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Photovoltaic Power Plants in Electrical Distribution Networks: A Review on Their Impact and Solutions

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Abstract: Photovoltaic (PV) technology is rapidly developing for grid-tied applications around the globe. However, the high level PV integration in the distribution networks is tailed with technical challenges. Some technical challenges concerns the stability issues associated with intensive PV penetration into the power system are reviewed in this paper. To mitigate the voltage disturbances in a system with massive PVs integration, some techniques are devoted such as frequency regulation techniques, active power (AP) curtailment, reactive power (RP) injection, and storage energy. Also, with a high penetration level of distributed generators, the potential of dynamic grid support is discussed. Islanding operation and microgrid (MG), operating using different control techniques, which ensure a smooth transition (ST) between grid-connected and islanded operation modes as well as synchronization between the two modes, are discussed.

1. Introduction

Among the most advanced forms of power generation technology, photovoltaic (PV) power generation is becoming the most effective and realistic way to solve environmental and energy problems [1]. Generally, the integration of PV in a power system increases its reliability as the burden on the synchronous generator as well as on the transportation lines is mitigated [1]-[2]. However, the high level penetration of PV lead to damage the distribution network like frequency instability, voltage limit disturbances at point of common coupling (PCC) [3], grid instability issues.

Grid operators have modified grid codes and regulations in order to accommodate the grid connected PV systems. Some major standards for PV integration in distribution system such IEC 61727, IEEE 1547, and VDE-AR-N4105 are defined and used in [4] to ensure that the power quality and stability defined by grid codes for PV sources connected to grid are maintained. In [5], Hudson and el. presented current and previous situation of integration RES in control and network planning.

In [6], the impacts of massive penetration of PV into utility grid in the case of medium voltage distribution networks are presented. A renewable energy management system (REMS) is developed in [7] to control smart PV inverters. This proposed method is able to prevent the voltage rise problems in case of high PV penetration. The maximum admissible limit of PV generators is evaluated in a proposed method in [8] on the low-voltage supply lines of the distribution network. Different techniques of mitigation techniques are presented in some researches [9]–[11].

The goal of the presented work is to review:

- The main defiance of integrating the photovoltaic energy production generation in the public electric network.
- Grid inertia and frequency control for solar PV integration.
- How electrical systems performance can be improved via different proposed techniques with deep PV integration.

The rest of the paper is organized as follows: Section 2 explores the PV penetration impact on power system stability and voltage profiles. Comprehensive analysis of grid support is presented in section 3. Fault ride through is presented in section 4. Power quality and harmonics are investigated in section 5. Both grid-connected and islanded microgrid (MG) operations are shown in section 6.Section 7 presents solar radiation forecasting. Finally, section 8 summarizes retained interpretations from this study followed by some future work proposals.

2. PV penetration impact on voltage profiles and control solutions

2.1. *Active power curtailment*

Voltage regulation is a challenge with increasing PV integration in low voltage networks. For over voltage, the active power curtailment is one of the possible solutions. In the case of low voltage, the voltages of the systems become more sensitive to the RP. This return to the more resistive line characteristics, RP control may lead to over-current, higher loss, and decreased power factor at the feeder input.

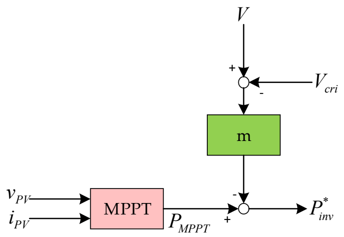

Fig. 1. *Droop-based active power curtailment (APC) of the PV inverter.*

To overcome the above mentioned issues, active power curtailment can be considered to be an interesting solution. In [12], coordination of different distributed installations such as the shunt regulator and capacitors, a step-by-step voltage regulator, a load ratio control transformer, with optimal control of the distribution system voltage are proposed. The proposed method in [13] makes it possible to reduce the statically active power to guarantee the non-rise of voltage in the case of high PV integration in LV radial type power supplies as illustrated in figure 1.

Droop control is a technique, which is adopted for operation and power sharing among the parallel connected generators, mostly relating frequency with active power. In LV networks, the relationship between voltage and active power is in fact stronger than with RP considering the highly resistive line characteristics. Usually, grid-connected inverters are monitored as current sources with integrated maximum power point tracking (MPPT) algorithms [14]-[17]. The power delivered by the inverter as a function of the dc voltage V is approximated [18]:

$$P_{inv}=P_{MPPT}-m(V-V_{cri}) \tag{1}$$

The coefficient m can be obtained in the case of dividing the power desired to be curtailed in this period by the voltage variation, $V \geq V_{cri}$ and $P_{inv} \geq 0$. There, P_{MPPT} is the maximum power available in the PV array according to a given solar irradiance (kW), and V_{cri} is the voltage above which the power delivered by the inverter is reduced with a droop factor. For $V<V_{cri}$, P_{MPPT} is injected by the inverter. Using local voltage permit to determine exactly the value of power, which must be curtailed from each PV inverter. The selection of parameters of the inverter (*m* and V_{cri}) is done with respect to the voltage limits on their connection buses. Using them in coordination with PV inverters, leads to share the AP reduction need the maintaining of all bus voltages in the acceptable interval without the need of a communication channel. The approach used to integrate (1) is illustrated in figure 1.

