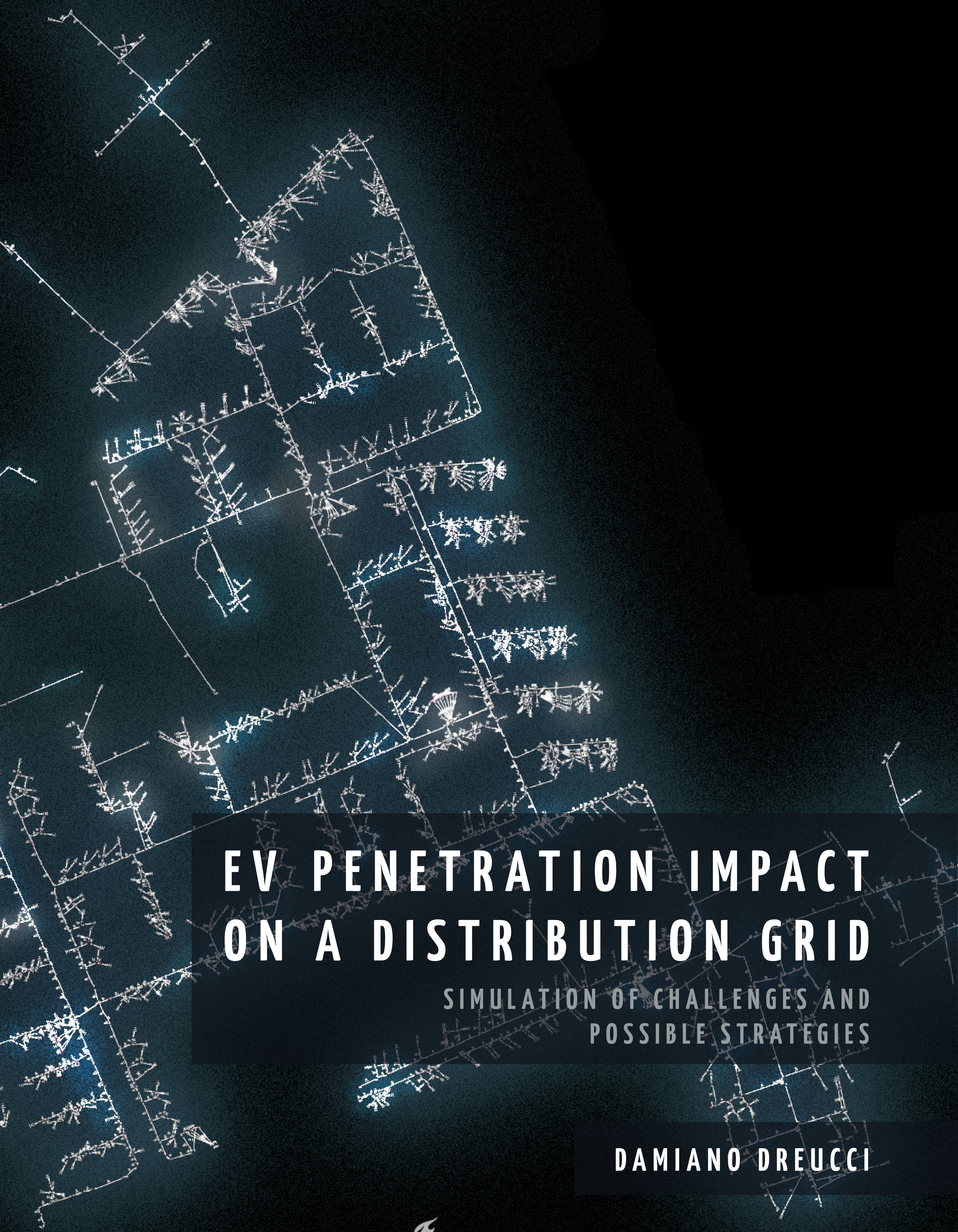

# EV PENETRATION IMPACT ON A DISTRIBUTION GRID

## SIMULATION OF CHALLENGES AND POSSIBLE STRATEGIES

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# EV Penetration Impact on a Distribution Grid

## Simulation of Challenges and Possible Strategies

by

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# *Preface*

There are many thoughts and reflections that would be worth sharing about this thesis, but a couple of pages turned out not to be enough to convey all of them. In truth, I feel like also this report, imperfect as it is, can poorly transmit what I consider the real results of this study. Like in any similar work, there is the statement of a problem, the description of a solution and some results to prove the method right or wrong. This should probably make any reader find in these pages exactly what he (or she) expects to see. Nevertheless, I find hard getting rid of this sensation of incompleteness, because what I consider being the main result of this study is nowhere to be seen. Nor in this report, nor anywhere else. In fact, I believe the main outcome of these last 11 months is the experience I have gained.

Ray Bradbury said in his novel *Fahrenheit 451*: "If you hide your ignorance, no one will hit you and you'll never learn"[1]. I tried to live by this idea every day I spent on this research and I exposed my ignorance every time it was needed. Now that I have reached the end of this journey, though, I feel my thirst for knowledge has not been quenched yet and that I need to proceed in this direction further. Therefore, I want to consider this arrival point only as the beginning of a new chapter, where new knowledge and experience await to be found.

The work you have in your hands – or that you are reading on the screen of your computer – is my conclusive project to obtain the degree of Master of Science in Sustainable Energy Technology. I started this project in the department DCE&S in September 2019 and back then, this final report seemed only a very far goal. Now that is over I cannot help looking at it as the result of all the efforts that brought me here since I started walking the path to become an engineer. I sincerely hope you will find the results I present here of any relevance for your work or even only for your interest.

I would also like to use these few lines to thank all those people who helped me throughout this period and that made the development of this thesis possible. Before anyone else, I want to thank my PhD supervisor MSc. Y. Yu, who guided and helped me in countless occasions. The freedom she left me and the patience she always showed are two aspects that I have truly appreciated. Then, a huge gratitude goes also towards my supervisor Dr.ir. G. R. Chandra Mouli and my "technical advisor" Dr.ir. A. Shekhar. Their help and capacity to give feedback was fundamental and clearly showed their experience in the field. Furthermore, it would have not been possible to carry out this work without the data and information provided by ElaadNL and Enexis. Therefore, I sincerely thank both companies for their support.

Besides them, many other people supported me throughout these months. My flatmates Francesco and Marco always took good care of my mental health during these months. They listened to all my boring complains and helped me celebrating all my small successes. Everyone who knows me will understand how difficult this task is and

[1]Bradbury, Ray, "Fahrenheit 451", New York: Simon and Schuster, p. 104, 1967.

my girlfriend Déborah probably realised it more than anyone else. For her capacity to stay around me and the way she turned the quarantine we all lived into an incredible period, she would probably deserve a statue.

It is also impossible not to mention all those friends who shared with me these last two years. The group "Originals" made many evenings unforgettable and for this I thank all of them. Delft would have not been the same without them. Likewise, I also want to thank the group of "OHMies" with whom I shared so many yoga classes and experiences. The time spent with them has left a very deep mark on me. All these people, along with the friends from the university, bouldering, the "Italian community" in Delft and *my* Italian community in Rome, supported me during this time and gave a crucial contribution only by making my days better.

Last but not least, my deepest gratitude goes towards my parents. This thesis would not exist and I would not even be here if they had not believed in me two years ago. They supported me both financially and spiritually, and for this I will never thank them enough.

Thank you all.

*Delft, 23 July 2020*

# *Abstract*

Although the idea of electric vehicles fell out of favour in the 1930s, it seems this phenomenon is now reversing and that many companies are willing to invest again on this technology. The advantages are clear: no emissions and the possibility to power vehicles by means of sustainable sources. On the other hand, a high number of simultaneously active charging stations would likely lead to severe problems in the electrical network, e.g. grid congestions and voltage issues. One of the main goals of this work is to estimate the impact that a higher EV penetration has on the power loading of the lines and transformers in a distribution grid. Once these effects are clear, the focus can move towards the investigation of possible strategies to limit it.

Excluding an equipment reinforcement, the only possible way to keep a grid operating when the general working conditions approach the technical limits, is to improve the power management. In this regard, five control strategies were tested in different combinations. Among these, three were implemented on a single charging station level to control the charging operations of the single vehicles. These are the *uncontrolled charging* (the most commonly used strategy worldwide), the *average power charging*, where a constant low power is provided during the whole parking time, and the *local optimisation charging*, where a completely local optimisation analysis is carried out to calculate the cheapest operation possible. The other two strategies instead were implemented at central level, to curtail power in case of necessity. These are the *Equal Curtailment Method*, that prioritises an equal division of the curtailment among the chargers, and the *Flexible Curtailment Method*, that optimises the curtailment considering the *flexibility* of the charging stations.

Several tests were run by means of simulations on real Dutch distribution grid models and they showed that simple charging strategies – such as the average power charging – can lead to both low charging prices and low loading percentages. It seemed hardly possible, though, to make the charging stations take greater advantage of the low prices at night, without causing overloading issues. However, this could be achieved if a curtailment scheme was also included by means of a central coordination unit. Therefore, it is clear that different levels of complexity may bring benefits to the network, but they may also present drawbacks. The purpose of this work is to shed some light on the different possibilities and to provide hints on how to choose the most appropriate strategy for each situation.

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# *List of abbreviations*

**BEV** Battery Electric Vehicle

**BPM** Belasting van Personenauto's en Motorrijwielen

**CC** Central Controller

**DR** Demand Response

**DSO** Distribution System Operator

**ECM** Equal Curtailment Method

**EV** Electric Vehicle

**EVSE** Electric Vehicle Supply Equipment

**FCM** Flexible Curtailment Method

**GHG** Greenhouse Gas(es)

**ICEV** Internal Combustion Engine Vehicles

**IEA** International Energy Agency

**LRM** Localisation Reference Matrix

**LV** Low Voltage

**MG** Microgrid

**MRB** Motorrijtuigenbelasting

**PHEV** Plug-in Hybrid Electric Vehicle

**PV** Photovoltaic (panel)

**RES** Renewable Energy Source

**SOC** State Of Charge

**TSO** Transmission System Operator

**V2G** Vehicle to Grid

# 1 Introduction

The integration of Electric Vehicles (EV) in the grid is an ongoing process that is attracting more and more attention. A lot of research has already been made on the topic to allow a safer, more convenient and more efficient integration of this emerging new technology. In this regard, it is interesting to notice that a significant number of sources focused only on its introduction by means of *microgrids*[1] (MG). In many of these studies, it was proved that a very efficient charging operation could be achieved. However, such solutions could only be applied where MGs are already widely integrated in the system, which is currently not a very common condition. A more common situation (in the Netherlands as well) is that consumers are connected to the grid via nodes[2] that do not operate like MGs. These nodes may differ from MGs in terms of dimension and because they cannot operate in islanded mode. Therefore, the natural question that arises is: *how to integrate EVs in the current distribution system?*

In this regard, one of the most important aspects to consider is that a higher penetration of electric vehicles is expected to significantly affect the electrical network. In particular, the load demand would increase a great deal in peak hours, and – in case Vehicles-to-Grid (V2G) mechanisms are implemented – also the power flow could be considerably altered and become bi-directional. Therefore, many *Transmission System Operators* (TSO), *Distribution System Operators* (DSO) and energy companies are now investigating whether the current status of the grid is sufficient to withstand a higher and higher penetration of EVs and, if so, to what extent. However, it should also be mentioned that the results of this analysis may differ depending on how this technology is going to be implemented in practice. In fact, it is obvious to expect that by adopting smarter charging strategies or introducing a curtailment scheme to be used in case of potentially dangerous situations, EVs could be regarded as safer and less problematic. Therefore, the purpose of this thesis is to compare some of the different strategies and schemes that could be adopted to implement these new elements in the grid and observe the effects they lead to. By doing so, it is possible to shed some light on some of the challenges and possibilities that await what could be called the *electrical power system of the future.*

[1]These are defined by [5] as systems that can manage themselves and operate both autonomously or grid connected.

[2]In this report, the term *node* is used to refer to the point at which the connection of one or multiple utilities occurs.

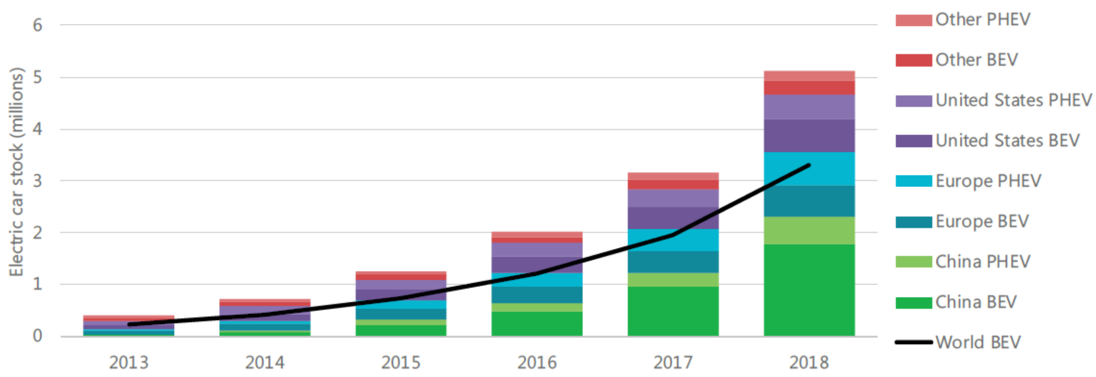


Figure 1.1: Passenger electric car stock in main markets [1]

## 1.1 A new Transportation Revolution: Electric Vehicles

In this section, an overview of the spreading of electric vehicles is provided. Section 1.1.1 describes the trends of this phenomenon on a global scale, whereas section 1.1.2 focuses only on the situation in the Netherlands. The information contained in these first two parts should give a first insight into what is foreseen to be the future of mobility. Then, section 1.1.3 provides an overview on the challenges and the benefits that come with EVs.

### 1.1.1 Electric vehicles in the world

An electric vehicle can be defined as "a vehicle that is driven by an electric motor which draws its current either from storage batteries or from overhead cables" [6]. There is already a long history behind this topology of vehicles. In fact, although it is still discussed to whom the credit for this invention belongs to, the first EVs date back to the 1830s. Since then, they had become more and more popular, until they almost completely died out because of the development of Internal Combustion Engine Vehicles (ICEV) in the 1930s [7].

Nowadays, it seems the phenomenon has started reversing and EVs are getting progressively more common almost everywhere around the world. As of the end of 2018, the global number of EVs reached 5.1 millions (considering both fully electric and hybrid vehicles). As shown by figure 1.1, more than 40% of the global electric fleet is located in China, while Europe and USA accounts for 24% and 22%, respectively. The outstanding percentage reached by the People's Republic of China can be explained through the several policies adopted by the government, such as the "China's 12th 5-year plan" [8]. Also in other countries the electric vehicles' integration is reaching very interesting results, such as in Japan, where there are now more EV charging points than petrol stations [9].

Furthermore, the exponential rise in sales registered so far, visible in figure 1.1, seems to be in line with what stated in the Paris Agreement. This was signed by the representatives of 195 countries and set the goal of maintaining the global rise in temperature at 1.5 °C above pre-industrial levels and, in the worst case, not to exceed a 2 °C limit. Being the transport sector accountable for almost one quarter of the energy-related global GHG emissions, it is clear that a transport electric revolution will play a major role in this sustainable transition. As a matter of fact, according to the IEA, around 75% of all the vehicles sold worldwide has to be electric by 2050 [10, 11]. In this sense, along with the very well known Tesla, other car brands started producing their own electric models. Among them are Nissan, Peugeot, Mitsubishi, General Motors and Chevrolet [12].

### 1.1.2 Electric vehicles in the Netherlands

As of 2018, the overall number of EVs registered in the Netherlands is around 143,000, of which approximately 98,000 are Plug-in Hybrid Electric Vehicles (PHEV), while the rest are Battery Electric Vehicles (BEV) [13]. According to the same source, this number is not the highest in Europe, as other countries such as Norway (249,000), United Kingdom (198,000), Germany (194,000) and France (166,000) have bigger EV fleets, as of the same year. Nevertheless, the results obtained by the Netherlands can still be regarded as exceptional, since its population is considerably smaller than in the other countries (except for Norway). Furthermore, the Dutch electrical network has an outstanding number of 37,000 charging points, which is the highest in Europe. For all these reasons, the Netherlands is considered one of the front runners in the field of EVs.

The current situation is likely to improve even further thanks to the goals set in the coalition agreement presented by the leaders of four of the most important parties in the Dutch parliament. According to this, "The aim is for all new cars to be zero emission by 2030 at the latest" and "[...] ensure that charging infrastructure is in place to meet the needs of the new stock of electric vehicles" [14, p. 43]. To practically achieve these goals, several government incentives have been introduced. Among these are subsidy schemes for fully electric vehicles and the possibility to use dedicated bus lanes for electric taxis and other specific categories of EVs [13]. Furthermore, all fully electric vehicles are exempt from both purchase tax (Belasting van Personenauto's en Motorrijwielen, or BPM) and road tax (motorrijtuigenbelasting, or MRB) until 2020 [15]. It is important to notice that these exemptions are not valid for PHEVs. In fact, hybrid vehicles need to pay additional fees on the BPM based on the CO2 emitted and get only an adjusted discount on the MRB [16, 17]. This caused a decline in the sales of PHEVs, as it can be seen in figure 1.2.

In the same figure it is also possible to see that the sales of BEVs increased exponentially. According to [18], the EV penetration could already reach a percentage of 47% by 2030. Therefore, it is clear that this phenomenon of steadily higher sales of EVs needs to carefully be analysed, so to make sure that all the possible consequences (described in the next section) are kept under control.

### 1.1.3 Challenges and benefits of EVs

As explained in the previous sections, the penetration of EVs in the electrical network is likely to be massive in the coming years. This will come with both challenges and new possibilities for the electrical networks.

EVs' new loads are likely to make the operation of the electrical systems even more complex than it already is. As a matter of fact, their introduction in the network comes with several disadvantages, such as high uncertainty, disparity and non linearity [19]. Furthermore, these kinds of vehicles are characterised by a very high power demand. For instance, a 24 kWh packed Nissan Leaf has a power consumption very close to a single

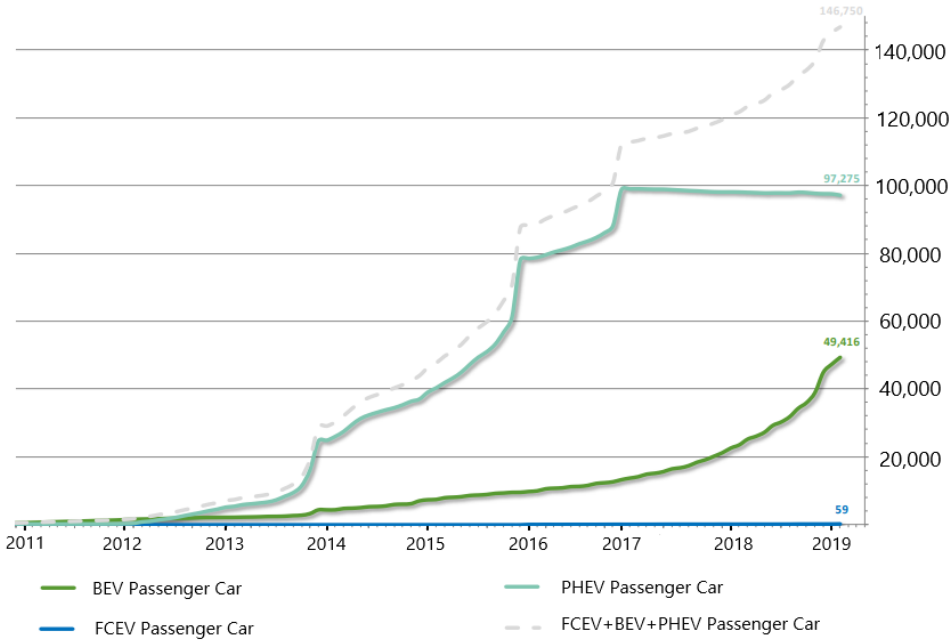


Figure 1.2: Development in the number of EVs registered in the Netherlands [2]

household in Europe [20]. Therefore, a high penetration of this technology constitutes a serious threat for the grid.

According to [21–24], some of the problems that are likely to be experienced are overloads of lines and equipment, voltage deviations, degradation of power quality and higher power losses in the grid. On top of that, also a significant reduction of the expected life of the distribution transformer is foreseen [25, 26]. Potential effects of a higher EV penetration in the Netherlands are studied in [27], where the results show that a 42% increase in the load peak would be registered in case all vehicle owners switched to a fully electric one. A similar research was carried out for the U.K. and the results showed that an EV penetration of 20% would already cause an increase in the peak load of 35.8% [28].

On the other hand, EVs can bring many benefits as well. According to [29] and [30], EVs, on average, drive daily 38 km and are parked at home or in work places for around 22/23 hours per day. This means that electric vehicles are particularly suitable for integrating Demand Response (DR) mechanisms and ancillary services. As highlighted by C. Ahn et al. [31], because of their fast response time, EVs may help system operators' job of responding to the minute-by-minute fluctuations in the network. Their implementation in the electrical system for frequency regulation and energy storage purposes is discussed in [12] too. Finally, EVs can also be used to flatten peak demands (*valley filling*) and therefore increasing the amount of utilities connected to the grid, without reinforcing it [18, 32]. In this sense, EVs could really help the introduction of renewable sources to the energy generation portfolio. However, to do so, some technical problems need to be solved first, such as the expected cycle life of the batteries mounted on the EVs [20]. This holds even more true if solutions like the V2G are adopted[3].

[3]The implementation of DR mechanisms does not necessarily imply EVs giving energy to the grid (V2G). It can also be achieved by simply postponing the charging process of the connected vehicles.

As stated at the beginning of this chapter, the way through which EVs and charging stations are decided to be introduced in the grid could make a huge different on the final outcomes. Some strategies are certainly smarter and more efficient than others, but may suffer of other problems, such as high complexity, or rely on grid conditions or assumptions not entirely fulfilled. Therefore, the control schemes to be adopted will most likely be a trade-off of all the possible solutions and necessary conditions.

Some of the possible strategies are based on a completely local control, some on a completely central entity, whereas some others mix these two possibilities. Throughout this thesis, several comparisons on different combinations of schemes are presented, so to give a wide overview of the topic.

## 1.2 Renewable distributed generation

One important aspect that also needs to be considered is the presence of Renewable Energy Sources (RES) in the electrical network. The use of these "clean" technologies allows a more sustainable energy production and, therefore, would increase the chances to meet the goals set with the Paris Agreement.

However, the integration in the grid of technologies such as solar and wind power also leads to great challenges. One of these is that their presence makes the system's behaviour more subject to weather uncertainties. This could lead to sudden and very significant changes in the power generated, causing in turn issues in the grid, such as voltage oscillations and under voltage situations. On top of that, the introduction of distributed generation – mainly photovoltaic (PV) panels in the residential sector – also has effects on the flow of power, that because of this change is now becoming bidirectional. This has very serious consequences on the protection systems, since circuit breakers may have problems in isolating a faulty section in case of a bidirectional flux of power.

Furthermore, another problem could arise when the power flows in the opposite direction, from the nodes towards the upper feeder. Van Amstel describes this problem by means of the *coincidence factor*, that is used to "describe the affiliation of the peak demand of individuals to the peak demand of a group" [29, p. 26]. Elements like the PV panels have a coincidence factor that is remarkably close to 1. This means that when the sun starts shining, all the solar panels installed start producing power at the exact same moment. A sudden voltage rise would be the direct consequence of it and, in case of high power installed, line overloads could occur as well. This coincidence factor close to unity is also the reason why a solar eclipse is a big challenge for TSOs [33].

On the other hand, a local sustainable generation would also lead to several positive effects. In case power is generated locally, there would be less necessity of transporting huge quantities of energy. Therefore, less losses would be registered on the lines and the possibility of having overloading and (especially) under voltage situations could decrease if these technologies are implemented efficiently.

The conclusion of these few observations is that the benefits brought by a steadily higher PV penetration in the network come with several challenges as well. Nevertheless, the number of solar panels installed all over the world are skyrocketing. For instance, the installed solar capacity in the Netherlands increased from 287 MWp in 2012 to 4522 MWp in 2018 [34]. For this reason, numerous PV panels were added to the models of the grids, as it is better explained in section 6.2.

## 1.3 Research questions

The previous sections show the relevance that EVs currently have on the electrical power system and give an idea of what could be the potential impact of a higher EV penetration in future. This EV penetration is expected to lead to different consequences depending on the topology of the grid analysed (rural, urban or sub-urban), but in all cases it is foreseen to be very significant. In order to relieve the impact of this phenomenon, one solution is to improve the power management in the grid. In particular, it is possible to operate on two different levels: on a local level and on a central level.

The former refers to the possibility of implementing different charging behaviours at the single chargers. These could reach various levels of complexity but, being their operation entirely local, their uncoordinated actions could easily lead to severe consequences on the network. The central level instead offers the advantage of including in the analysis the operation of all the elements involved in the system. In particular, the central scheme considered in this research is a curtailment mechanism to ensure that the technical constraints of the grid are always satisfied.

The main objective of this study is to evaluate the impact that different charging strategies have on the distribution grid and the effects of the implementation of a central curtailment scheme. Therefore, the main research question is the following:

*What is the impact on the distribution grid of different charging strategies and how can these coordinate with a central entity?*

Besides it, the following three sub-questions are also introduced (more details about the single questions can be found in section 3.3).

- *To what extent are grids affected by higher EV penetrations?*
- *How and to what extent does a smart charging scheme affect the grid with respect to uncontrolled charging?*
- *Can a local control strategy coordinate with a central curtailment scheme to efficiently solve overloading situations occurring in the grid?*

## 1.4 Research outline

The content of this work is organised as follows. Chapter 2 provides an overview of the literature present on the topic, followed by a critical analysis of it. In chapter 3 all the main assumptions are listed and both the focus and the methodology of the research are described. The next two chapters go into the methods and schemes adopted in this thesis, by describing the two main parts of this work: the development of a local controller (Chapter 4) and the development of a central controller (Chapter 5). Chapter 6 provides some relevant information concerning the grids and the data used for the simulations. Finally, chapters 7 and 8 show respectively the most relevant results of this work and the main conclusions of it.

# 2 State of the Art

The purpose of this chapter is to give an overview of the different strategies and solutions proposed in literature to front all the problems and challenges highlighted in chapter 1. The first topics of interest are the possible different charging strategies that exist to power the electric vehicles connected to the grid. Then, the focus can move towards methods through which different entities, with different goals, could operate and coordinate with each other to achieve global optimal solutions. These global optimal solutions not only refer to the grid operating in the cheapest possible way, but also to ensure the system always stays within its technical limits.

The chapter is organised as follows. Section 2.1 goes trough some of the most relevant charging strategies that exist in literature. Section 2.2 describes several aspects regarding microgrids and the way this topic can be relevant for the thesis. In section 2.3, instead, the role of aggregators is discussed, along with how these entities can coordinate with each other and/or with a central entity. Finally, section 2.4 summarises the main papers studied on the topic of power curtailment, queuing strategies and the way fairness could be considered in a model.

