Impact and solutions to cope with high penetration scenarios of photovoltaic micro generation embedded in low voltage distribution networks

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ABSTRACT

Nowadays, due to the increasing rate of microgeneration penetration in Low Voltage distribution networks, overvoltage issues are more likely to occur since we are experiencing a more bidirectional operating grid.

The aim of this master thesis is to test three overvoltage mitigation strategies in a high photovoltaic penetration scenario in an unbalanced 55 bus test Low Voltage network. Active Power Curtailment, Reactive Power Support and a Hybrid Technique combining the benefits of previous both methodologies were tested.

The tests executed in the presented study conclude that Reactive Power Support strategy itself manages to smooth voltage profile, through the absorption of reactive power by a smart PV inverter, although proves ineffective to tackle overvoltage issue, allowing voltage profile values to raise above 1,1 pu (the maximum threshold allowed by law).

On the other hand, Active Power Curtailment technique is tested in two scenarios, with a full and a precise energy curtailment. Executing a full energy curtailment, all overvoltage issues are overcome. This would be extremely positive if this technique did not represent a waste of profits to the producer and an inefficient clean energy use. In the other test case merely the correct curtailment is performed, maximizing renewable energy penetration in the grid and assuring the expected profits to the producer. The hybrid technique combines the both techniques benefits and strengths, proving itself as the best strategy to tackle overvoltage issues in the test Low voltage network.

KEYWORDS

Distributed generation, photovoltaic, overvoltage, reactive power, active power curtailment, overvoltage mitigation techniques

RESUMO

Com o aumento da geração de energia nas proximidades do consumidor final, há mais possibilidades de ocorrerem problemas de sobretensão nos barramentos da rede de teste, especialmente nos mais afastados do transformador.
O objetivo desta tese de mestrado é testar três estratégias de mitigação de sobretensão num cenário de alta penetração fotovoltaica numa rede desequilibrada de Baixa Tensão com 55 barramentos. As estratégias testadas são o Corte de Potência Ativa, a absorção de Potência Reativa e uma Técnica Híbrida, que combina os benefícios das metodologias anteriormente testadas.

Os testes executados no estudo apresentado concluem que a estratégia de absorção de Potência Reativa isoladamente, apenas consegue suavizar o perfil de tensão, através da absorção de energia reativa por um inversor fotovoltaico inteligente, embora se mostre ineficaz para resolver problemas de sobretensão, permitindo que a tensão alcance valores nos barramentos superiores a 1,1 pu (o limite máximo permitido por lei).

Por outro lado, a técnica baseada no Corte da Potência Ativa é testada em dois cenários, com um corte total de energia e outro cenário com o corte desejado. Optando por um corte total de energia, todos os problemas de sobretensão deixam de existir. No outro caso de teste, apenas a percentagem corte desejada é realizado, maximizando a penetração de energia renovável na rede e assegurando os lucros esperados para o produtor.

A técnica híbrida combina os benefícios e as forças das duas técnicas anteriores, provando-se como a melhor estratégia para lidar com problemas de sobretensão na rede de baixa tensão.

PALAVRAS-CHAVE

Microgeração, fotovoltaico, sobretensão, potência reativa, corte de potência activa, estratégias de mitigação de sobretensão

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CHAPTER 1

Introduction

Framework

In recent years, world population has grown increasingly fast. Cities are developing themselves, infrastructures and accommodations are built at an outstanding pace to meet our needs. Industries appear in the center of development and are the main drivers towards an increase of fossil fuels utilization and the releasing of carbon emissions to the atmosphere.

Humanity is facing a battle against climate change. Extreme temperatures are continuously felt, dry locations are getting even dryer and an alarming and rising number of CO2 particles in the atmosphere is being registered, trapping the heat in its particles for long periods. Last year, in May of 2018, a record number of 411 ppm of CO2 was measured in average in the atmosphere [1]. We are currently averaging an increase of more than 2 ppm a year. This leads to a greater probability of facing even more natural disasters, which we are not prepared to manage, such as heat waves and its obvious consequences to human being's health.

It is urgent to act. Legislators throughout the world are stimulating the access to renewable energy production, to integrate and deliver, namely PV energy, to the operating LV network, tackling the conventional fossil fuel energy production. Another factor that is helping this shifting and acceptance mentality is the implementation price of the technology, which is turning more and more competitive and affordable to everyone.

However, the distribution network as is conceived and designed nowadays is outdated. Large scale energy generation points are scattered through the country, reaching our homes and its customers through transmission and distribution networks, operating under the premise that end users only consume. This unidirectional constructed system represents itself as an inefficient and carbon intensive way of producing and distributing energy.

Therefore, a complete reform in the structure of the energy system in taking place. With an increase of a greener and more sustainable citizens awareness, enforced by EU legislations policies, main adoption of microgeneration concept is increasing in domestic neighborhoods - renewable PV energy production, mainly of small-scale systems, with few kW, placed in our house rooftops.

In this way, the end user is put on the heart of the system, being able to produce, store and consume the energy locally due to self-consumption framework, reducing the stress on the distribution feeder and enhancing system performance.

Naturally, this measure is going to emphasize and increase renewable energy integration in the LV network. However, the progressive implementation of distributed generation in the proximity of its end users, besides minimizing power losses, raises challenges of technical nature as maintaining power quality, the reliability of the system and voltage profile issues in the grid busbars.

Whenever PV generation substantially exceeds the load demand of the LV grid, during high insolation period, voltage profile increases and there is even the possibility of reverse power flow. In case of exceeding 1.1 pu, overvoltage issues occur and may cause grid imbalances and a power quality deterioration.

If there is an overvoltage issue in a certain bus, one of the possible corrective strategies should be applied until voltage is returned to its legal boundaries. The operation and result analysis of the available methodologies is approached in this thesis and will be explained in further chapters.

Objectives

The overall main objective of this Master Thesis is to present a study of the impact of renewable microgeneration integration, namely PV, in LV distribution network. Firstly, it is of vital importance to develop an appropriate three-phase unbalanced load flow model operating behind the test network, based on Backward/Forward Sweep load flow algorithm and power summation method (further explained).

The forward corrective strategies proposed were conceived with the aid of a programing tool, MATLAB, to create an algorithm that models overvoltage corrective strategies behavior in the LV grid with high PV penetration.

The main objectives of this study are:

- To assess the performance of a LV distribution network in a high PV penetration scenario, more precisely regarding voltage profile control;
- To evaluate the effectiveness of the proposed methodologies (Active Power Curtailment, Reactive Power Support and a Hybrid Methodology) to tackle this issue, due to the increasing implementation of PV distributed generation next to consumers.

Structure

The present Master Thesis is divided into four main chapters and organized as it follows.

In Chapter 1, a brief introduction to the theme is made, in a general overview of the studied issue. The objectives are outlined, and the structure of the dissertation is drawn.

Chapter 2 refers to an article developed in the scope of these dissertation, with Professor Rui Castro as a co-author and further published in the International Journal of Renewable Energy Research, volume

6, number 1 (2016), from pages 117 to 131[†]. Here, a review of the state of the art regarding overvoltage corrective strategies during a high PV penetration scenario in a LV network is portrayed. Several cases are presented and supported, with a wide range of techniques documented.

Chapter 3 is divided into two subchapters. In the first one, it is possible to find the computation method behind the modelling of the LV test grid – shows how the three-phase power flow can be calculated. In the second section, the real network is presented and its technical characteristics are exposed.

Chapter 4 presents the different test overvoltage mitigation techniques. Each section focuses on one technique, from Active Power Curtailment to Reactive Power Support and a Hybrid technique, evidencing its benefits and restrictions in tackling overvoltage in a high PV penetration scenario.

The study conclusions are drawn in Chapter 5. Moreover, a path of future works is highlighted in this section.

References

[1] "https://climate.nasa.gov/vital-signs/carbon-dioxide/," NASA CLimate Change, https://climate.nasa.gov/vital-signs/carbon-dioxide/.

[†] It is possible to find the article at: https://www.ijrer.org/ijrer/index.php/ijrer/article/view/3192

CHAPTER 2

State of the Art

Introduction

In the last years, there have been major efforts from governments all over the world and also from European organizations to grow a strong concept of environmental awareness. People have been warned to change consumption patterns, to reduce fuel fossil consumption and carbon emissions. It is in this perspective that renewable energy and, specifically, microgeneration (µG) concept arises.

Nowadays, modern civilizations demonstrate a large dependency on energy consumption needs. A major concern that should be in our minds is that fossil energy sources are exhaustible and with the population growth and refined needs, they will not be available for future generations without serious environmental impacts. The price of fossil fuels is in an increasing trend, the rate of consumption is not decreasing, and does not seem to diminish in the next years.

Consequently, actions should be undertaken in crucial points related to supply and demand. One should be capable of diminishing the consumption patterns, therefore requiring less energy from the grid, but that action should not compromise the comfort, quality of life as well as the welfare and development of populations. Here is where renewable energy can have a major impact in the energy supply. Their increased penetration in the grid should continue to be promoted, so that more and more energy is consumed from renewable sources, aiming at decarbonizing Europe's power system.

In fact, renewable sources are already a major cut of the generation mix, and Photovoltaic (PV) is getting stronger and stronger. According to the European Photovoltaic Industry Association (EPIA), the total installed capacity in Europe could reach between 119 and 156 GW in 2018, starting from 81.5 GW at the end of 2013, which demonstrates a strong investment in the area [1].

Power grid as it was known in the 21st century is facing constant changes. We have been used to have a unidirectional power system from the power plant, through transmission and distribution network, finally reaching consumers loads. Nowadays, with the implementation of µG (mainly PV) on the consumers' side connected to the Low Voltage (LV) grid, a new paradigm shift is arising, from a centralized system to a decentralized one, with both consumers and producers interacting with the LV distribution network and power flowing in both directions.

Up until now, law obliged owners of PV panels to inject all the produced energy in the grid. Due to the paradigm shift of power system organization, with consumers' capacity of interaction with the grid, a new concept arose, the so called prosumers. Under this new concept, it is possible to inject and/or consume its own energy, what reduces the load as seen from the electrical system and, moreover, the fossil fuel dependency, and confirms the decentralization and increased flexibility of the current power system.

Distribution Generation (DG) is the so called decentralized power generation, differing from the centralized form of generation, because it takes place in locations where a traditional power plant could not be installed, which contributes to a better geographic distribution of power generation [2]. The DG context gave birth to µG concept, that consists in the combination of generation sources, usually renewable (e.g. PV), typically sized in the range of some kW, usually mounted in the roofs of buildings, integrated in the LV distribution network, through fast acting power electronics.

This new challenge is posing new threats in the distribution network and may bring some disadvantages [3]. Investigating how µG will affect the operation of the LV distribution network will be of central importance, in order to maximize the benefits taken from its installation [4].

The presence of a large number of grid connected PV systems in the LV grid may have some impacts, power quality being one example [5], [6]. From this point of view, the objective is to obtain a sinusoidal waveform as output of the grid connected PV. However, due to power converters, harmonics are present in the output form, which result in a distortion of the system voltage.

Although most LV networks have not yet experienced high penetrations of PV systems, impacts such as network protection issues, overloading of the network components, Power Factor (PF) changes (a poor PF increases line losses and turns voltage regulation more difficult) and fault current levels are expected to occur as µG penetration increases [7], [8], [9].

On the other side, producing locally through PV units and injecting power into the grid is reducing the net load as seen from the electrical system. The issue is that load reduction or even load reverse, increases the voltage, in a phenomenon known as overvoltage. At the end of the day, this is the most relevant issue. The main concerns of the increasing renewable penetration, mainly PV in the LV grid, is that micro-generators may cause excessive voltage rise, exceeding the hosting capacity of the grid, or in an even worse scenario, causing a reverse power flow. This phenomenon can decrease the life of most household appliances and can also damage sensitive electronic equipment that may be interconnected to the grid, for example, wind turbines or other PV panels.

However, µG is not all about disadvantages, restrains and concerns, it also has benefits, for instance, a reduction of Joule losses, since the consumed power is generated in a source closer to the demand. This increases service quality from the customer point of view. Furthermore, renewable energy is generated, which strongly contributes to help the bet of European governments in order to increase countries independence from fossil fuels [10].

Moreover, grid-connected PV systems have other advantages such as flexibility, simplicity to install wherever solar radiation is reachable, it is a clean technology, non-polluting, that emits no noise and that requires little maintenance. It is in this perspective that many countries are encouraging the installation of PV systems in order to reduce the power consumed through the network, helping reducing household electricity costs and contributing to a lower framework of $CO2$ emissions to the atmosphere [11].

As mentioned before, the local distribution grid overvoltages is one of the main issues, as far as the increasing penetration of micro-generation is concerned. Some mitigation and corrective strategies are available to prevent overvoltage situations. Table 1 shows the techniques currently used to mitigate overvoltages in distribution grids under a high penetration of renewable micro-generation.

Table 1. Distribution grid overvoltages mitigation techniques

No	Technique	Description
T1	Limitation of PV penetration	The Distribution System Operator (DSO) imposes an *a priori* limit to the number of micro-generation units that may be connected to the distribution grid.
T2	PV generation curtailment	Micro-generation units are granted a permission to connect to the grid but are obliged to disconnect or suffer a partial curtailment when the voltage is above a specified value. This is an *a posteriori* limitation that is activated when overvoltages occur.
T3	Reactive power support	Reactive power management is used to control the voltage through PV inverters capabilities. Other power electronics devices, such as STATic synchronous COMpensator (STATCOM), Static VAR Compensator (SVC) or Dynamic Voltage Regulators (DVR) may be used with the same purpose.
T4	New network infrastructures	This includes the construction of new power lines to alleviate overvoltage stress.
T5	Automatic voltage regulation transformers	On Load Tap Changer (OLTC) transformers can be installed in distribution grids, in order to offer voltage regulation by adjusting voltage magnitudes and shifting phase angles.

T6	Self-consumption methods	The possibility granted to the households to consume their own produced energy implies a reduction of the load as seen from the service transformer, therefore decreasing overvoltage risk.
T7	Demand Side Management (DSM)	Adequate management of domestic appliances by the households may increase the load in off-peak periods and prevent voltage increase in those periods.
T8	Batteries or super-capacitors energy storage	In off-peak periods, the surplus energy is not injected in the distribution grid and is used to charge storage devices instead. This prevents overvoltages to occur.

From the overvoltage mitigation techniques listed in Table 1, four techniques (T2, T3, T5 and T8) emerged as the ones that may achieve more effective results. As so, the state-of-the-art of these four techniques is reviewed in this paper, through a comprehensive insight on the available literature on the following overvoltage mitigation techniques: PV generation curtailment, Reactive power support, Automatic voltage regulation transformers and Batteries or super-capacitors energy storage. Table 2 shows the distribution of the reviewed literature by overvoltage mitigation technique (note that some papers approach different techniques).

Table 2. Reviewed literature on overvoltages mitigation techniques

Technique	Main references
PV generation curtailment	[30], [31], [32], [33], [34], [35], [36], [37], [38], [39], [40], [41], [42], [43], [44], [45]
Reactive power support	[22], [33], [34], [35], [36], [38], [45], [46], [47], [48], [49], [50], [51], [52], [53], [54], [55], [56], [57], [58], [59], [60], [61]. [62], [63], [69]. [70], [71], [75], [87], [88], [89], [98], [99], [100]

Automatic voltage regulation transformers	[22], [35], [52], [53], [63], [64], [65], [66], [67], [68], [69], [70], [71], [72], [73], [74], [75]
Batteries or super-capacitors energy storage	[22], [31], [32], [49], [50], [76], [77], [78], [79], [80], [81], [82], [83], [84], [85], [86], [87], [88], [89], [90], [91], [92],]93], [94], [95], [96], [97], [100]

The paper cites 100 references with the following distribution: 46 in top journals (the majority of them indexed in SCImago Q1 – IEEE, Elsevier, etc.), 50 in international peer-reviewed conferences (the majority of them are highly prestigious conferences – CIRED, ISGT, IECON, IEEE General Meeting), 2 technical reports and 2 theses. On the other hand, the yearly distribution of the references is as follows: 2008 – 1; 2009 – 2; 2010 – 8; 2011 – 18; 2012 – 22; 2013 – 10; 2014 – 25; 2015 – 14. This means that 89% of the references have been published in the past five years and shows that the research has been concentrated on recent publications.

This paper is divided in 4 sections. In the Introduction, some related topics are briefly referred and a framework overview is set. In Section 2, the main overvoltage mitigation strategies – PV generation curtailment, Reactive power support, Automatic voltage regulation transformers and Batteries or super-capacitors energy storage – are presented and in section 3 they are developed, discussed and supported with case studies. Finally, in section 4 some conclusions are drawn and some directions of future research in the area are offered.

2. General Overview of Overvoltage Mitigation Strategies

Nowadays, with a large number of PV panels installed in the distribution grid, there are some problems to be aware of. From the above-mentioned disadvantages and concerns of the increasing trend of μG penetration in the LV network, we will be focusing on the overvoltage mitigation and corrective strategies. Many studies are being developed in this research area, in order to analyse and comprehend the behaviour of the power distribution grid in a context of increasing DG penetration.

Overvoltages are actually happening because of the integration of renewables near consumers, but reversed power flow is a near future problem that is already being carefully studied. The concern turns to be even bigger in rural areas, which are far away from the substation transformer. Where once there was only consumption of energy, due to the rise of μG installations, some energy generation will appear, therefore making voltage to rise. If the volume of power generated exceeds the power consumed in the grid, power flow can be reversed on the distribution feeder, which causes further increase in bus voltages, leading to added imbalances in the network [12].

In order to analyse overvoltages and the possibility of bidirectional power flow, two main distinct time periods are of interest due to different patterns of consumption and power system response.

At night, due to high residential loads and low injection of PV units, undervoltage problems may occur. On the other side, during the day, PV power production reaches its peak, which contrasts with low loads, mainly in residential areas, because people are outside working. This fact may cause bus voltages to rise and overvoltages are bound to occur [13], [14].

In most cases, a few small-sized PV incorporating the grid will not influence the operation of the distribution system and therefore their impacts on the power quality and voltage profile can be neglected. However, incorporating a substantial volume of µG in a system that is not designed for such a generation mix could lead to disturbances in the overall dynamics of the power system [15], [16].

Another issue that should be carefully analysed at the planning stage is the case of the location of the PV unit in the grid line. Studies demonstrate that DG installed in different locations and with the right capacity have impacts on the amplitude of the power system short circuit current and voltage stability, thus in the power quality. How many units are adequate for a particular segment of the LV distribution system and the technical and safety problems associated with those decisions is a question to have in mind. It has been concluded that PV units located closer to the point of consumption allow for reduced losses in the power grid and usually increase voltage profiles in the LV network and enhances its PF [17], [18].

Thus, if properly integrated, DG may bring benefits to the network in many ways by providing ancillary services, such as reactive power and voltage control, supply of reserves, voltage regulation and enhanced stability [19].

It is in this perspective, with the objective of improving power system operation, with no technical and safety implications, that mitigation and corrective strategies are applied to the network. In this chapter, different strategies of overvoltage mitigation are considered as an overview set to minimize all the disadvantages of such a great non-polluting power generation source.

Since this topic has been recognized of central importance, many solutions have been provided relating to the overvoltage issue. In a wider approach, the most relevant ones are generation curtailment, reactive power support, using power electronic devices, transformer tap changing, and, at last but not the least important one, through the connection of batteries in each PV array.

When the voltage value in the radial electricity grid is outside the range defined as the statutory limits, some measures have to be defined. One type of solution to apply is generation curtailment, where the active power output is diminished until voltage is within an acceptable range. What happens is that when the voltage rises, above the legal limits near consumers, generation PV units are disconnected from the bus with a higher overvoltage and subsequent ones, until the voltage is in an acceptable value. In fact, the producers who have invested their money in DG dislike this approach, because this measure is going to lead to some losses in their revenues. This measure is suggested when all the usual means of voltage control are exhausted, since although is a well-proven solution, in the point of view of producers is quite troublesome [20], [21].

