Voltage Control Approach from Solar Photovoltaics with Battery Energy Storage System in Low Voltage Distribution Grid

AALBORG UNIVERSITY

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Synopsis:

The form of energy achievement is facing a change due to environmental concern. Nowadays, distributed generators specifically renewable energy sources are taking more relevance concerning energy production; wind turbine, solar photo-voltaic, among others. High penetration of these renewable energy sources may produce different electrical issues on the grid.

This project is focusing on the over-voltages that high penetration of solar photo-voltaic produce. For this purpose, a LV benchmark model is selected. In order to regulate the voltage, different voltage control methods are implemented. This project focuses on the voltage control methods by providing reactive power support (fixed power factor, Volt/VAr control method) or curtailing the active power.

A battery energy storage system is used for voltage regulation purposes, by store the over production of solar photo-voltaic energy and supply power when the load demand is higher than the solar photo-voltaics production. The results of all the different voltage control methods are displayed and discussed. Ending the report with a conclusion of the overall project.

Preface

This report has been made during the 4th semester on the Electrical Power Systems and High Voltage engineering MSc. programme at Aalborg University.

The individual chapters in the report are introduced and concluded with a section written in the *italic* font. Throughout the report there will be stated references all listed by the end of the paper in the Bibliography. The references are denounced cf. the Harvard method hence a statement will be referred by [Surname, year]. If more than one reference from the same year has the same author, these will be denoted with a, b, c and so forth. This reference refers to the bibliography where books are referred by author, title, ISBN-number, publisher, edition and year while websites are referred by author, title, year, URL and time of last visit. Technical papers are referred by author, title and year. If the source is added before a full stop it implies that it belongs to the contents of that sentence. However, if the source is added after a full stop, it covers the contents of the entire previous paragraph. A CD containing all Data, models, downloaded web pages and PDF references, is attached to the physical copy of the report.

Figures, tables and equations are numbered according to the particular chapter they're placed in. The first figure in chapter three will herefore be assigned with figurenumber 3.1 and the second 3.2 etc. Descriptive captions for tables and figures are found under relevant tables and figures.

DomAlSø

Dominique Alonso Sørensen

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I would like to thank to my family, they mean everything to me. My mother, she is always there when I need her. To my father who teach me that the hard work has always a reward. To my brother, as small brother, indirectly he taught me responsibility.

Write...

Contents

Nomenclature

Abbreviation	Description
AAU	Aalborg University
AC	Alternate Current
BESS	Battery Energy Storage System
BMS	Battery Manager System
DC	Direct Current
DG	Distributed Generator
DSO	Distributed System Operatior
DSL	DIgSilent Simulation Language
ESS	Energy Storage System
FACTS	Flexible AC Transmission System
FF	Fill Factor
kV	kilovolts
kW	kilowatts
kVA	kilo volt amps
kVAr	kilo volt amps reactive
LV	Low Voltage
PCC	Point of Common Couple
pu	per unit
RES	Renewable Energy Systems
SOC	State Of Charge
SPV	Solar PhotoVoltaics
STATCOM	Static Synchronous Compensator
SVC	Static VAR Compensators
OHL	Over Head Lines
OLTC	On Load Tap Changer
UG	Under Ground

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Chapter 1

INTRODUCTION

In this chapter, the motivation behind the project is presented, briefly introducing the current situation of the government policies regarding renewable energies. This project investigates the issues that high penetration of solar photo-voltaics (SPV) may cause on the low voltage grid. Besides, the objective of the project is to solve the over-voltages that this high penetration level may cause. Subsequently, the methodology and limitations of the work are stated. The chapter will conclude with a scope of the overall work.

1.1 Background

During the 20th century, the main form of energy production was provided by fossil fuels [1]. Energy based on fossil fuels has negative impacts on the environment because of the emissions of greenhouse gases into the air, provoking acid rain, land pollution, among others [2]. Therefore, some protocols have been implemented to change the form of energy production from non-renewable to renewable energy sources.

Different governments agreed on protocols based on environmentally friendly sustainable energy in order to change the form of energy production. The most important one is the Kyoto protocol, which was the first international agreement established between countries to face the climate change [3]. This protocol was signed in the '90s, becoming the first commitment effective in 2008 and ending in 2012. A second commitment started the very same year and remains effective nowadays. This agreement is the Doha Amendment protocol [4].

In order to make a difference, the Danish government has made strategies to be fossil fuels free by 2050. According to these strategies, Denmark has set an intention to cover the fifty percent of the energy consumption with wind and solar power production by 2020. This has a straight impact on the CO_2 emissions [5], therefore, the Renewable Energy Systems (RES) have been under a continuous expansion.

Figure 1.1, shows the different energy sources (in %) from where the energy is produced in Denmark in 2014 (blue bar) compared to 2013 (orange bar). From the figure, it can be observed how the Renewable Energies (REs) have a great impact on the Danish electrical system, having a power installed of 47% from wind and sun energy sources (in 2014). The figure, shows how the RE is increasing the importance in terms of power generation, and the non-renewable energies are decreasing the generation power installed.

Wind and solar power is expected to increase up to 50% in the next few years, thus, the electric system is under a continuous change, replacing the big centralized power plants to more Distributed Generators (DG) [6]. This changes the electrical systems behaviour, making also the system to be more complex (by mismatching of generation-consumption and fluctuations of power) having extra electrical issues, at the same time. These electric issues are: voltage deviation, systems frequency variations, power flow changes, protections, as well as reactive and active power conditioning [6].

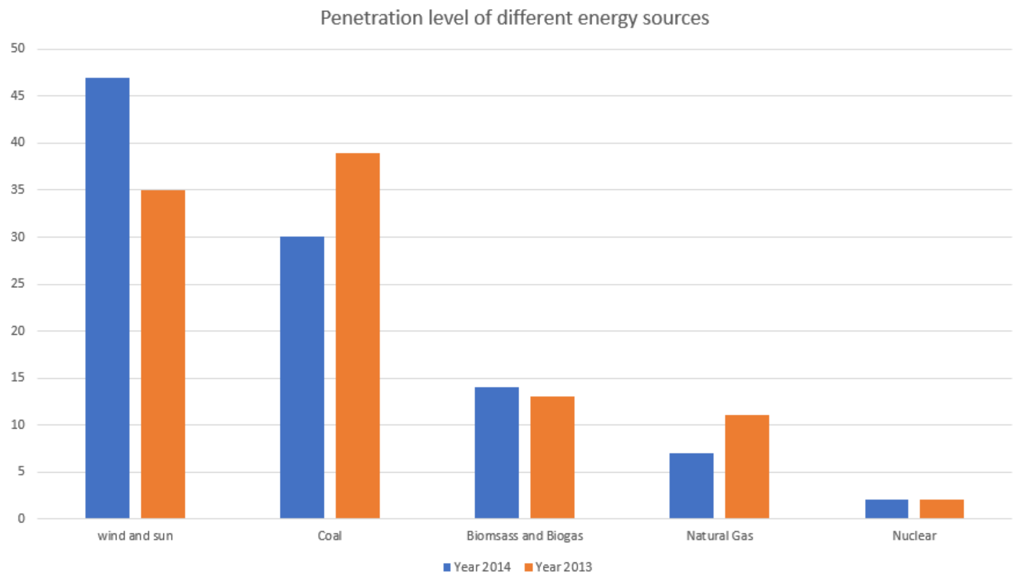


Figure 1.1: Power sources installed in Denmark in 2014 (blue bar) and in 2013 (orange bar) in percent [7].

Figure 1.2 shows the traditional form of energy production. In traditional systems, the energy production demand dictates the production. The system's power follows the next equation: $P_{generation} = P_{endUser} + P_{losses}$, where the generation power was equal to the end user consumption and the power transmission losses. [8]

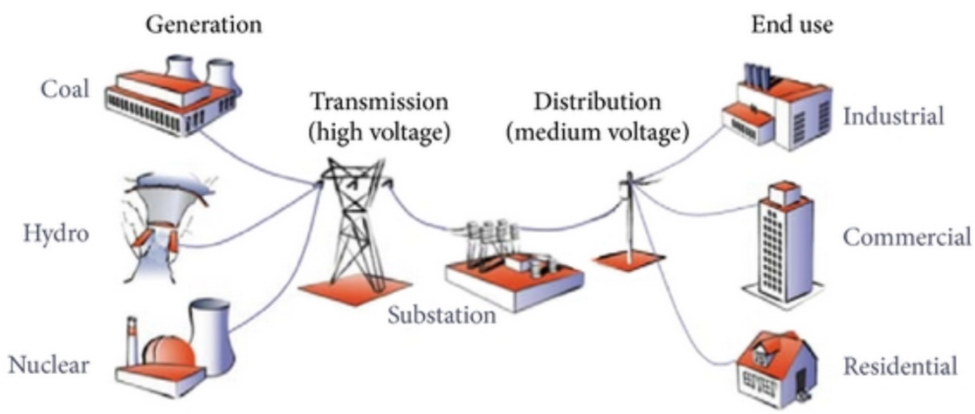


Figure 1.2: Traditional electrical system.

Nowadays, the inclusion of DGs may produce different power quality issues (voltage deviation, power-frequency variations, flicker intensity [9]) while increasing the percentage of wind and solar power. When the local power generated by a RE source surpass the loads consumption, the voltage at the Point of Common Coupling (PCC) will rise. There is no guarantee that sun or wind will provide power when it is needed, or stop producing power when there is no need of power due to low load consumption. This makes systems more complicated, due to the intermittent behaviour of the renewable sources. Hence, technical investigations need to minimize the problems that RE causes on the distributed grid. On the other hand, DGs have some technical advantages as congestions in the network, reduction of the costs of energy losses [10], among others. For this reason, different actions can be carried out to come down with the inconveniences as voltage drops when the buses are far from the transformer and cable congestions. [11]. [12]

This project is only concerned about Low Voltage (LV) network, therefore, wind turbines are not considered. Hence, this project focuses on the voltage rise, due to high penetration level of Solar PhotoVoltaics (SPV) .

RE penetration level can be defined as a portion of the energy presented in an electric network that has been obtained from renewable sources. In Denmark, the penetration level of SPVs is increasing, augmenting the SPVs capacity in the electrical network. In 2014, the SPVs capacity was 560 MW. Afterwards, in 2020, the SPVs capacity is estimated to increased to 840 MW, whereas, in 2035, the estimated SPV capacity will be 1740 MW [13].

The effects that SPVs have on the voltage rise is investigated in [14]. Figure 1.3 illustrate the voltage rise investigated on [14].

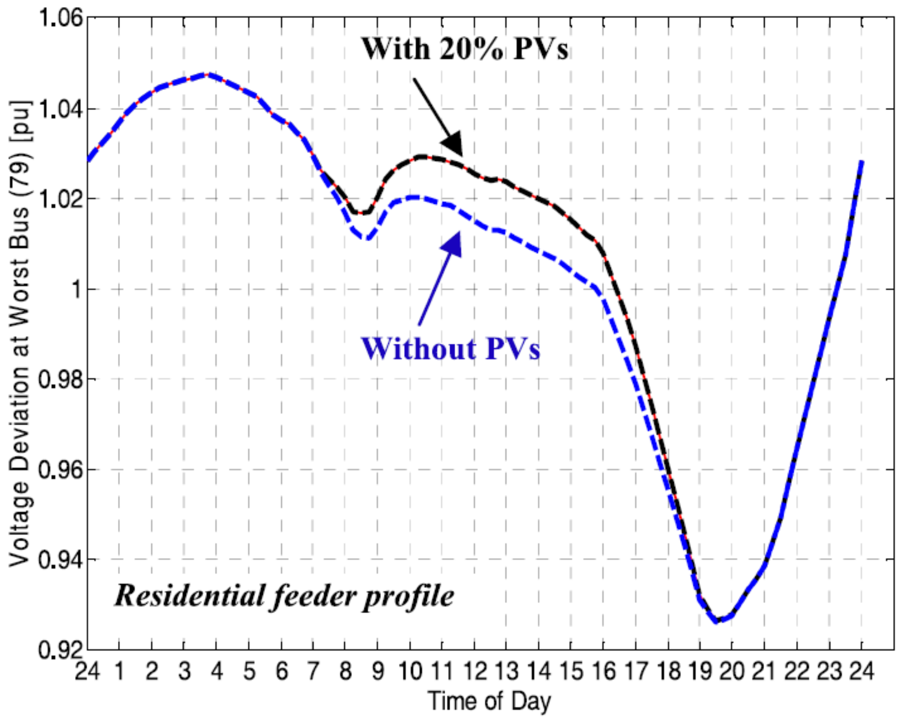


Figure 1.3: Arbitrary network voltage level comparison with and without SPV [14].

Figure 1.3 presents the voltage of a residential bus without SPV installed, and how the voltage rises with a 20% of penetration level of SPV, demonstrating that SPV have a tendency to cause voltage rise during peek production.

1.2 Problem Formulation

The scope of this project is to analyze the technical impact of installing high penetration level of Solar PhotoVoltaics (SPV) to a Low Voltage (LV) grid. As it is stated before, high level of RE, such as wind and solar power, may cause some disadvantages regarding power quality. With a good control of the DGs, the system can deal with these disadvantages and improve the advantages (cable congestion system's loading) that DG contribute to.

The analyzed scenario includes high SPV penetration. This generates technical issues as over-voltages at the Point of Common Coupling (PCC) and frequency variations [15]. The Distributed System Operator (DSO) is in charge of providing good electricity quality, therefore, it has to cope with the technical issues that high penetration of SPV causes.

Instead of installing different equipments as Flexible AC Transmission System (FACTS), Static VAR Compensators (SVC) or Static Synchronous Compensator (STATCOM) [16], which can provide voltage regulation and solve the issues that DGs can create; this project is going to solve the over-voltage problems without any external devices, providing voltage support from the SPV inverters.

To achieve the over-voltage issues, different strategies are going to be implemented. In this work, the voltage is going to be regulated by different active and reactive power control methods. A case with a Battery Energy Storage System (BESS) [17] is going to be presented in order to analyze if the BESS can benefit the voltage profile, as well as the transformers loading and line congestions.

This project aims to develop different operation strategies and a combination that allows an efficient voltage regulation and energy supervisory strategies. For this purpose, the operation of the SPV inverters are going to be coordinated to solve the problems regarding over-voltages.

1.3 Objective

The objective of this project is to solve the voltage deviation that occurs when high penetration of SPVs are connected to the LV distribution system.

In order to solve the over-voltages that may take place, different reactive power control methods are applied. As well as active power control methods, the active power control methods can be an active power curtailment or the installation of Battery Energy Storage System (BESS) to keep the voltage within the desirable limits. In order to provide voltage support, different steps have been followed, and they are summarized as follows:

- Steady-state analysis impact of the SPV installed in the LV distribution grid.
- Dynamic modelling of the SPV.

- Implementation of different reactive power control methods to provide voltage regulation.
- Implementation of active power method to provide voltage control regulation.
- Dynamic modelling of the BESS.

1.4 Methodology

In order to fulfill the purpose of this work, the main tool used has been DigSilent PowerFactory. In the first case, a steady-state analysis of the LV distribution grid has been accomplished, carrying out load flow simulations. This program uses Newton Raphson as a calculation method.

The loads, SPV and BESS have been implemented using DigSilent PowerFactory, making use of Digsilent Simulation Language (DSL) modules. Ultimately, RMS simulations have been used to make the time variation simulations. The input data for the SPV has been calculated using Matlab/Simulink and the sun irradiance data has been taken from DataGUI, provided by Aalborg University.

The applied methodology can be summarized as:

- A load flow analysis is accomplished in the base case study, obtaining information of the SPV impact on the LV grid.
- This project follows the grid code compliance regarding voltage deviation. Investigating different active and reactive power control methods from SPVs to regulate grid voltage.
- The Dynamic model of the SPV and different simulation scenarios are accomplished. The location of the SPV is selected to be at the nodes where the loads are placed. On the other hand, the SPV size is selected according to the peak load where the SPV is located.
- A comparison of the different voltage control is carried out, presenting the advantages and disadvantages of the different voltage control methods in the selected network.
- BESS modelling embedded with energy management schemes are accomplished taking into account the State Of Charge (SOC) of the battery and the power that is injecting or storing. The energy management system is developed to contribute with voltage regulation.

1.5 Limitations

To accomplish this project, different limitations are considered as following:

- The loads of each node are assumed as lumped loads.
- The loads are assumed to be balanced, faults are not considered on this work.
- The LV grid under study is simplified to one residential feeder, disregarding the other feeders of the grid.
- This project is going to focus only on the voltage deviation, keeping out of investigation the possible issues as harmonics, unbalance and fast voltage variations.
- The inverters are simplified, for control purposes. The inverters limitations and topologies are not considered.
- The BESS is placed at the beginning of the feeder (close to the transformer). A deeper investigation on where is the best location to place the BESS is not considered in this project. A deeper investigation on which size will benefit more the feeder is not considered neither.
- The BESS is going to contribute only with active power, therefore, reactive power methods in the BESS are not considered.

1.6 Outline of the project

The project can be summarize as following:

- **Chapter 2 - State the Art:** This chapter collects the most important topics related with the project, being these topics: Distributed networks topology, grid codes, voltage control techniques and energy storage systems.
- **Chapter 3 - Steady State and Electrical Grid Analysis:** This chapter presents the LV benchmark model with its technical parameters (cables and transformer), as well as the loads and SPV location on the distributed network. A power flow of different cases are carried out, in order to gain a deeper understanding on grid's behavior.
- **Chapter 4 - Dynamic Model Implementation in DigSilent PowerFactory:** In this chapter, the SPV and the BESS composite models are presented, as well as their working principle, together with the equation of the control methods selected.
- **Chapter 5 - Active and Reactive Power Control to Voltage Support - RMS Simulation:** In this section, different voltage control techniques are applied according to the base case, in consonance with the voltage issues that were found. The main parameters under study are: Voltage profiles, reactive power compensation, system's loading and transformer power flow.
- **Chapter 6 - Battery Implementation to Voltage Support - RMS Simulation:** Firstly in this chapter, the BESS size that can make an impact on the last bus is calculated, the location of the BESS is found on bus 1. The most interesting parameters are then presented (Voltage profile, transformer's loading, battery output and the SOC.).

- **Chapter 7 - Conclusion:** A resume of the overall project is presented in order to conclude.
- **Chapter 8 - Future Work:** This chapter presents the different strategies that can be carried out to continue investigating on the topic.

Chapter 2

State of the Art

In this section, different topologies of the distribution network system are described, followed by the statement of the prescriptive grid codes. Besides, different active and reactive voltage control techniques are briefly defined, whereas the more relevant techniques are detailed more in deep. The chapter ends with a description of the BESS technology and a conclusion of it as a whole.

2.1 Danish Power Network

The Danish power network is divided into two differentiated areas; East and West Denmark, they are connected by means of Direct Current (DC) cables, East Denmark is connected also to Germany through a DC cable and Western Denmark is connected to Germany through an AC Over Head Lines (OHL). Sweden, is connected to East Denmark by AC OHL. Western Denmark is connected with Norway through numerous DC cables.

These two areas cooperate with two different system networks, East Denmark is member of the Nordic grid, whereas West Denmark is member of the European grid.[18]

Moreover, the Danish electric network has two different levels of electric power transmission, these two levels are differentiated by the voltage level. These two levels are the transmission system and the distribution system. Transmission systems voltage level are from 400 kV to 150 kV. The distribution system voltage scale are from 60 kV to 0.4 kV. This project is carried out on the distribution level, specifically at the LV level of 0.4 kV.

2.2 Distribution Network

The distribution network is responsible to provide electricity to the end user (residential, commercial and industrial). Therefore, the inclusion of DGs has become a critical aspect to investigate, as the DSO has to maintain the power quality according to the European grid codes [19].

The voltage level at the distribution network is from 60 kV to 0.4 kV. The distribution network is divided into three different topologies, according to their architectural topology. The electric network can benefit different aspects as costs, supply reliability, technical aspects, among others [20]. The three architecture topologies are illustrated at 2.1 and it can be explained as it follows:

- **a) Radial Structure:** This structure is the simplest on. It consists of a single line connected by several buses. The biggest advantage of this structure is the simplicity. The main disadvantage is that in case of fault, the buses after the this become isolated from the power source, being, then, the power quality compromised.
- **b) Ring Structure:** As its name indicates, this structure consists of a circular network. Every single bus can supply two buses. Compared to the radial structure, this is more reliable in case of faults, as in this case, the buses are not isolated from the rest of the feeder. The main disadvantage is that, as it has to be sized to endure the extra amount of power, the costs of this structure are higher compared to the radial structure.
- **c) Mesh Structure:** This structure consists of an interconnection of diverse feeders and networks, involving the two already mentioned architectural structures. This topology is the most reliable.