## 2.1 Local charging strategies

When it comes to electric vehicles and the way they interact with the grid, one of the most important aspects to consider is the charging strategy that is adopted. Many different possibilities exist and, among them, the *uncontrolled charging* is certainly the most common one. This strategy – sometimes also called *dumb* or *unregulated charging* – starts charging the EVs with the highest tolerated power immediately after their connection. When compared with other charging schemes, the uncontrolled charging very often leads to less efficient results in terms of costs and impact on the grid.

In this regard, the authors of [35] proved possible to obtain a lower peak demand and a higher minimum voltage with both the so-called *profit maximization charging* and the *power factor control charging*. The purpose of the former is to prioritise the charging operation at low price moments, while the latter reduces the power factor of the charging process any time there is a violation of the voltage, so to always maintain the voltage at all nodes above a set level. Saldanha et al. [36] also investigated over the possibility to replace the uncontrolled charging with a smarter strategy, in order to reduce the grid impact of the electric vehicles. In this case, though, the comparison was made with the *delayed charging*. This strategy makes use of two different prices: a low peak hour price from 00:00 to 07:00 and a high peak hour price during the rest of the day. The *delayed charging* led to a lower impact of the EV on the grid, but showed also a second peak of power occurring during off-peak hours. This charging scheme is sometimes also called *double-tariff charging* and the impact of its implementation is discussed by the authors of [37] too.

Müller et al. [38] describe and compare in their research another possible charging strategy. In particular, they illustrate the working principles of the *Voltage Guided Control*. This strategy adjusts the power given to the EVs according to the voltage registered at the junction. As long as the voltage stays within the allowed limits, the charging process is carried on at the rated power. In case the voltage drops below the set limit, the charging power is reduced linearly so to increase the voltage. Besides this voltage based strategy, they also analysed a price oriented strategy similar to the one described in [35]. The results of their simulations showed that this strategy led to the most serious grid impact as a result of the high charging concentration registered at night.

This last result highlights one of the most relevant obstacles to the implementation of a smart charging strategy that is completely local. In fact, the lack of coordination can very often lead to high charging concurrency at low price moments. For this reason, the authors of [39] describe an optimisation charging strategy that aims at making use of the low prices registered at night, while also coordinating with the DSO. By means of this approach the overall network operation cost is minimised and the overloads are mitigated. Other possible approaches to mitigate the impact on the grid of higher EV penetrations are described in the following sections.

## 2.2 Similarities with MGs' coordination strategies

As of 2018, only a few MGs exist in the Netherlands and all of them are still part of research projects [40], therefore a solution for the integration of EVs in this country cannot rely yet on the use of this technology. Nevertheless, many of the authors who discussed about the integration of EVs and RESs through MGs described problems and challenges similar to the ones that are likely to occur in a traditional electrical network. While considering their studies, though, it is important to keep in mind that there are some crucial differences between a microgrid and a node [41]. The most important one is that the former can operate in islanded mode, therefore completely disconnected from the feeder, while the latter cannot. This makes the problem of safe islanded mode operation – discussed in many sources – completely irrelevant for the research of this thesis.

Sources [42–44] focuses on hierarchical systems and coordination between MGs. In all cases, each MG performs its individual optimisation and then communicates the solution to a central system which returns new set-points to all MGs. In [42] the idea of the authors is to minimise the costs at the single MG level by setting a very high purchasing price (from the grid) after a power limit value is exceeded. Once the optimisation analysis is completed at the MG level, each MG sends to the central system the total power it needs (load minus RES generation) and the central controller behaves accordingly. This means that in general, each MG adjusts its own peak power, while the central system adjusts the optimum point for the whole system. [43] focuses more on describing the *System of Systems* method to coordinate and interconnect multiple MGs. The idea in this case is to connect heterogeneous autonomous systems so to make them operate as a single larger entity. The authors of [44], instead, optimise the coordinated behaviour of MGs by setting internal price incentive mechanisms. By establishing appropriate selling and buying prices they believed (and proved) possible to stimulate the trading of energy in a multiple microgrid context. This method is based on setting appropriate prices for the next hour that are communicated to all the MGs. This has an influence on the results of their individual optimisation analysis of the next hour and also leads to better PV utilisation. The Stackelberg game theory is adopted for the price setting optimisation.

In all the cases here reported, the global system optimisation is performed by coordinating (in different ways) power exchange between MGs and between single MGs and the upper grid. This situation is very different from that of a node, which can exchange power only with the feeder at which is connected. However, the architecture described in [42], where the global optimal solution is reached after a hierarchical coordination process between MGs and a central entity, appears to be applicable also in case of a regular grid, namely where no MGs are included. Instead, all those methods relying on price control for the coordination process are more unlikely to be adopted. This is because the current Dutch electrical network does not allow direct power exchange between nodes, unlike in the interlinked community described in [45], where all MGs are assumed to be interlinked via an AC bus.

Finally, the authors of [30] follow a slightly different approach to the problem. The first analysis is performed by the central controller and this determines the best power to give/take to each MG considering all the loads. The EVs in this analysis are regarded as both loads and batteries. Once the schedule is completed and sent to all the MGs, these in turn optimise their strategy according to their specific EVs' requests. Therefore, the approach is very similar to the ones described above, with the difference that the analysis starts from the central entity instead than from the single local ones.

## 2.3 Aggregator's role

Before discussing about research on *aggregators* in an electrical grid, it would be useful to provide a general definition of this term. In the Official Journal of the European Union, an aggregator is defined as "a demand service provider that combines multiple short-duration consumer loads for sale or auction in organised energy markets" [46, p. 14]. So, being its function the coordination of several small entities, its role in the whole EV integration process could be very relevant and it seemed, therefore, worth studying deeper.

In [47], the authors deal with problems that are similar to the ones described in the previous section, namely they try to coordinate different aggregators to reach a global optimal solution. In this sense, however, it is more similar to the approach followed in [30]. In fact, the process starts with the central entity sending initial set-points to the aggregators, which reply in turn with an adjusted solution. When the convergence criteria are met, the method stops. This method, although theoretically very valid, could suffer from high solving time, due to the several iterations that could be run before the convergence criteria are eventually met.

The authors in [48], instead, describes a complete different approach where there is a strong communication system between all the aggregators. However, they dive deeper into other aspects, such as *mobility awareness* (arrival time calculated by means of speed, routes, etc.). This is a very interesting approach, because it allows in theory to get relevant information from EVs before they reach a charging point. Therefore, the advantage of this strategy is that the charging process of all the electric vehicles can be organised in a more efficient manner. On the other hand, this method necessarily ends up dealing with a higher quantity of information that needs to be shared in innovative ways, by means of the vehicle itself or via an app connected to the EV. Also in research [49] the authors describe the possibility of including in the analysis parameters such as EV routes and traffic. Although the results of both these two studies make their approach appear very promising, the difficulties in implementing such a strategy , namely traffic and EVs remote control, make the implementation of these strategies very unlikely in the near future.

It is also relevant to analyse the study carried out by S. Paudyal et al. [3], where a similar approach is followed and they use the driving distance of the vehicles to calculate their State of Charge (SOC). In this case, however, they also describe an interesting hierarchical strategy, where the optimal operation of the single charging stations and the global optimal operation of the grid are carried out on two different levels. The methodology followed in this paper is briefly summarised in the diagram of figure 2.1.

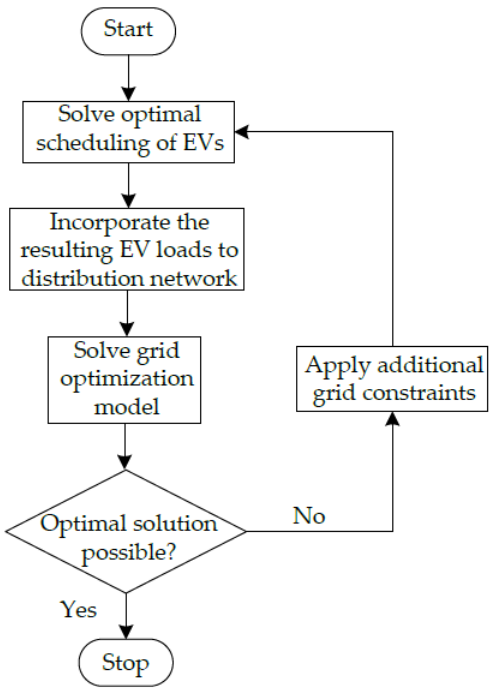


Figure 2.1: Principle of application of the method described in [3]

## 2.4 Power curtailment methods and queuing models

In case a central controller is included in the system to coordinate all the nodes, it is likely it would also be responsible for curtailing some of the flexible loads when potentially dangerous situations are detected. This procedure could activate, for instance, if any line or transformer approaches its technical limits. If so, this central entity would be in charge of deciding when to activate this protection mechanism and which elements should be curtailed first. According to [29], this is one of the four possible ways to implement flexibility on the demand-side and it is defined as *direct control*. When such a scheme is adopted , the DSO has permission to control the connection of all the present flexible devices, by switching them on or off depending on the situation. In general, these flexible loads receive an incentive for their availability [50]. Nevertheless, it is clear that anytime a curtailing situation occurs and it is needed to decide which loads to curtail first, this decision cannot be taken lightly. In fact, DSOs are not allowed to discriminate one customer over the others [51]. These issues turn therefore into fairness problems, which solutions could in general be subjective and could not apply in the same way to all situations. Furthermore, as the authors of [52] highlight, efficiency and other goals may be considered having a higher priority with respect to fairness. The same paper is also used to describe other aspects, such as the way fairness can be measured in a system and how consumers' satisfaction is affected by other consumers' higher or lower consumption. These elements, the authors point out, could significantly affect the curtailment actions.

Another source reviewed on the topic of power curtailment is the work presented by N. Leemput et al. [53], where the authors provide an interesting analysis of the impact of uncontrolled charging on the grid. They also give an interesting way to define the priority for charging an EV. In particular, they decide to use the final time at which the charging process has to start in order to have the battery fully charged at the departure time. Then, they also discuss the weak correlation between PV panels and electric vehicles, namely the fact that the power demand valley created by PV power production around noon is not filled up through coordinated charging. As clearly explained in the paper, "at the moment the PV installations are producing power, most vehicles are not charging, because they are not located at home or they are already fully charged" [53, p. 3].

Also in [54], some parameters for defining the priority of the electric vehicles connected at the charging points are given. These are the State of Charge (SOC) of the EV, the energy already given to the vehicle and the *time-slack* (defined as the remaining connection time minus the minimum charging time required). Especially, this last parameter seems very effective in conveying the room for manoeuvre of an EV, i.e. its flexibility, by means of a single number. On the other hand, the first two (SOC and given energy) appear to be more related with what concerns the *fairness* of the charging process management. Further details on this topic are given in section 5.6.3.

The authors of [55] propose an interesting approach for PV over voltage, however it relates more to real-time control on a local basis. As a matter of fact, the described strategy includes warning voltages that have to be pre-set on a node level. Such parameters are used to calculate the maximum power allowed at that node, so not to make the grid operate beyond its technical limits. Also in [56] the focus is on the voltage behaviour. In this, also a thorough analysis on the higher influence of the nodes at the end of the feeders is given, where a correlation between the X/R value and the higher voltage compensation of the PV inverters at the end of the feeder is given. As far as the curtailment process is concerned, the authors assumed an equal division of power curtailment among all the elements involved. A similar fair division of the curtailment is assumed in [57] as well.

# 3 Research methodology and objectives

In this chapter, some of the most important aspects of the thesis are presented. In particular, section 3.1 describes what are considered to be the most important contributions of this work, followed by a description of its main focus. Then, in section 3.2 all the main assumptions adopted for this analysis are listed, along with a brief explanation for them. Finally, the methodology followed for this study is presented in section 3.3.

## 3.1 Contribution and focus of the thesis

The many papers, research and books mentioned in the previous chapter show the enormous relevance that the topic has been having in the last decade. The introduction of EV technologies is likely to be massive and it is better to be prepared for it, so to avoid more serious problems in future. In this regard, many of those studies proved to have effective approaches to front the future challenges that await the grids all over the world. Nevertheless, many times they also present disadvantages or technical difficulties, which make their utilisation trickier. Some of the strategies proposed in those studies, for instance, could be adopted only under very specific conditions. Others instead, did not consider the combination of different elements, such as the presence of both EVs and PVs.

For this reason, the main purpose of this thesis is to analyse and compare some of the possible strategies described – more or less extensively – in literature. The wished result is to reach a better understanding of what schemes and methods are more likely to be adopted in future and, eventually, which ones could be used in combination. In this sense, the two aspects considered in this research are the charging strategies adopted on a local level – therefore, on a single charging station or on a single node level – and the possible presence of a central unit. This second entity would be in charge of ensuring the technical constraints of the grid are always satisfied, by means of a curtailment scheme introduced to prevent any potentially dangerous operation.

As explained in section 1.1.3, the higher penetration of EVs in the grid is bound to lead to several negative effects, among which are overloads, under voltage and voltage fluctuations. Being these topics very wide, although very related one to the others, this work focuses on one of them only, i.e. the overloading issues. Therefore, the goal of this study is to analyse and develop solutions to congestion problems related to both lines and transformers in a distribution grid. Voltage problems, although could in theory be solved by means of similar schemes, are not covered in this work. More details on this can be found in section 8.2. This choice also had a substantial effect on the necessary curtailment schemes.

A second aspect that is necessary to highlight is that, although it was in the initial intentions, no PV curtailment scheme was finally implemented in this work. This choice was made after obtaining the results of the first simulations. In these, none of the possible technical problems related to photovoltaic panels, such as over voltage situations or lines overloaded for high power injection, was detected. Therefore, this curtailment scheme was theorised, but, in the end, it was not implemented.

## 3.2 Main assumptions

Every time any kind of system needs to be represented by means of a model, the number and the nature of the adopted assumptions is fundamental. This is also the case for this thesis, where several assumptions were adopted to create the models of the grids on the software and to use the algorithms described in the next chapters. The main assumptions used for this thesis are listed below.

1. Regular loads, such as households, cannot be curtailed. In case problems are experienced in the grids, only charging stations can be curtailed. This assumption was introduced to account for the fact that residential and industrial loads are rarely flexible. Therefore, any time a load-shedding operation includes one of these elements, there could in general be a loss in terms of money, as a compensation from the DSO is due to it [58]. On the contrary, charging points can in theory provide more flexibility to the system, as their charging process can be interrupted if needed and they could still receive all the energy they need on time.

2. For the sake of simplicity, the grid topology is assumed to be fixed. This is an important assumption, as load-shedding is in general considered by DSOs as the very last resource to use in case of problems in the grid. As explained in [59, 60], other methods, such as network reconfiguration by means of changes in the open/close status of the switches, are in general preferred to solve foreseen overloading situations.

3. Regular loads have priority in using the power coming from the PV panels. Charging stations connected at the same node will use that solar power only when there is a surplus in generation.

4. In chapter 5 a central entity is described, which is authorised to totally control all the charging stations present in the grid. This entity receives data regarding the connected electric vehicles from the charging stations and has the power to curtail them whenever it is needed. This role could be thought as taken by the DSO.

5. The foreseen behaviour of both regular loads and solar panels – used by the nodes for their local optimisation analysis – is considered to be known with 100% accuracy. On the contrary, the same nodes do not have any information on the EVs that will connect to their charging points until the moment of connection.

6. All the regular loads and charging stations are connected to the nodes via 3-phase connections only. There are two main reasons for this assumption. First, it avoids any imbalance in the grid between the three phases – since this is considered out of the scope of this study – and second, it significantly increases the convergence ratio of the simulations, as better explained in section 6.4.

7. All the regular loads and charging stations are modelled with a constant power behaviour. This assumption negatively affects the convergence of the simulations. More details on this assumption are given in section 6.4.

8. The prices that are used for energy purchasing are the ones taken from the Day-ahead Market. This assumption was made as these prices are already known from the previous day, so they allow to better optimise the charging process of the EVs that are connected for several hours. As highlighted by Limmer et al., this is not entirely realistic as "it requires the knowledge or at least a good prediction of the energy requirements of the EVs that have to be charged on the next day" [61, p. 1]. However, the prices from the two markets appear to have in general similar evolution and, as mentioned in [62], the difference in price between the Day-ahead and the Intraday markets is generally below 10 €/MWh.

9. In this study, only the active component of the power was considered. This assumption comes from the large quantity of power electronics that is installed along with PV panels and charging stations. The presence of this equipment is expected to bring the average power factor value close to unity.

## 3.3 Research Methodology

As already said in section 3.1, this work aims at comparing different control schemes for all the charging points in the electrical distribution network, with the intention to make its operation safe, reliable and, eventually, also cheap and fair to all consumers. All these goals could be achieved by following different strategies to be implemented either on a local or on a central level. Then, the combination of schemes implemented on both levels could in theory lead to even better results.

Therefore, different local control strategies were introduced to study their effects on the grids. In this sense, there was a large variety of schemes that could be implemented on a local level – as summarised in section 2.1 – and it was interesting to notice how some of them led to several advantages that were paid, even so, with a low computational complexity.

The three local schemes compared in this thesis are the *uncontrolled charging* (the most common strategies adopted nowadays), the *average power charging* (where a constant low power is provided during the whole parking time) and the *local optimisation charging*. In this last scheme, a completely local optimisation analysis is carried out at each charging station, so to calculate the most convenient charging behaviour possible. More information about these three schemes can be found in chapter 4.

The other way a charging point can be controlled is by means of a central unit in charge of controlling the global operating status of the network and that takes care of ensuring the whole grid operates within the limits. In fact, by controlling the EV chargers on a local level only, their combined effect is not considered and this could lead to disastrous effects, such as huge peaks of power in the network. For this reason, a central curtailment scheme could be implemented to ensure the absence of overloading situations – as this is the focus of the thesis – throughout the whole simulation time.

As it can be easily found out, there is abundant literature describing similar systems and one of the main points in the most studies is the strategy according to which loads are curtailed in case of necessity. Many different possibilities exist and two of them were tested on the model to see the effects in terms of grid conditions and EVs' satisfaction at the time of their departure. The first strategy tested – here defined as *Equal Curtailment Method* (ECM) – prioritises an equal division of the curtailment among the charging stations. The second one instead – defined as *Flexible Curtailment Method* (FCM) – tries to optimise the curtailment operation by considering the "room for manoeuvre" at each charger. A more detailed explanation of these schemes is provided in chapter 5.

Finally, some of these different strategies were used in combination, trying to take the best aspects out of each method. By doing so – therefore, by comparing the results of all those combinations – it was possible to get a better insight into what are the best possible strategies to allow a smoother EV integration process.

All these schemes and control strategies – written as Python scripts to be executed on models in *PowerFactory* of real Dutch low voltage grids – were used to answer to all the questions listed in section 1.3. Those questions are reported here in further detail.

- **To what extent are grids affected by higher EV penetrations?**
  Experience shows that the currently used grids are in general reliable and fully working for regular operations at any time throughout the year. However, it is foreseen severe overloading problems will be experienced with increasing penetrations of EVs in the system. How much do these problems increase with higher EV penetrations in the grids? How much does the topology of the grid affect these results?

- **How and to what extent does a smart charging scheme affect the grid with respect to uncontrolled charging?**
  Uncontrolled charging has already been proved poorly effective in many previous studies. Nevertheless, it still is the most commonly adopted strategy nowadays. How significant is the difference in results when a smarter charging strategy is adopted at all charging points? To what extent would this influence the use of solar power and the charging price of the EVs? How much does a smarter charging strategy affect the necessity of implementing a central unit to control the full grid?

- **Can a local control strategy coordinate with a central curtailment scheme to efficiently solve overloading situations occurring in the grid?**
  Once the effects of different local charging strategies are tested, it would be interesting to see whether they can also coordinate with a central unit. In such a combination the local controllers would take care of scheduling the charging processes, whereas the central unit would ensure no overloading situations occur. Can the respect of technical limits be ensured by adopting such a combination? What would be the effect on the EVs' satisfaction at the time of their departure? Would a smart curtailment strategy lead to better results with respect to a strategy that priorities equal shedding among the elements?

# 4 *Local controller model*

One of the most relevant aspects concerning the whole EV charging field is probably the power that is used for the process. This depends in general on both the Electric Vehicle Supply Equipment (EVSE), i.e. the charging station, and the electric vehicle itself. The charging power has a major role in the operation, especially in terms of the time needed to complete the charge and the losses that are overall registered. Clearly, the higher the charging power, the lower the time needed for a complete charge of the vehicle. However, a higher charging power could also lead to a lower efficiency of the operation. Furthermore, fast chargers also represent a more serious threat for the grid, as they may have power requests even 10-20 times higher with respect to the slow ones. All these aspects highlight how important are the charging schemes that are implemented at the single charging stations.

In this chapter, three possible strategies are detailed. In section 4.1, the easiest charging method, known as *uncontrolled charging*, is described. Then, a slightly more sophisticated method – here defined as *average power charging* – is reported in section 4.2. Finally, in section 4.3 it is explained how to implement an optimisation analysis at a local level to obtain a cheaper charging process.

## 4.1 Uncontrolled charging

The first and the easiest method that can be used to charge an electric vehicle is the so-called *uncontrolled charging*, also sometimes playfully referred to as *dumb charging*. When this charging scheme is adopted, the vehicle's battery starts getting power from the EVSE immediately after the EV is connected. As far as the power used for the process is concerned, this will be the maximum power that the combination EVSE-EV allows and that will be maintained constant for the whole duration of the operation.

As it is easy to understand, there is no smart strategy behind this method and in case an EV asks power at a charging station during a peak period, no mechanism is implemented to avoid an even higher peak load. This aspect is particularly relevant, as the majority of the electric vehicles are connected to a charger when the owner gets home after work. This happens in general at around 6-8 pm, which is the moment when the grid power demand is already the highest. Therefore, such a behaviour is bound to create problems if the grid is already operating close to its limit conditions.

Although these problems are very well known by the scientific community, the uncontrolled charging is still the most common charging scheme adopted around the globe.

This is mainly due to the simplicity of the strategy that makes its implementation easier than any other option.

In order to simulate this charging strategy in the model, an uncontrolled charging behaviour is specifically made for every new EV reaching a charging station. A power input equal to the rated power is assigned to the EV at all the time-steps needed for the charge but the last one. In fact, if the same rated power was used at the last time-step as well, the final given energy would be slightly less or would exceed to a small degree the energy demand of the vehicle. This would happen as the time-steps set for the simulations lie in the order of several minutes. Although this could have been in general considered as an acceptable approximation, it was preferred to include this different last time-step, so to make the comparisons with the other strategies more precise. In figure 5.4, it is possible to observe an example of the application of a different charging power at the last time-step.

## 4.2 Average power charging

The second charging scheme discussed in this thesis is here defined as *average power charging*. Also in this case, the charging process starts immediately after the EV connection and the whole process is carried on using a constant power. However, the power used is not simply a rated power depending on the electric vehicle and the charging station, but it is calculated considering a few parameters. In particular, this power is calculated by means of the following formula

$$P_{avg} = \frac{E_{asked}}{T_{dep} - T_{arr}} \tag{4.1}$$

where $E_{asked}$ is the overall energy asked by the EV, $T_{arr}$ the arrival time and $T_{dep}$ is the expected departure time.

There are two main differences between this scheme and the previous one. The first difference is that, in order to calculate the charging power, the user needs to provide some information, namely the overall energy required and the expected departure time. This implies that the charging process is not anymore connect-and-charge, but that there is also a moment where the user has to provide this kind of information. This could be done, for instance, by means of an app on the smartphone or directly using the charging column.

The second main difference is in one of the implications that come with this method, namely that there is power flowing from the EVSE to the EV for the whole parking duration. In the previously described scheme, instead, this situation was unlikely, especially with a long parking time. Therefore, the main idea behind the average power charging strategy is to fully use the parking time of the EV. This aspect can be fully appreciated by looking at the graph in figure 4.1. In this, the areas enclosed by the two rectangles have to be the same in order to provide to the EV the same total amount of energy by using either of the two methods.

By comparing the two rectangles and considering the *coincidence factor* aspect explained in section 1.2, it is apparent that the uncontrolled charging scheme is more likely to cause overloading issues than the average power scheme.

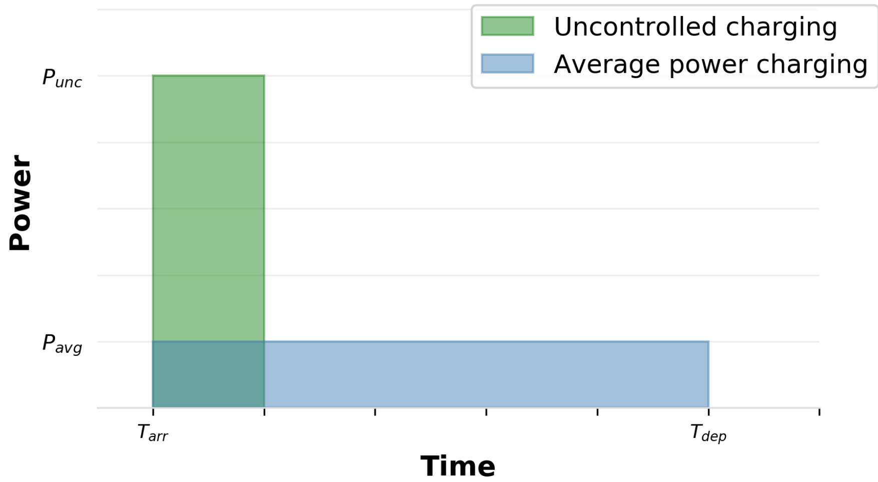


Figure 4.1: Comparison of uncontrolled charging and average power charging

## 4.3 Local algorithm: optimisation at the single node

The most sophisticated charging scheme tested in this thesis is based on the results of the work of my PhD supervisor, MSc. Y. Yu. The work she presented – as part of the OSCD project [4] – focuses on the analysis of a single node's behaviour in an electrical grid and on the creation of a local optimisation control strategy that aims at minimising the charging cost of any electric vehicle connected to the analysed node. This is based on the fact that the electricity price is not constant throughout the day. Therefore, by choosing a low price period, the EV charging overall costs can be diminished.

### 4.3.1 General method

Several aspects need to be considered in this approach. First, it is necessary to include in the analysis the behaviour of all the elements connected to the node. These could be in general 'regular' loads – such as households, small industries and so on – photovoltaic panels and charging stations of different kinds (residential, public, etc.). As far as regular loads and PV panels are concerned, the behaviour of these can be predicted by means of past data for the former and weather forecasts for the latter. Obviously, these forecasts come in general with a certain error that can be more or less severe depending on different aspects. However, it was assumed in this thesis that the foreseen behaviour of both regular loads and PV panels is 100% accurate. On the contrary, the behaviour of the electric vehicles that connect to the different charging points, although follows some known general patterns, it was assumed to be unknown in the node analysis. Therefore, only when an EV reaches the charging station the node receives the data about it.

In this regard, like in the average power charging scheme, also this strategy needs data like the expected departure time and the required energy. On top of that, additional data regarding the node itself is required to consider the technical limits of the node, such as the maximum allowed exported or imported power. Therefore, information about the connection of the charging stations to the node and of the node to the electrical grid also needs to be considered for the optimisation. Finally, also information about the prices for the next hours needs to be known.

Once all this information is available, an optimisation analysis can be executed to determine the best charging behaviour for all the electric vehicles connected at that moment. It is important, though, to specify when this optimisation analysis takes place in practice, i.e. it is fundamental to specify what are the conditions that trigger it. This is in fact a very important point as it has a great impact on the computational complexity of the whole code.