Another type of manoeuvre can be applied when the voltage exceeds the statutory limits, such as PF control, based on reactive power support devices. The inverters of the PV microgenerators, which hold

PF regulation capabilities, can locally perform this action. Besides this, it is proven to be not a straightforward solution, due to the low inductive characteristics of the LV cables. In other words, the improvement of this technique in the radial distribution grid is marginal. However, since each case is independent, there are examples where it may prove to be effective.

Alternatively, reactive power support can be made through power electronic devices, such as STATCOM or SVC, where voltage rises caused by DG can be reduced by the absorption of reactive power.

This kind of local compensation methods have several advantages in terms of efficiency, optimizing grid losses, flexibility and reliability, maximizing equipment life duration, etc. [20], [21]. However, they have some monetary implications, such as the necessity of sensors for communications and complex control systems.

Traditional MV/LV transformers are equipped with off-load tap changing transformers (note the difference between these transformers and OLTC transformers), which have to accomplish a careful and difficult two-fold objective. They have to comprise the voltage along the entire feeder is above the lower limits in the peak load period, and, on the other hand, during generation hours, it has to be under the upper voltage limit, which is a very hard task to attain.

Modern voltage regulation in a LV grid with renewable penetration is made through the implementation of OLTC transformers, switched capacitors and Step Voltage Regulator (SVR), or by a mix of resources strategies. OLTC transformers are an efficient method but may not be very cost-effective since the replacement of power transformers in substations is required.

OLTC transformers are stocked with a component called a relay, which automatically increases or decreases the voltage, changing the tap position according to its needs, which naturally improves the performance, reduces maintenance costs over the traditional mechanisms, and can provide a coordinated control with communication. One major disadvantage of this technique is that the operation of the tap changer is limited to its capability [21], [22].

A new solution is being addressed in recent times, one that will not only control the voltage rise due to the increase penetration of µG, as well as be a very cost efficient technique for the owners of this technology. Battery Energy Storage (BES) systems cope with overvoltage issue, showing an incredible effectiveness and a good way of preserving the prosumers' revenues, as well as controlling line losses.

Basically, each PV panel will be attached to a battery system. In the case of occurrence of an overvoltage in a determined bus or buses, the correspondent generator will be disconnected from the grid and will start charging the battery, until its storing capacity is fully reached. Then, at night, when the load is at its highest point and voltages tend to be at their lowest, is when batteries complete their function and return the stored energy to the grid, discharging softly what they have accumulated during the day, in order to prevent voltage spikes. This procedure can be executed in the bus with the higher overvoltage value, as well as be consequently done in several neighbour buses, until optimum voltage values are attained [23]. Instead of returning energy to the grid, batteries can be used for self-consumption of the accumulated electricity, therefore diminishing the net imports from the grid. This solution has echoed in Europe and, in some countries, as is the case of Germany, a feed-in tariff encourages self-consumption, promoting batteries installation.

As always, there are some constraints [24]. Batteries are included in an area of investigation that is still being discovered and refined, and the best solution to store energy, in great amounts, is yet to be found. There are two main delimitations, known as the discharge time and the power rating of the batteries. Some literature comparing batteries characteristics can be found in [25].

As the state of the art among batteries, Super Capacitors (SC) emerge. There are, nowadays, hybrid Energy Storage System (ESS), composed by batteries and SC, in the extent that their characteristics complement each other. Batteries offer high-energy storage density and relatively low power density. On the other hand, a higher power density and a long lifecycle contrasting with a worse energy density characterize a SC [26].

Nevertheless, it is important to point out, that there is not a right strategy to implement, but in several cases, a mix of mitigation strategies is the most suited option. Using several complementary overvoltage mitigation techniques portrays numerous benefits, proving to be efficient in the overvoltage issue and minimizing the impacts suffered by the grid, in deferral to grid reinforcement, due to a large penetration of μG.

3. Review of the Main Overvoltage Mitigation Techniques

In this Section, a review of the main overvoltage mitigation techniques – PV generation curtailment, Reactive power support, Automatic voltage regulation transformers and Batteries or super-capacitors energy storage – is further developed, discussed and supported with case studies.

3.1. PV Generation Curtailment

In this section, the literature on PV generation curtailment as a tool to prevent overvoltages to occur is reviewed. Some papers approach optimal generation curtailment algorithms [30], [37], [39-44], while others discuss hybrid techniques: generation curtailment + energy storage [31-32]; generation curtailment + reactive power support [33-34], [36], [38], [45]; generation curtailment + reactive power support + automatic voltage regulation transformers [35].

Disconnecting PV generators in descendent overvoltage bus order can reduce voltage rise, triggered by an increase of DG penetration in the LV grid. PV curtailment has the objective of enabling the connection of more generators without compromising the network itself and other network users, and seems very attractive in the view that it requires minor modifications in the inverter [27]. Moreover, this process is only used when needed, thus minimizing the amount of curtailed active power. In most cases, removing a small number of PV generators is enough to have voltage back within legal range, but extreme cases require the disconnection of a greater number [20]. It is straightforward to mention that high levels of curtailment lead to reduced yields, and at some point is no longer beneficial to add more generators [28].

Due to the intermittency of PV power, the necessity of frequency regulation services increase. In reference [29], a new task of the PV inverters is presented, namely its frequency regulation and potential benefits, actually occurring during increasing generation periods or in response to a decreasing load.

PV curtailment seems to be a non-complex process, but disconnecting one PV generator has direct influence in neighbour buses, and can create even bigger grid unbalances [3].

In [30] a new dynamic active power curtailment technique is dealt with, imposing a maximum limit of active power that can be injected in the LV network, leading to only one third of energy losses compared to traditional methods, according to [31]. This same paper also compares this solution with and without energy storage coupling.

An economical and technical analysis is carried out in [32], comparing three methods, in which a mix of a power curtailment and battery storage strategy turned to be the most cost-effective solution.

References [33] and [34] compare active power curtailment and reactive power support method in LV grids, as the most common mix of overvoltage mitigation strategies, resorting to the latter in case the first one shows inefficiency. However, in [35], reactive power support is preferred in situations where PV systems have available capacity for reactive power exchange. If not, active power curtailment methodology alongside with tap changing transformers is reported as being the best way to improve voltage profile regulation.

With large PV integration, a case of active power curtailment technique enhanced with inverter reactive power injection can be found in [36]. The Reactive Power Injection – Active Power Curtailment method keeps voltage boundaries in acceptable values, independently of the PV location, and minimizes the total number of tap-changes in line voltage regulators.

Not only overvoltage problem is dealt with in [37], as well as overloading of the power system during the period of high generation. This paper proposes a distributed control coordination strategy to manage multiple PV systems within a network. PV systems reactive power is used to deal with overvoltages and PV systems active power curtailment is regulated to avoid overloading.

A comparison between active and reactive power generated and curtailed, both in a distributed and a centralized system, is made in [38].

In [39], a distinction between hard and soft curtailment concepts is proposed, and the implications each method brings, calculating the curtailed and generated electricity as a function of the installed capacity, are reported.

According to references [40] and [41] a droop based active power curtailment method is proposed to deal with the overvoltage issue. In these papers, an estimation of how much power should be curtailed from each PV inverter is made through the local voltage monitoring. A strategy that shares the output power losses through all inverters is also presented.

In [42] an example of a Dutch LV feeder is presented, with several curtailment strategies. Microinverter curtailment applications in order to increase μG penetration while minimizing network impacts is proposed. It is demonstrated as a cost-effective solution but sensitive to temperature.

Reference [43] highlights an artificial neural network virtual sensor that optimizes the inverter power and determines the right amount of power that needs to be curtailed in order to prevent overvoltage issues. The study concludes that overvoltage situations were eliminated and grid losses reduced in 69%.

In a residential area of Belgian Flanders, [44] presents different penetration scenarios and study the effects of active power curtailment strategy on an already problematic feeder. Results show that overvoltage situations were eliminated and unbalances between different phases were mitigated. Despite all benefits, a major disadvantage is that active power curtailment is not made equally through the feeder, it depends on the connection phase and on the PV generator location and size.

In study [45] an unbalanced three-phase four-wire LV distribution network is considered and a PV generation assessment and control strategy is presented, based on active power curtailment and reactive power control. Here a multi-objective optimal power flow model, comprising the improvement of voltage profile, minimization of network losses and generation costs is proposed, evolving to a single-objective problem through a weighted sum model. Simulations are performed during 24h with high PV penetration scenarios, showing effective results.

3.2. Reactive Power Support

The literature on reactive power support as a way to prevent overvoltages is reviewed in this section. Some papers deal with the PV inverters capabilities [46-48], [51], [54], while others introduce advanced power electronics devices to perform the required tasks [55-62], [98-99]. Still, others present hybrid solutions: reactive power support + energy storage: [49-50]; reactive power support + automatic voltage regulation devices: [52-53].

In the last years, we were used to deal with DG in the LV network, operating at unity PF, and disabled to control voltage profile. This means that the PV reactive power inverter capability was kept at zero, providing all of its capability to the active power generation. Nowadays, partly due to the Germany effort in assigning grid codes, the reactive power flow for voltage control is majorly done in a locally and decentralized system, through smart PV inverters of the microgenerators. These devices gather the multiple function of ensuring PF control for enhanced grid stability. Whenever real power injection is less than the inverter rated power, the remaining inverter capacity can be used for reactive power control.

Nevertheless, some authors (e.g. [20]) argue that, due to the low inductive component of the distribution cables, this strategy seems to be ineffective with a small marginal improvement scale.

Due to the increasing DG penetration, the primary objective of smart PV inverters is to absorb reactive power, in order to decrease bus overvoltages and possibly prevent reversed power flow. Their action is only limited by the current carrying capacity of the semiconductor switches [46].

In [47], through a methodology based on the optimal management of reactive power supply by the PV inverters and a decentralized auto adaptive controller, reduced system losses are attained.

In a 15-bus Japanese system [48], voltage problems were found to be associated with DG increased penetration. Through the presented algorithm, the right amount of reactive power compensation is calculated, based in the worst-case scenario of the network. A comparison of the voltage profile regulation simulated results, with and without reactive power support, was made. The conclusion was that the first one revealed to be a good strategy to keep the voltage within the specified limits.

Another different algorithm is tested in a 6-bus test network presented in [49]. A coordinated and efficient way of preventing overvoltages in the LV network, through the reactive capability of PV inverters and resorting to the use of BES is presented. Results show a significant improvement of voltage profile.

Reference [50] compares the effectiveness of reactive power strategy through PV based inverters in rural and urban areas. The research concluded that in rural areas, due to a higher R/X ratio (R and X are the line resistance and reactance, respectively), it is more difficult to proceed to overvoltage mitigation, therefore, frequently resorting to BES method. The paper also compares the costs associated with the voltage control reactive power strategy with the battery usage one.

In paper [51], a comparison of four autonomous inverter control strategies, with the aim of reducing overvoltage and increasing hosting capacity of the grid, can be found. Economic and technical studies were made, concluding that the reactive power strategy is a reasonable approach.

In an Australian LV distribution network, paper [52] refers four standard reactive power injection strategies, with different methodologies and objectives. Then, a new integrated approach is presented, based on a transformer electronic tap changer working alongside with PV inverter reactive power injection algorithm, for each PV generator. This strategy enables the local supply of the necessary amount of reactive power, thus minimizing feeder losses. Results show that during the entire day, and subject to energy and load fluctuations, the presented method reveals effectiveness and a substantial performance improvement in voltage profile regulation.

With the objective of minimizing power losses, relieving OLTC transformers stress issue and using local reactive power injection to control voltage profile at LV level, paper [53] emerges with a new proposal. Fixed PF – fixed Q (reactive power) method, based in an interaction between OLTC transformers and inverter based PV, reveals to be the most suitable voltage regulation strategy, compared to two other alternative solutions.

In [54], different reactive power supply strategies are presented, focusing on static droop characteristics, more precisely in the "reactive power – voltage" characteristic method. This strategy proved to be efficient in reducing overvoltage issues, meaning to keep voltages variations at the point of common coupling below a 3% range. The main disadvantage of this methodology is that excessive reactive power is absorbed.

An optimized algorithm of the same method is also dealt with in the same paper. It uses a centralized controller, which sends the minimum possible amount of reactive power to each PV inverter. The main advantages are minimizing network losses, reducing stress problems in the transformer, increasing PV capacity in the network, due to a better usage of PV capacity, and, finally, controlling the overvoltage issue, as well.

In some occasions, as stated in [55], voltage profile cannot be fully compensated through reactive power support by PV based inverters, requiring the use of power electronic devices, such as STATCOM, SVC, or a combination of SVC and shunt capacitor banks. These devices are well known by its fast acting response time; thus they provide a better voltage control in case of a sudden voltage drop. According to [56], a STATCOM device is a comprehensive solution to mitigate all power quality related issues.

Besides that, a new Distribution STATCOM (DSTATCOM) topology is found in reference [57]. Due to an unbalanced three-phase system, this device manages to conduct the power from the phase with excess of generation to the ones that are lacking, preventing reverse power flow from LV to MV grid. Results show effectiveness in this voltage control methodology in LV network.

DSTATCOM are already being utilized in real applications to conform to local grid interconnection requirements. For example, back in 2011 the British distribution company Scottish & Southern Energy installed a single inverter DSTATCOM to provide adequate voltage regulation. More recently, in 2015, EDF Energy Renewables installed a DSTATCOM in Fallago Rig wind farm, in Scotland, UK, as a flexible and cost-efficient solution to achieve grid-code compliance and ensure that the grid is not affected by the intermittency associated with wind energy. Another one is in operation since 2014 in Rosehall wind farm in the Scottish Highlands to provide real and reactive power so that wind farm can effectively meet grid code requirements and provide its renewable power to the utility grid.

Paper [58] proposes a new integrated PV-STATCOM system, with voltage regulation and PF control capabilities, during day and night-time, demonstrating effective results.

Similarly, in [98] a PV-solar farm is used as a PV-STATCOM to mitigate power quality issues, like poor PF, voltage variations and current harmonics.

As it is stated in reference [59], with the objective of maintaining the voltage profile within legal ranges for an increased number of DG and loads, the use of DSTATCOM alongside radial distribution feeders is analysed. Here, a piecewise linear droop line is proposed. A lower level of reactive power is injected nearby the feeder, and a more significant quantity is inserted where theoretically problems should appear, that is at the end of the feeder. This is an example of the application of modern power electronics devices to deal both with generation and loads issues.

Paper [60] presents a comprehensive comparative study between the use of DSTATCOM and DVR in LV network, specifying as well the place where they should be deployed, and analysing different load situations. Through numerical analysis, it is shown that DSTATCOM provide better results in voltage unbalances and voltage profile regulation than DVR.

On the other hand, paper [99] presents an approach for the voltage regulation problem by using reactive power compensation through a Distribution-Unified Power Flow Controller (D-UPFC) at the DG connected bus. Simulation results reveal that in the worst scenarios of the test system, the proposed control method is able of maintaining the voltage of the system within the permitted range.

In a Danish branch of the distribution network, through the combination of uneven penetration of reactive and active power and by the distribution of active power by the three-phase system, a more efficient voltage unbalance and overvoltage mitigation method was presented in paper [61].

Current Source Inverter (CSI) topology can be used to regulate the exact quantity of reactive power that is injected in the grid. As it is analysed and demonstrated in [62], through a grid-connected current source boost inverter and a switching pattern technique, denominated as Phasor Pulse Width Modulation, it is possible to obtain good results, as far as voltage regulation is concerned.

3.3. Automatic Voltage Regulation Transformers

This section deals with the use of automatic voltage regulation transformers in distribution grids with penetration of renewable μG. Some papers are concerned with the regulation algorithms of the devices [64-68], [72-74], but others discuss hybrid solutions composed by automatic voltage regulation devices + reactive power support [63], [69-71], [75].

OLTC transformers can be installed in LV networks, in order to prevent under and overvoltage situations through adjusting voltage magnitudes and shifting phase angles. Automatic Voltage Control (AVC) relays and Line Drop Compensators (LDC) accompany in most cases these auxiliary devices [63].

According to paper [64], in a test case network, the application of OLTC transformer is not able to maintain the voltage magnitude within legal limits due to a single transformer feeding two radial branches with high penetration of DG. This case illustrates that its applicability and efficiency in solving overvoltage issue is not clear in all cases.

Nevertheless, recurring to OLTC-fitted transformers in LV networks is being considered nowadays as a solution to mitigate overvoltage situations, in a high PV penetration scenario. In [65], three different OLTC control strategies are assessed: constant set-point control, time-based control and remote-monitoring control. With the objective of increasing PV hosting capacity whilst reducing tap operations as well as voltage profile issues, remote-monitoring based control should be addressed. As a cheaper option, without associated monitoring costs, the authors indicate time-based control as showing a comparable performance on the voltage profile issue.

Reference [66] deals with a real LV network, situated in the UK, under a high PV penetration scenario. A techno-economic analysis is carried out, comparing the benefits of including an OLTC-fitted transformer or choosing the traditional network reinforcement. Results indicate that OLTC can significantly improve PV hosting capacity. In a more specific insight, the authors suggest that in the case of high PV penetrations (above 70%), OLTC show themselves as a cheaper and more efficient option.

Paper [67] emerges with a solution regarding another application case, in a UK LV network, using a real time intelligent control of OLTC-fitted transformers. Here two cases are observed, the introduction of voltage control with remote monitoring (calculating the voltage at the end of the feeder, where most problems are likely to occur), and without monitoring, using estimation methods instead. Analysing test results, the authors argue that through the proposed control logic with remote monitoring, satisfactory results are achieved up to 80% PV penetration scenarios. It must be taken into account that communication infrastructure costs are associated with this kind of procedure.

Moreover, in [68], it is highlighted the importance of the location of remote monitoring points in the feeders and the control cycle length. Test results show that in order to implement a cost effective approach, to minimize tap operations and voltage profile issues monitoring should be only located at the end of the feeder and the ideal cycle length is 30 minutes, therefore causing less impact in the OLTC usage.

In a five-branch LV test network, OLTC coping with PV inverter reactive power injection methodology is analysed. Firstly, voltage profiles with each one of the above mentioned techniques are tested separately and results are compared, achieving, as was expected, smoother outcomes. Through the combination of these two regulation techniques, results are showing them as promising concepts to influence voltage in LV networks [69].

Moreover, reference [70] states that reactive power injection by PV inverters coping with OLTC transformers and voltage regulators is useful not only in voltage control but also ensuring better operating life of these devices.

The authors of paper [71] propose a methodology with two different objectives: voltage profile control and reduction of distribution losses through a limited number of operations in the specified devices. Here, a coordinated optimal control method is presented, based in the integration of OLTC transformers, SVR, Shunt Capacitors and SVC. Simulation results attest their effectiveness.

In reference [63], the presence of active devices controlling the voltage profile in the MV/LV network is analysed. This study introduces the concept of Active MV/LV Substation and performs a comparison between OLTC, STATCOM, with and without energy storage, and dump loads.

In a three-phase four-wire LV residential feeder, three distinct voltage control methodologies are analysed. In the first set of test results, PV systems in the rooftops are using all their capabilities to generate active power, and in the second case, they are using only 3kW of a total of 5kW, in which the remaining may be used as injected reactive power. The authors in [35] concluded that for the cases where reactive power injection may occur, this method turns itself as the most efficient one. The combination of applying OLTC transformers, facilitating active power curtailment as well as reactive power exchange, achieved satisfactory results, showing a proper voltage rise control along the feeder.

Reference [72] proposes a methodology to manage cascade transformers equipped with OLTC in a bidirectional power flow situation, most likely to occur nowadays due to a strong bet in DG in LV grids. By testing different network scenarios, it is possible to conclude that besides sparing a few extra tap operations, voltage quality improvement is denoted, through proper coordination of cascade transformers.

According to paper [73], a regulated distribution transformer prototype, which is still in the first test phase, is efficiently addressing the voltage stability problem, more precisely, eliminating the upper boundary of the voltage profile control, using a reasonable number of switching operations.