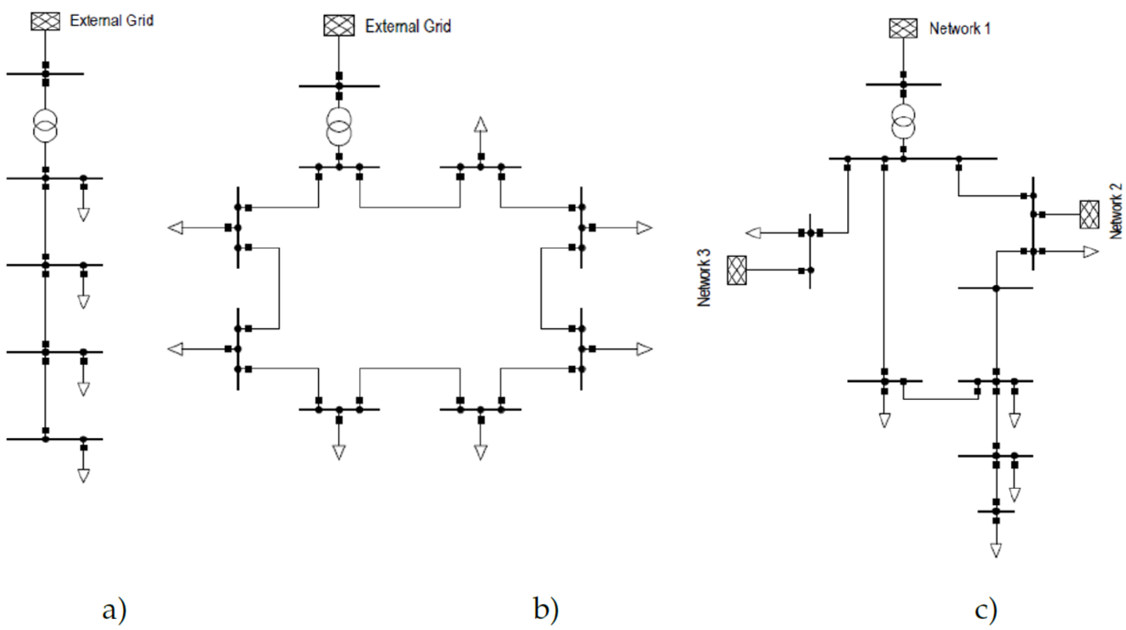


Figure 2.1: Single-line sketch of the different architectural topologies.

2.3 Grid Codes

There is some technical regulation that has to be followed in order to guarantee grid operation and protect the electrical network and all the devices that take part of the system. This technical regulation is recognized as the grid codes, consisting them on rules that grid operators, grid owners, and plant owners must follow. In Denmark, the regulations are established by the Danish Energy Regulatory Authority and "Energinet" as the transmission system operator. The grid code concerning voltage quality is the European Standard EN 50160 [21].

There are some grid connection requirements for SPVs that have to be follow when applying voltage control methods. When reactive power control method is applied, the power factor has to be as maximum 0.95 lagging of P. All PV power plants require a minimum active power control, according to [22].

This project aims to investigate the installation of high penetration of SPV in the LV electrical network, specifically, the voltage deviation. The standard EN 50160 imposes in medium voltage and LV grid a $\pm 10\%$ of the nominal voltage. In this project a deviation of $\pm 6\%$ of the nominal voltage is going to be applied. Hence, the voltage limits are 0.94 p.u. and 1.06 p.u..

2.4 Voltage Control Techniques

In this section, different voltage control techniques are going to be described. Traditionally, the On Load Tap Changer (OLTC) was the one that regulated the voltage deviation, whereas, nowadays, more complex voltage control techniques, as power electronics, reactive and active power control methods, have been developed and enhanced. In the LV level, these new voltage control techniques are the ones more used, as there is no OLTC for such voltage level.

2.4.1 Automatic Voltage Control

The Automatic Voltage Control relay compares the voltage to the target voltage. The relay defines if the OLTC has to adjust the turn ratio of the transformer in order to maintain the voltage between the desirable voltage. The tap selection of a tap changer is made via the automatic voltage control system. [23]

2.4.2 Power Electronics

The power electronics are increasing their interest on the distribution network due to the high efficiency and the elevated performance in the electric power systems [16]. The most important devices in power electronics for distribution systems are FATCS, SVC and the STATCOM [24]. Power electronics can improve the voltage profiles by supplying or consuming reactive power. [25]

2.4.3 Reactive and active Power Control Methods

There are different reactive and active power methods for voltage regulation. The following section describes the more relevant ones.

Unity Power Factor: This method is the simplest, the SPV inverter is operating at unity power factor, which means that the reactive power support towards to the grid is always the same. This control method is an open loop, thus, the voltage is regulated indirectly at the PCC, which means that the reactive power support is not varying based on the voltage at the PCC. [26]

Fixed Power Factor Q(P): This method is found to be a good method to regulate the voltage when there is high penetration of SPVs. This method makes the inverter to operate with a leading or lagging power factor, this is suitable after an extensive research before hand.[27]

$$cos(\theta) = \frac{P_{output}}{S_{output}}$$

$$Q = \sqrt{S_{output}^2 - P_{output}^2}$$

Q is the reactive power output of the inverter with a fixed power factor $cos(\theta)$, the P_{input} is the power output of the SPV inverter in each moment and S_{output} is the apparent power output.

This method as the previous, is a open loop, means that the input is not a function of the output. In other words,the voltage at the PCC is regulated indirectly.

Variable Power Factor Q(P,X/R): This method is like Q(P) method, taking into account that this method is a function of P_{output} and the X/R ratio on the PCC. This method is varying the voltage at the PCC indirectly, however, it provides reactive power output taking both P_{output} and X/R parameters into consideration. [28]

Volt/VAr Control: This voltage control method is the most complicated, the first difference between this method and the already stated methods is that this method is closed loop. The inverter is monitoring the voltage at the PCC, the reactive power output is based on the voltage monitored in real-time. Figure 2.2 shows the reactive power output taking into account the voltage measured. From Figure 2.2, it can be seen how the reactive power output depends on the voltage measured at the PCC.[26]

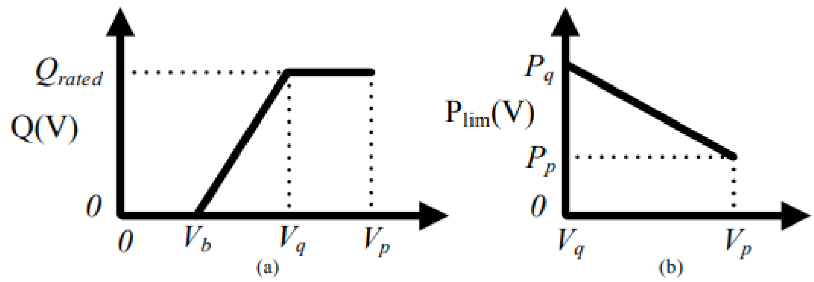


Figure 2.2: Droop control of both Q(V) and $P_{lim}(V)$.[29]

The main disadvantage of this method, is that the reactive power support from the SPV inverters along the feeders are different. This results on an unfairness reactive power sharing of all the SPV inverters. This is caused by the fact that the voltage V_b and V_q is the same for all the SPVs. In [29] they propose an enhanced method based on the calculation of the voltage bands V_b and V_q. The voltage band calculation is derived from the voltage sensitivity analysis.

Active Power Curtailment: This method consist on cutting the active power when the voltage reaches a certain limit.

Active power curtailment takes also the voltage measured at the PCC into consideration, in order to calculate the power that has to be curtailed to set the voltage at the desirable limits. This method can be used together with reactive power control methods to voltage regulation.

2.5 SPV

Solar power can be obtained in different ways, the SPV, make a direct conversion of the sun irradiance into electricity, as well as the concentrated solar power and hybrid systems, among others [30]. However, this project focuses on the SPV technology. The SPV takes advantage of the photovoltaic effect, which converts the solar irradiance into DC current. In order to connect SPV in AC distribution networks, it is necessary to add an inverter which converts the DC to AC.

The expected peak generation is found during the midday hours, when the sunlight waves are perpendicular to the solar panel, this can result on over-voltages during the midday if there is a low load consumption. This fact is more notorious in weak systems.

Concerning the SPVs generation, Equation 2.1 express how the power is directly proportional to the solar irradiance.

$$P = S_{irr} \cdot A_{irr} \cdot \eta \cdot FF \tag{2.1}$$

P is the power of the SPV (W), A_{irr} is the irradiated area (m^2), S_{irr} is the instantaneous solar irradiance($\frac{W}{m^2}$), η is the SPVs efficiency and FF is the Fill Factor (quality of the SPV cell).[31]

2.6 Energy Storage System

These days, electrical power is obtained in different ways, not only by non-renewable energy sources. As the Danish government has implemented some policies (already stated in Chapter 1) that require more RES for the power systems, a part of the solution of the problems that RES may cause can be solved by different Energy Storage System (ESS) technologies.

There are diverse forms of classifying the ESS. They are classified in two categories: access-oriented and capacity-oriented. In the access-oriented category, there are devices like a flywheel and a super capacitor. On the other hand, batteries enter into the category of capacity-oriented. In this project, the ESS used is the battery. [32]

2.6.1 Batteries

Batteries technology has been developed through the years in terms of life cycle and size. Batteries can be found nowadays as a solution for voltage regulation [33].

Battery Storage Calculation

An important parameter that has to be known is the SOC. This is the percentage of energy stored compared to the maximum capacity of the battery. The SOC is changing along the time by battery charge or discharge. Equation 2.2 describes how the SOC can be calculated [34].

$$\frac{\mathrm{d}}{\mathrm{d}t}SOC = \frac{-Pbat[W]}{C[W \cdot h]} \cdot \frac{1[h]}{3600[s]} \cdot 100\% \tag{2.2}$$

$$SOC = \int_0^{100} \frac{-Pbat \cdot 100}{C \cdot 3600} \cdot dt$$

Where P_{bat} is the power that the battery is supplying every moment (W). C is the energy capacity of the battery ($C = P_{batteryRated} \cdot hours$) ($W \cdot h$). The SOC is entirely discharged when the SOC is 0% and is fully charged when SOC is 100 %. In order to increase the life of the battery, the SOC should be within a lower and upper limit, these limits are [35]:

$$SOC_{min} \leq SOC \leq SOC_{max} \tag{2.3}$$

In this project, the SOC chosen are: $SOC_{max} = 90$ % and $SOC_{min} = 10$ %.

2.7 Conclusion

Denmark is divided into different power networks. These power networks are on the transmission level and the distribution level. This project is focused on the distribution level, therefore the different topologies at the distribution level are described. The network used to perform the different simulations follows the radial architectural structure.

There are regulations that have to be followed regarding voltage deviation. In chapter 1, it was stated that high penetration of SPV may produce voltage rises when peak production. Thus, different control techniques have been described, going these from the adjustment of the transformer turn ratio, through the OLTC technology (this project is going to be carried out in the LV level, therefore OLTC is not considered), and power electronic devices, such as FACTS device, AVC, among others.

There are also different control techniques which use the inverters that connect the SPVs to the network. These control techniques consist on providing with reactive power by supplying or consuming reactive power to adjust the voltage, or, on the other hand, active power curtailment control method.

Different reactive power control methods are going to be applied in order to solve the voltage rise, as well as an active power curtailment control method.

Ultimately, the BESS is explained, as it is going to be part of the solution in this project. There are two parameters that are going to be considered in this project: The SOC and the amount of power that the BESS is going to store or supply.

Chapter 3

Steady State and Electrical Grid Analysis

The goal of this chapter is to investigate the systems behavior when there is high penetration of SPVs. Besides, cable and transformer parameters are presented. Additionally, the analysis is followed by load and SPV location, as well as their size on the network. The primary focus of this chapter is to show the results in different cases (with and without SPV), in order to investigate how the system behaves under these circumstances. The chapter ends with a conclusion of the overall work.

3.1 Benchmark Model

The benchmark model under study is the LV CIGRE, "Benchmark system for Network Integration of Renewable and Distributed Energy Resources" [36]. This benchmark model consists on three differentiated feeders: An industrial one, a commercial one and a residential feeder.

The last one is going to be the target in this project, as the other two feeders will not be analyzed here. The main purpose is to study the consequences of high penetration ratio of SPV in such systems, therefore, a residential feeder is sufficient to achieve this objective.

The residential feeder consists of 18 buses. There is a main radial feeder which is composed by 10 buses and 8 buses that take part of the sub-radial feeders. Figure 5.8 represents the residential feeder from the LV CIGRE benchmark model. The benchmark model is supplied by a 20/0.4 kV transformer, in which the buses are connected by cables. Those specifications are included in Table 3.2. These parameters are the original values of the LV CIGRE network. With regard to the cable length of the main feeder, each one is 35 meters, whereas between the sub-feeders and the main feeder buses each cable length is 15 meters.

Table 3.1: SPVs and load power installed in the residential network

Total power installed		
Loads Consumption	8x Residential Load	468 kVA
SPVs Generation	8x SPV Units	468 kW

In Table 3.1, the power load installed is for the 8 loads placed on the distribution network, the same logic is applied with the SPV. The network is reaching the 92% of

Table 3.2: System Parameters

<table>
<tr><td>Distribution Transformer</td><td colspan="2">Dyn11
20/0.4 kV
S_n=500 kVA.
Short-circuit voltage 5%</td></tr>
<tr><td>Cable 1</td><td>Conductor ID: UG1</td><td>Type NA2XY
$X_{ph} = 0.136\ [\Omega/km]$
$R_{ph} = 0.163\ [\Omega/km]$</td></tr>
<tr><td>Cable 2</td><td>Conductor ID: UG2</td><td>Type NA2XY
$X_{ph} = 0.151\ [\Omega/km]$
$R_{ph} = 0.266\ [\Omega/km]$</td></tr>
</table>

capacity, being the transformer rated to 500 kVA and 468 kVA the load power installed, as it can be seen in table 3.1.

Two different cables are used in this project, the UG1 and the UG2. UG1 is used for the main feeder (buses 1 to 10), whereas the latter is used for the sub-feeders. The X/R ratio of the former is 0.84, being 0.57 the X/R ratio of UG2. Appendix A specifies the connections between buses.

3.1.1 Load and SPV Power Installed

The loads are installed in different buses, following all of them the same profile. The difference between them is the power installed at each bus. Regarding the SPV, they are going to be installed in the buses where a load is placed.

The aim of this project is to study which issues may be caused by high penetration level of SPV on the network. The different strategies to solve the subsequent problems are also analyzed in this section. For this purpose, the SPV penetration level is going to be almost 100%. According to [37], penetration level is defined as the installed DG equal to the peak load demand.

Table 3.3: Loads and SPV Power Installed

Load/SPV	Load (S) kVA	cos(ϕ)	SPV (P) kW
1	65	0.95	65
2	70	0.95	70
3	65	0.95	65
4	60	0.95	4
5	65	0.95	65
6	45	0.95	45
7	48	0.95	48
8	45	0.95	45

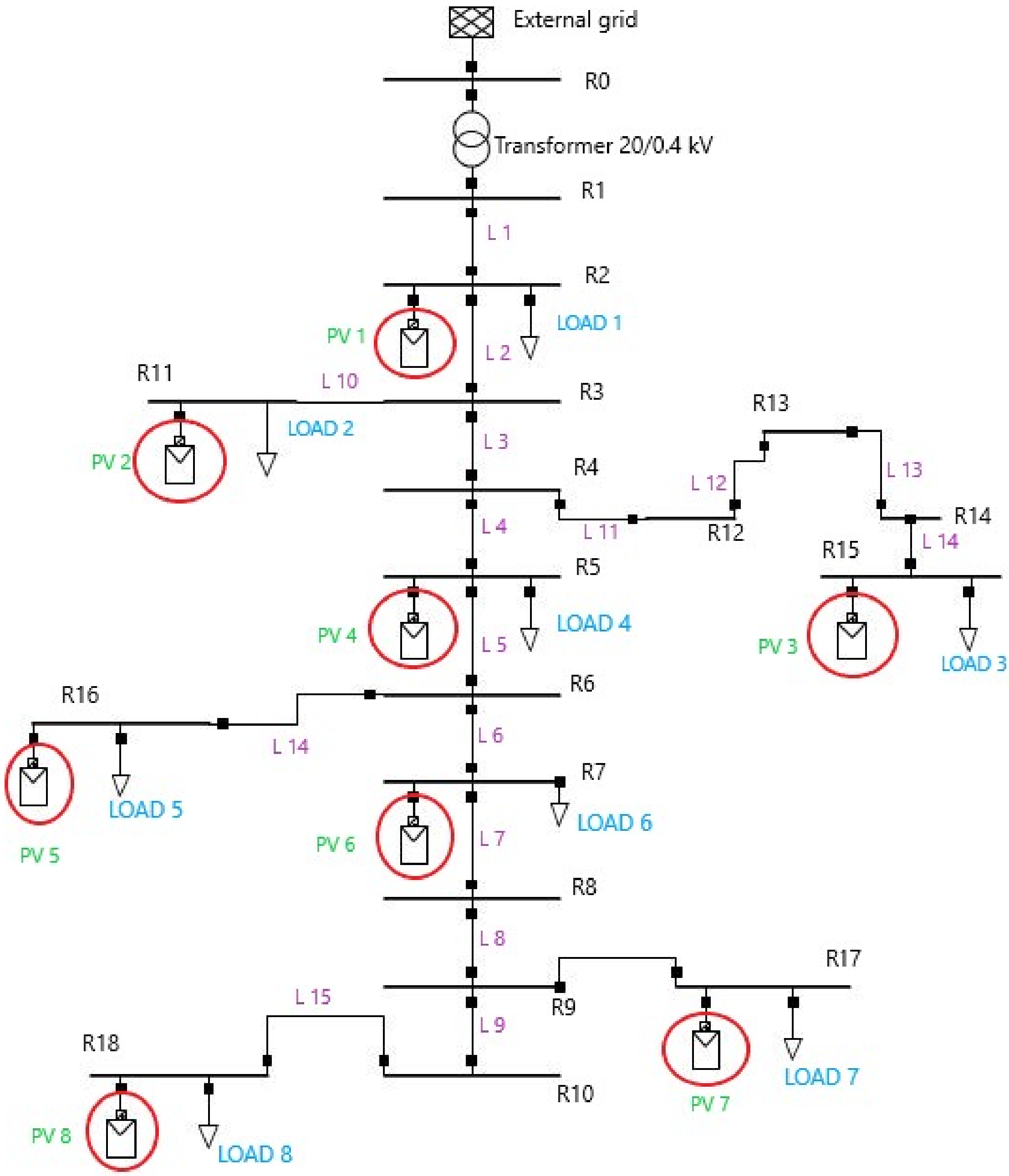


Figure 3.1: CIGRE LV residential feeder [36] with SPVs.

3.2 SPV and load profiles

The SPV and the load profiles are going to be presented in this section, being both profiles equal for all devices of the network.

3.2.1 SPV Profile

The solar irradiance data for the SPVs is taken from a AAU weather station. The data is supplied by a tool called DataGUI, provided by Aalborg university, and it is collected from the 07/26/2016 at 00:00 to 07/27/2016 at 00:00.

The choice of a summer day is due to high solar irradiance. The data resolution is every minute. The oscillations showed in 3.2 are produced by weather conditions, mainly clouds. In this project, all the SPV has the same profile, as the SPVs are not far from each other.

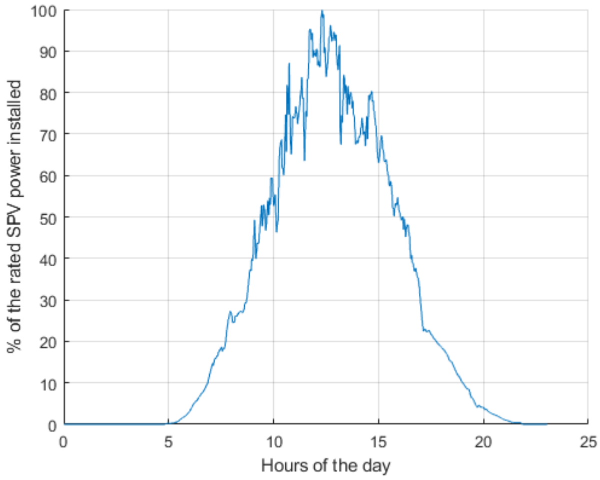


Figure 3.2: Daily SPV profile.

3.2.2 Load Profile

The load profile is taken from the LV CIGRE benchmark model and the data resolution is hourly. All loads along the feeder follow this profile. With regard to the used power factor, it is the same one along the feeder.

