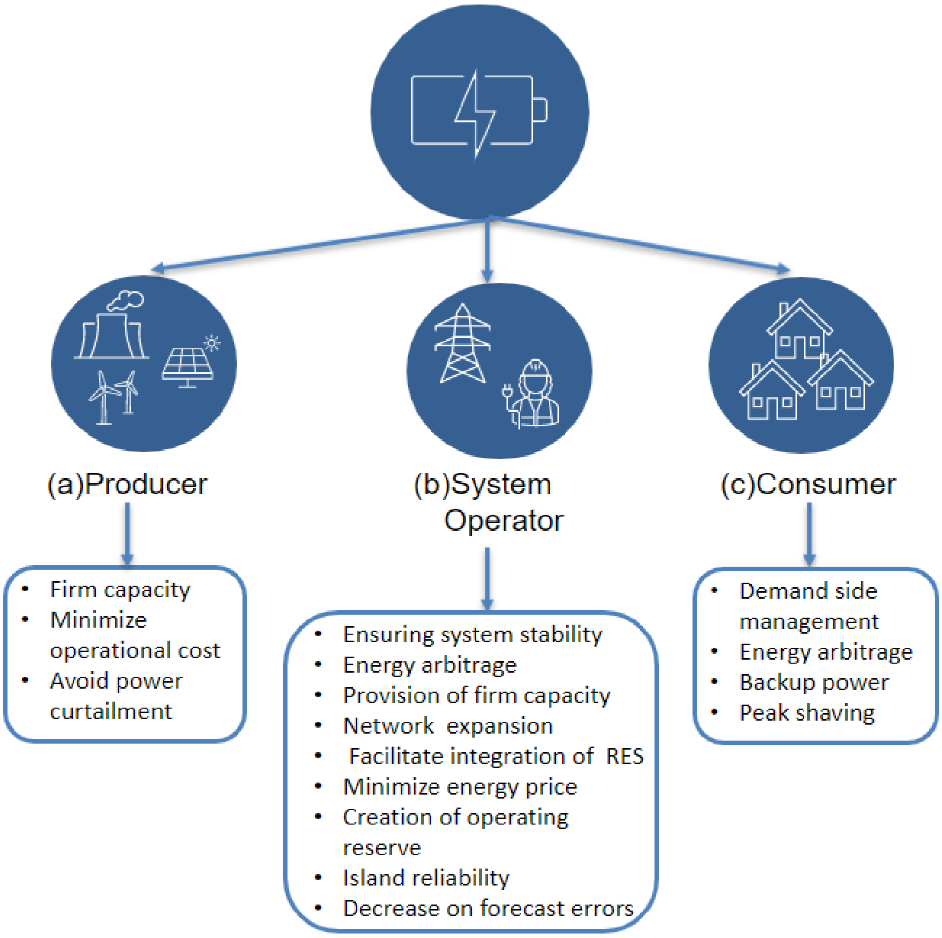


**Figure 2.5:** Application of BESS on the network from a (a) Producer, (b) System Operator and (c) Consumer perspective [4].

## 2.3. Control methods for integration of BESS in a Low Voltage Distribution Grid

The high penetration of renewable energy sources such as PV units create fluctuations in the voltage magnitude of a low voltage distribution system. BESS aim in offering stability to the grid by absorbing or offering power when the renewable energy generators produce more than demanded or the demand is higher than the power produced. The use of BESS can prevent the curtailment of active power, which is considered a waste of energy. The BESS provides power control and voltage regulation and this makes it necessary in network systems which include renewable energy sources.

The increase of BESS in a network system is very challenging as all BESS need to be controlled in order to secure a normal operation. The three main strategies for controlling BESS are, centralized control, decentralized control and distributed control. The centralized strategy contains a central management system which is in charge of making decisions regarding the contribution of each battery based on the voltage magnitude fluctuation. In a decentralized control strategy, according on local measurements, each battery changes its contribution. In a distributed control strategy, there is a communication between neighboring agents which exchange local measurements.

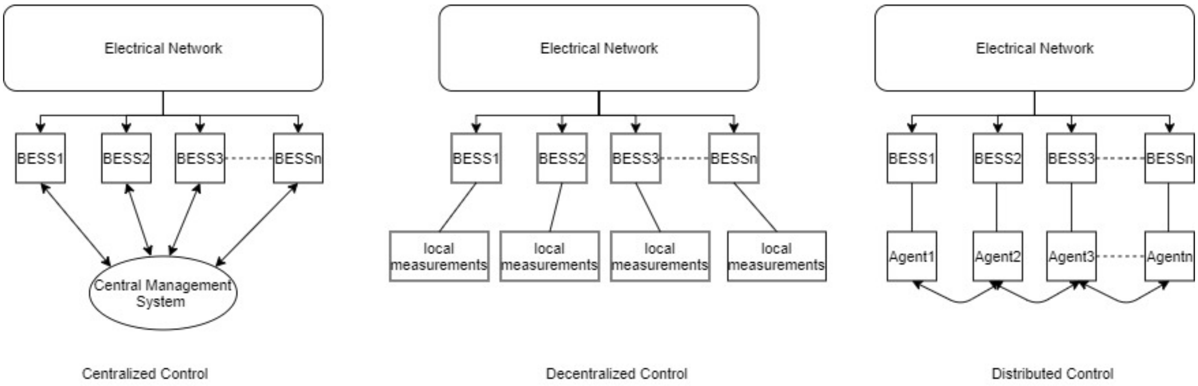


**Figure 2.6:** (a) Centralized Control. (b) Decentralized Control. (c) Distributed Control.

In [5] a centralized coordination approach is being presented and an aging analysis of the battery is performed. More specifically, each storage system sends local measurements to the central controller and the central controller, based on the availability of each storage system and the place where the overvoltage occurs, decides which BESS will be used. In [29] a centralized control scheme is proposed and a tap changer transformer is used for tackling the overvoltage problem. The centralized controller will inform the state of charge controllers so that the batteries will start to charge during off peak hours and discharge during peak hours. In [6] the energy management system communicates with the power conversion interfaces in order to manage the power changes. In a centralized control a communication method is required to control and monitor each storage device. However, in case of an error in the central controller, which is a common phenomenon, the system may become unstable, moreover centralized control does not facilitate the expansion of the network. Thus, this control makes the implementation of multiple BESS more difficult to control, the proposed control of this study has as a goal to facilitate the increasing number of BESS in order to achieve voltage regulation and no central controller is needed.

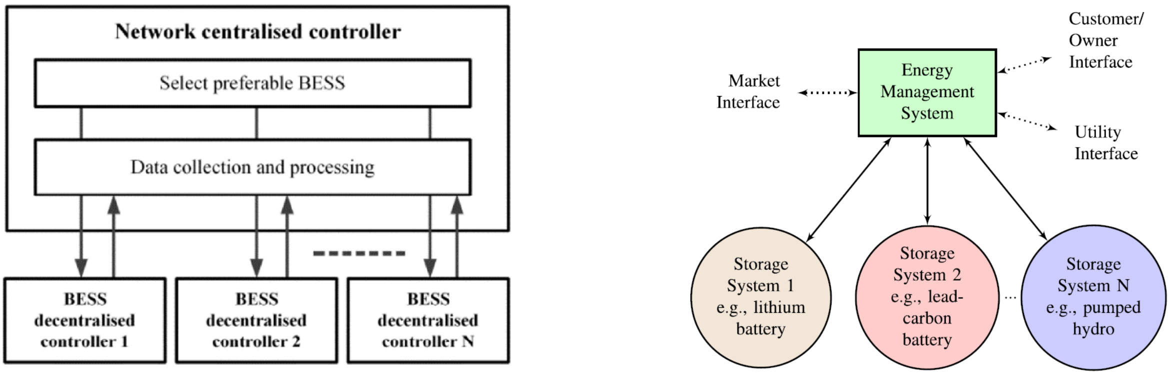


**Figure 2.7:** (a) Centralized Control scheme implemented in [5]. (b) Centralized energy management system used in [6].

In [30] a decentralized control strategy is being developed. Local measurements of voltage magnitude define the amount of power that should be injected to the system or to the local

BESS. The control is implemented on each inverter connected to the BESS. In [31] a decentralized control method is implemented based on changes on the DC voltage of the DC link where the BESS and the PV unit are connected. In [32] a decentralized control strategy is implemented on BESS, more specifically frequency changes due to events are used to create the reference power value for each BESS. In [7] a decentralized control, based on state of charge changes of each BESS, is presented. In these studies frequency deviations and state of charge are used for determining the amount of power that the batteries should contribute, however the case where one BESS necessary for voltage regulation becomes unavailable is not studied. The proposed control strategy takes into account this case and what consequences may the unavailability of one BESS necessary for voltage regulation have on the voltage regulation.

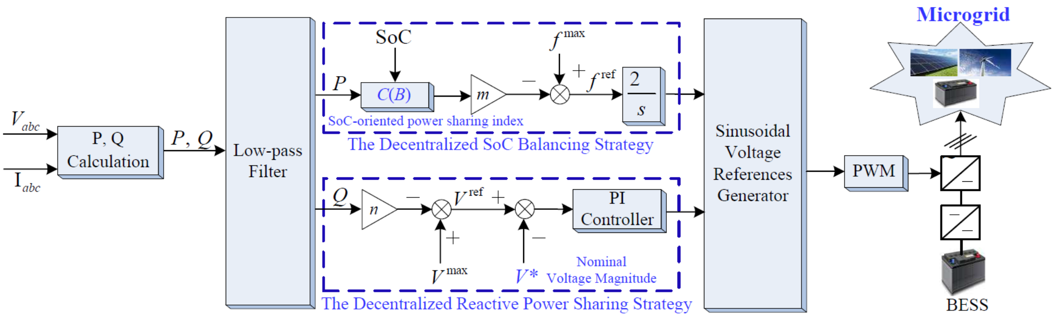


**Figure 2.8:** Decentralized control method implemented in [7].

Distributed control is considered more efficient when it comes to the coordination of multiple storage units, communication between storage units is limited, usually neighboring storage units share information between them. In [33] a distributed control of BESS is used for frequency regulation, the BESS set points are calculated and the appropriate power set points are decided. In [34] a distributed battery management system is used for controlling the state of charge of each battery and communicating with neighboring batteries. More specifically, a Kalman filter is being used to calculate and update information regarding the state of charge of each BESS. Distributed control is used in this study however in the above mentioned studies distributed control is focused on frequency regulation and on controlling the state of charge. In this proposed control the distributed control has as a goal the communication of BESS for voltage regulation.

In a multi-agent system, agents communicate and interact with other agents or the environment in order to calculate and distribute local measurements and information received by other agents. Thus, each agent can accept new information, process them and take actions to perform tasks [8]. These systems contain small tasks which are managed by the agents. Thus, agents have local information and they use the local information in order to execute tasks. The multi-agent system can be used in a distributed control strategy or on a partially centralized control.

In [35] a multi-agent sliding mode control is being proposed for state of charge balance. Each storage unit of the system is considered an agent and these agents communicate together. The links of communication are given by an undirected graph. Each agent uses local measurements and information from other agents, that it communicates, to update its value [36]. The sliding mode control signal determines the participation of each BESS in the power supply.

The aim of this control is that each BESS reaches a balanced state of charge based on the state of charge of neighboring agents/BESS. However, very fast changes in the participation of the BESS leads in high current magnitude changes and this reduces the lifetime of BESS. In this thesis study, BESS are considered agents, however the goal of the proposed control is not to reach a balance in the SoC, but to define a utilization factor for each BESS in order to provide the necessary amount of power for voltage regulation and the state of charge is not used to control the contribution of the BESS.

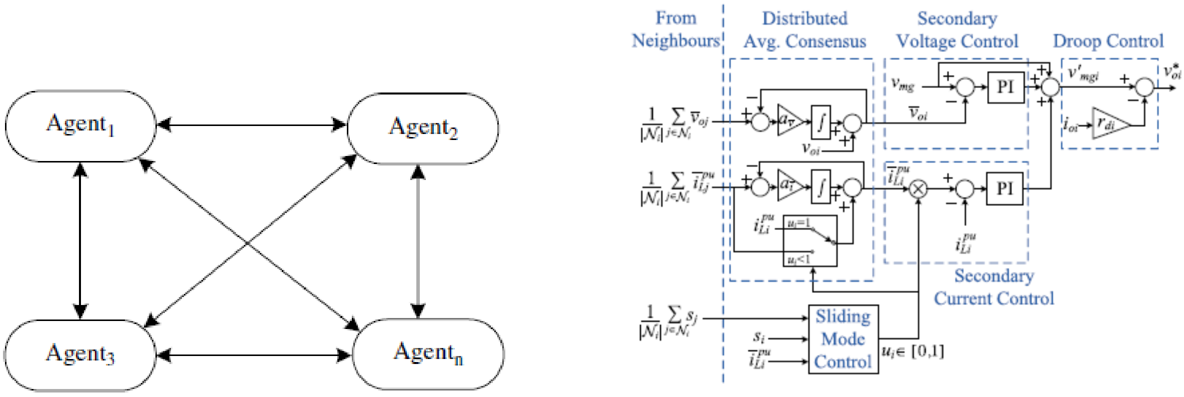


**Figure 2.9:** (a) Multi-Agent system communication [8]. (b) Distributed control implemented in [9].

From the literature review it can be noticed that in most cases a combination of control methods is being used. In existing researches, the control approach used is not only distributed or only decentralized.

Another method of control is presented in [37], where the aggregation of multiple energy storage systems is used to optimize the contribution of them so that they offer flexibility to the network. One of the challenges illustrated in this research is the difficulty of aggregating different type of storage units. In order to target this problem a framework was proposed where units that have similar characteristics would be faced as one energy storage unit. More specifically, the storage units are divided into groups based on each storage's charging time and the charging time of the group and afterwards the state of charge of each group. In this study batteries are chosen as storage units, for the reasons explained in section 2.2, and their aggregation is not done based on their charging times but they are distributed into ”neighborhoods” and exchange messages between them. Thus, the proposed control facilitates the increasing number of BESS as their characteristics are not affecting their implementation, while the above aggregation method restricts the implementation of storage units based on one characteristic.

In [38] a contract net protocol for decision making is used for communication of multiple agent systems. In [10] an intelligent control with the use of fuzzy-logic for charging and discharging of BESS is implemented. Each storage unit is considered an agent and the fuzzy control is used to balance the state of charge within the permitted limits as well as to achieve optimal power sharing between distributed generators and BESS. Thus the main focus is to control the state of charge, however the voltage regulation is not studied.

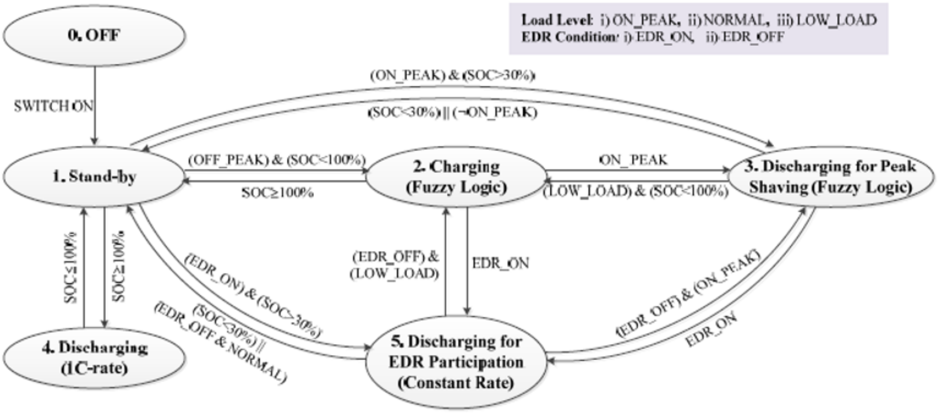


**Figure 2.10:** Fuzzy-logic algorithm for control of BESS in [10].

Consensus algorithm has been used in distributed control in order to facilitate the voltage and frequency restoration of energy networks. However, in these studies the algorithm was aiming into reaching an agreement in the value of power given by the batteries, thus all batteries should contribute the same. This way voltage regulation is achieved however batteries are not operating efficiently as they absorb or produce more power than needed. In [39] first the power needed for voltage regulation is decided through a local control for each BESS, this amount of power is optimized then based on a consensus algorithm as well as the battery's availability and after that the final power contribution of each BESS is determined.

In this thesis study a coordination control of multiple BESS is developed and a consensus algorithm is used in order to regulate voltage. However, consensus is reached when voltage is regulated within the limits and not when all the batteries contribute the same amount of power. Thus, the algorithm is terminated as soon as voltage is regulated and not when all batteries agree on the same amount of power contribution to the system. Furthermore, the state of charge of each battery is controlled locally and only when the limit of state of charge is reached the battery will instantly be disconnected and neighboring batteries will equally contribute the amount of power, that the unavailable battery would contribute under normal operation, until the battery becomes available for use again. The developed control is further explained in chapter 3.

### 2.3.1. *Contribution of this research study*

The contribution of this research study is the development of a control method that facilitates the increasing number of BESS in the network while focusing on regulating voltage violations created by the high penetration of PV units. According to the literature review, the main research goals in most studies were frequency deviations and state of charge control rather than voltage limit violation due to PV unit penetration. Moreover, a comparison of the proposed coordination control strategy to the decentralized control will contribute in giving insight on why the proposed control could be more beneficial in voltage regulation problems. More specifically, for this purpose the case of one BESS being unavailable for providing power will be studied with both control methods. Finally, the behavior of one of the BESS with the proposed control implemented will be tested in the laboratory in order to evaluate the behavior of the BESS in real-time application compared to the simulation. This will contribute in determining whether this control can be further implemented in real distribution networks to mitigate voltage limit violations caused by the intermittency of renewable energy sources. In the conclusions (6.2) the contributions of this research study are presented after the examination of the results.

# 3

# Coordination Control Strategy

In this chapter the proposed coordination control strategy of BESS is presented. In section 3.1 the graph theory used in the consensus algorithm is explained. In section 3.2 the developed coordination control strategy is depicted in detail. The control of the inverters is given in section 3.3. Finally, in section 3.4 the coordination control strategy is implemented on the distribution networks used for the simulations presented chapter 5.

## 3.1. *Graph Theory*

In a multi-agent system the communication of the agents is achieved by communication links which can be presented in a graph. Neighboring agents can send information to one another (bidirectional) or one agent can only send information to another and not receive from him (unidirectional).

The graph, in particular, consists of agents connected together by links (communication links). The graph is mathematically represented as $G =$ (V,E), where $V$ represents the agents and $E$ represents the edges or communication links.The edges are represented as a set of nodes $(v_\text{i}, v_\text{j})$ that show the connection between the starting point $i$ and the ending point $j$. It is critical for developing the consensus algorithm to be aware of each agent's neighbors.

The graphs can be $Directed$ or $Undirected$. In an undirected graph there is a bidirectional connection between the agents, thus the set of agents $(v_\text{i}, v_\text{j})$ is the same with the set of agents $(v_\text{j}, v_\text{i})$. In a directed graph every edge has one direction and each set of agents represent only one communication link.

Graphs can also be characterized as Complete when all agents are connected with each other. These graphs are represented mathematically as $K_\text{n}$, where n is the number of agents. Cycle graphs are another type of graph in which an agent is considered a starting point and following the direction of the edges the ending point is the same as the starting point. These graphs are denoted by the symbol $C_\text{n}$, where n is the number of agents [40].

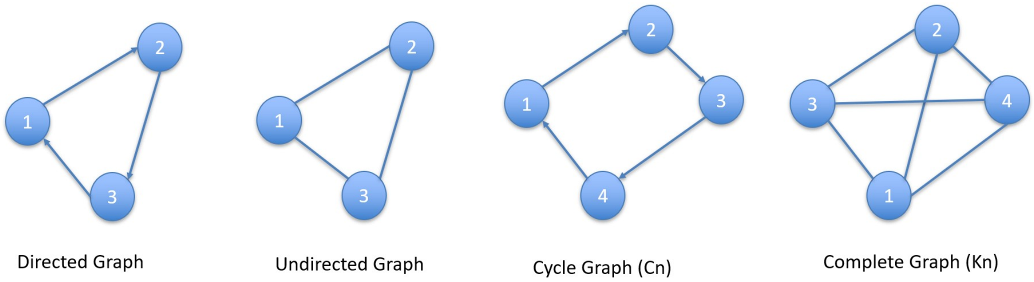


**Figure 3.1:** Directed, Undirected, Cycle and Complete Graph.

### 3.1.1. *Degree Matrix, Adjacency Matrix and Laplacian Matrix*

The Degree Matrix of an undirected graph $D(\mathsf{G})$, is a diagonal matrix. The values of the diagonal matrix represent the number of neighbors that each agent has.

$$D(\mathsf{G}) = \begin{bmatrix} D(\mathsf{V1}) & 0 & ... & 0 \\ 0 & D(\mathsf{V2}) & ... & 0 \\ : & 0 & D(\mathsf{V3}) & : \\ : & 0 & 0 & D(\mathsf{Vn}) \end{bmatrix} \tag{3.1}$$

The Graph in the figure 3.2 will be shown as an example.

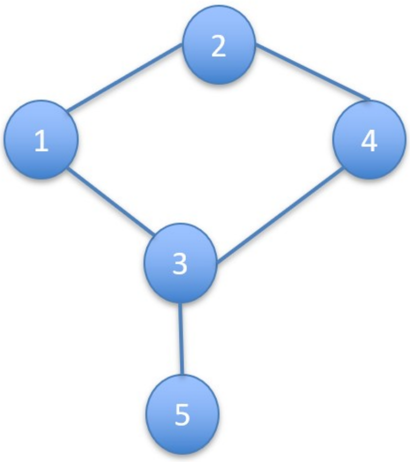


**Figure 3.2:** Example graph.

The Degree Matrix of the graph in figure 3.2 is:

$$D(\mathsf{G}) = \begin{bmatrix} 2 & 0 & 0 & 0 & 0 \\ 0 & 2 & 0 & 0 & 0 \\ 0 & 0 & 3 & 0 & 0 \\ 0 & 0 & 0 & 2 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.2}$$

For instance agent one has two neighboring agents, while agent three has three neighboring agents. The Adjacency matrix $A(\mathsf{G})$ contains information about which agents are neighbors.

As a result, it reveals which agents communicate with one another. For undirected graphs, this matrix is symmetric.

$$A(\mathsf{G}) = \begin{cases} 1 & \text{if nodes i-j are connected, or i=j} \\ 0 & \text{otherwise} \end{cases} \tag{3.3}$$

The Adjacency Matrix of figure 3.2 is:

$$A(\mathsf{G}) = \begin{bmatrix} 1 & 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 1 & 0 \\ 1 & 0 & 1 & 1 & 0 \\ 0 & 1 & 1 & 1 & 0 \\ 0 & 0 & 1 & 0 & 1 \end{bmatrix} \tag{3.4}$$

The Laplacian Matrix $L(G)$ contains all of the important details of the graph. The difference between the degree matrix and the adjacency matrix is defined as the Laplacian matrix. $L(G) = D(G) - A(G)$

From the example given in figure 3.2 the Laplacian Matrix is equal to:

$$L(\mathsf{G}) = \begin{bmatrix} 2 & 0 & 0 & 0 & 0 \\ 0 & 2 & 0 & 0 & 0 \\ 0 & 0 & 3 & 0 & 0 \\ 0 & 0 & 0 & 2 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} - \begin{bmatrix} 1 & 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 1 & 0 \\ 1 & 0 & 1 & 1 & 0 \\ 0 & 1 & 1 & 1 & 0 \\ 0 & 0 & 1 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & -1 & -1 & 0 & 0 \\ -1 & 1 & 0 & -1 & 0 \\ -1 & 0 & 2 & -1 & 0 \\ 0 & -1 & -1 & 1 & 0 \\ 0 & 0 & -1 & 0 & 0 \end{bmatrix} \tag{3.5}$$

Laplacian matrix consists of positive eigenvalues $(0 = \lambda_1 \leq \lambda_2 \leq \lambda_i \leq \lambda_n)$ ,the minimum eigenvalue is zero.