In a Danish LV network, reference [74] deals with the possibility of controlling LV voltages through an OLTC placed at the secondary substation transformer. The new approach is capable of regulating each single-phase tap changer through a decoupled OLTC Medium Voltage/Low Voltage (MV/LV) transformer. Distinct scenarios are assessed and test results are published, in order to analyse the voltage magnitude and unbalance level in the feed-end, as well as the kind of tap changer issue (continuous or discrete).

An overview and comprehensive analysis of the integration of OLTC transformers equipped with AVC relays in the distribution network is addressed in [75]. Several cases are presented, with series and parallel control schemes. New techniques, namely with local measurements and coping to other devices, as STATCOM, are also presented.

3.4. Batteries or Super-Capacitors Energy Storage

In this section, energy storage is approached as a way to mitigate overvoltages in distribution grids. Several storage strategies and types of storage devices are presented in [76-86], [90-97], while hybrid energy storage + reactive power support alternatives are discussed in [87-89], [100] and energy storage + automatic voltage regulation transformers + reactive power support is the topic of [22].

BES present themselves as an excellent strategy to cope with overvoltage mitigation techniques. During the day, when generation is at its peak, batteries store the produced surplus energy and, at night, when demand is at its peak, energy is returned to the grid enhancing voltage profile and increasing hosting capacity, diminishing line losses as well.

Another great feature of this type of technique is its profitability in the consumers' point of view. As stated in [76], through simulations performed during a 24h period, the predictive optimization method, together with batteries support, allowed for a 13% gain in the electricity bill.

A comprehensive review of the several existing methods based in ESS can be found in [77], ranging from electrochemical storage to flywheel and pumped hydroelectric storage, among others.

In reference [78], a cooperative methodology between DSO and customers with ESS, can be found. Here, DSO pay to customers a certain subsidy (bridging initial equipment costs), so that they regulate the output energy of the storage devices during a specific time period. Through numerical simulations, the authors assure that ESS are effective in the voltage profile regulation.

A trade-off analysis between voltage profile regulation, annual cost of equipment and the reduction of peak power is made in [79], as a tool in the decision of whether to install this kind of devices or not. Here, a BES system is used in deferral to grid reinforcement in a Belgian LV network. It is also concluded that a PV inverter can regulate voltage profile, but batteries added value in the case is illustrated.

In [80], a method to achieve the optimum size of the battery storage system, that is able to control voltage regulation and peak shaving, is presented. It also carries out a cost-benefit analysis in a way that the user may clearly see the trade-off between economic and operational benefits.

In a high penetration PV generation grid, ESS are introduced as a way of preventing overvoltage and helping in the peak shaving issue [81]. Using smart PV inverters and ESS, voltage regulation is improved. Paper [81] also points out the benefits of an optimum placement of the ESS along the lines regarding the final project profitability.

The main purpose of paper [22] is the voltage rise mitigation under a high PV penetration scenario, through voltage regulators, as OLTC and SVR, coping with ESS. The results are compared with traditional systems (without batteries), concluding similar results in the voltage profile issue but with several other benefits. An optimization of the operation taps changer and less distribution losses are the main achievements of this methodology. Moreover, due to batteries usage, a peak load shaving function and a longer life cycle can be obtained, through a limited depth of discharge.

In a comprehensive Belgian LV network, an energy buffer is introduced. In [82] the energy buffer installation will be used when the injected power exceeds a predefined power value. Authors state that all overvoltage issues can be cut off if the storage device can buffer 34% of the average daily PV energy.

In paper [83] a comparison between three different situations is proposed. No production losses and no storage devices characterize reference situation. Then, in a critic feeder, with production losses due to an overvoltage issue, the yearly production and payback time of the technology are assessed, yet without storage. In the last case, a storage device (energy buffer) is introduced with the objective of increasing the total yield and regulating the voltage profile, as well. An economic evaluation based in Net Present Value (NPV) is also made.

In order to avoid power curtailment and grid reinforcements, as well as reducing power losses and increase power quality, a new approach based in decentralized energy storage devices is presented in [84]. In a high PV scenario in a LV grid, a novel strategy proposed a voltage sensitivity analysis to identify an optimized power threshold point. From this point on, the battery charging is activated, therefore preventing overvoltage instead of starting to charge the devices when PV output power is greater than the house load. Simulations are made by changing the PV penetration rate.

In a Danish three-phase LV feeder, a methodology to determine what is the minimum amount of storage energy devices installed at different locations, capable of eliminating overvoltage issue, is proposed in [85]. The method is also based in voltage sensitivity analysis and considers the injected power in the grid as well as the consumption, through a novel remaining power curve concept.

In an Australian four-wire LV distribution feeder, a Community Energy Storage based concept is introduced as a new dynamic mitigation approach. The main objective is to balance and adjust the power exchange with the power system, mitigating neutral current and voltage unbalance. Through the presented results in [86], the method shows effectiveness.

A comparison between two different grid allocations modus operandi in energy storage devices is made in [87]. Centralized Storage and Distributed Storage concepts are introduced. The first concept places a single storage unit along the feeder, and the second one places each PV with its associated storage unit. Three different reactive power topologies, with PF variations, coping with energy storage are also analysed. Conclusions taken from a Belgian LV grid show that the integration of the reactive power control alongside with centralized storage or decentralized storage can lower the required minimum storage power before achieving an overvoltage and minimize the practice of active power curtailment, while voltage profile regulation is achieved.

Another coordinative method, characterized both by distributed and localized control is dealt with in [88]. Through a dedicated algorithm, distributed control can perform feeder voltage regulation adequately and through localized control, the State of Charge (SoC) of the battery system is modelled. Several test cases are analysed, with different weather conditions and different values of batteries SoC. A comparison with a traditional droop based method is also made.

Reference [89] deals with a methodology based in local and distributed control strategies. The coordination algorithm tackles the overvoltage issue while avoiding power curtailment, with reactive power control through the inverter based PV and taking advantage of energy storage units.

Further research on BES systems is published in [90]. Once again, due to PV and storage coupling, stability and reliability of power systems is increased as well as voltage and frequency profile regulation.

In a review paper [91] the integration of PV panels coupled with sodium-sulphur (NaS) batteries is investigated. According to the authors, this technology is well developed, having longer life time devices and greater efficiency compared with other batteries. Due to their smaller size, they require less space for installation, being a key point in urban areas. It shows itself as an efficient methodology to peak shaving feature and towards a more stable power grid.

Batteries have shown several benefits, helping in grid voltage regulation. However, due to renewable energy interruptible characteristics, detrimental effects on batteries life and stress have been pointed out in [92] and [93]. That is the reason why batteries and SC combination emerged. SC are used with the main objective of enhancing batteries life while reducing their stress.

Paper [94], compares the results obtained in a network with an ESS composed by a Vanadium Redox Battery (VRB) and the ones adding a SC to the system, forming a hybrid mitigation solution. Hybrid systems take advantage of complementary devices with advantageous characteristics that help avoiding device limitations by working together.

A review paper displaying several Hybrid Energy Storage systems [95] is presented with the main objective of ease and enhance the penetration of μG in microgrids. In the same perspective, numerous methods and combinations of storage equipments are assessed and compared in [96].

A new hybrid system, comprised by a PV array, Solid Oxide Fuel Cells (SOFC) and a hydrogen ESS is evaluated in [97]. Results show a high efficiency addressing voltage profile regulation, as well as power quality and grid stability.

The use of a photovoltaic-battery storage system to supply electric power in the distribution grid through a multilevel inverter is investigated in [100]. The proposed control scheme ensures the injection of a reference power in the distribution grid and controls the reactive power with fast dynamic response.

4. Conclusions

In the recent past, power systems around the world have suffered several changes. What was known as a one-side delivery energy grid, due the expansion and increasing of μG in the distribution grid, is being changed to a bilateral one. Integrated near residential loads, mainly PV, backed by subsidies and governmental fees, are the driven forces of this organizational change.

Side by side with this distributed renewable integration, power system is evolving into a smarter and more efficient grid, making a bridge from a centralized substation to a decentralized operational type, betting in smart devices and sensors along feeder distribution lines.

The main issue in renewable sources LV grid integration, that experts have to take in minds, is how to tackle or mitigate the overvoltage problems, occurring during excess generation periods whilst consumer loads are requiring less power.

In an overview perspective, there are two different ways of looking into the proposed problem. Power systems work based in power delivery and consumption patterns. This way, overvoltage issue can be addressed through the utility demand side or near the consumer loads.

Firstly, considering the grid itself, it is possible mainly to operate grid reinforcements, which are expensive, or to limit the active power production, having its consequences aggregated as profitability losses.

And secondly, near consumer loads, there are numerous methodologies addressed and studied nowadays. This paper reviewed several strategies, from voltage regulation devices, reactive power injection, OLTC transformers and ESS, with the main purpose of overcoming overvoltage issues in LV grids.

This paper aimed at reviewing overvoltage mitigation techniques, demonstrating throughout real LV networks, which are their benefits and limitations according to grid details. For instance, there are several cases that due to the integration of an OLTC transformer in a specific place can actually mitigate overvoltage issue and increase hosting capacity, or that by recurring to smart PV inverter reactive power capabilities might minimize the problem and reduce power losses along the lines.

Others, try for a grid reinforcement or active power curtailment option with similar results, depending on network details. A safer but more expensive solution is coupling BES solutions to peak shave the surplus of generation and deliver it back to power system when consumer loads require it the most, especially at night. Through this kind of measures, power systems reliability and stability are enhanced as well as the regulation of voltage profile. Moreover, the impact in devices stress can be reduced.

It is not possible to say which one is the best technique to solve or mitigate this problem, since there is not one universal strategy that is always efficient and economically viable. There are numerous factors influencing the grid and voltage regulators devices, as for instance where to place them, optimum sizing and consumption/generation grid patterns.

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CHAPTER 3 – System Description

3.1. Theoretical Framework

Unbalanced Load Flow Three-Phase Algorithm

Nowadays more and more photovoltaic panels are installed next to consumers in residential neighborhoods. Renewable microgeneration is implemented in the distribution network with the main objective of reducing the amount of electricity produced by fossil fuels and due to self-environmental awareness of the conscious citizens. This renewable microgeneration is produced mainly by small photovoltaics generators, usually conceived with only few kilowatts (kW), implemented in the roofs of the houses and connected to the Low Voltage (LV) grid.

Hence, a paradigm change is happening in LV distribution networks. Before the existence of this sophisticated energy production devices, power flew from power plants to the final consumers, clients at home. The totality of customers' needs was supported entirely by the grid.

Nowadays, with the installation of the microgenerators near the consumers, the power produced can be used to its own consumption, to lighten the total client load, or can be injected into LV grid. Power can flow bi-directionally, either from power plants to end-users, or clients injecting power into the distribution grid. Final consumers can now decide whether to self-consume their own created power or to inject it into the grid. With the paradigm change, a shift in legislation scenario was needed as well.

Self-consumption was not allowed in the previous Portuguese legislation, with the energy producer being obliged to inject all their production into the grid, and then supply their needs again from the grid. Currently, according to Law Decree 153/2014, customers can consume their own production and if there is an electricity surplus are also allowed to inject it into the grid. This recent scenario allowed the introduction of the prosumer concept (consumers that both produce and consume electricity).

In an overview through the classic LV distribution grid, with no connected PV generators, voltage values tend to decrease along the entire line, reaching their lowest values in the busbars located far from the MV/LV transformer. If the voltage is lower than 0.95pu, an undervoltage issue arises. On the other hand, in a modern LV distribution scheme, with microgeneration integration and consequently power injection into the network, busbars overvoltage issues appear. This happens due to a high rate of PV production during the day facing a supposedly weak load period of the day in residential areas. This fact may cause overvoltage issues, which means exceeding the legal limits, where the voltage should be kept within ±5–10% of nominal voltage.

In an even worse scenario, due to a high number of PV generators and an increasing microgeneration penetration in LV grid, this may lead to reverse power flow situation, next to the distribution feeder, which may increase bus voltages even more.

In this perspective, the proposed corrective overvoltage methodologies are tested in different simulation conditions to overcome this issue. Here is possible to observe active and reactive power control strategies, decreasing voltage values at the busbars to the legal limits.

The study of the three-phase unbalanced load flow methodology has been fiercely discussed in the last years. Unbalanced power flow calculation takes place mainly in low voltage grids, near end-users, where there are different loads in each phase due to each customer consumption patterns.

The existing unbalanced power flow methods can be split into three distinct groups: Direct methods, Newton-Raphson methods and Forward/Backward Sweep methods.

In [2] we can find an unbalanced three-phase load flow program taking into account the mathematical models of Distributed Generators. This method is enclosed on the direct approach algorithm and has the advantages of fully exploiting the network structures of distribution feeders. The proposed load flow algorithm is based in Bus Injection to Branch Current (BIBC) and Branch Current to Bus Voltage Matrix (BCBV) matrices. Test results show the validity and efficiency of the presented technique.

A three-phase power flow program based on Newton Raphson (NR) algorithm is presented to model the DG injection issues in an unbalanced system. Some authors cited in this study used the NR single phase algorithm and revealed poor convergence characteristics. [3] proposes a modified three-phase NR load flow solution which reveals a high-performance ratio and complete immunity to convergence problems.

A simplified power flow calculation, based in a loop analysis method, for a distribution network with distributed generation is presented in [4]. Test results show good accuracy and shorter times to reach convergence.

A three-phase power flow Forward-Backward Propagation technique is used in an IEEE 34 bus system [5] . The algorithm presents good appliance into the system as well as robustness and good convergence characteristics in the radial distribution grid.

[6] is mainly focused in FBS algorithm incorporating an efficient method for handling PV nodes within a loop analysis.

An appropriated methodology based in BFS power flow for unbalanced radial LV network is presented in [7], using power summation method, modified with the main advantage of calculating the neutral voltages.

Another load flow analysis formulation is presented in [8] based on a quasi-symmetric matrix, which works with real variables instead of complex variables used in backward-forward sweep techniques.

In the other side, the presented paper [9] offers an improved and robust alternative to ill-conditioned asymmetrical networks compared to Newton Raphson or forward-backward sweep methods. According to the author these methods encounter convergence issues due to complex earthing arrangements. The model is based in a 4-wire representation of a suburban distribution network in Dublin, Ireland, proposing a Fringing Correction Currents (FCC) methodology.

Many techniques are used independently with acceptable results. [6] also presents a Hybrid Power Flow (HPF) technique, based in two strategies. BFS methodology with favorable convergence for meshed networks adding Newton's method in order to solve the correction equations for the power mismatch of the PV nodes.

With the main objective of studying and comparing results between three tested methods to mitigate overvoltage, an existing unbalanced power flow three-phase radial LV model of distribution network is used and presented further in the study.

Among the previous aggregated techniques, Backward/Forward Sweep (BFS) Power Flow Algorithm was chosen as the most appropriated method [10] since takes full advantage of the weakly meshed structure of distribution networks and is highly efficient for the expected test results. [11] presents power flow calculation for different testing DG unit operation modes – active and reactive power - and can verify the effectiveness and success of this methodology.

There exist three main variants of the well-known backward/forward sweep method that have their differences on the type of electric quantities that, at each iteration, are calculated starting from the end nodes toward the source node, in the backward sweep. These three variants are: the current summation method, where the branch currents are calculated; the power summation method, where the power flows (Active and Reactive Power) are evaluated; and the admittance summation method, in which the driving point admittances are estimated, node by node. [12]

The proposed method consists mainly in three steps:

1. The so-called Backward sweep, in which the currents or power flow in each load node and flowing between branches are calculated, starting from the end nodes to the ones closer to the feeder, where can be found the service transformer. The basis of power flow equations modeling for a three-phase LV distribution network is founded in the Kirchhoff's Laws.
2. The Forward sweep technique, that works in the opposite direction with the objective of computing the voltage at each load node and the voltage drop in each branch, through Ohm's Law. The implementation of this technique starts near the source node towards the end nodes.
3. Evaluation of the convergence of the methodology [13]

The algorithm used in these simulation tests, is BFS based on the power summation method. However, it was modified taking into consideration the loads characteristics, based in the elasticity concept, allowing the neutral voltages calculation due the utilization of a [4∗4] matrix structure – phases A, B, C and neutral (N) - which can be interesting in unbalanced networks assessment. Most algorithms methodologies, in unbalanced radial distribution networks, use the Kron reduction technique, to transform a [4∗4] in a [3∗3] matrix, which can be found in [14] and [15].

There are three main existing types of constant loads elasticity's simulating a power distribution network: constant power (elasticity equal to 0), constant current (elasticity equal to 1) and constant impedance (elasticity equal to 2).

In this study, load elasticity is 1. For instance, according to $I = V/R$ equation, a constant current load adjusts dynamically its resistance whilst the load voltage varies.

As stated before and since the power flow model variant adopted in this test is the power summation technique, the first step in backward walk, is the power flow calculation. Starting from the branches connected to the end buses, the updated effective power flows are obtained in each branch.

Since in order to obtain the power values, the computed bus voltages are needed, an iterative process must be implemented to reach the final voltages solution.

Using as reference the imposed voltage at the feeder, the phase voltages are initially assigned this predefined value, on the buses with load or with microgeneration and the power in each branch is calculated through the individual sum of each load or generator.

The forward sweep is responsible for the update of the nodal voltages, starting in the source node towards the end buses, using the previously obtained complex powers. [16]

At last, the third and final step is checking for the method convergence. In this step, the new obtained voltages are compared to the previous ones and if the difference is greater than a predefined value, the entire process should be repeated until convergence is reached. [17]

Figure 1 represents a generic three-phase network portion for a better and comprehensive understanding of the equations and method demonstrated. Regarding the small-scale example below, the power injected at bus m must be equal to the sum of the power injected at bus n, $S_{\psi n}$, taking into consideration the power injected in the grid by the microgenerators – negative signal refers to the fact that energy is being injected into the grid – as well as the inherent line power losses between buses m and n.

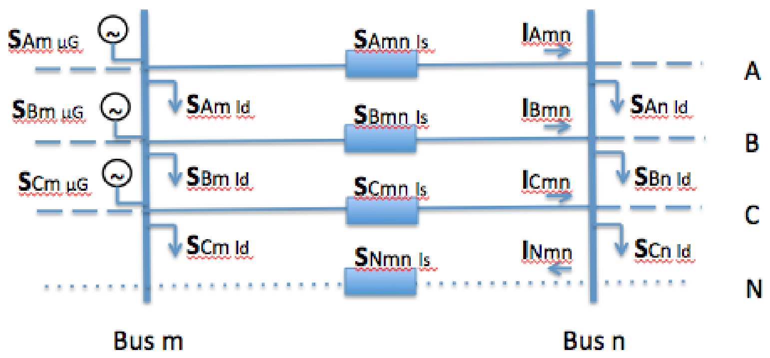

Figure 1 - Generic bus-to-bus three-phase network – A, B, C phases and Neutral wire (N)

$$S_{\psi m}^{k} = -S_{\psi m_{\mu G}} + S_{\psi n}^{k} + S_{\psi m_{ld}} + S_{\psi mn_{ls}}^{k} - S_{\sigma mn_{ls}}^{k}$$

Equation 1

$$\psi = [A, B, C], \sigma = [neutral]$$

Equation 2

According to equation 1, the specified quantities refer to: $S_{\psi m}$ and $S_{\psi n}$ represent the power in phase ψ at buses m and n; $S_{\psi m_{\mu G}}$ corresponds to the injected power by PV microgenerators; fourth term refers to the absorbed power by the load connected at phase ψ; the fifth and sixth terms, cover the power losses, in branch m-n, of phases ψ and σ, respectively. The last equation term appears with a negative signal taking the assumption that the current flows in the opposite way in the neutral line (N).

Having finished the first step of the model, the second step is reached, where voltage bus calculation is found.