The general rule is to start a new optimisation analysis at node $n$ anytime a new vehicle reaches that node to charge. When this happens, the period considered for the optimisation analysis extends from the current moment until the last expected EV departure, i.e. the departure time of the electric vehicle that leaves the node last. When a new optimisation starts, the analysis horizon, namely the period considered for the analysis, may be extended with respect to the previous analysis. This may happen in case the just arrived EV expects to leave the node after the previous last expected EV departure. For instance, if at 13:00 the last departure time of all the EVs connected is at 18:00, the optimisation horizon extends until 18.00. If at 13:30 a new vehicle arrives at the node, expecting to leave at 20:00, the new optimisation analysis will now consider all the points in time until 20:00. This is what is called *dynamic receding horizon.*

When an EV reaches a node, as just said in the previous paragraph, a new optimisation analysis starts. It is now important, however, to see what happens if there are already other vehicles connected to other chargers at the same node when the new EV arrives. In that case, the charging process of those EVs is considered as split into two parts: from their arrival time until the new EV's arrival time and from the new EV's arrival time until their expected departure time. The energy demand for the second part is calculated as

$$E_{req,2} = E_{total} - E_{given,1} \tag{4.2}$$

where $E_{total}$ is the overall EV energy demand, while $E_{req,2}$ and $E_{given,1}$ represent the energy demand for the second part of the charging process and the energy given during the first one, respectively.

In case an EV leaves the node instead, nothing happens apart from some parameters being set to zero or to their default values.

In figure 4.2 it is possible to see the example of a node with 4 charging stations. At the simulated time $t_i$ a new vehicle arrives at Charger 1 and the horizon is set to $T_2^d$, that is the last expected departure time of all the vehicles. Furthermore, as stated in the previous paragraphs, the already present vehicles get their charging process 'split' into two parts (only from an analysis point of view, as physically nothing changes). Finally, at Charger 3 nothing happens, as there are no EVs connected.

### 4.3.2 Optimisation analysis

As far as the optimisation analysis is concerned, the objective is to minimise the operation costs at all the $J$ charging stations at node $n$. Being $t$ a single time-step in the dynamic receding horizon and $i$ the index of the $i$-th EV connected to node $n$, the optimisation variables are defined as follows.

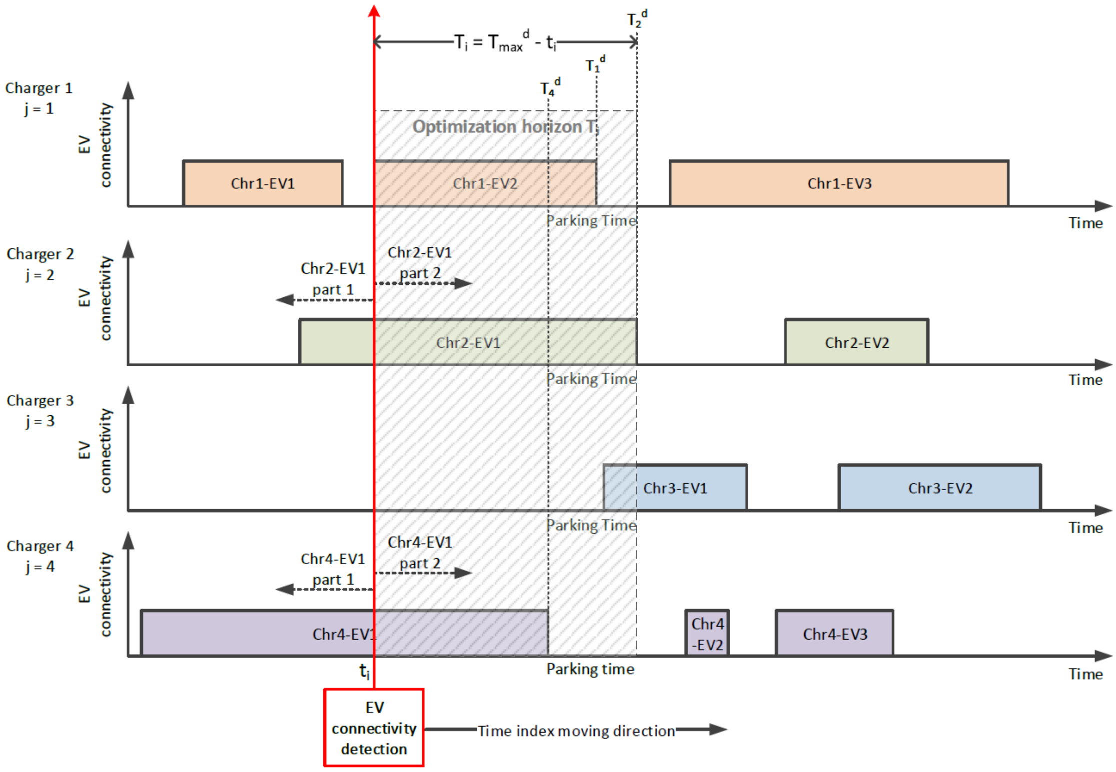


Figure 4.2: Evolution of the optimisation horizon in a node with 4 charging stations

- **EV battery energy:** $b_{EV,i,t}$ $(B_{arr,i} < b_{EV,i,t} < B_{arr,i} + D_{ch,i} \quad \forall\, i, t)$
- **Node imported power:** $p_{imp,t}$ $(0 < p_{imp,t} < P^{up}_{imp} \quad \forall\, t)$
- **Node exported power:** $p_{exp,t}$ $(0 < p_{exp,t} < P^{up}_{exp} \quad \forall\, t)$
- **PV power used:** $p_{PV,t}$ $(0 < p_{PV,t} < P_{PV,produced,t} \quad \forall\, t)$
- **EV charging power:** $p_{EV,i,t}$ $(0 < p_{EV,i,t} < P_{EV,rated} \quad \forall\, i, t)$

The battery energy at the arrival $B_{arr,i}$ and the total energy request $D_{ch,i}$ are provided by the EVs when they connect to a charger. The parameters $P^{up}_{imp}$ and $P^{up}_{exp}$ are instead set by the DSO (or any other entity responsible for the correct operation of the grid) to ensure the power always stays within the allowed capacity of the node.

The power equations are fulfilled by means of the following constraints.

$$p_{imp,t} - p_{exp,t} = \frac{\sum_{i=1}^{J} p_{EV,i,t}}{\eta_{ch}} + P_{load,t} - p_{PV,t} \quad \forall\, t \tag{4.3}$$

$$b_{EV,i,t} = B_{arr,i} + \sum_{t=T_{arr}}^{t} p_{EV,i,t} \cdot \eta_{EV} \cdot \Delta t \quad \forall\, i, t \tag{4.4}$$

In these, $P_{load,t}$ is the sum of all the loads connected at the node, while $\Delta t$ is the time-step length set for the simulation. The efficiencies $\eta_{ch}$ and $\eta_{EV}$ of power conversion from the grid to the charger and from the charger to the EVs were set to the ideal value of 1, as this allowed a more coherent and clear comparison of the different local charging strategies,

Finally, the objective of the optimisation analysis can be summarised by means of the following mathematical expression. In this, $T_{hor}$ indicates the last time step of the dynamic receding horizon.

$$\sum_{i=1}^{J}(B_{arr,i} + D_{ch,i} - b_{EV,i,T_{dep}}) \cdot c_{penalty} + \sum_{t=t_0}^{T_{hor}}(p_{imp,t} \cdot c_{buy,t} - p_{exp,t} \cdot c_{sell}) \cdot \Delta t \tag{4.5}$$

The three different prices included in this equation are all expressed in €/kWh. The first one ($c_{penalty}$) indicates the penalty to be paid (potentially by the DSO) in case the EVs do not receive all the energy they required. Provided that – to the best of the author's knowledge – no information on the topic exists in literature, this parameter was set to the extremely high value of 100 €/kWh, so to make the algorithm avoid consumers' dissatisfaction at all costs. The other two parameters instead – $c_{buy,t}$ and $c_{sell}$ – refer to the prices associated with the import and export transactions. The former is a variable value taken from the Day-ahead Market, while the latter is a constant value to account for the presence of a feed-in tariff. This fixed value was set to 0.02 €/kWh.

One final aspect that has to be mentioned is that before any local optimisation analysis is started some general acceptance criteria are checked. These make sure, for instance, that the EV is not asking for too much energy in a too short time or that the overall energy required does not exceed the limits of the battery.

A summary of some of the most important aspects regarding the three local charging schemes is provided in table 4.1.

| | **Charging start time** | **User information** | **Charging power** |
|---|---|---|---|
| **Uncontrolled charging** | Right after EV connection | Not needed | Rated power |
| **Average power charging** | Right after EV connection | Needed | $P_{avg} = \frac{E_{asked}}{T_{dep} - T_{arr}}$ |
| **Local optimisation charging** | Depending on optimisation results | Needed | Depending on optimisation results |

Table 4.1: Summary of the main information concerning the 3 charging schemes

# 5 *Central controller model*

In the previous chapter, the logic of the different local controller schemes are thoroughly described. However, as it will be explained in the following section, a completely delocalised strategy presents several disadvantages. In this regard, the introduction of a central entity, or a central controller (CC), may bring huge benefits to the system. The roles it should fulfil are twofold: ensuring that the technical constraints of the feeder are not violated and coordinating the EVs' charging process, so not to generate consumers' dissatisfaction. To ensure this, though, it may sometimes be necessary to curtail power somewhere in the grid. When such a process takes place, there are three main steps to follow: detect the loads to shed, calculate the overall amount of power to cut and distributing the power to be cut among the loads.

This chapter goes through all the mentioned points and it is organised as follows. In section 5.1 some of the most relevant problems of a completely delocalised scheme are described. In section 5.2 the general working scheme of the CC is described, while sections 5.3 and 5.4 describe the methods adopted to detect the loads to shed and to calculate the amount of power to cut, respectively. Then, section 5.5 describes the first method according to which the power to shed is divided among the different loads, the *Equal Curtailment Method*. A possible alternative curtailment strategy – the *Flexible Curtailment Method* – is instead described in 5.6. Finally, section 5.7 goes through some modifications of the curtailment strategy in case the grids are operated as meshed.

## 5.1 Problems of a completely delocalised architecture

One of the main advantages of implementing a completely local control at the single nodes is its exceptionally low computational complexity. By not making the nodes continuously exchange information with a central entity and by also considering a lower amount of data, the computational burden results significantly lighter with respect to a central control scheme [11, 63]. This makes the local optimisation problem more likely to be solved in an acceptable period of time (in this sense, the definition of acceptable depends on the application itself). On the other hand, this approach presents a very important downside too. The lack of information about the external environment, namely the behaviour of the other nodes, and their consequent lack of coordination inevitably cause mediocre results. Sometimes this could even lead to the failure of the whole optimisation process, as it will be explained in the following paragraphs.

When it comes to EVs' integration in the network, there are several issues that are likely to arise with a controller scheme that is entirely local. All these problems arise at the feeder or at its transformer and are very often caused by the too high power requests. As it has already been highlighted in previous studies [12, 64, 65], a high penetration of EVs into the network could significantly stress the electrical grid. This could happen because EVs' owners would probably start charging their vehicles as soon as they get home, therefore during an already high peak power moment. This behaviour seems very similar to the one described for PVs in section 1.2. In fact, because of the similar behaviour of their owners, EVs are also considered to have a high coincidence factor.

With the implementation of a local scheme only, nodes will request power or inject some without considering what the other nodes are doing. For this reason, a very high EV penetration is expected to cause two different kinds of problems: technical problems and dissatisfaction of the consumers.

As far as the former are concerned, two of the most serious problems are caused by an excessive power demand. These are lines (or transformers) overloads and under voltage issues (this last phenomenon is more likely to be registered at the nodes that are farther from the transformer). However, as already stated in section 3.1, the focus of this thesis is on overloading issues only.

The dissatisfaction of the consumers instead can be easily explained by means of a few examples where a completely local optimisation control scheme is implemented. In case there is a general high consumption in the grid, for instance at around 8 pm, EVs will ask for little power because of the high price of electricity. In case the price is low instead, all the EVs will ask for power and a demand peak will be registered. This would cause in turn technical problems that, however, could be easily solved by introducing a power limitation scheme at all the nodes.

However, if there is no high consumption and price is neither low nor high, nodes may decide to postpone EVs' charging to a low price moment (for instance at 5 am), since the only power exchange constraints they have are the technical ones dictated by their own connection to the feeder. If all the nodes behave in the same way, the consequent peak of power at 5 am will be curtailed because of the limits of the feeder. This means that, since at around 7/8 am also regular loads will ask for more power and some EVs will need to leave, there is a high chance that many EVs will not be able to fulfil their charging process.

## 5.2 Central controller logic

Now that the reasons for introducing a central curtailment unit have been described, it is possible to be more specific on how such a controller operates in practice. This is briefly summarised in the diagram of figure 5.1.

When the load flow at a certain instant of time is run and a problem is detected (for instance a congested line), the curtailment scheme is activated. The first part of the process consists in compiling a list of all the charging points eventually available to be curtailed. In this regard, as it will be further explained in section 5.3, the two main factors to be considered are the charging points' position, i.e. whether they are located downstream of the problematic element, and if there are EVs currently connected. In case there are charging stations fulfilling both these two conditions, the vehicles connected to them are added to the list of possible EVs to curtail. The list of vehicles that will actually experience a reduction in their consumption and the extent of this reduction

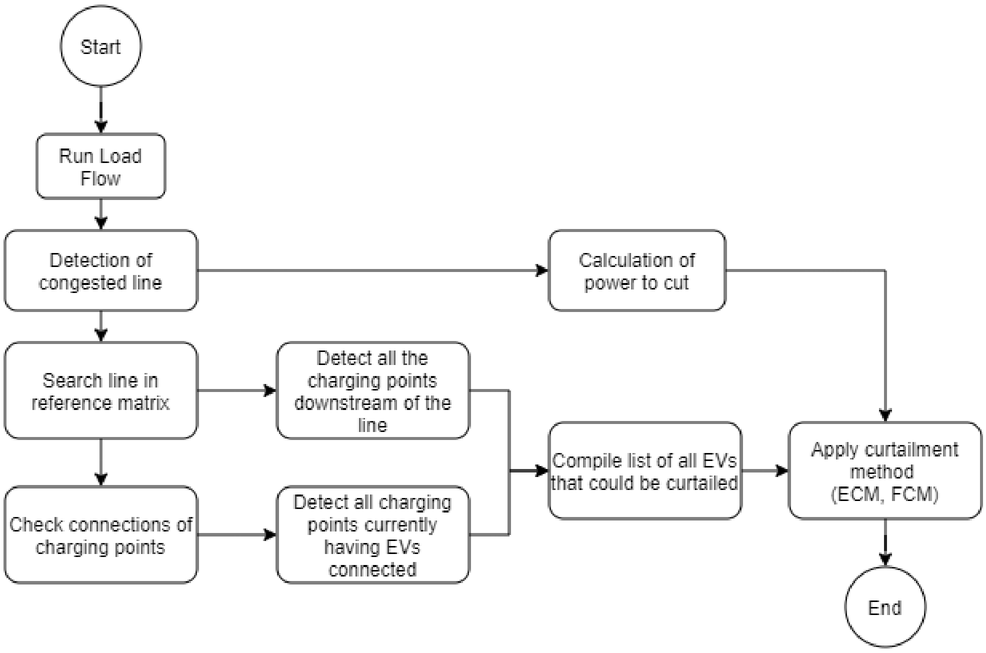


Figure 5.1: Principle of application of the method in case of a congested line

depend on the result of the curtailment method, but this is the last step. Before that, it is necessary to calculate the power that has to be cut to solve the congestion problem. This calculation, described in section 5.4, is done by means of basic electric mathematical relations and formulae reported in the DIgSILENT *PowerFactory* manual [66]. Once this calculation is executed, the power-shedding can be finally divided among the involved charging points according to the *Equal Curtailment Method* (ECM), described in section 5.5, or to the *Flexible Curtailment Method* (FCM), described in section 5.6.

## 5.3 Localisation of the nodes to curtail

As already highlighted in the previous sections, when problems in the grid, such as line congestion or transformer overloading, are detected, it is possible to solve them by curtailing some of the loads connected at that moment. One of the main assumption of this thesis, though, is that regular loads cannot be curtailed. Therefore, the only available loads to be temporarily disconnected in such situations are the electric vehicles that are charging when the grid problems are experienced.

In this regard, EVs offer a lot of flexibility, as, even in case they get curtailed, they may still get all the energy they need before the departure time. However, when a problem like an overloaded line is registered, power has to be cut at charging stations that have an influence on that line. This means that whenever any problem in the grid occurs, before taking any action, it is first necessary to localise the charging stations that affect the registered phenomenon. The criteria according to which a charging point has an influence on it or not is if it comes after (according to the power direction) the problematic element. Therefore, the only charging stations that should (or could) be curtailed are the ones downstream of the interested line or transformer.

### 5.3.1 General method

Distribution grids are very often built following a meshed design, but they are usually operated in a radial fashion, mostly because of technical limitations in the protection system [67–70]. When they are operated radially, the flux of power is very easy to predict. In fact, power always flows from the transformer to the end of the branches following the same path, as, when any load asks for power, this can come from one direction only and always taking the same way. Thank to this characteristic, it is possible to create a *Localisation Reference Matrix* (LRM) – like the one shown in figure 5.2 – that connects every single line in the network to all the charging stations that may have an influence on it. The advantages of this method are the following:

- Anytime a problem is experienced at a line or at a transformer, it is sufficient to check this reference matrix to know what are the best charging stations to curtail.
- Once the LRM is created, it can be used in every situation and at any moment of time. The computational complexity of the analysis is therefore lighter, as it is not needed to run the calculations at every load flow.
- The creation of this reference matrix can be done by means of scripts specifically made for the purpose (see section 5.3.2).
- The use of this LRM method allows to curtail only the charging stations that affect the problematic element without making any position discrimination, such as the distance from the transformer.

Figure 5.2 shows a part of the LRM built for *Rural Grid*. The elements on the vertical axis represent the names of the lines, whereas the ones on the horizontal axis are the names of the charging points. When there is a unit value at the intersection of a line and a charging station, it means the latter has an influence on the former (therefore the charging point is downstream of the line).

However, this reference matrix only is not sufficient to understand what are the charging stations to disconnect in case of technical issues. The reasons for this are twofold: 1) not all the charging points downstream of an overloaded element have necessarily electric vehicles connected at that moment of time and 2) even in case there are vehicles connected, this does not imply that they are currently being charged.

For these reasons, if a problem is experienced, it is necessary to check what are the charging points with EVs connected and which ones are asking for power at that moment of time. This operation can be done very easily and it hardly affects the complexity of the code.

### 5.3.2 Building of the Localisation Reference Matrix

The creation of a correct Localisation Reference Matrix is of vital importance for the successful operation of the curtailment actions executed by the central unit. To do so, several methods had been tried out until a satisfying result was finally reached.

Two possible main designs were considered: one based on the voltage behaviour of the nodes and one only looking at the power flowing through the lines and the transformers. Although the design of the latter would have been significantly easier, it was finally

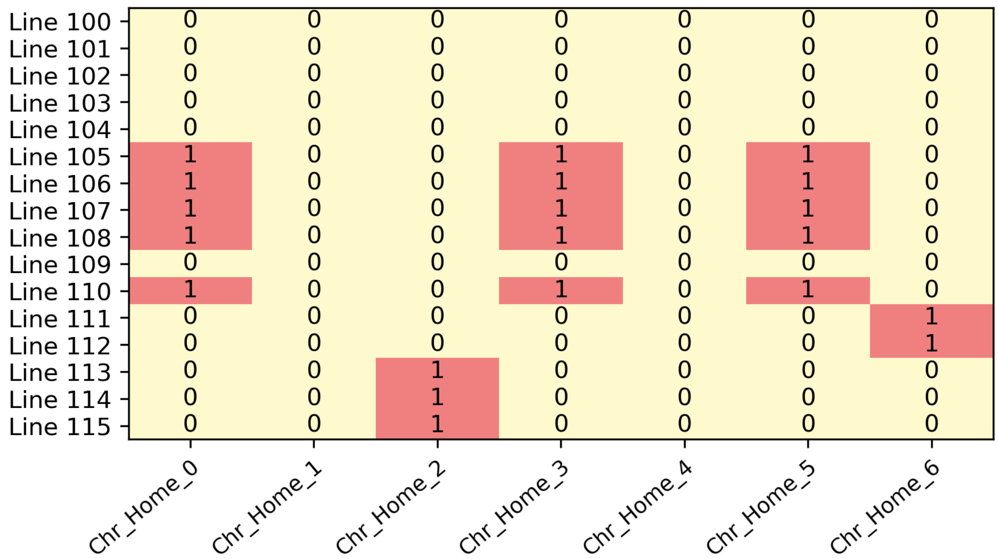


Figure 5.2: Part of the Localisation Reference Matrix built for *Rural Grid*

decided to proceed with the voltage option. This decision was made considering future applications of the codes where a voltage control scheme could also be included.

The general idea behind this scheme is to activate at the same time all the charging points present in the model with a constant power (for instance set to 2 kW). After a load flow is run, all the lines present in the grid (in this case defined as *primary lines*) are checked one by one. When any primary line is checked, an iteration starts. Starting from this primary line, all the lines (in this case defined as *secondary lines*) located downstream of the primary one will be analysed in a sequence and if a charging point is encountered, that charging point is registered at the right spot of the LRM. For instance, in case '*line 105*' is the primary line analysed and the charging point '*Chr_Home_3* is encountered while analysing the downstream secondary lines, a value of 1 will be registered at the right position of the matrix, as shown in figure 5.2. In order to understand what is the 'downstream direction' at any line, the nodes at the 2 extremes of the line are checked to find out which one has the lowest voltage. When there are no more secondary lines downstream of a primary line, a new iteration starts where a new line (considered as a primary line) is checked.

For this scheme to be effective, all the 'regular' loads and PV panels need to be set to zero power, so not to cause undesired variations in the voltage. For the same reason, also the capacitance of all the lines has to be set to zero. In fact, the presence of phenomena such as the Ferranti effect [71, 72] could lead to wrong outcomes. Obviously, all these parameters are changed only for the construction of the reference matrix and are set back to their original values to run the simulated scenarios.

This scheme was tested on different grids and the results obtained were verified and proved to be 100% accurate in case of radial grids.

## 5.4 Calculation of the power to cut

In this section, the second step of the curtailing process – the calculation of the power to be cut to solve an overloading issue – is described. The procedure here reported refers to the calculation of this power in case of line overloads, but the same logic can also be used in case the overloaded element is a transformer.

The starting point is the loading percentage of the problematic line taken into consideration. From this number, expressed as a percentage, the desired result is the corresponding power to be cut, so to bring back the loading percentage below the safety limit. This safety limit can be set depending on the situations.

The line loading percentage, according to the manual provided by DIgSILENT [73], is calculated as

$$loading = max\left\{\frac{|I_{bus,i}|}{I_r}, \frac{|I_{bus,j}|}{I_r}\right\} \cdot 100 \tag{5.1}$$

where $I_{bus,i}$ and $I_{bus,j}$ are the magnitudes of the currents at the two terminals $i$ and $j$, while $I_r$ is the rated current of the line.

Being the lines used 3-phase, the current flowing through each phase could be different from the others. This means that equation 5.1 could return 3 different values when used on the 3 different phases. For the assumptions listed in 3.2 though, this does not happen and the currents flowing on the three phases are all the same. Nevertheless, all the calculations that are here reported refer to the general case where a phase could be more loaded than the others.

Therefore, for the calculation in equation 5.1, the phase considered is the one where the highest current is registered. The next step is to find a relation between this current and the power flowing through the line.

Being $P_p$ and $Q_p$ respectively the active and the reactive power at phase $p$, the complex power $S_p$ at the same phase can be defined as

$$S_p = \underline{U_p} \cdot \underline{I_p*} = P_p + jQ_p \tag{5.2}$$

with

$$\underline{U_p} = U_{base}(u_{p,real} + ju_{p,imm}) \tag{5.3}$$

$$\underline{I_p*} = I_{base}(i_{p,real} - ji_{p,imm}) = I_p(cos\phi_i - jsin\phi_i) \tag{5.4}$$

where all the voltages $u_p$ and the currents $i_p$ are expressed in p.u.. The parameters $U_{base}$ (expressed in V) and $I_{base}$ (expressed in A) refer to the base values for the voltage and the current, respectively, while the term $I_p$ (also expressed in A) refers to the magnitude of the current. Combining equations 5.3 and 5.4 with 5.2 and considering only the real part, it is possible to find the relation between the magnitude of the current and the power flowing through one phase of the line. This relation is shown in equation 5.5.

$$I_p = \frac{P_p}{U_{base}(u_{p,real}cos\phi_i + u_{p,imm}sin\phi_i)} = \frac{P_p}{K_{load}} \tag{5.5}$$

Finally, combining equations 5.1 and 5.5 it is possible to obtain relation 5.6 that allows to obtain the power flowing through phase $p$ starting from the loading percentage of the line.

$$P_p = \frac{loading}{100} K_{load} I_r \tag{5.6}$$

By means of this formula it is possible to calculate the power $P_p$ that is flowing at the time of the overloading and the maximum power allowed $P'_p$, so to have a loading percentage below the set safety limit. The difference $\Delta P = P_p - P'_p$ is the amount of power that has to stop flowing through that phase in order to solve the overloading issue.

However, as mentioned in section 3.2, two of the assumptions of this analysis are that the only loads that can be curtailed are the charging stations and that these are always connected to the network by means of 3-phase connections. This has a big impact on the model. For instance, in case it is necessary to reduce the power flowing through a phase by $x$ kW in order to solve the overloading problem of a specific line, cutting that amount of power downstream of the line is not enough. For the assumptions made, the reduction of power at any charging station is distributed equally among the 3 phases. Therefore, whenever a reduction of $x$ kW is needed to solve an overloading problem (calculated for a single phase), a curtailment of $3x$ should instead be applied.

## 5.5 Equal Curtailment Method (ECM)

### 5.5.1 General method

The logic behind this method is very straightforward and effective. Whenever any overloading problem in the grid is registered and some power needs to be curtailed, the ECM guarantees a fair absolute division of the burden among the nodes. This division is calculated by means of a an optimisation analysis carried out using the *Gurobi* optimisation library (see section 6.1). The steps performed by the algorithm – according to the general scheme of action described in section 5.2 – are the following:

- A load flow analysis is executed. This returns that lines $l_0, l_1, ..., l_L$ are overloaded. In this example no transformers are overloaded, but in case there were, the procedure would be exactly the same.

- The power in excess at all the overloaded lines is calculated as $P_{l_0}$ for $l_0$, $P_{l_1}$ for $l_1$ and so forth. These parameters $P_{l_i}$ refer to the $\Delta P$ defined in the previous section.