The Consensus algorithm is used in order to achieve coordination of multi-agent systems. The term consensus, in this context, refers to the agents' agreement on a certain shared decision that is conveyed between them. When the agents agree on that decision the consensus is achieved. In consensus algorithm, agents communicate the value of interest amongst them and the algorithm updates the information of the neighboring agents. Consensus algorithm is divided into two categories: consensus with a leader and consensus without a leader agent [41].

The consensus algorithm involves the agents exchanging information and adjusting their behavior to achieve consensus. The primary state of the agents is determined and then it is updated based on the communication with the neighboring agents until a common goal $x$ is reached.

$$x_{\mathsf{i}}[t_{\mathsf{s}}] = x_{\mathsf{i}}[t_{\mathsf{s}} - 1] + u_{\mathsf{i}}[t_{\mathsf{s}} - 1] \tag{3.6}$$

$$u_{\mathsf{i}}[t_{\mathsf{s}} - 1] = \sum_j A(x_{\mathsf{j}}[t_{\mathsf{s}} - 1] - x_{\mathsf{i}}[t_{\mathsf{s}} - 1]) \tag{3.7}$$

where, A is the Adjacency Matrix which depicts the neighboring nodes. From the equation 3.6:

$$x_{\mathsf{i}}[t_{\mathsf{s}}] = \sum_j C_{\mathsf{ij}} x_{\mathsf{j}}[t_{\mathsf{s}} - 1] \tag{3.8}$$

$$C_{\text{ij}} = \begin{cases} 1/n_{\text{i}} & \text{if nodes i-j are connected} \\ 0 & \text{otherwise} \end{cases} \tag{3.9}$$

The equation 3.9 shows the communication weights of the neighboring agents. The consensus goal is achieved by taking into account the previous value of the agent and the state of the neighboring agents.

Consensus is achieved in a distributed way, there is no need for central controller. As it can be concluded consensus algorithm can be used for the coordination of multiple agents [39].

## 3.2. *Coordination Control Strategy of BESS*

As the number of renewable energy sources grows, so does the number of energy storage solutions. The stochastic nature of weather events causes uncertainty in electricity power output, resulting in an overvoltage or undervoltage problem. Because the BESS can assist in resolving this issue, a local and a distributed control are chosen for their coordination [39].

The distributed control is achieved with the use of consensus algorithm. The buses of the low voltage distribution network that have BESS connected are considered as nodes, the BESS connected on them as agents and the lines that connect the buses are considered as the communication links that share the information between the neighboring agents. Each of these agents have an initial state and a utilization factor is allocated to everyone of them. The utilization factor is of great importance as it determines how much each BESS contributes to the voltage regulation. The consensus algorithm updates the utilization factors until the voltage magnitude of the buses does not surpass the limit points, ensuring that all BESS contribute the necessary amount of power for achieving voltage regulation.

In order to initialize the consensus algorithm, a utilization factor is considered as a *leader* $(u_{\text{leader}})$ and it gets updated until the voltage regulation of the system is achieved. This utilization factor is considered as leader because it performs as a reference for the utilization factors of the other batteries $(u_{\text{i}})$ [5].

In order to achieve the voltage regulation of the low voltage distribution network by using the consensus algorithm, the leader utilization factor $(u_{\text{leader}})$ represent the battery connected to the node/bus (leader bus) that has the highest voltage, if the higher limit of voltage is violated, or it represents the battery connected to the node/bus that has the lowest voltage, if the lower limit is violated. The leader utilization factor is updated in discrete time step (based on the Simulink's Discrete Sample Time, Ts= 5e-05 sec) until the voltage is regulated within the limits and the rest of the utilization factors (followers-$u_{\text{i}}$) follow that value and their value is determined by the communication with the neighboring BESS. This communication between the leader and the followers is accomplished through communication links, which in this case are network lines.

The consensus algorithm uses voltage limits so that if the voltage exceeds the upper limit, the battery charges and if the voltage falls below the lower limit, the battery discharges. More specifically, if the voltage of the leader bus (case 1: overvoltage problem) exceeds the upper limit, the utilization factor increases, whereas if the voltage of the leader bus (case 2: undervoltage) falls below the lower voltage limit, the utilization factor decreases. In all other cases, when the voltage does not exceed any limits, the utilization factor is zero, and the batteries do not contribute to the system. The equation for the calculation of the leader utilization factor is 3.10.

$$u_{\text{leader}} = \begin{cases} u_{\text{leader}}(t - t_{\text{s}}) + G_{\text{ov}}(V_{\text{n}}(t) - 1.05) & \text{if voltage of the bus is } V_{\text{n}}(t) > 1.05 \text{ p.u.} \\ 0 & \text{if voltage of the bus is } 0.95\text{p.u.} < V_{\text{n}}(t) < 1.05 \text{ p.u.} \\ u_{\text{leader}}(t - t_{\text{s}}) + G_{\text{un}}(V_{\text{n}}(t) - 0.95) & \text{if voltage of the bus is } V_{\text{n}}(t) < 0.95 \text{ p.u.} \end{cases} \tag{3.10}$$

where, $t_{\text{s}}$ is the sampling time and $G_{\text{ov}}, G_{\text{un}}$ are gains that control the speed of voltage regulation.

The battery connected to the leader bus will be the first one to be informed about any changes in the utilization factor. The other batteries will be informed about changes in their utilization factor according to the following equation 3.11, 3.12.

$$u_{\text{i}[t]} = \sum_{j=1}^{n} C_{\text{ij}}[t] u_{\text{i}}[t - t_s] \tag{3.11}$$

$$C_{\text{ij}}[t] = \frac{A_{\text{ij}}[t - t_{\text{s}}]}{\sum_{j=1}^{n} A_{\text{ij}}[t - t_{\text{s}}]} \tag{3.12}$$

The utilization factor of the BESS connected to the leading bus increases or decreases according to the voltage of the bus, compared to the permitted limits, the same path is followed by the utilization factors of the other BESS of the following buses until the voltage is regulated.

The amount of power that a battery can provide or store is determined by its utilization factor. When a battery charges, its utilization factor is positive, whereas when it provides energy to the network, it has a negative utilization factor. A local controller is in charge of controlling each battery's state of charge so that it does not surpass the limits. In case a battery has surpassed the state of charge limit then the battery will not contribute to the system and the power that was needed from this battery will be provided by the neighboring batteries, until the battery becomes available for use again.

Following the proposed control scheme, all batteries will contribute to the grid, despite their limitations and capabilities. Thus, the available capacity of each BESS is not affecting the power contribution from them.

In figure 3.3 the flowchart of the proposed control is presented. The consensus control finds the voltage of all the buses; if all voltage magnitudes are within the limits, the batteries do not contribute; in the next time step, these values are updated and checked again to see if any voltage magnitude exceeds any limit points; if so, the bus with the higher voltage is considered the leader (case: overvoltage) or the bus with the lower voltage is considered a leader (case: undervoltage) and the utilization factor of the battery connected to this bus is calculated by the equation 3.10. Following that, the utilization factor for the remaining batteries is computed based on the equations 3.11. The voltage magnitude of all buses is recalculated, and if there is still an overvoltage or an undervoltage at one of the buses, that bus becomes the leader, and the utilization factor of the battery connected to the leading bus, as well as the utilization factors of the other batteries, are calculated again. This process is repeated until all buses' voltages are regulated. In case both voltage magnitude limits are exceeded at the same time due to a fault, then the consensus algorithm will regulate the overvoltage problem and a local control will handle the undervoltage problem.

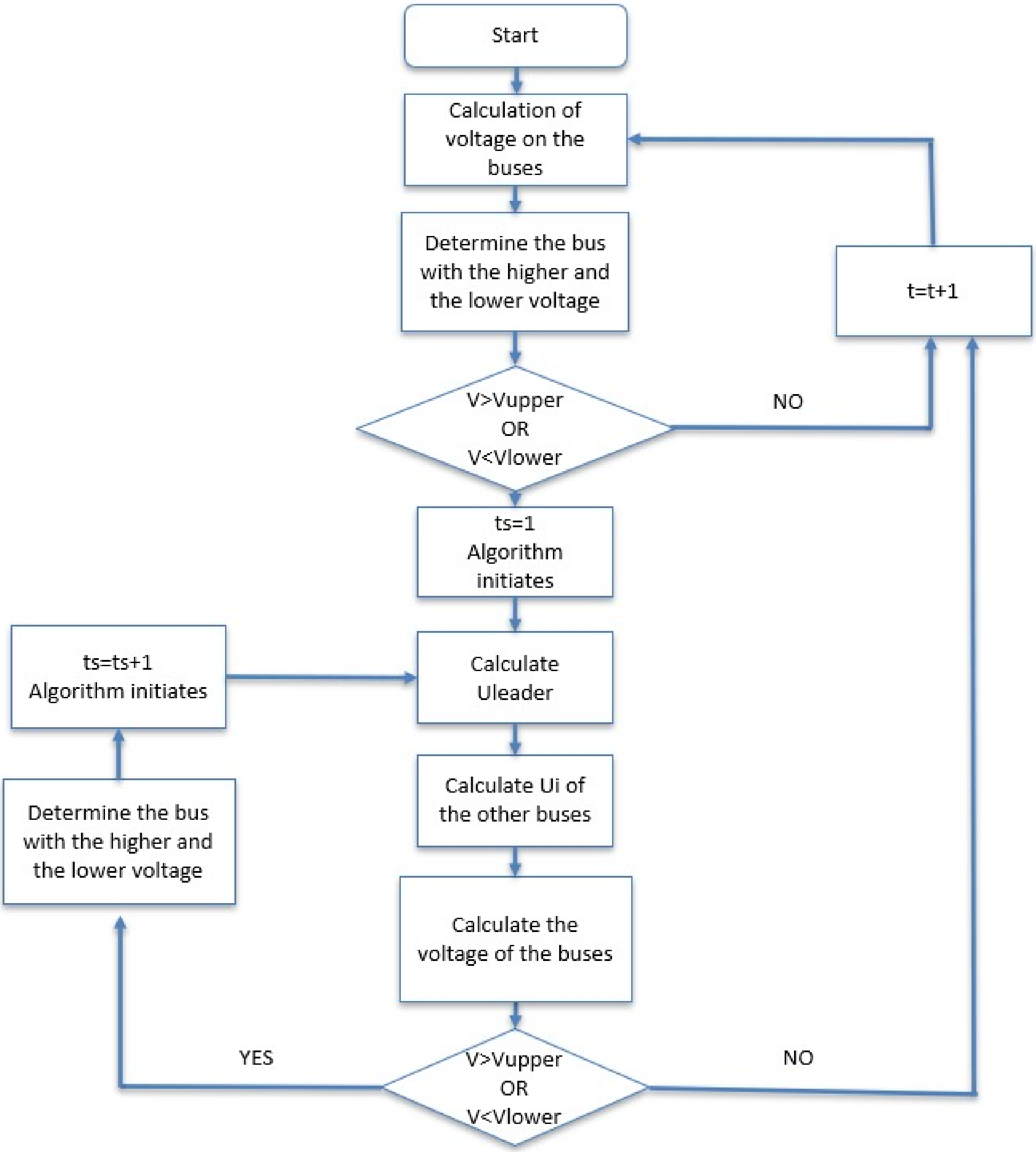


**Figure 3.3:** Consensus algorithm flowchart.

## 3.3. *Control of Inverters*

### 3.3.1. *Control of inverter during coordinated operation of BESS*

The batteries are connected to the network through an inverter. The control of the inverter is of great significance as it determines the operation of the battery. In the figure 3.4 the proposed control of the inverter can be noticed [42]. The Park transformation (d-q frame) is used in order to convert the voltage and the current of the network to a synchronous rotating frame, thus the three phase voltage and current signals are transformed to DC signals. The term *Pref* refers to the reference power that the battery should absorb or provide to the grid. The *Pref* is calculated from the nominal power of each battery multiplied by the utilazation factor of the battery given by the consensus algorithm.

$$P\text{ref}_\text{i} = P\text{nomBat}_\text{i} * u_\text{i} \tag{3.13}$$

In the low voltage distribution network the R/X ratio of the lines is large, thus the use of active power to control overvoltage and undervoltage problems is more effective. As a result the control method proposed focuses on active power instead of changes in the voltage of the DC link which is more commonly used.

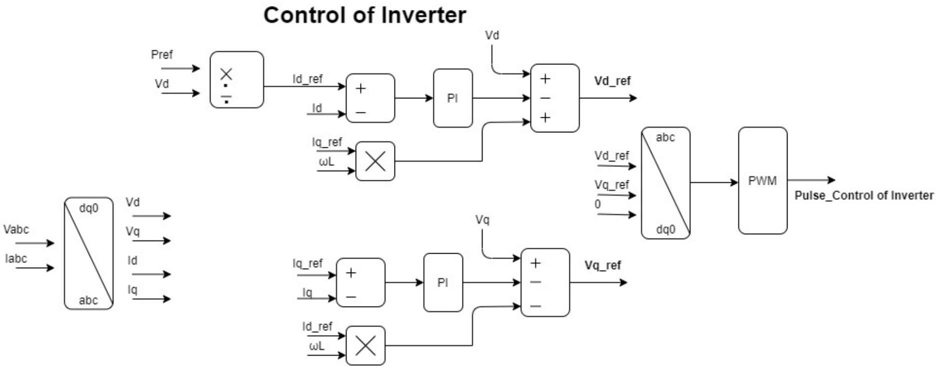


**Figure 3.4:** Control of inverter for the coordination of BESS.

### 3.3.2. *Control of inverter for decentralized operation of BESS*

The decentralized control scheme is based on local measurements of voltage. When the voltage magnitude limits are violated a droop control is used to determine the power needed by the battery so that the voltage restoration within limits is achieved. The reference active power is calculated by the droop coefficient multiplied by the deviation of the voltage magnitude from the limit points.

$$P\text{ref} = \begin{cases} m * (V_\text{n} - 1.05) & \text{if voltage of the bus is } V_\text{n}(t) > 1.05 \text{ p.u.} \\ 0 & \text{if voltage of the bus is } 0.95 \text{ p.u.} < V_\text{n}(t) < 1.05 \text{ p.u.} \\ m * (V_\text{n} - 0.95) & \text{if voltage of the bus is } V_\text{n}(t) < 0.95 \text{ p.u.} \end{cases} \tag{3.14}$$

where,

$$m = \frac{P_\text{PVmax} - P_\text{loadmax}}{|V_\text{limit} - V_\text{n}|} \tag{3.15}$$

A positive value of active power represents the amount of power that the battery should absorb while a negative value of active power represent the amount of power that the battery should provide to the network.

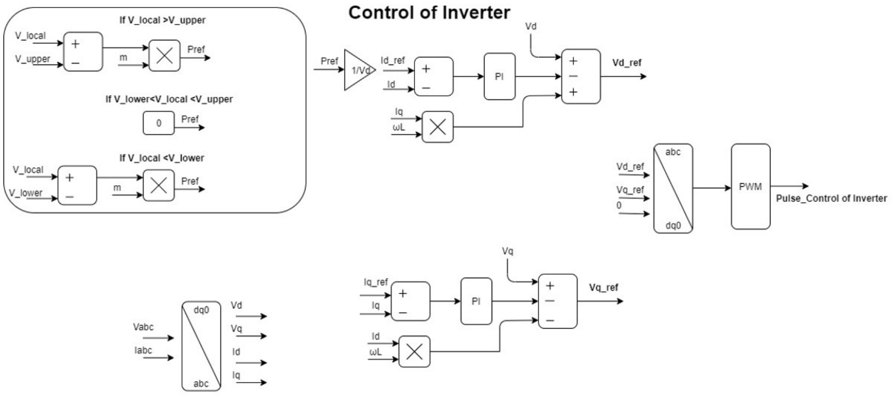


**Figure 3.5:** Control of inverter for decentralized operation of BESS.

During the simulation this control will be used in order to compare the behavior of a low voltage distribution network with the coordination control strategy implemented and with the decentralized control implemented.

One of the basic concerns of a decentralized control scheme is the case when a battery is not available due to maintenance or due to surpassing a state of charge limit and at the same time the voltage on that bus has violated the upper or the lower limit. This case will be studied in section 5.2.

## 3.4. *Development of coordination strategy on Distribution Networks*

### 3.4.1. *Coordination control strategy of BESS on the Eight-Bus System*

In order to evaluate the proposed coordination control an Eight-Bus System is created. This is a low voltage network and it contains three BESS and three PV units. The location of BESS was decided near the load and PV unit, as the main goal of this study is the coordination of BESS regardless their location. This facilitates the expansion of the networks since it can be implemented in all cases regardless the location of the BESS and can be expanded to other types of storage units such as electric vehicles. In the figure 3.6 the network can be seen.

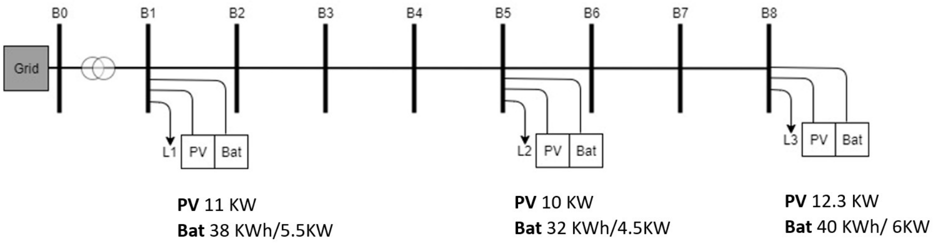


**Figure 3.6:** Eight-Bus Low Voltage Distribution Network.

The communication between the batteries is depicted in the figure 3.7. Battery 1 communicates with battery 2 and itself, battery 2 communicates with battery 1, battery 3 and itself and battery 3 communicates with battery 2 and itself. These communication weights on the lines of figure 3.7 depict the number of batteries that each battery has as neighbors including itself and are used for the calculation of the utilization factors and as a consequence they determine the amount of power each battery will contribute so that voltage stability can be maintained when disturbances happen or when high amount of power is injected by the PV units.

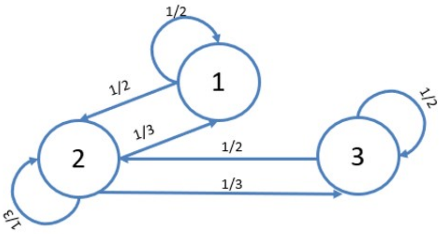


**Figure 3.7:** Communication of BESS in the distribution feeder.

The communication matrix used by the consensus algorithm, which originates from the communication graph of figure 3.7, is:

$$C(\mathsf{G}) = \begin{bmatrix} 1/2 & 1/2 & 0 \\ 1/3 & 1/3 & 1/3 \\ 0 & 1/2 & 1/2 \end{bmatrix} \tag{3.16}$$

### 3.4.2. *Coordination control strategy of BESS on the CIGRE Low Voltage Distribution Network*

Furthermore, the consensus algorithm will also be applied to the CIGRE Low Voltage Test Distribution Network which consists of eighteen buses, six PV units and six BESS, in order to examine the proposed control when a higher number of batteries is used. The location of BESS was chosen to be near the PV unit and loads as explained in the section 3.4.1.

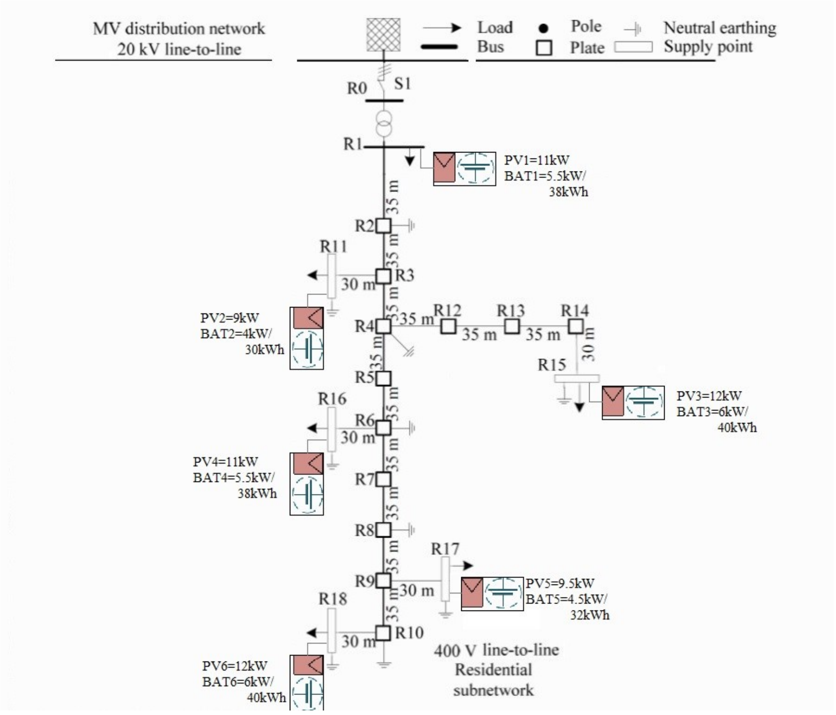


**Figure 3.8:** CIGRE Low Voltage Test Distribution Network with PV and BESS.

In the figure 3.9 the communication graph of BESS can be seen, the numbering (1/n) on the communication lines depict the number of batteries that each battery has as neighbors, for example the number 1/3 denotes that the agent communicates with two neighbor agents and itself.

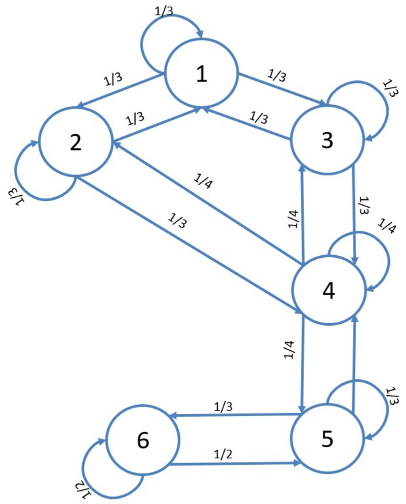


**Figure 3.9:** Communication graph of BESS.

The Degree Matrix and the Adjacency Matrix of the CIGRE Network in figure 3.8 are:

$$D(\mathsf{G}) = \begin{bmatrix} 2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 2 & 0 & 0 & 0 & 0 \\ 0 & 0 & 2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 3 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.17}$$

$$A(\mathsf{G}) = \begin{bmatrix} 1 & 1 & 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 1 & 0 & 0 \\ 1 & 0 & 1 & 1 & 0 & 0 \\ 0 & 1 & 1 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 1 & 1 \end{bmatrix} \tag{3.18}$$

The communication matrix used by the consensus algorithm is:

$$C(\mathsf{G}) = \begin{bmatrix} 1/3 & 1/3 & 1/3 & 0 & 0 & 0 \\ 1/3 & 1/3 & 0 & 1/3 & 0 & 0 \\ 1/3 & 0 & 1/3 & 1/3 & 0 & 0 \\ 0 & 1/4 & 1/4 & 1/4 & 1/4 & 0 \\ 0 & 0 & 0 & 1/3 & 1/3 & 1/3 \\ 0 & 0 & 0 & 0 & 1/2 & 1/2 \end{bmatrix} \tag{3.19}$$

# 4

# Simulation of Low Voltage Distribution Networks

In this chapter the specification of the low voltage distribution networks used for simulations are given. More specifically, in section 4.1 the details of the simple Eight-Bus Low Voltage Network are presented. The specification of the CIGRE Low Voltage Test Network are given in section 4.2. In section 4.3 the CIGRE network developed in MATLAB/Simulink is illustrated. Finally, in section 4.4 the laboratory setup used for the test conducted on the behavior of one of the batteries, with the proposed control implemented, is shown.