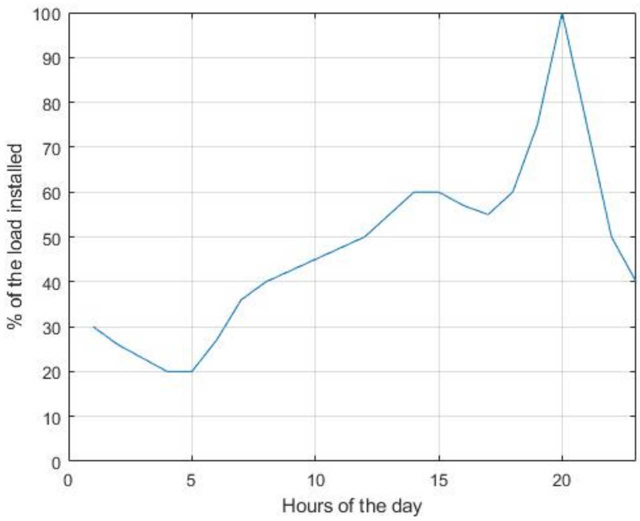


Figure 3.3: Daily load profile.

3.3 Base Case

The base case is going to be presented in this section, being two different scenarios displayed, for that purpose. The first case is called "Maximum SPV Generation" and it occurs when the SPV is supplying the rated power while the loads are disconnected. On the contrary, the second case occurs where the load consumption is maximum and there is no SPV installed and it is called "Maximum Load Consumption".

3.3.1 Maximum SPV Generation

In this sub-section, the voltage and the loading of the system are presented. These parameters are presented when there is a maximum SPV generation and the loads consumption is zero. The SPV maximum generation is found at 14:00, as it can be seen in Figure 3.2.

Bus Voltages

Figure 3.5 shows the voltage at the different buses in which the SPVs are connected. The sub-radial feeder is composed by buses 11 to 18, whereas buses 2, 5 and 7 are part of the main feeder.

It can be seen how the voltage profiles are higher at the sub-radial feeders. This occurs due to the fact that these buses are farther from the transformer, resulting in higher impedance. On the other hand, buses 2, 5 and 7 show lower voltages, as a result of their proximity to the transformer. Bus 5 shows higher voltage compared to bus 7. The reason behind this higher voltage is that the greater current of bus 5 in regard to bus 7.

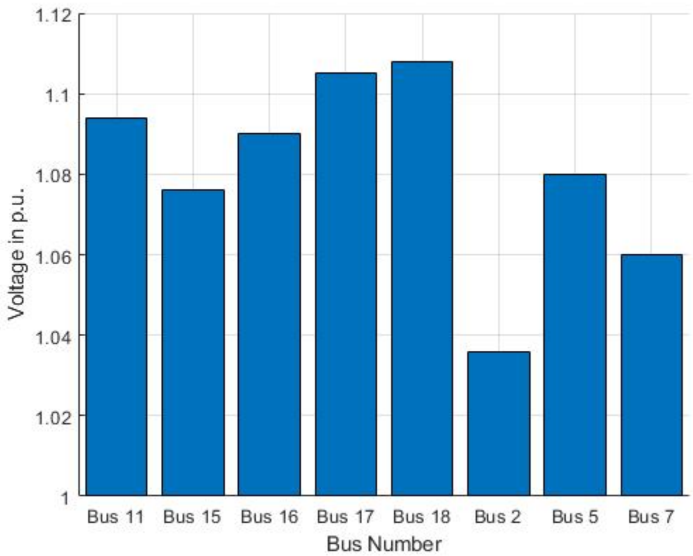


Figure 3.4: Bus voltage along the feeder.

$$V = I \cdot Z$$

Ohm's law expresses how the voltage drop is directly proportional to the impedance and the current, i.e. if two buses are consuming/supplying the same amount of current, but the impedance of those are different, due to ohm's law, the voltage will be different; by contrast, if the impedance is the same in these buses, but they are consuming or supplying a different amount of current, the voltage will be different. Same logic can be applied to this radial network.

System's Loading

Table 3.3, displays the loading of different segments where a load and a SPV are connected, being these segments cables between two buses. It can be seen from Appendix A between which buses they are connected.

Line Segment	Loading %
1	63.225
4	41.269
6	17.10
10	10.87
13	9.45
14	10.46
15	10.154
16	10.356
Trafo	87.3

Table 3.4: Systems Loading

Line segments 1, 4 and 6 present higher loading's compared to the rest of the line segments, being those cables that are part of the main feeder. Their rated current is higher compared to the sub-radial networks, but their loading is higher as they have to endure with all the power supplied from all the SPV. Therefore, line 1 has the highest loading. This cable is enduring all the SPV generation, whereas line 4 is enduring all of them, except from the SPV of bus 2, and so occurs, successively, with the rest of the line segments.

The loading at the transformer is found to be close to the 100%, therefore, in the worst case scenario, the transformer is above the normal limits of operation.

3.3.2 Maximum Load Consumption

The subsection presents the buses voltage when a SPV and a load is found, as well as the loading of the line segments and the transformer .

In this case, at the selected hour (20:00), the loads are consuming the maximum and all the SPVs are disconnected.

Bus Voltages

Buses 11 to 18 represent the buses of the sub-radial networks, showing a higher voltage drop, compared to the buses of the main feeder.

The logic applied in the previous case can be applied here as well. The voltage is deviated due to line length and the consumption/supplying of the devices in the different nodes. Thus, the voltages at the sub-networks are lower, compared to those on the main feeder.

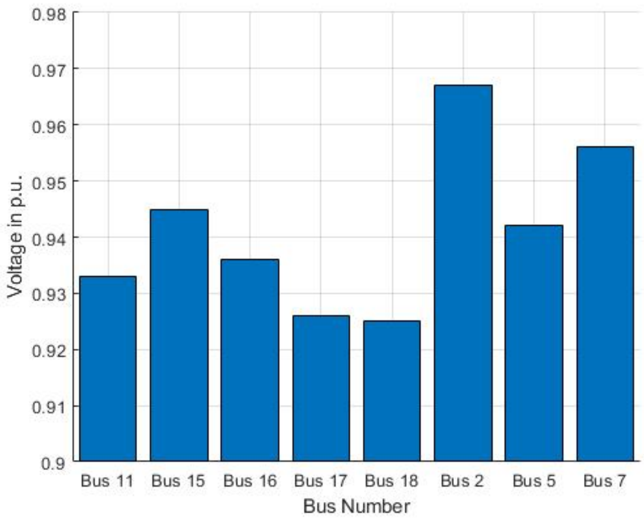


Figure 3.5: Bus voltage along the feeder.

System's Loading

Table 3.4 displays the loading of the different segments when a load and a SPV are connected. These segments are cables between two buses. From Appendix A, it can be seen among which buses they are connected.

Line segments 1, 4 and 6 present higher loadings compared to the rest of the line segments. This occurs due to the fact that lines 1, 4 and 6 are cables part of the main feeder. Their rated current is higher, compared to the sub-radial networks, but their loading is higher, as they have to endure with all the power supplied from all the SPVs. Therefore, line 1 has the highest loading, as this cable is enduring all the SPV generation, whereas line 4 is enduring all of them, except from SPV in bus 1, and so occurs with the rest of the line segments.

Line Segment	Loading %
1	66.225
4	42.269
6	19.10
10	11.3
13	9.32
14	11.46
15	11.926
16	11.944
Trafo	89.3

Table 3.5: Systems Loading

The loading at the transformer is found to be close to the rated power, however, is not exceeding the 100% of loading, therefore, in the worst case, the transformer is within normal limits of operation.

3.4 24 Hours Simulation Case

This section presents two different cases towards a 24 hours simulation. At the first case, there is going to be only a SPV installed, and, on the other hand, the case called "Normal Case" is a case where a SPV and the load are supplying/consuming power, following their power profiles.

3.4.1 Case - Only SPV Generation

In this case, only the SPVs are going to be connected to the network, being the loads disconnected. This will result on over-voltages along all the buses, due to current injection to the system.

Voltage Profiles

In this sub-section, the voltage profile during 24 hours is displayed, for three different buses. A bus close to the transformer (bus 2), a bus in the midway (bus 15), and lastly, a bus at the end of the feeder (bus 18).

It can be seen at Figure 3.6 how the voltages are always above 1 p.u.. This occurs due to the fact that only power is being injected during the 24 hours. The voltages are different due to their location on the feeder. As it has been stated, the farther the bus is from the transformer, the more sensitive the bus voltage is. Therefore, the voltage at the beginning is lower, compared to the other 2 buses, being bus 15 lower to the bus at the most farthest point.

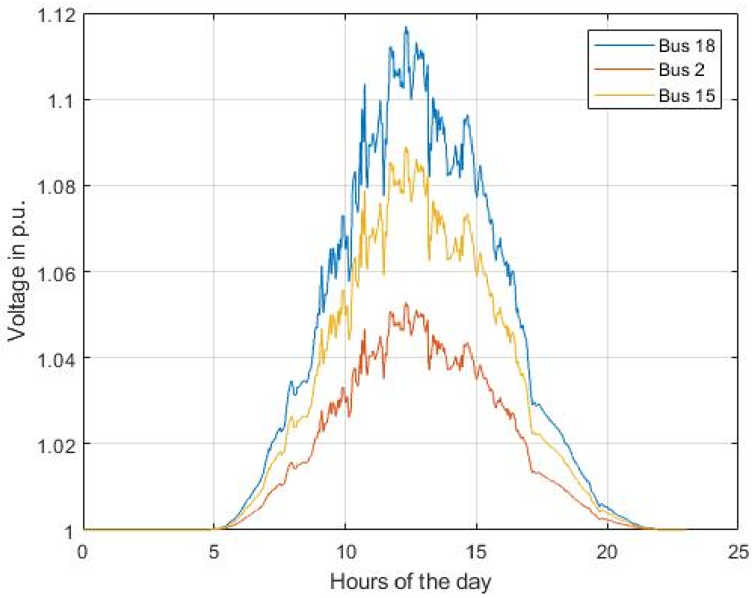


Figure 3.6: Bus voltages.

System's Loading

In this sub-section, the loading of different line segments during 24 hours is displayed.

From Figure 3.7 it can be seen the loading of the different line segments.

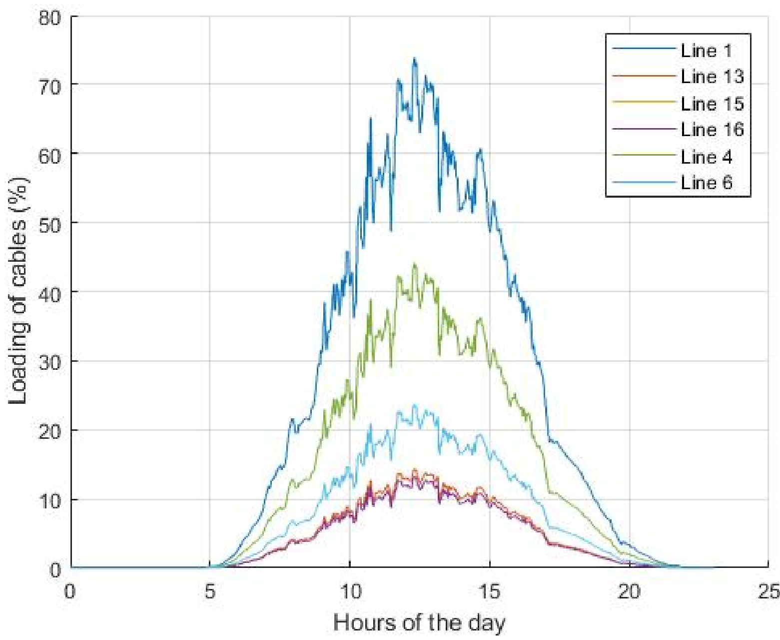


Figure 3.7: Cable loading's.

Lines 1, 4 and 6 present higher loadings compared to lines 13, 15 and 16. This occurs due to the fact that these first lines are located at the main feeder, incurring in higher current flow across the lines. Line 1 has to endure higher current flowing, as it is located at the beginning of the feeder. Therefore, it seems important to size correctly the lines, due to the current that can flow across the cable. The main feeder cables are rated to higher current, compared to the sub-radial networks, however, the amount of current flowing on this cables is quite higher.

3.4.2 Normal Case

This section addresses the normal case. "Normal case" means that both SPV and loads are working in normal conditions. In this case, the current across the transformer is going to flow from the transformer towards the feeder (when the loads consumption surpass the SPVs generation), as well as from the bottom of the feeder up to the transformer (when the SPVs generation exceeds the load consumption).

Voltage Profile

This sub-section presents the voltage of 3 different buses: One at the beginning of the feeder, another in the midway and one on the bottom of the feeder.

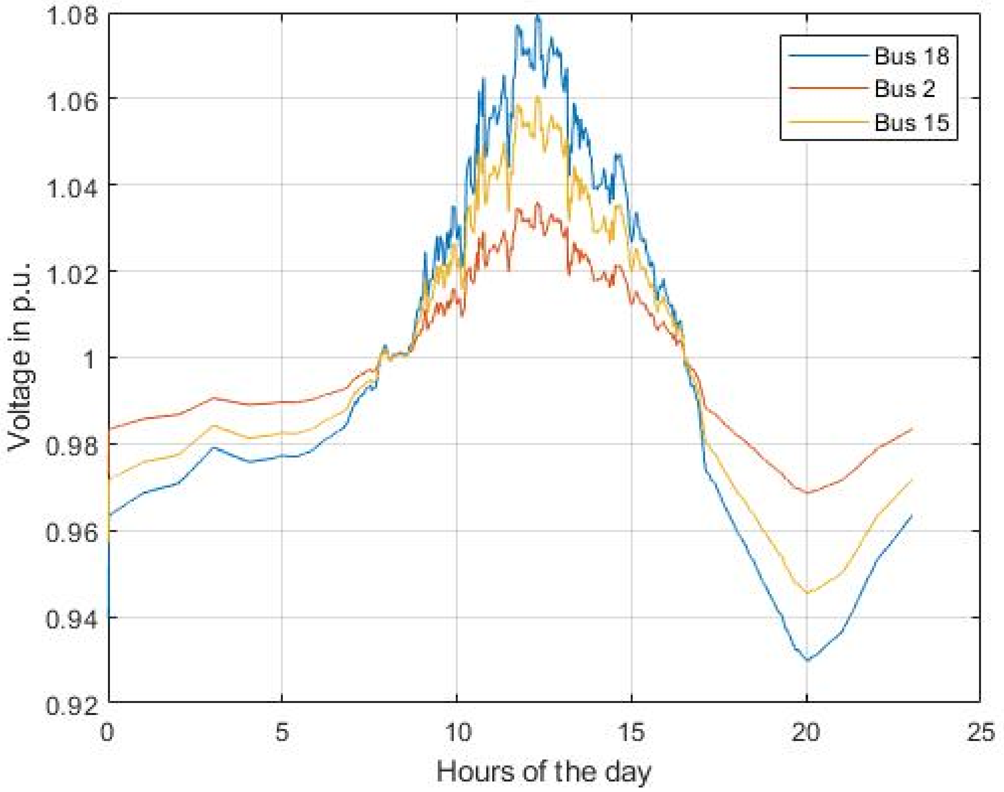


Figure 3.8: Bus voltages.

From Figure 3.8, it can be seen how the voltages of the 3 buses are going from values above 1 p.u. to values bellow 1 p.u.. Voltages above 1 p.u. are found, when the net power ($P_{net} = P_{load} - P_{SPV}$) is negative, means that the SPV generation is higher than the loads consumption. On the other hand, when the voltage are bellow 1 p.u., the net power is positive, this is when the load consumption is greater than the SPV generation.

It can be seen how the voltage at bus 18 have higher voltages compared with the others when the SPV generation is higher than the load and lower voltage when the load consumption is higher than the SPV generation. This occur due to the fact that bus 18 is located further away from the transformer (Line impedance is higher compared to the others, in other words, the bus is more sensitive)

System's Loading

This sub-section, present the line loading of different segments of the feeder, during a 24 hours simulation.

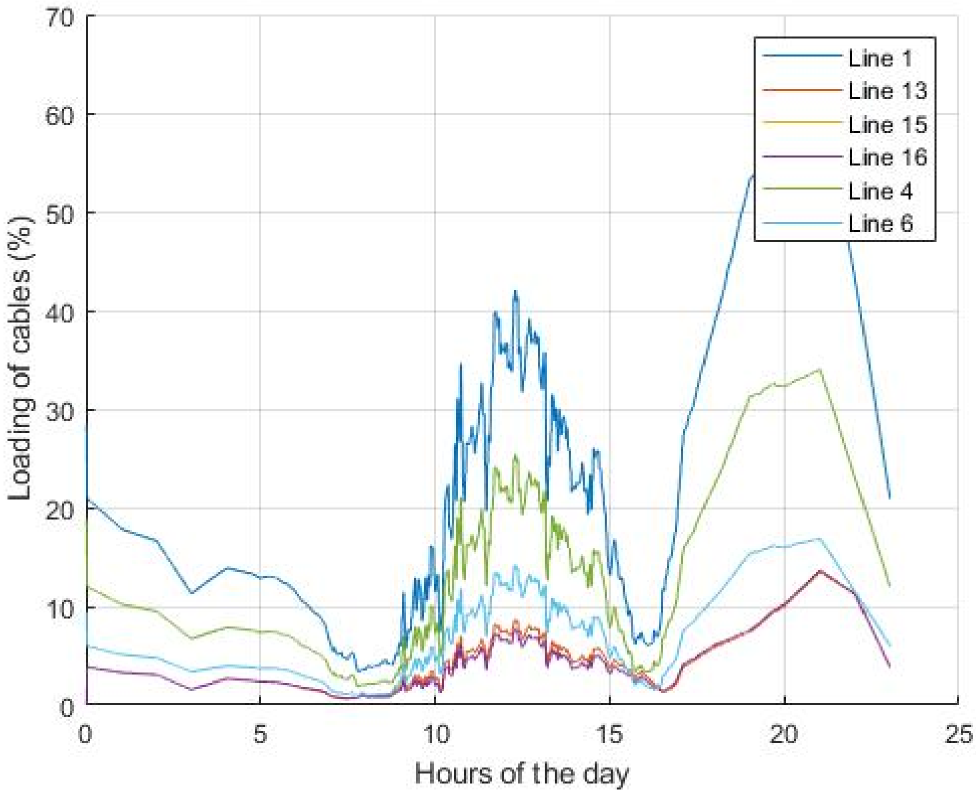


Figure 3.9: Cable loading's.

From Figure 3.9, it can be seen how there are two different stages where the loading increases. The first phase is from 10 to 15. During that time frame, the SPVs are generating power until the peak at midday. The fact that loads are also consuming ($P_{line} = P_{load} - P_{SPV}$) at that time creates a decrease in the loading to the 40%, approximately. At 20:00, the loading of the cable is at its maximum, when there is a peak load consumption and there is no generation from the SPV.

3.5 Summarizing

3.5.1 Case Comparison

Here there is a comparison of the cases where the maximum SPV is connected without load consumption; the peak load consumption case without SPVs, and the normal case of operation.

Figure 3.10 shows the voltage at the different presented cases. It can be seen how the voltage is rising up to non-desirable limits when no load is connected and SPV is supplying the maximum power. On the other hand, the case where the load is consuming the maximum, and no SPV is connected, presents under voltages close to the limit required by the grid codes. At last, the normal case, presents voltages above

1.06 p.u., which is the limit stated in this project, where the lower limit is not violated. Therefore, this project is going to focus on the over-voltages.

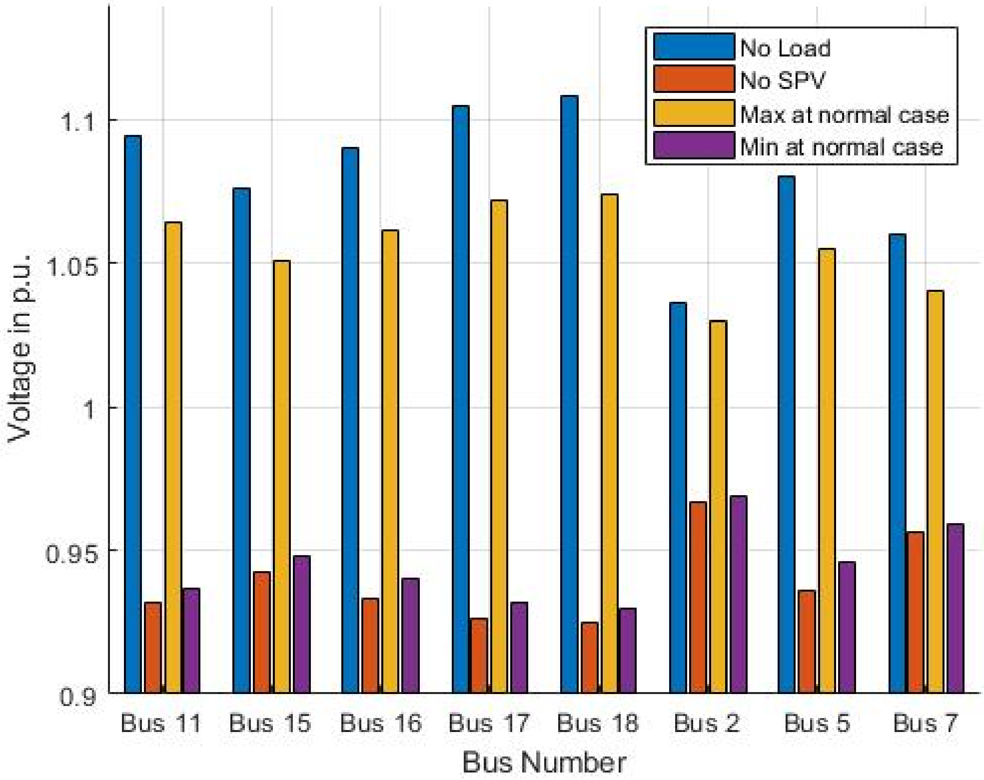


Figure 3.10: Voltage comparison between cases.