- A list of all the charging stations downstream of each overloaded line is compiled by means of the LRM described in section 5.3. Then, among all the chargers, only the ones with an EV asking for power at that moment of time are considered. These charging points will be labelled as $j_o, j_1, ..., j_N$. The correspondence of the overloaded lines with their active downstream charging stations is summarised in matrix $\tilde{A}_{L,N}$ (equation 5.7). In this the indexes $k_{l,i}$ have a value of 1 in case charger $i$ is downstream of line $l$ and is currently asking for power. They are set to zero otherwise. The size of the matrix is $L \times N$, where $L$ is the number of overloaded lines, while $N$ is the overall number of (active) charging stations involved in the analysis, that is the union of all the active chargers downstream of each line. It should be noted therefore that matrix $\tilde{A}_{L,N}$ is different from the LRM, as the latter does not consider if there are EVs asking for power at the chargers.

$$\tilde{A}_{L,N} = \begin{bmatrix} k_{0,0} & k_{0,1} & \cdots & k_{0,i} & \cdots & k_{0,N} \\ k_{1,0} & k_{1,1} & \cdots & k_{1,i} & \cdots & k_{1,N} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ k_{l,0} & k_{l,1} & \cdots & k_{l,i} & \cdots & k_{l,N} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ k_{L,0} & k_{L,1} & \cdots & k_{L,i} & \cdots & k_{L,N} \end{bmatrix} \tag{5.7}$$

The variables of the optimisation analysis are $P_{j_0}, P_{j_1}, ..., P_{j_N}$, that are the power to be cut at charging stations $j_o, j_1, ..., j_N$, respectively. For these variables the following conditions apply:

$$P_{j_0}, P_{j_1}, ..., P_{j_N} \geq 0 \tag{5.8}$$

$$P_{j_i} \leq P_{MAX,j_i} \tag{5.9}$$

Where $P_{MAX,j_i}$ represents the maximum power that is possible to curtail at charging station $j_i$.

As far as the constraints are concerned, these are built so that the overloading situation is solved once the optimisation analysis is carried out. Being $\bar{p}_j$ and $\bar{p}_l$ two vectors containing all the optimisation variables and the power to be cut at each line, respectively, the set of constraints can be expressed in matrix notation as

$$\tilde{A}_{L,N} \cdot \bar{p}_j \geq \bar{p}_l \tag{5.10}$$

where

$$\bar{p}_j = \begin{Bmatrix} P_{j_0} \\ P_{j_1} \\ \vdots \\ P_{j_N} \end{Bmatrix} \tag{5.11}$$

$$\bar{p}_l = \begin{Bmatrix} P_{l_0} \\ P_{l_1} \\ \vdots \\ P_{l_L} \end{Bmatrix} \tag{5.12}$$

that leads to the equations

$$\begin{gathered} k_{0,0} \cdot P_{j_0} + k_{0,1} \cdot P_{j_1} + ... + k_{0,N} \cdot P_{j_N} \geq P_{l_0} \\ k_{1,0} \cdot P_{j_0} + k_{1,1} \cdot P_{j_1} + ... + k_{1,N} \cdot P_{j_N} \geq P_{l_1} \\ \vdots \\ k_{L,0} \cdot P_{j_0} + k_{L,1} \cdot P_{j_1} + ... + k_{L,N} \cdot P_{j_N} \geq P_{l_L} \end{gathered} \tag{5.13}$$

In this optimisation analysis there are two objectives with different priorities. These are shown in equations 5.14 and 5.15

$$minimise \quad \sum_{i=0}^{N} P_{j_i} \tag{5.14}$$

$$minimise \quad \sum_{i=0}^{N}\sum_{k=0}^{N}|P_{j_i} - P_{j_k}| \tag{5.15}$$

The first objective guarantees that the minimum possible amount of power is curtailed to solve the overloading problem, whereas the second one aims at minimising the differences between the power cut at the different charging stations. These two objectives are set with different priorities. Namely, objective 5.14 is set with a higher priority with respect to objective 5.15. This means, according to the *Gurobi* manual [74], that the second objective is considered only to discern among all the optimal solutions of the first objective. This is the so-called *hierarchical approach*. Once this optimisation analysis is executed, the amount of power to cut at each node is known.

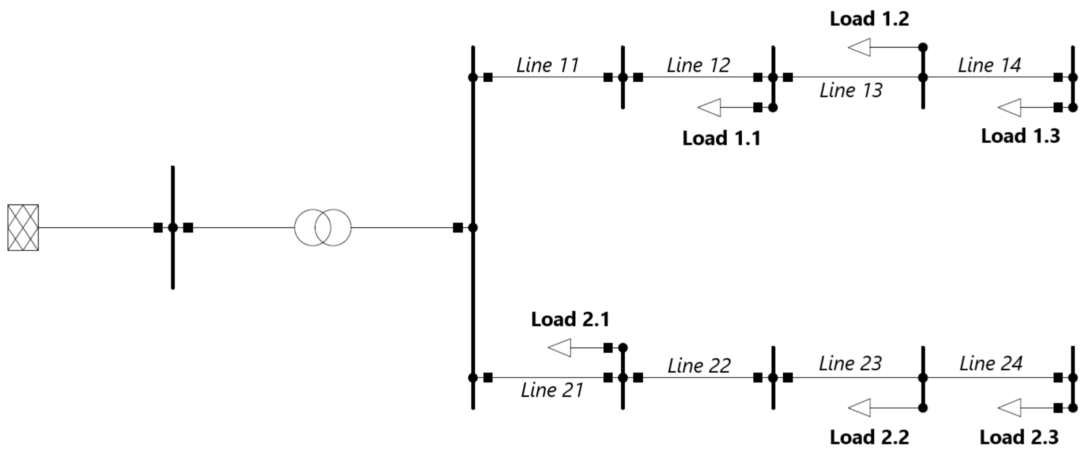


Figure 5.3: 2-feeder grid example

One important aspect to highlight is the reason why the minimisation of the differences between the power cut at each charging station was set as an objective instead than a constraint. This was done as it is not expected to have all chargers cutting down the same amount of power and that this minimisation of the differences should only be done provided that the total power curtailed does not increase. This is immediately clear by looking at the example of figure 5.3. Let us assume to have a single objective (equation 5.14) and that both *line 11* and *line 21* are overloaded, with an excessive 3 kW at the former and 6 kW at the latter. In this case the constraints would be

$$\begin{aligned} &P_{cut}(1.1) + P_{cut}(1.2) + P_{cut}(1.3) \geq 3\,kW && (Line\ 11)\\ &P_{cut}(2.1) + P_{cut}(2.2) + P_{cut}(2.3) \geq 6\,kW && (Line\ 21) \end{aligned} \tag{5.16}$$

To solve the problem at *line 11*, for instance, it is necessary to cut a total of 3 kW from the loads *1.1*, *1.2* and *1.3*. Any summation of the 3 curtailments leading to a total of 3 kW would do the job. However, in order to have a fair process, the desired goal would be to have a power curtailment equal at all the 3 loads, namely to cut only 1 kW at each of them. A similar reasoning can be followed for *line 21*, where the optimal solution would be to curtail 2 kW at each load.

This could be obtained by means of a constraint, that forces, for instance, the variables present in the same inequality of the set (equation 5.13) to all assume the same value. Therefore, the constraints of the just studied example would be

$$\begin{aligned} &P_{cut}(1.1) = P_{cut}(1.2) = P_{cut}(1.3) &&(Line\,11)\\ &P_{cut}(2.1) = P_{cut}(2.2) = P_{cut}(2.3) &&(Line\,21) \end{aligned} \tag{5.17}$$

However, this method would stop working as soon as the same variable is present in two or more different inequalities, i.e. if there is a node that is downstream of two or more different overloaded lines. This can again be observed by means of figure 5.3. If *line 13* too is overloaded with an excessive power of 5 kW, the situation would be totally different. In this case, the conditions to be fulfilled would be:

$$\begin{aligned} &P_{cut}(1.1) + P_{cut}(1.2) + P_{cut}(1.3) \geq 3\,kW &&(Line\,11)\\ &P_{cut}(1.2) + P_{cut}(1.3) \geq 5\,kW &&(Line\,13)\\ &P_{cut}(2.1) + P_{cut}(2.2) + P_{cut}(2.3) \geq 6\,kW &&(Line\,21) \end{aligned} \tag{5.18}$$

The conditions to be satisfied to make all the variables present in the same inequality to be the same would be the same as before (equation 5.17). Therefore, the solution to 5.18 would be

$$\begin{aligned} &P_{cut}(1.1) = P_{cut}(1.2) = P_{cut}(1.3) = 2.5\,kW\\ &P_{cut}(2.1) = P_{cut}(2.2) = P_{cut}(2.3) = 2\,kW \end{aligned} \tag{5.19}$$

Such a solution is not optimal, as the constraints 5.17 are too limiting. On the other hand, when the variables present in the same inequality are not forced to be equal (therefore constraints 5.17 are not considered), but objective 5.15 is included instead, an optimal solution can be found as shown below

$$\begin{aligned} &P_{cut}(1.1) = 0\,kW\\ &P_{cut}(1.2) = P_{cut}(1.3) = 2.5\,kW\\ &P_{cut}(2.1) = P_{cut}(2.2) = P_{cut}(2.3) = 2\,kW \end{aligned} \tag{5.20}$$

### 5.5.2 Rescheduling the power after curtailment

This section of the chapter is used to describe the last needed step of a curtailment operation, that is rescheduling the EV charging process after some power is curtailed.

In case of uncontrolled charging, an example of the rescheduling operation is shown in figure 5.4. In the upper part of the graph it is possible to see the charging process that is scheduled for a vehicle arriving at 18:50, requiring 10 kWh of energy and expecting to leave at 19:40. The first three time-steps are characterised by a rated charging power, whereas the last one shows a lower power , so to exactly reach the amount of 10 kWh asked.

In the lower part of the graph, the same charging process is shown, where also a curtailment scheme is implemented. This scheme intervenes during the second time-step and cuts down the charging power to 5 kW. At the time-step after this curtailment operation, since no more curtailment actions are taken, the charging process goes back to the rated power and completes the operation. Therefore, in both cases, the same amount

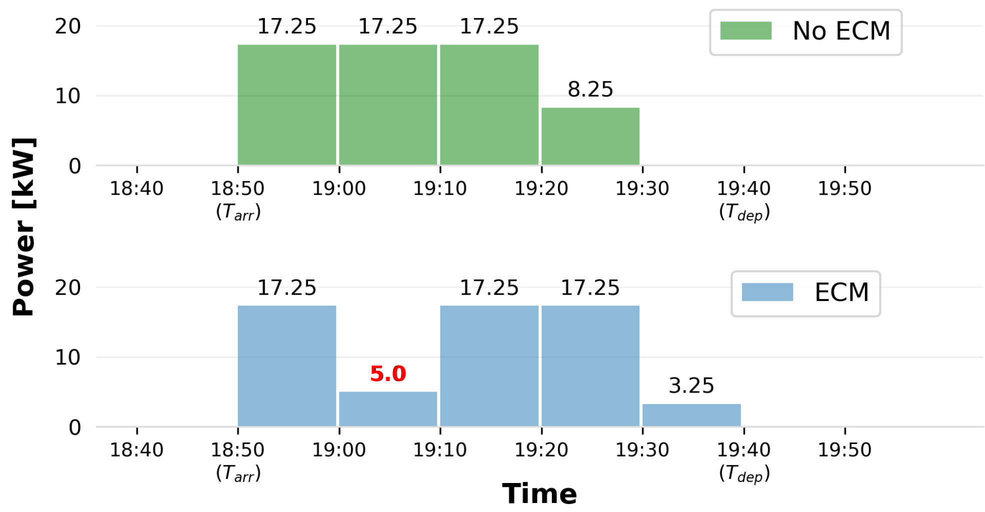


Figure 5.4: Example of rescheduling process in case of uncontrolled charging ($T_{arr}$: 18:50, $T_{dep}$: 19:40, *Required energy*: 10 kWh).

of energy was given within the allowed period. Naturally, depending on how severe are the curtailing conditions, this may not be always the case and it could happen that EVs have to leave before they have received the required energy. In this case the charging station would have *failed* to complete the charge.

A similar process is needed also in case the charging strategy adopted at the single nodes is the *local optimisation charging* scheme. In this case, though, rescheduling the power is slightly more complicated than in the uncontrolled scheme. In a nutshell, every time a node gets curtailed, a new optimisation analysis has to be carried out at that node to re-plan the whole charging operation. In this new analysis, the energy needed by the electric vehicles is the energy they required in the first place minus the energy they have already received. Furthermore, a new constraint has to be set, to limit the maximum power that the node can import during the current time-step according to the restrictions set by the CC. This new constraint is shown in equation 5.21, where $P_{cut,i}$ represents the energy curtailed at chargers $i$ obtained from the CC optimisation.

$$p_{EV,i,t} < P_{EV,rated} - P_{cut,i} \tag{5.21}$$

## 5.6 Flexible Curtailment Method (FCM)

In this section, some of the disadvantages of the ECM strategy presented in section 5.5 are briefly described. Then, a possible alternative design for the curtailment scheme – defined as *Flexible Curtailment Method* (FCM) – is illustrated. The implementation of this design can in theory lead to better results in terms of percentage of successfully completed charging processes after a curtailment operation.

### 5.6.1 Disadvantages of ECM

The method described in section 5.5 was thought up as a process to guarantee a fair curtailment operation to be used as an emergency scheme to prevent any overloading situation in the grid. Although efficient results and fairness towards all the involved parties were considered as the two main priorities, this scheme still suffers from a few issues concerning these two specific aspects.

One of the most relevant issues of the ECM is that this method does not consider the magnitude of the charging power at the single charging stations, meaning that its goal is to cut the same absolute power from all of them (naturally, only up to power they are currently providing). Therefore, the same amount of power could be cut at two different charging stations, one having, for instance, twice the power demand of the other. This approach can be acceptable under the assumption (mentioned in section 3.2) that EVs are the only elements that are going to be curtailed by the ECM. However, should also regular loads be considered in future research, it is clear that residential loads and industrial loads, for instance, could not be curtailed in the same way. In order to avoid this, it could be in theory possible to cut the same amount of relative power to all the involved elements (taken singularly or considering the nodes), instead of the absolute power. However, it should be noted that such a strategy could hardly be applied in case of multiple constraints, i.e. multiple elements overloaded. In a nutshell, the difficulties in this case would arise from the fact that different overloaded elements could lead to different curtailment percentages of the same charging stations. These problems could be overcome by using the highest percentage calculated for every charging station, but in that case the objective of equation 5.14 would not be efficiently satisfied.

Another relevant issues with the ECM strategy is that there is a chance that the same amount of power is curtailed at a highly *flexible* charging station, i.e. which is not urgently requiring power, and at a highly *unflexible* one. This would probably lead to plenty of room for manoeuvre at the former and a high consumer dissatisfaction at the latter. Therefore, the grid reliability, which is a very important aspect especially in the Netherlands, would significantly be affected. To avoid this and in order not to pay a penalty for not meeting the EVs' requests, adopting a method that considers the flexibility of each node may be a better strategy. The next section will deal with this specific aspect and will describe a method that considers the flexibility of the charging stations before curtailing them.

### 5.6.2 Flexible Curtailment Method

One of the main point of this method is probably the definition of a priority parameter, so to translate a charger's urgency of power into a number. This number can be compared with the ones of the other charging stations and, when necessary, power will be curtailed accordingly. Several studies have already been made on the topic [11,53,54]. In particular, [54] cites a parameter that could be considered as a *priority factor*. This can be defined as follows

$$PF_i = \frac{\Delta t_{min,i}}{\Delta t_i} \tag{5.22}$$

where $\Delta t_i$ is calculated as the difference $T_{dep,i} - t$ at charging station $j_i$, where $t$

represents the present time of calculation and $T_{dep,i}$ the expected departure time of the vehicle connected to the charger. The term $\Delta t_{min,i}$ refers instead to the minimum time necessary to complete the charging process and it is calculated as

$$\Delta t_{min,i} = \frac{d_{ch,i}}{P_{r,i}} \tag{5.23}$$

where $d_{ch,i}$ is the remaining energy asked by the vehicle and $P_{r,i}$ is the rated power of the charging station $j_i$. This priority factor $PF_i$ gives an indication of how urgent is the need of power at the studied element and the closer it gets to 1, the more urgent it needs power to charge its EV. In case $PF_i > 1$, it will not be possible anymore to complete the charging process. This parameter could be used to decide which charging stations should be curtailed first in order to cause the least dissatisfaction possible. To do so, the charging stations with a low $PF_i$ should be curtailed first and the once with a $PF_i$ close to 1 should not be curtailed at all.

It should also be noted that the parameter $PF_i$ refers to the current flexibility of the charging station, i.e. to the flexibility calculated at the moment of the curtailment. Another possibility would be to use the "historical flexibility". This could be done by simply calculating $\Delta t_i$ as the difference $T_{dep,i} - T_{arr,i}$, instead than using the current time $t$, and $d_{ch,i}$ as the total energy request of the EV. The choice to implement the current flexibility was made as the other option does not consider the energy already given to the EVs. In a scenario where the chargers could operate with very different behaviours – for instance when much PV power is available with a local optimisation charging scheme implemented – the historical flexibility could not really express the real energy urgency of a node with respect to the others.

The implementation of this mechanism can be done in a very straightforward way, by simply keeping unchanged all the equations from 5.7 to 5.14 and modifying 5.15 only. In fact, equation 5.15 was specifically introduced to guarantee a fair division of the curtailment. This time, instead, this division should be made according to the $PF_i$ values of the charging stations and this can be done by using the following low priority objective instead of equation 5.15

$$minimise \quad \sum_{i=0}^{N} PF_i \cdot P_{j_i} \tag{5.24}$$

### 5.6.3 Fairness of the approach

In the previous section, the logic according to which the FCM curtails power at the charging stations is explained. It is important to highlight that the main goal of this strategy is to generate as little consumers' dissatisfaction as possible. In fact, the idea is that consumers would not mind being curtailed as long as they still receive the energy they have asked before their departure time. Therefore, any time it is needed, it could be a better choice to curtail some charging stations instead of others, although this may be considered not fair from a consumer point of view.

In case significant curtailments are foreseen, though, this strategy could lead to a very unfair distribution of dissatisfaction among the consumers. In fact, a very small difference in the $PF_i$ could cause one EV to get a full charge, while another one not to get any energy at all, before they both leave. This is a very important drawback of this approach that should be carefully considered before implementing this strategy in any grid.

As far as fairness is concerned, there are also other aspects that should be taken into account. These are not considered in this thesis and are here reported only for possible future studies on the same topic.

One of these aspects can be described by means of an example. Let us assume that EV $j_1$ arrives at node $n_1$ at time $t_{arr1}$, while EV $j_2$ arrives at node $n_2$ at time $t_{arr2}$. The relation $t_{arr1} < t_{arr2}$ is valid and the two vehicles let the system know that they will leave at the same time, therefore $t_{dep1} = t_{dep2} = t_{dep}$. Furthermore, the two vehicles ask for the same energy, that means $d_{ch,j1} = d_{ch,j2} = d_{ch,j}$. A local optimisation charging scheme is implemented at both chargers and, as a result of their analyses, none of the EVs has received any energy yet at time $t_0$, such that $t_{arr1} < t_{arr2} < t_0 < t_{dep}$. This decision was made with the intention to charge the vehicles during lower price moments. However, when the price is low, it is possible that the high charging concurrency of all the chargers in the network leads to the activation of the curtailment mechanism. One possible consequence of this curtailment is that the system realises that it will not be able to fulfil the energy requests of both $j_1$ and $j_2$. Should we only consider the equations described in sections 5.5.1 and 5.6.2, EVs $j_1$ and $j_2$ would result having the same flexibility (and therefore being curtailed in the same way). However, this could be considered unfair to $j_1$ since it waited for that energy for a longer time.

Similar situations may present when considering two other aspects: the state of charge (SOC) and the energy that has already been provided to the vehicles. Including the former in the analysis would make the system prioritise the charging operation of the EVs with a lower SOC, while the latter would also allow to consider which vehicles have received less energy with respect to the others.

## 5.7 Meshed Grids

According to literature, most distribution grids are operated radially even when they present meshed characteristics. However, this is not always the case and, provided that an adequate protection system is included, these could also operate maintaining a meshed structure. The method described in section 5.3 can in general be applied to meshed grids as well, but some modifications need to be introduced.

### 5.7.1 Building of the Localisation Reference Matrix

In case of radial networks, the path and the direction followed by the power through the lines is always the same. However, when it comes to meshed grids, this rule does not apply anymore. In fact, depending on which loads and charging stations are active and on the magnitude of their power requests, power could follow different paths and – in extreme cases – even different directions. In a nutshell, this means that the charging points downstream of a line may be different with a different power request from the loads. Therefore, the construction of a general matrix, like the ones built for the radial grids, presents problems and disadvantages.

One way to overcome these obstacles follows from the assumption that, although power flow may be different from time to time, such variations are never too extreme. Therefore, the list of vehicles downstream of a congested line obtained from a general reference matrix is, in the general case, not different from a list specifically compiled for that moment of time. In general, this approximation may be more or less severe depending on the number of loops in the meshed network. Nevertheless, it proved to always hold true in the studied meshed grids, where different simulations were run to verify this theory a posteriori.

Nevertheless, the construction of the LRM proved to be harder than in the radial case. In fact, when the method used for radial grids was applied to the meshed networks, some of the results were evidently not representative of the real situation. The main reason for these wrong results were the loop themselves that were causing the algorithm to check the same line multiple times. To solve the problem, a simple code to avoid a double check of the same line was introduced. Nevertheless, some of the results were still wrong. This was caused by the fact that the grid topology significantly affects the extent to which the charging stations influence the voltage in the network. To avoid this problem, a new similar code was created where the charging stations are activated one by one and each time the lines of the whole grid are checked.

Naturally, this last modification has a huge effect in terms of computational complexity. However, being this code needed to be run only once per grid, the cost was considered worth the result. As a matter of fact, the outcome of the code was checked again and no mistakes were found. It should be noted, though, that different configurations of the same grid (obtained by changing the status of the switches present) are associated to different LRMs.

### 5.7.2 Power curtailment

In case of meshed grids another relevant problem arises from the fact that the nodes in the network are in general served by multiple lines. This makes the curtailment process slightly trickier and the reason can be easily seen by means of an example. If a charging station is receiving a power of $P_{chr}$ coming from two different lines, line A and line B, and line A is overloaded (for instance there is $P_{extra}$ extra power flowing through it), then cutting only $P_{extra}$ from the charging station is not sufficient to solve the problem. This is because, on average, $0.5 \cdot P_{extra}$ will stop flowing through line A and another $0.5 \cdot P_{extra}$ through line B, instead of the desired result of cutting $P_{extra}$ from line A. This implies, being one of the assumptions that the grid topology is fixed, that a larger amount of power has to be cut downstream of a line, with respect to the power calculation described in section 5.4. To what extent this power has to be increased depends on the grid topology and on the current load demand.

In order to calculate it, a curtailment process in 2 runs was implemented.

- A first load flow is run and, in case overloads are detected, the power to be cut for each overloaded element is calculated by means of the formulae presented in section 5.4. Then, the optimisation analysis is run and the power to cut at all chargers is obtained.

- The next step is to run a second load flow. If overloading situations are still detected, the power to be cut for each overloaded line is calculated again using the formulae of section 5.4. The power $P_1$ that had to be cut at the first run for the overloaded line $l$ is now compared with the power $P_2$ that has to be cut now. The power to be cut to relieve line $l$ at this second load flow, therefore, is not $P_2$, but $k_{incr} \cdot P_2$, where $k_{incr}$ is defined as

$$k_{incr} = 1 + \frac{P_2}{P_1} \tag{5.25}$$

However, being this method only an approximate way to include the influence of the meshed grid topology in the algorithm, a safety factor also needs to be included. This safety factor $k_{sf}$ is in general different from grid to grid and it can be adjusted according to the results obtained. As a general approximation, however, it lies around 5% for transformers and 50% for lines. It is important to notice that this second percentage, although appears very high to be a safety factor, it corresponds, in the general case, only to a few kWs (1 or 2 in the most cases) as it is only used to adjust an already reduced power demand. Once this safety factor is known, the power to be cut at the second load flow is

$$P_2' = P_2 \cdot k_{incr} \cdot (1 + k_{sf}) \tag{5.26}$$

# 6 *Case studies and scenarios*

This chapter summarises the main information regarding the simulated scenarios and the elements included in them. In particular, section 6.1 gives an overview of the main tools that were used to carry out the work, while section 6.2 describes the nature and the sources of all the data needed to simulate the behaviour of the main elements present in the grids, such as PV panels, loads and EVs. Then, section 6.3 lists all the simulated grids, along with their main characteristics. Finally, a few considerations and remarks on the simulation of complex grids are expressed in section 6.4.

## 6.1 Programming language and software

The software that was used for the simulations of all the grids is *PowerFactory*, that allows to create, modify and simulate any kind of grids (big, small, radial, meshed, etc.). The data used for the simulations can be easily given in input to all the different elements present in a grid. This aspect makes *PowerFactory* – once some experience on the software is gained – a very useful and user-friendly tool. For the simulations different combinations of elements and data-types had been tried, but finally, after comparing results and simulation times, it was decided to feed almost all the data to the software as *.ChaVec* [66]. Another potential option was the use of *Quasi-dynamic simulations* in combination with *.ChaTime* objects. However, when it came to set the desired simulated periods, this solution showed considerably less flexibility.

In order to correctly simulate the studied scenarios, many parameters and elements had to be set according to the specific situations. In case the *local optimisation charging* scheme or either of the two curtailment methods were implemented, some parameters and values needed to be changed during the simulations as well. To do so, different algorithms were developed as scripts in *Python*. Once these scripts are imported in *PowerFactory* and executed, they coordinate the whole simulation process. In particular they take care of:

- importing the necessary data
- assigning the correct parameters and "behaviours" to all elements
- launching and controlling the simulation
- saving the results

These scripts were not written specifically for the tested grids and were in general thought up to be used on any other grid in *PowerFactory*.

One last tool that needs to be mentioned here is the *Gurobi Optimizer*. As already explained in chapters 4 and 5, the *local optimisation charging* scheme and both the curtailments schemes (ECM and FCM) need to execute optimisation analyses. For this reason, the *Gurobi* library was downloaded and imported in all the codes that required that. This, as well as *PowerFactory*, is a commercial product that provides free licenses to students and made, therefore, this thesis possible.

## 6.2 The simulated data

In order to simulate all the scenarios in *PowerFactory*, a significant amount of data was needed. Focusing this thesis on the effects experienced in the grid with the introduction of different percentages of electric vehicles (with respect to the number of regular vehicles registered in the Netherlands), it is clear that the EV data was of vital importance. This was obtained from the company ElaadNL [75]. This data includes all information needed regarding the electric vehicles, such as their arrival and leaving time, and their energy demand. This data provides information concerning electric vehicles coming and leaving for a full week period. In particular, it refers to the first week of January 2018. In order to be able to simulate any moment of the year 2018, this data was replicated and used for the whole year.

Being the EV market very uncertain for the future, it was assumed that all EVs have either a 50 or a 100 kWh battery size. More specifics on this are provided in table 6.1.

| **Electric Vehicle** | **Percentage** | **Battery size** | **Charging power** |
|---|---|---|---|
| Type 1 | 70% | 50 kWh | 17.25 kW (3×25A) |
| Type 2 | 30% | 100 kWh | 17.25 kW (3×25A) |

Table 6.1: Specifics of the two types of electric vehicles used for the simulations

Another relevant set of data is the one concerning the simulation of all the "regular" loads in the grid. These were simulated by means of their yearly energy demand in kWh (data provided along with the grids by the Dutch DSO Enexis) and standardised load profiles [76]. Finally, the production of the PV panels was simulated using the data provided by the authors of [77], who thoroughly researched on the topic.