## 4.1. *Eight-Bus Low Voltage Network Specification*

An Eight-Bus Low Voltage Network was modeled in order to develop and test the coordination control strategy for the coordination of BESS. In chapter 3 the developed and implemented control was explained. In this section the details of this system are given. In this simple low voltage network three BESS and three PV units were integrated into the system. The system's frequency is 50 Hz and the three phase voltage is 400 Volts.

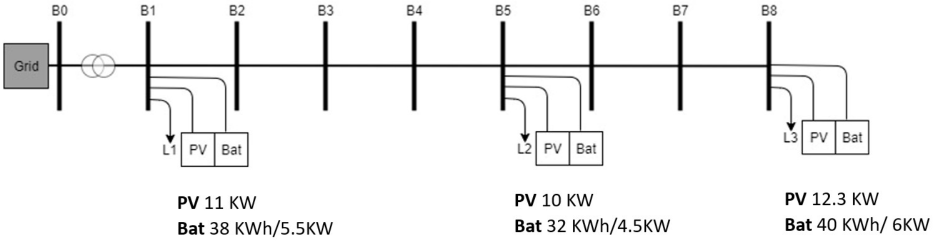


**Figure 4.1:** Eight-Bus Low Voltage Distribution Network.

In table 4.1 the details of the Photovoltaic (PV) units integrated in this network are shown.

**Table 4.1:** PV units in Eight-Bus Low Voltage Network.

| PV | Power (kW) | Bus |
|---|---|---|
| PV 1 | 11 | Bus 1 |
| PV 2 | 10 | Bus 5 |
| PV 3 | 12.3 | Bus 8 |

In table 4.2 the details of the batteries (BESS) integrated in this network are shown.

**Table 4.2:** BESS in Eight-Bus Low Voltage Network.

| BESS | Power (kW) | Energy (kWh) | Bus |
|---|---|---|---|
| BESS 1 | 5.5 | 38 | Bus 1 |
| BESS 2 | 4.5 | 32 | Bus 5 |
| BESS 3 | 6 | 40 | Bus 8 |

## 4.2. *CIGRE Low Voltage Network Specification*

The implemented control strategy on the CIGRE Low Voltage Network was explained in chapter 3. In this section the details of the network are given. The specifications of the Cigre Low Voltage Network are found in the Pandapower Library. In section 4.2.1 the frequency and the voltage of the medium voltage distribution System are presented. In 4.2.2 the specification of the transformer are shown and section 4.2.3 the specification of the three phase lines are depicted. Finally, in section 3.1 the power rating of the PV units and BESS of the systems are shown.

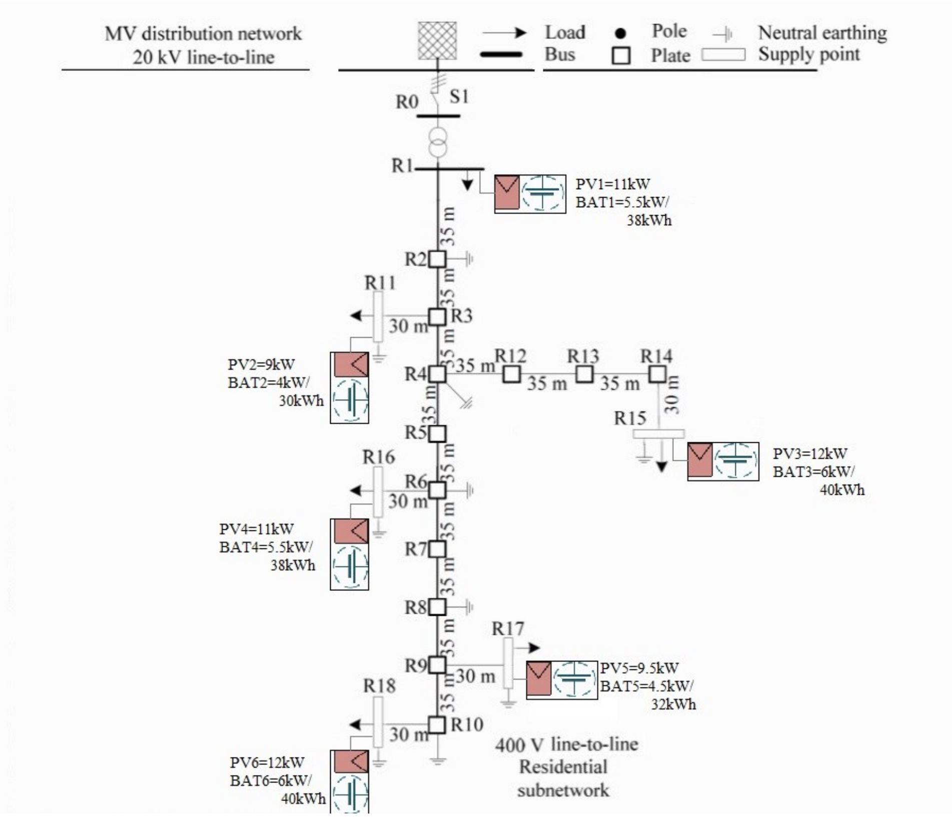


**Figure 4.2:** CIGRE Low Voltage Test Distribution Network with PV and BESS.

### 4.2.1. *Medium Voltage Transformer*

**Table 4.3:** Medium Voltage.

| **Frequency** ***(Hz)*** | **Voltage Magnitude** ***(kV)*** | **SC1/SC0** ***(MVA)*** | **X1/R1=X0/R0** |
|---|---|---|---|
| 50 | 20 | 1000 | 1 |

### 4.2.2. *Transformer*

**Table 4.4:** Transformer Characteristics.

| **Srated** ***(KVA)*** | **V1/V2** ***(KV)*** | **Rr(%)** | **Xr(%)** | ***Topology*** |
|---|---|---|---|---|
| 500 | 20/0.4 | 1 | 4 | Dyn |

### 4.2.3. *Line Specification*

In this section the details of the lines of the CIGRE Low Voltage Network used for the simulations are presented in table 4.5.

**Table 4.5:** Line Specifications.

| | **from_bus** | **to_bus** | **c_nf_per_km** | **r_ohm_per_km** | **x_ohm_per_km** |
|---|---|---|---|---|---|
| 0 | 2 | 3 | 0 | 0.1620 | 0.0832 |
| 1 | 3 | 4 | 0 | 0.1620 | 0.0832 |
| 2 | 4 | 5 | 0 | 0.1620 | 0.0832 |
| 3 | 5 | 6 | 0 | 0.1620 | 0.0832 |
| 4 | 6 | 7 | 0 | 0.1620 | 0.0832 |
| 5 | 7 | 8 | 0 | 0.1620 | 0.0832 |
| 6 | 8 | 9 | 0 | 0.1620 | 0.0832 |
| 7 | 9 | 10 | 0 | 0.1620 | 0.0832 |
| 8 | 10 | 11 | 0 | 0.1620 | 0.0832 |
| 9 | 4 | 12 | 0 | 0.8220 | 0.0847 |
| 10 | 5 | 13 | 0 | 0.8220 | 0.0847 |
| 11 | 13 | 14 | 0 | 0.8220 | 0.0847 |
| 12 | 14 | 15 | 0 | 0.8220 | 0.0847 |
| 13 | 15 | 16 | 0 | 0.8220 | 0.0847 |
| 14 | 7 | 17 | 0 | 0.8220 | 0.0847 |
| 15 | 10 | 18 | 0 | 0.8220 | 0.0847 |
| 16 | 11 | 19 | 0 | 0.8220 | 0.0847 |

### 4.2.4. *Renewable energy generators and Storage Units*

In order to examine the operation of the coordinated control method in the CIGRE Low Voltage Distribution Network, six PV units and six BESS are integrated in the system. In each bus where a PV unit is installed there will also be a BESS. In table 4.6 the PV unit nominal power produced can be noticed and in table 4.7 the BESS characteristics are shown.

**Table 4.6:** PV units in CIGRE Low Voltage Network.

| **PV** | **Power (kW)** | **Bus** |
|---|---|---|
| PV 1 | 11 | Bus 1 |
| PV 2 | 9 | Bus 11 |
| PV 3 | 12 | Bus 15 |
| PV 4 | 11 | Bus 16 |
| PV 5 | 9.5 | Bus 17 |
| PV 6 | 12 | Bus 18 |

The power produced by the PV units can be used to power residential loads and small scale businesses [43].

**Table 4.7:** BESS in CIGRE Low Voltage Network.

| **BESS** | **Power (kW)** | **Energy (kWh)** | **Bus** |
|---|---|---|---|
| BESS 1 | 5.5 | 38 | Bus 1 |
| BESS 2 | 4 | 30 | Bus 11 |
| BESS 3 | 6 | 40 | Bus 15 |
| BESS 4 | 5.5 | 38 | Bus 16 |
| BESS 5 | 4.5 | 32 | Bus 17 |
| BESS 6 | 6 | 40 | Bus 18 |

## 4.3. *CIGRE Low Voltage Network in MATLAB/Simulink*

In figure 4.3 the modeled CIGRE Low Voltage Network in MATLAB/Simulink is presented. This is used in order to evaluate the developed coordination control strategy.

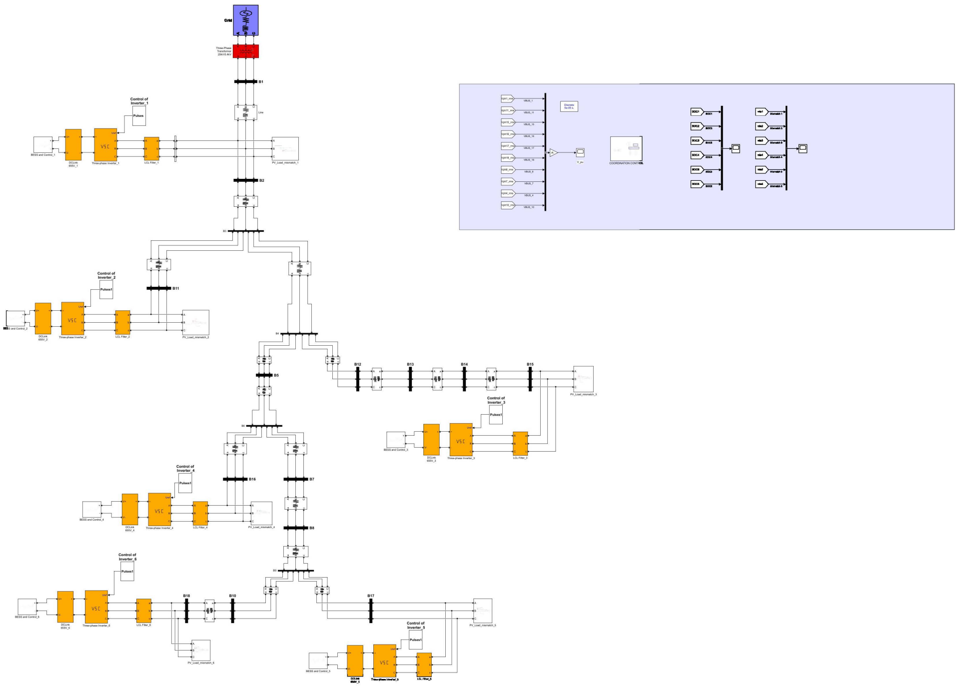


**Figure 4.3:** CIGRE Low Voltage Network in MATLAB/Simulink.

In figure 4.4 the calculation the leader utilization factor is shown. This is developed based on the equation 3.10 presented in chapter 3. This is of great significance as it determines the other utilization factors and as a consequence the contribution of BESS for voltage regulation. In figure 4.5 the calculation of the other utilization factors in MATLAB/Simulink is depicted. These are calculated from the equations 3.11,3.12 of chapter 3.

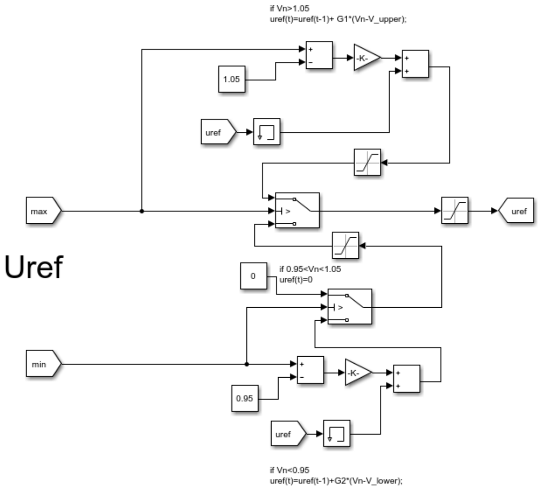


**Figure 4.4:** Computation of the leader utilization factor in MATLAB/Simulink.

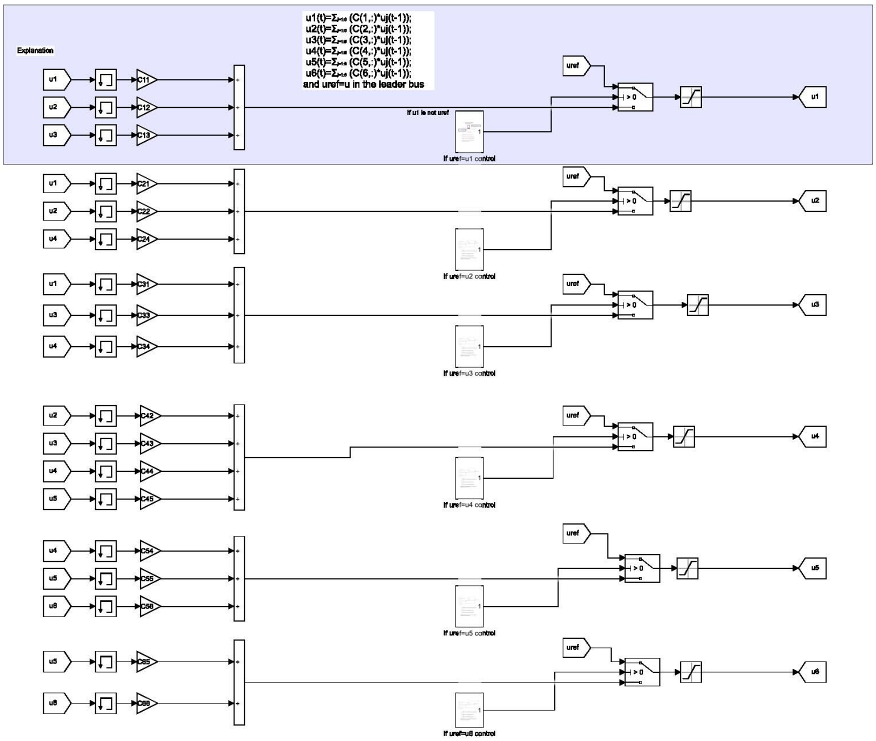


**Figure 4.5:** Computation of utilization factors for all the BESS.

Finally, in figure 4.6 the developed control of the inverters connected to the batteries is shown. This was developed based on control scheme presented in section 3.3.1 of chapter 3. In this subsystem the contribution of each BESS is controlled based on the utilization factor determined for that BESS.

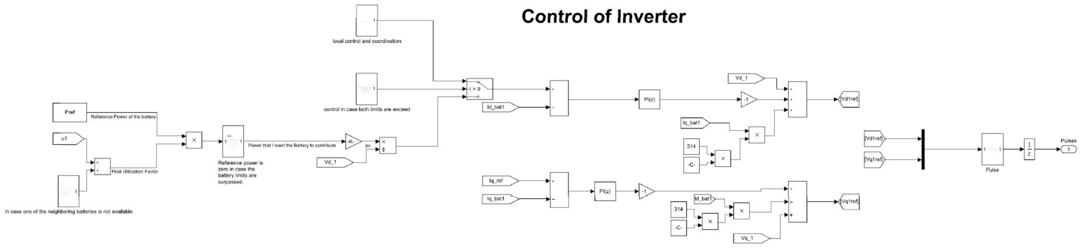


**Figure 4.6:** Control of inverter modeled in MATLAB/Simulink.

## 4.4. *Laboratory Setup*

The CIGRE Low Voltage Network was developed in RT-Lab, which is a software used in real-time applications. More specifically, RT-Lab provides the possibility to validate simulated programs in real-time. This software is connected to the laboratory setup. Figure 4.7 depicts the laboratory setup used for the real-time testing of the developed coordination control strategy by emulating one of the system's batteries.

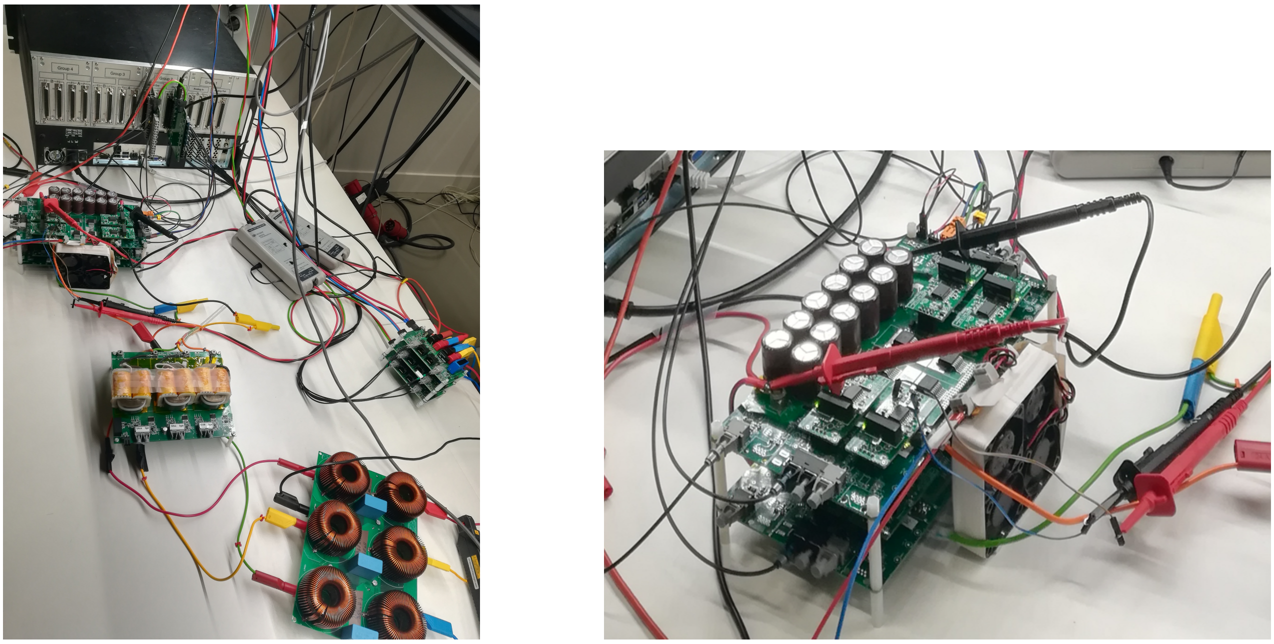


**Figure 4.7:** (a) Laboratory setup. (b) Inverter connected to BESS 1.

A DC source is used as a battery, which is connected to the inverter. The inverter is connected to a filter in order to eliminate harmonics. The filter is connected to an AC source which represents the bus of the battery connected to the Low Voltage Network. In figure 4.8 the electrical design of the lab setup is shown.

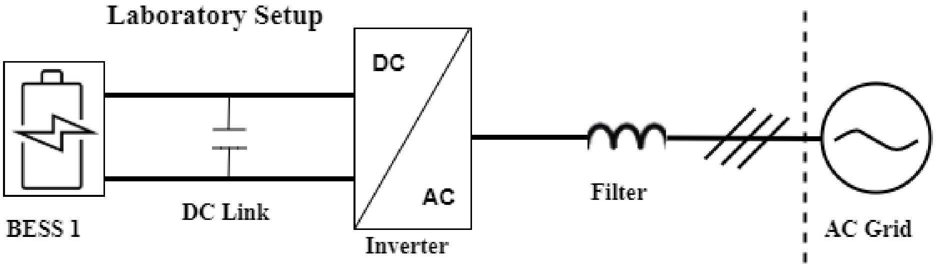


**Figure 4.8:** Electrical design of the laboratory setup.

The RT-Lab simulation is used for the control of the inverter. The main goal of this laboratory testing is to examine the behavior of the battery's contribution in real-time application in comparison to the results of the simulation, in order to validate the developed coordination control strategy in real-time conditions. In chapter 5.2.4 the results of the laboratory testing are illustrated.

# 5

# Simulation and Laboratory Results

In this chapter the simulation results and the results from the laboratory test conducted are presented. In sections 5.1-5.2 the simulation results from the Eight-Bus and CIGRE Low Voltage Distribution Networks are given. In section 5.2.4 the laboratory results are shown. Finally, in section 5.3 the conclusions from the simulation results are illustrated.

## 5.1. *BESS coordination in the Eight-Bus System*

A daily profile mismatch is used, where the PV and load data hold the same value every 15 minutes for presenting the daily mismatch pattern. It is assumed, since simulations are focusing on a distribution network (residential area), that customers have identical power mismatch profiles. In figure 5.1 the mismatch used during the simulations on the Eight-Bus System is shown.

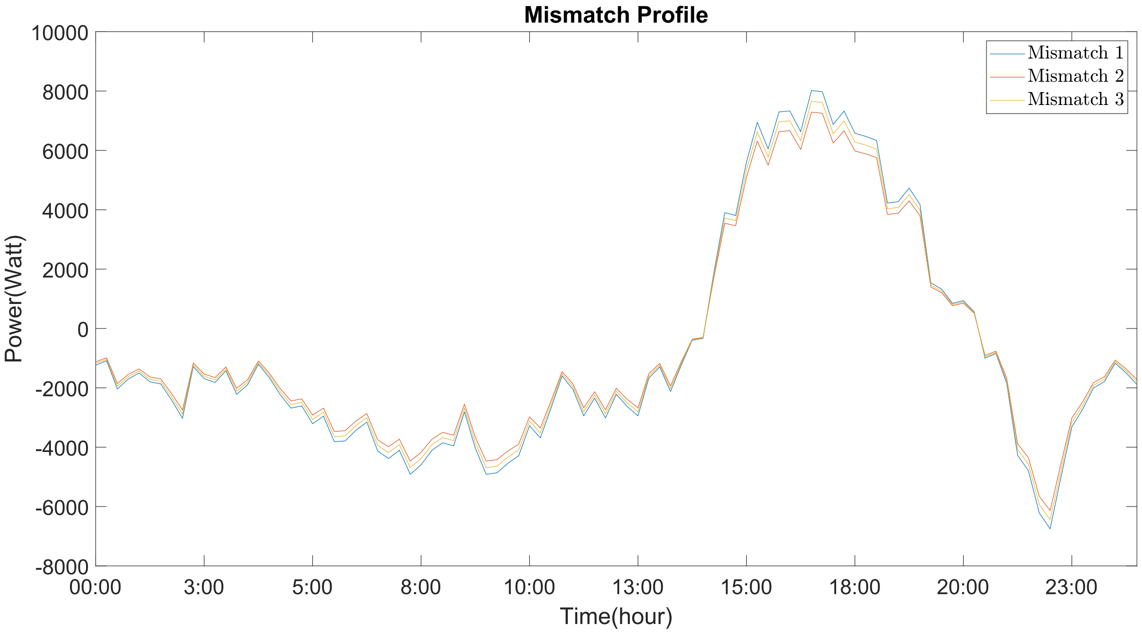


**Figure 5.1:** Daily mismatch profile.

In this low voltage test network there are three BESS and three PV units integrated. When no control is implemented the voltage magnitude of the buses surpasses mainly the upper limit of

1.05 p.u. and reaches and surpasses instantly the lower limit of 0.95 p.u., this can be noticed in figure 5.2.