At this moment, new voltage values are calculated in the opposite direction, from the feeder bus towards the end buses of the distribution network. The complex powers calculated in the previous step are used, plus the reference voltage value, given by the service transformer bus.

$$V_{\psi n}^{k} = V_{\psi m}^{k} - Z_{\psi mn_{line}} \left(\frac{S_{\psi n}^{k-1}}{V_{\psi n}^{k-1}} \right)^{*}$$

Equation 3

$$V_{\sigma n}^{k} = V_{\sigma m}^{k} + Z_{\sigma mn_{line}} I_{\sigma n}^{k-1}$$

Equation 4

The referred quantities in Equation 3 are: $V_{\psi n}^{k}$and $V_{\psi m}^{k}$ correspond to voltage of phase ψ at buses n and m; k stands for iteration; $Z_{\psi mn_{line}}$ represents the impedance of the line branch m-n at phase ψ, without taking into account the mutual impedances. In Equation 4, you can find: $V_{\sigma n}^{k}$ and $V_{\sigma m}^{k}$ referring to the neutral voltage at buses n and m and the impedance of the neutral line between m-n. $I_{\sigma n}^{k-1}$ stands for the neutral current in busbar n.

In order to calculate phase to neutral voltage - V_{an}^{k}- the following equation is given:

$$V_{\alpha n}^{k} = V_{\psi n}^{k} - V_{\sigma n}^{k}$$

Equation 5

Proceeding with the methodology, the current calculation is made with the voltages and powers obtained before, and it is assumed, at first iteration, that all currents are null, based on the following equations:

$$I_{\psi n}^{k} = \left(\frac{S_{\psi n}^{k}}{V_{\psi n}^{k}}\right)^{*}$$

Equation 6

$$I_{\sigma n}^{k} = \sum I_{\psi n}^{k}$$

Equation 7

In the previous Equations 6 and 7, the major focus lies in the calculation of the current of phase ψ at bus n - I_{yn}- and the neutral current in neutral σ at bus n - I_{sn} .

For last, the equations needed to calculate the power losses, through lines m-n, can be found bellow:

$$S_{\psi mn_{ls}}^{k} = \left(V_{\alpha m}^{k-1} - V_{\alpha n}^{k-1}\right)\left(\frac{V_{\alpha m}^{k-1} - V_{\alpha n}^{k-1}}{Z_{\sigma mn_{line}}}\right)^{*}$$

Equation 8

$$S_{\sigma mn_{ls}}^{k} = \left(V_{\sigma m}^{k-1} - V_{\sigma n}^{k-1}\right)\left(\frac{V_{\sigma m}^{k-1} - V_{\sigma n}^{k-1}}{Z_{\sigma mn_{line}}}\right)^{*}$$

Equation 9

All the referred quantities in Equations 8 and 9 are captioned above.
The iterative process in order to obtain the final voltage solutions ends comparing the new and old voltages, with k and k-1 superscript, respectively. If the difference between them is greater than a specified value, the entire process is repeated until convergence is reached.

The proposed methodology is presented and tested in order to verify the best solutions to mitigate overvoltage in a real unbalanced LV distribution network [7].

3.2. Simulation Conditions

Case-Study Definition

An unbalanced three-phase low voltage distribution grid has been used in this case study. In a conventional load flow scheme, high and medium voltage network power system is known as balanced. In this scenario, a single-phase analysis is needed to comprehend the power system.

However, in LV distribution networks, due to the unbalance of domestic loads, the grid itself is characterized as unbalanced. In order to study and analyze the grid, the so-called three-phase load flow is applied, where the behavior of each phase is considered individually.

A diagram of the tested unbalanced three-phase LV network is represented in Figure 2.

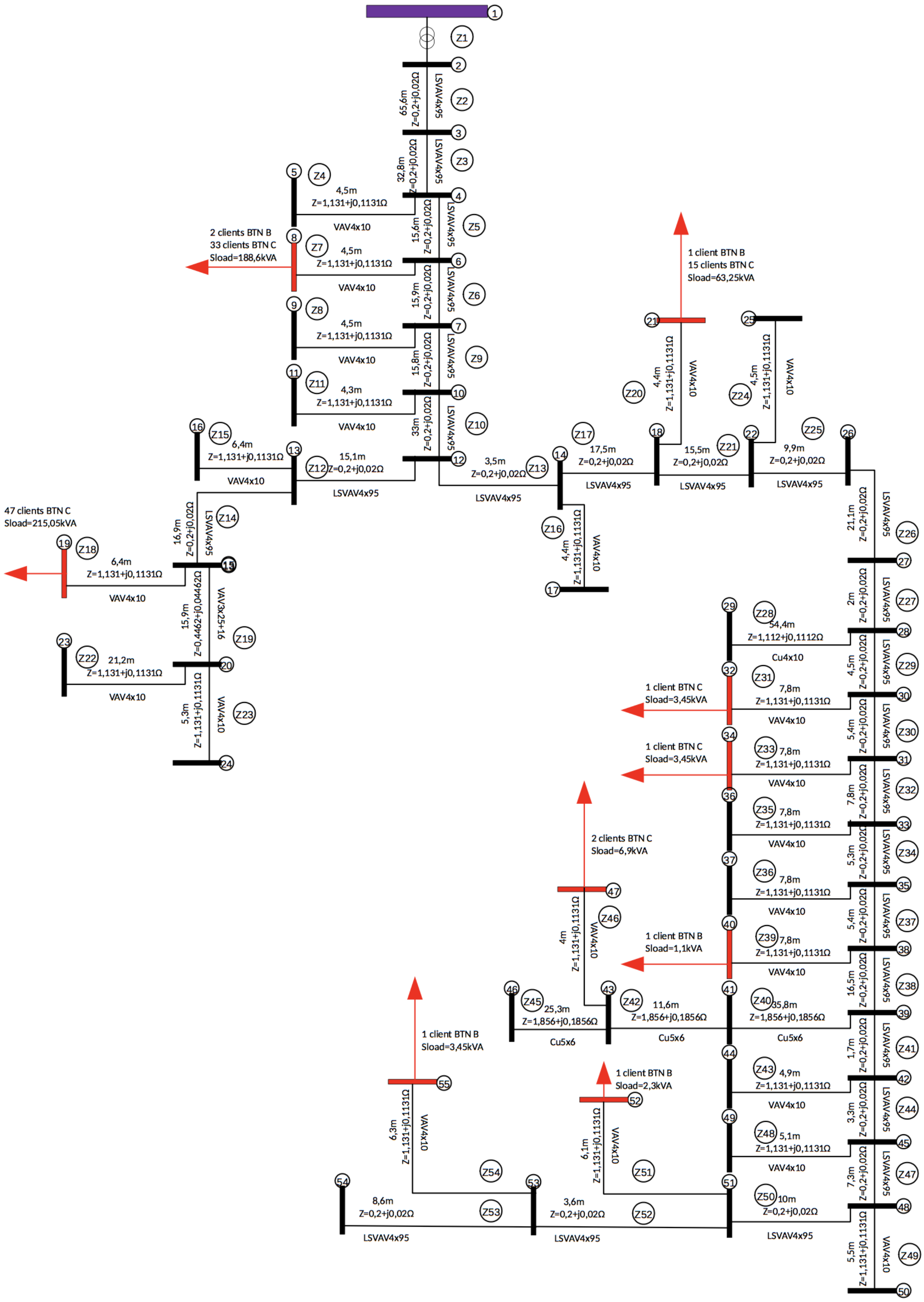

Figure 2 - Diagram of the unbalanced LV network at study

Due to its considerable size and in order to reduce the same, a single line diagram of the test radial LV distribution network can be observed in Figure 3, highlighting only the buses where prosumers are connected.

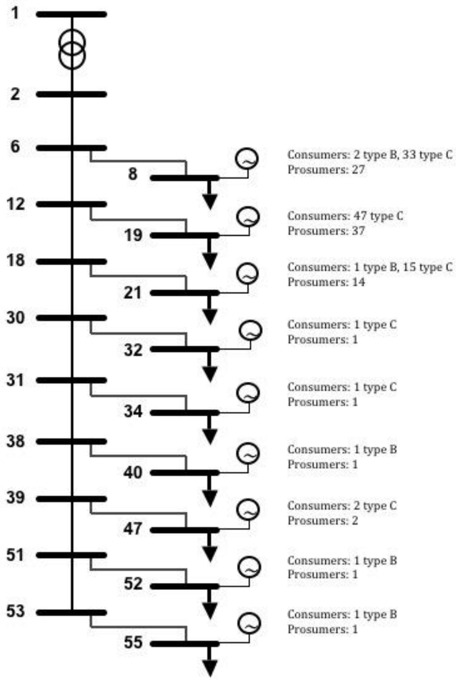

Figure 3 - Single line diagram of the LV distribution network at study

The LV distribution network is equipped with a MV/LV transformer, near the substation, characterized by a delta connection type in the primary windings and star type with earthing in the secondary, having a transformation ratio of 15kV to 0.4kV. The total apparent power of the transformer reaches 630kVA. Inverters are also needed in the LV distribution grid. Since PV generators output is expressed in Direct Current (DC) and the power flowing in the LV grid, which is supplied to households, in Alternating Current (AC) there is the need to resort to this kind of power electronics devices.

The cables that compose the test distribution grid at study have their characteristics presented in the following Table 1.

As it can be observed, two distinct cables, LSVAV 4×95 mm^2 and LSVAV 4×16 mm^2, model LV test distribution grid.

A relationship between the cables resistance (R) and the reactance (XL) can be assumed by the following equation XL=R/10.

Table 1 - Cable types with section and resistance per kilometer

Cable Type	Section [mm^2]	R [Ω/km]	Impedance (Z=R+jXL)
LSVAV 4×95 mm^2	95	0.32	0.32+j0.032
LSVAV 4×16 mm^2	16	1.91	1.91+j0.191

The network is composed by 55 buses, where only 9 of them have prosumers connected to the grid, reaching a total number of 85 prosumers, distributed in phases A, B and C.

In Table 2 is possible to observe in which buses are the PV generators located, as well as the number of clients connected to each phase.

Table 2 - Generation client's distribution

	Bus								
Phase	8	19	21	32	34	40	47	52	55
A	9	13	4	0	0	0	1	0	1
B	9	12	3	0	0	0	1	1	0
C	9	12	7	1	1	1	0	0	0

At the beginning of its useful life, each PV device reaches its maximum performance rate, as it is expected to decrease along with its use. Each prosumer is equipped with a PV generator set totaling a maximum capacity of 3.68 kWp (peak-power).

Portuguese Energy Services Regulatory Authority, ERSE, studies and classifies clients' consumption patterns in order to have a reliable distribution of the clients' needs. According to No5/2014 ERSE Directive, three typical consumption profiles for LV distribution network were approved, according to their contracted power and energy. These three consumption profiles can be observed in Table 3.

Table 3 - Typical consumption profiles for LV (Data from ERSE)

Type	Contracted Power (KVA)	Energy (kWh)
A	>13.8	Any
B	≤ 13.8	> 7140
C	≤ 13.8	≤ 7140

It's important to highlight that according to Law Decree nº 153/2014, of 20th October, the 5th article, b), states that the connection power of the production unit must be equal or less than the contracted power in the energy supply contract.

Regarding consumption, there are 105 residential customers connected to the network. From those 105, 100 are type C clients and only 5 are characterized as type B clients. Both show contracted powers inferior than 13.8 kVA, as is illustrated in Table 3.

The proposed MATLAB algorithm was developed and programmed by Fernando Camilo in the scope of his doctoral thesis, and tested in the network above, in order to tackle overvoltage issues through mitigation strategies.

ERSE website provides all the useful information to characterize a load and generation profile, in 15 minutes intervals, illustrating the moments of the day when energy is more required from the grid as well as reaches its production peaks.
This study is based in collected data referring to the past year of 2015.

Overvoltage cases tend to surge when a consumption and generation curve mismatch occurs. Typical periods which maximize PV generation are found from 10am until 5pm. On the other hand, the daily consumption peaks are localized early in the morning and in the evening, where the production is at its lowest or near zero. During a typical summer day, a high solar PV production is recorded whilst a low consumption is required. Therefore, voltage profile values increase in busbars and overvoltage cases arise.

Through a careful analysis of the LV distribution network, buses with a higher number of clients connected to their different phases, in addition to an uneven distribution across phases and crescent distances to the transformer, are facing a troublesome scenario, having greater probability of causing imbalances in the grid. Consequently, these buses and its adjacent ones, for example busbars 19 and 21, will have a higher voltage fluctuation when microgeneration starts being injected into the network.

Tests were performed choosing two distinct seasons: Summer and Winter typical days, August the 4th and January the 7th, respectively.

Naturally, during summer season, PV production is usually higher due to a larger fraction of irradiance reaching the solar modules. This fact increases the generated power, possibly even reversing power flow, and contributes to increase the chances of an overvoltage issue in the network. As illustrated in Figure 4, both microgeneration curves are similar, excepting on the power range, reaching higher values during summer.

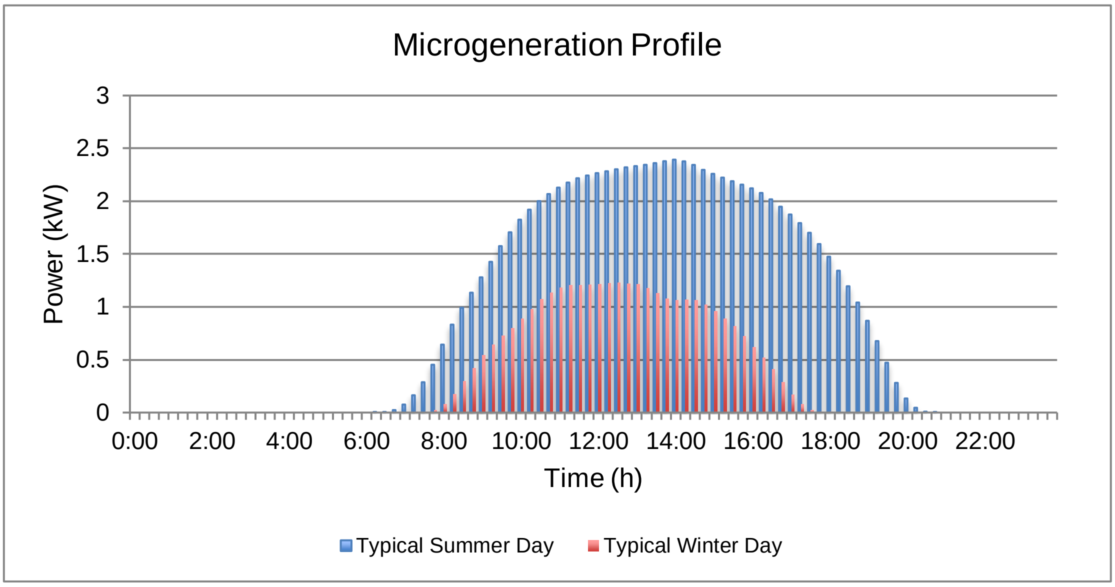

Figure 4 - Typical daily microgeneration profile of each prosumer

The maximum power that can be generated by the total number of prosumers connected to the grid is 312.8 kW, which it would only be possible if the 85 prosumers were generating the maximum 3.68 kW of each PV set.

The total maximum power values are only attainable under Reference or Standard Test Conditions (STC). These are the industry standard conditions under which solar panels are tested. Using a fixed set of conditions, it is easier to accurately compare results between each other. Since the current across the PV cell is highly dependent on irradiance (G^r) and temperature (θ^r), there was the need by the manufacturers to create a reference for these parameters, which are: Cell temperature equal to 25 ºC or 298.15K; incident solar irradiance of the cell equal to 1000 W/m^2; and an air mass 1.5 (AM1.5) spectrum.

In outdoor tests, these standard test conditions are not possible to have in practice, with temperature and irradiance in constant change, which leads to a variation in the standard expected values.

Through the collected data from ERSE, a typical profile of the maximum generated PV power per prosumer, for typical winter and summer days, is 1.23 kW and 2.39 kW respectively.

Regarding consumption, there are two types of clients to have into consideration, type B and C clients, each of them with different consumption patterns.

Focusing on type B clients, the peak load for winter and summer is 0.41 and 0.31 kW, respectively, per prosumer, as it can be seen on Figure 5. Considering that the distribution grid is composed by 5 type B clients, the total peak power results in 2.05 and 1.55 kW in winter and summer, respectively.

For a more comprehensive and wider analysis of the distribution network, the load for those seasonal typical days are presented next.

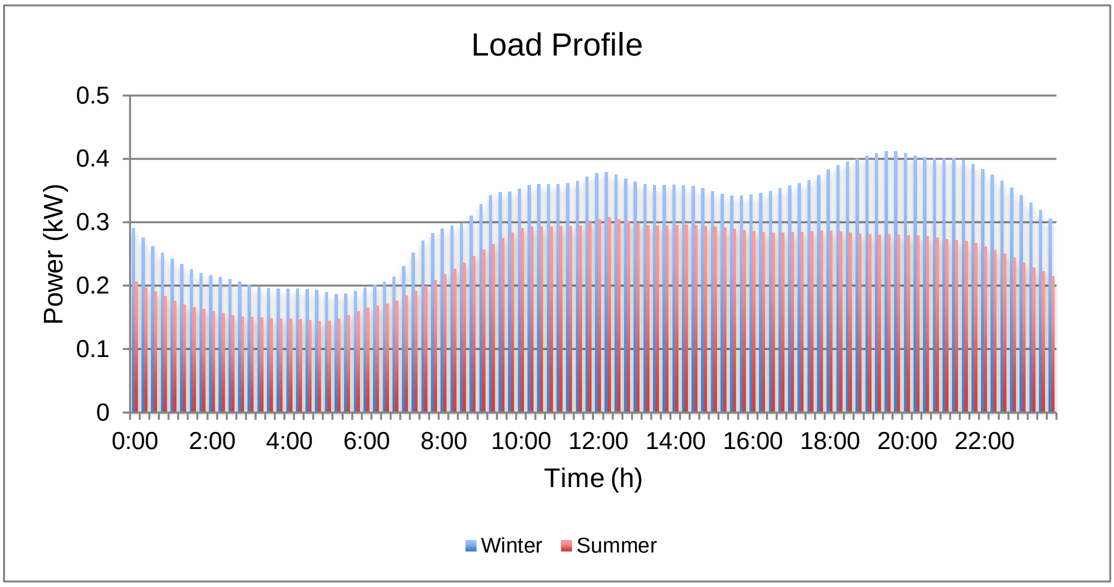

Figure 5 – Type B clients load curve during Summer and Winter

Moreover, considering now only type C clients, the peak load for winter and summer is 0.53 and 0.33 kW, respectively, which means that taking in consideration the total number of type C clients (100), leads to a total peak load of 53 and 33 kW.

The load curves for summer and winter typical days for type C clients are presented in Figure 6. The presented distribution grid, considering type B and C clients, is characterized by a total peak load of 55.05 kW in winter and 34.55 kW in summer.