As already mentioned in the previous section, this data was imported into the model by means of the scripts used for the simulations.

## 6.3 The simulated grids

In this section, a quick overview of the 3 grids used for the simulations is given. These were chosen as representative cases of the three main possible categories of grids: rural, urban and sub-urban. For the sake of simplicity, these categories are also used as names to refer to them. Therefore, the three grids used for all the simulations are referred to as *Rural Grid*, *Urban Grid* and *Sub-urban Grid*.

The first one – *Rural Grid* – represents the typical case of lines installed far from the urban centre, where all the loads are located far from each other. This constitutes the easiest study scenario, as it is a completely radial network. A map of the model on *PowerFactory* can be seen in figure 6.1. The other 2 categories instead – *Urban Grid* and *Sub-urban Grid* – have both meshed networks. Their models can be seen in figures 7.5 and 7.6, respectively. The nominal voltage of all three categories is 230/400 V (line-to-neutral and line-to-line voltages).

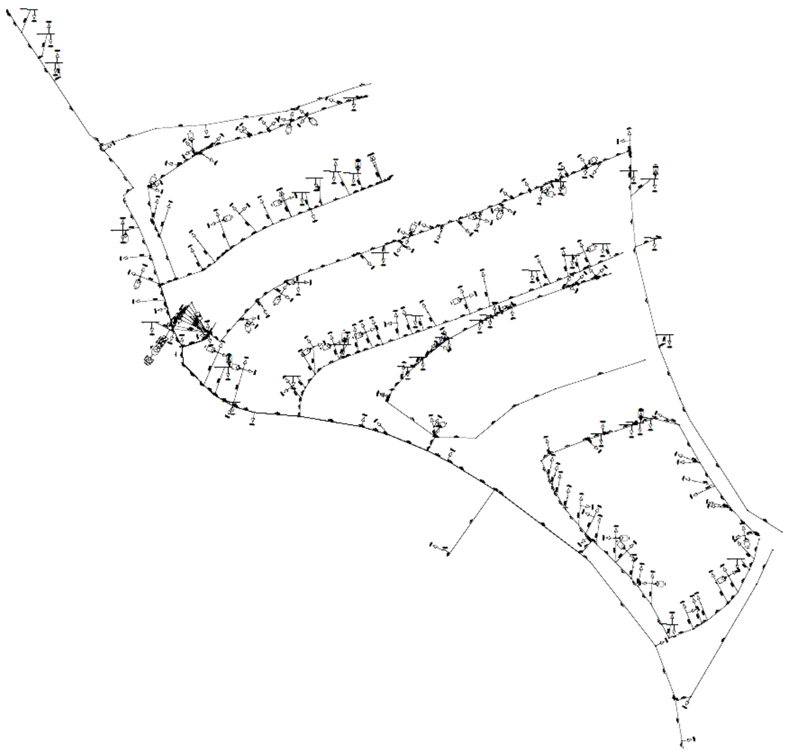

Figure 6.1: Model map of *Rural Grid*, 80% EV penetration

These grids represent real electrical networks located in the Netherlands and their models were provided by the Dutch DSO Enexis, along with all the necessary data to simulate them.

For all these networks four possible different EV penetration percentages are implemented: 0%, 20%, 50% and 80%. These percentages refer to the fraction of EVs out of all the vehicles present in those grids. In particular, these numbers were obtained by considering the average number of cars per household as reported in table 6.2.

The same table also reports the percentages of the different kinds of charging stations that are included in the grids. This aspect is crucial as the charging behaviours registered at the three kinds of charging point are very different one from the others.

As far as the photovoltaic panels are concerned, these were added to the different grids following the specifics reported in [4]. All this information is summarised for all the grids in table 6.3.

| Region | Avg car/HH | Home charger | Semi-public charger | Public charger |
|---|---|---|---|---|
| Rural | 1.25 | 70% | 15% | 15% |
| Urban | 0.5 | 25% | 37.5% | 37.5% |
| Sub-urban | 0.9 | 50% | 25% | 25% |

Table 6.2: Average number of cars per household in different regions and percentages of different charging stations [4]

| | General | | | Elements | | EV penetration | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Topology | Nodes | Transformers | PVs | Reg. loads | | 20% | 50% | 80% |
| **Rural Grid** | Radial | 511 | 1 | 35 | 138 | *Home* | 13 | 33 | 53 |
| | | | | | | *Semi-public* | 2 | 6 | 10 |
| | | | | | | *Public* | 2 | 6 | 9 |
| **Urban Grid** | Meshed | 1684 | 2 | 18 | 349 | *Home* | 4 | 10 | 15 |
| | | | | | | *Semi-public* | 5 | 13 | 20 |
| | | | | | | *Public* | 4 | 11 | 18 |
| **Sub-urban Grid** | Meshed | 2553 | 3 | 122 | 809 | *Home* | 40 | 99 | 159 |
| | | | | | | *Semi-public* | 17 | 43 | 69 |
| | | | | | | *Public* | 15 | 39 | 62 |

Table 6.3: Summary of the main information concerning the 3 studied grids

## 6.4 Simulation of complex grids

A countless number of simulations were launched during the development of this study and some of them highlighted crucial aspects that needed to be considered. In particular, *convergence problems* were very often registered. This term is used to describe the situation where the iteration process – that is run to find a solution to the load flow analysis – does not reach convergence and that, therefore, leads to no results that can be used.

One aspect that has to be mentioned is what happens in *PowerFactory* in case an iteration process does not reach convergence. As explained in the manual [66], if a solution is not found within the maximum numbers of set iterations, the *automatic model adaptation for convergency* option comes into play. Once an iteration process has failed to converge, this option slightly changes the model so to make it more linear and, therefore, more likely to converge. This adaptation is operated in levels (from Level 1 up to Level 4), where the higher the level reached, the more severe are the changes made to the model.

The problem of load flow non-convergence is certainly not novel in literature and several authors throughout the years have researched on the topic. Some of the solutions proposed by these were tested [78–80], but they all seemed of no use for the issues registered during the simulations. Therefore, different tests were run, so to detect what was the cause of those convergence issues.

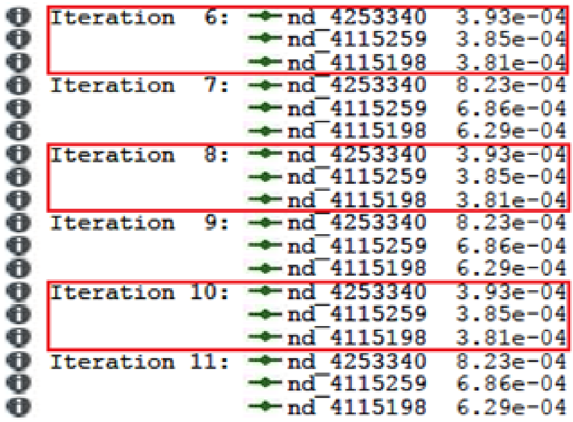


Figure 6.2: Largest errors registered in *Sub-urban Grid* during a simulation

All these problems were studied in the network *Sub-urban Grid*, as this seemed to be the most seriously affected grid by these problems. The starting point was the error messages returned by the software anytime a simulation failed to converge. As it can be seen in figure 6.2, the errors alternated between two values. Two possible causes for this were indicated in the *PowerFactory* manual and in the book "PowerFactory Applications for Power System Analysis" [81]. The former states that an error not continuously decreasing may be an indication of voltage stability issues. To verify this, the grid was made ideally lossless, so to keep the voltage stable at 1 p.u. at every point of the network. Nevertheless, the same problems of figure 6.2 were still registered. Also the possible cause indicated in [81] turned out not to be the right one. This indicates weak networks with high amounts of PV generation as a possible reason for algorithms alternating between two values. However, similar results were again obtained with the PV panels out of service.

Some positive effects, though, were registered when the grid was simplified by means of a script that summarises all the loads, PVs and charging stations along a whole radial branch in a few elements only. The branches on which it is desired to have such simplification can be selected one by one. The effect of this operation is a much simpler grid to simulate the same amount and nature of loads. The effects of this modification are shown in figure 6.3. While simulating with the simplified version of the grid, less convergence problems were registered. This seems to imply that the convergence problems arise for the high complexity of the grids, that leads in turn to a more complex set of equations.

This conclusion is also supported by the way through which these problems cease to appear when the automatic model adaptation intervenes. Before any load flow is run and if not specified otherwise, the software assigns a constant power model to all the loads by default. This means that the voltage has no influence on the magnitude of power. However, when the automatic model adaptation is activated, one of the most relevant modified factors is the voltage dependency of the loads. In addition, this dependence is increased with increasing levels of adaptation. This means that whenever the automatic model adaptation for convergency comes into play, the results of the load flow do not

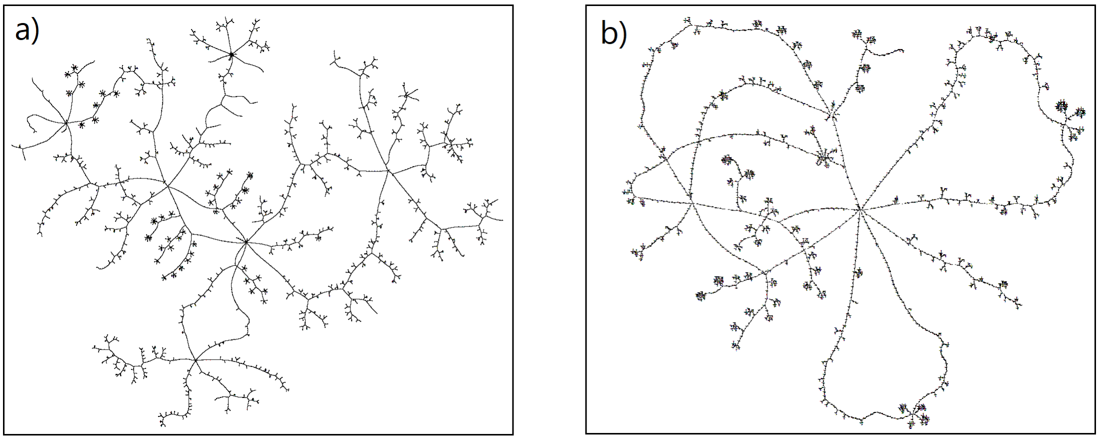


Figure 6.3: Expanded models of *Sub-urban Grid*: a) original version, b) simplified version

refer anymore to a constant power behaviour. In fact, depending on the level of adaptation reached, different coefficients for the constant power, constant current and constant impedance are introduced [66]. More details about how these coefficients influence the load behaviour are given in the next paragraphs.

The reason why convergence is reached more easily with a voltage dependent behaviour is thoroughly explained in several sources, among which are [82,83]. In particular, Soman et al. say that

> Constant power loads lead to stability problems because there is a tendency to increase the current, in order to maintain constant power even though voltage drops. This can lead to a further drop in the voltage. Constant impedance loads, on the other hand tend to damp voltage oscillations [83, p. 13].

This is why several sources [66,81,84] recommend to model loads as voltage dependent elements, especially in low voltage networks. This is usually done by means of two different approaches:

1. *ZIP-Model*

$$P = P_0 \cdot \left( aP + bP \cdot \left( \frac{v}{v_0} \right) + cP \cdot \left( \frac{v}{v_0} \right)^2 \right) \tag{6.1}$$

$$Q = Q_0 \cdot \left( aQ + bQ \cdot \left( \frac{v}{v_0} \right) + cQ \cdot \left( \frac{v}{v_0} \right)^2 \right) \tag{6.2}$$

$$a + b + c = 1 \tag{6.3}$$

where $a$, $b$ and $c$ are the coefficients for the constant power, constant current and constant impedance contributions, respectively. $P$ represents the power asked by the load (different from the nominal value $P_0$), which depends on the ratio of the registered voltage $v$ to the nominal voltage $v_0$. The same logic applies to the reactive power $Q$.

2. *Exponential Model*

$$P = P_0 \cdot \left(\frac{v}{v_0}\right)^{eP} \tag{6.4}$$

$$Q = Q_0 \cdot \left(\frac{v}{v_0}\right)^{eQ} \tag{6.5}$$

Possible values for the exponential parameters are reported in [85]. This model is less common in literature.

Depending on the values assumed for all the different coefficients, it is clear that the voltage dependence of the active power $P$ and the reactive power $Q$ could be very significant. Furthermore, being the voltage drop along a feeder very much dependent on the kinds of loads present, it is straightforward that the way of representing them is crucial to simulate an accurate voltage drop.

This aspect, however, collides a great deal with the data used for the analysis. In fact, this data specifies the yearly energy consumption of the single loads and, when a constant impedance behaviour was used to simulate them, differences up to around 50% were registered in the overall consumption. Therefore, in order to guarantee the fulfilment of the yearly energy condition, it was decided to simulate all the scenarios with loads modelled as constant power elements. To do so, the ZIP-Model was used where the coefficients were set as

$$a = 1$$

$$b = c = 0$$

The assumption described in section 3.2 to consider all the loads connected to the grid with a 3-phase connection made the constant power modelling possible. In fact, the conversion of all single-phase loads into 3-phase loads significantly simplified the models and allowed to simulate them without registering any convergency problem.

# 7 *Simulation results*

In chapters 1 and 3 several questions are posed. All of them concerns either the current status of the grids or the effects that different control strategies could have on the electrical network. Then, some of those strategies are thoroughly described throughout the rest of the thesis. The goal of this chapter is to finally answer to all the initially posed questions by showing the outcomes of several different analyses specifically thought for the purpose. These analyses were carried out simulating different scenarios on the grids described in section 6.3. One of the most recurrent parameters reported for the studied scenarios is the maximum loading percentage, that refers to the highest loading percentage registered among the lines and the transformers.

This chapter is organised as follows. In section 7.1 the impact of a higher EV penetration on the current status of the grid is described. Then, in section 7.2 there is a comparison between the three charging strategies described in chapter 4 and their effects on the grid. Finally, section 7.3 describes the effect of a coordination between the local charging stations and a central curtailment unit.

## 7.1 Effects of a higher EV penetration

The first point of interest was the extent to which grids are affected by higher EV penetrations and whether their operation is still safe when a higher number of EVs connect simultaneously. These kinds of questions are particularly relevant nowadays, as several companies and organisations worldwide are pushing more and more for the introduction of these technologies. Therefore, a thorough study of this phenomenon should be carried out to allow a higher EV penetration only where that is possible. A reinforcement of the grid could instead be considered if that higher EV penetration causes problems to the network.

For all the simulations presented in this section, the charging strategy adopted was always the *uncontrolled charging*, as this is the most common charging scheme used nowadays all over the world. Furthermore, no central entity to control the flux of power was implemented.

### 7.1.1 Rural Grid

In general, almost all the studied grids proved to withstand a very high penetration of electric vehicles. For instance, *Rural Grid*, where the system's topology was strictly radial, registered no problems at all and the integration of charging stations proceeded

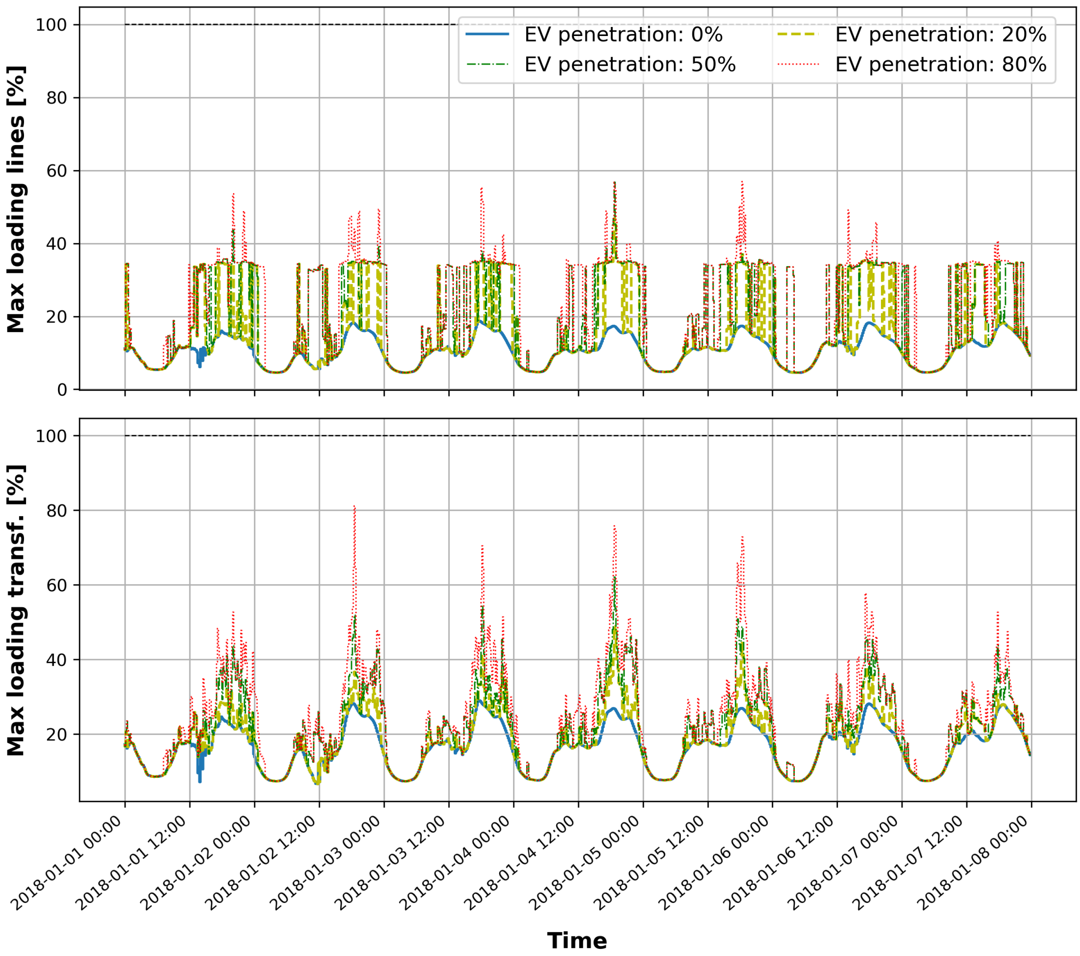


Figure 7.1: Maximum loading percentage of lines and transformers at each moment of time for *Rural Grid* (uncontrolled charging case), Winter Scenario (Period: 01/01/2018, 00:00 - 07/01/2018, 23:50; Time-step: 10 min).

| | **Peak value max loading [%] (Transformer)** | **RMS max loading [%] (Transformer)** | **Peak value max loading [%] (Line)** | **RMS max loading [%] (Line)** | **Max total power demand [kW]** |
|---|---|---|---|---|---|
| **EV penetration: 0%** | 28.95 | 17.47 | 18.72 | 11.24 | 115.14 |
| **EV penetration: 20%** | 48.83 | 19.73 | 46.80 | 18.36 | 192.72 |
| **EV penetration: 50%** | 62.06 | 23.25 | 56.76 | 23.50 | 244.47 |
| **EV penetration: 80%** | 81.16 | 26.90 | 56.91 | 26.40 | 319.71 |

Table 7.1: Summary of the main information regarding the four tested EV penetrations for *Rural Grid* (uncontrolled charging case), Winter Scenario (Period: 01/01/2018, 00:00 - 07/01/2018, 23:50; Time-step: 10 min).

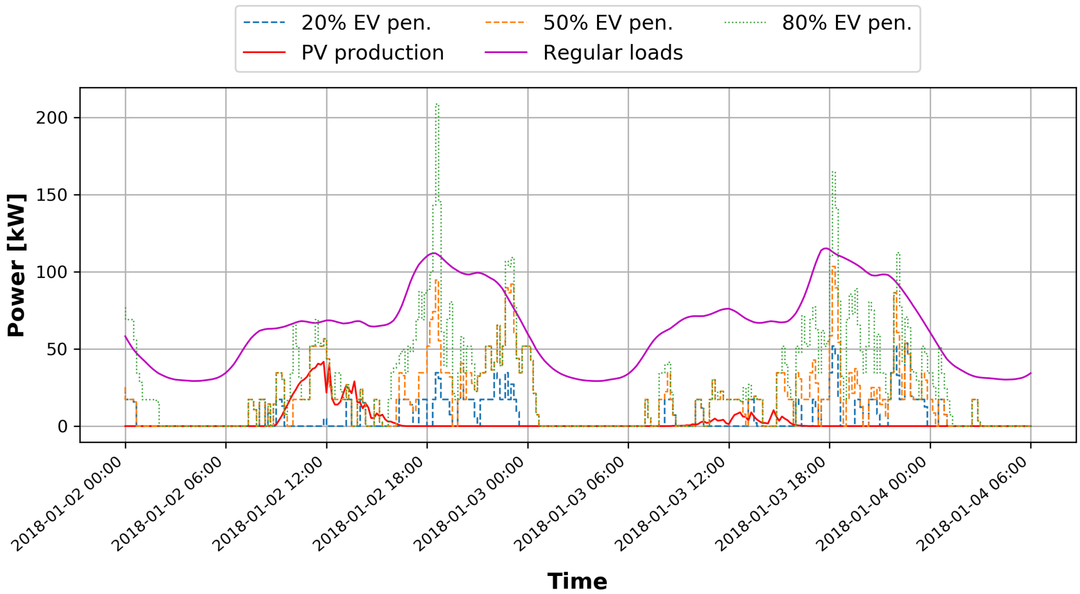


Figure 7.2: General overview of power in kW at each moment of time for *Rural Grid* (uncontrolled charging case), Winter Scenario (Period: 01/01/2018, 00:00 - 07/01/2018, 23:50; Time-step: 10 min). Only 2 days are shown.

smoothly even with the highest percentage tested of 80%. In figure 7.1 it is possible to see the effects on the loading of the different EV penetrations tested on *Rural Grid*. In particular the parameters plotted in this graph are the maximum loading percentage registered at each moment of time among all transformers and lines. From the figure it is possible to see that the only transformer present is the element that registered the highest loading percentages. This is a direct consequence of the fact that there is a single transformer in the grid and that the charging stations are evenly distributed within the network. As better specified in table 7.1, the highest peak registered by the transformer increased by more than 50 percentage points from the 0% penetration case to the 80% one. Nevertheless, no overloading was registered throughout the whole simulated week.

Figure 7.2 instead, gives an overview on the power flowing through the grid for all the EV penetration percentages tested. Although the cumulative effect of the loads and charging stations together is not shown in the graph, table 7.1 reports the peak value of this cumulative power that was registered during the simulated week.

From the table and the two figures it is clear that reinforcements of the grids are not always necessary, even when the number of charging points introduced is comparable to the number of regular loads (in *Rural Grid*, for instance, the ratio of the absolute numbers of EVs to regular loads is 72/138 in the 80% penetration scenario). However, this is not always the case, as it will be shown in the next sections.

### 7.1.2 Urban Grid

In this section, the results of the simulations run on *Urban Grid* are reported. The approach used to evaluate the impact of a higher EV penetration is the same that was

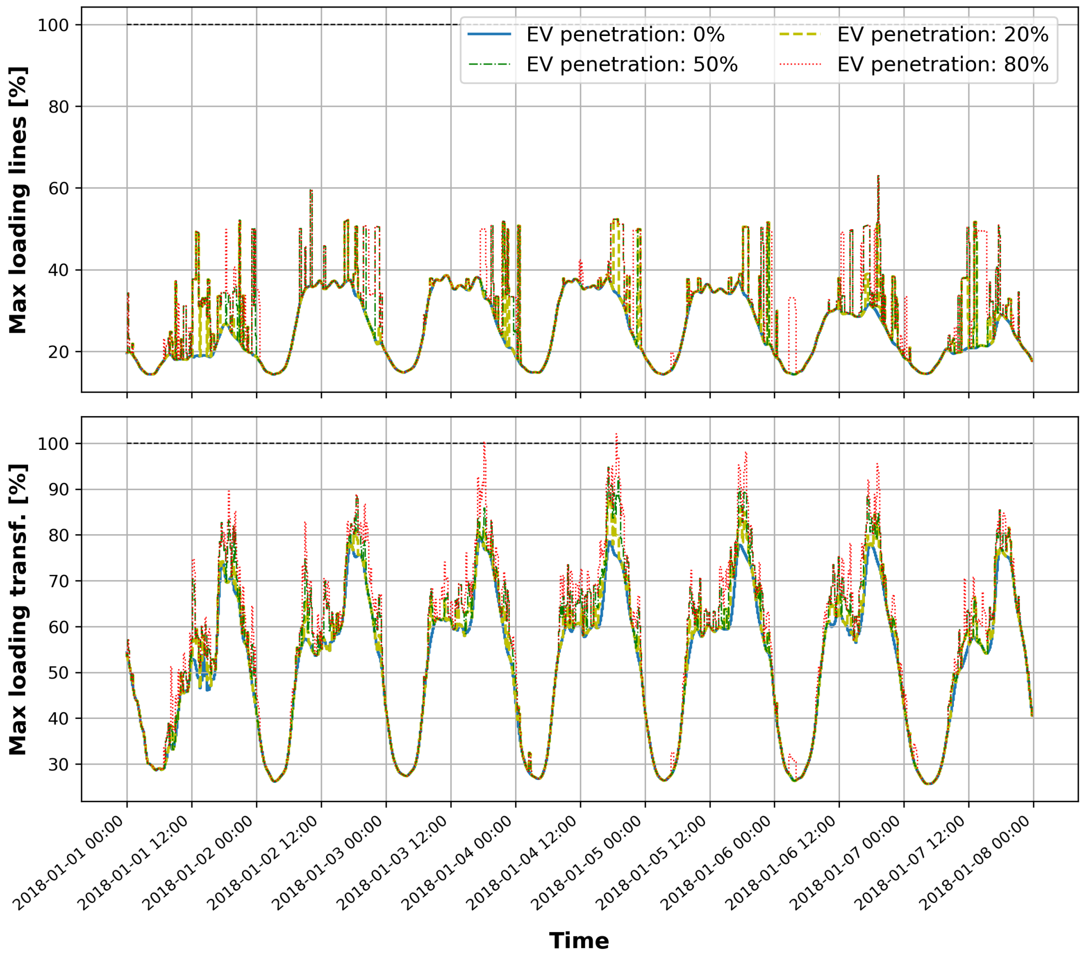


Figure 7.3: Maximum loading percentage of lines and transformer at each moment of time for *Urban Grid* (uncontrolled charging case), radial operation (switches '331848940', '331842504' and '331847842' open), Winter Scenario (Period: 01/01/2018, 00:00 - 07/01/2018, 23:50; Time-step: 10 min).

| | **Peak value max loading [%] (Transformer)** | **RMS max loading [%] (Transformer)** | **Peak value max loading [%] (Line)** | **RMS max loading [%] (Line)** | **Max total power demand [kW]** |
|---|---|---|---|---|---|
| **EV penetration: 0%** | 79.60 | 53.64 | 38.60 | 26.12 | 346.93 |
| **EV penetration: 20%** | 87.80 | 55.06 | 52.35 | 28.26 | 379.11 |
| **EV penetration: 50%** | 94.76 | 57.08 | 62.99 | 30.21 | 406.26 |
| **EV penetration: 80%** | 102.05 | 59.06 | 62.82 | 31.69 | 431.63 |

Table 7.2: Summary of the main information regarding the four tested EV penetrations for *Urban Grid* (uncontrolled charging case), radial operation (switches '331848940', '331842504' and '331847842' open), Winter Scenario (Period: 01/01/2018, 00:00 - 07/01/2018, 23:50; Time-step: 10 min).

applied in the previous section. Therefore, four different EV penetrations were tested: 0%, 20%, 50% and 80%. The main results in numbers of these simulations are reported in table 7.2. For these simulations the switches '331848940', '331842504' and '331847842' were kept open and, therefore, the grid was operated radially. This was done according to the instructions provided by the Dutch DSO Enexis.