3.6 Conclusion

The steady state results are summarized in the previous section, presenting the issues that high penetration level of SPV causes to the LV Benchmark model described above.

Figure 3.10 shows the voltages of all the buses at the different scenarios. The results present how the voltage is violated in the case where the SPV was maximum and the loads consumption were disconnected (worst case scenario), and how it is violated in the normal case with voltage above 1.06 p.u.. Consequently, different control strategies have to be implemented in order to solve the voltage deviation issues. Regarding cable congestion, the system seems to have decent values, however, a study of the system's loading is going to be carried out to ensure that the voltage control strategies are not congesting the network.

Chapter 4

Dynamic Model Implementation in DigSilent PowerFactory

This chapter describes the SPV and the battery composite models implementation on DigSilent PowerFactory. Subsequently, the different voltage control methods are described more in deep, as well as the battery working principle.

4.1 Composite Models

Chapter 3 displayed the issues regarding over-voltages when there is high penetration level of SPVs. The aim of this project is to mitigate the over-voltages. In order to diminish the over-voltages, different voltage control strategies are going to be used. To achieve this purpose, SPVs and a BESS are going to be used. The SPV and the BESS, are modeled using DSL models and the internal DigSilent PowerFactory scripting.

4.1.1 SPV Composite Model

This sub-section describes the composite model of the SPV used in the project.

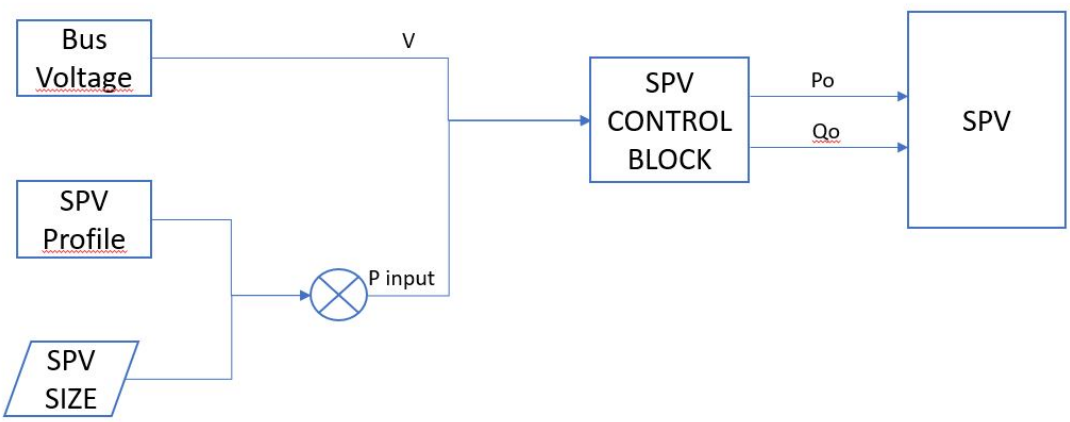


Figure 4.1: SPV composite model.

Figure 4.1 presents the blocks used to model the SPV. The first block (Bus Voltage) is a measurement block, monitoring in real-time the bus voltage. SPV profile block is the one which provides the SPVs generation profile already stated in Figure 3.2. This block is multiplied by the size of the SPV placed in the different buses of the feeder. SPV CONTROL BLOCK is the block which controls the output power based on the control method used. SPV block is the SPV itself which injects power based on the inputs Po and Qo.

4.1.2 Working Principle

This section describes the different methods that are applied in this project for voltage regulation purposes. In order to describe the methods, different equations are going to be used for a better understanding on how they provide reactive or active power support for voltage regulation. This methods are scripted and they are part of the SPV CONTROL BLOCK (code can be found in Appendixes C and E).

Fixed Power Factor

The power factor used is 0.95, based on the grid codes [38]. Next equations present the output reactive power based on the power factor and the SPV active power.

$$cos(\theta) = \frac{P_{SPV}}{S} \Longrightarrow S = \frac{P_{SPV}}{0.95} \tag{4.1}$$

$$Q_{output} = \sqrt{S^2 - P_{SPV}^2} \tag{4.2}$$

P_{SPV} is the power that the SPV is providing in real-time. S is based on the changing of power, due to the output power of the SPV. Q is the reactive power output that is contributing to the system.

Volt/VAr

Volt/VAr method is based on a) of Figure 2.2. The reactive power output is provided taking into account the selected voltage bands. In this project, the voltage V_b is selected to be 1.04 and V_q to be 1.06.

When the voltage is within V_b and V_q, the reactive power output follows Equation 4.3. Q_{output} is the output reactive power and as for Q_{rated}, it is the rated reactive power, based on the power factor of 0.95 and the rated SPV active power. V_{meas} is the measured bus voltage. V_b and V_q have the same values along all the SPV inverters of the network.

$$cos(\theta) = \frac{P_{rated}}{S} \Longrightarrow S = \frac{P_{rated}}{0.95}$$

$$Q_{rated} = \sqrt{S^2 - P_{rated}^2}$$

$$Q_{output} = \frac{Q_{rated}}{1.06 - 1.04} \cdot (V_{meas} - 1.04) \tag{4.3}$$

Power Curtailment

This method is based on the active power control. When the voltage violate the maximum voltage allowed by the grid codes, the output power is curtailed, until the voltage is bellow the voltage limit. Based on b) Figure 2.2, the output power curtailment follows the next equation:

$$P_{output} = \frac{P_q - P_{meas}}{V_p - V_q} \cdot (V_m - V_q) \tag{4.4}$$

Where P_q is the rated power of the SPV, P_{meas} is the measured power, V_p and V_q are the voltage bands. In this project the V_q is 1.06 p.u. and V_p is 1.1 p.u..

4.1.3 Battery Composite Model

In this sub-section, the composite model of the battery used in this project is described.

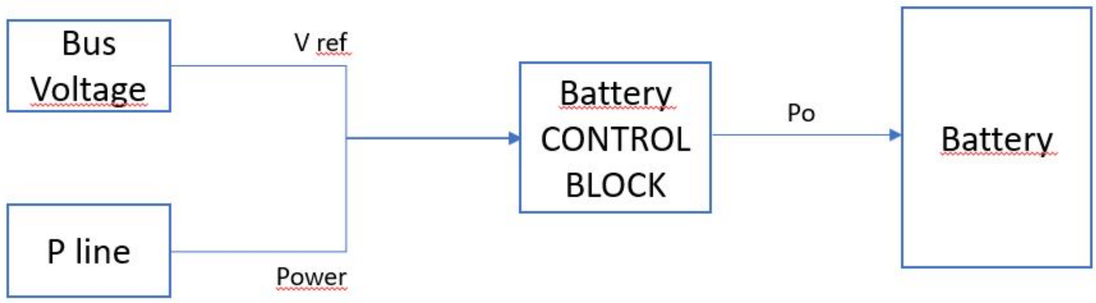


Figure 4.2: Battery composite model.

4.2 show the blocks that are used to model the battery. Bus voltage block is a measurement block that monitors the bus voltage in real-time. P line block decides how much power has to store or supply. Battery CONTROL BLOCK is the one which makes the different decisions, based on the needs of the system. Battery block is the battery itself, which provides or stores the energy, based on the input power that comes from the battery control block.

4.2 Working Principle

The battery is subjected to the SOC and the energy that has to supply or store. This section will describe with a flowchart the battery working principle.

4.2.1 Battery

Figure 4.3 shows the working principle of the BESS. The BESS charging mode is subjected to the SOC and the P_{line}. In order to have energy stored at the beginning of the day, the initial SOC is set to 50%. The BESS is capable to charge or discharge, only if the SOC is within the minimum and maximum SOC.

The BESS charge or discharge decision is subjected to the power flow measured on line 1. If the power is flowing towards the transformer (from the grid to the external network), the BESS will store the remaining power. On the other hand, if the power is flowing to the network, the BESS will provide energy to the system.

The power that the BESS can store or supply is subjected to the BESS rated power.

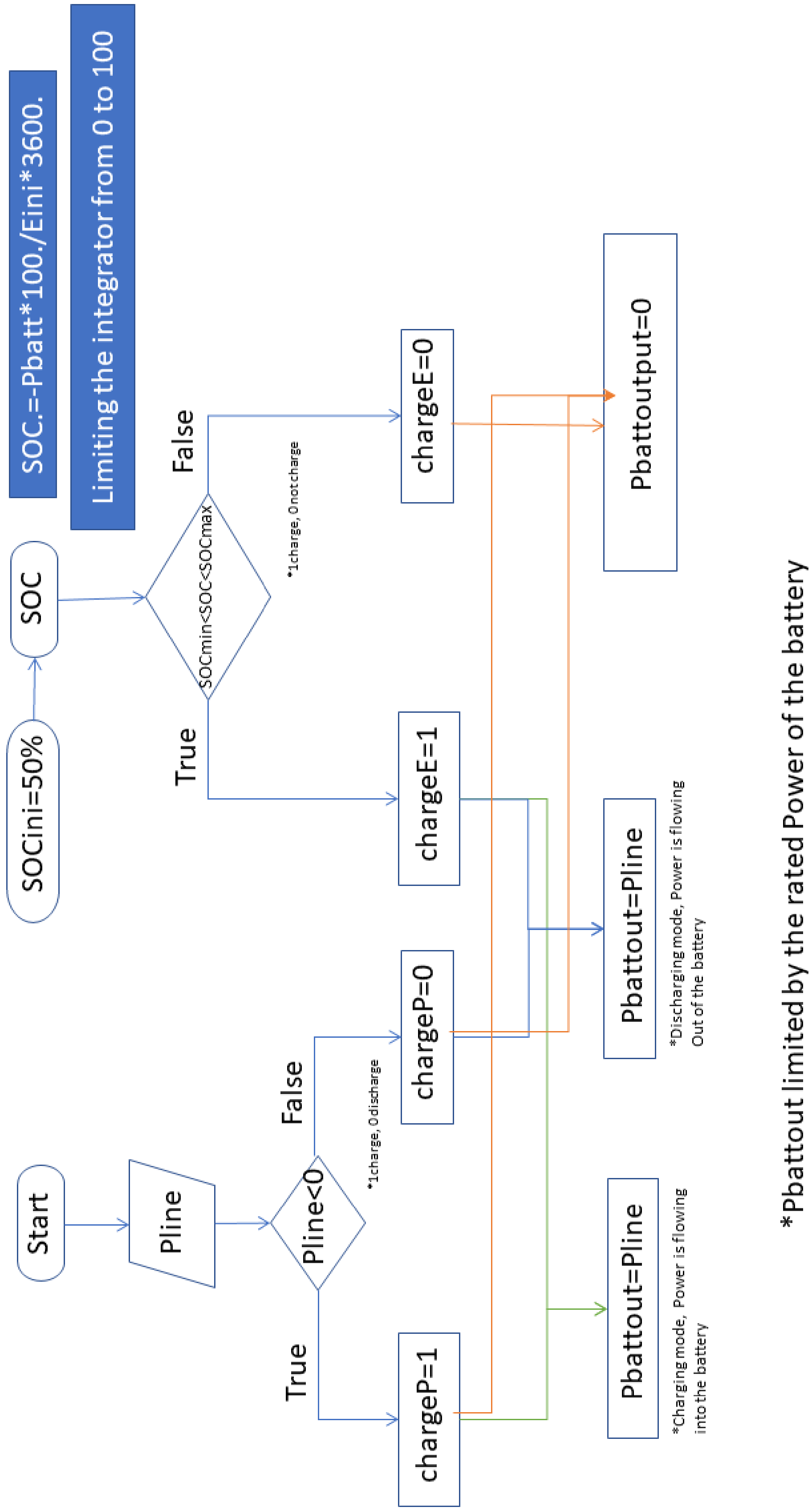


Figure 4.3: Battery flowchart.

Chapter 5

Active and Reactive Power Control to Voltage Support - RMS Simulation

In this chapter, the reactive power control method is applied in the normal case, whereas the active power control method is employed in the worst case scenario, which is when there is a SPV and there is no load connected.

Table 5.1: Control Methods Specifications

Control Method	Vb	Vq	$\cos(\phi)$	Scenario
Fixed Power Factor	-	-	0.95	Normal Case
Volt/VAr	1.04	1.06	0.95	Normal Case
Active Power Curtailment	-	1.06 to 1.09	0.95	Maximum SPV
Volt/VAr and Active Power Curtailment	1.04	1.06 to 1.08	0.95	Maximum SPV

Table 5.1 contains the voltage bands of the different control methods, as well as their power factor. The fixed power factor control method and the Volt/VAr control method are investigated on the normal case scenario, which is the case where the SPV and the loads are consuming/supplying power. The base case presented over-voltages, therefore, the reactive power control methods are applied in this scenario.

On the other hand, the active power curtailment control method and the Volt/VAr with active power curtailment control method are applied in the scenario "Maximum SPV". This scenario is chosen due to the presented high over-voltages.

5.1 Fixed Power Factor

In this section, different parameters, as voltage profiles, reactive power compensation, systems loading and the power flow of the transformer are displayed when the fixed power control is selected.

5.1.1 Voltage Profile

The voltage rise caused by the addition of the DGs has been presented in Chapter 1. Figure 5.1 presents the voltage level at the most critical bus, with the case in which there is no voltage regulation, and the case in which the SPVs are providing voltage control.

From Figure 5.1, it can be seen how the case without voltage regulation control presents an over-voltage ($u \geq 1.06$ $p.u.$), where the voltage reaches a voltage value of 1.08 $p.u.$. In order to decrease the voltage, the fixed power factor control method is integrated.

The Figure 5.1 presents the bus voltage, once the fixed power factor control method is integrated, whereas the new voltage at bus 18 presents a maximum voltage of 1.04 p.u.. This voltage drop is caused by the fact that all the SPV inverters, along the feeders, are contributing with its maximum reactive power compensation.

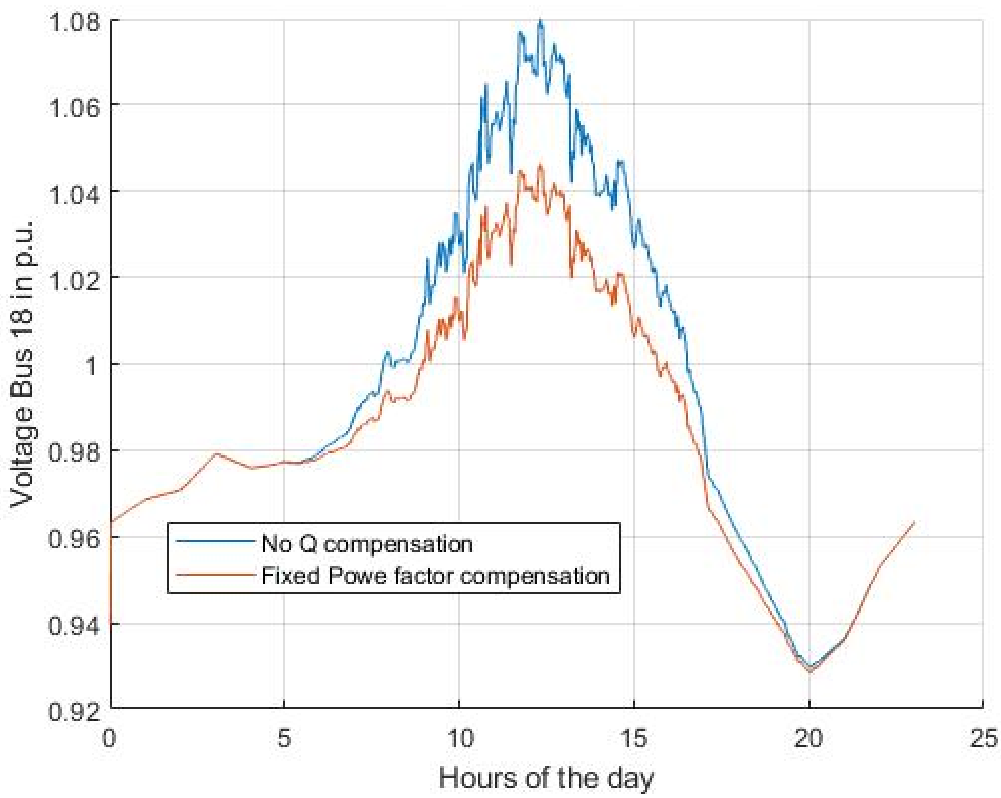


Figure 5.1: Voltage profile comparison.

5.1.2 Reactive Power Compensation

This sub-section presents the reactive power compensation of the SPV inverters in two different buses. The reactive power compensated by all the inverters follows the same curve. The difference between them is due to the fact that the reactive power is proportional to the active power that each SPV inverter supplies.

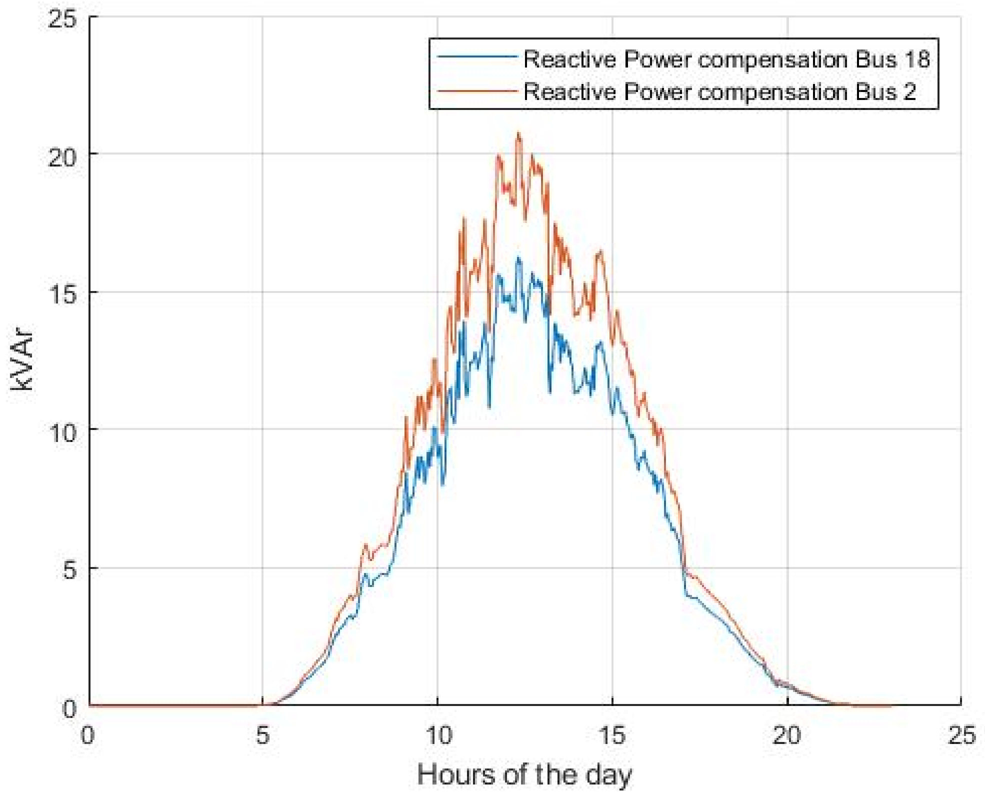


Figure 5.2: Reactive power compensation profiles.

Figure 5.2 represents the reactive power support from the SPV inverter at bus 2 and bus 18. It can be seen how the profiles are not providing reactive power during the night time. This occur as they are proportional to the SPV active output power, therefore, the peak is found at midday.

5.1.3 System's Loading

This sub-section is going to display different line loadings along the feeder.