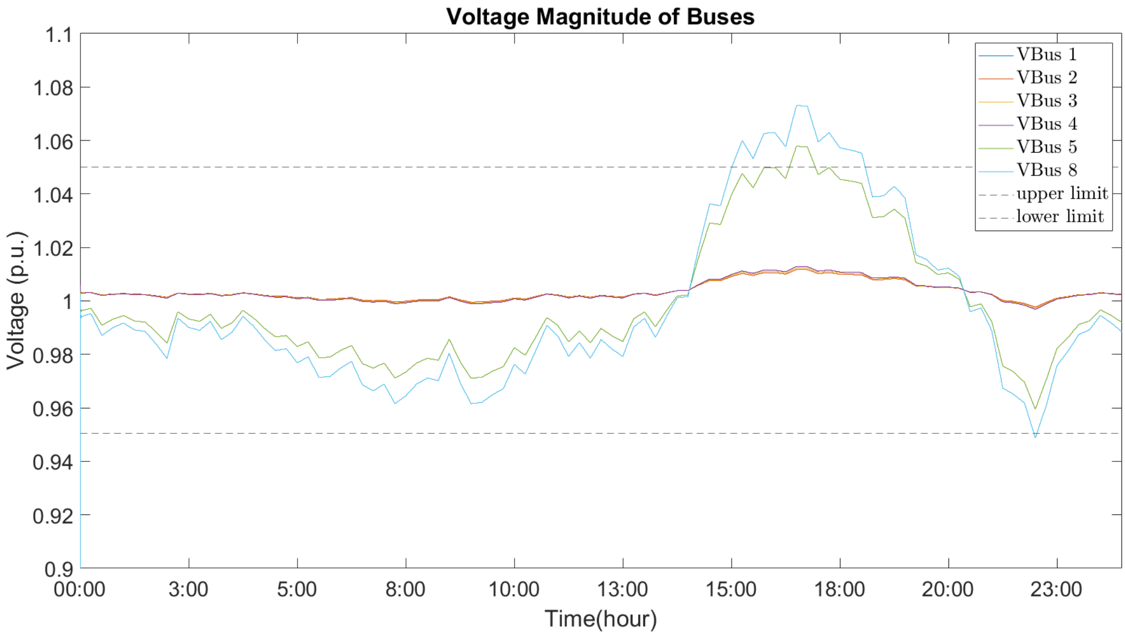


**Figure 5.2:** Voltage magnitude in the Eight-Bus system when no control is implemented.

In the figure 5.3 the results of the implemented coordination control strategy is shown. The voltage magnitude of the buses is successfully regulated within the allowable limits.

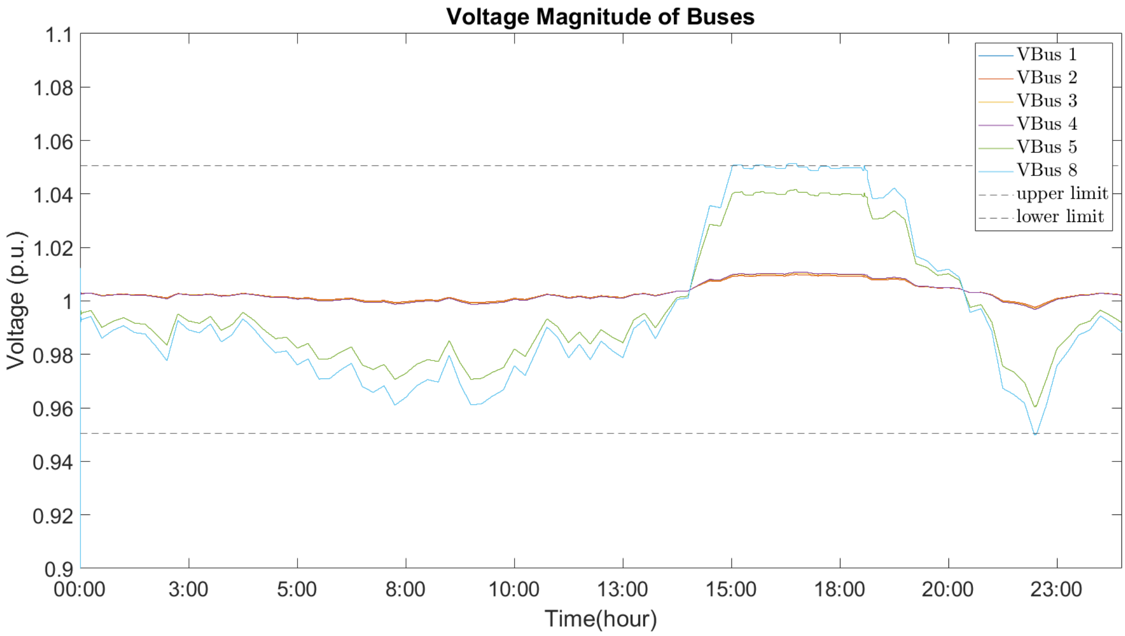


**Figure 5.3:** Voltage magnitude in the Eight-Bus system with the coordination control strategy implemented.

The utilization factors used for the voltage regulation were calculated through the coordination algorithm and they determine the amount of power that each BESS should contribute to the network in order to regulate the voltage. In figure 5.4 the utilization factors for the simulation in the Eight-Bus system are presented. When the utilization factors have a positive value, the BESS should absorb power from the grid while when they have a negative value the BESS should provide power to the grid.

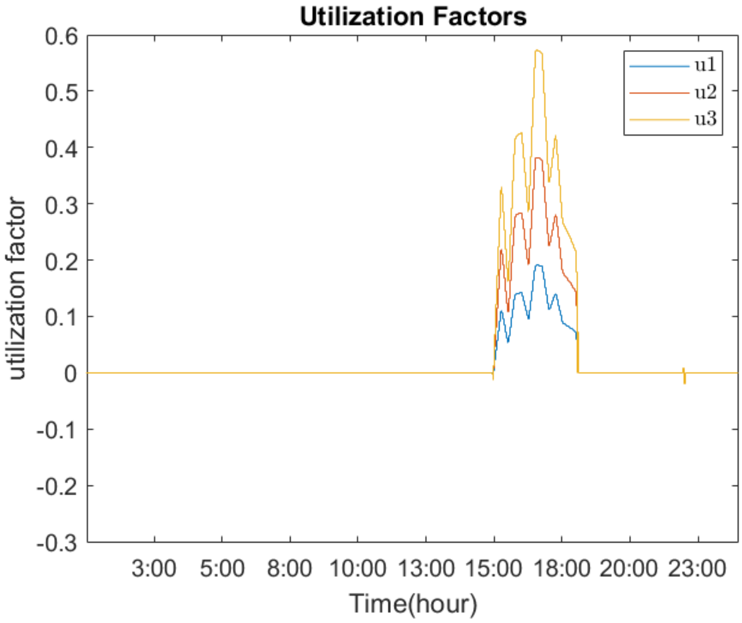


**Figure 5.4:** Utilization factors of BESS in the Eight-Bus system.

In figure 5.5 the state of charge of the batteries is shown, between 15:00 to 19:00 the batteries are charging. No discharge can be noticed because around 22:00 a very small amount of power is provided to the grid instantly so the change in the batteries available capacity is very small.

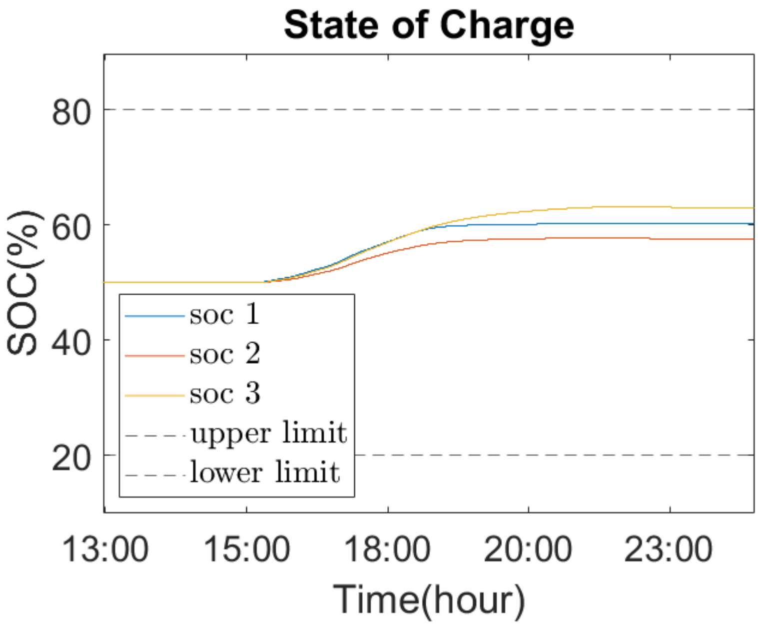
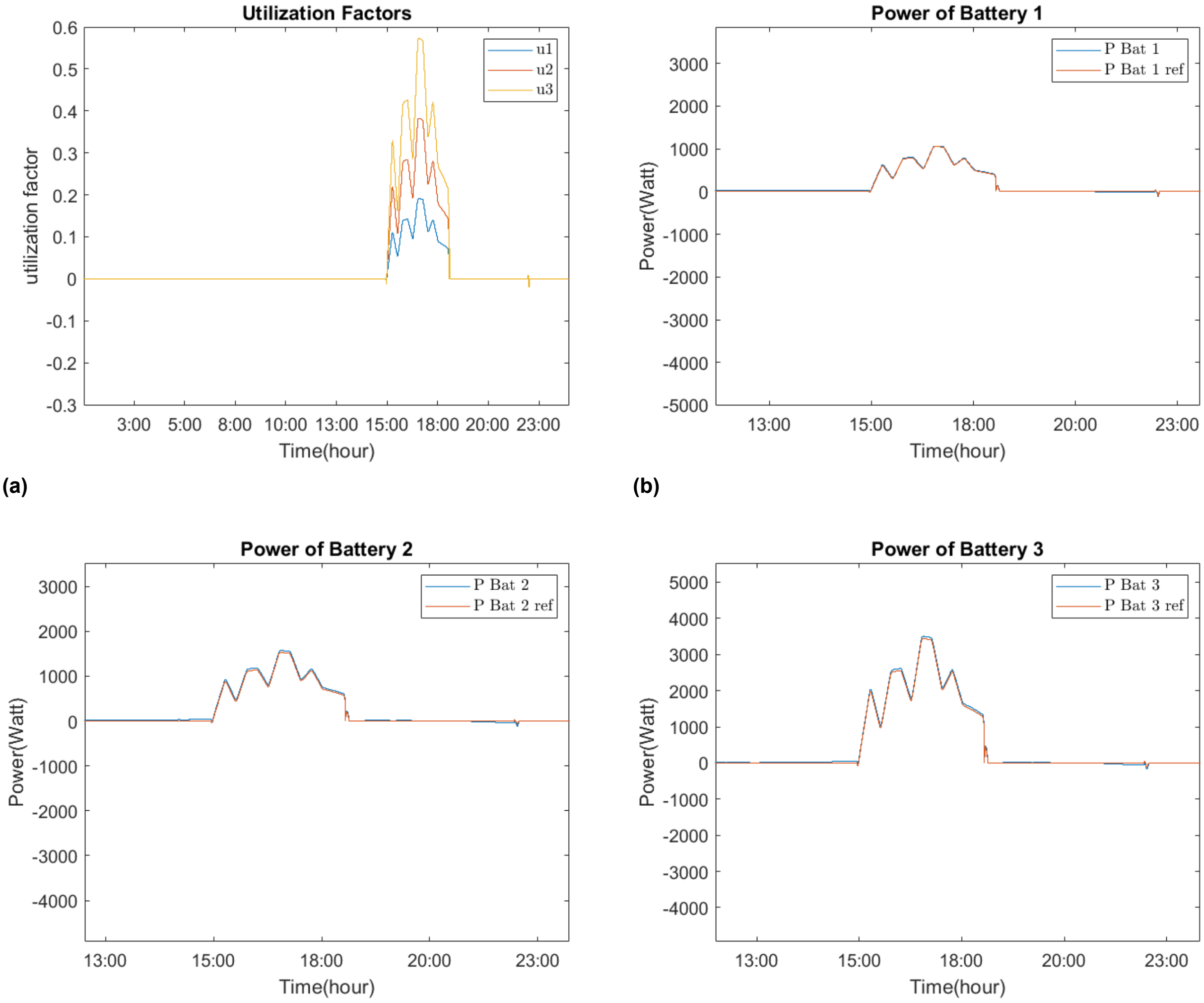


**Figure 5.5:** State of Charge of BESS (%).

In figure 5.6 the power contribution of the three batteries is illustrated. It can be seen that the pattern of the power is similar in all batteries and similar with the pattern of the utilization factor. This shows how the utilization factors affect the contribution of the batteries. Moreover, in all batteries the reference power that is required for the voltage regulation is nearly equal to the amount of power the battery actually contributes which confirms the proper operation of the developed control strategy.



**(a)** **(b)** **(c)** **(d)**

**Figure 5.6:** (a) Power contributed by BESS 1. (b) Power contributed by BESS 2. (c) Power contributed by BESS 3.

## 5.2. *BESS coordination in the CIGRE Distribution Network*

In this section the Cigre Low Voltage Network will be used for the simulations and four case-studies will be conducted. In the first case-study all the BESS will have the same state of charge (subsection 5.2.1), in the second case-study (subsection 5.2.2) BESS will have different state of charges in order to see how the control performs when all batteries have different available capacity and the performance of the coordination control will specifically be tested when one of the BESS becomes unavailable due to reaching the upper limit (80%). In the third case-study the decentralized control strategy implemented on the BESS will be presented and compared with the coordination control strategy (subsection 5.2.3). Finally, the results of the behavior of one of the BESS tested on the laboratory with the implementation of the coordination control will be illustrated (subsection 5.2.4).

In all case-studies a daily profile mismatch is used, where the PV production and load data hold the same value every 15 minutes for presenting the daily mismatch pattern as it was explained in the Eight-Bus system simulations. During the times of day when limits are violated, a detailed profile with data every 3 minutes will be presented to examine the proper operation of the control strategy with more detailed data.

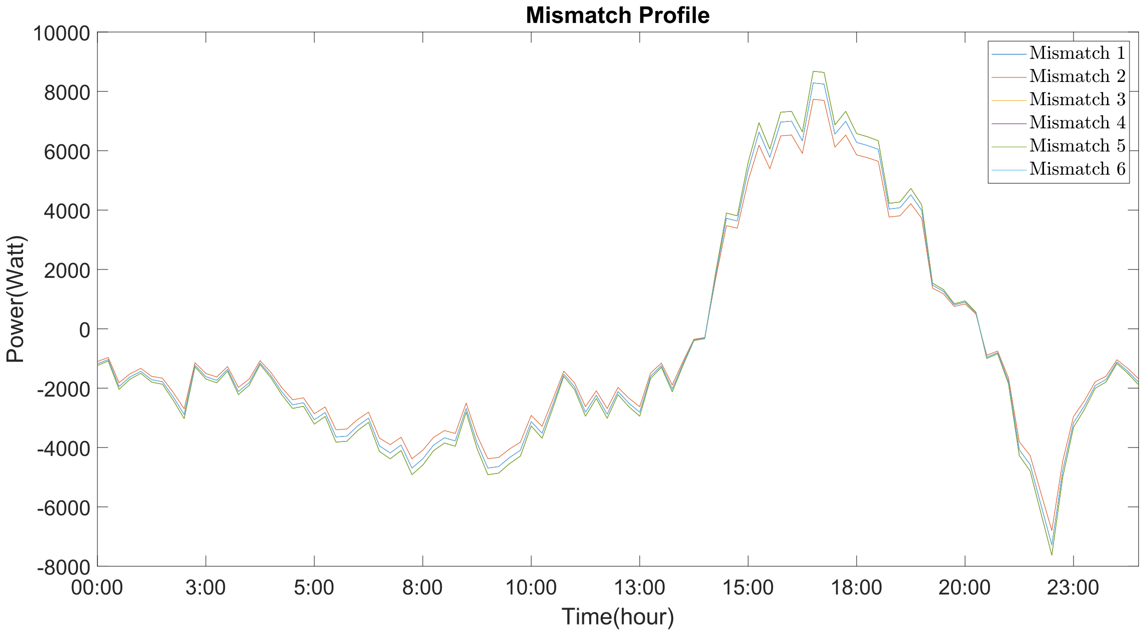


**Figure 5.7:** Daily mismatch profile.

### 5.2.1. *BESS with the same SoC (50%)*

Figure 5.8 depicts the voltage magnitude of the buses if no control and no BESS are implemented in the low voltage distribution network. Voltage in buses 15, 17, and 18 reaches and exceeds the upper limit of 1.05 p.u. between 15:00 and 19:00 o clock, causing problems with network stability. Furthermore, between 21:00 o clock to 23:00 o clock, the voltage on buses 15 and 18 reaches and exceeds the lower limit of 0.95 p.u..

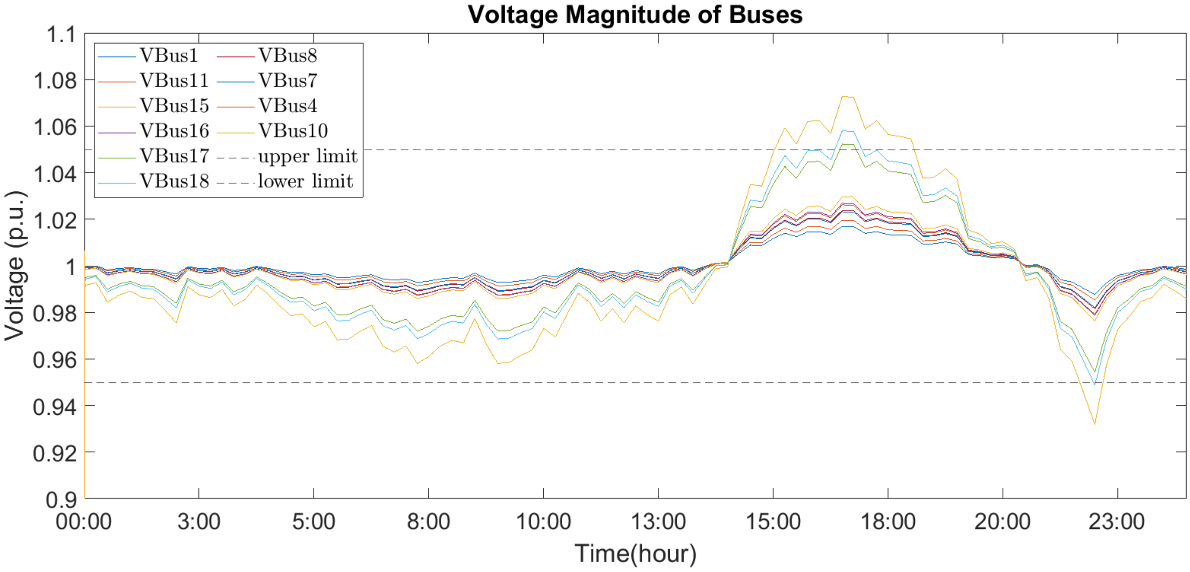


**Figure 5.8:** Voltage magnitude of buses with no control implemented.

These limit violations occur since during the period between 15:00 and 19:00 o clock, when PV unit production is high and demand is low, a large amount of power is inserted into the grid, causing an overvoltage, and during the period between 21:00 and 23:00 o clock, when PV unit production is low and demand is high, an undervoltage problem occurs. Thus, with the integration of the BESS and the implementation of the developed control these limit violations should be mitigated.

After the implementation of the control strategy it is expected that the problem of overvoltage and undervoltage should be overcome. The voltage of the buses after the implementation of the control strategy can be seen in the figure 5.9. The voltage magnitudes of the buses that had exceeded the limits are now restored into values within the limits.

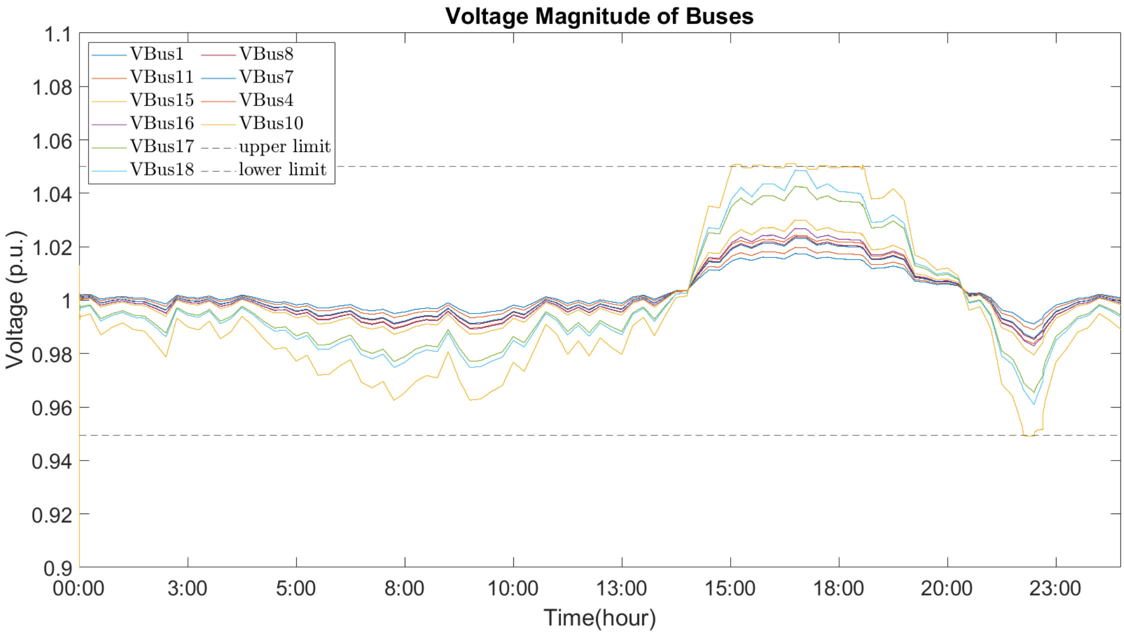


**Figure 5.9:** Voltage magnitude of buses with the coordination control implemented.

As aforementioned, during 15:00 to 19:00 o clock and 19:00 to 23:00 o clock the problems of overvoltage and undervoltage occur. To address the issue during those times, a detailed four-hour mismatch is used, with the PV and load data holding the same value every 3 minutes rather than every 15 minutes, in order to test the implementation of the control strategy in a more detailed data-set. The voltage of the buses during the two time periods with the coordination control implemented can be seen in the figures below (figure 5.10 and figure 5.11). It is depicted that the voltage limits after the implementation of the control are not exceeded, ensuring network's stability, having similar results as when data every 15 minutes were used.