Figure 7.3 shows results for the lines that are similar to the ones obtained for *Rural Grid*. However, it is clear that in this case the loading percentages obtained for the transformers are a more serious problem. In fact, during the one week simulation, the technical limit of 100% was exceeded twice and in other two moments the working conditions were close to this limit. From this, it is clear that *Urban Grid* is not able to withstand a too high EV penetration.

The main reason for this result is the fact that this grid was already operating not too far from its technical limits. This can be clearly seen in figure 7.3, where the maximum loading percentage of transformers reaches peaks of almost 80% before any EV is introduced. Although the average number of cars per household was the lowest among the three different topologies of network studied (see table 6.2), the already very busy operation of the grid made the reaching of the limit working conditions inevitable.

### 7.1.3 Sub-urban Grid and the need for data verification

| | **Peak value max loading [%] (Transformer)** | **RMS max loading [%] (Transformer)** | **Peak value max loading [%] (Line)** | **RMS max loading [%] (Line)** | **Max total power demand [kW]** |
|---|---|---|---|---|---|
| **EV penetration: 0%** | 109.06 | 65.06 | 118.72 | 69.75 | 554.47 |
| **EV penetration: 20%** | 151.94 | 70.84 | 194.45 | 77.42 | 705.08 |
| **EV penetration: 50%** | 188.66 | 80.53 | 204.40 | 88.93 | 885.04 |
| **EV penetration: 80%** | 243.16 | 91.85 | 344.46 | 105.59 | 1034.80 |

Table 7.3: Summary of the main information regarding the four tested EV penetrations for *Suburban Grid* (uncontrolled charging case), Winter Scenario (Period: 01/01/2018, 00:00 - 07/01/2018, 23:50; Time-step: 10 min).

The simulation of *Sub-urban Grid* was without a doubt the trickiest one, as not only was this grid the most complex one in terms of number of nodes, but it was also highly meshed. In this regard, the information given by the Dutch DSO Enexis included a number of switches to be kept open during operation, but this was not sufficient to interrupt many of the loops. This means that the grid was still highly meshed. As already explained in section 5.3, it is uncommon for distribution grids to be operated in a meshed configuration and in case they are, the number of loops tends not to be too high. For this reason and for the results obtained from the simulations (briefly presented in the next paragraph), it is reasonable to assume the data received is either incomplete or incorrect. One possible cause for the incorrect functioning of the model may be the fact that other switches have to be kept open during operation. Being this only an assumption, it was decided to contact the DSO Enexis for clarifications about this grid. However, as of the date of handing in this thesis, no reply was received from them. Therefore, the results presented in the next paragraph are to consider strictly qualitative and are only reported

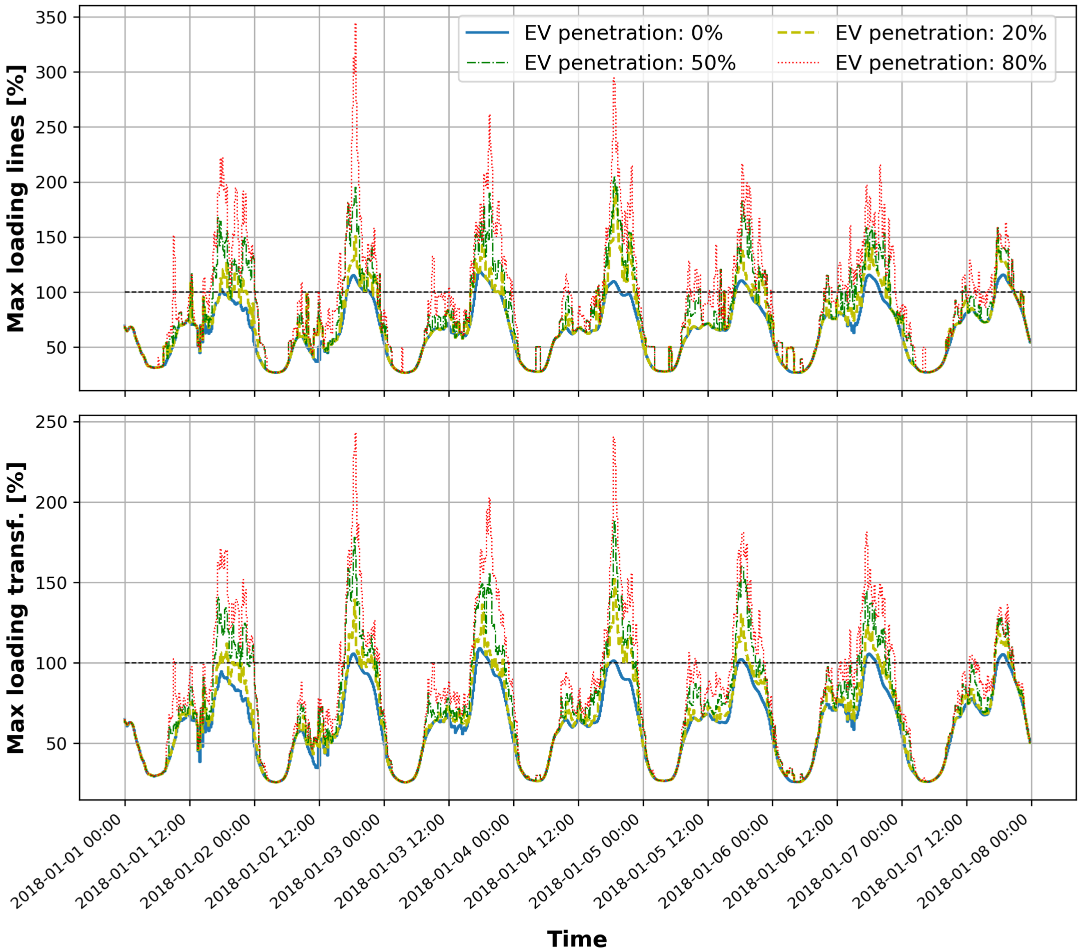


Figure 7.4: Maximum loading percentage of lines and transformer at each moment of time for *Sub-urban Grid* (uncontrolled charging case), Winter Scenario (Period: 01/01/2018, 00:00 - 07/01/2018, 23:50; Time-step: 10 min).

for the sake of completeness.

As it is possible to see from figure 7.4, there are overloading situations in *Sub-urban Grid* occurring at both lines and transformers even before the introduction of electric vehicles. This, of course, would mean that the studied grid is currently not operating within its technical limit. Being *Sub-urban Grid* the model of a real existing grid, the only possible explanation is that there is some inconsistency in the data used. For this reason, as already said in the previous paragraph, a communication process was started to verify the data. More information on the results obtained from the simulations run on *Sub-urban Grid* is provided in table 7.3.

### 7.1.4 Reinforcement of the grid

When the average operating conditions of any electrical network get too close to the technical limits there are two possible solutions: reinforcing the grid or improving the power management. The second solution is usually preferred, where possible, as it comes in general with lower costs with respect to the other one. However, improving the power management is not a solution that can always be applied and, sometimes, new investments on the grids are inevitable. Therefore, it is clear that which one of the two solutions is applied depends mainly on two aspects: general operating conditions of the grid and costs of the two solutions.

A quick evaluation of the needed grid reinforcements can be easily done once the operating conditions are known all over the network. The data saved during the simulations allows to easily make this analysis. In fact, at the end of the simulation, one file is created that contains a list of all the elements that got overloaded, along with other useful information.

**Urban Grid**

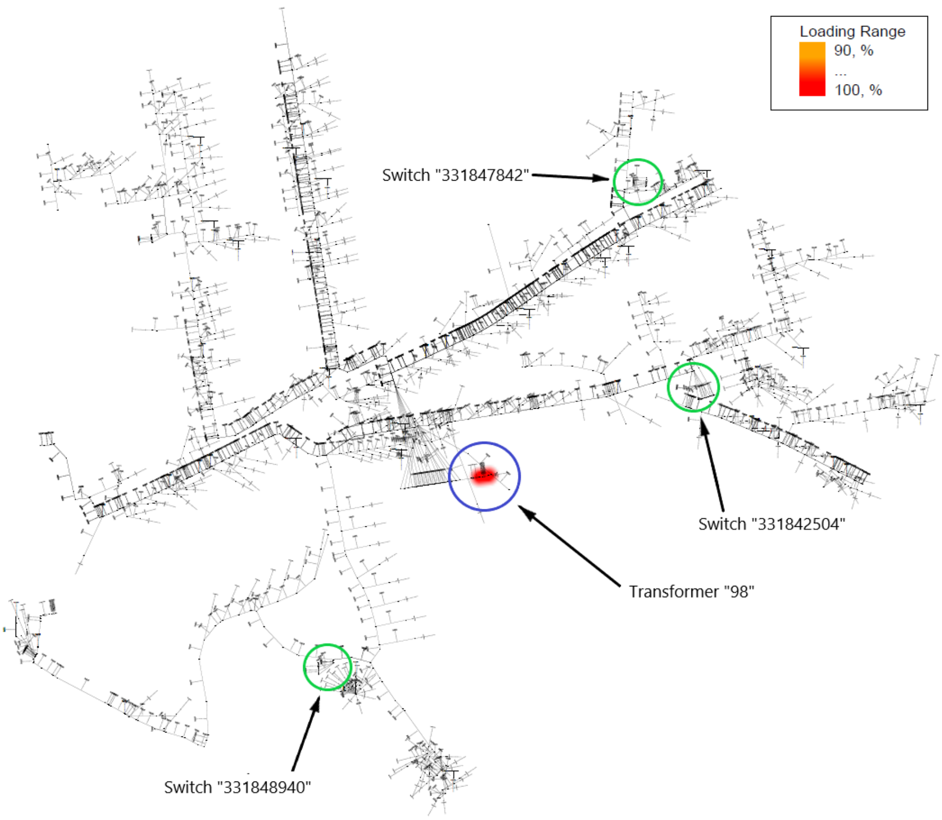


Figure 7.5: Loading heat-map of *Urban Grid*, uncontrolled charging case, 80% EV penetration, 04/01/2018 18:20.

In the case of *Urban Grid*, figure 7.3 shows that transformers are not able to withstand an EV penetration of 80%. In particular, one of the two transformers – labelled in the model with the name ”98” and with a rated power of 0.4 MVA – reaches a peak of 102.05% (as it can also be seen in table 7.2). Being the power factor equal to 1 and the three phases all balanced, it is possible to calculate the LV rated current of the transformer single phases as $I_r = P_r/(U_{L-L} \cdot \sqrt{3})$. By means of this formula, equation 5.1

and knowing that the highest phase current registered at the transformer is 592.1 A, it is possible to calculate the needed rated power of the transformer. The result of such calculations is that, in order to always keep the loading percentage below 90%, a new transformer is needed with a rated power of 0.46 MVA.

**Sub-urban Grid**

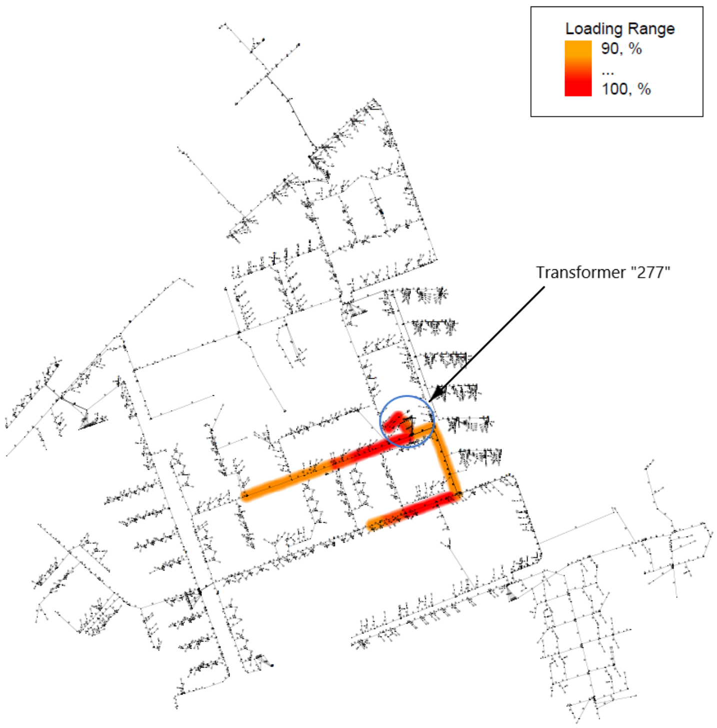


Figure 7.6: Loading heat-map of *Sub-urban Grid*, uncontrolled charging case, 0% EV penetration, 02/01/2018 18:00.

Regardless of the issues reported in the previous section, a similar analysis can also be done for *Sub-urban Grid*. For instance, it is possible to get an idea of the reinforcements needed in order to make the grid safely operate in the base case of 0% EV penetration. Being this grid already very loaded, the goal in this case is to keep all the elements only below the limit of 100% instead of 90%. In figure 7.6 it is possible to see the overloaded elements at one peak moment of the simulation.

From the results of the analysis, only two types of cables registered loadings over 100%:

- *Type 1*: 1229 GPLKh $4 \times 35\, mm^2\, Cu + 4 \times 2.5\, mm^2\, Cu$ (Rated current 0.13 kA, Rated Voltage 0.75 kV)
- *Type 2*: 1016 V-VMvKhsas $4 \times 50\, mm^2\, Al + 4 \times 2.5\, mm^2\, Cu$ (Rated current 0.145 kA, Rated Voltage 0.75 kV)

The total length of these cables that have to be replaced is 181 m (per phase) and their position is visible in figure 7.6. Assuming to make the calculations only by means of the highest current registered in these lines of 172.5 A, the result comes straightforward from equation 5.1. Therefore, in order to keep the loading percentage of all those lines always below 100% a cable is needed with a rated current of around 175 A. Different possible solutions can be found in the library of the model and one of them is the cable 1253 GPLKh $4 \times 50\, mm^2\, Cu + 4 \times 6\, mm^2\, Cu$ (Rated current 0.175 kA, Rated Voltage 0.75 kV).

Finally, an analysis similar to the one made for *Urban Grid* can be done for the problematic transformer named "277", highlighted in figure 7.6. By means of the same approach used before and knowing that the highest registered current is 632.8 A, it is possible to conclude that the needed rated power to make the transformer always operate below the limit of 100% is 0.44 MVA.

### 7.1.5 Effects on the voltage

Although not included in the focus of the thesis, it is still interesting to observe what is the voltage behaviour of the simulated grids when the overall number of EVs in the network rises. Figures 7.7 and 7.8 are reported for the purpose and show the voltage situation in *Rural Grid* and *Urban Grid*, respectively.

As it is possible to see, peaks of around 0.955 p.u. represent the most critical situations in both grids. According to the international standard IEC 60038 [86], the voltage tolerance for the LV networks is defined as ±10% of the nominal voltage. Therefore, these limits are still met even in the case of the highest EV penetration tested.

However, it is clear that this deviation of the voltage from its nominal value is highly dependent on the loads that are active in the network. This means, for instance, that the only way to assess the voltage levels present in a network during the planning phase is a probabilistic analysis. Similarly, the simulations run in this thesis made use of standardised load profiles that do not exclude, therefore, the possibility of voltages lower than the ones showed in the two figures. On top of this, as also pointed out by Nijhuis [87], it is also possible that voltage deviations in the MV network propagate into the LV voltage one. For this reason, it could be a better approach to consider a more stringent limit of ±5%. If this last tolerance is used, the two grids are then operating close to the allowed limits and, although the congestion issues seem to appear more urgent, also the voltage situation should be carefully considered when evaluating the impact of EVs in the network.

## 7.2 Comparison of different charging behaviours

Another relevant part of this thesis concerns the different results that are obtained from the simulations of a grid, by setting different charging behaviour strategies at the single charging stations. Three different options are described in chapter 4: *uncontrolled charging*, *average power charging* and *local optimisation charging*. Their main characteristics are summarised in table 4.1.

To run the tests, two different scenarios were used (Winter Scenario and Summer Scenario), where the EV penetration, the time period and the time-step were set. Their main characteristics are here listed:

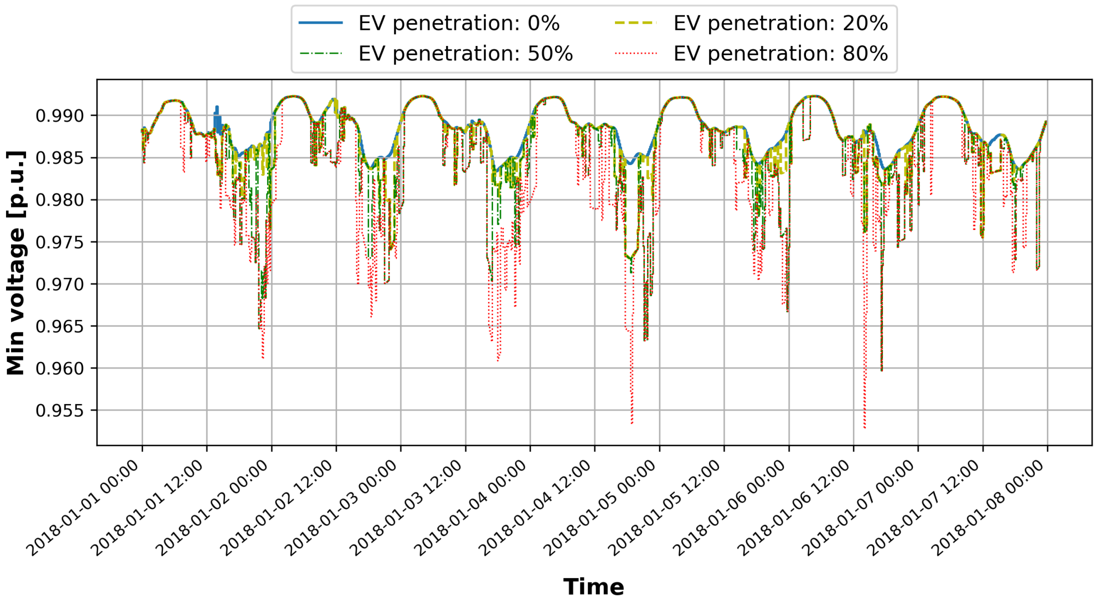


Figure 7.7: Minimum voltage registered at each moment of time for *Rural Grid* (uncontrolled charging case), Winter Scenario (Period: 01/01/2018, 00:00 - 07/01/2018, 23:50; Time-step: 10 min).

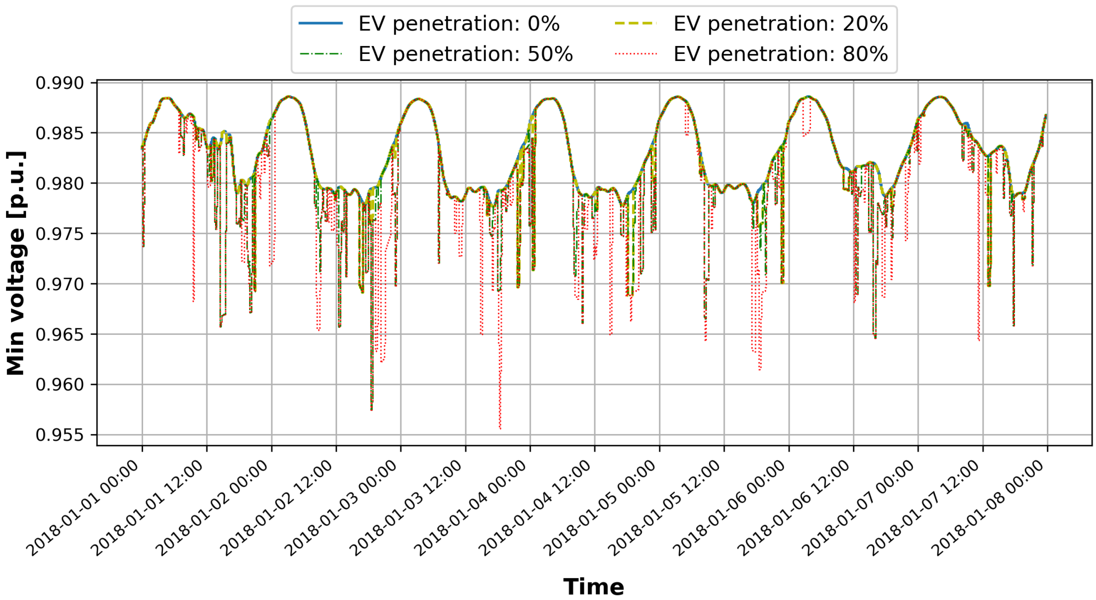


Figure 7.8: Minimum voltage registered at each moment of time for *Urban Grid* (uncontrolled charging case), radial operation (switches '331848940', '331842504' and '331847842' open), Winter Scenario (Period: 01/01/2018, 00:00 - 07/01/2018, 23:50; Time-step: 10 min).

- **Winter Scenario**: *Grid*: Rural Grid, *EV penetration*: 80%; *Period*: 01/01/2018, 00:00 - 07/01/2018, 23:50; *Time-step*: 10 min
- **Summer Scenario**: *Grid*: Rural Grid, *EV penetration*: 80%; *Period*: 02/07/2018, 00:00 - 08/07/2018, 23:50; *Time-step*: 10 min

On each scenario, the 3 different charging strategies were tried out one at a time, so to observe how the 3 different local controls could deal with the same situation.

The main results of the winter scenario simulations are summarised in figure 7.9, figure 7.11 and table 7.4, while the main results of the summer scenario simulations in figure 7.10, figure 7.12 and table 7.5.

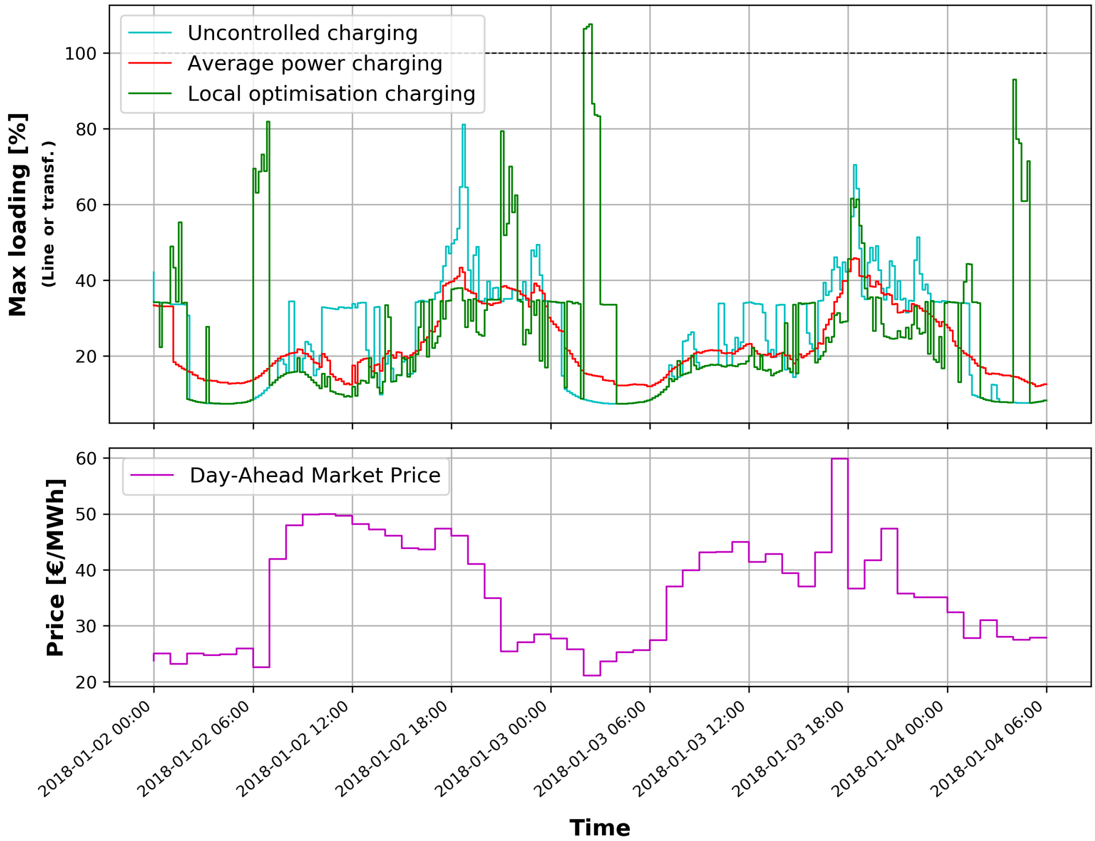


Figure 7.9: Comparison of the maximum loading percentage of lines and transformer of the 3 different strategies on *Rural Grid*, Winter Scenario, EV penetration: 80% (Period: 01/01/2018, 00:00 - 07/01/2018, 23:50; Time-step: 10 min). Only 2 days are shown.

By looking at figures 7.9 and 7.10 it is immediately clear that in both scenarios the only charging strategy that leads to overloading issues is the local optimisation charging. The evolution of the Day-ahead market price reported for both graphs highlights the cause of the overloads: those were moments of very low prices. Therefore, being the optimisation of the costs the main objective of the analyses carried on at each charging station, all of them scheduled the highest power amount for those moments in time. As already mentioned in section 5.1, the lack of information about the external environment

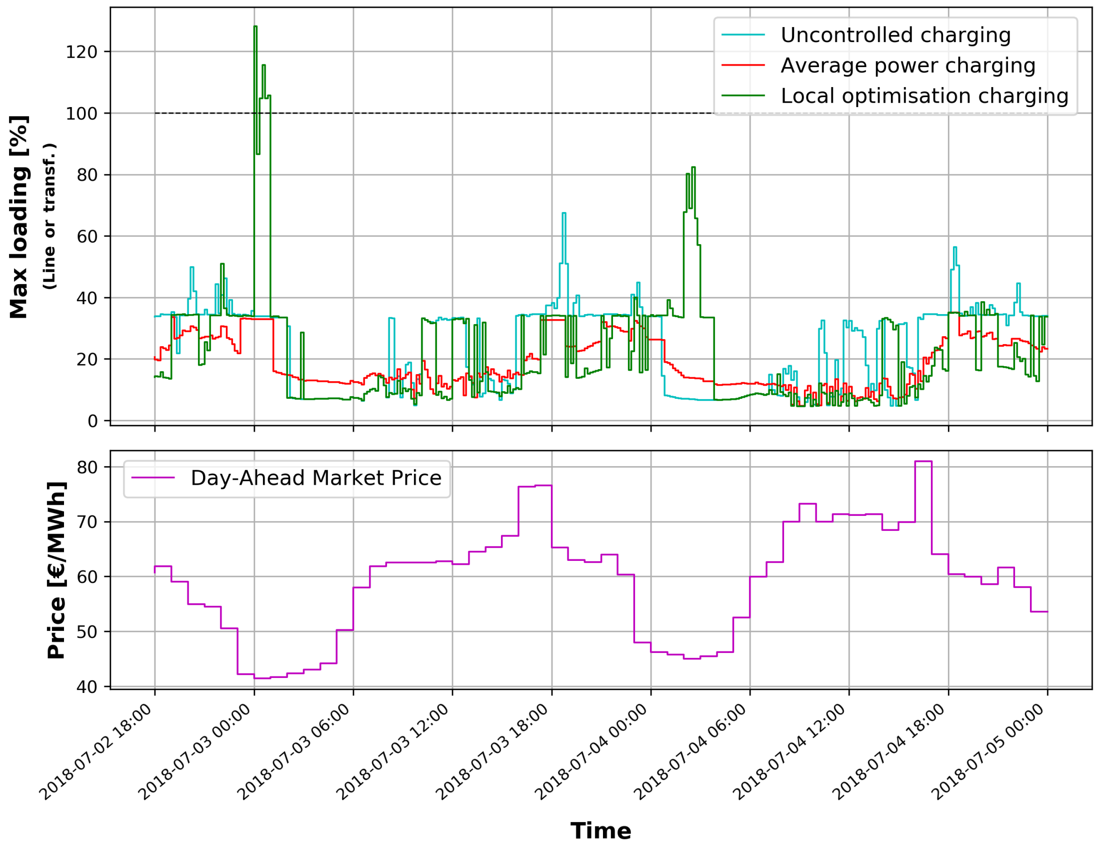


Figure 7.10: Comparison of the maximum loading percentage of lines and transformer of the 3 different strategies on *Rural Grid*, Summer Scenario, EV penetration: 80% (Period: 02/07/2018, 00:00 - 08/07/2018, 23:50; Time-step: 10 min). Only 2 days are shown.

and, therefore, the complete lack of coordination between the nodes, inevitably leads to mediocre results. In particular, they led in this case to overloading issues.