To prevent overvoltage issues during load transfer between distribution systems, a real power reduction and RP compensation of the PV source system has been proposed as a combined approach in [19]. For distribution networks with increasing PV integration, a local voltage regulation approach is suggested in [20]. A very short term solar generation forecast, a medium intelligent PV inverter and a reduction of the active power are reported as forecast technique. The robustness of this suggested method has been verified on a standard test feeder with PV generation data and real time load.

An encompassing cost benefits study for various voltage control methods is presented in [21]. It has been shown that the reduction of the need for voltage-powered network reinforcement is achieved by PV active power reduction methods and local RP control methods. In [22], the output PV power is limited by its MPPT. The smoothing effect is proposed to limit the PV increases to 1% of the nominal PV capacity per minute. To restrict PV increases to 1% of its nominal capacity every minute, it is proposed to use a smoothing effect. The PV generation constriction in the decrease event of solar radiation is not affected by this method but it has been reported that the output fluctuation is reduced by 28% taking into account the state of the changes in the deviation of voltage and frequency.

2.2. Reactive power injection

Some effects caused by the intermittent characteristic of the PV source and the imbalance between demand and production, lead to voltage rises. Indeed, the performance improvement of the PV systems can be carried out through limiting the maximum PV power generation and reducing the penetration rate of PV systems in the network. Although, these solutions are in conflict with the main objective of reducing conventional energies consumption that causes environmental pollution in the European countries especially Germany and Italy and widely adopt renewable energies. Therefore, it has been shown in many studies that through reactive power (RP) control, voltage regulation is successfully released by integrating PV systems. Indeed, the performance improvement of the PV systems can be carried out through limiting the maximum PV power generation and reducing the penetration rate of PV systems in the network. Although, these solutions are in conflict with the main objective of reducing conventional energies consumption that causes environmental pollution in European countries especially Germany and Italy and widely adopt renewable energies.

In [23], RP injection strategies for single-phase PV systems are explored with different constraints as the control of active mean power, the control of active and constant peak currents and the optimized thermal control strategy. All of these methods respond to currently active network codes, however, with various purposes. Optimized thermal control is confirmed by simulations of a 3 kW single-phase PV system.

Figure 2 illustrates the conformity of the thermal optimized RP control method with both RPI requirement in low voltage ride through (LVRT) ("Grid Requirements" unit) and the reliability demand can be ameliorated ("Thermal Optimization" unit). In ordinary operation mode, when a power factor is very small, only the references (PL* and QL*) are set by the system for the central control unit; while the power references (PL* and QL*, PJ* and QJ*) are transferred by the two control units while the voltage dip. The central control unit then optimizes the power to realize all objectives. The expression of optimization function is as follows:

$$\left\{P^*, Q^*\right\} = f_{opti}\left(P_L^*,\ Q_L^*,\ P_J^*,\ Q_J^*\right) \tag{2}$$

The junction temperatures, considering mean junction temperature, *Tj* max, and temperature swings ΔT_j,

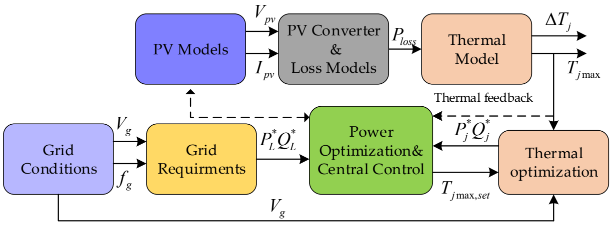

Fig. 2. *Optimized thermal structure using reactive power control.*

have an effect on the lifetime of a power device, and the whole system reliability.

$$N_f = \alpha \Delta T_j^{\beta_1} e^{\frac{\beta_2}{T_{j\max}}} t_{on}^{\beta_3} i^{\beta_4} \tag{3}$$

where, N_f is the cycle-to-failure number, $\beta_{1,2,3,4}$ and k are coefficients related to the device material, t_{on} is the width of the switching pulse, and i is the wire current.

To avoid problem related to solar irradiance variation, some researchers are focusing to generate ancillary services to the backbone such as RP injection and frequency support. [24] focused on PV inverters , which provide ancillary services, support network and control strategies for RP generation and harmonic current cancelation. In [25], it is observed that an important auxiliary service is based on the injection of the RP carried out by the PV inverters. Thus, using the PV inverter's power margin to provide RP to industrial machines can decrease the reactive power consumption of the power system, reducing its loss and improving the system stability. In [26], the authors reported that the main role of the RP control capability into the PV inverter leads to the regulation of the voltage.