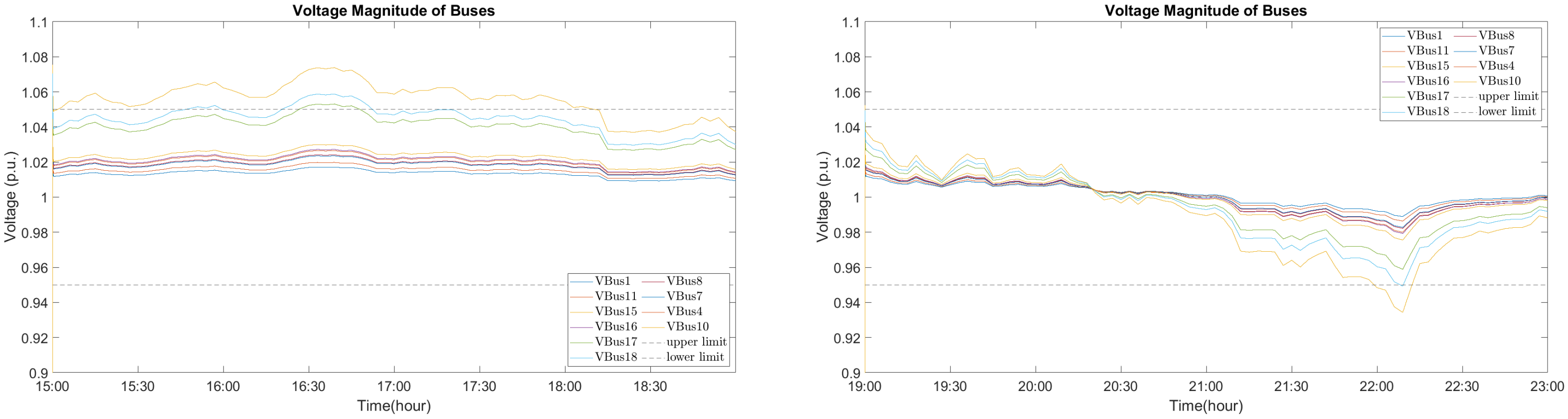


**Figure 5.10:** (a) Voltage magnitude with no control implemented between 15:00 to 19:00 o clock. (b) Voltage magnitude with no coordination control implemented between 19:00 to 23:00 o clock.

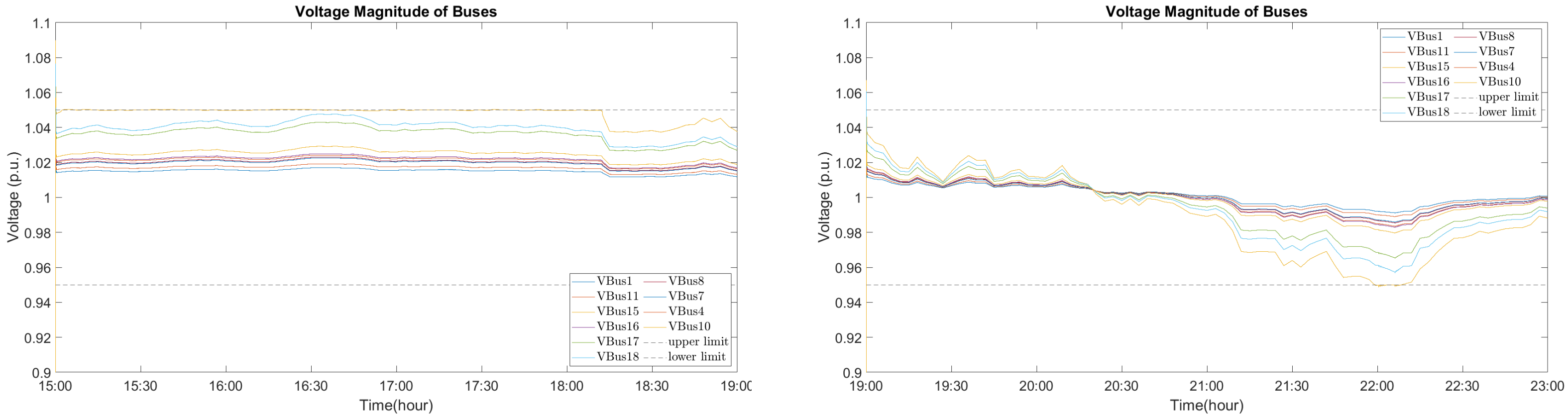


**Figure 5.11:** (a) Voltage magnitude with coordination control implemented between 15:00 to 19:00 o clock. (b) Voltage magnitude with coordination control implemented between 19:00 to 23:00 o clock.

For the next cases, since the control implementation performs properly using either every 3 minute or every 15 minute changing data, in order to reduce the simulation time only the daily mismatch with data changing every 15 minutes will be simulated.

Figure 5.12 depicts the utilazation factors used during the coordination control. They determine how much power each BESS should absorb or provide to the network in order to achieve voltage restoration within limits. When overvoltage occurs, the utilization factor of each BESS becomes positive and follows the pattern of the mismatch profile; the higher the voltage violation on each bus, the higher the utilization factors for the BESS connected to the bus and the neighboring BESS, and as a result, a greater amount of power must be absorbed. When there is an undervoltage, the utilization factors are negative, and the batteries must provide power to the network.

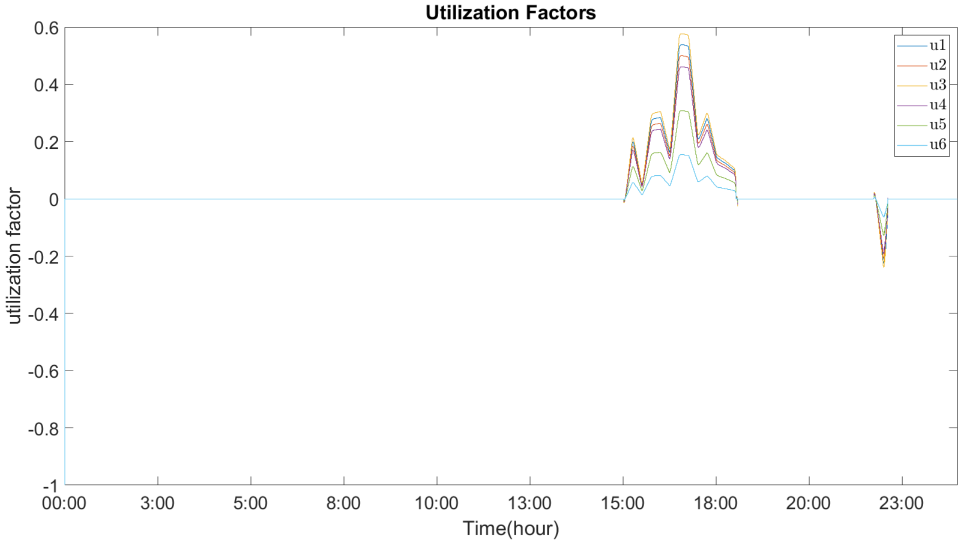


**Figure 5.12:** Utilization factors.

The SoC of the batteries can be seen in figure 5.13. When the utilization factors are equal to zero, the batteries do not contribute to the network and the SoC remains constant; when the utilization factors are positive, the batteries charge and the SoC increases until voltage restoration is achieved. When there is undervoltage, the utilization factors are negative, the batteries discharge in order to keep the voltage within limits, and the SoC begins to decrease. In this case since the undervoltage is for a very short period of time (30 minutes) and as can be noticed from the utilization factors the amount of power needed from each BESS is smaller than during the overvoltage problem, the decrease of the SoC is very small compared to the increase during the overvoltage.

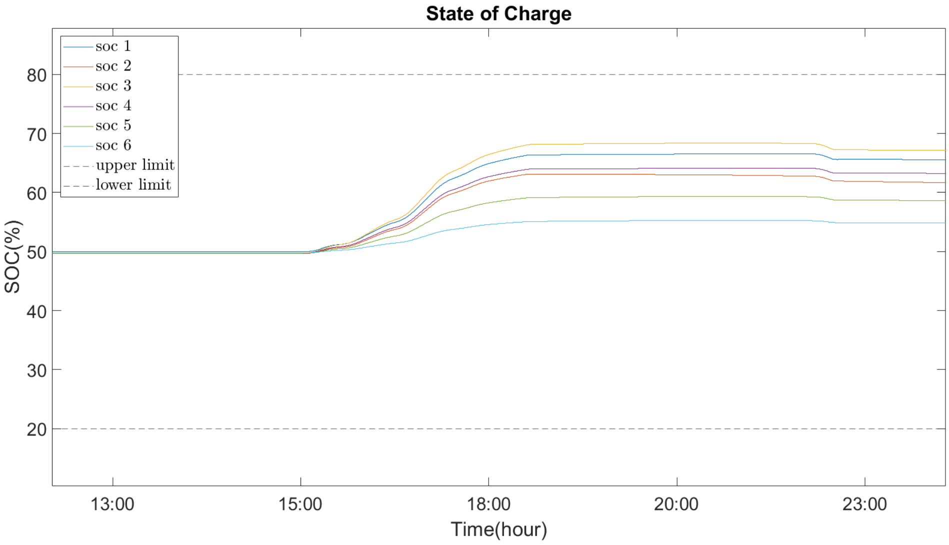


**Figure 5.13:** State of Charge of BESS (%).

The power contributed by the system's BESS is shown in the figures 5.14. Each sub-figure shows the power that the battery contributes after the control is implemented, as well as the reference power that results from the utilization factor multiplied by the battery's reference power. It is worth noting that the reference power is equal to the power produced by the battery, ensuring that the control performs properly and that the target of regulating voltage magnitude is met. Moreover, it can be seen that BESS power contribution pattern follows the pattern of utilization factor, as expected since the power that the battery contributes is determined by the equation 5.1, where only the utilization factors ($U_{\mathrm{i}}$) determine the changes of the power.

$$P\mathrm{ref}_{\mathrm{i}} = P_{\mathrm{nomBati}} * u_{\mathrm{i}} \tag{5.1}$$

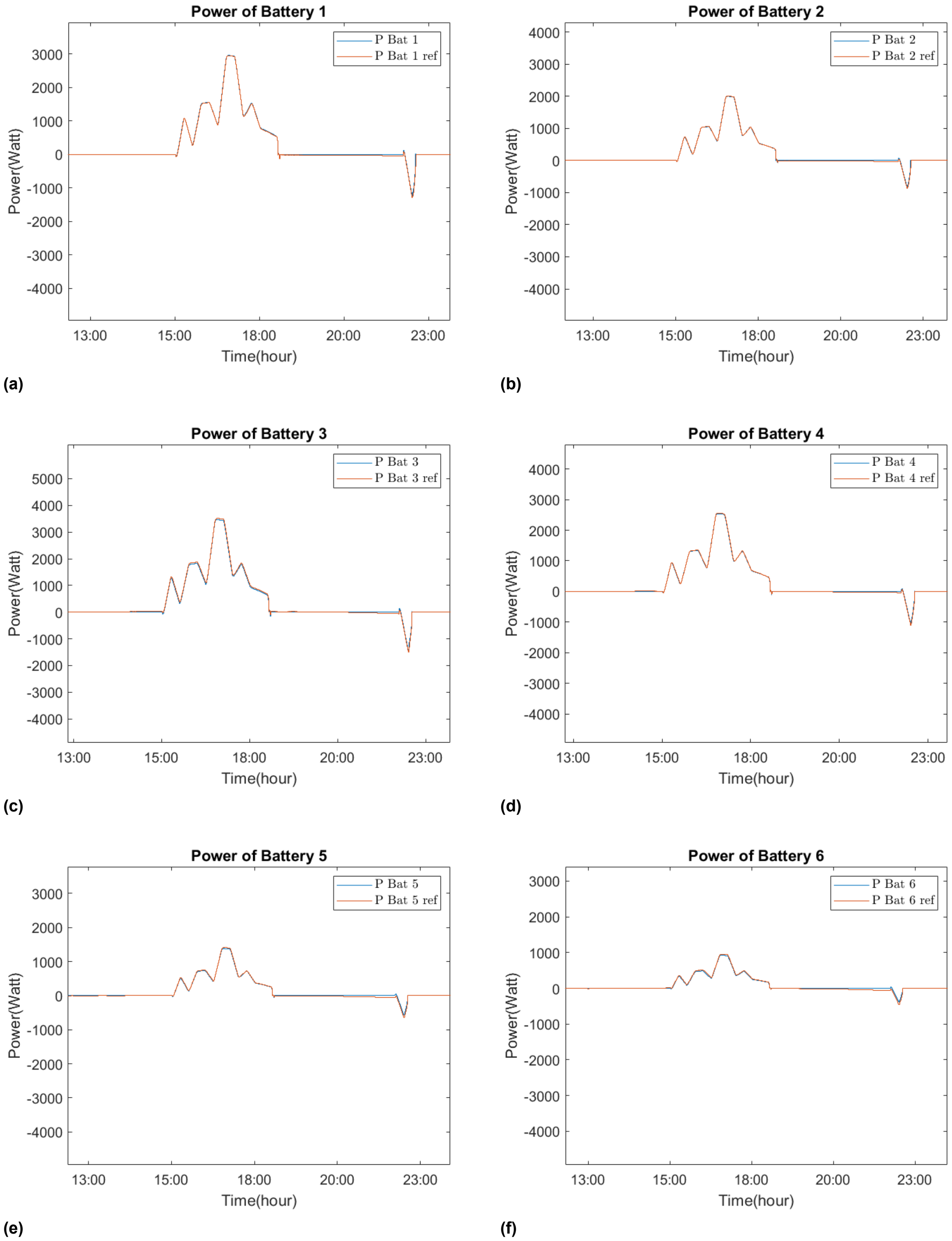


**Figure 5.14:** (a) Power contributed by BESS 1. (b) Power contributed by BESS 2. (c) Power contributed by BESS 3. (d) Power contributed by BESS 4. (e) Power contributed by BESS 5. (f) Power contributed by BESS 6.

### 5.2.2. *Bess with different SoC*

The case of having different SoC with the coordination control strategy implemented will be presented in this subsection. Moreover,an example of having one BESS unavailable due to reaching a limit in the SoC will be analysed.

The SoC for the network's batteries is shown in table 5.1.

**Table 5.1:** State of Charge (SoC).

| **BESS** | **State of Charge (%)** |
|---|---|
| BESS 1 | 60 |
| BESS 2 | 35 |
| BESS 3 | 40 |
| BESS 4 | 60 |
| BESS 5 | 50 |
| BESS 6 | 60 |

The voltage magnitude of the buses with no control was depicted in figure 5.8. After implementing the coordination control, the voltage is regulated and no limits are exceeded. This is depicted in figure 5.15 (a), and the state of charge of the BESS is depicted in figure 5.15 (b). There is no violation of the state of charge (SoC) limits (20%<SoC<80% ), so the figures in this case are identical as in the first case, where all of the BESS had the same SoC of 50%. In this case, with different SoC, the utilization factors are also the same as in the previous case (figure 5.15 (c)), as the available capacity of each BESS is not taken into account when calculating the utilization factors for each BESS.

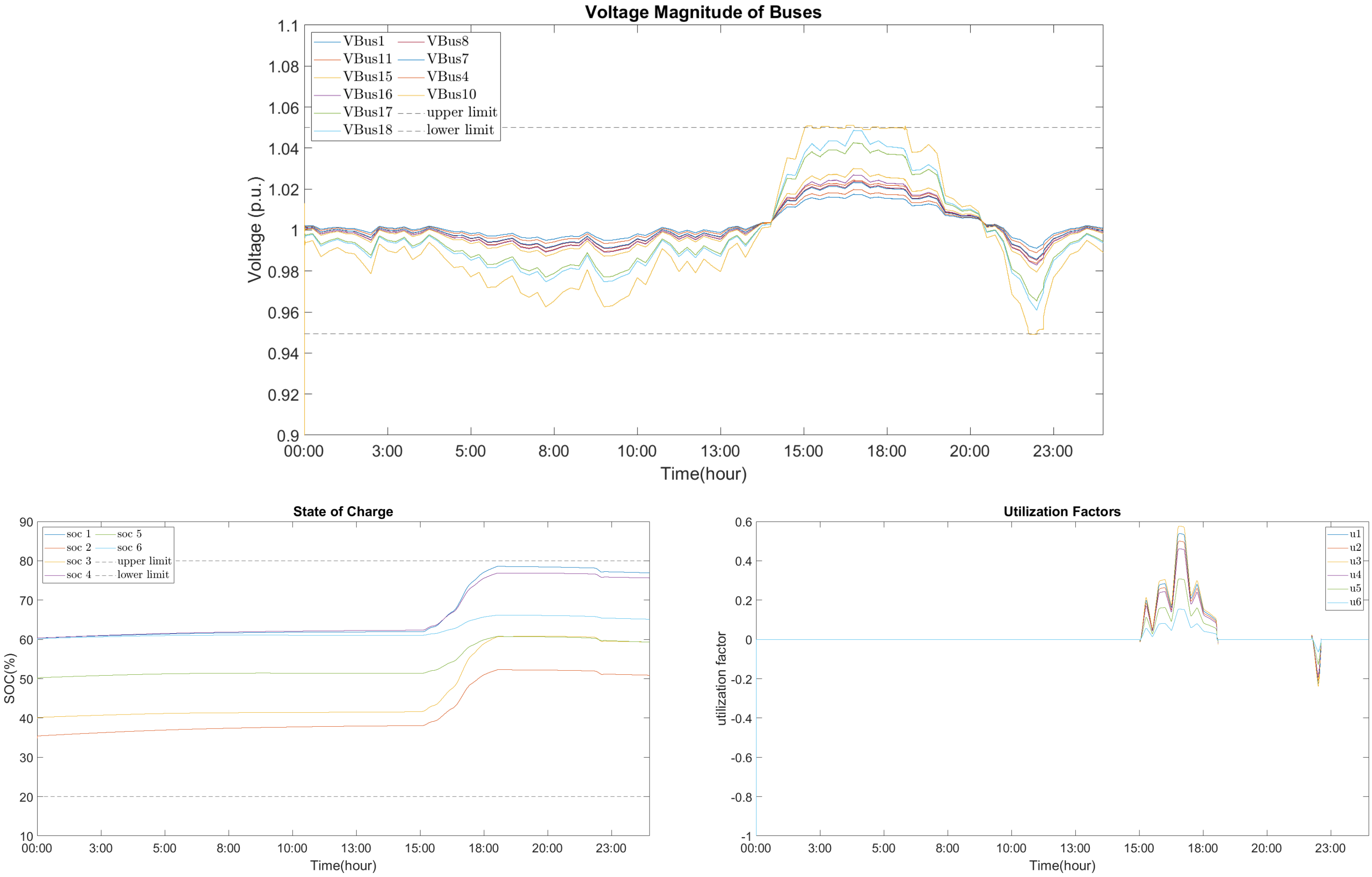


**Figure 5.15:** (a) Voltage magnitude of buses with coordination control. (b) State of Charge (%). (c) Utilization factors.

It is worth investigating the operation of the control strategy when one of the BESS is not available. This could be due to either maintenance or violation of the state of charge limit. In this case, the state of charge of BESS 4 is set at 65%; however, around 18:00 o clock, the SoC of the battery has reached the limit of 80% (figure 5.16). In this case, the developed coordination control distributes the power required from BESS 4 equally to the neighboring batteries, ensuring voltage stability.

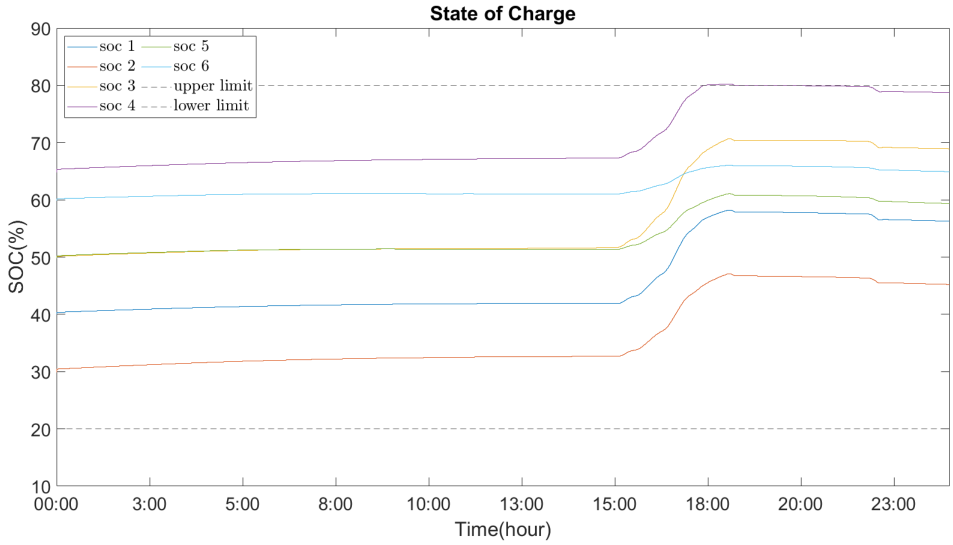


**Figure 5.16:** State of Charge of BESS (%).

Even though one of the batteries is not available for use, the voltage magnitude of the buses is kept within the limits in figure 5.17. When the battery is disconnected, a small peak is observed, but the control strategy manages to regulate the voltage and mitigate this transient voltage change.

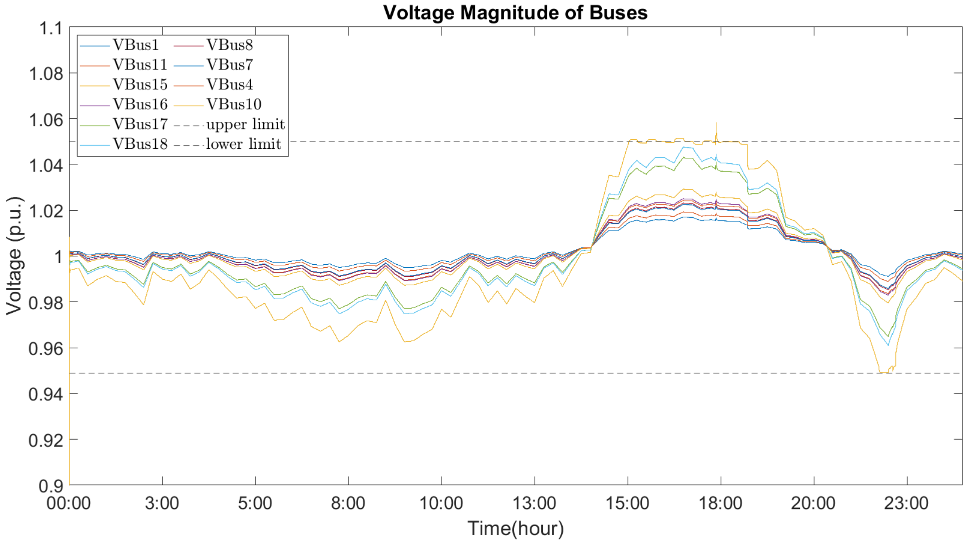


**Figure 5.17:** Voltage magnitude of buses with coordination control implemented.

In figure 5.18 (a) the utilization factors of the neighboring batteries (BESS 2, BESS 3 and BESS 5) have increased when compared to the original values. More specifically, the utilization factor of BESS 4 is 0.12 and it needs to be divided to three neighboring BESS so an increase of 0.04 should be noticed in the BESS utilization factors. At the highest point, BESS 2 has increased from 0.13 to 0.17, so there is a difference of 0.04 as expected,BESS 3 increases from 0.16 to 0.2 and BESS 5 increases from 0.08 to 0.12. As a result, the neighboring batteries cover the required power that BESS 4 is unable to provide.