The uncontrolled charging scenario confirmed instead the expected results of registering the highest load peaks around 18:00 - 19:00. It was positive, though, to observe that those peaks did not exceed the technical limits of the grid. Finally, the average power charging scheme led to a very smooth behaviour where no significant peaks in the loading were registered. All information regarding peaks and root mean square values for the two scenarios are reported in tables 7.4 and 7.5.

The overall energy given to the EVs throughout the whole week is not reported in the tables, but it lies around 4696 kWh for all the scenarios, as all of them were simulated using the exact same EV behaviour. However, some small differences between these values were registered due to the slightly different approximations on the calculations executed for the 3 different strategies. Nevertheless, these differences never exceeded the 0.01%.

On the third column of the two tables, the percentage of the energy given to the EVs coming from PVs is reported. This indicates the energy that from the photovoltaic panels was directly fed into the charging stations out of the total energy received by the EVs.

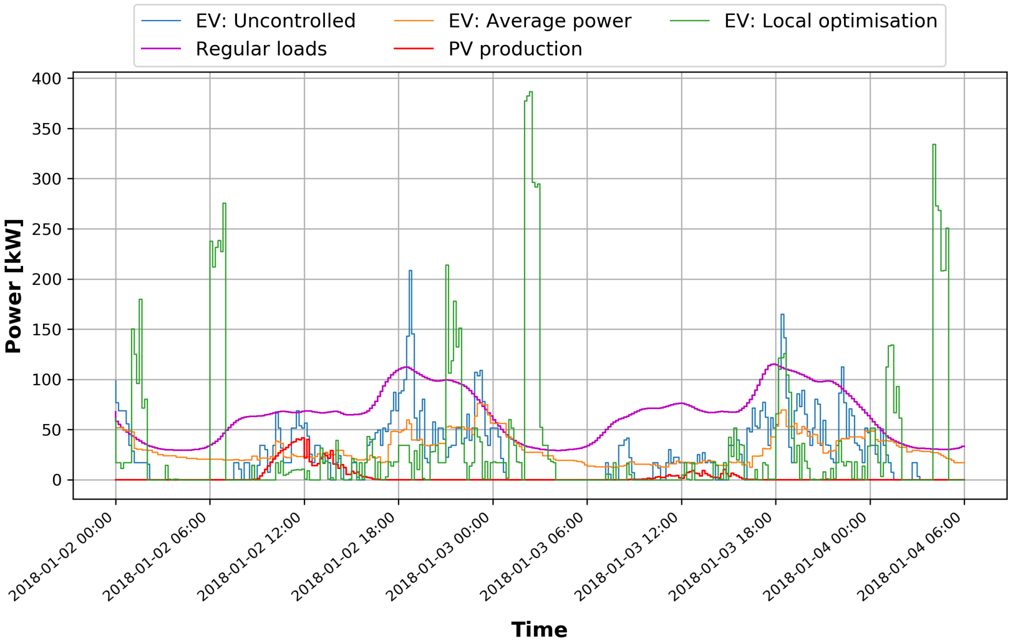


Figure 7.11: Comparison of power of the 3 different strategies on *Rural Grid*, Winter Scenario, EV penetration: 80% (Period: 01/01/2018, 00:00 - 07/01/2018, 23:50; Time-step: 10 min). Only 2 days are shown.

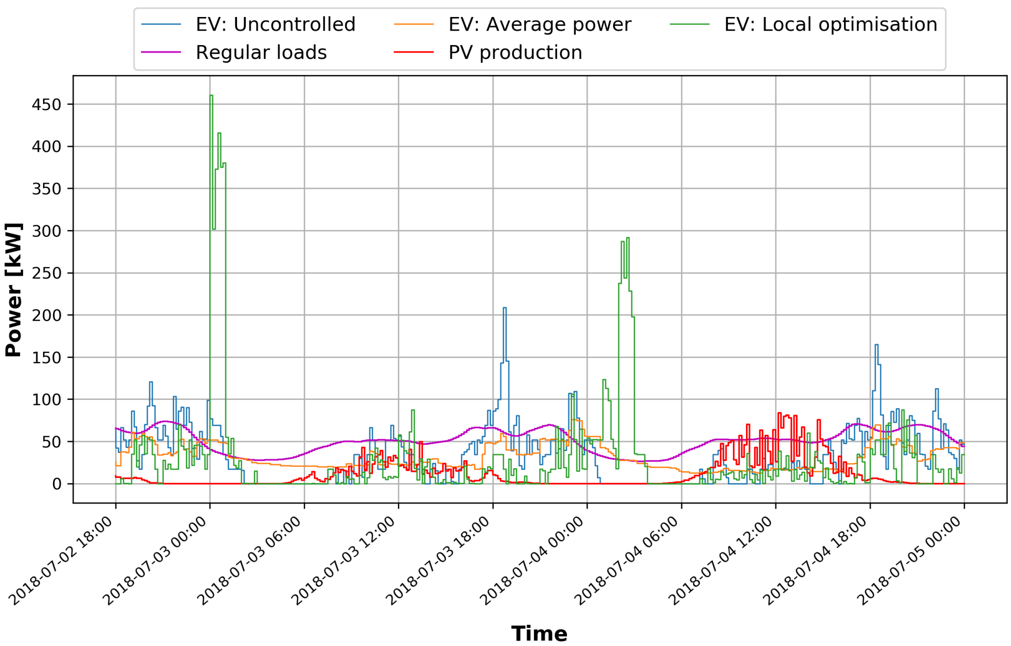


Figure 7.12: Comparison of power of the 3 different strategies on *Rural Grid*, Summer Scenario, EV penetration: 80% (Period: 02/07/2018, 00:00 - 08/07/2018, 23:50; Time-step: 10 min). Only 2 days are shown.

As it can be immediately noticed, the difference between the winter and the summer scenario is very significant. This, of course, is due to the higher solar irradiation that is in general registered during the summer. However, it is also important to notice another detail in this same column: the highest amount of solar energy is used in the average power charging scenario and not in the local optimisation one, as one would expect. The reason of this result is one of the constraints set for the optimisation analysis. To avoid an ever-changing behaviour, that could in general affect the EVs' battery, a lower limit to the charging power was given. This led the electric vehicles not to use the PV power when that was too low.

As far as the PV energy is concerned, there is one last aspect that needs to be mentioned, namely the assumption that the energy produced by the PV panels is given to the EVs only if there is a surplus in generation. In fact, as already specified in section 3.2, the regular loads connected at the same node have priority in receiving that power. This assumption significantly limited the solar power utilisation obtained with the *local optimisation* scheme. Nevertheless, it is still possible to observe a higher concentration of EV charging processes in case of high solar production. The time-period around "2018-07-04 12:00" (in figure 7.12) shows a very high solar production with respect to the time-period around "2018-01-03 12:00" (in figure 7.11). From the same figures it is also possible to see how this translates into a higher concentration of EV charging operations in the *local optimisation* scheme. This effect can be directly associated to the PV panels for two reasons. First, both those days are Wednesdays, which means that the EV behaviour simulated is the same in the two cases (see section 6.2). Second, as it is possible to see in figures 7.10 and 7.9, both those periods are characterised by high market prices.

Finally, the last two columns of the tables report the price per 10 kWh in two different perspectives. The first column indicates the average price in case the whole amount of energy was purchased and taken from the grid, while the second column distinguishes the power taken directly from the PV panels, that was assumed to be taken for free.

According to those numbers, there is a quite significant difference in average price between the different cases and, as expected, the uncontrolled charging is the strategy with the highest price, while the local optimisation strategy led to the cheapest one. The prices registered for the average power charging scheme lie almost exactly in the middle between them. In the summer scenario, it is also possible to see a very relevant difference between the average price registered with or without considering the PV contribution. In particular, the local optimisation scheme tried to exploit PV power as much as possible, while the average power charging scheme 'naturally' did that, as there always were EVs connected asking for little power that could, therefore, be taken from PVs.

From the results of this analysis, it seems that the average power charging scheme leads to the overall best results. As a matter of fact, the price is an acceptable trade-off between the 2 extremes registered in the uncontrolled and in the local optimisation cases. Furthermore, as it can be seen by comparing the peak and RMS values, it is also the case with the lowest loading percentages registered. These reasons, along with the fact that it needs very little information to be implemented, make this strategy a good choice for a higher and safer integration of EVs in the network.

| | Peak value max loading [%] (Transformer or line) | RMS max loading [%] (Transformer or line) | Total EV energy from PV [%] | Avg charging price [€/10 kWh] | Avg charging price (PV included) [€/10 kWh] |
|---|---|---|---|---|---|
| **Uncontrolled charging** | 81.16 | 29.58 | 0.06 | 0.399 | 0.399 |
| **Average power charging** | 45.87 | 25.17 | 0.44 | 0.354 | 0.352 |
| **Local optimisation charging** | 107.61 | 29.50 | 0.31 | 0.274 | 0.273 |

Table 7.4: Main results of the simulation of *Rural Grid*, Winter Scenario, EV penetration: 80% (Period: 01/01/2018, 00:00 - 07/01/2018, 23:50; Time-step: 10 min)

| | Peak value max loading [%] (Transformer or line) | RMS max loading [%] (Transformer or line) | Total EV energy from PV [%] | Avg charging price [€/10 kWh] | Avg charging price (PV included) [€/10 kWh] |
|---|---|---|---|---|---|
| **Uncontrolled charging** | 67.44 | 25.58 | 0.82 | 0.583 | 0.578 |
| **Average power charging** | 36.07 | 17.76 | 10.83 | 0.547 | 0.490 |
| **Local optimisation charging** | 128.20 | 25.68 | 9.06 | 0.478 | 0.429 |

Table 7.5: Main results of the simulation of *Rural Grid*, Summer Scenario, EV penetration: 80% (Period: 02/07/2018, 00:00 - 08/07/2018, 23:50; Time-step: 10 min)

## 7.3 Coordination with a central unit

One of the most interesting aspects of the previous section is the high difference in price between the different charging schemes. On the other hand, this very relevant difference also came with high loading percentages caused by the complete lack of coordination between the different charging stations. From the results observed in the previous sections it is clear that the electrical network would benefit a great deal from the installation of a power control mechanism ensuring that the grid constraints are always fulfilled. The logic that this mechanism should follow and more details on how it was built up are better described in chapter 5. This section is used instead to evaluate the effects of its implementation.

### 7.3.1 Coordination with ECM

In this first subsection the effects of the Equal Percentage Method (ECM) are observed. Figure 7.13 shows the result of a simulation run on the winter scenario, in case of uncontrolled charging, where the maximum loading percentage allowed (of both lines and transformers) was set to to 60%. Naturally, such a strict limit would hardly be used in real networks and this simulation was only intended to test the operation of the curtailment scheme.

Considering the grid constraints only, the results were excellent, as the mechanism

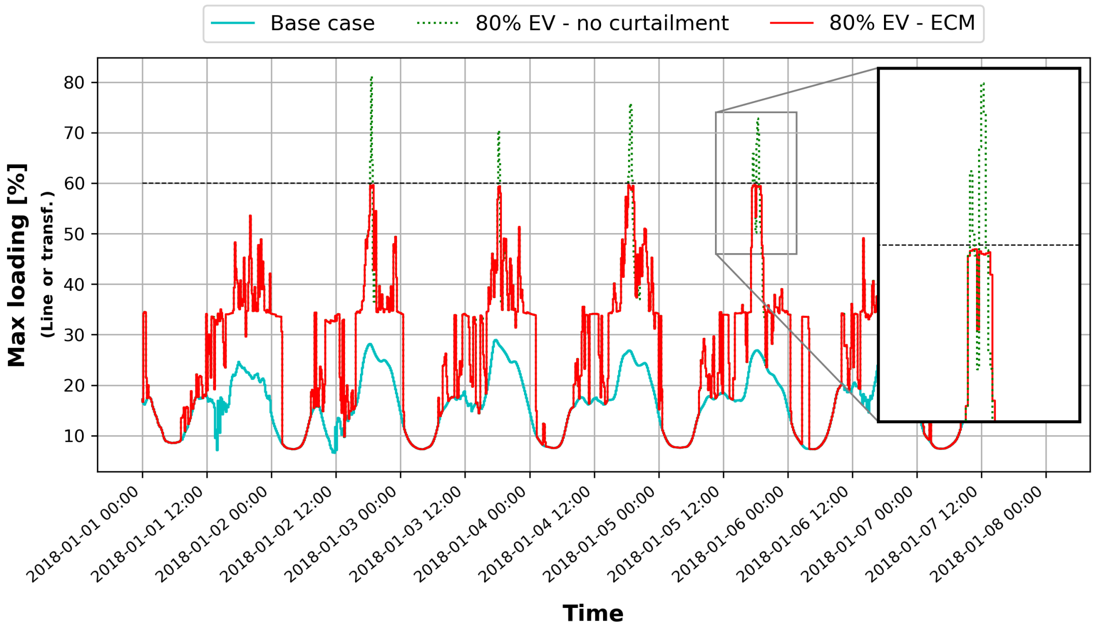


Figure 7.13: Test of implementation of ECM on *Rural Grid*, Winter Scenario, Uncontrolled Charging, EV penetration: 80%, Set loading limit: 60% (Period: 01/01/2018, 00:00 - 07/01/2018, 23:50; Time-step: 10 min)

proved to be correctly implemented and forced the grid to operate within the new set limit. From the EV side instead, a few remarks need to be made. Anytime an EV charging process was curtailed, this was re-scheduled according to the logic described in section 5.5.2. In theory, this causes only a postponement of the charging process. However, this does not always hold true, as if the parking time is limited, the EVs could leave without having received the desired energy. This is exactly what happened in the tested scenario where a total amount of 3.6 kWh was failed to be provided in four different charging processes. Considering that the whole energy provided during the week was 4696 kWh, the successful charging percentage is 99.92%. This of course represents an economical loss as well – although small – because it is likely a penalty to be paid would be introduced in these cases.

Figure 7.14 instead shows the result of the implementation of the ECM on *Urban Grid* when operated radially. In this case the upper loading limit for both lines and transformers was set to 90%. The total energy that was failed to be provided to the EVs is 6.7 kWh out of the total 3050.3 kWh asked. Therefore, this leads to a successful charging percentage of 99.78%.

When the same grid was operated in a (slightly) meshed configuration, by keeping the three switches '331848940', '331842504' and '331847842' closed, different results were obtained. In fact, the successful charging percentage is now of 99.92%, being the overall energy failed to be provided of only 2.5 kWh. A small difference in the loading evolution can be observed by comparing figure 7.14 with figure 7.15. This last simulation proved in particular that the curtailment scheme can be also applied to meshed grids.

A failure in some of the charging processes was also registered when the ECM was

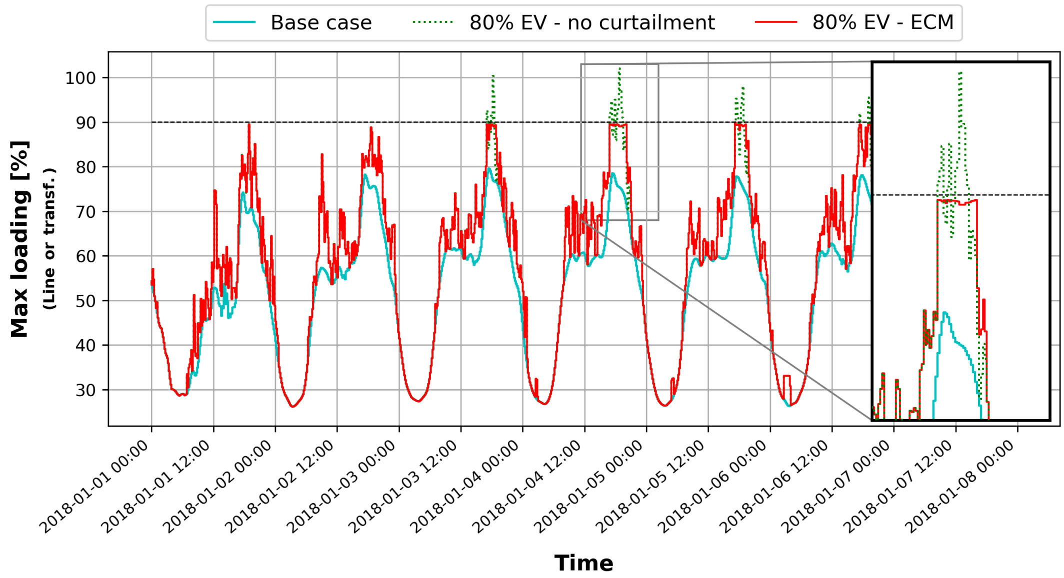


Figure 7.14: Test of implementation of ECM on *Urban Grid*, Winter Scenario, Uncontrolled Charging, radial operation (switches '331848940', '331842504' and '331847842' open), EV penetration: 80%, Set loading limit: 90% (Period: 01/01/2018, 00:00 - 07/01/2018, 23:50; Time-step: 10 min)

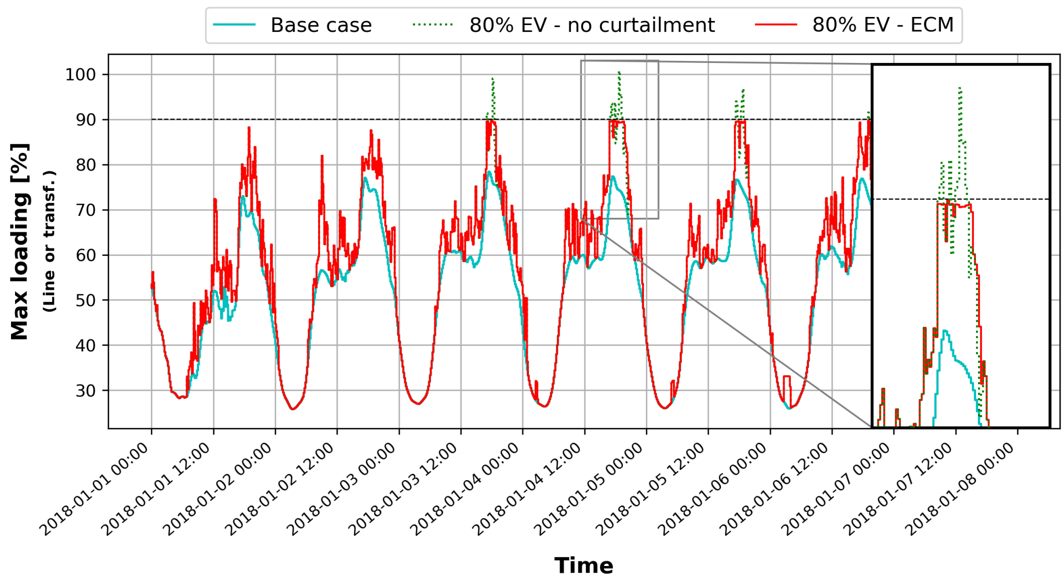


Figure 7.15: Test of implementation of ECM on *Urban Grid*, Winter Scenario, Uncontrolled Charging, meshed operation (switches '331848940', '331842504' and '331847842' closed), EV penetration: 80%, Set loading limit: 90% (Period: 01/01/2018, 00:00 - 07/01/2018, 23:50; Time-step: 10 min)

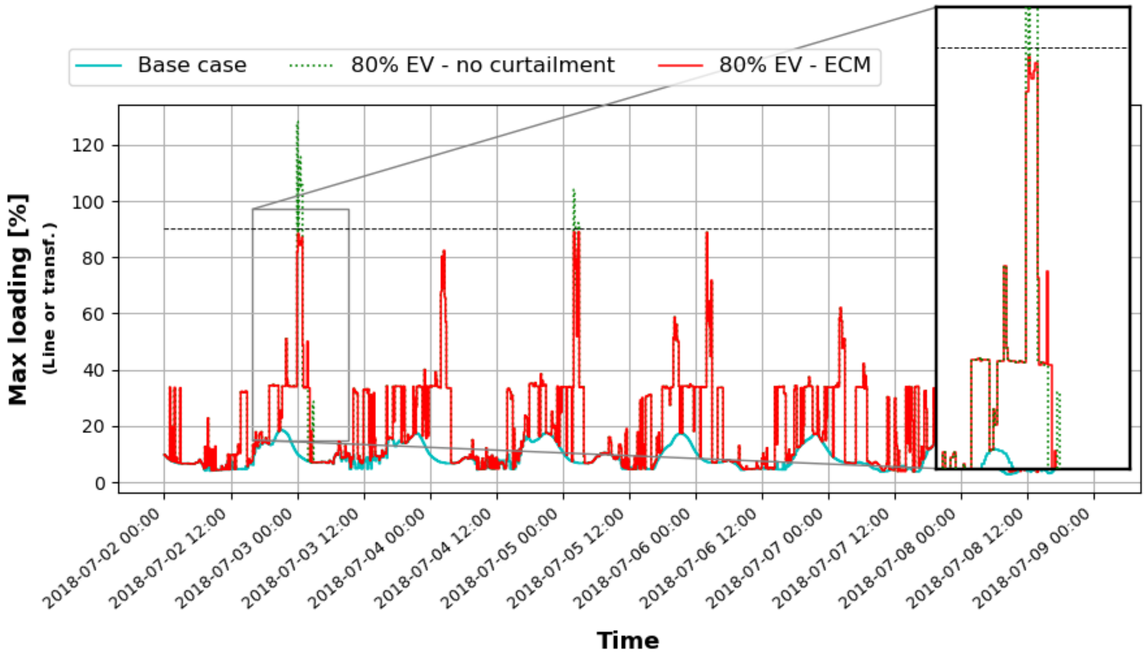


Figure 7.16: Test of implementation of ECM on *Rural Grid*, Summer Scenario, Local Optimisation Charging, EV penetration: 80%, Set loading limit: 90% (Period: 02/07/2018, 00:00 - 08/07/2018, 23:50; Time-step: 10 min)

tested with a local optimisation charging strategy implemented at the nodes. As explained in section 5.5.2, in this case the rescheduling operation is carried out by means of new optimisation analyses.

This test was run on the summer scenario of *Rural Grid* and the maximum loading percentages (of either lines or transformers) at each moment of time are shown in figure 7.16. As it can be seen, the curtailing mechanism worked perfectly in this case too, as the set limit of 90% was always respected. The energy that was failed to be provided amounts to approximately 11.3 kWh (out of 4696 kWh). Therefore, the successful charging percentage of this test is 99.76%.

Some differences between the two mechanisms shown in figures 7.13, 7.14 and 7.15 on one side and figure 7.16 on the other side can be observed by means of their zoomed sections. In the last mentioned graph it is possible to see a sudden loading spike (that was not present in the non-curtailed case) occurring a few time-steps after the curtailment process had taken place. This formed as a result of the new optimisation analyses carried out at the nodes. Similar sudden spikes cannot form in case of uncontrolled charging, as the rescheduling process postpones all the charging processes to the time-steps immediately after the curtailment operation.

Finally, it is important to highlight why all these successful charging percentages below 100% are obtained. In fact, it is reasonable to imagine that a better planning of the EV operations by the CC could lead to better results. However, such an operation comes with many difficulties. The first one is that, on the contrary of regular loads behaviour and solar power forecasts, that are assumed to be known with 100% accuracy, the CC does not have any information regarding the EVs before they connect to the chargers.

This means that it is not possible to include into the local optimisation analyses the behaviour of EVs that are not connected yet to the grid. A possible way to solve this would be to implement a first-come-first-served logic, where the EVs that arrive later are not allowed to schedule charging operations at already very "busy" moments. In this case, though, a huge amount of data and calculations would be needed, as it would be necessary to check the effect of each new EV on every element of the grid at all moments of time. On top of that, a first-come-first-served logic also inevitably leads to fairness problems. In alternative, another possibility would be to carry out a new optimisation analysis at all nodes any time a new EV connects anywhere in the grid. However, in this case the amount of calculations needed would increase exponentially. Therefore, in order to solve the problem, it was decided to implement instead a smarter curtailment strategy (see section 5.6). The result of its implementation are shown in the next section.

### 7.3.2 Coordination with FCM

The last aspect considered in this work concerns the different results that could be obtained by using different curtailing mechanisms. In the previous section it was highlighted how the ECM brought to the desired results in terms of grid constraints, but also that there was a percentage of electric vehicles that left the charging station before receiving the desired amount of energy. That happened because among the vehicles that got curtailed were some urgently needing power, as their departure time was close. In fact, one of the main disadvantages of the ECM, as explained in section 5.6.1, is that the method does not consider the flexibility of the charging stations, namely how urgently they need the power they are asking for. Therefore, the purpose of the FCM is to consider this flexibility before curtailing the different charging stations.

To observe the effects of the FCM, this method was tested on the same scenario of figure 7.16. A difference between the application of the two schemes (ECM and FCM) can be observed in figure 7.17, where it is possible to see a slightly different evolution of the loading and the power profiles. These differences are caused by the fact that different EVs were curtailed in the two scenarios. In fact, in the FCM scenario the EVs with a high priority factor kept on receiving all the power they were asking. The effects of this different strategy can be fully appreciated by considering that the successful charging percentage in the FCM case is 100%, against the 99.76% of the ECM case.

A similar analysis was also made for the scenario of figure 7.14. Similarly to the test run on *Rural Grid*, the successful charging percentage increased from 99.78% (ECM case) to 100% (FCM case).

