Microgeneration Impact on LV Distribution Grids: A Review of Recent Research on Overvoltage Mitigation Techniques

António Manzoni*, Rui Castro**‡

*Instituto Superior Técnico, University of Lisbon, Portugal

** INESC-ID/IST, University of Lisbon, Portugal

‡ Corresponding Author; Rui Castro, INESC-ID/IST, University of Lisbon, Portugal, Tel: +351 21 8417287, rcastro@tecnico.ulisboa.pt

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Abstract-Nowadays, due to the increasing rate of microgeneration penetration in Low Voltage distribution networks, overvoltage and power quality issues are more likely to occur in a more and more bidirectional operating grid. This paper offers a recent review on the main techniques available to mitigate and regulate voltage profile: PV generation curtailment, reactive power support, automatic voltage regulation transformers, and battery or super-capacitors energy storage systems. Whenever possible, published results in real and test low voltage grids are called to support each given example.

KeywordsOvervoltage mitigation techniques; PV curtailment; Reactive power support; OLTC transformers; Battery Energy Storage.

List of acronyms

μG – Microgeneration
PV – Photovoltaic
EPIA – European Photovoltaic Industry Association
LV – Low Voltage
DG – Distributed Generation
PF – Power Factor
DSO – Distribution System Operator
STATCOM – STATic synchronous COMpensator
SVC – Static VAR Compensator
DVR – Dynamic Voltage Regulators
OLTC – On Load Tap Changer
MV – Medium Voltage
SVR – Step Voltage Regulator
BES – Battery Energy Storage
SC – Super Capacitor
ESS – Energy Storage System
DSTATCOM – Distribution STATCOM
D-UPFC – Distribution Unified Power Flow Controller
CSI – Current Source Inverter
AVC – Automatic Voltage Control
LDC – Line Drop Compensators
SoC – State of Charge

1. 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 PV is getting stronger and stronger. According to the 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 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.

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, 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 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 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 STATCOM, SVC or 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	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 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. 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, SC emerge. There are, nowadays, hybrid 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 scenario case 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 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 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].

CSI topology is another strategy that 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. AVCrelays and 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 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, and 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 is able to 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 charging 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 takes into account 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 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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