Figure 5.3 presents the line loadings of different cables of the network. Any cable is close to its critical current capacity. However, line 1 is the most loaded cable. This is due to the fact that it has to endure with the power of all the SPVs and loads of the feeder.

The loading has increased, compared to the base case loading Figure 3.9. This happens by the extra power that is carrying by the additional power flowing through the cables (the supplemental reactive power).

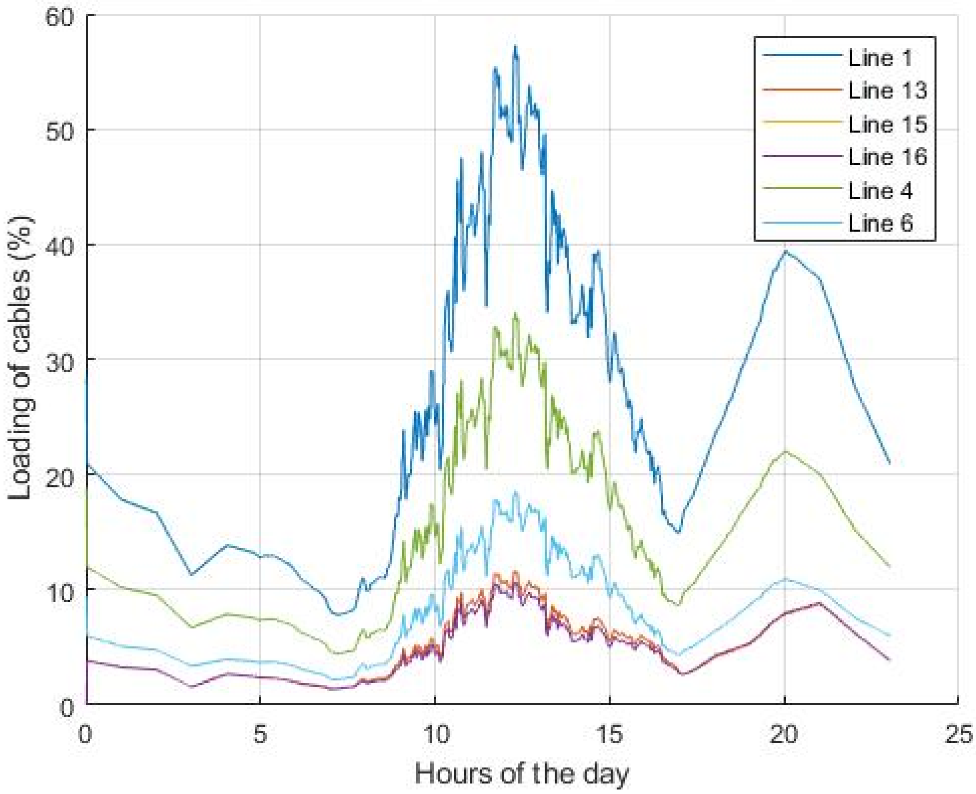


Figure 5.3: Cable loading of different lines.

5.1.4 Transformers Power Flow

The power flow of the transformer can be evaluated considering the energy flowing through the transformer. Figure 5.4 displays the active and reactive power flowing across the transformer.

Positive values mean that the power is flowing from the network to the external grid. On the other hand, negative values present the power flowing from the external grid to the LV network.

During the night, until 09:00, the current is flowing from the external grid towards the transformer. This occurs when the loads consumption is higher than the SPV generation, whereas at midday the power of flow is reverted by the exceed of the SPV power over the loads consumption.

Regarding reactive power flow, it can be seen how the system is always consuming reactive power. During the nigh period, the reactive power consumption is lower compared to the midday, as at midday, the SPV inverters are providing reactive power support.

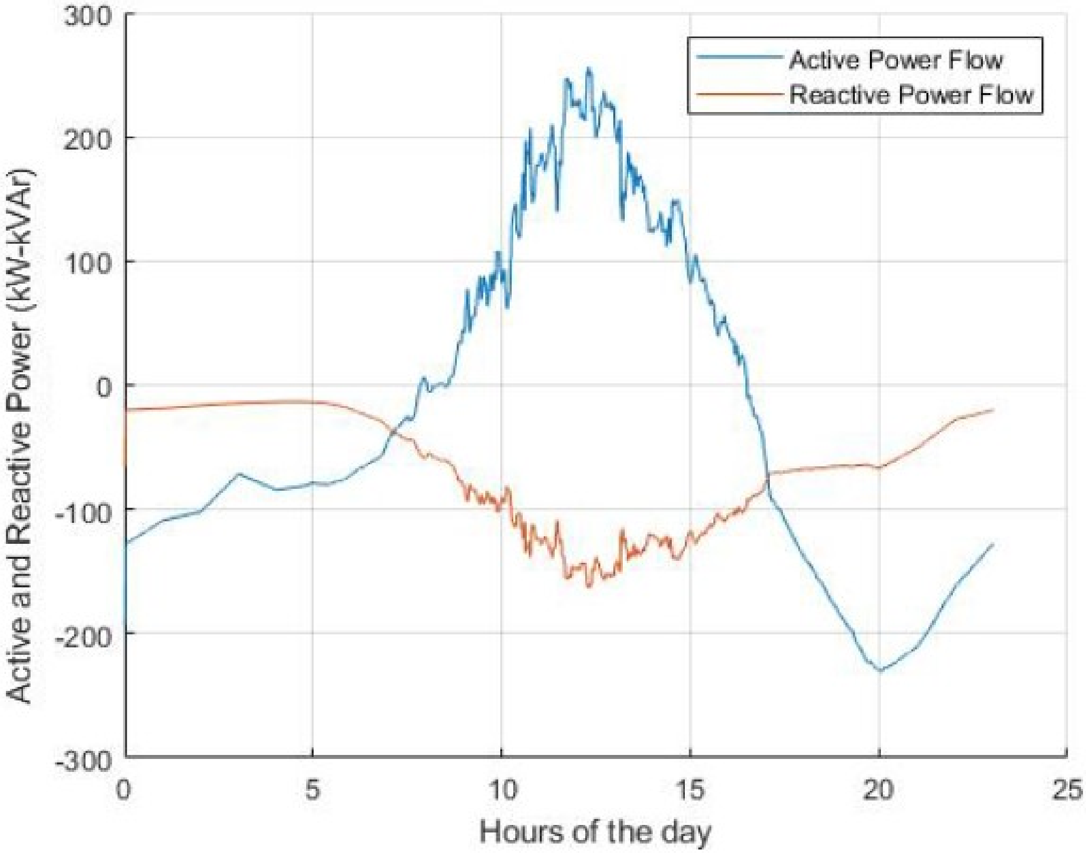


Figure 5.4: Transformers power flow.

5.2 Volt/Var

In this section, different parameters, as voltage, reactive power compensation, system's loading and transformer's power of flow are displayed when the Volt/VAr control is applied.

5.2.1 Voltage Profile

Figure 5.5 presents a voltage comparison at the most critical bus, when there is no voltage regulation and the case where the SPVs inverters are providing voltage support.

From Figure 5.5, it can be seen how the case without voltage regulation control presents an over-voltage ($u \geq 1.06\ p.u.$), in which the voltage reaches a voltage value of 1.08 $p.u.$. In order to decrease the voltage,the Volt/VAr control method is applied.

The Volt/VAr power control starts to act when the voltage reaches the value of 1.04 p.u.. From that moment, the reactive power supports follows the Equation 4.3 until the voltage cross 1.06 p.u..

It can be seen from Figure 5.5 how the voltage is decreased when the voltage reaches 1.04 p.u., with a smooth voltage drop. The voltage never reaches the value of 1.06 with this control method. In this scenario, the SPV inverters are capable to set the voltage into the limit selected of 1.06 p.u. without contributing to the rated reactive power of the SPV inverters.

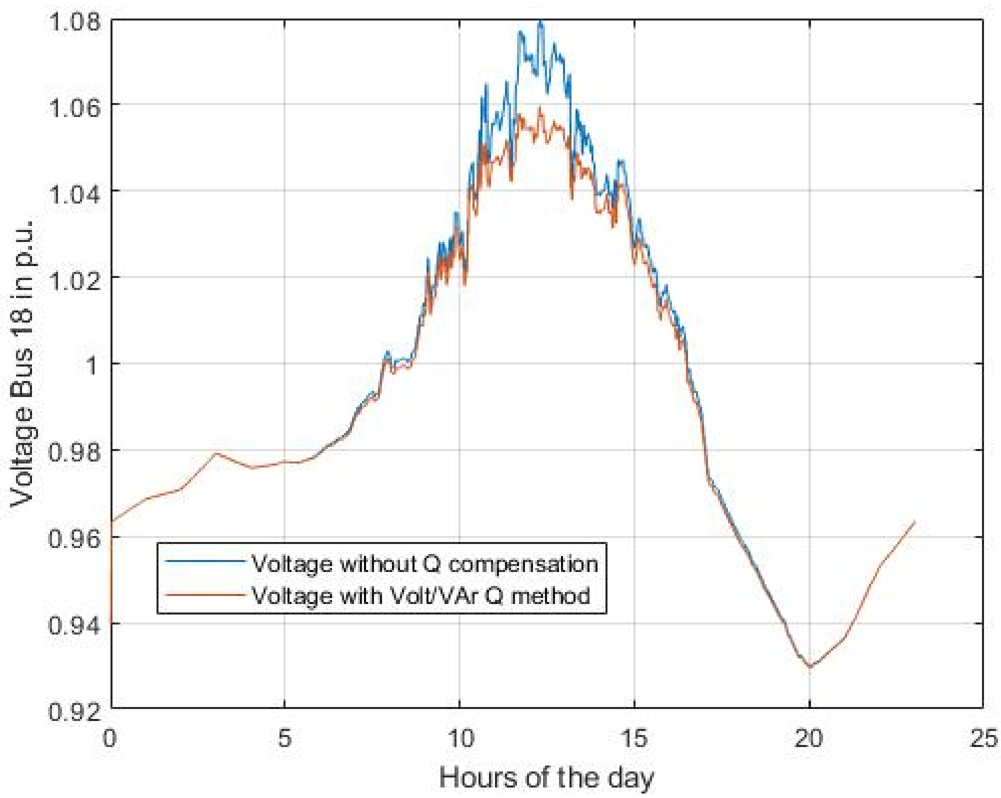


Figure 5.5: Voltage comparison with/without Volt/VAr control.

5.2.2 Reactive Power Compensation

This sub-section displays the reactive power contribution of the most critical bus.

The reactive power block is selected to act when the voltage surpasses 1.04 p.u., From that point, the SPVs inverters start to contribute with reactive power, following the Expression 4.3.

When the voltage crosses 1.06 p.u., the reactive power will support with the rated power of the SPV inverters. In this scenario, the voltage is not crossing the upper-limit.

There is a peak of reactive power support. This value is close to the rated power of the SPV inverters. The reactive power peak occurs when the voltage is close to 1.06 p.u..

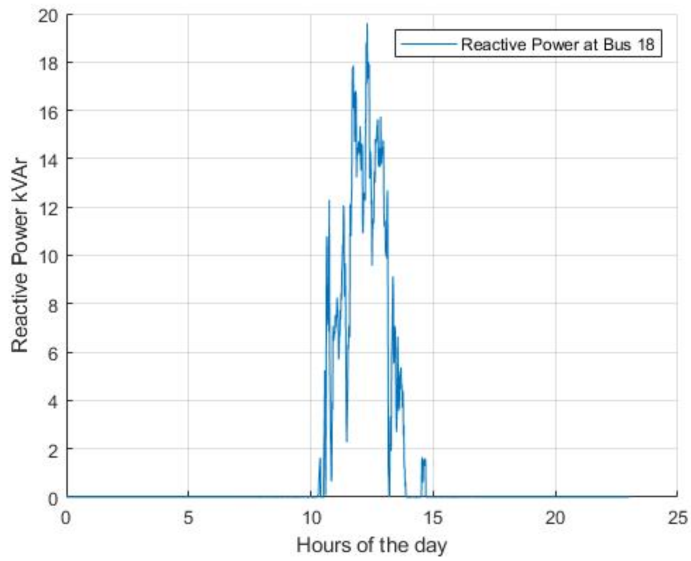


Figure 5.6: Reactive power contribution bus 18.

5.2.3 System's Loading

There are different selected lines of the feeder; lines 1, 4, 6 are part of the main feeder, whereas line 13, 15, 16 present the cables of the sub-radial feeders.

The main feeder presents higher loadings compared to the sub-radial feeders. The reason behind that is that the main feeder is enduring more power flowing through the cables. However, they are far from their rated current.

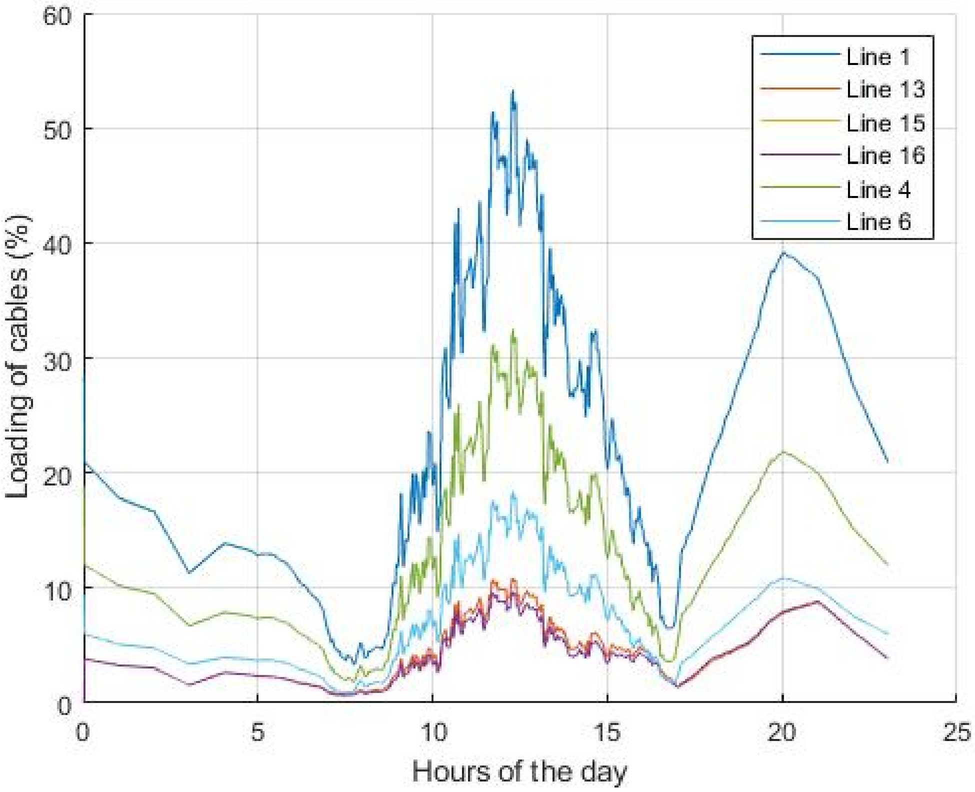


Figure 5.7: Cable loading of different lines.

5.2.4 Transformers Power Flow

The current is flowing (from 00:00 to 09:00) from the external grid to the transformer. This is when the loads consumption is higher than the SPV generation, whereas at midday the power of flow is reverted by the exceed of the SPV power over the loads consumption.

Regarding reactive power flow, it can be seen how the system is always consuming reactive power. During the nigh period, the reactive power consumption is lower compared to the midday, as at midday the SPV inverters are providing reactive power support.

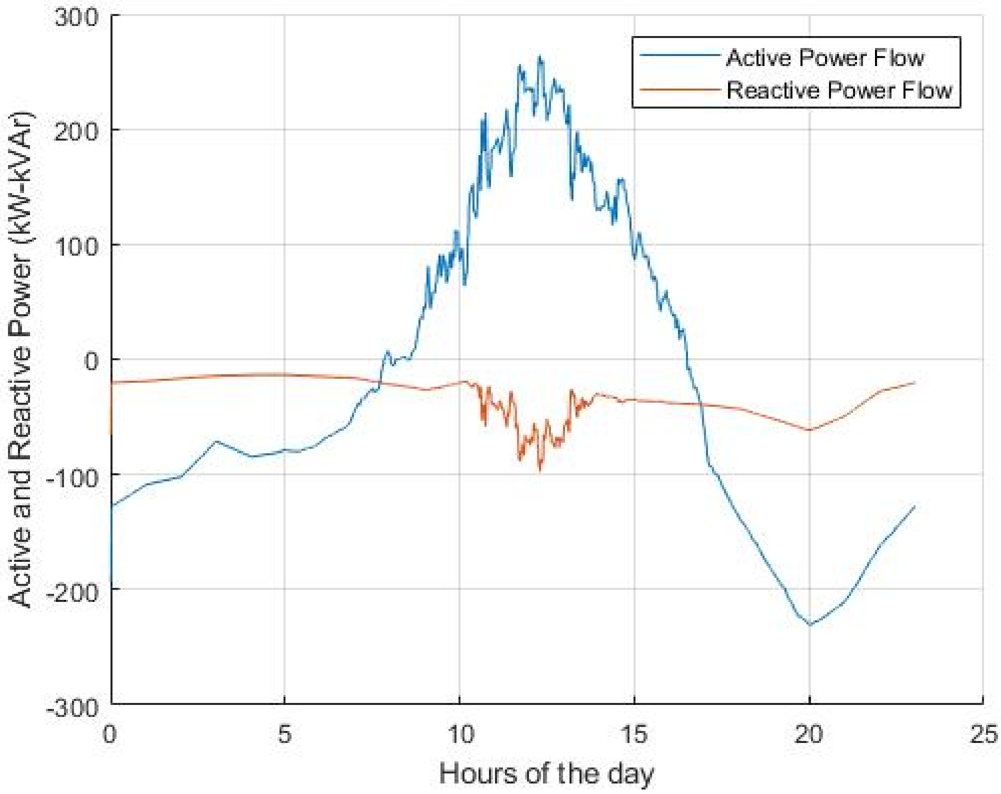


Figure 5.8: Transformer power flow.

5.3 Active Power Curtailment

In this section, the voltage and the active power output are displayed from the scenario where the SPVs are providing active power and the loads are disconnected.

The power flow of the cable congestion and transformer are not presented, as this method is curtailing the active power. This decreases the cable congestion, whereas the transformer power flow follows the same shape as the previous methods.

5.3.1 Voltage Profile

Figure 5.9 show the voltage level at the most critical bus, comparing the case in which there is no active power curtailment and the case developed with the voltage control method.

It can be seen from Figure 5.9 how the voltage of both scenarios are the same, until the voltage reaches 1.06 p.u.. From that moment the power is curtailed until the voltage is bellow 1.09 p.u., which is the maximum voltage selected for this method.

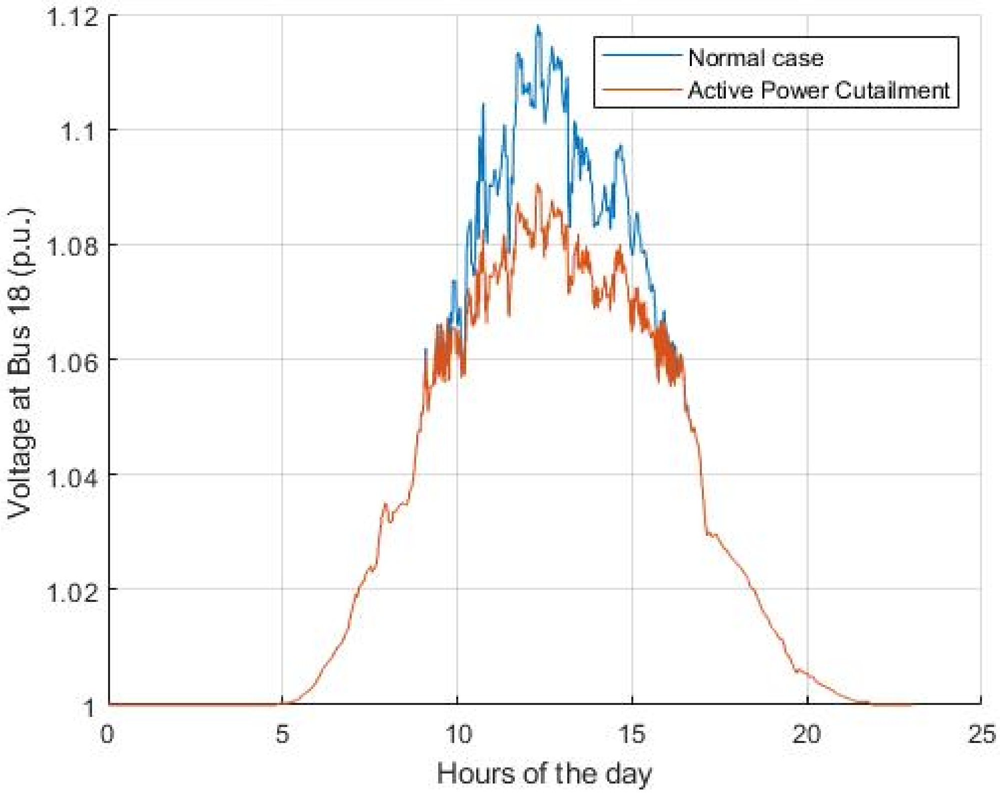


Figure 5.9: Voltage profile comparison.