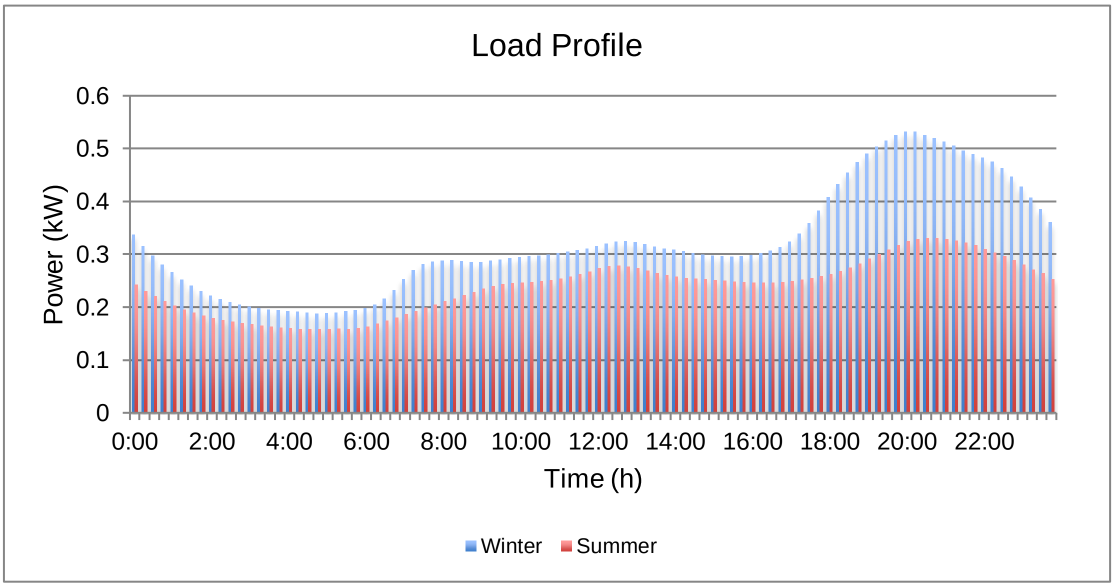

Figure 6 – Type C clients load profile during Summer and Winter

To have an overview of the studied distribution network and to analyze the generation and load curves in the same diagram, Figure 7 is addressed as an example. Here is possible to observe that there are two main periods, in the morning until 7 am and in the evening after 21pm, where the loads required by the grid exceed the generated power of the PV sets.

In the afternoon, due to high solar exposure and temperature, a higher rate of power production is attained which creates an excess of generated power.

However, mainly in the afternoon, households are characterized by having low demands which ends in power surplus, that can be sold and injected again into the grid or can be stored in batteries and used later, in periods where consumer loads are high and generated power lacks.

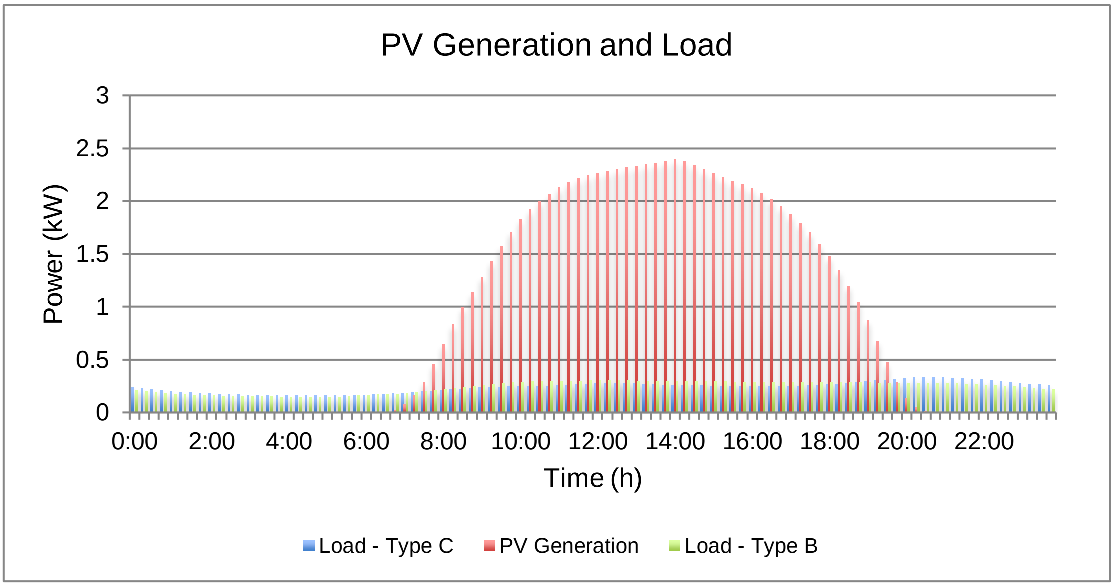

Figure 7 - Load and generation Profile on a typical Summer day

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CHAPTER 4 – Results & Analysis

In the previous section, an overview of the grid details was made to know its characteristics as well as consumption and generation data information.

The goal of the study presented in this section is to assess the behavior of the LV distribution network in the presence of PV microgeneration, evaluation of the voltage profile in a residential test grid, as well as the application of mitigation and corrective strategies to overcome overvoltage issues.

This study is only focused on overvoltage cases and techniques to solve it. Thus, three solutions to cope with overvoltage cases are presented: Active Power Curtailment, Reactive Power Support and a Hybrid Technique.

For the study at hand, several simulations based on the LV three-phase unbalanced power flow algorithm described in section 3.1. are performed before and after microgeneration integration in the distribution network.

The inclusion of PV units during daylight, when consumer loads are supposed to be low, especially in residential areas, originate overvoltage issues.

When the voltage values in the distribution grid are outside the statutory limits, measures must be taken. One type of technique to apply is generation curtailment, where the active power output is curtailed, disconnecting PV generation units from the bus showing overvoltage, until voltage diminishes to an acceptable range. This maneuver is employed as a last resort option, since, despite being an efficient technique, it is discouraging to the producers as it leads to some losses in their possible revenues.

Alternatively, reactive power support can be made using power electronic devices or through the inverter in the PV generation set. These smart PV inverters can absorb reactive power, therefore decreasing bus overvoltage. The maximum reactive power value that can be absorbed is equal to 0.9 of the injected active power.

However, this methodology has its limitations, due to the low inductive characteristics of the LV distribution network cables. It has proven to be a marginal enhancement in voltage profile. In some cases, there is the need to resort to hybrid technologies, adding Reactive Power Support to PV Curtailment technique.

The results and the correspondent analysis are presented below, in typical Summer and Winter days, divided into three different sections. Active power curtailment technique is referenced in section 4.1., whilst Reactive power support in subchapter 4.2. then followed by a Hybrid Solution that can be found in section 4.3.

4.1- Active Power Curtailment

The distribution grid, as we know it, is constructed unidirectional, from the power source to the end consumer loads. To begin the analysis, the LV distribution grid is tested in its normal operation state, without any type of power injection, to examine voltage profiles and their behavior with only residential customer loads connected. In this way, it is possible to establish a comparison model, when the grid is with and without embedded photovoltaic microgeneration.

In a traditional LV distribution network without *μG* integration, which can be observed in Figure 8, voltage tends to decrease along the feeder due to the load demand. Therefore, buses situated further away from the substation transformer are more likely to be outside the statutory voltage limits or register lower voltage values. However, none undervoltage issues occur in Figure 8, once all voltage values are superior than the minimum threshold (0.95 pu).

On the other hand, once *μG* integration takes place into the LV grid, the equivalent load is reduced, and the voltage on that specific bus tends to increase, eventually causing an overvoltage situation, as it is illustrated on Figure 9.

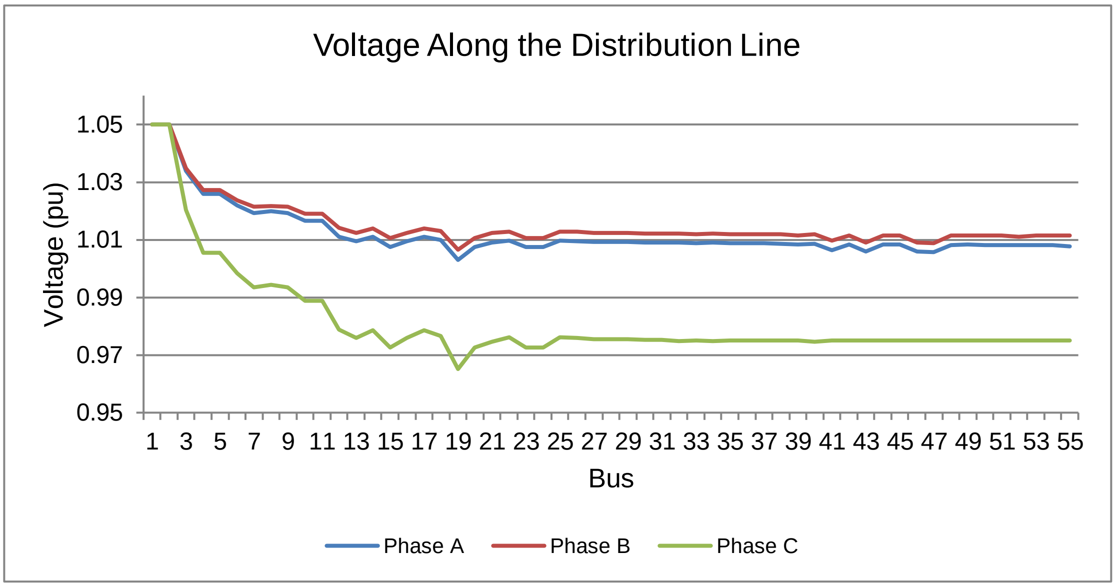

Figure 8 - Phase A, B and C voltages along the distribution line, without µG integration, on a typical summer day, at 14:00h

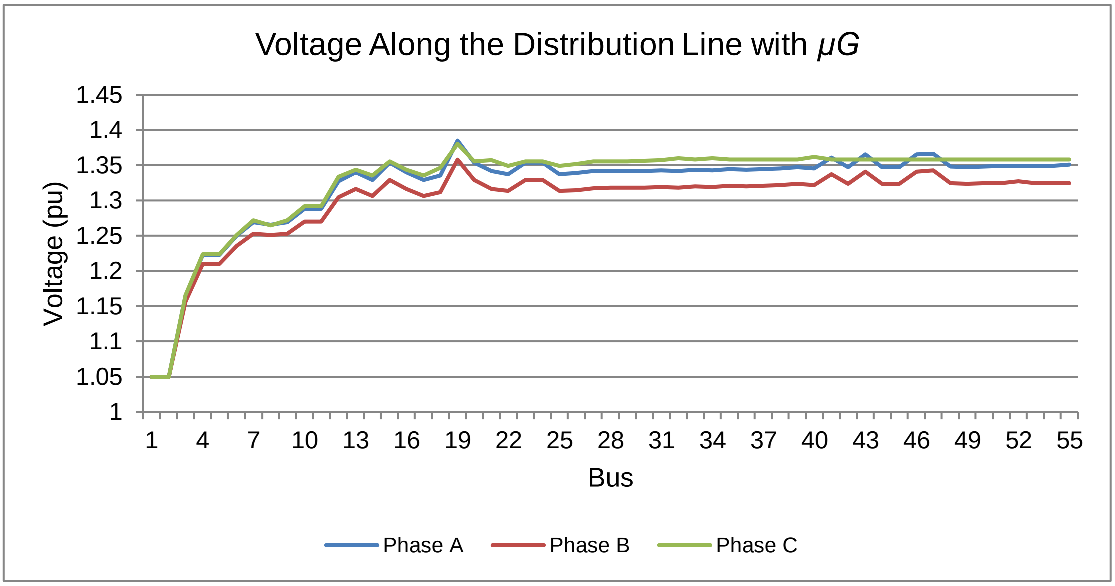

Figure 9 - Phase A, B and C voltages along the distribution line, with µG integration, on a typical summer day

From busbars 1 to 55, each one of them has a different number of connected prosumers and residential consumers in each phase. That fact is what turns the grid as unbalanced.

Through the bus analysis of the entire grid, it is possible to state that Bus 19 is the most unbalanced node.

In fact, analyzing Figure 3 and Table 1, is possible to cross the information and identify that Bus 19 is the one with a higher number of residential loads to supply as well as the highest number of prosumers connected to the grid, being the targeted bus to assess the results of simulations.

Moreover, the period of the day where voltage attains higher values is registered being at 14:00h.

The objective of the study presented here, is to analyze the performance of overvoltage mitigation strategies, in an unbalanced LV network with a high PV penetration. This section focuses on the benefits and constraints of using Active Power Curtailment methodology.

Figure 10 portrays bus 19 voltage profile, for each phase, during a typical summer day, illustrating only customer load requirements, without any means of connected PV microgenerators. In these cases, overvoltage issues are not expected to occur. Moreover, none undervoltage cases were registered and all exhibited voltage values in Figure 10 are within legal range.

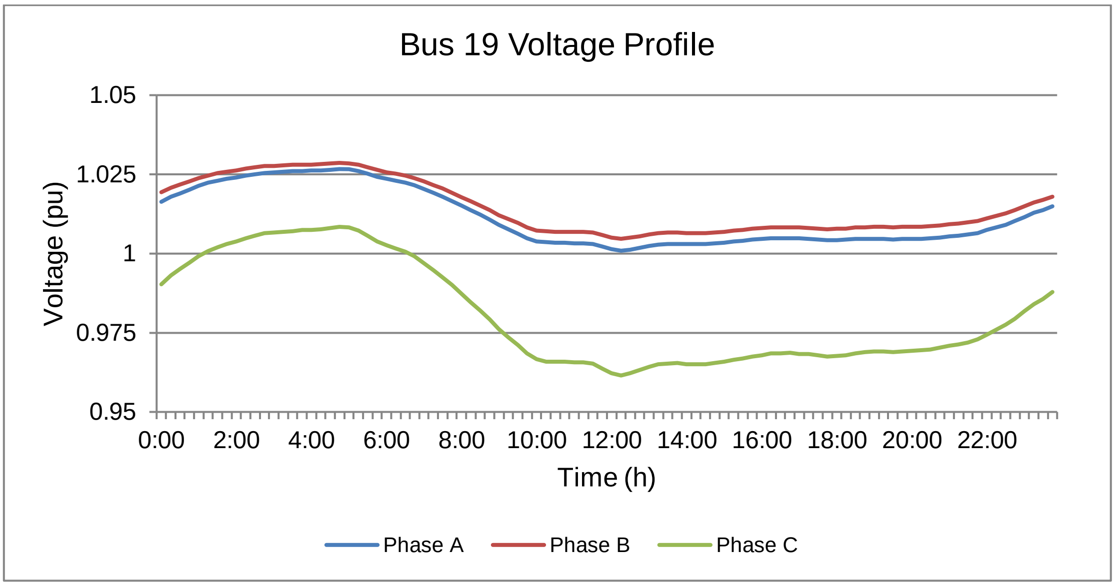

Figure 10 - Bus 19 Voltage Profile without µG penetration in LV network, in a typical summer day

Most of the times, overvoltage situations are expected to occur around lunch time (13pm-15pm). A reasonable explanation to this issue is related to the fact that the period which maximizes PV production is situated around noon, which usually is characterized as a low consumption period, due to a non-occupancy of the domestic households. This two-fold combination ends in a voltage rise.

Figure 11 shows the daily representation of the voltage profile behavior at bus 19, with PV microgeneration embedded in the LV grid. In this example, the highest overvoltage situations occur in the above-mentioned period.

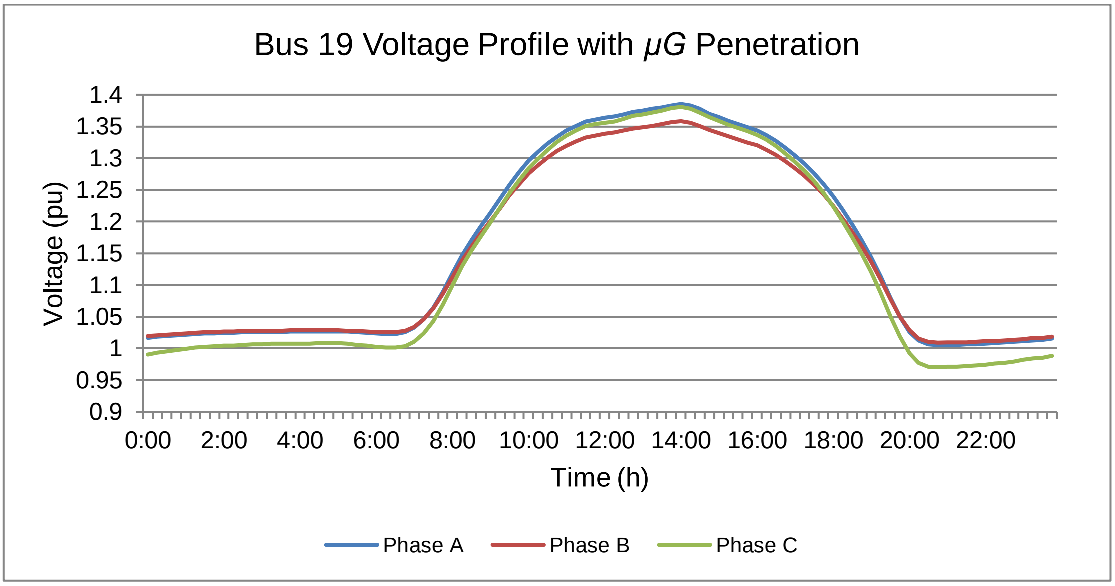

Figure 11 - Bus 19 Voltage Profile with µG penetration, throughout a typical summer day

In the previous example, from 8:15am to 19:30pm, it is possible to observe several overvoltage situations in these specific bus of the unbalanced test LV network. As a result of these undesired situations to the normal operation of the network, corrective strategies are applied, such as PV Curtailment.

PV Curtailment technique tracks voltage values, in every node of each phase of the network. Whenever the voltage reaches 1.1 pu or higher values, PV power is curtailed and the specific PV generator is disconnected from the grid, until the voltage decreases to acceptable values – below 1.1 pu.

One particularity of the proposed technique is the amount of power curtailed (0-100%), which can be regulated for each type of desired output. In this specific example, illustrated in Figure 12, simulations are running with a complete PV cut off. This allows to understand the extent and efficiency of the tested strategy. Once its effectiveness is proved and no overvoltage-related issues happen, a different level of curtailment is tested to improve the methods' efficiency, diminishing the losses of clean renewable energy.

As a result of this PV power total curtailment strategy, potential profits are lost in the producer point of view. In the event of a partial power cut off, it is possible to minimize those losses to a minimum value.

Looking at Figure 11, voltage reaches 1,38 pu when the maximum allowed by legislation is 1,1 pu.

Therefore, APC technique is applied on the specific busbars of the LV grid where overvoltage issues are taking place, which translates in a disconnection of PV generation units from the grid - immediate results are expected. Figure 12 demonstrates that regarding this overvoltage mitigation technique, voltage values diminish and reach inferior values compared to the statutory threshold.

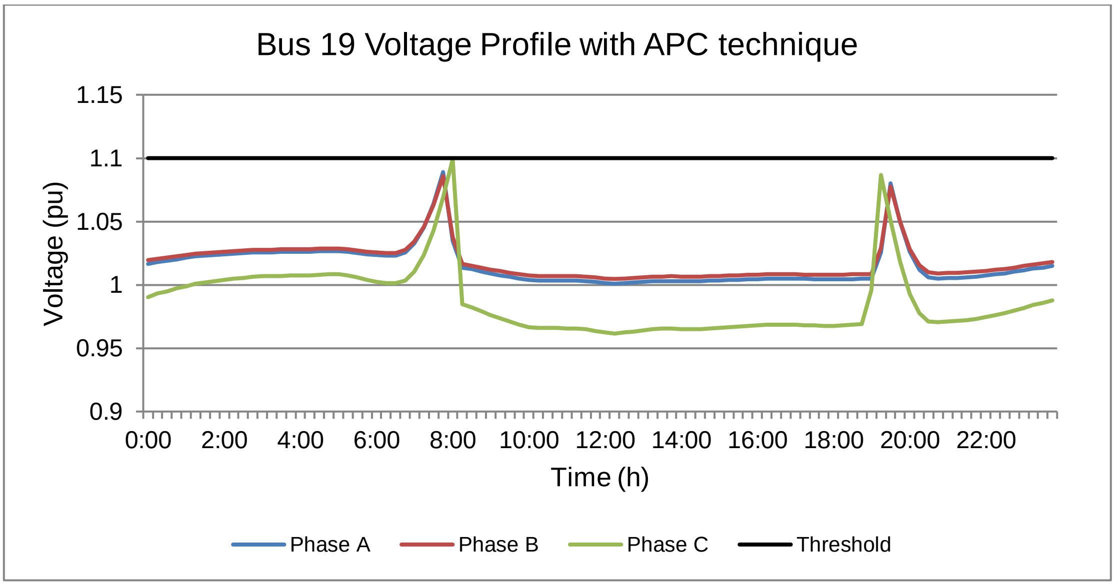

Figure 12 - Active Power Curtailment technique (100%) in Bus 19 voltage profile, in a typical summer day

To begin with, all overvoltage cases were extinct due to the implementation of the mitigation strategy. Each PV generator located at a bus experiencing overvoltage issues is removed from the LV grid and this procedure is repeated until all bus voltages are within legal bounds.