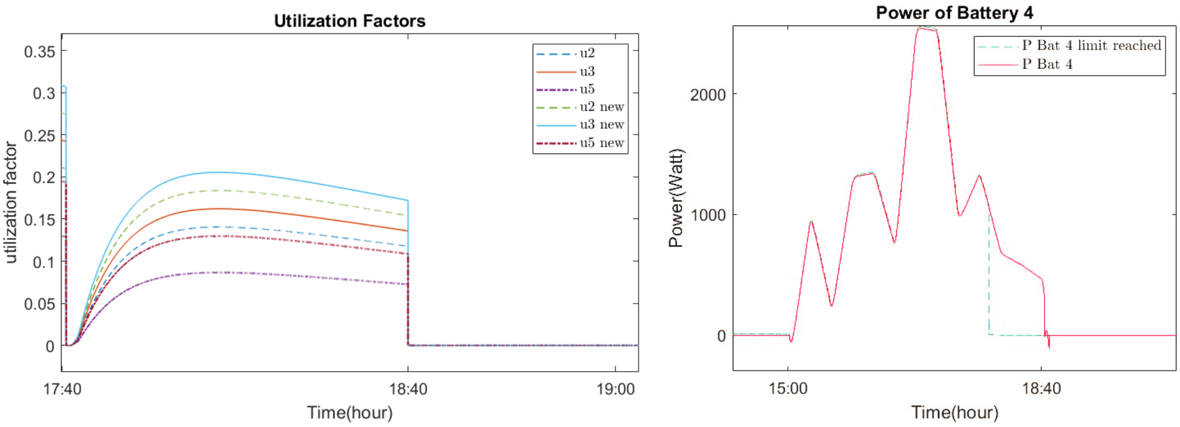


**Figure 5.18:** (a) Utilization factor changes between normal operation and with a BESS unavailable. (b) Power contributed by BESS 4 under normal operation in comparison to BESS 4 becoming unavailable.

In figure 5.18 (b) the power contribution of BESS 4 under normal operation when no limit of SoC is violated in comparison with this case where the limit of state of charge is violated is shown. When the state of charge reaches 80% the battery is disconnected until it becomes available again.

Thus, even when BESS have different SoC the coordination control strategy mitigates the voltage violations. The SoC is not taken into account when determining the utilization factor of each BESS and as a result the power contribution of each BESS. However, when the limit of SoC is reached then that BESS becomes unavailable and the neighboring BESS are in charge of providing the amount of power needed for the voltage regulation. More specifically, the utilization factor of the BESS that is unavailable is equally distributed to the neighboring BESS and this is done in the reference power ($Pref$) calculation section, that is used as an input in the control of the inverter. As a consequence, the power contributed by the neigboring batteries is given by eq. 5.2, where $U_{\text{i}}^{'}$ is the new utilization factor for the neighboring batteries.

$$Pref_{\text{i}} = P_{\text{nomBati}} * u_{\text{i}}^{'} \tag{5.2}$$

$$u_{\text{i}}^{'} = u_{\text{i}} + u_{\text{unavailableBESS}}/n_{\text{o}} \tag{5.3}$$

where $n_{\text{o}}$ is the number of the neighboring BESS.

### 5.2.3. *Decentralized control strategy*

The results of implementing a decentralized control instead of the coordination control will be shown and compared in this subsection.

In order to be able to compare the results of the decentralized control strategy with the coordination control strategy, the same mismatch profile is used as in the cases with the coordination control strategy, thus the voltage magnitude of the buses with no control implemented is the same as in figure 5.8. The implemented decentralized control is explained in section 3.3.2.

In this case, each battery is controlled locally, so the amount of power required is determined by the voltage magnitude on the bus to which the battery is connected. Figure 5.19 depicts the voltage after decentralized control is implemented. Although the voltage is regulated within acceptable limits, multiple fluctuations can be observed, affecting power quality. It can be noticed that the voltage fluctuations are higher when the overvoltage is higher and this is noticeable especially during 16:00 o clock. This can also be explained as the droop control has often a poor transient performance. In the case of the coordination control strategy the voltage behavior did not include frequent sudden changes around the limit point.

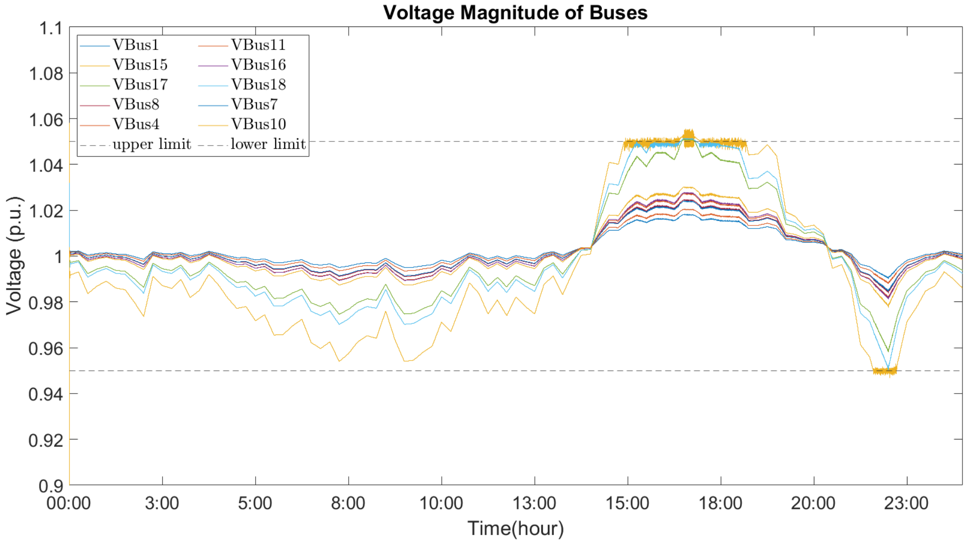


**Figure 5.19:** Voltage magnitude of buses with decentralised control implemented.

Furthermore, not all batteries help with voltage regulation, in this study only BESS 3 (Bus 15) and BESS 6 (Bus 18) contribute while the rest are not operating as the voltage on their buses does not surpass any limit. Thus, only the battery connected to a bus that exceeds the limits contributes, necessitating a larger capacity than in the case of coordinated control strategy. This is depicted in the figure 5.20 and it can be noticed that the power provided by BESS 3 is always higher with the decentralised control, more specifically with the coordination control the state of charge of BESS 3 reached 68% while with the decentralized control the state of charge of the same BESS reached 79% and all the frequent changes in the voltage magnitude can be observed in the power contribution of the battery. These frequent changes in the power output of the battery reduces its lifetime, making decentralized control strategy less appropriate to use [44].

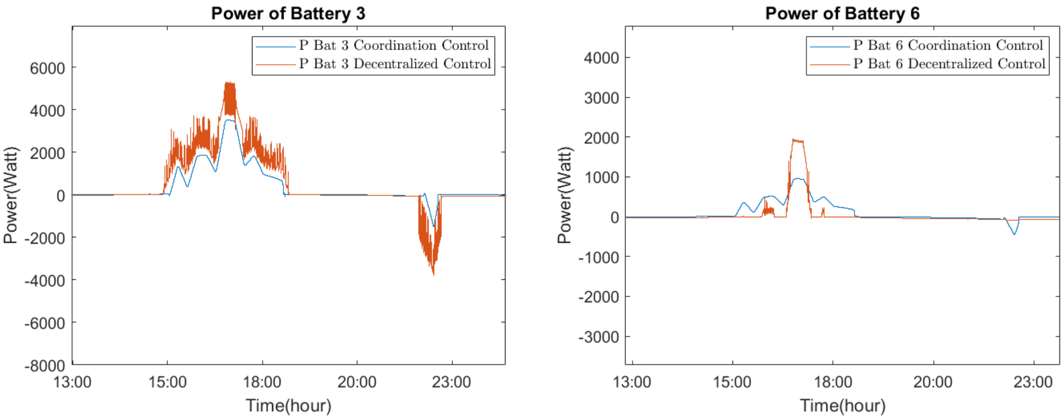


**Figure 5.20:** Comparison of power contribution of (a) BESS 3 and (b) BESS 6 with coordination control strategy and decentralised control strategy.

Finally, if one of the batteries used in voltage regulation reaches a SoC limit or is unavailable due to maintenance, the other batteries cannot provide the necessary power, and the voltage cannot be restored to acceptable levels. This is depicted in the figure 5.21, where BESS 3 is not available around 18:00 o clock. The magnitude of the voltage is not regulated and has exceeded the limit. When the coordinated control strategy is used, it was shown that this is avoided.

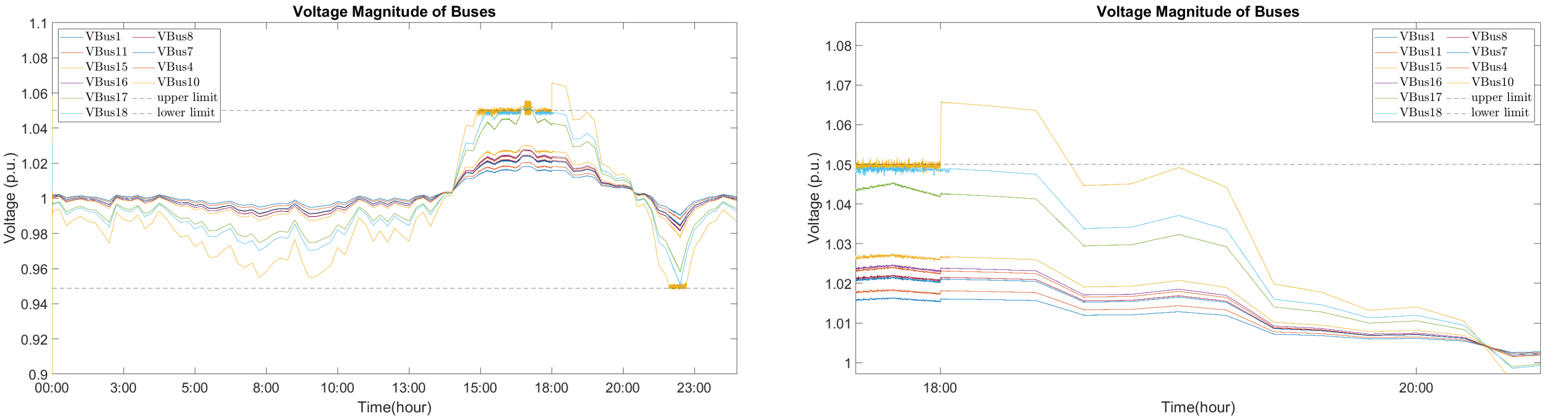


**Figure 5.21:** Voltage magnitude of buses when BESS 3 becomes unavailable, with decentralized control implemented.

### 5.2.4. *Laboratory Results*

The developed coordination control strategy was simulated in the previous sections, and various case studies were presented. In this section the developed control is tested in the laboratory using the CIGRE Low Voltage Network. More specifically, BESS 1 is emulated in the laboratory in order to test the behavior of the control in real-time operation, more specifically to test whether the contribution of the emulated BESS in the laboratory matches the simulated case. For this purpose RT-Lab software was used in combination with the laboratory equipment. BESS 1 is tested in the laboratory while the other BESS are simulated in RT-Lab software. For the purpose of this experiment, data that could create overvoltage and undervoltage problems in the network were used, since the real mismatch data used in the previously simulated cases required a long period of time to simulate.

In the figure 5.22 the preliminary mismatch data used for the laboratory testing are shown.

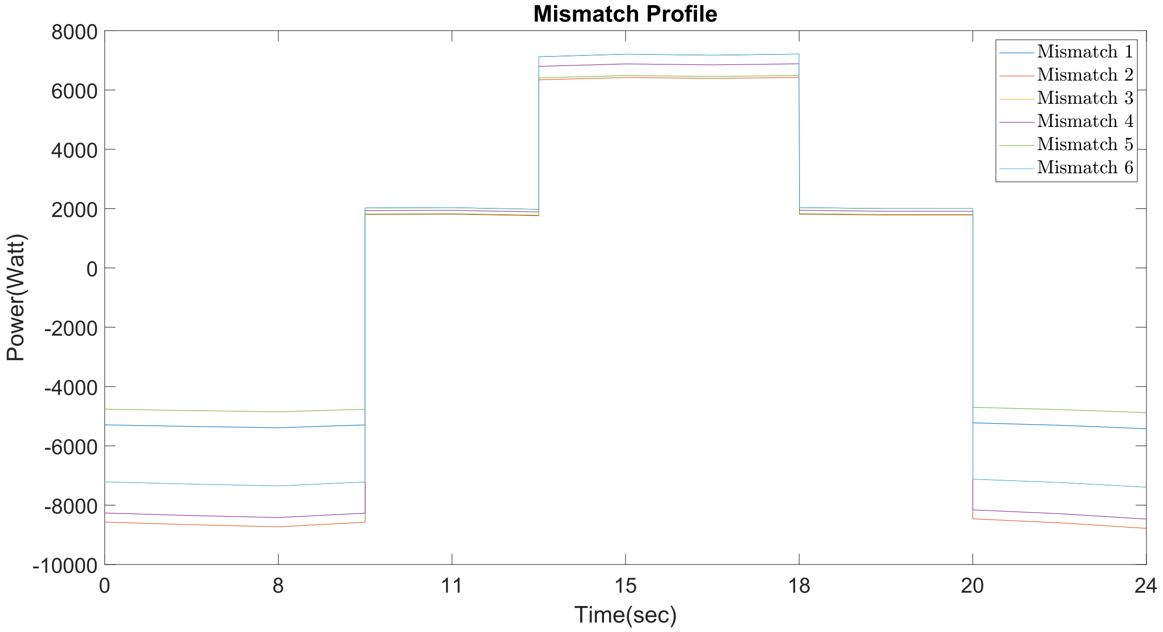


**Figure 5.22:** Daily mismatch profile.

When no control is implemented in the low voltage network the voltage magnitude of the buses can be noticed in figure 5.23. It can be observed that voltage magnitude of Bus 15 and Bus 18 surpass the limit of 1.05 p.u. and 0.95 p.u..

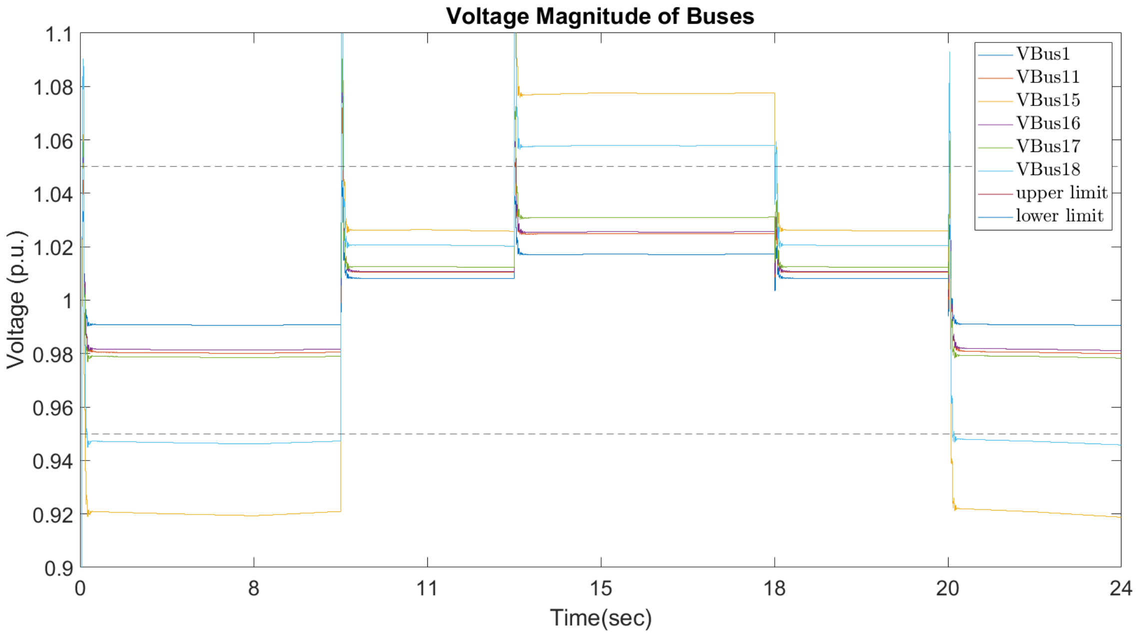


**Figure 5.23:** Voltage magnitude in the CIGRE Low Voltage Network when no control is implemented.

After the implementation of the control the voltage magnitude is regulated within the limits. In figure 5.24 the voltage magnitude of the buses is shown, the voltage magnitude of bus 1 results from the laboratory testing while the voltage of the other buses result from the simulation. In this figure the correct operation of the developed control under real conditions is proved.

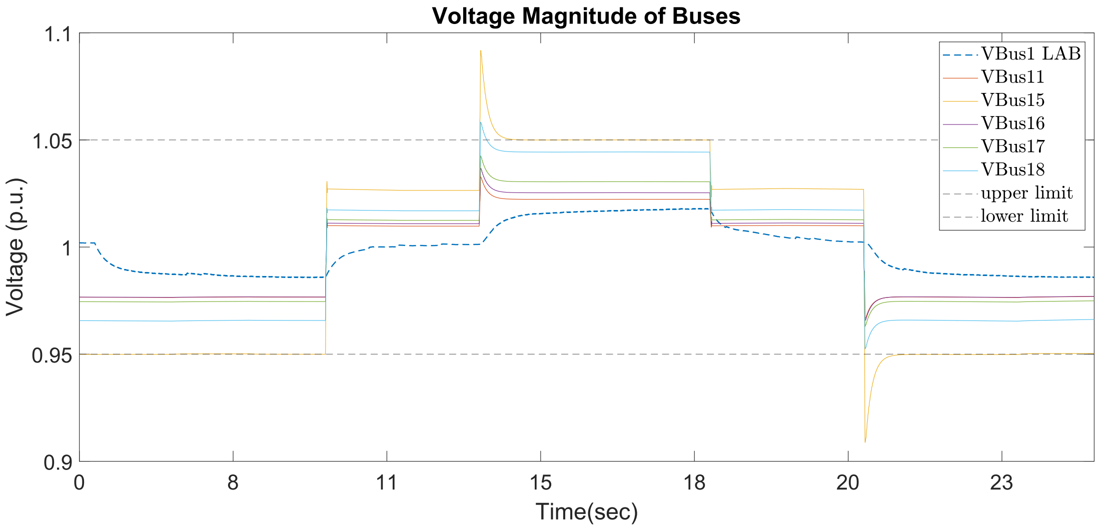


**Figure 5.24:** Voltage magnitude in the CIGRE Low Voltage Network when coordination control is implemented and BESS 1 is emulated in the laboratory.

In figure 5.25 (a) the comparison of the voltages of bus 1 when tested in the laboratory and when simulated is presented. It can be noticed that the results from the laboratory follow the simulation, there are few minor differences which are created from measurement accuracy errors.

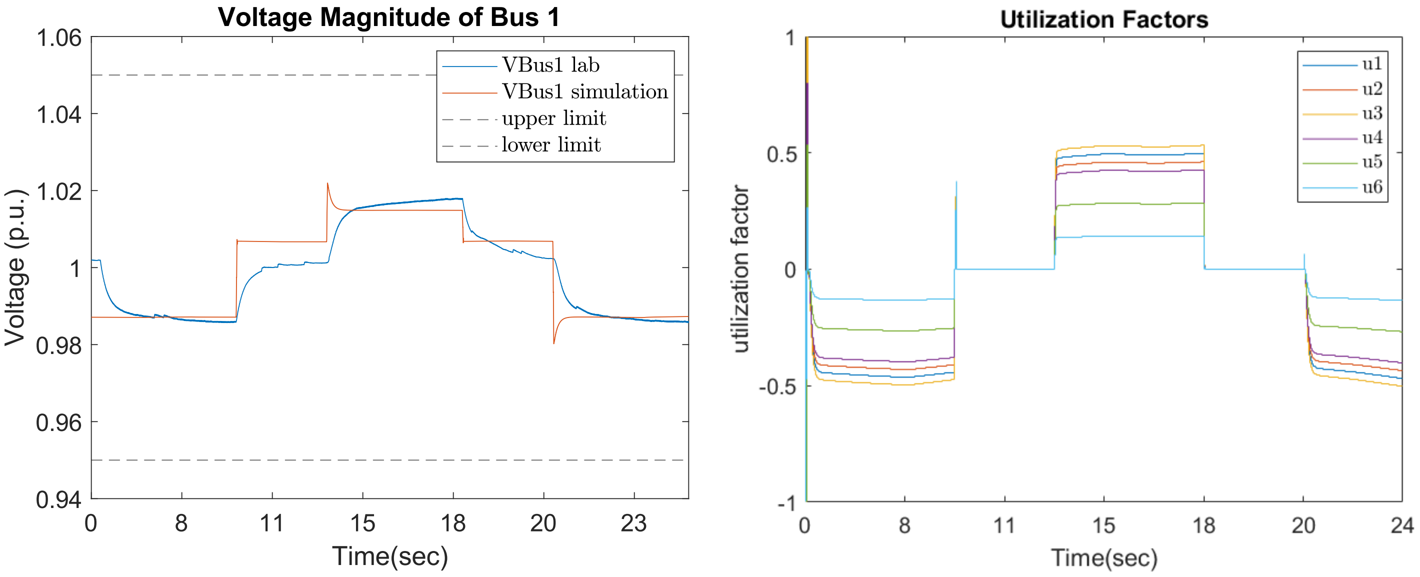


**Figure 5.25:** (a) Voltage magnitude of BESS 1 when simulated in MATLAB/Simulink in comparison to it being tested in real-time at the laboratory. (b) Utilization factors.

Figure 5.26 depicts the contribution of BESS 1 when it is simulated and when it is tested in the laboratory. It is of great significance that the battery's response in the laboratory testing matches the response of the simulation. For safety reasons a slower control was used on the inverter and this is the reason for battery's slower response in the laboratory compared to the simulated case. More specifically, the sampling time (Ts $= 1 * 10^-4$sec) used in the laboratory testing was higher than the sampling time when the same case was simulated in MATLAB/Simulink (Ts $= 5 * 10^-5$sec), in order for the equipment to follow the changes implemented. In figure 5.25 (b) the utilization factors of the batteries is shown and it matches the pattern of the contributed power of the battery as it was explained by the equation 5.4.

$$Pref_{i} = P_{nomBati} * u_{i} \qquad (5.4)$$

.

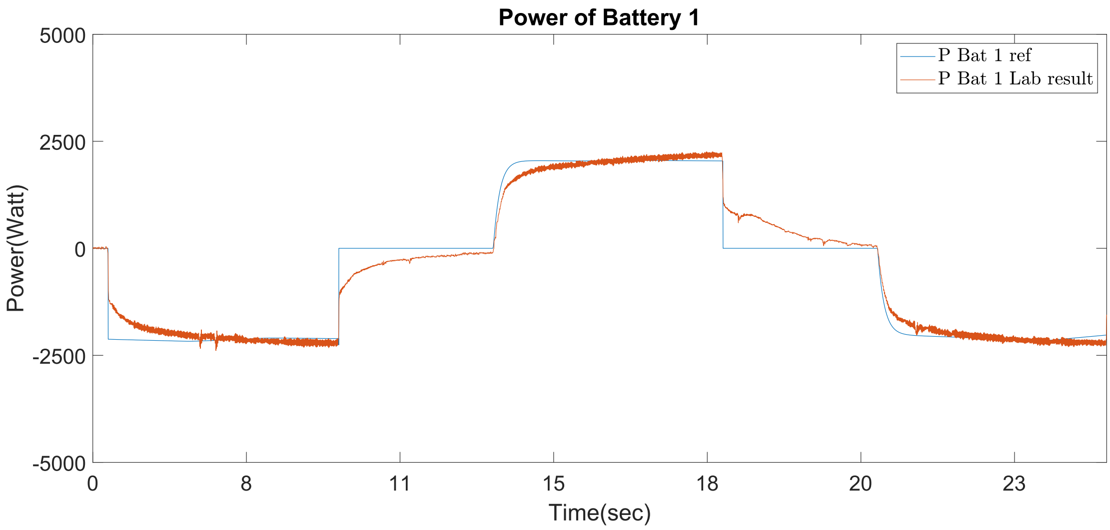


**Figure 5.26:** Power contribution of BESS 1 when simulated in MATLAB/Simulink in comparison to it being tested in real-time at the laboratory.