5.3.2 Active Power Curtailment

This sub-section presents the active power provided from the SPV inverter at bus 18, from the case with no active power curtailment and the case with active power curtailment.

From Figure 5.10, it can be seen how the active power starts to curtail the power. This is due to the voltage measured at the PCC. When the voltage reaches 1.06 p.u., the SPV inverter starts to curtail the active power output.

From the active power curtailment, the power has been curtailed a 72 % of the maximum power. This percentage is the maximum power curtail needed to set the voltage into the limit of 1.09 p.u..

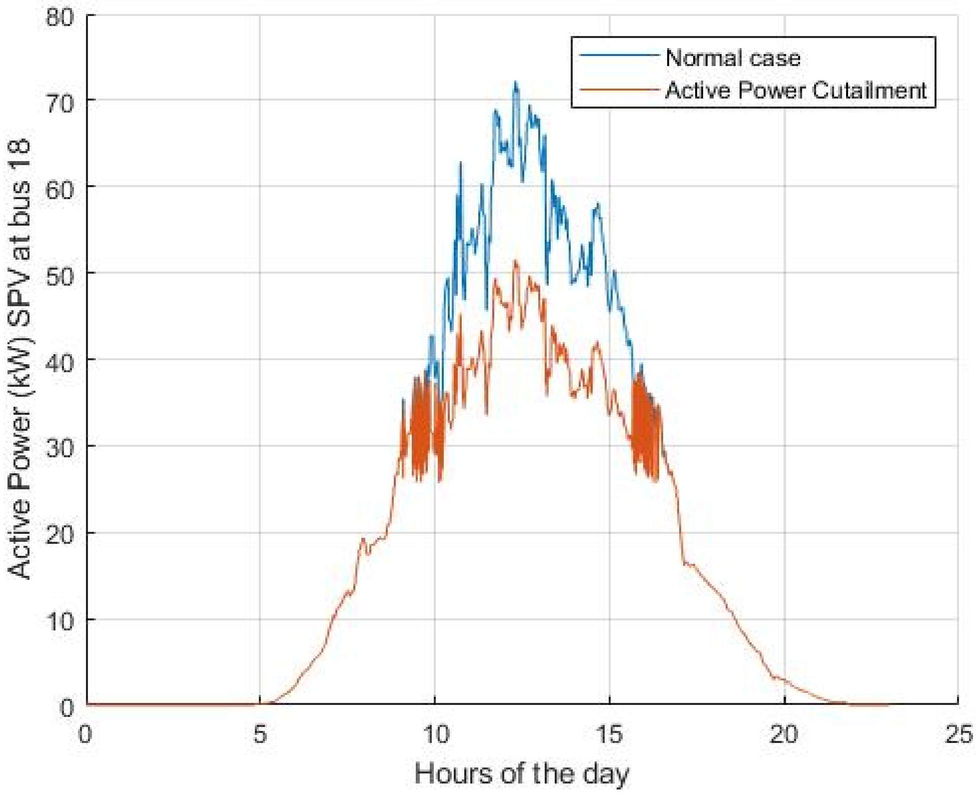


Figure 5.10: SPV power output comparison.

5.4 Volt/VAr and Power Curtailment

In this section, the Volt/VAr method is applied together with the active power curtailment.

In this method, the Volt/VAr control method starts to act when the voltage reaches 1.04 p.u., until 1.06 p.u.. From that moment, the active power is curtailed until the voltage is decreased to the voltage of 1.08 p.u.

5.4.1 Voltage Profile

In this sub-section, the voltage profile is presented in the case without voltage support, and the case where the Volt/VAr and the active power curtailment provide voltage support.

From Figure 5.11, it can be seen how the voltage primarily had a peak voltage of 1.13 p.u., whereas after the control method, the SPV inverters were capable to regulate the voltage until 1.08 p.u..

It is clear to see how the control method is selected to act when the voltage reaches 1.04 p.u.. From 1.04 to 1.06 p.u. the control method which is acting is the Volt/VAr method. Once the reactive power is supporting with its maximum power rated, the active power is curtailed until the voltage is bellow 1.08 p.u.

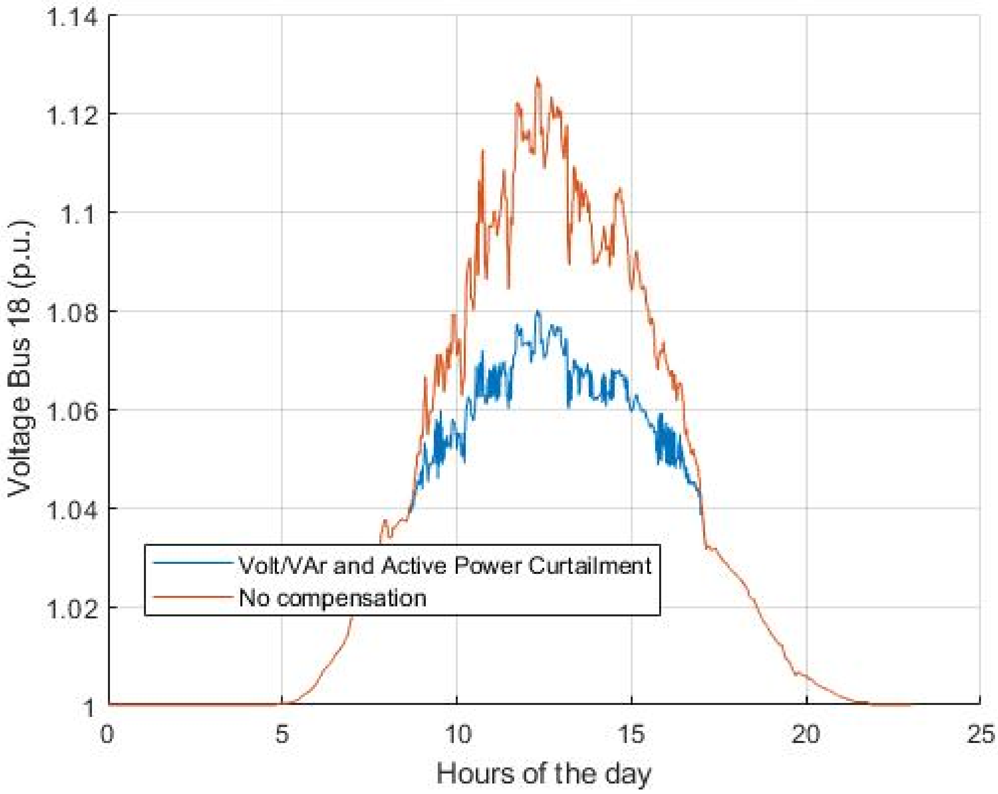


Figure 5.11: Bus voltage comparison.

5.4.2 Reactive Power Compensation

In this sub-section, the reactive power of the most critical bus is presented.

From Figure 5.12, it can be seen the reactive power compensation to voltage support. The reactive power is set to act following the Equation 4.3 from the voltage 1.04 to 1.06 p.u.. In the Figure, this band represents the increasing and decreasing part.

Once the voltage reaches the voltage of 1.06 p.u., the SPV inverters provide with its maximum reactive power support. The flat part of the graph represents the maximum reactive power support.

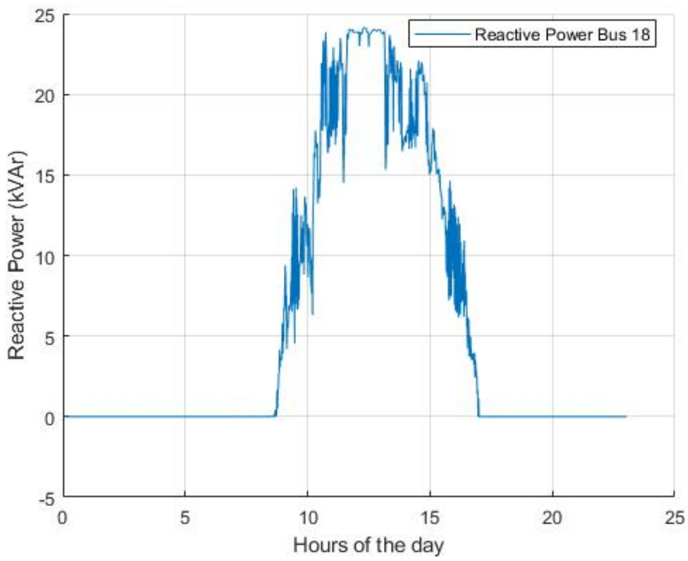


Figure 5.12: Reactive power compensation.

5.4.3 Active Power Curtailment

In this sub-section, the active power curtailment is presented in the normal scenario, as well as the case where Volt/VAr and active power curtailment control methods are applied.

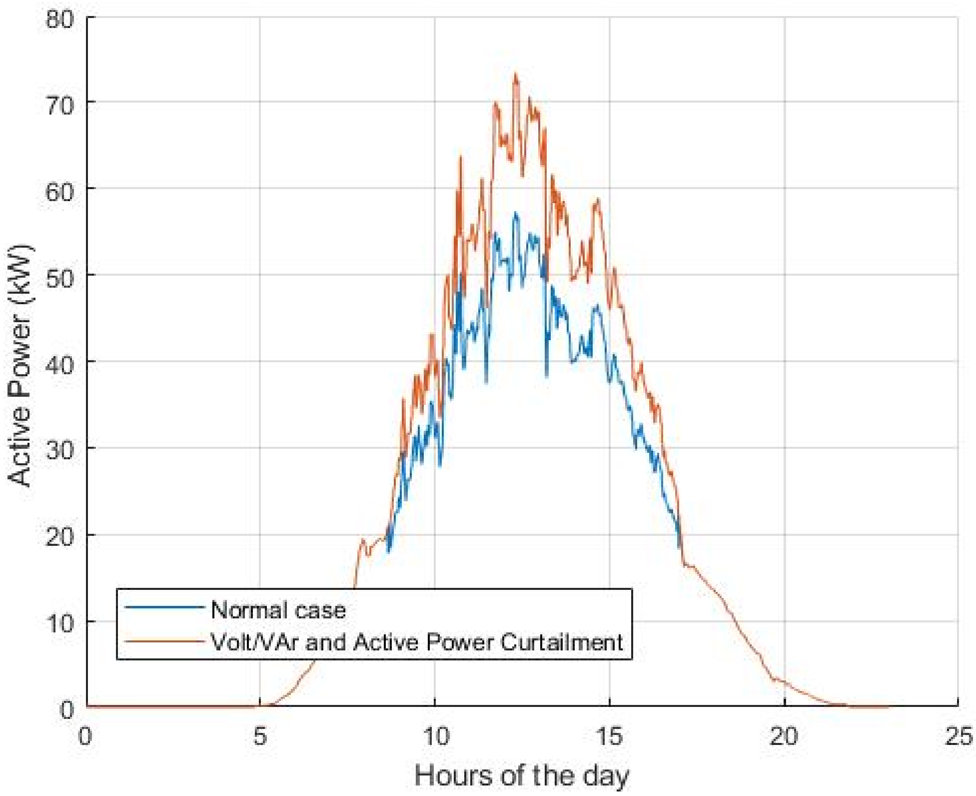


Figure 5.13: SPV active power comparison.

From Figure 5.19 it can be seen how the active power is curtailed around 80 % of the power. This is due to the fact that the controller is set to curtail the power when the voltage surpasses 1.06 p.u.. The active power curtailment stops when the voltage is lower than 1.08 p.u..

5.5 Summarizing

In this section, the different control methods are compared in order to present the different advantages between them. For that purpose, the voltage profiles, cable loading, reactive power compensation and active power curtailment are presented.

5.5.1 Fixed Power Factor, Volt/Var Comparison

In this sub-section, the fixed power factor and the Volt/VAr control methods are going to be compared. These two control methods are studied under the same scenario, therefore, they can be compared in order to investigate the advantages or disadvantages that each method presents.

Voltage Comparison

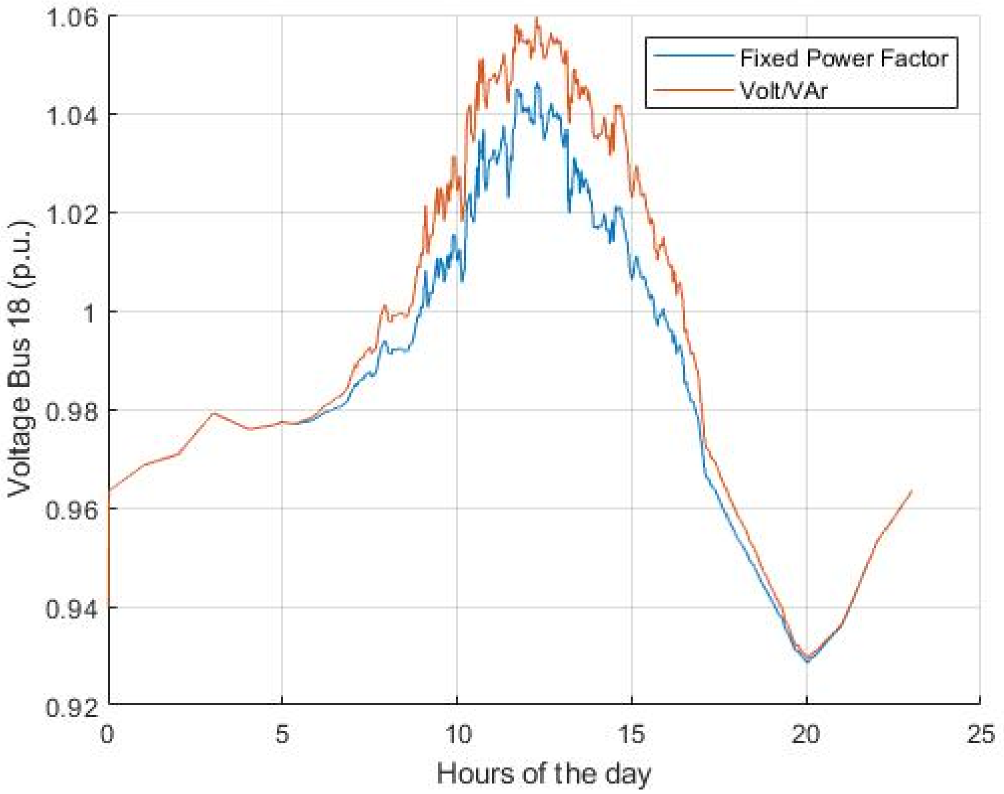


Figure 5.14: Voltage comparison.

From Figure 5.14 it can be seen a comparison of the fixed power factor and the Volt/Var control methods.

The fixed power factor control method presents a lower voltage profile compared with the Volt/VAr control method. This is due to the fact that the reactive power contribution is independent from the voltage measured at the PCC. The reactive power support is proportional to the active power of the SPVs inverters.

The case where the Volt/VAr control method is applied shows how the voltage from 1.04 to 1.06 p.u. have a flatter shape, compared to the voltage of the fixed power factor control method. The reason is that the reactive power is adjusting its output power based on the voltage measured at the PCC.

Reactive Power Comparison

This sub-section presents the reactive power support from the fixed power and the Volt/VAr control methods.

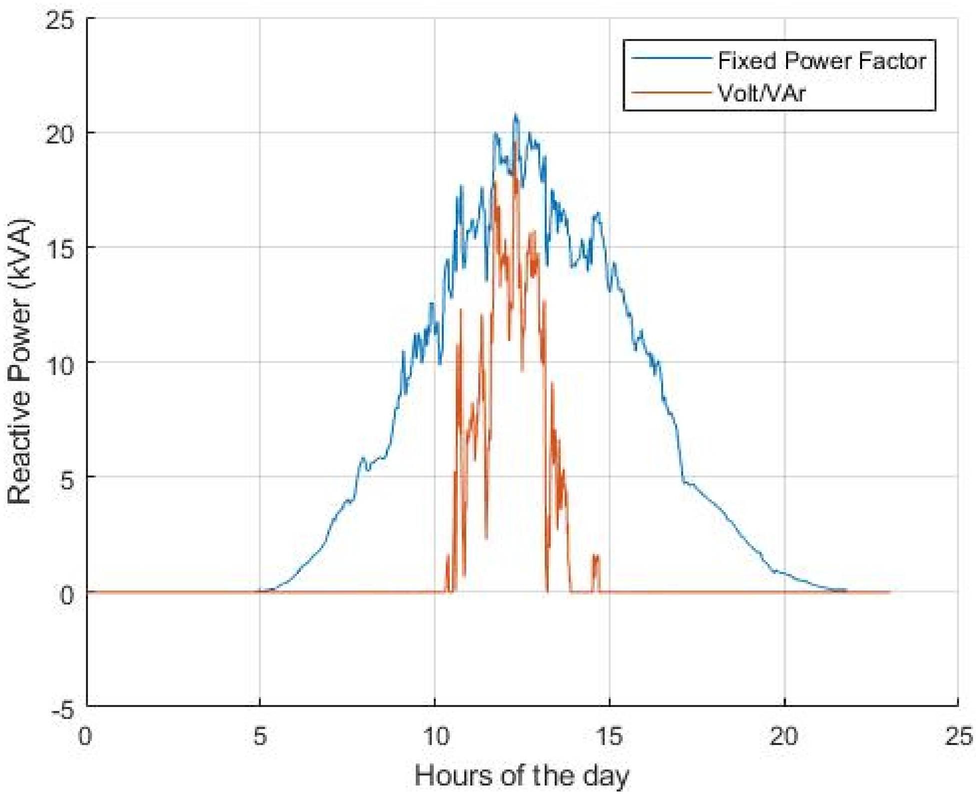


Figure 5.15: Reactive power comparison.

From Figure 5.15, it can be seen how the fixed power factor is contributing with reactive power during a larger time frame, compared to the Volt/VAr control method. This is due to the fact that the fixed power factor is contributing with reactive power as long as the SPV inverters are supplying active power, with a lagging power factor of 0.95.

The Volt/VAr control method is acting only when the voltage is above 1.04, therefore, the reactive power support is less.

The main advantage of the Volt/VAr is that the reactive power support is acting only while the system needs voltage support. On the other hand, the fixed power factor's main advantage is that all the SPV inverters are contributing with the same reactive power.

5.5.2 Active Power Curtailment and Volt/Var with Active Power Curtailment

Voltage Comparison

This sub-section presents the voltage comparison of the active power curtailment with and without the Volt/VAr control method. Figure 5.16 shows the voltage profile of both

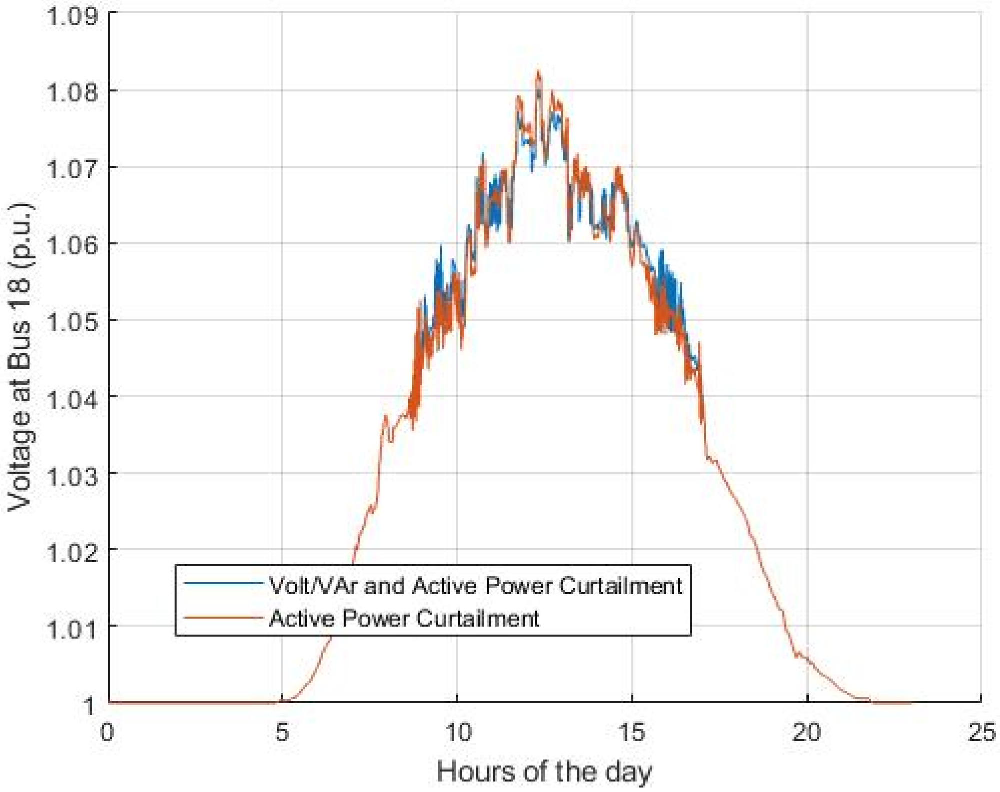


Figure 5.16: Bus voltage comparison.

control schemes. It can be seen how the voltage profile is similar in both cases, where the peak voltage is found at the same time and almost the same voltage of 1.08 p.u.