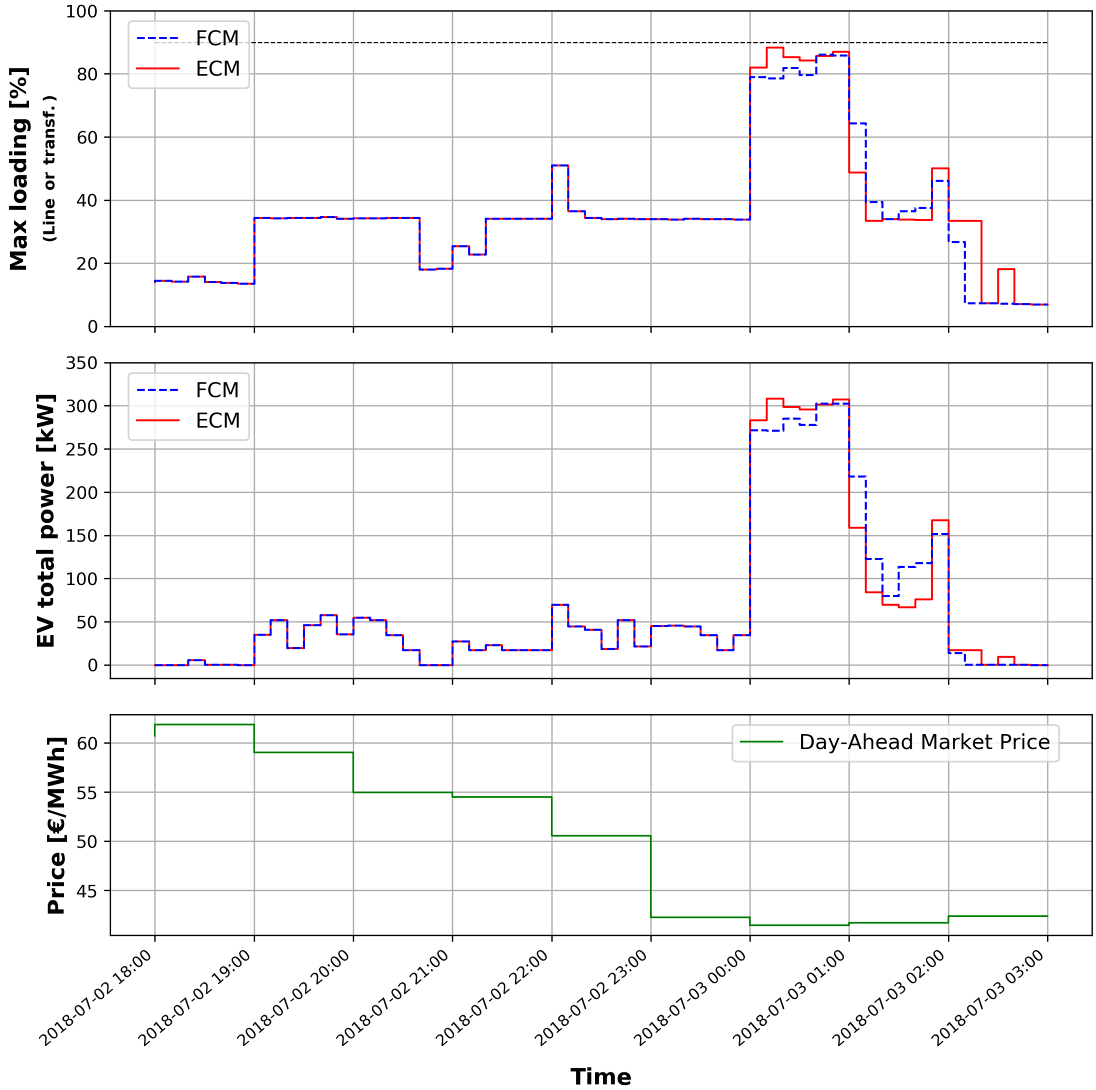


Figure 7.17: Comparison of ECM and FCM on *Rural Grid*, Summer Scenario, Local Optimisation Charging, EV penetration: 80%, Set loading limit: 90% (Period: 02/07/2018, 00:00 - 08/07/2018, 23:50; Time-step: 10 min). Only 9 hours are shown.

# 8 Conclusions and recommendations

The purpose of this study is to analyse and compare some of the possible strategies that can be used to ease a higher penetration of electric vehicles in the grid. These different strategies were tested on several scenarios to delineate some of the most important aspects involved, such as the respect of the grid constraints and the price of the charging processes.

The chapter is divided into two parts: section 8.1, where the main conclusions of this thesis are reported, and section 8.2, where it is possible to find some relevant recommendations for further research.

## 8.1 Conclusions

On the basis of the results described in the previous chapter, it is now possible to answer to all those questions that were posed in chapter 1.

1. *To what extent are grids affected by higher EV penetrations?*

   As it was already expected, the impact of a higher EV penetration on a distribution grid is huge. However, the effects that are registered seem to depend a great deal on the topology of the examined network. This is mainly due to the different average number of cars per household. In fact, when tested with the same high EV penetration level of 80%, *Urban Grid* registered an increase in its peak transformer loading of almost 23%, while *Rural Grid* showed an increase of the same parameter of more than 50%.

   To further support this, the results obtained for *Sub-urban Grid* – although strictly qualitative – seem to suggest an even more serious impact of the electric vehicles on the network. This is not unexpected, as this topology of grid has a large average number of cars per household and a very dense concentration of loads.

   There are two other aspects that are noteworthy. First, one of the main reasons why *Rural Grid* did not show overloading situations was the fact that it was operating very far from its technical limits before the introduction of any EV. Clearly, this is not always the case. Second, a lower impact of the EVs on the lines with respect to the transformers is a very positive phenomenon in rural grids like the tested one. As a matter of fact, the typical topology of these networks is strictly radial and, therefore, does not allow load balancing operations to prevent possible overloads in the system

2. *How and to what extent does a smart charging scheme affect the grid with respect to uncontrolled charging?*

   The almost universal use of the *uncontrolled charging* scheme at the charging stations is due to its incredible technical and practical simplicity. Nevertheless, the results of the simulations proved that high peaks of power demand - and therefore of both lines and transformers loading - are inevitable. These are always concentrated at already very busy moments of the day, usually at around 18:00/19:00.

   Interestingly, the *local optimisation charging* scheme led to more severe concentrations of the power demand, although at a different time. In fact, all charging stations tried to postpone their charging operations to very low price moments at night, leading to overloading issues even in grids that were considered safe when operating with the *uncontrolled charging* scheme. The *average power charging* scheme, instead, showed the lowest loading percentages of all the three studied strategies.

   Another significant difference between the three schemes is in the average charging price. As expected, the *uncontrolled charging* strategy led to the highest price, while the *local optimisation charging* strategy to the lowest one. In the simulated scenarios the difference in the average charging price between these two schemes reached outstanding percentages of around 30%. The price of the *average power charging* strategy lies approximately in the middle between the other two schemes.

   Finally, it is important to highlight how the *local optimisation charging* scheme always tried to optimise the use of power from PVs. The relevance of this contribution can be fully appreciated observing the results of the simulated summer scenario, where the energy taken from the solar panels reached values more than 10 times the ones registered in the *uncontrolled charging* simulations. In this regard, also the *average power charging* strategy showed high solar utilisation percentages. In fact, this scheme "naturally" exploits solar energy, as there always are EVs connected asking for little power that can, therefore, be taken from PVs.

3. *Can a local control strategy coordinate with a central curtailment scheme to efficiently solve overloading situations occurring in the grid?*

   Both the implementation of the *uncontrolled charging* scheme and of the *local optimisation charging* scheme led to the expected result of recurrent overloading issues in the grid. The main reason for them was the complete lack of coordination between the single charging stations. Once this coordination was introduced by means of the ECM, though, the grids started operating again within the allowed limits.

   However, this practice showed in the simulations two of the foreseen main limits: higher percentages of EV dissatisfaction in case of grids operating close to their technical limits – as it was natural to expect – and a tendency of this percentage to increase when the *local optimisation charging* scheme was implemented. This second effect in particular was caused by the high concentrations of EV power demand and the fact that some EVs postponed their charging process until the very last moment – for cost reasons – without being able to carry it out because they got curtailed.

In this regard, the simulations showed that better results can be obtained when implementing a smarter curtailment scheme. When tested on the same scenarios, the ECM and the FCM led to different successful charging percentages of 99.76% (or 99.78%) and 100%, respectively. This means that the implementation of curtailment methods that consider the 'flexibility' of the charging stations before taking any action might be a substantial contribution for a smooth introduction process of electric vehicles in society.

## 8.2 Future research

As specified in the first chapters, the main focus of this work is on the analysis of possible overloads that could arise from the introduction of a higher number of electric vehicles in the network. However, the problems encountered while analysing *Sub-urban Grid* did not allow to obtain quantitative information on that grid, but only qualitative results. These showed that the impact on this topology of network is potentially huge. Therefore, it is imperative to further analyse this missing grid topology in order to get a complete image of the impact that EVs may have on distribution grids.

Another aspect that may be relevant for future studies is represented by the possible presence of voltage issues as well. In this regard, the brief analysis carried out for the purpose showed very frequent sudden drops of the voltage. Although not exceeding the technical limits, those drops are quite significant and, being the voltage variations very steep, the grid could suffer from their presence. Should this turn out to represent a serious problem, an EV curtailment mechanism for under voltage issues could also be considered. In this case, though, particular attention should be paid to the topic of fairness towards the users. In fact, the distance of a node from the upper transformer is a crucial aspect when it comes to voltage issues. Therefore, the idea of solving under voltage problems by mainly curtailing the nodes farther from the transformer could in general be tempting. Naturally, this would be unfair towards all those nodes, as they would always be the ones to get curtailed first.

Other possible topics that might be of interest are the possibility to include errors in the PV production and load forecasts, the introduction of single-phase loads in the model (to evaluate the effect of a possible unbalanced network) and the simulations of the loads by means of more sophisticated models to include their dependence on the voltage. All these aspects would add further details to the grid modelling and would therefore guarantee more accurate results.

Finally, it would be wise in any future research to keep in closer contact with all the companies that are interested or involved in the project. This aspect is particularly important as it seems DSOs have a modus operandi which is not often reported in books. This aspect, along with all the information and data they posses, makes a higher involvement from their side a crucial point to get relevant results in shorter times. Therefore, a closer collaboration with them may be a substantial point to consider in future studies.

# *Bibliography*


[1] International Energy Agency, "Global ev outlook 2019," tech. rep., 2019.

[2] Netherlands Enterprise Agency, "Statistics electric vehicles in the netherlands (up to and including february 2019)," tech. rep., Netherlands Enterprise Agency (RVO.nl), 2019. Commissioned by the Ministry of Infrastructure and Water Management.

[3] S. Paudyal and G. R. Bharati, "Hierarchical approach for optimal operation of distribution grid and electric vehicles," in *2015 IEEE Eindhoven PowerTech*, pp. 1–6, 2015.

[4] Y. Yu and L. Felix, "Orchestrating smart charging in mass deployment (OSCD) - D2.1 scenario definition and simulation description," 2019.

[5] IEEE.org, "IEEE standard for the specification of microgrid controllers," 2017. IEEE 2030.7-2017.

[6] Collinsdictionary.com. [Online], https://www.collinsdictionary.com/dictionary/english/electric-vehicle, 2019. [Accessed: 2020-05-15].

[7] S. Cutcliffe and D. Kirsch, "The electric vehicle and the burden of history," *Environmental History*, vol. 6, p. 326, 04 2001.

[8] APCO Worldwid, "China's 5-year plan," tech. rep., 2010.

[9] J. McCurry, "Japan now has more electric car charge points than petrol stations," *The Guardian*, 2016.

[10] International Energy Agency, "Global ev outlook2016 - beyond one million electric cars," tech. rep., 2016.

[11] D. A. Chekired, L. Khoukhi, and H. T. Mouftah, "Queuing model for evs energy management: Load balancing algorithms based on decentralized fog architecture," *2018 IEEE International Conference on Communications (ICC)*, pp. 1–6, 2018.

[12] S. Deilami, A. S. Masoum, P. S. Moses, and M. A. S. Masoum, "Real-time coordination of plug-in electric vehicle charging in smart grids to minimize power losses and improve voltage profile," *IEEE Transactions on Smart Grid*, vol. 2, no. 3, pp. 456–467, 2011.

[13] Netherlands Enterprise Agency, "Electric transport in the netherlands - 2018 highlights," tech. rep., 2019. Commissioned by the Ministry of Infrastructure and Water Management.

[14] People's Party for Freedom and Democracy (VVD), Christian Democratic Alliance (CDA), Democrats '66 (D66) and Christian Union (CU), "Coalition agreement 'confidence in the future'," tech. rep., Government of the Netherlands, 2017.

[15] Netherlands Enterprise Agency, "Mission zero - powered by holland," tech. rep., 2019. Commissioned by the Ministry of Infrastructure and Water Management.

[16] Belastingdienst Nederland, "Motorrijtuigenbelasting." [Online], https://www.belastingdienst.nl/wps/wcm/connect/bldcontentnl/belastingdienst/prive/auto_en_vervoer/belastingen_op_auto_en_motor/motorrijtuigenbelasting/, 2019. [Accessed: 2020-02-13].

[17] Belastingdienst Nederland, "Calculate and pay bpm." [Online], https://www.belastingdienst.nl/wps/wcm/connect/bldcontenten/belastingdienst/individuals/cars/bpm/calculate_and_pay_bpm/, 2019. [Accessed: 2020-02-13].

[18] E. Veldman and R. A. Verzijlbergh, "Distribution grid impacts of smart electric vehicle charging from different perspectives," *IEEE Transactions on Smart Grid*, vol. 6, no. 1, pp. 333–342, 2015.

[19] M. Zhang and J. Chen, "The energy management and optimized operation of electric vehicles based on microgrid," *IEEE Transactions on Power Delivery*, vol. 29, no. 3, pp. 1427–1435, 2014.

[20] F. Un-Noor, P. Sanjeevikumar, L. Mihet-Popa, M. Mollah, and E. Hossain, "A comprehensive study of key electric vehicle (ev) components, technologies, challenges, impacts, and future direction of development," *Energies*, vol. 10, 07 2017.

[21] S. Deb, K. Tammi, K. Kalita, and P. Mahanta, "Impact of electric vehicle charging station load on distribution network," *Energies*, vol. 11, 1 2018.

[22] S. Deb, K. Kalita, and P. Mahanta, "Review of impact of electric vehicle charging station on the power grid," pp. 1–6, 12 2017.

[23] R. Shi, X. P. Zhang, D. C. Kong, N. Deng, and P. Y. Wang, "Dynamic impacts of fast-charging stations for electric vehicles on active distribution networks," in *IEEE PES Innovative Smart Grid Technologies*, pp. 1–6, 2012.

[24] C. Dharmakeerthi, M. Nadarajah, and T. Saha, "Overview of the impacts of plug-in electric vehicles on the power grid," 11 2011.

[25] C. Roe, E. Farantatos, J. Meisel, A. P. Meliopoulos, and T. Overbye, "Power system level impacts of phevs," pp. 1–10, 2009.

[26] A. Hilshey, P. Hines, P. Rezai, and J. Dowds, "Estimating the impact of electric vehicle smart charging on distribution transformer aging," *IEEE Transactions on Smart Grid*, vol. 4, pp. 905–912, 06 2013.

[27] A. Beltramo, A. Julea, N. Refa, Y. Drossinos, C. Thiel, and S. Quoilin, "Using electric vehicles as flexible resource in power systems: A case study in the netherlands," *2017 14th International Conference on the European Energy Market (EEM)*, pp. 1–6, 2017.

[28] K. Qian, C. Zhou, M. Allan, and Y. Yuan, “Modeling of load demand due to ev battery charging in distribution systems,” *IEEE Transactions on Power Systems*, vol. 26, no. 2, pp. 802–810, 2011.

[29] M. van Amstel, *Flexibility system design for electric vehicles: performing congestion management for the DSO*. PhD thesis, University of Twente, Netherlands, 12 2018.

[30] D. Wang, X. Guan, J. Wu, P. Li, P. Zan, and H. Xu, “Integrated energy exchange scheduling for multimicrogrid system with electric vehicles,” *IEEE Transactions on Smart Grid*, vol. 7, no. 4, pp. 1762–1774, 2016.

[31] C. Ahn, C.-T. Li, and H. Peng, “Optimal decentralized charging control algorithm for electrified vehicles connected to smart grid,” *Journal of Power Sources*, vol. 196, no. 23, pp. 10369 – 10379, 2011.

[32] S. V. Oprea, A. Bâra, and G. Ifrim, “Flattening the electricity consumption peak and reducing the electricity payment for residential consumers in the context of smart grid by means of shifting optimization algorithm,” *Computers & Industrial Engineering*, vol. 122, pp. 125 – 139, 2018.

[33] J. Vorrink, C. Timmerman, and C. Schneiders, “The successful stress test of europe’s power grid – more ahead,” tech. rep., 2015.

[34] StatLine.cbs.nl, “Zonnestroom; vermogen bedrijven en woningen, regio (indeling 2018).” [Online], https://opendata.cbs.nl/statline/#/CBS/nl/dataset/84518NED/table?ts=1581491112239, 2019. [Accessed: 2020-01-24].

[35] J. A. Lopes, F. Soares, P. Almeida, and M. Moreira da Silva, “Smart charging strategies for electric vehicles: Enhancing grid performance and maximizing the use of variable renewable energy resources,” 01 2009.

[36] M. Nour, A. Ali, and C. Farkas, “Evaluation of electric vehicles charging impacts on a real low voltage grid,” vol. 9, 04 2018.

[37] J. Saldanha, E. Santos, A. Mello, and D. Bernardon, *Control Strategies for Smart Charging and Discharging of Plug- In Electric Vehicles*. 12 2016.

[38] M. Mueller, F. Samweber, and P. Leidl, *Impact of different charging strategies for electric vehicles on their grid integration*, pp. 41–55. 09 2017.

[39] C. Srithapon, P. Ghosh, A. Siritaratiwat, and R. Chatthaworn, “Optimization of electric vehicle charging scheduling in urban village networks considering energy arbitrage and distribution cost,” *Energies*, vol. 13, p. 349, 01 2020.

[40] F. D. Graaf, “New strategies for smart integrated decentralised energy systems,” tech. rep., Metabolic, 2018.

[41] E. Ng and R. El-Shatshat, “Multi-microgrid control systems (mmcs),” pp. 1 – 6, 08 2010.

[42] W. Lee, J. Choi, and D. Won, "Coordination strategy for optimal scheduling of multiple microgrids based on hierarchical system," *Energies*, vol. 10, p. 1336, 09 2017.

[43] B. Zhao, X. Wang, D. Lin, M. M. Calvin, J. C. Morgan, R. Qin, and C. Wang, "Energy management of multiple microgrids based on a system of systems architecture," *IEEE Transactions on Power Systems*, vol. 33, no. 6, pp. 6410–6421, 2018.

[44] T. Rui, G. Li, Q. Wang, C. Hu, W. Shen, and B. Xu, "Hierarchical optimization method for energy scheduling of multiple microgrids," *Applied Sciences*, vol. 9, p. 624, 02 2019.

[45] L. Che, M. Shahidehpour, A. Alabdulwahab, and Y. Al-Turki, "Hierarchical coordination of a community microgrid with ac and dc microgrids," *IEEE Transactions on Smart Grid*, vol. 6, 03 2015.

[46] European Parliament, "Directive 2012/27/eu of the european parliament and of the council of 25 october 2012 on energy efficiency." Official Journal of the European Union, 2012.

[47] M. Mohiti, H. Monsef, and H. Lesani, "A decentralized robust model for coordinated operation of smart distribution network and electric vehicle aggregators," *International Journal of Electrical Power & Energy Systems*, vol. 104, pp. 853 – 867, 2019.

[48] J. C. Mukherjee and A. Gupta, "Distributed charge scheduling of plug-in electric vehicles using inter-aggregator collaboration," *IEEE Transactions on Smart Grid*, vol. 8, no. 1, pp. 331–341, 2017.

[49] F. Xia, H. Chen, L. Chen, and X. Qin, "A hierarchical navigation strategy of ev fast charging based on dynamic scene," *IEEE Access*, vol. 7, pp. 29173–29184, 2019.

[50] R. Tang, S. Wang, and C. Yan, "A direct load control strategy of centralized air-conditioning systems for building fast demand response to urgent requests of smart grids," *Automation in Construction*, vol. 87, pp. 74–83, 12 2017.

[51] Overheid.nl, "Elektriciteitswet 1998." [Online], https://wetten.overheid.nl/BWBR0009755/2018-07-28, 1998. [Accessed: 2020-02-17].

[52] B. Hekkelman and H. la Poutré, "Fairness in smart grid congestion management," in *2019 IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe)*, pp. 1–5, 2019.

[53] N. Leemput, F. Geth, B. Claessens, J. Van Roy, R. Ponnette, and J. Driesen, "A case study of coordinated electric vehicle charging for peak shaving on a low voltage grid," pp. 1–7, 2012.

[54] K. N. Kumar, B. Sivaneasan, and P. L. So, "Impact of priority criteria on electric vehicle charge scheduling," *IEEE Transactions on Transportation Electrification*, vol. 1, no. 3, pp. 200–210, 2015.

[55] S. Alyami, Y. Wang, C. Wang, J. Zhao, and B. Zhao, "Adaptive real power capping method for fair overvoltage regulation of distribution networks with high penetration of pv systems," *IEEE Transactions on Smart Grid*, vol. 5, no. 6, pp. 2729–2738, 2014.

[56] N. Karthikeyan, B. R. Pokhrel, J. R. Pillai, and B. Bak-Jensen, "Coordinated voltage control of distributed pv inverters for voltage regulation in low voltage distribution networks," in *2017 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe)*, pp. 1–6, 2017.

[57] M. M. V. M. Ali, P. H. Nguyen, W. L. Kling, A. I. Chrysochos, T. A. Papadopoulos, and G. K. Papagiannis, "Fair power curtailment of distributed renewable energy sources to mitigate overvoltages in low-voltage networks," in *2015 IEEE Eindhoven PowerTech*, pp. 1–5, 2015.

[58] Liander.nl, "Compensatie na een storing." [Online], https://www.liander.nl/storingen/compensatie, 2020. [Accessed: 2020-03-04].

[59] M. E. Baran and F. F. Wu, "Network reconfiguration in distribution systems for loss reduction and load balancing," *IEEE Transactions on Power Delivery*, vol. 4, no. 2, pp. 1401–1407, 1989.

[60] Qin Zhou, D. Shirmohammadi, and W. . E. Liu, "Distribution feeder reconfiguration for service restoration and load balancing," *IEEE Transactions on Power Systems*, vol. 12, no. 2, pp. 724–729, 1997.

[61] I. Naharudinsyah and S. Limmer, "Optimal charging of electric vehicles with trading on the intraday electricity market," *Energies*, vol. 11, p. 1416, 06 2018.

[62] K. Gerrit, B. Nico, K. Mihail, M. Pierre, and B. Maximilian, "Market review 2017 - electricity market insights," tech. rep., TenneT, 2017.

[63] L. Gan, U. Topcu, and S. H. Low, "Optimal decentralized protocol for electric vehicle charging," *IEEE Transactions on Power Systems*, vol. 28, no. 2, pp. 940–951, 2013.

[64] O. Hafez and K. Bhattacharya, "Queuing analysis based pev load modeling considering battery charging behavior and their impact on distribution system operation," *IEEE Transactions on Smart Grid*, vol. 9, no. 1, pp. 261–273, 2018.

[65] S. Habib, M. Kamran, and U. Rashid, "Impact analysis of vehicle-to-grid technology and charging strategies of electric vehicles on distribution networks – a review," *Journal of Power Sources*, vol. 277, pp. 205 – 214, 2015.

[66] DIgSILENT Technical Staff, "Powerfactory 2019 - user manual." DIgSILENT, 2019.

[67] J. Schlabbach and K. Rofalski, *Power System Engineering : Planning, Design, and Operation of Power Systems and Equipment.* 07 2014.

[68] M. R. M. Cruz, D. Z. Fitiwi, S. F. Santos, and J. P. S. Catalão, "Meshed operation of distribution network systems: Enabling increased utilization of variable res power," in *2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I CPS Europe)*, pp. 1–6, 2018.

[69] M. R. M. Cruz, D. Z. Fitiwi, S. F. Santos, S. J. P. S. Mariano, and J. P. S. Catalão, "Prospects of a Meshed Electrical Distribution System Featuring Large-Scale Variable Renewable Power," *Energies*, vol. 11, no. 12, pp. 1–17, 2018.

[70] J. de Jong, "Elep: European local electricity production - workpackage 2: commercial & market plocy issues - deliverable 2.2," tech. rep., European Commission, 2006. Contract EIE/04/175/S07.38664.

[71] M. Forcan, M. Banjanin, and G. Vuković, "Advanced teaching method for balanced operations of overhead transmission lines based on simulations and experiment," *The International Journal of Electrical Engineering & Education*, vol. 55, no. 1, pp. 14–30, 2018.

[72] L. Sluis, *Transients in Power Systems.* Wiley, 01 2001.

[73] DIgSILENT Technical Staff, "Technical reference documentation - overhead line models - elmlne, typlne, typgeo, typtow." DIgSILENT, 2019.

[74] GUROBI Optimization Technical Staff, "Gurobi optimizer reference manual." GUROBI, 2018.

[75] ElaadNL, "Elaadnl open datasets for electric mobility research." [Online], https://platform.elaad.io/analyses/index.php?url=ElaadNL_opendata.php, 2019. [Accessed: 2020-12-03].

[76] NEDU.nl, "Profielen elektriciteit 2018." [Online], https://www.nedu.nl/documenten/verbruiksprofielen/, 2018. [Accessed: 2019-11-05].

[77] G. R. Chandra Mouli, P. Bauer, and M. Zeman, "System design for a solar powered electric vehicle charging station for workplaces," *Applied Energy*, vol. 168, pp. 434–443, 04 2016.

[78] P. J. Lagace, M. H. Vuong, and I. Kamwa, "Improving power flow convergence by newton raphson with a levenberg-marquardt method," in *2008 IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century*, pp. 1–6, 2008.

[79] Y. Yubin, W. Dan, C. Yong, and W. Zhiliang, "The effect of small impedance branches on the convergence of the newton raphson power flow," in *2008 Third International Conference on Electric Utility Deregulation and Restructuring and Power Technologies*, pp. 1141–1146, 2008.

[80] D. J. Tylavsky, P. E. Crouch, L. F. Jarriel, J. Singh, and R. Adapa, "The effects of precision and small impedance branches on power flow robustness," *IEEE Transactions on Power Systems*, vol. 9, no. 1, pp. 6–14, 1994.

[81] F. Gonzalez-Longatt and J. Rueda, *PowerFactory Applications for Power System Analysis.* Springer, 01 2015.

[82] S. Sairam, "Analysis of zip load modeling in power transmission system," *International Journal of Control and Automation*, vol. 11, pp. 11–24, 01 2018.

[83] S. Soman, S. Khaparde, and S. Pandit, *Computational Methods for Large Sparse Power Systems Analysis.* Springer-Verlag New York Inc, 01 2002.

[84] H. L. Willis, *Power Distribution Planning Reference Book.* CRC Press, 03 2004.

[85] S. Bhattacharyya, Z. Wang, J. Cobben, J. Myrzik, and W. Kling, “Analysis of power quality performance of the dutch medium and low voltage grids,” pp. 1 – 6, 11 2008.

[86] International Electrotechnical Commission (IEC), “IEC 60038:2009: IEC standard voltages,” 2009.

[87] M. Nijhuis, *Long-term planning of low voltage networks.* PhD thesis, Technische Universiteit Eindhoven, 2017.