In figure 5.27 the operation of the inverter used in the laboratory is shown. When the battery needs to contribute power to the system the current output goes from zero to the necessary current output in order to achieve voltage regulation.

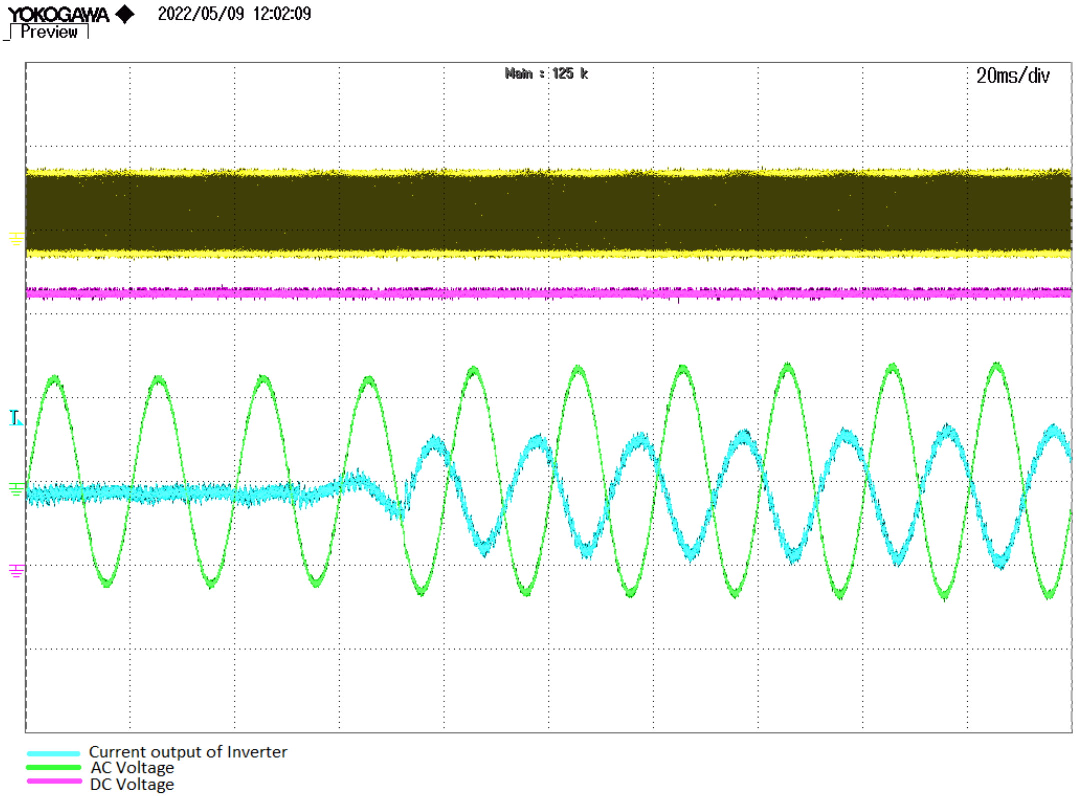


**Figure 5.27:** Laboratory inverter operation when battery contributes power to the network.

As a result, the laboratory testing of the developed coordination strategy was carried out effectively. Under laboratory conditions, the battery performed as expected, exhibiting the same response as during the simulation. Differences in voltage and power contributed are caused by measurement accuracy errors, equipment used, and slower implemented control on the inverter for safety reasons.

## 5.3. *Conclusions*

In this chapter the results from performance of the coordination control with different case-studies was presented. The decentralized control performance was illustrated and compared to the coordination control. Finally, the behavior of one of the batteries with the coordination control strategy implemented tested on the laboratory was analysed.

Firstly, the coordination control strategy was implemented and tested on the Eight-Bus System, where 3 PV units and 3 BESS were integrated. The coordination control managed to regulate the voltage within the permitted limits. Then the coordination control strategy was implemented and tested on the CIGRE low voltage distribution network, where 6 PV units and 6 BESS were integrated. Even though there was a higher number of BESS the coordination control was successful and managed to regulate the voltage. Moreover, the control was able to restore the voltage even when one of the BESSs was unavailable due to reaching the limit of state of charge.

Furthermore, the decentralised control implemented on the CIGRE low voltage distribution network was able to restore the voltage but many fluctuations could be noticed on the voltage, however when BESS 3 was unavailable due to reaching the limit of state of charge the voltage could not be regulated within the limits making the system unstable. In the table 5.2 the comparison of the coordination control strategy and decentralised control strategy is illustrated.

**Table 5.2:** Comparison of Coordination and Decentralized control strategy.

| | **Coordination Control** | **Decentralized Control** |
|---|---|---|
| **Voltage Magnitude** | The voltage is regulated within the limits and there are no frequent changes around the limit points. | During voltage regulation many frequent voltage changes around limit points are noticed and their magnitude is higher at the points where overvoltage is higher. |
| **Battery Contribution** | The power needed for voltage regulation is distributed among the batteries. | The battery connected to bus with the higher voltage deviation from the limits will participate more in the voltage regulation in comparison with other batteries. |
| **Battery Availability** | If one of the batteries cannot provide power then the utilization factor of that battery will be divided equally to the neighboring batteries and voltage regulation is achieved. | When a battery has reached its limits and is necessary for the voltage regulation then the system becomes unstable as the voltage is not restored. |

# 6

# Conclusion

In this chapter the main research question as well as the sub-research questions will be answered in section 6.1, then in section 6.3 the recommendation for future research will be presented.

## 6.1. *Conclusions*

First the three sub-research questions will be answered in order to answer the main research question.

- ***What are the benefits that multiple BESS offer to networks?***

Renewable energy sources introduce numerous challenges to grid and system operators, as their reliance on weather influences power production from renewable energy technologies. This causes voltage fluctuations, lowers power quality, and has an impact on grid reliability. BESS are used to address the issues raised by the integration of renewable technologies. As renewable technologies become more essential in energy production, the number of batteries in the network has been increasing. BESS contribute to the integration and growth of renewable energy technologies. Renewable technologies are often paired with BESS, since they provide network flexibility that cannot be provided by sustainable technologies, whose power production cannot be controlled. Aside from that, BESS provide environmental benefits by assisting in the replacement of conventional power plants when combined with renewable technologies. Conventional power plants are considered to be responsible for a significant amount of greenhouse gas emissions, which can be reduced by using BESS.

Furthermore, BESS can improve system reliability and contribute to energy management. More specifically, BESS can provide very fast power to the grid when demand is high, making them a prominent option for Peaker Plant replacement, which emit a lot of greenhouse gases. When a failure occurs, large-scale BESS can assist in system restoration by providing reliability and flexibility. Moreover, BESS can be used in the energy market for energy trading; their participation in energy scheduling can reduce energy costs and benefit consumers by lowering their energy bills.

• ***What effect does the proposed BESS coordination control strategy have on the voltage fluctuations caused by high PV Unit penetration?***

As it was illustrated by the literature study, BESS can contribute in voltage regulation by providing flexibility to the systems with high PV penetration. They absorb excess power generated by PV units and provide power when demand exceeds production. In this study a coordination control strategy was developed where all batteries were coordinated together in order to achieve voltage regulation. This coordination control strategy was tested in a low voltage distribution network using MATLAB/Simulink.

The coordination control strategy determined the contribution of each BESS in order to regulate the voltage within the permitted limits. The simulations showed that the proposed control managed to face the overvoltage problem by storing the excess power in the BESS and it managed to face the undervoltage problem by offering power to the grid. The negative impact of the high PV unit penetration was overcome. Furthermore, the behavior of one of the BESS, with the coordination control implemented, was tested in the laboratory. The conducted test showed that in real-time applications the proposed control was operating properly by achieving the goal of mitigating the voltage fluctuations and regulating the voltage within the limits. This was concluded since the contribution of the BESS in the laboratory matched the contribution of the same BESS when simulated.

• ***Why distributed control of BESS is more effective than decentralized control in distribution networks with high penetration of PV Units?***

Decentralized control is one of the most commonly used control methods because, unlike centralized control, it does not have a central controller, which is considered prone to failures, especially when dealing with a large amount of BESS, which increases the communication links and message number. Thus, a decentralized control was developed and simulated in order to compare it to the proposed coordination control strategy. In section 5.3 the detailed comparison of the two control methods was presented. The decentralized control even though it managed to regulate the voltage, led to many fluctuations around the limit points, which is common as droop control is characterized by poor transient performance. This was not noticed with the implementation of the proposed coordination control strategy.

Moreover, the proposed strategy can regulate the voltage even if one of the BESS is not available, as the neighboring BESS become in charge of offering the necessary amount of power. BESS cooperate together to achieve the goal of voltage regulation. In the decentralized control case, it was shown that if a BESS, connected to a bus where voltage limit violation occurred, was not available then the voltage could not be regulated and the system became unstable. These factors confirmed that a distributed control, such as the proposed control, is more effective than a decentralized control in dealing with the voltage violation problem caused by high PV unit penetration.

Answering the above sub-research questions assists in answering the main research question:

***How can the increasing number of BESS be controlled and coordinated more effectively in order to regulate voltage in a Low Voltage Distribution Network with high PV Unit penetration?***

The proposed coordination control strategy was tested in a simulated environment as well as in a laboratory environment and the goal of voltage regulation was achieved. The conducted simulations had as a goal to test the proposed control under different case scenarios in order to validate its proper performance. Firstly, three BESS were coordinated together in order to mitigate the overvoltage caused by the high PV unit penetration in the simulated Eight-Bus system. The developed control was successful in keeping the voltage within the permitted limits. Afterwards, the CIGRE low voltage distribution network was simulated where the developed control was in charge of coordinating six BESS in order to mitigate the overvoltage and undervoltage problem caused by PV unit power generation. The coordination strategy performed well by managing to regulate the voltage despite the increased number of BESS. The proposed control was then evaluated using different case scenarios in which BESS had the same and different state of charges. The developed strategy achieved the goal of overvoltage and undervoltage mitigation in all cases. The behavior of one of the batteries was then tested in the laboratory to see if the proposed control was effective in real-time applications. The results showed that the battery's response in the lab was similar to the simulation response, indicating that the proposed control could be implemented in real-time applications.

## 6.2. *Contributions*

After the implementation of the coordination control strategy, the results contribute in the research of mitigating voltage limit deviations caused by renewable energy technologies, by illustrating the effectiveness and the benefits of the proposed control. Moreover, of great importance are the laboratory results, which indicate the prospective implementation of the proposed control in real distribution systems. More specifically:

- The coordination control strategy facilitates the implementation of multiple BESS in the network and achieves the voltage regulation. Since, even when the number of BESS increased between the Eight-Bus System and the CIGRE LV Network simulations, the proposed control managed successfully to regulate the voltage within limits.

- The comparison of the coordination control to the decentralized control illustrated that the proposed control was more successful. Especially, the comparison of the cases where a BESS becomes unavailable, with the proposed control implemented and the decentralized control implemented, indicates that the proposed control is more beneficial for dealing with the voltage regulation problem studied in this thesis.

- The proposed control was evaluated in the laboratory, where the power provided by one of the BESS, with the coordination control implemented, was compared to the simulated case and the result showed the same response. Thus, this result contributes in the future implementation of the proposed control in real networks.

## 6.3. *Recommendation for future research*

In this section recommendations for future research on the integration of multiple BESS in electricity networks are presented.

- In this study, each BESS contribution is based on a utilization factor that is dependent on the communication of neighboring BESS. More research could be done by developing an algorithm for the most efficient clustering of BESS as ”neighbors,” which would result in the lowest utilization factor for achieving voltage regulation. This could improve BESS utilization even more.

• The aging of BESS was not considered in this study; however, in order to increase the lifetime of BESS in a distribution network, it is worth investigating how battery aging affects BESS behavior in overvoltage and undervoltage mitigation. This can help to reduce maintenance and replacement costs, allowing for further BESS implementation in the network.

• Model predictive control (MPC) can be used to determine the demand and the power production from renewable technologies daily. In this research a consensus algorithm was used to determine the contribution of each battery in the network, it would be worth examining if MPC can be used as an indicator of which batteries in a distribution network should contribute based on the predictions of production and demand. This way batteries can be aggregated daily based on their expected contribution to the network. This may be used to examine which algorithm leads to a better utilization of BESS.

• Moreover, a techno-economic research on the most efficient allocation of BESS in a distribution system can be conducted and the results can be compared to the main case, which was used in this study, where all BESS are allocated near the renewable energy sources.

• As it was shown in this study excess power generated from renewable energy sources poses numerous challenges to the network. It would be interesting to investigate how a curtailment factor, that derived from yearly data, can be used to determine the optimal capacity of BESS implemented in each region.

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# A

# PV and Load Data

The data used for creating the mismatch that was used during the simulation can be seen in figure A.1. In figure A.1 (a) the power produced by a PV unit during a summer day is shown and in figure A.1 (b) the daily demanded power is presented. The mismatch used has resulted from :

$$Mismatch = Production - Demand$$

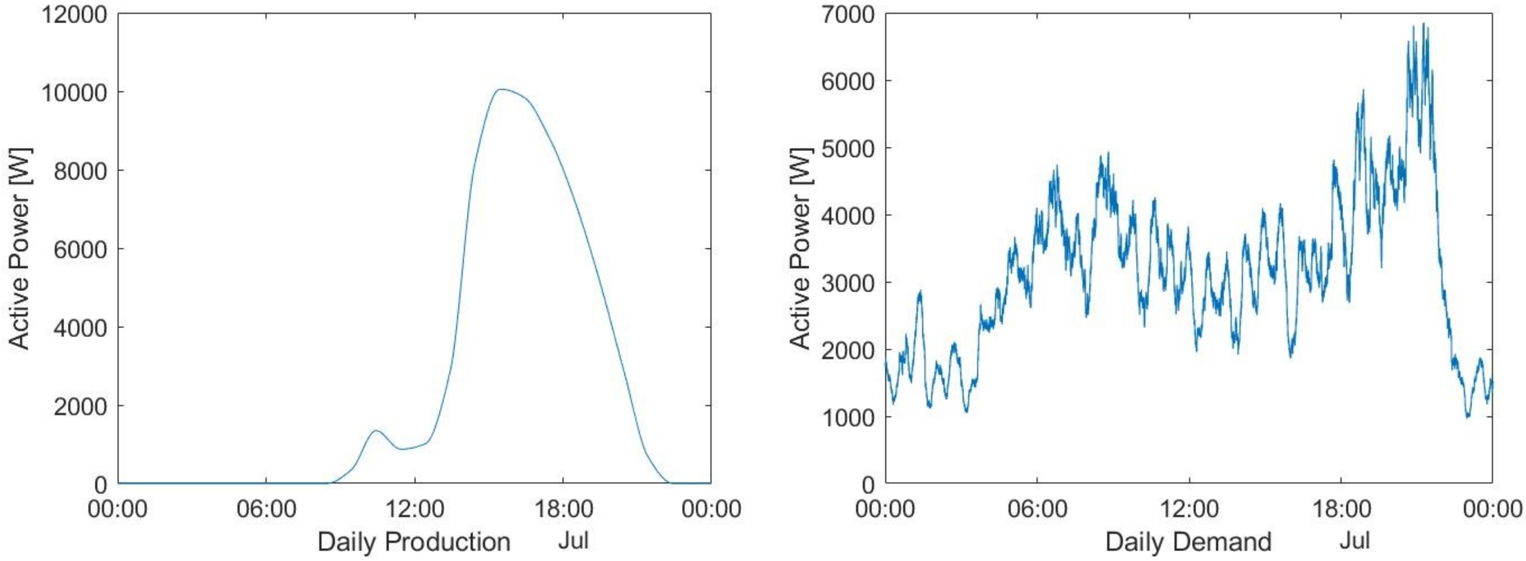

**Figure A.1:** (a) Power produced by PV Unit used as data for the simulations. (b) Power demand by load used as data for the simulations.

# B

# Conference Paper

The results of conducted research study have been used to create a paper in order to present the contribution to the research field and as a consequence the contribution to the energy transition towards a sustainable future. In the next pages the research paper is presented.

# Control and Coordination of multiple BESS in a Low Voltage Distribution Network

Margarita Kitso, Marco Stecca, Laura Ramírez Elizondo, Pavol Bauer

***Abstract*—In this paper a coordination control strategy of multiple BESS has been developed to address the network's overvoltage and undervoltage issues caused by the high penetration of Photovoltaic (PV) units. The coordination control strategy is based on a consensus algorithm that determines each battery's contribution to the network. The goal of this control strategy is to maintain the grid's voltage within the limits. When a battery is not available due to a state of charge (SoC) limit violation or maintenance, the amount of power that this battery would contribute under normal operation is distributed equally to the neighboring batteries until the battery becomes available again. The CIGRE Low Voltage Distribution Network is modeled in MATLAB/Simulink in order to test the proposed control. The developed coordination control strategy is compared to a decentralized control strategy. Moreover, one of the batteries is emulated in the laboratory in order to examine the behavior and contribution of the battery, with the coordination control strategy implemented, in real-time application in comparison to the simulation. After the implementation of the control in different case scenarios in low voltage distribution networks, using MATLAB/Simulink, the goal of mitigating voltage limit violation due to high PV unit penetration was achieved. The results illustrated that the proposed control is more effective in voltage regulation than the decentralized control. Finally, the results of the laboratory testing demonstrated that the proposed control could be implemented in real-time applications.**

***Index Terms*—BESS, PV unit, Low Voltage, distribution, coordination, overvoltage, undervoltage, renewable, MATLAB/Simulink.**

## I. INTRODUCTION

One of the primary goals set by European countries in the EU Energy Roadmap 2050 and during the COP26 climate change conference is to achieve carbon-neutral energy production by 2050. According to the IEA, renewable energy capacity is expected to increase by 60% by 2026 when compared to renewable energy capacity installed in 2020. Solar power is one of the renewable energy sources that has grown in popularity over the years [1]. During 2019 to 2020 the installed capacity worldwide increased by 18% [2]. Moreover, globally an increase of 9% is expected every year for Photovoltaic (PV) units installation until 2050 [3].

The stochastic nature of renewable energy sources, has an impact on power generation from renewable technologies. Their production is dependent on the availability of energy sources; for example, changes in the irradiance that reaches PV units will result in a change in the PV unit's power output. One of the main network issue caused by the integration of renewable sources is voltage magnitude deviations, such as overvoltage when demand exceeds supply [4]–[6].

Battery energy storage systems (BESS) are used to store excess power generated by renewable sources and deliver it to the grid when demand is high. BESS are frequently used in combination with PV units to address the aforementioned issues.

This paper focuses on low voltage distribution networks that have a high penetration of PV units. Voltage fluctuations are caused by PV units due to a mismatch between the power produced by the PV unit and the demand. BESS are integrated into low voltage distribution networks to maintain voltages within acceptable limits. To coordinate the growing number of BESS in a low voltage distribution network, a distributed control strategy will be developed. In addition, the developed control will be tested in overvoltage and undervoltage conditions.

The paper is divided into five sections. In Section II the main control methods used for control of BESS in low voltage distribution networks will be illustrated. Section III presents the developed coordination control strategy. The consensus algorithm used is explained. In section IV the developed control is implemented in the CIGRE Low Voltage Network and its performance is evaluated. Finally, in Section V the conclusions will be given.

## II. REVIEW OF CONTROL METHODS

The three main strategies for controlling BESS are, centralized control, decentralized control and distributed control. The centralized strategy contains a central management system which is in charge of making decisions regarding the contribution of each battery based on the voltage magnitude fluctuation. In a decentralized control strategy, according on local measurements, each battery changes its contribution. In a distributed control strategy, there is communication between neighboring agents which exchange local measurements.

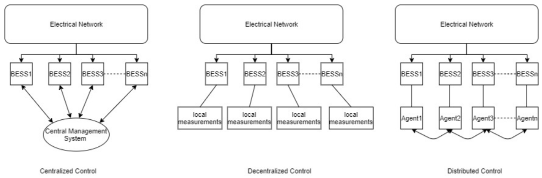

Fig. 1. (a) Centralized Control. (b) Decentralized Control. (c) Distributed Control.

In [7]–[9] a centralized coordination approach is being used. According to these studies, a storage system could send local measurements to a central controller and the central controller, based on the availability of each storage system and the place where the overvoltage occurs, will decide which BESS will be used. In some cases a centralized controller will inform the state of charge controllers so that the batteries will start to charge during off peak hours and discharge during peak hours. Moreover, an energy management system is used in one of the studies in order to communicate with the power conversion interfaces so that to manage the power changes. In a centralized control a communication method is required to control and monitor each storage device. However, in case of an error in the central controller the system may become unstable. Furthermore, a centralized control does not facilitate the expansion of the network. Thus, this control makes the implementation of multiple BESS more difficult to control, the proposed control of this study has as a goal to facilitate the increasing number of BESS in order to achieve voltage regulation.

In [10]–[13] a decentralized control strategy is being developed. In these studies local measurements of voltage magnitude define the amount of power that should be injected to the system or to the local battery. More specifically, based on changes of the DC voltage of the DC link, where the BESS and the PV are connected, the deviation of the DC voltage from the reference value is used to determine the amount of power contributed by the BESS. In one of the studies frequency changes are used to create the reference power value for each BESS. In these studies the case where one BESS necessary for voltage regulation becomes unavailable is not studied. The proposed control strategy takes into account this case and what consequences may the unavailability of one BESS necessary for voltage regulation have on the voltage restoration within limits.

Distributed control is considered more efficient when it comes to the coordination of multiple storage units, communication between storage units is limited, usually neighboring storage units share information between them. In [14]–[20] a distributed control of BESS is used for frequency or SoC regulation, the BESS's set points are calculated and the appropriate power set points are decided. In distributed control each storage unit of the system is considered an agent and these agents communicate together. In one of the studies intelligent control with the use of fuzzy-logic for charging and discharging of BESSs is implemented in order to balance the state of charge within the permitted limits. Consensus algorithm has been used in distributed control in order to facilitate the voltage and frequency restoration of electricity networks. However, in these studies the algorithm was aiming into reaching an agreement in the value of power given by the batteries, thus all batteries should contribute the same. This way voltage regulation was achieved, however batteries are not operating efficiently as they absorb or produce more power than needed.

In this paper a coordination control strategy of multiple BESS is developed and a consensus algorithm is used in order to regulate voltage. Consensus is reached when voltage is regulated within the limits. Furthermore, the state of charge of each battery is controlled locally and only when the limit of the state of charge is reached the battery will instantly be disconnected and neighboring batteries will equally contribute the amount of power that the battery would contribute if it was available, until the battery becomes available for use again. The contribution of this research study is the development of a control method that facilitates the increasing number of BESS in the network while focusing on regulating voltage violations created by the high penetration of PV units and the examination if this method could be used in real-time applications. The developed control is further explained in section III and is compared to a decentralised control.