Active Power Comparison

This sub-section is more interesting compared to the voltage of the two different control methods.

It can be seen from Figure 5.17 how the power output of the active power control is higher compared to the active power curtailment without Volt/VAr control.

The fact that the active curtailment with Volt/VAr control method active power is higher, with the same voltage profile, makes the system increase the hosting capacity of itself.

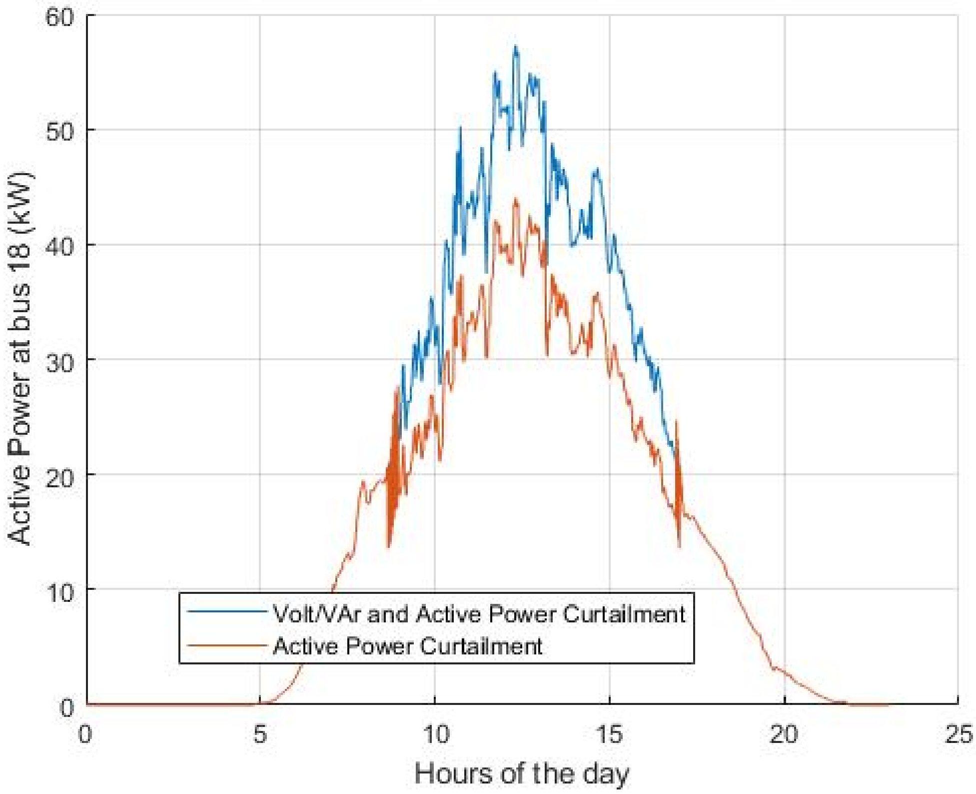


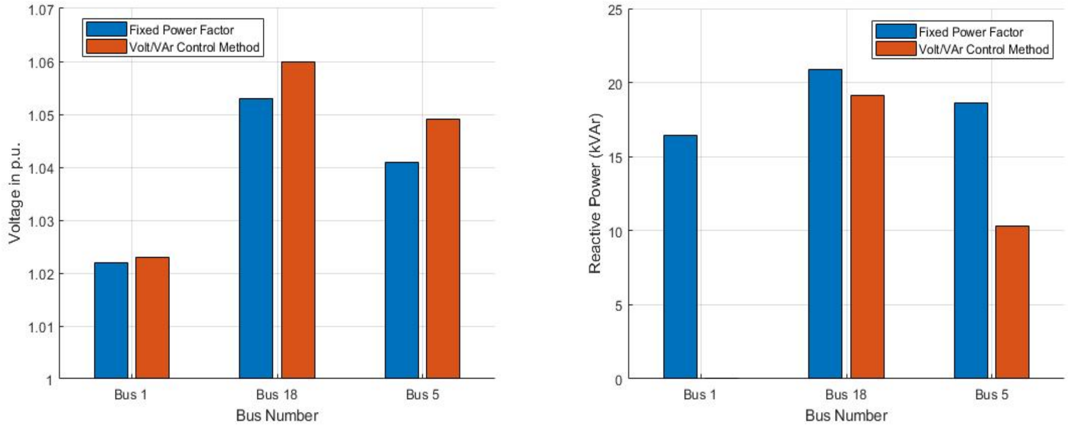
Figure 5.17: Active power comparison.

5.6 Conclusion

In this chapter, the proposed control methods for voltage support are presented. The different methods present different advantages and disadvantages, regarding voltage profiles and the power support.

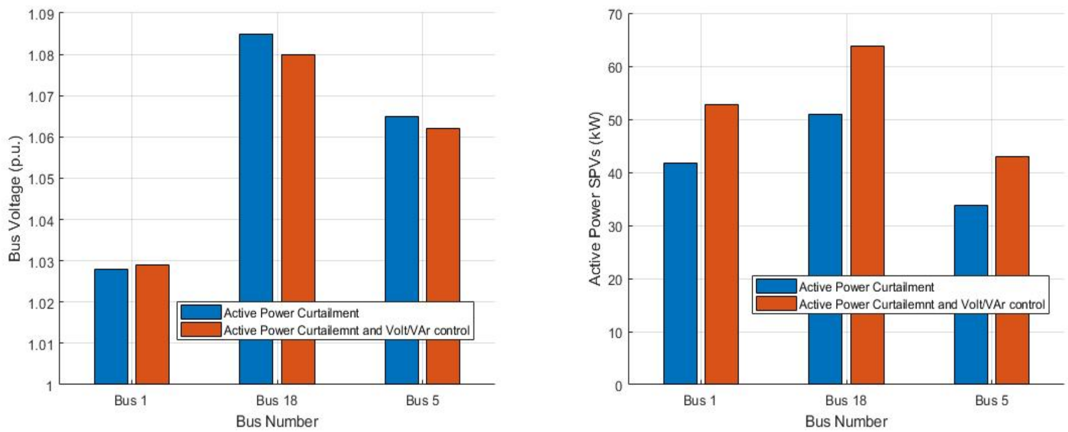
Figure 5.18b and 5.18a shows how the voltage of the fixed power factor control methods are lower in the buses far from the transformer (where the reactive power support is more significant). In order to get these better voltage profiles, a contribution with much more reactive power is needed. On the other hand, the Volt/VAr presents almost the same voltage profiles with less reactive power support. In cases where the SPV power production is high, the fixed power factor is more suitable, due to high reactive power contribution.

Figure 5.19b and 5.19a present the voltage of three different buses. It can be seen how the voltage is almost the same in all the buses. In order to get these almost equal voltages, the amount of active power is quite different. Active power curtailment with Volt/VAr control presents a 19% of higher active power output to get the same voltages. This means that the active power curtailment with Volt/VAr control increases the hosting capacity of the system, being more suitable to higher penetration of SPVs.



(a) Bus Voltage **(b)** Reactive power support

Figure 5.18: Comparison of fixed power factor and Volt/VAr control methods.



(a) Bus voltage **(b)** Active power curtailment

Figure 5.19: Comparison of active power curtailment with and without Volt/VAr control methods.

Chapter 6

Battery Implementation to Voltage Support - RMS Simulation

The "normal case" is the analyzed scenario in this chapter. The parameters under study are the voltage profiles in the case with BESS as well as in the base case; the transformer loading; the BESS output power supplied or stored, and the SOC of the battery. The chapter ends with a conclusion of it.

6.1 Battery Implementation

The BESS is placed in bus 1 of the network and it is sized to make a significant impact at the most critical bus. Table 6.1 presents the battery specifications. The battery energy is set to endure 10 h storing or supplying with rated power. In this project, the battery stresses and power supplying limitations are not considered. Therefore, the battery can endure the energy supplied or consumed to the rated power. Equation 6.1 expresses the necessary power to decrease the voltage at bus 18, from 1.08 to 1.060 p.u.

Table 6.1: Battery Specification

Battery	%	kW	kWh
Rated Power	-	150	-
Battery Energy	-	-	1500
$SOC_{Initial}$	50	-	-
SOC_{min}	10	-	-
SOC_{max}	90	-	-

$$P_{BESS} = \frac{\Delta V}{\frac{\delta V_{ij}}{\delta P_{ij}}} \Rightarrow P_{BESS} = \frac{0.02 p.u.}{0.000133[p.u./kW]} = 150kW \tag{6.1}$$

$\frac{\delta V_{ij}}{\delta P_{ij}}$ is the voltage sensitivity. i is bus 1 and j is bus 18. ΔV is the voltage difference between the normal value and the value selected to achieve. The voltage sensitivity expresses how the voltage changes while variations of power.

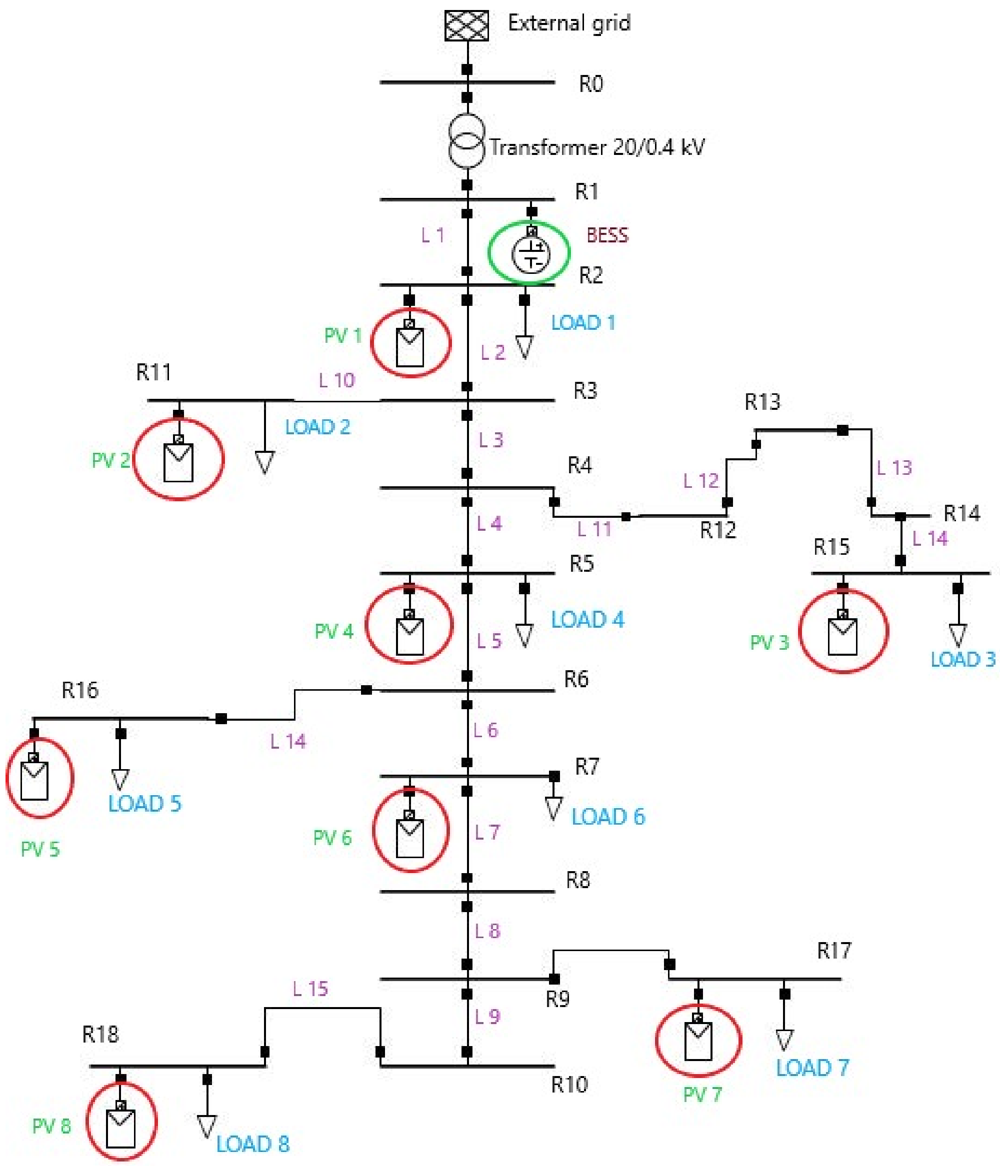


Figure 6.1: CIGRE LV Residential feeder [36] with SPV and BESS.

Figure 6.1 presents the network with the BESS placed at bus 1. The topology and the dynamic devices (loads and SPVs) are maintained in the same location and the same size as previous chapters.

6.1.1 Battery and Active Power Curtailment

The BESS is implemented along with the active power curtailment control method. In order to investigate how the BESS improves the systems performance, different parameters are compared to ensure the improvement of the BESS on the system.

Voltage Profile

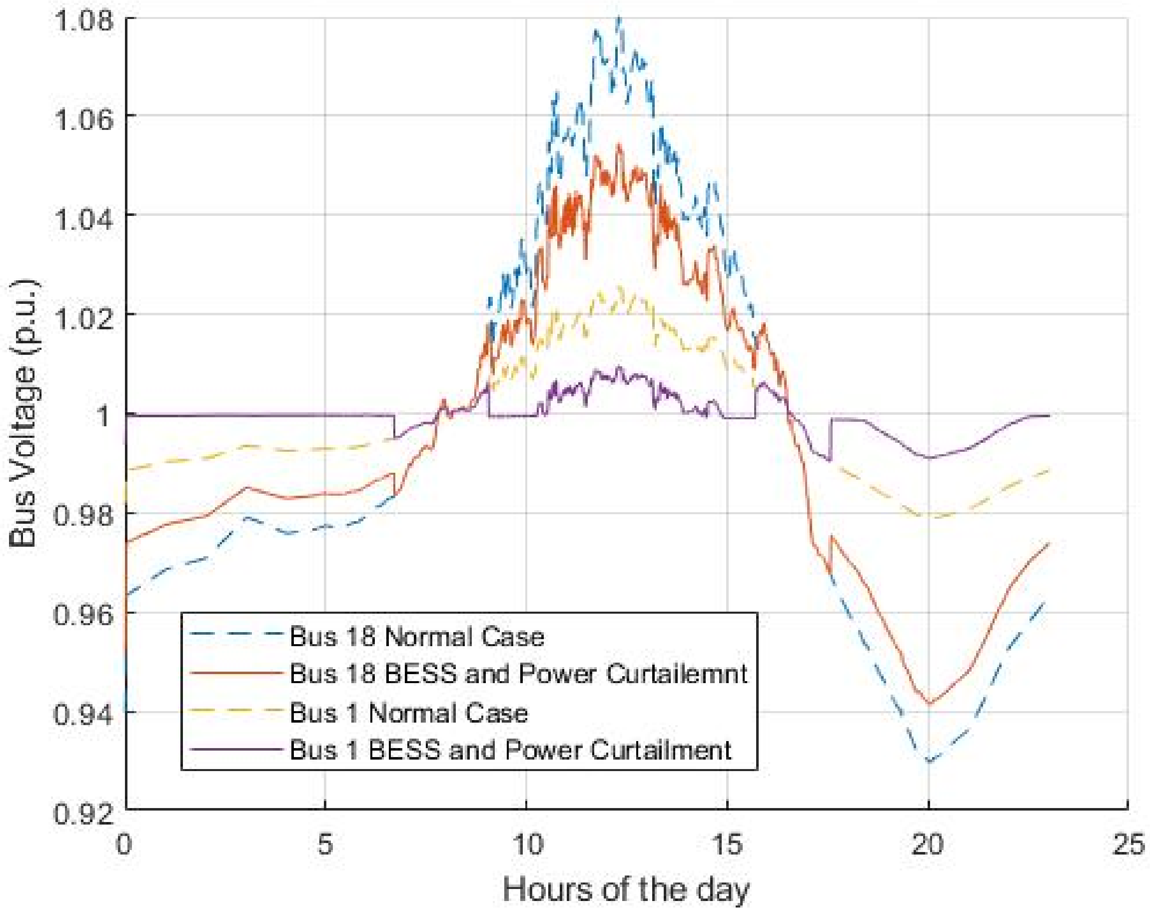


Figure 6.2: Voltage Profiles Comparison.

Figure 6.2 presents the voltage profiles of the closest bus and the farthest bus from the transformer. From Figure 6.2, it can be seen an improvement on the voltage profiles. Bus 1, where the BESS is connected, presents voltages close to 1 p.u. due to the BESS impact, whereas at the most critical bus, the voltage is improved by the absorption of the extra power generated by all the SPVs.

The battery is performed to absorb or supply power, based on the measured power of line 1 (from bus 1 to bus 2).

Transformer Loading

This sub-section presents the transformer loading in the normal operation case, in the scenario with BESS and the base case.

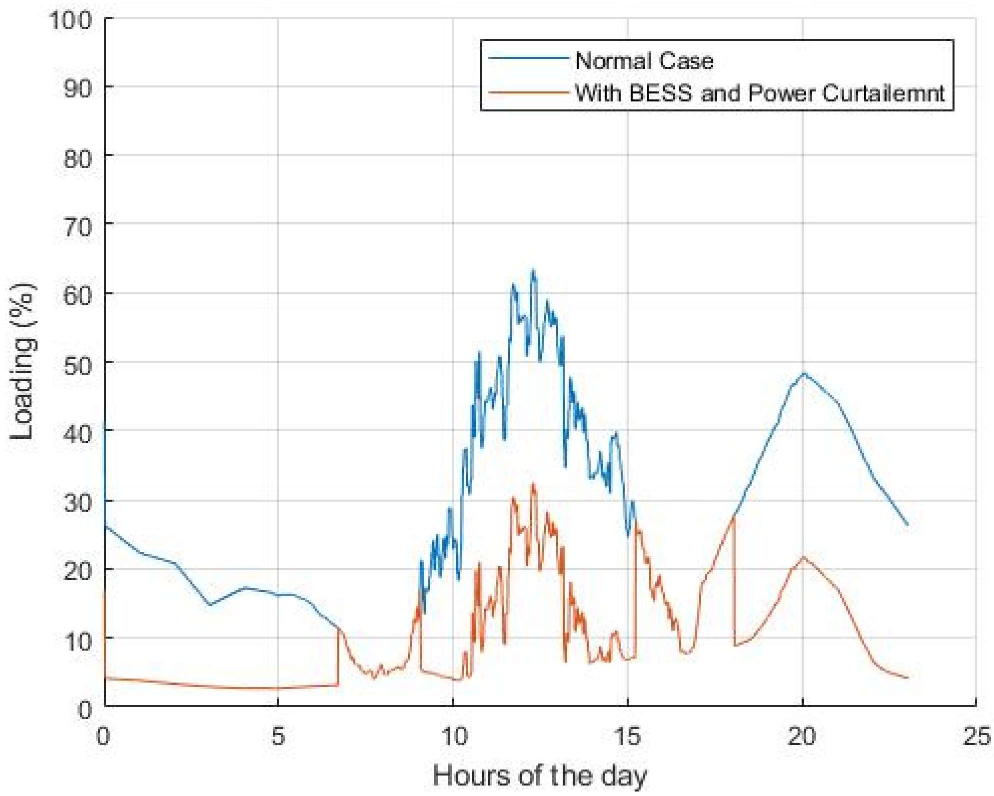


Figure 6.3: Transformer's Loading Comparison.

It can be seen from Figure 6.3 how the transformer loading is significantly decreased with the BESS implementation.

From 00:00 to 7:00, it can be seen how the loading of the transformer is close to zero and it has a flat shape. This is caused by the discharging of the BESS, due to loading consumption. The BESS is set to supply the necessary power to comply the Equation $P_{line} = P_{battery}$, if the battery power is sufficient to complete this equation and the BESS has enough energy.

From 10:00 to 15:00, it can be seen how the power in the base case is increasing until reaching the peak (when the solar irradiance is maximum). At this moment, as the SPVs are delivering more power, compared to the loads consumption, the BESS is in charging mode, therefore, the net power of the line is decreased.