The APC technique does not allow voltage to surpass 1.1 pu, the maximum voltage value allowed by legislation. In this context, each time voltage approaches its maximum value, the APC technique is enabled and the disconnection of the PV generation sets takes place, in order to reinstate the normal operation voltage values. That fact is illustrated in Figure 13: if all the PV generation sets were connected to the grid, in the period from 8 am to 19pm, a high number of overvoltage cases would be presented, as the blue curve portrays. However, based in APC technique, represented in red, once overvoltage issues appear, the specific PV generation set is disconnected, and this fact continuously happens along the distribution line, preventing voltage values to rise and maintaining inferior to the legal bounds.

It is interesting to analyze the periods of the day in which voltage peaks are attained. As it is expected to occur, the morning and late voltage peak take place due to high consumption patterns associated and low production rate due to the lack of sun. Bearing this, it can be stated that overvoltage issues in an unbalanced LV network are overcome using APC technique. On the other hand, it is important to highlight the unnecessary amount of curtailed PV power that occurred in this initial example and is completely wasted.

Figure 13 helps to realize that a higher fraction of PV power was curtailed rather than strictly the necessary. The figure below portrays, on one hand, in blue, phase A, the moment when μG is introduced into the LV grid. On the other hand, in red, phase A voltage values, when APC technique, with a 100% cut off is in use. In black, it is outlined a threshold voltage line, which stipulates the statutory voltage limits. The space between the APC technique curve and the voltage threshold horizontal line, shows that the curtailed portion of PV power through the proposed strategy could be significantly less. This fact would increase the PV penetration in the grid, reducing the equivalent grid load, hence increasing bus voltage, that can rise at most to 1.1 pu.

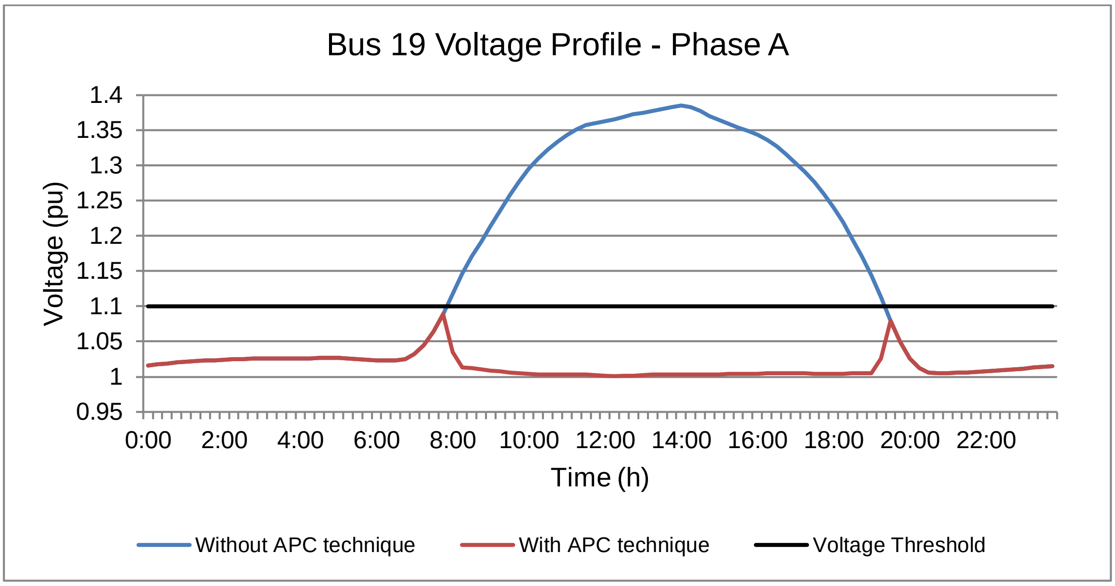

Figure 13 - Comparison between bus 19 phase A voltage profiles of two distinct situations: with and without APC technique, on a typical summer day

As a result, a new simulation is considered, with a partial PV power curtailment procedure, represented in Figure 14. It can be easily observed that with a lower amount of curtailed PV power, around 75% of the energy produced on a typical summer day, instead of its whole amount, turns the renewable energy lost in the curtailment process considerably less, which is seen as a profit for the producer. As expected, the gap between APC technique and the threshold is minimum, confirming the feasibility of the technique cut off applied.

APC technique with a total PV power cut off, proves itself as an efficient strategy in the correction of overvoltage issues in an unbalanced radial network. In the same way, it is also associated with an energy and profit loss in the eyes of the producer. However, the mentioned technique has a good performance index in the task of keeping the voltages below the legal limits in the voltage profile.

As an alternative and portrayed in Figure 14, APC technique with a partial power cut off appears with the solution of minimizing the undesired and wasted energy fraction and consequent profits losses.

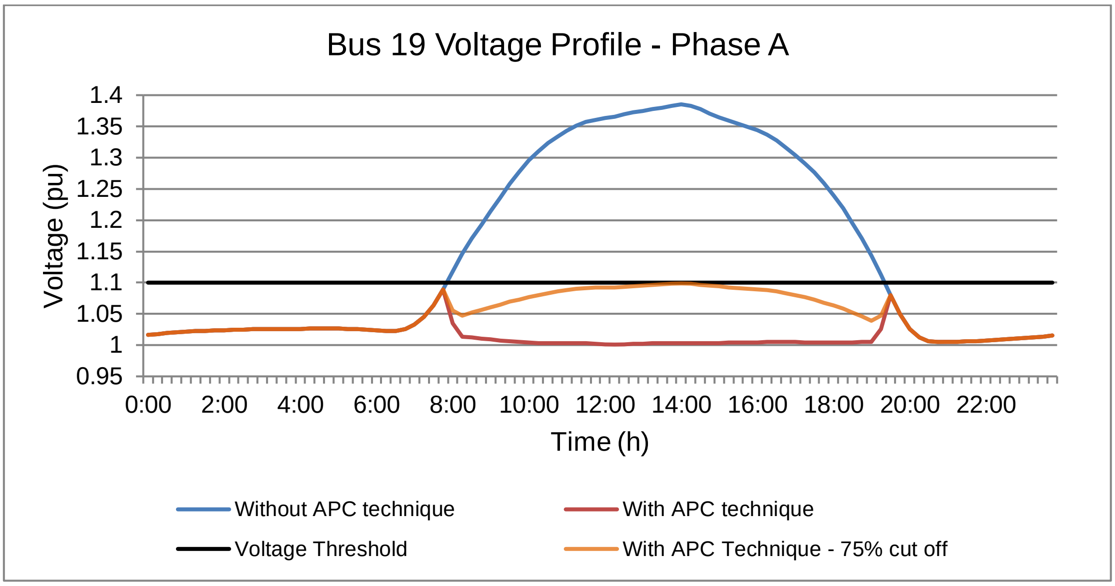

Figure 14 - Bus 19 voltage profile in three distinct situations: Without APC technique, using fully APC technique and partially APC strategy (100% and 75%), on a typical summer day

The study in question proposes to analyze voltage profile of the most problematic bus of an unbalanced LV grid, not only on summer but also on typical winter days.

Winter season is characterized as being mostly a rainy and cloudy season. That fact means that less irradiance reaches the earth surface, hence a lower amount of irradiance contacts with PV modules cells. With that in mind, a minor PV production is expected when compared to typical summer days.

In its turn, if the renewable energy produced is less, a lower amount of PV power is injected into the grid, resulting in lower voltage values in the radial LV network.

Figure 15 represents a daily evolution of bus 19 voltage profile, during a typical winter day, portraying only the influence of customer loads requirements to the grid. Some under voltage issues arise in phase C.

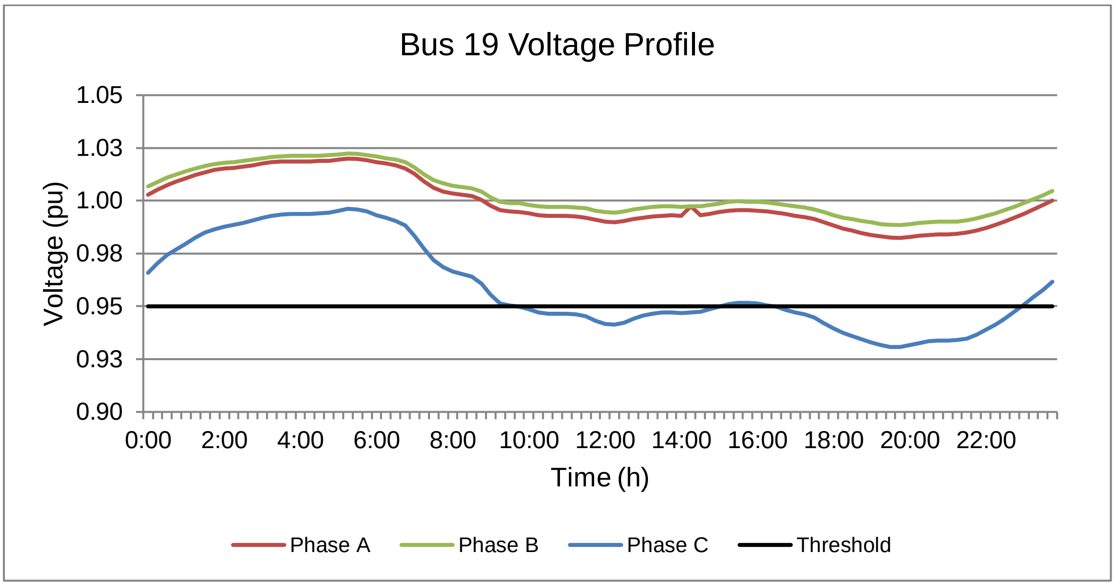

Figure 15 - Voltage profile without µG penetration in LV network, in a typical winter day.

The next proposed step is to introduce *µG* in the distribution network. As Figure 16 exhibits and comparing to the data collected in a typical summer day, illustrated in Figure 11, a lower generation peak is obtained in this specific winter case. Even so, from 9:45am until 16pm, overvoltage cases take place, being the highest voltage value attained at 12:30pm, reaching 1.186 pu.

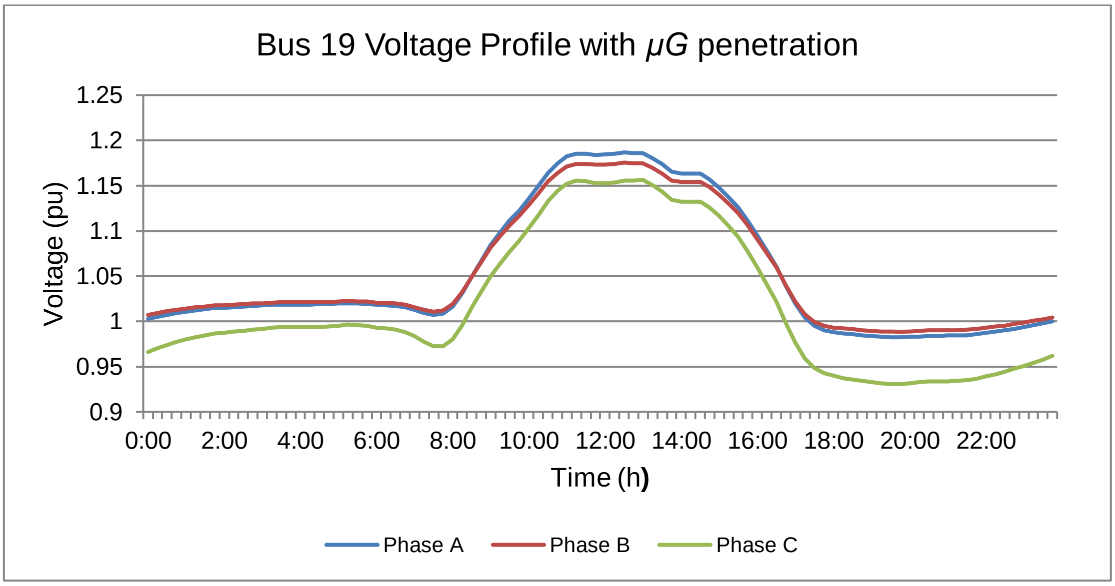

Figure 16 - Voltage profile with µG penetration, throughout a typical winter day

With a high overvoltage occurrence spectrum, in all phases, during the above-mentioned time frame, Active Power Curtailment strategy appear as a solution to cope with this undesired problem in LV networks. Figure 17 exhibits that APC strategy manages to mitigate all overvoltage situations, especially in the most problematic period.

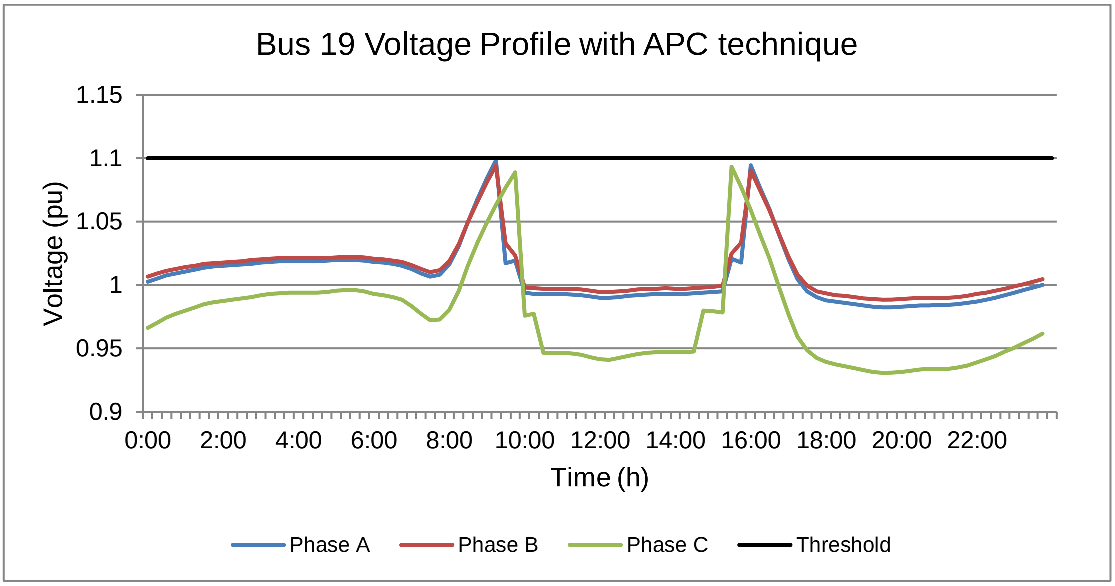

Figure 17 - Active Power Curtailment technique (100% cut off) in Bus 19 voltage profile, in a typical winter day

From now on, within the three-phases, Phase A is the chosen to be analyzed since is the most problematic, recording a higher register of overvoltage cases in the LV test network.

Figure 18 appears comparing APC methodology with different levels of curtailment facing the standard curve without any corrective overvoltage method involved.

Observing the simulation results, all overvoltage issues are mitigated using APC, which proves itself as an efficient measure. However, this strategy can be divided into two different scenarios.

On one side, with a total PV curtailment associated, there's clearly one downside: the quantity of energy and potential profits that are wasted, without jeopardizing the normal operation of the grid. This is shown to be surpassed in the second approach of the APC Technique where a percentage of the PV power cut is analyzed and dimensioned to each case, illustrated in purple on Figure 18.

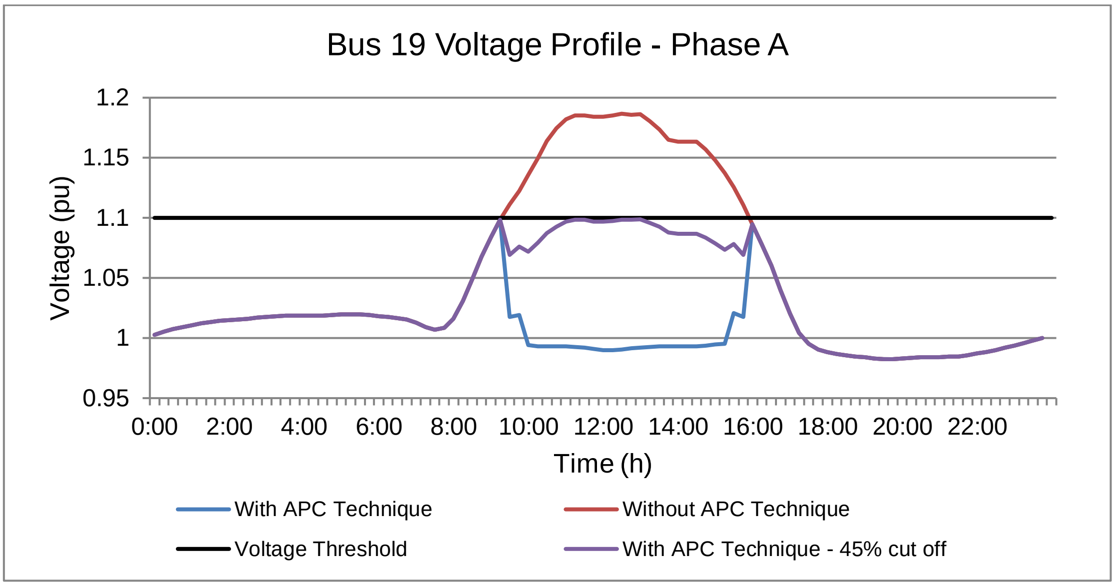

Figure 18 - Bus 19 voltage profile in three distinct situations: Without APC technique and using fully and partially APC strategy (100% and 45%), on a typical winter day

During winter, due to a tendential lower share of renewable energy produced by PV system, it is expected to present a lower PV curtailed share of renewable energy into the distribution grid. As a matter of fact, in Figure 18 it is possible to observe that a curtailment of 45% of the produced PV energy is enough to keep the voltage in the entire grid below the statutory limits.

All things considered, the obtained results lead to the conclusion that APC strategy allows to mitigate overvoltage issues along the distribution grid. However, this technique if applied with a total PV cut, represents a substantial loss of renewable energy amongst the curtailment process, which leads to a loss of profits in the producer's view. Alongside these characteristics, it is important to have the capacity of smoothing the voltage profile, which is not attained when APC is fully curtailing PV energy, causing considerable voltage drops.

On the other side, experiencing a smoother PV cut off, tackles all the undesired details and proves itself globally as a more efficient option to pick.

4.2 - Reactive Power Support

Transmission grid is characterized by a low R/X ratio (R and X refers to line resistance and reactance, respectively), where a large amount of power is flowing through the cables at high voltages.

On the other hand, distribution systems operate at lower voltages, with a higher R/X associated, which translates into higher resistance and losses in the LV grid cables.

A different solution to prevent overvoltage issues is analyzed hereby and presented in the following subchapter. After Active Power Curtailment application in the previous section, Reactive Power benefits are tested in the LV grid with PV integration embedded.

Reactive Power Support, through the important role of smart PV inverters, aims a reduction of the power losses as well as an improvement in the hosting capacity and power quality along the lines of the conventional power system.

Referenced in Chapter 2, section 3.2., Reactive Power mitigation strategy proved its effectiveness due to smart PV inverters primary objective of absorbing reactive power, preventing overvoltage issues, thus optimizing voltage profile and enhancing its general power quality along the grid.

The analysis of Reactive Power support performance begins with the exhibition of bus 19 voltage profile, in Figure 19, characterized by the lack of PV microgeneration integration in the LV grid. Expectably, no cases of overvoltage or undervoltage occur.