## III. COORDINATION CONTROL STRATEGY

The coordination control strategy developed for the coordination of multiple BESS is a combination of a local and a distributed control. The distributed control is achieved with the use of consensus algorithm. The consensus algorithm is used in distributed systems as it manages to achieve agreement on a certain decision by the agents and this way it provides the flexibility of creating a control method based on the desired goal. The lines that connect the buses are used as communication links that share the information between the neighboring agents/BESS in order to achieve a consensus when voltage magnitude of buses is within limits. Each of these buses and BESS has an initial state and a utilization factor is allocated to each BESS. The utilization factor is of great importance as it determines how much power each BESS contributes for the voltage regulation. The consensus algorithm updates the utilization factors until the voltage magnitude does not surpass the limit points, ensuring that all BESS contribute the necessary amount of power for achieving voltage regulation.

In order to initialize the consensus algorithm, a utilization factor is considered as a *leader* $(u_{\text{leader}})$ and it gets updated until the voltage regulation of the system is achieved. This utilization factor is considered as leader because it performs as a reference for the utilization factors of the other batteries $(u_{\text{i}})$ [7]. In order to achieve the voltage regulation of the low voltage distribution network by using the consensus algorithm, the leader utilization factor $(u_{\text{leader}})$ represent the battery connected to the bus (leader bus) that has the highest voltage, if the higher limit of voltage is violated, or it represents the battery connected to the bus that has the lowest voltage, if the lower limit is violated. The leader utilization factor is updated in discrete time step until the voltage is regulated within the limits and the rest of the utilization factors (followers-$u_{\text{i}}$) follow that value and their value is determined by the communication with the neighboring agents.

The consensus algorithm uses voltage limits so that if the voltage exceeds the upper limit, the battery charges and if the voltage falls below the lower limit, the battery discharges. More specifically, if the voltage of the leader bus (case 1: overvoltage) exceeds the upper limit, the utilization factor increases, whereas if the voltage of the leader bus (case 2: undervoltage) falls below the lower voltage limit, the utilization factor decreases. In all other cases, when the voltage of the buses does not exceed any limits, the utilization factors are zero, and the batteries do not contribute to the system.

$$u_{\text{leader}} = \begin{cases} u_{\text{leader}}(t-t_{\text{s}}) + G_{\text{ov}}(V_{\text{n}}(t) - 1.05) & V_{\text{n}}(t) > 1.05 \text{ p.u.} \\ 0 & 0.95 \text{ p.u.} < V_{\text{n}}(t) < 1.05 \text{ p.u.} \\ u_{\text{leader}}(t-t_{\text{s}}) + G_{\text{un}}(V_{\text{n}}(t) - 0.95) & V_{n}(t) < 0.95 \text{ p.u} \end{cases} \tag{1}$$

where, $t_{\text{s}}$ is the sampling time and $G_{\text{ov}}, G_{\text{un}}$ are gains that control the speed of voltage regulation.

The battery connected to the leader bus will be the first one to be informed about any changes in the utilization factor. The other batteries will be informed about changes in their utilization factor according to:

$$u_{\text{i}}[t] = \sum_{j=1}^{n} C_{\text{ij}}[t] u_{\text{i}}[t-t_s] \tag{2}$$

$$C_{\text{ij}}[t] = \frac{A_{\text{ij}}[t-t_{\text{s}}]}{\sum_{j=1}^{n} A_{\text{ij}}[t-t_{\text{s}}]} \tag{3}$$

Following the proposed control scheme, all batteries will contribute to the grid, despite their limitations and capabilities. Thus, the available capacity of each BESS is not affecting the power contribution from them. In Fig. 2 the flowchart of the proposed control is presented. The power that each BESS will contribute is a result of its utilization factor multiplied by its nominal power. This way each BESS provides the necessary power for voltage regulation based on:

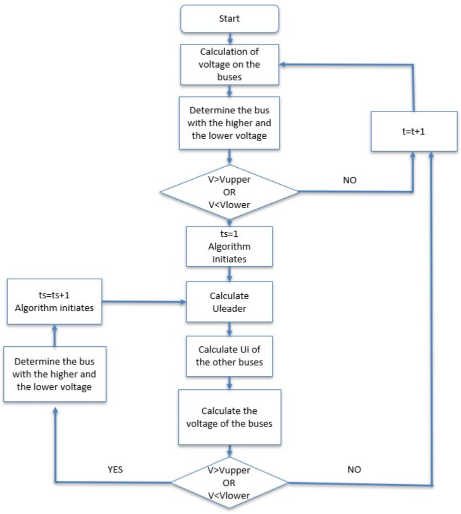

Fig. 2. Consensus algorithm flowchart.

$$Pref_{\text{i}} = P\text{nomBati} * u_{\text{i}} \tag{4}$$

## IV. COORDINATION CONTROL STRATEGY IMPLEMENTATION TO THE CIGRE LOW VOLTAGE NETWORK

The CIGRE Low Voltage Test Distribution Network, consists of eighteen buses, where six PV units and six BESS are integrated. The location of BESS was chosen to be near the PV unit and loads. In Fig. 3 the CIGRE network is presented. In Fig. 4 the communication graph of BESS is depicted, the numbering $(1/n)$ on the communication lines shows the communication weights, $n$ is the number of batteries that each battery has as neighbors including itself. The communication matrix used by the consensus algorithm is:

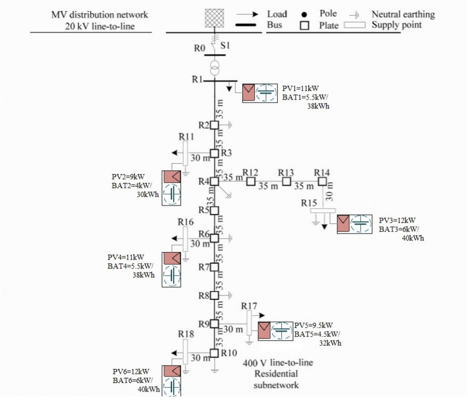

Fig. 3. CIGRE Low Voltage Test Distribution Network with PV and BESS.

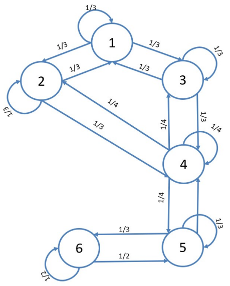

Fig. 4. Communication graph of the BESS.

$$C(\text{G}) = \begin{bmatrix} 1/3 & 1/3 & 1/3 & 0 & 0 & 0 \\ 1/3 & 1/3 & 0 & 1/3 & 0 & 0 \\ 1/3 & 0 & 1/3 & 1/3 & 0 & 0 \\ 0 & 1/4 & 1/4 & 1/4 & 1/4 & 0 \\ 0 & 0 & 0 & 1/3 & 1/3 & 1/3 \\ 0 & 0 & 0 & 0 & 1/2 & 1/2 \end{bmatrix} \tag{5}$$

So BESS 1 communicates with BESS 2, BESS 3 and itself (n=3), this is shown in the first row of the matrix as well as in Fig. 4.

### *A. Simulation Results: BESS with the same SoC*

Fig. 5 depicts the voltage magnitude of the buses if no control is implemented in the low voltage distribution network. Voltage in buses 15, 17, and 18 reaches and exceeds the upper limit of 1.05 p.u. between 15:00 and 19:00 o clock, causing problems with network stability. Furthermore, between 21:00 o clock to 23:00 o clock, the voltage on buses 15 and 18 reaches and exceeds the lower limit of 0.95 p.u.

These limit violations occur since during the period between 15:00 and 19:00 o clock, when PV unit production is higher

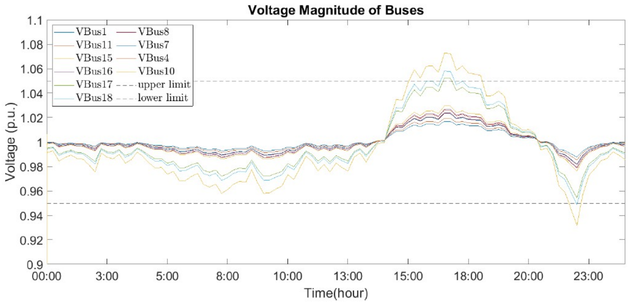

Fig. 5. Voltage magnitude with no control implemented.

than demand, a large amount of power is inserted into the grid, causing an overvoltage, and during the period between 21:00 and 23:00 o clock, when PV unit production is low and demand is high, an undervoltage problem occurs. Thus, with the integration of the BESS and the implementation of the developed control these limit violations should be mitigated.

The voltage of the buses after the implementation of the proposed control strategy can be seen in the Fig. 6, so the voltage magnitudes of the buses that had exceeded the limits are now restored into values within the limits.

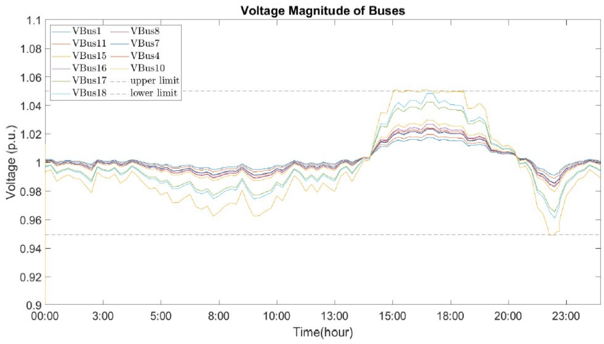

Fig. 6. Voltage magnitude with coordination control implemented.

Fig. 7 depicts the utilazation factors used during the coordination control. They determine how much power each BESS should absorb or provide to the network in order to achieve voltage restoration within limits. When overvoltage occurs, the utilization factor of each BESS becomes positive, the higher the voltage violation on a bus, the higher the utilization factor of the BESS connected to that bus, and as a result, a greater amount of power must be absorbed from the batteries. When there is an undervoltage, the utilization factors are negative, and the batteries must provide power to the network.

The SoC of the batteries can be seen in Fig. 8. When the utilization factors are equal to zero, the batteries do not contribute to the network and the SoC remains constant; when the utilization factors are positive, the batteries charge and the SoC increases until voltage restoration is achieved. When there is undervoltage and the utilization factors are negative, the batteries discharge in order to keep the voltage within limits, and the SoC begins to decrease. In this case since the undervoltage is for a very short period of time (30 minutes) and as can be noticed form the utilization factors the amount of power needed from the battery is smaller than during the overvoltage problem, thus the decrease of the SoC is very small compared to the increase during the overvoltage.

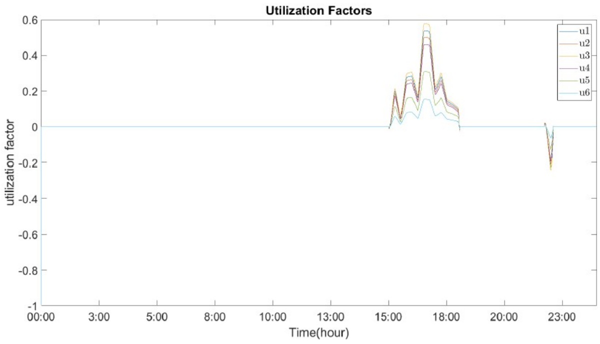

Fig. 7. Utilization factors.

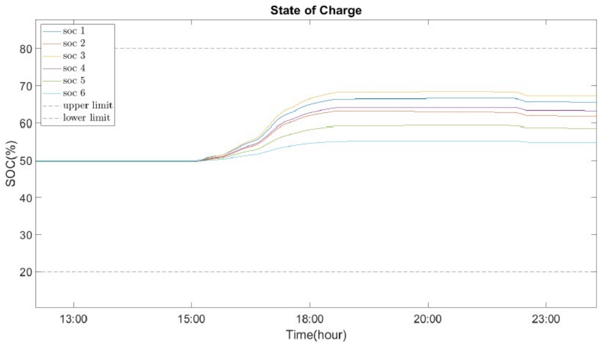

Fig. 8. State of Charge of BESS(%).

### B. Simulation result: BESS with different SoC

It is worth investigating the operation of the control strategy when one of the BESS is not available. In this case, the SoC of BESS 4 is set at 65%; however, around 18:00 o clock, the SoC of the battery has reached the limit of 80% (Fig. 9). The developed coordination control distributes the power required from BESS 4 equally to the neighboring batteries, ensuring voltage stability.

Even though one of the batteries is not available for use, the voltage magnitude of the buses are kept within the limits as it can be observed in Fig. 10. When the battery is disconnected, a small peak is observed, but the control strategy manages to regulate the voltage and mitigate this transient voltage change.

In Fig. 11 (a) the utilization factors of the neighboring batteries (BESS 2, BESS 3 and BESS 5) have increased when compared to the original values. More specifically, the utilization factor of BESS 4 is 0.12 and it needs to be divided to three neighboring BESS so an increase of 0.04 should be noticed in the BESS utilization factors. At the highest point, BESS 2 has increased from 0.13 to 0.17, so there is

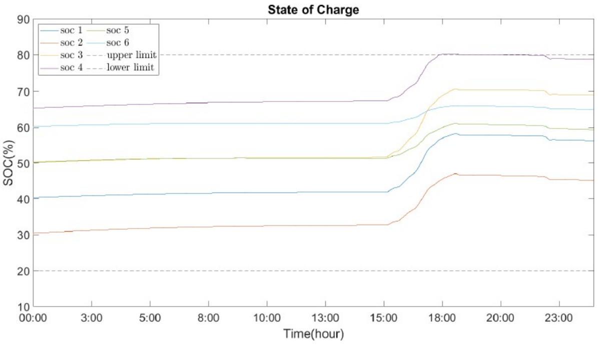

Fig. 9. State of Charge of BESS(%).

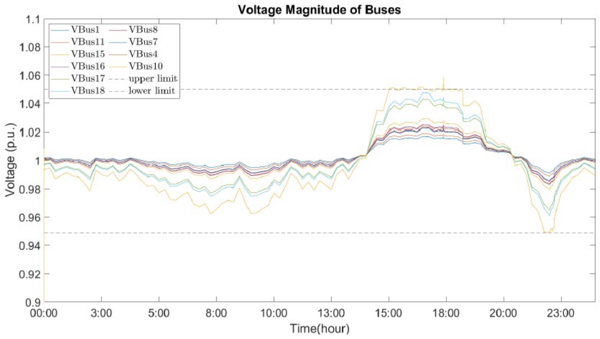

Fig. 10. Voltage magnitude of buses with coordination control implemented.

a difference of 0.04 as expected, BESS 3 increases from 0.16 to 0.2 and BESS 5 increases from 0.08 to 0.12. As a result, the neighboring batteries cover the required power that BESS 4 is unable to provide. In Fig. 11 (b) the power contribution of BESS 4 under normal operation when no limit of state of charge is violated in comparison with this case where the limit of SoC is violated is shown. When the state of charge reaches 80% the battery is disconnected until it becomes available again.

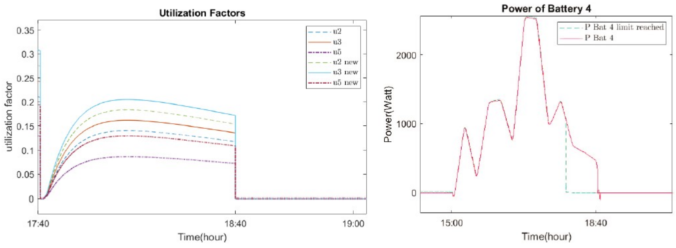

Fig. 11. (a)Utilization factor changes between normal operation and with a BESS unavailable. (b)Power contributed by BESS 4 under normal operation in comparison to when BESS 4 becomes unavailable.

### C. *Comparison to Decentralized Control Strategy*

In order to be able to compare the results of the decentralized control strategy with the coordination control strategy the same mismatch profile used as in the cases with the coordination control strategy, thus the voltage magnitude of the buses with no control implemented is the same as in Fig. 5.

In this case, each battery is controlled locally, so the amount of power required is determined by the voltage magnitude on the bus to which the battery is connected. Fig. 12 depicts the voltage after decentralized control is implemented. Although the voltage is regulated within acceptable limits, multiple fluctuations can be observed, affecting power quality. It can be noticed that the voltage fluctuations are higher when the overvoltage is higher. This can also be explained as the droop control has often a poor transient performance. In the case of the coordination control strategy the voltage behavior did not include frequent sudden changes around the limit point.

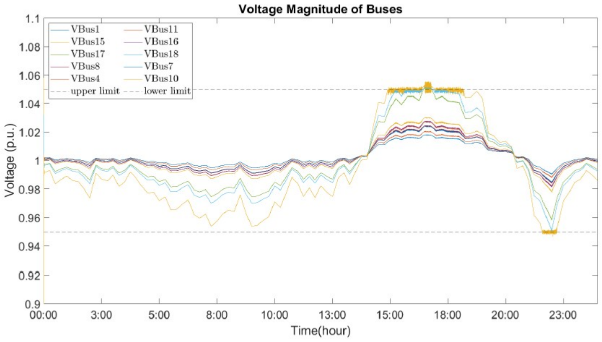

Fig. 12. Voltage magnitude of buses with decentralised control implemented.

Furthermore, not all batteries help with voltage regulation, in this study only BESS 3 (Bus 15) and BESS 6 (Bus 18) contribute while the rest are not operating as the voltage on their buses does not surpass any limit. Thus, only the battery connected to a bus that exceeds the limits contributes, necessitating a larger capacity than in the case of coordinated control strategy. This is depicted in the Fig. 13 and it can be noticed that the power provided by BESS 3 is always higher with the decentralised control, moreover, all the frequent changes in the voltage magnitude can be observed in the power contribution of the battery. The frequent changes of the voltage are affecting the power contribution due to the poor performance of the droop control. These frequent changes in the power output of the battery reduces its lifetime, making decentralized control strategy less appropriate to use [21].

Finally, if one of the batteries used in voltage regulation reaches a SoC limit or is unavailable due to maintenance, the other batteries cannot provide the necessary power, and the voltage cannot be restored to acceptable levels. This is depicted in the Fig. 14, where BESS 3 is not available around 18:00 o clock. The voltage is not regulated and has exceeded the limit. When the coordination control strategy was used this was avoided.

## V. *Laboratory Results*

The developed coordination control strategy was simulated in the previous sections, and various case studies were presented. In this section the developed control is tested in the

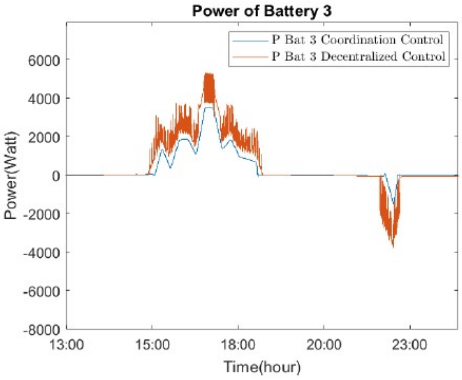

Fig. 13. Comparison of power contribution of BESS 3 with coordination control strategy and decentralised control strategy.

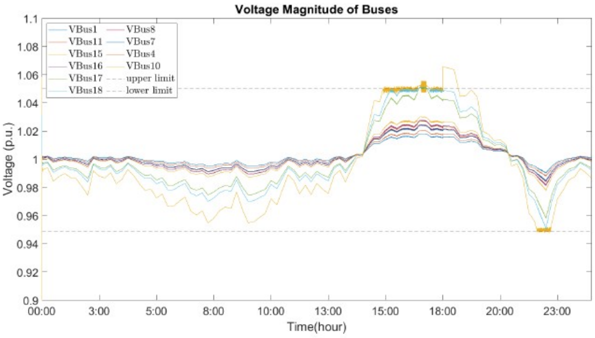

Fig. 14. Voltage magnitude of buses when BESS 4 becomes unavailable.

laboratory using the CIGRE Low Voltage Network. More specifically, BESS 1 is emulated in the laboratory in order to test the behavior of the control in real-time operation, more specifically to test whether the contribution of the emulated BESS in the labotatory matches the simulated case. For this purpose RT-Lab software was used in combination with the laboratory equipment. Mismatch data that could lead to voltage violation were used instead of the data used for the simulation as they required a very high simulation duration.

In Fig. 16 (a) the comparison of the voltages of bus 1 when tested in the laboratory and when simulated, with the coordination control implemented, is presented. It can be noticed that the results from the laboratory follow the simulation, there are few minor differences which are created from measurement accuracy errors.

Fig. 17 depicts the contribution of BESS 1 when it is simulated and when it is tested in the laboratory. It is of great significance that the battery's response in the laboratory testing matches the response of the simulation.

As a result, the laboratory testing of the developed coordination strategy was carried out effectively. Under laboratory conditions, the battery performed as expected, exhibiting the same response as during the simulation. Differences in voltage and power contributed are caused by measurement accuracy errors, equipment used, and slower implemented control on

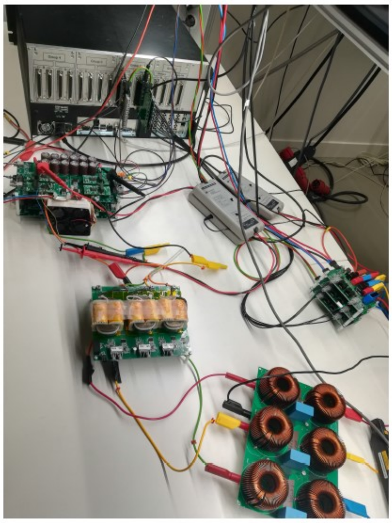

Fig. 15. Laboratory setup.

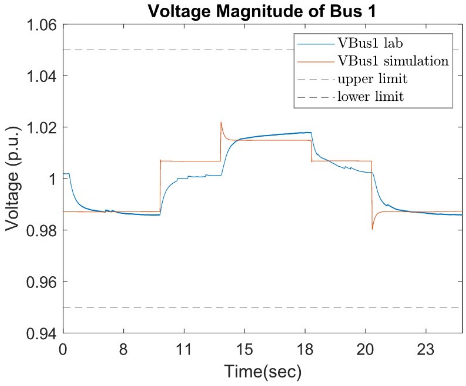

Fig. 16. Voltage magnitude of BESS 1 when simulated in MATLAB/Simulink in comparison to it being tested in real-time at the laboratory.

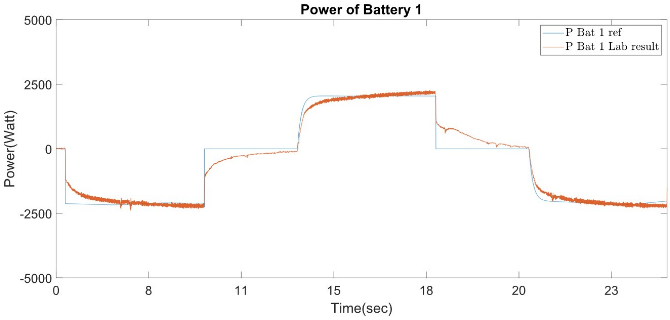

Fig. 17. Power contribution of BESS 1 when simulated in MATLAB/Simulink in comparison to it being tested in real-time at the laboratory.

the inverter for safety reasons.

## VI. CONCLUSIONS

The proposed coordination control strategy for multiple BESS was tested in different case scenarios in low voltage distribution networks, using MATLAB/Simulink, and the goal of mitigating voltage limit violation due to high PV unit penetration was achieved. Moreover, coordination control strategy of BESS was compared to a decentralized control and the results illustrate that the proposed control is more effective in voltage regulation. Finally, the behavior of one of the BESS was examined in laboratory environment, with the proposed control implemented, and the coordination control led to similar contribution of the BESS to the simulated case, demonstrating that the proposed control could be implemented in real-time applications.

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