Battery Power Output

The battery is rated to the power of 150 kW, which means that the power the BESS can supply or consume can not exceed this power. Figure 6.4 displays the BESS power output. Negative values mean that battery is discharging, whereas, on the other hand,

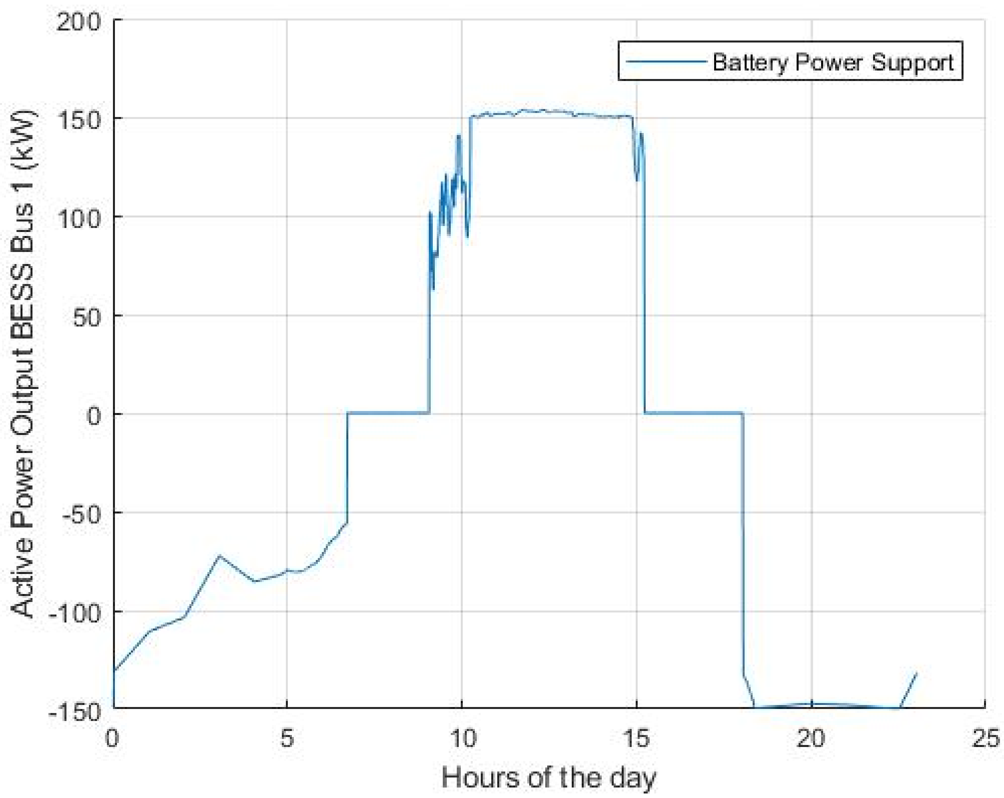


Figure 6.4: BESS output Power

positive values mean that the battery is charging.

The battery is performed to consume or supply power according to the power measured on line 1 (from bus 1 to bus 2), therefore, it is adjusting the power following this premise.

The upper limit of 150 kW and the lower limit of 150 kW is due to the battery rated power. The instant when the output power is zero is the moment when the BESS has reached the maximum or minimum SOC. In Figure 6.4, the first part, where the BESS reaches zero, is due to the battery discharge. The second moment where the BESS is zero is when the BESS has reached the maximum SOC.

SOC

In this project, the simulation is carried out during 24 hours. The initial SOC is presupposed to be 50%. Otherwise, the BESS will be initialized without energy stored.

Figure 6.5 presents the SOC of the battery. As it is stated, the initial SOC is set to be 50%. It can be seen that the battery starts to discharge from the initial SOC until reaching the value of 10%. This is the minimum SOC selected in this project. This discharge is due to the line power (load is consuming more power that the SPV is supplying).

Once the battery reaches the minimum SOC, it is discharged, therefore, the battery can not supply more power.

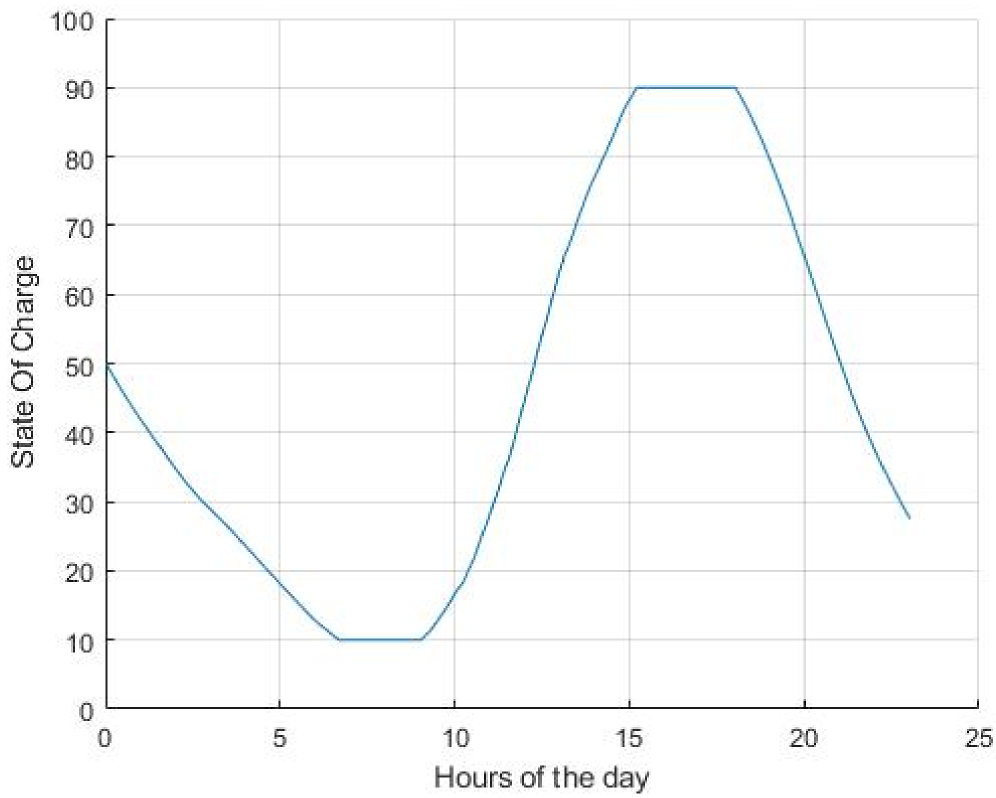


Figure 6.5: Battery State Of Charge (%).

Since the SPV produces more power, compared to loads consumption, the battery starts to charge, until the battery reaches the maximum SOC, which is 90%. After the SOC is fully charged, the battery stays fully charged until the loads consumption surpasses the SPVs power production. At that time, the battery is discharging.

6.2 Conclusion

In this chapter, the BESS is implemented together with the active power curtailment method. With the selected size, the battery was capable to decrease the bus voltage at the last bus 0.2 p.u.. Once the battery decreases the voltage, if the bus voltage was above 1.06 p.u., the SPV inverter curtails the active power until reaching the required voltage.

The energy stored at the end of the day is around 27 %, which means that it has energy to cover the next days requirement for voltage support.

The BESS has improved the loading of the system by absorbing the remaining power from the SPVs and supplying the required power when the load demanded higher power than the SPVs production. The BESS has increased the hosting capacity of the system by absorbing this remaining energy, in other words, the BESS is capable to improve the voltage at the most critical bus 0.15 p.u., increasing the hosting capacity of the system.

Chapter 7

Conclusion

The objective of this project was to analyze the voltage deviation that high penetration of SPVs may cause on the distribution network, as well as provide voltage regulation with different voltage control methods. The first chapter presented the background, the formulation problem and the objective of this project. Additionally, different limitations have been settle in order to accomplish the project. The work focuses on the voltage rises that the distribution grid could face in cases of high penetration of SPV in the LV distribution network. In order to analyze the LV benchmark model, the tool used was the DigSilent PowerFactory. The LV benchmark model used consists on 3 different feeders: an industrial feeder, a commercial one and a residential one, being this project focused on the latter, which consists on a main radial feeder with small radial feeders as well.

Subsequently, a steady state analysis has been carried out in two different scenarios: on the one hand, a scenario in which there were only SPVs connected, and on the other hand, a normal scenario with both SPV and load following their demand profiles. The results of the base case were analyzed without any voltage regulation technique. The base case was analyzed in two different scenarios, the first one was the "maximum SPV generation and no load consumption" case. It presented voltages above 1.10 in the two buses farther from the transformer, where several buses presented voltages above 1.06 p.u., which is the selected voltage limit. The case with maximum load consumption presented under-voltages close to 0.93 p.u., but always above the value. After investigating the two worst scenarios, a 24 hours simulation was carried out in two different cases: a case containing only SPV generation, on the one hand, and a normal case, on the other hand. The first case presented voltages close to 1.12 p.u. whereas in the other one, the voltages were higher, but close 1.08 p.u..

As previously stated, the LV benchmark model presented over-voltages that had to bee mitigated. For this purpose, a control block has been implemented with different reactive and active power control techniques. All the control techniques have been analyzed and found to be suitable to control the voltage in this LV benchmark model. Different advantages and disadvantages are found among these different control techniques. The fixed power control is found to be a good voltage control method in large systems with high SPV penetration level, as this method is always contributing with the maximum reactive power. The voltage is controlled indirectly at the PCC, as this control method is not monitoring the voltage. The best control method found was the Volt/VAr control method, which consists on a close loop controller, where the reactive power support depends on the voltage measured on the PCC. The voltage at the PCC is the parameter which will give the output of the reactive power. Different active power methods were used in this project, such as the active power curtailment and the active power curtailment with Volt/VAr control method. The active power curtailment with Volt/VAr presented lower active power curtailment with the same voltage profile, compared to the active power curtailment, resulting this on an increase of the hosting capacity of the network.

At last, a BESS was placed on the system with voltage regulation purposes. It was placed at the first bus. After analyzing the impact of the BESS on the different buses, the voltage profiles have improved.

Different power control strategies have been carried out without any economic and technical feasibility studies. Without taking this into consideration, and based on the results, the two best methods for voltage mitigation are found on the reactive power control methods. These methods increased significantly the hosting capacity of the network. The BESS was found to be a good voltage control method. The systems hosting capacity has increased because of storing the surplus of energy.

Chapter 8

Future Work

This chapter gathers the tasks that can be implemented in the future to expand and complete the present work.

- **Economic and technical feasibility study:** In order to gain a key knowledge on which voltage control method is more suitable, an economic study could be addressed, making a cost/benefit approach of every control method.
- **BESS powers capacity:** In this project, the battery is capable to supply its rated power whilst the battery has stored energy. Therefore, it could be interesting to investigate the impact of a real BESS on the network.
- **Long term studies:** This project is carried out considering a time frame of 24 hours. A deeper investigation could be addressed by a long term study, in order to see the BESS performance.
- **optimal BESS placement:** In this work, the battery is placed on the first bus. So as to select the most optimal placement a deeper study could be executed.
- **Power electronic component:** It could be interesting to study different power electronic devices along with the control methods selected in this project.
- **Under-Voltages:** As this project is focused on the over-voltages, an enhancing control can be addressed to cover all the voltage deviation that might emerge on the system.
- **Enhanced Volt/VAr control method:** During the development of the project, the voltage bands on the Volt/VAr method are the same in all the SPV inverters along the feeder, provoking unfair reactive power support. Therefore, an optimized voltage band for each bus could be carried out in order to share the reactive power more equally.

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Appendix A

Appendix

Table A.1: Line Parameters

Line Segment	Node from	Node to	Conductor ID	length [m]	Installation
1	1	2	UG1	35	UG 3-ph
2	2	3	UG1	35	UG 3-ph
3	3	4	UG1	35	UG 3-ph
4	4	5	UG1	35	UG 3-ph
5	5	6	UG1	35	UG 3-ph
6	6	7	UG1	35	UG 3-ph
7	7	8	UG1	35	UG 3-ph
8	8	9	UG1	35	UG 3-ph
9	9	10	UG1	35	UG 3-ph
10	3	11	UG2	15	UG 3-ph
11	4	12	UG2	15	UG 3-ph
12	13	14	UG2	15	UG 3-ph
13	14	15	UG2	15	UG 3-ph
14	6	16	UG2	15	UG 3-ph
15	10	18	UG2	15	UG 3-ph
16	9	17	UG2	15	UG 3-ph

Appendix B

Appendix

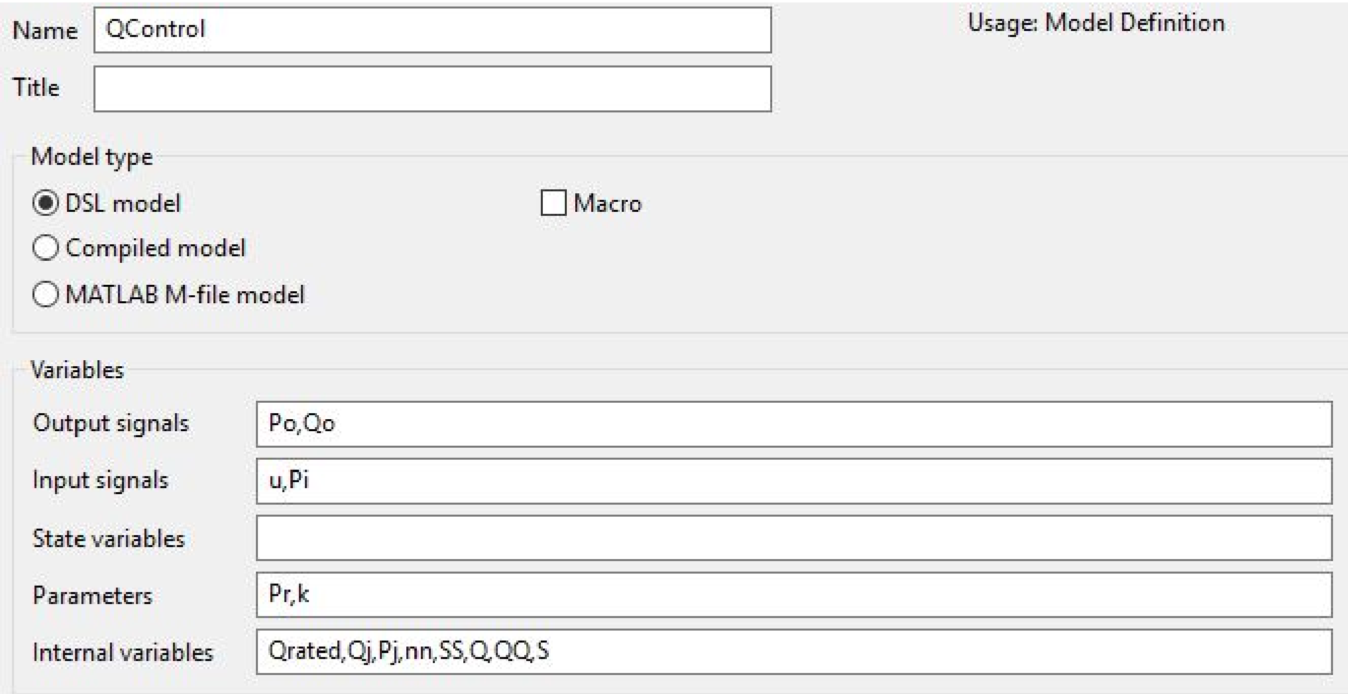

Figure B.1: SPV Model Definition.

Appendix C

Appendix

```
 !initialization
            inc(Qrated)=0;
            inc(Pi) = 0;
            inc(u) = 0;
            inc(S) = 0;
            inc(Qo) = 0;
            inc(Po) = 0;

        !Q rated calculation
       S=Pr/0.95
       Q=sqrt(S*S-Pr*Pr)
       Qrated=Q


!k is the constant factor Pinput=k*Poutput  k=1

 Po=-k*Pi

        !Condition for Q output (fixed Power Factor)
Qo=0
SS=Po/0.95
QQ=sqrt(SS*SS-Po*Po)
!Qo=QQ
!
       Qj=(Q/(1.07-1.04))*(u-1.04)
        !condition for Q output (Volt/Var method)

!Qo=select( u<=1.04 , 0, select(u>1.04 .and. u<=1.07, Qj , Qrated )  )

        !Condition for P output (Active Power Curtailment)

    Pj=     ( ((Pi*k)/(1.12-1.07))*(u-1.07   )       )

   nn=select(  u<1.08, 0,          0.75/((u-1.07)/(1.12-1.07))  )

!Po=select( u<1.04, -k*Pi , -Pj*nn)
```

Figure C.1: SPV Code for Voltage Control Methods.

Appendix D

Appendix

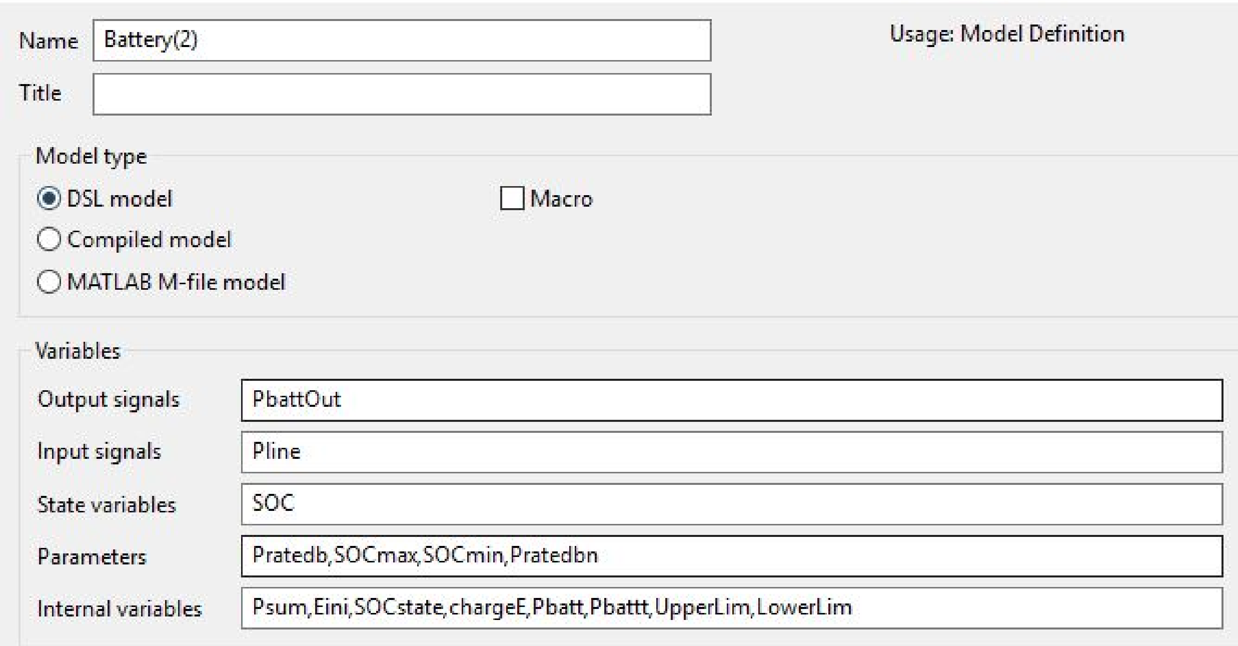

Figure D.1: Battery Model Definition.

Appendix E

Appendix

```
 inc(SOC)=50;  !Initial % of the SOC


    Psum=Pline
    Eini=Pratedb*10!kW*h

            !SOC Calculation
         SOC. = Pbatt* 100. / (Eini * 3600.);

SOCstate=select(SOC<=SOCmax .and. SOC>=SOCmin, SOC,
& select(SOC>SOCmax, SOCmax,SOCmin))

  !Conditions to select when to charge and when to discharge
           !Energy Condition
chargeE=select_const(SOC<SOCmax .and. SOC>SOCmin ,1,0)   !1 is charge mode, 0 not charging
           !Power Condition
chargeP=select_const(Psum<0, 1, 0)           !1 is charge mode, 0 is discharging mode

      Pbatt=select(chargeP=1, -Psum , -Psum)
        Pbattt=select(chargeE=1 .and. chargeP=1, -Psum,
        & select(chargeE=1 .and. chargeP=0, -Psum, 0))
   !Limits
  UpperLim=select(Pbattt>Pratedb,Pratedb,Pbattt)
  LowerLim=select(Pbattt<Pratedbn,Pratedbn,Pbattt)
       !Power output of the Battery with the actual Power available
  PbattOut=select(chargeE=1 .and. chargeP=1, UpperLim,
        & select(chargeE=1 .and. chargeP=0, LowerLim, 0))
        c=PbattOut
```

Figure E.1: Code for Battery Control.