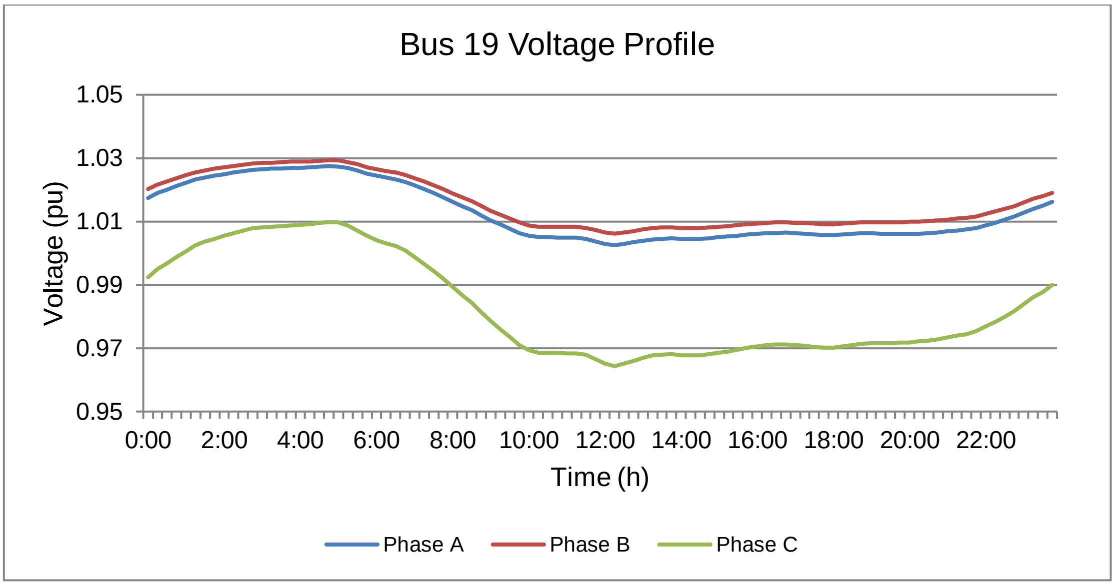

Figure 19 - Bus 19 voltage profile without μG penetration in LV network, in a typical summer day

Until some years ago, this type of graphic behavior was the most expected when analyzing a bus profile of the distribution network. Nowadays, with the modernization of the electric sector, and with the appearance of generation devices attached to the end user, cases as portrayed in Figure 20 are becoming more usual.

Each day, more and more people are resorting to the installation of the small-scale PV systems in rooftops and contributing to energy injection into the LV grid and diminishing their own electricity bill.

Grid regulations set voltage profile range limits, in order to ensure that the power quality delivered to our homes is reliable. In cases where a high PV generation and a low consumption profile occurs, simultaneously, overvoltage cases may rise as is exhibited below in Figure 20.

Figure 20 reflects PV energy integration in the LV grid, in a typical summer day. Numerous cases of overvoltage issues are here presented, since the voltage levels clearly trespass 1.1pu, even surpassing 1.3pu, probably due to a higher irradiance and temperature levels during summer.

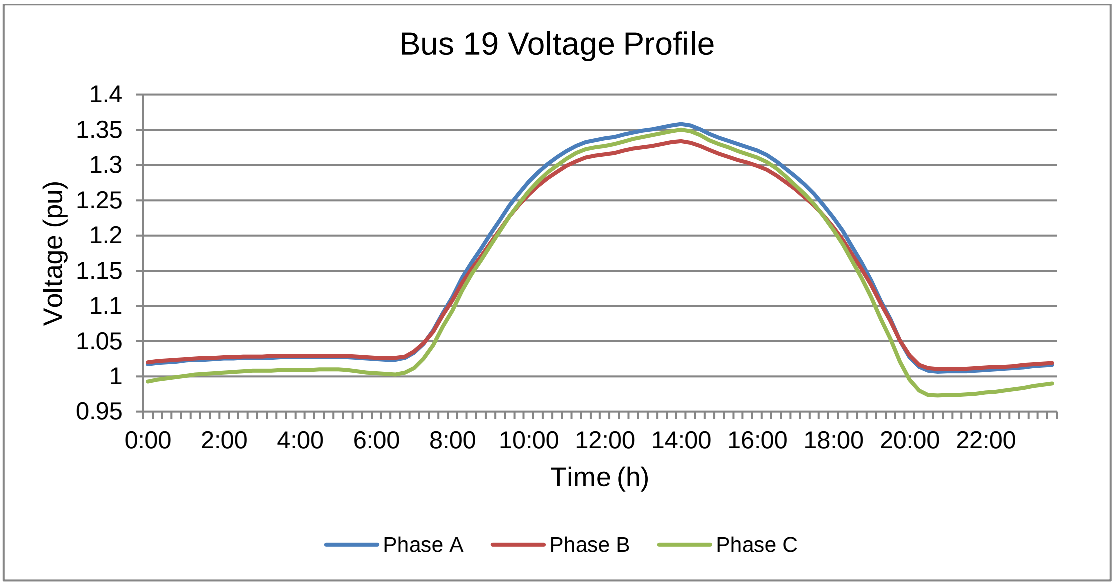

Figure 20 - Bus 19 voltage profile with μG penetration, throughout a typical summer day

To ensure a quality power delivery to the LV network, voltage must be kept within acceptable limits. Here is where Reactive Power Support acts, in order to sustain voltage profile within an allowable range.

In the following Figure 21, a voltage profile example with PV integration in the grid is represented at blue, while the same busbar with a corrective strategy based on Reactive Power Support is portrayed at red. The studied methodology uses smart PV inverters to absorb the reactive power in order to smooth the voltage profile. In this specific study, the maximum reactive power that can be absorbed equals 0.9 of the active power.

As expected, Reactive Power mitigation methodology smoothed the voltage profile, attaining lower voltage values. Still, the rate of voltage decrease is marginal, due to the low inductivity in the cables used in traditional LV networks, showing no real effect in controlling and ensuring the correct operation of the LV grid.

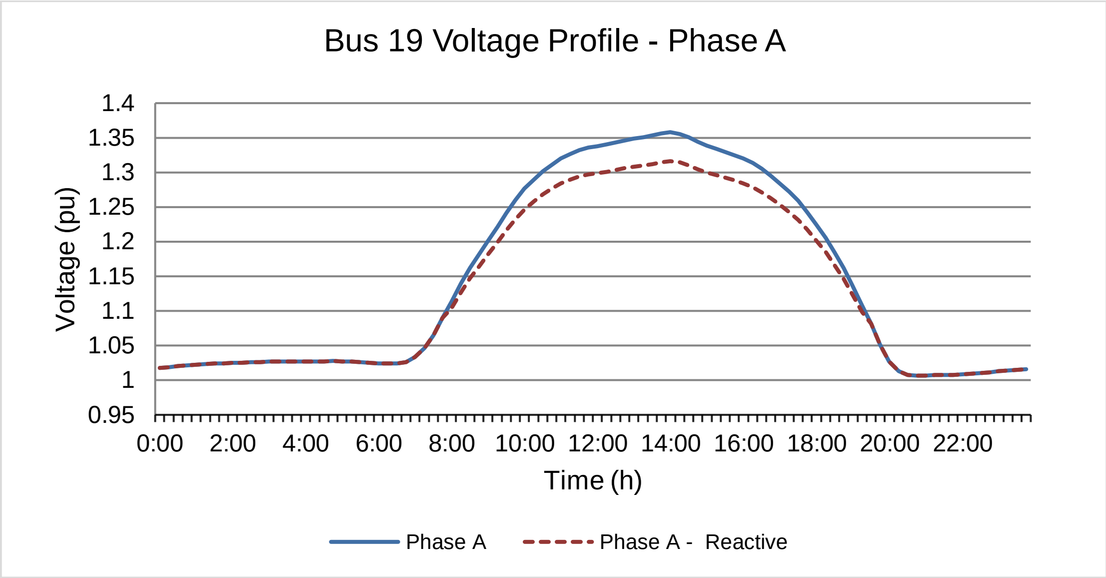

Figure 21 - Comparison between bus 19 phase A voltage profile with µG penetration and with Reactive Power Support technique, on a typical summer day

A similar analysis takes place in a winter case, where lower voltage values are expected to be found, since production is usually lower in this season. In this example, undervoltage issues are detected in Phase C.

It is possible to observe that without µG integration in the grid the minimum threshold can be attained or even trespassed below 0.95pu, as registered in Figure 22.

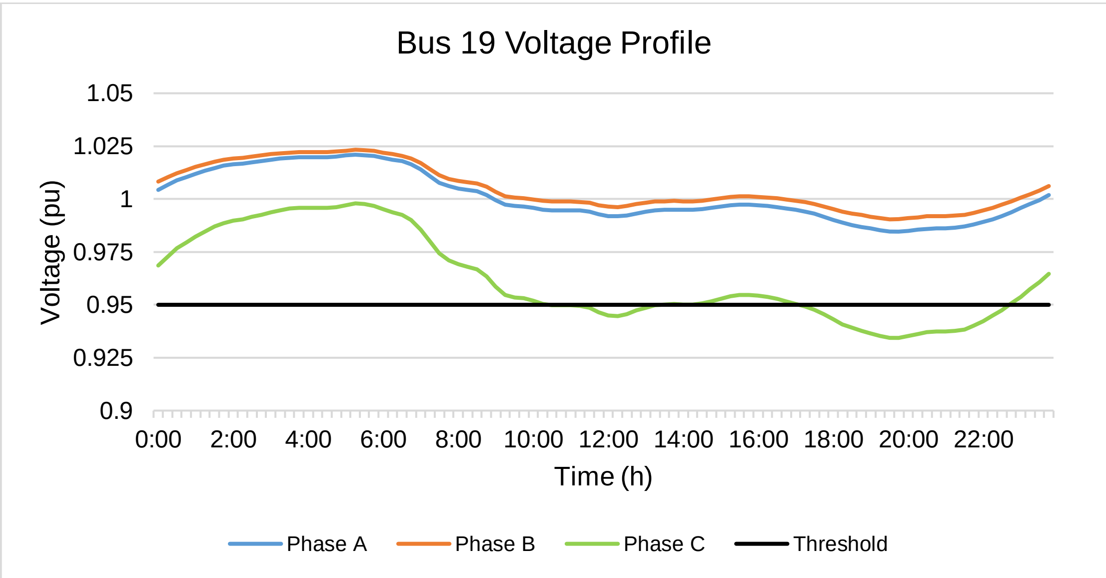

Figure 22 - Bus 19 Voltage Profile without PV integration in the distribution grid, on a typical winter day

On the other hand, once PV integration penetrates the LV test network, voltage profile instantaneously increases, especially between the hours of a greater sun exposure. As represented in the following

Figure 23, under and overvoltage issues occur, since either maximum and minimum voltage legal boundaries are crossed.

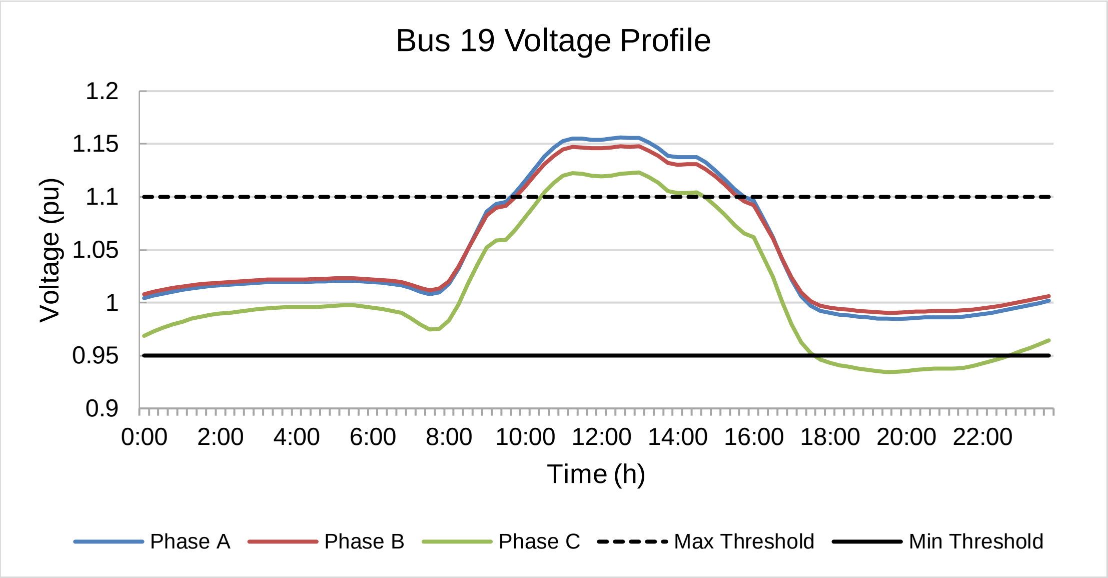

Figure 23 - Bus 19 voltage profile due to the PV integration in the LV grid, on a typical winter day

To help visualizing Reactive Power Support marginal enhancements, Figure 24 compares Bus 19 voltage profile with and without Reactive power technique, after PV integration in the LV grid.

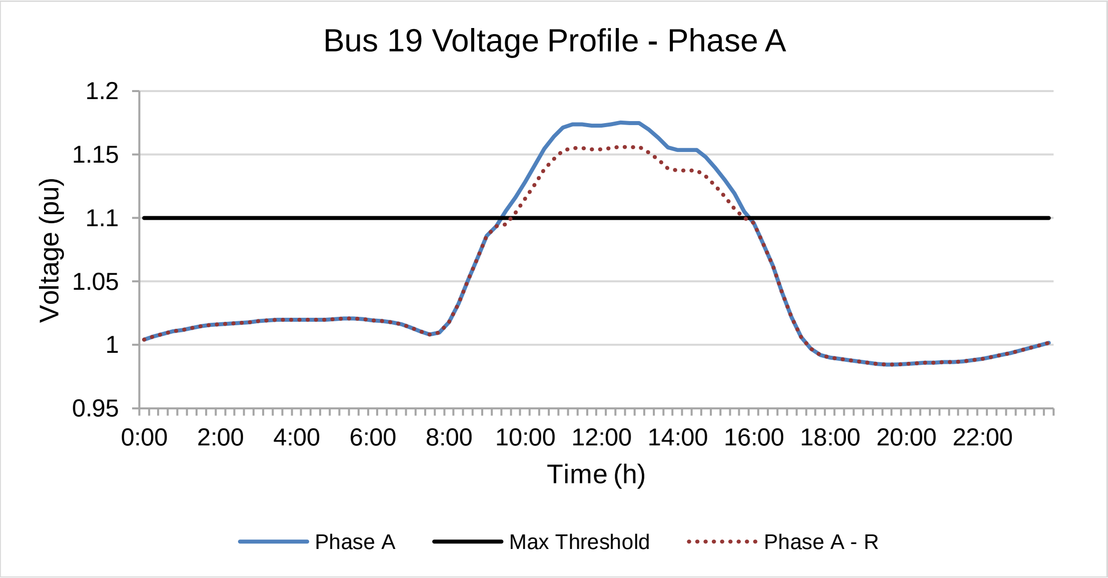

Figure 24 - Bus 19 voltage profile with PV integration in the LV grid and with Reactive Power support technique

Despite the positive effects of Reactive Power support observed in the above Figure 24, the objective of keeping voltage profile values within its legal boundaries and provide the normal operation requirements of the LV grid is not attained resorting only to Reactive Power technique.

4.3 - Hybrid Methodology

Once Reactive Power Support itself shows no capacity to help sustain voltage profile between its statutory limits, a hybrid solution is adopted to tackle overvoltage issues: a solution merging Reactive Power Support with the previously used APC technique.

When an overvoltage issue occurs in the test network, due to a period with high PV production matching low consumption levels, overvoltage corrective strategies must be applied to maintain the normal operation of the distribution network.

In this proposed Hybrid Solution, Reactive Power Support is the first technique to act, smoothing voltage profile, increasing hosting capacity and enhancing power quality.

In this specific test grid, taking into consideration the elevated number of energy producers and consumers allocated in Bus 19, this strategy alone will not prove itself as much successful, since presents only a marginal enhancement in the voltage profile, not being able to achieve its main objective of suppressing overvoltage issues in the LV test grid.

Doing so, APC technique gets in, automatically contributing to a higher efficiency of the corrective strategy. From the previous APC chapter analysis (Chapter 4.1), once voltage values rise and meet 1.1 pu threshold, the specific PV generation set is disconnected from the grid, and so on with the others that are causing overvoltage issues, until voltage is kept under the legislative range.

Firstly, during nighttime, approximately from midnight to eight in the morning, values registered in voltage profile are below the statutory threshold, which means that either APC or Reactive Power Support mitigation strategies are disabled.

Since there is no PV production at night and the tested scenarios don’t include energy storage devices in this period does not exist PV integration in the LV network, which translates in a greater balance in the LV network, without the occurrence of overvoltage issues.

As PV generators captures sunlight and start to produce photovoltaic energy, the voltage in busbars along the LV distribution network increases. Reactive Power support smooths the voltage profile but still is not much effective on eradicating the voltage profile overvoltage issue.

Although 100% APC curtailment solves the problem without a doubt, as is illustrated in blue in Figure 25, a high percentage of PV generators were disconnected from the grid, unnecessarily. Voltage profile would be efficient recording values near 1.1pu. Instead, voltage drops to near 1 pu, showing that a high fraction of energy is wasted, as well as its associated profits.

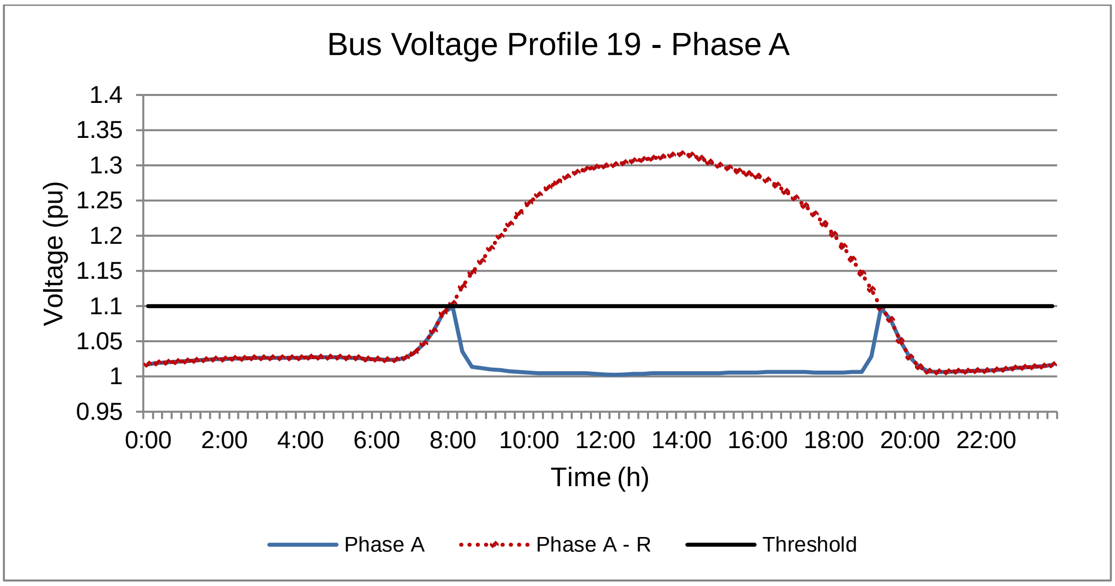

Figure 25 – Bus 19 Phase A voltage profile, with both Reactive power support and APC 100% cut off techniques

The Hybrid methodology combines the strengths of the two previously studied strategies. The following Figure 26 portrays a perfect summary of the studied solutions to tackle overvoltage issues in the distribution grid and helps realizing the efforts of each strategy to minimize the LV grid impacts.

Once microgeneration is penetrating the grid, approximately starting at 8am, numerous cases of overvoltage are registered in the LV grid (when Phase A curve, represented at blue, surpasses the threshold). Through the absorption of reactive power by the smart PV inverters, voltage profile appears to smooth and decrease its values (represented at red: Phase A – Reactive) as is illustrated below on Figure 26.

Then, if voltage values continue to surpass the acceptable range by law and Reactive Power Support itself cannot manage to decrease it, APC technique appears to control the situation.

This technique disconnects the PV generators from the network, where higher voltage values than the ones permitted by law are registered. In this way, allows voltage profile values to decrease to a minimum level, without wasting renewable energy and ensuring that there are no occurrences of trespassing those legal boundaries (near 1.1 pu).

Represented in light blue, Phase A 100% APC technique arises as a full curtailment, this means, disconnecting all the problematic PV generators and preventing microgeneration injection into the LV grid. This fact is illustrated in Figure 26, as a major voltage decrease and a relevant waste of renewable energy.

A higher PV curtailment represents less energy penetrating the LV grid, which results in lower voltage profile values. However, translates as well as an inefficient energy use since increases the waste of renewable energy (represented in Figure 26 as the energy gap between the 100% APC (represented at light blue) and the voltage threshold).

Through numerous simulations, it is possible to discover the precise energy amount that is advisable to curtail in order to register an efficient energy use (illustrated in orange: Phase A – Hybrid – 70% Curtailment).

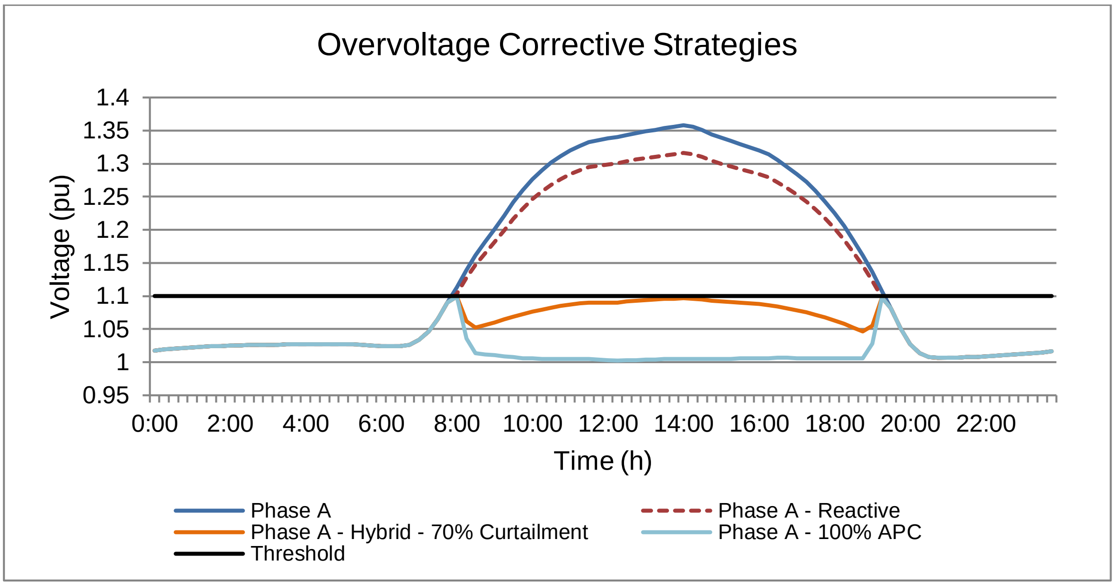

Figure 26 - Bus 19 voltage profile with µG integration, reactive power support, APC technique and the Hybrid Solution

In a typical summer day, for this specific test case, the advisable amount of PV curtailment in order to keep the voltage under the legislative limit (1.1 pu) is 70%.

To be noted that with a hybrid strategy, the fraction of curtailed energy diminishes comparing to the amount of curtailed energy whenever using APC method only.

According to Figure 27 and picking the example provided in Figure 26, Bus 19 voltage values are registered near 1.35 pu when PV microgeneration is penetrating the grid. Overvoltage cases arise and PV generators associated to busbar 19 microgeneration instead of being disconnected from the grid, suffer a precise (70%) curtailment of PV energy integration in the grid, decreasing its voltage values to near 1.1pu, the maximum allowed by the actual legislation.

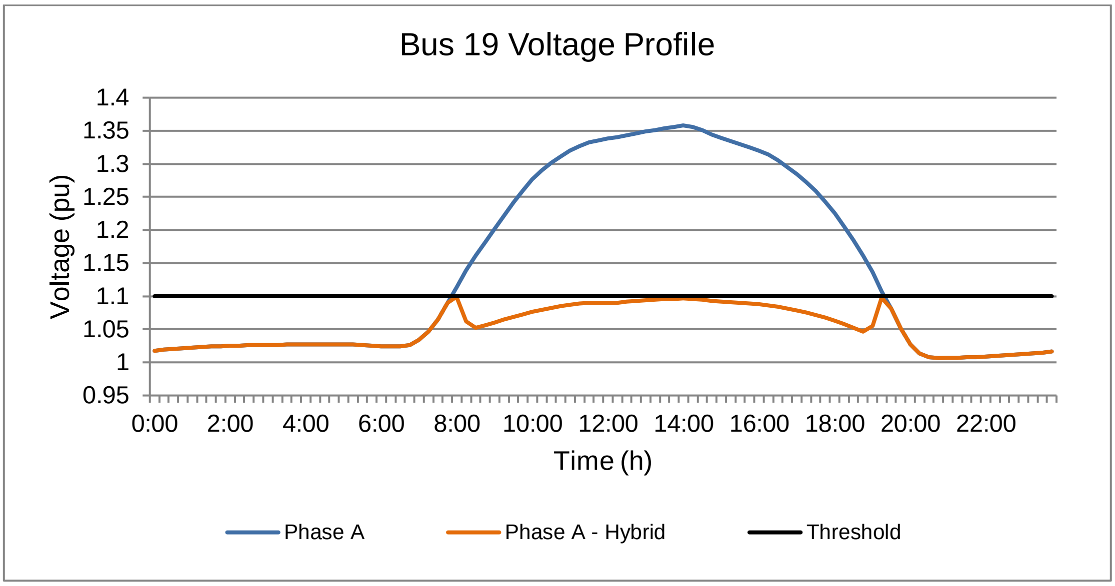

Figure 27 - Bus 19 voltage profile with µG integration and APC (70% cut off) technique

On the other way, through the application of the proposed Hybrid methodology, Reactive Power Support technique strikes first and smooths the voltage profile, decreasing voltage value from near 1,35 pu to 1,31 pu. As stated before, this measure itself does not prove as much efficient, but from that point on, the necessary amount of PV curtailment to achieve the maximum threshold is more reduced than the one in the previous example.

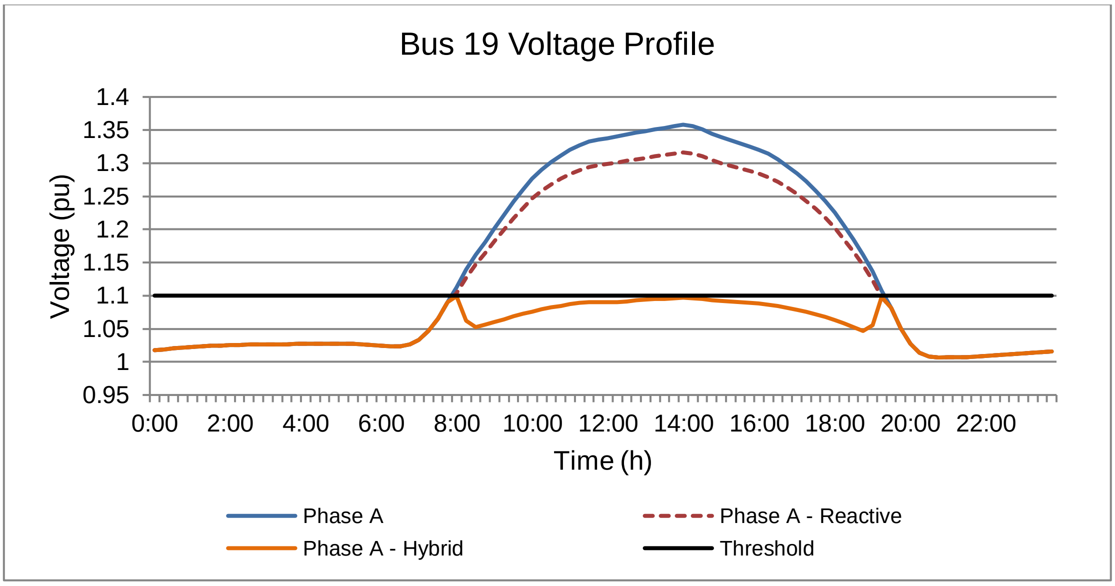

Figure 28 - Bus 19 voltage profile with µG integration, with Reactive Power Support and a Hybrid Technique

Moreover, according to Figure 28, not all the PV generators registering overvoltage issues will be automatically disconnected from the LV grid, resulting in a loss of energy, as happened in Figure 26 with a 100% APC technique.

Merely the precise PV fraction is curtailed, to maintain voltage profile within its statutory limits. Doing so, voltage profile decreases from approximately 1.31 pu to 1.1 pu.

In this way, it is possible to take advantage of the maximum possible production of the PV generators, and at the same time, stop wasting all the potential profits in the producer point of view.

Similarly, all the process is applied to a winter case study. As expected, a lower voltage peak is attained on winter, due to less irradiance that meets the solar panels, resulting in a minor PV production, facilitating its smoothing to the proper operation of the LV network.

Besides demonstrating Reactive Power Support inefficient performance in busbar 19, Figure 29 describes a full curtailment on the PV energy penetration in the LV network. As explained before, there is no need to curtail all the PV generated power integration in the grid.

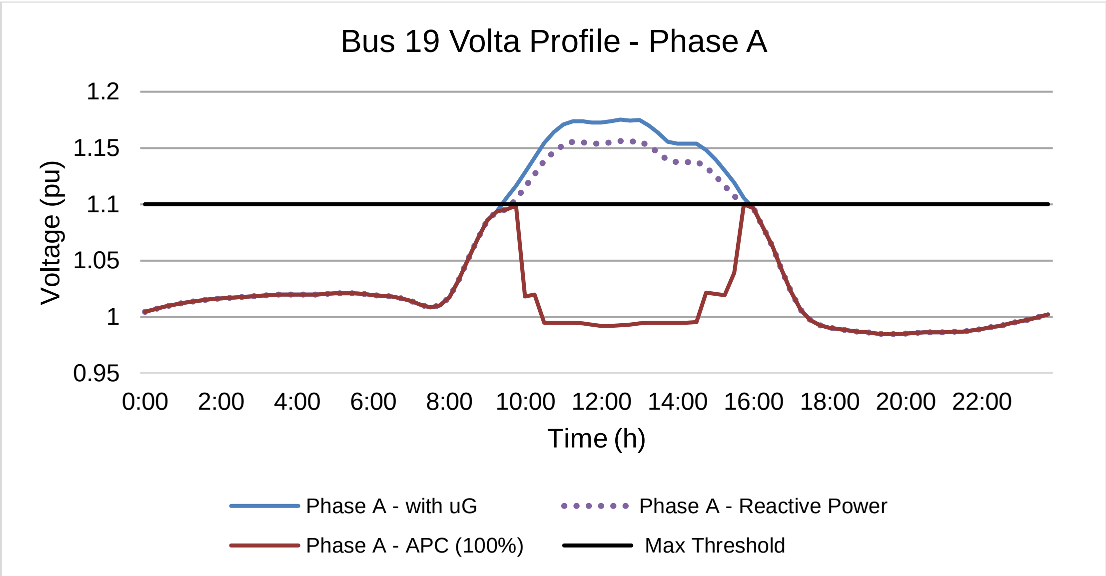

Figure 29 - Bus 19 voltage profile with a full energy curtailment, through the APC methodology. Reactive Power Support is enabled in the grid, as well

Two different curtailment scenarios for the proposed technique were tested. In one case, a full PV energy curtailment is found, and on the other hand, an option with the precise curtailed amount to prevent an increase above the maximum threshold, in the most problematic bus of the LV network.

As a result, Figure 30 portrays the precise necessary curtailed energy amount (represented at yellow) in order not to overcome the statutory limit, reaching a global curtailment of only 32%.

Using merely the APC technique, studied in chapter 4.1., a curtailment of 45% was needed to maintain all the LV grid buses below the voltage boundaries.

However, resorting to the hybrid solution is possible to diminish the percentage of PV energy curtailed, avoiding a wasted 13% energy loss, maximizing producers' profits and increasing the renewable energy mix integration in the grid.

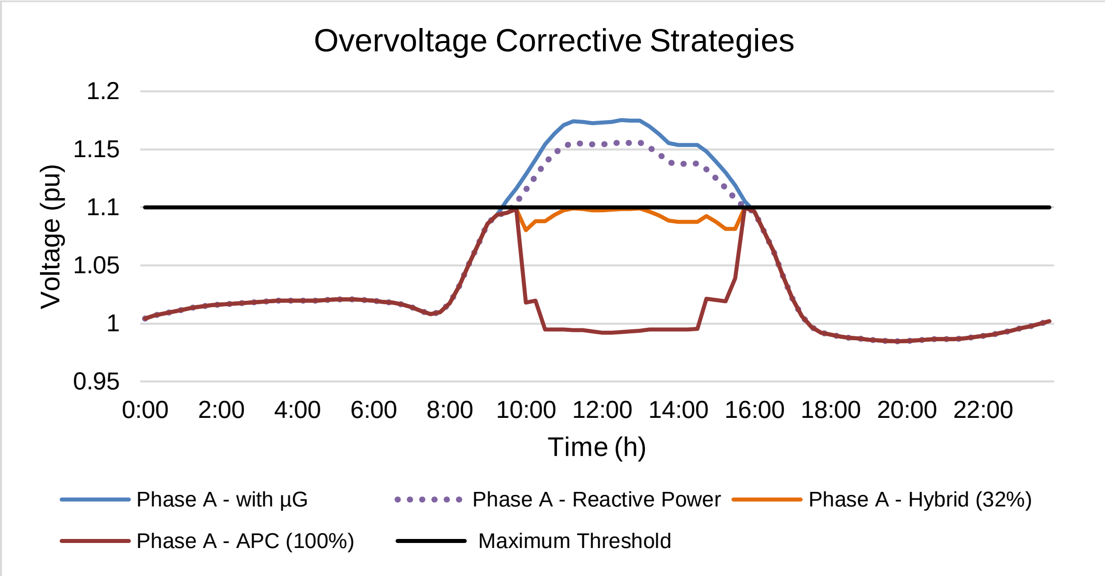

Figure 30 - Bus 19 voltage profile with µG integration, reactive power support and APC technique

After separately analyzing the proposed corrective strategies, a summary of the obtained results is hereby presented. From the three proposed methodologies it only makes sense to compare the techniques that involve curtailment processes, in order to assess which technique suits the best and saves the most.

The most efficient one should be characterized by balance between a high PV injection in the grid with a low associated rate of overvoltage issues.

This study evaluates and compares the effectiveness of the APC, Reactive Power Support and a Hybrid technique, managing overvoltage problems while avoiding excessive PV curtailment.

In the registered examples above, it is possible to understand the main weaknesses and strengths of the proposed overvoltage corrective strategies.

Table 4 presents a summary of the obtained results, representing the precise percentage of PV energy that each specific strategy curtails and prevents penetrating the LV test grid.

Table 4 - Summary of the obtained results of the strategies that involve curtailment processes

PV Curtailment		
Season	**APC (%)**	**Hybrid (%)**
Winter	45	32
Summer	75	70

Reactive Power Support methodology does not involve a curtailment process and should not be strictly compared to the other strategies results. The later, surges as a solution that allows a higher PV integration in the LV network, and consequently lower curtailment percentage, together with higher profits to the producer.

However, through the analysis of the results, it is possible to state that Reactive Power strategy alone, finds itself not enough to keep voltage beneath legislative boundaries.

Comparing the APC methodology with the precise curtailed amount of PV power and the Hybrid strategy, from the studied cases, the maximum curtailment is registered at Summer, with a curtailment of 70 to 75% of the produced energy, depending on the adopted corrective strategy.

During Winter, a diminished share of PV energy is produced, which translates in fewer overvoltage cases. Therefore, PV injection into the LV grid are more bearable, with curtailments, varying between 32% to 45%, without causing grid imbalances and ensuring its proper LV network operation and power quality.

In addition, the use of the above presented techniques helps sustaining voltage profile values within acceptable range as well as maximizing PV production and profitability.

References

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[2] M. Pais, M. Almeida and R. Castro, "Voltage Regulation in Low Voltage Distribution Networks with Embedded Photovoltaic Microgeneration," in *International Conference on Renewable Energies and Power Quality (ICREPQ'12)*, Santiago de Compostela, 2012.

CHAPTER 5 - Conclusion

The world population has now attained 7,64 billion humans on Planet Earth, with an increase of approximately 1% each year. Cities are expanding themselves and people are overloading its infrastructures.

To meet the energy needs of current world population, production has been at its highest levels. Consumption seems to be the word of order in this new era, and we have realized for a long time that this production processes, based on fossil fuels, are not healthy, sustainable and efficient enough for our Planet. Moreover, due to a strong ecological awareness that is rising in the community and to strict policies implemented by the European Union, we are assisting to a green mentality shifting, which leads to the crucial action point.

Each day, the installed photovoltaic power is increasing. Whether in open areas or in our roofs, here mainly for self-consumption, photovoltaic industry is getting bigger, maturing and gaining its space in the renewable energy mix.

As this industry is still in a development phase, a few issues are still being assessed to mitigate and correct PV integration in the low voltage network, with the scope of shaping a more reliable and dynamic network. Whenever photovoltaic microgeneration is high, and the load required from the grid is low, overvoltage issues may arise through the network, with more emphasis in the busbars further away from the substation transformer.

To develop the necessary simulations, a three-phase power flow Forward-Backward Propagation technique, based on power summation method, is applied in an IEEE 55 bus test system.

This study proposes three distinct corrective strategies to tackle overvoltage issues, using Active Power Curtailment technique, with different levels of curtailment, and a Reactive Power Support Technique, using a smart PV inverter. At last, a Hybrid solution is proposed to keep voltage profile values between the acceptable legal range, merging the two previous methodologies.

The obtained results reflect that Active Power Curtailment technique can eradicate all overvoltage issues in the low voltage network. To be noted that the amount of energy curtailed should be optimized in order not to waste clean photovoltaic energy and maximize its producer's profitability.

Otherwise, Reactive Power Support alone is ineffective to mitigate overvoltage on a low voltage network with a high photovoltaic penetration, as demonstrates itself uncapable of controlling voltage profile within its legal boundaries, exhibiting merely a marginal enhancement.

The results analysis suggests that the Hybrid solution, with Active Power Curtailment and Reactive Power Support is, as expected, the best way to tackle overvoltage in the test low voltage network presented. This maneuver is effective to maintain voltage values within an acceptable operating range, balancing the network and improving its power quality. Moreover, this technique compared only with the Active Power Curtailment method, allows to minimize the curtailed energy amount, resorting to higher profits to the producer.

5.1 - Future Work

For a broader comprehension of the subject here studied and to present a wider spectrum of tested possibilities, several adjustments can be made to the test grid or to the applied techniques.

For instance, all the simulations were carried with a load elasticity concept equal to 1 (constant current). Moreover, it would be interesting to explore the influence of the grid R/X (resistance and reactance, respectively) ratio and the hosting capacity of the low voltage network comparing the proposed methodologies effectiveness.

This study presents and compares three different techniques – Active Power Curtailment, Reactive Power Support and a Hybrid Solution. However, on the state of art chapter, several others are listed – for example On Load Tap Changers transformers, Batteries or Supercapacitors energy storage – that can also be tested, aiming to control overvoltage issues.

It would also be interesting to test and compare these new methods, specially including batteries, while observing its benefits and weaknesses to the low voltage network. The energy storage industry is englobed in a revolution era, where products become outdated in months, and prices are flying. It would be a wonderful solution to cope with overvoltage issue once the technology gets competitive and prices mature.