2.3. Energy storage and power flow control methods

The integration of the high number of RESs to the power systems may cause some problems as critical voltage stability issues. For this reason, to ensure the integration of high level of RESs to the power systems, some suggestions must be introduced as developing new storage technologies adopted for voltage regulation: with the growing of RESs connected into the grid, requirement of ESS becomes very important [27]-[28]. So, storage systems must be considered in others studies such as energy storage using superconducting magnetic, hydro pumping storage, and electrical vehicles storage (EVS) [29]. Different concepts of energy storage are presented in [30], in order to maintain the voltage limits in distribution networks with increasing PV, where the AP curtailment can be avoided. Figure 3 summarizes a PV system connected to the grid with battery storage.

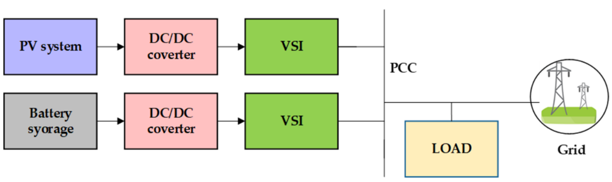

Fig. 3. *A PV system connected to the grid.*

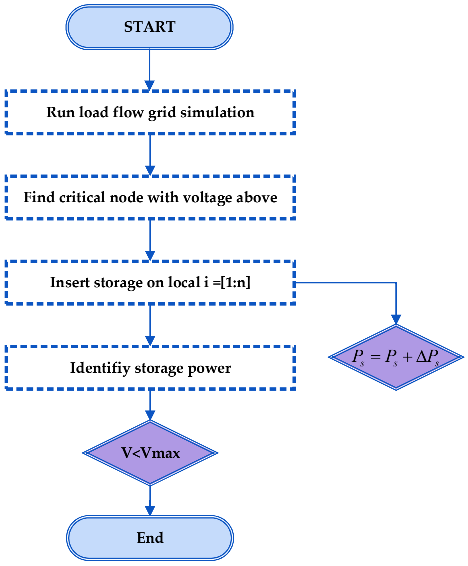

Fig. 4. *Flowchart of the storage control algorithm [31].*

The algorithm in figure 4 is employed for the allocation of the storage elements based on an iterative scheme. The algorithm, through the sensed voltages in different feeder locations, estimates the location for minimum power requirement, i.e. storage elements, for the voltage support [31].

Various researches have shown that the reduction of PV energy production or the surplus of energy are necessary to reduce voltage fluctuations, thus the storage systems can be used during the peak periods of the production while in period of demand peak, this stocked energy will be used [33]-[32]. Electrical energy storage (ES) have become numerous today. Such as the battery ES system (BESS), pumped hydraulic storage (PHS), flywheel, supercapacitors, etc. BESS is a very efficient technology and is regarded in applications according to the generations in distribution networks. Although it is more expensive than other technologies. The authors reported in [34] that ESS is involved in the amortization of wind and PV generation by recovering the additional energy provided by the system and returning it to the grid, where appropriate. The authors also studied the regulation of the distribution network voltage by integrating ESS with different control strategies. Coordinated control of distributed ESS with classical voltage regulators is proposed in a method in [35]. To mitigate fluctuation problems of voltage increase in LV distribution systems due to the massive PV integration, a method is devoted in [35], which uses the energy storage to eliminate voltage disturbances. The distribution network manager allows in this approach to perform the output of ESS during a specified period with a grant generated to the customer in exchange. In [36], the authors presented effects of massive integration and attenuation of solar PV energy. The proposed technique uses energy storage absorb the surplus of PV at the peak of generation and the stored energy is generated at the peak of load. In [37], to avoid problems of voltage increase in distribution systems by increasing PV integration, the efficient technique is applied based on energy storage by sizing the battery. Taking into account the transfer of advanced load and power generation, an analysis is also presented, the optimal allocation of the

ESS in distribution systems for maximum assistance in the integration of high PV source systems has been proposed in [38]. In addition, in [39], to prevent overvoltage problems in power distribution networks, the use of the battery has an important role and 3 various scenarios for grid conditions, are tested as the voltage control mode, mitigating reverse power flow mode and scheduling mode.

EV presents another method of control of energy storage systems with intermittent renewable energy sources. The proposed system is presented in [31]-[40] for voltage regulation in the distribution network.

Various control techniques have been integrated for EV charger to compensate the power unbalance related to the AP and RP.

In [41], a single- phase on-board EV charger was implemented. Indeed, the EV battery can be charged via the charger which can also deliver RP compensation to the grid referred to the RP command. In [42] an on-board charger has been developed for a single-phase EV. The proposed AP and RP to charger are determined according the EV and load demands. Hence, the reference current delivered by the AC/DC inverter of charger and battery are achieved using three-phase PQ strategy. Therefore, the charger state balances are given by PI and proportional resonant controllers combined with pulse-width-modulation. An EV fast charger is applied in [43] using constant current/constant voltage charging operation. Moreover, the feature of PF correction was considered in this fast charger. An EV fast charger, which is introduced in [44], is able to restore the grid voltage using RP compensation. This charger allows AP transfer and PF enhancement to the grid.

A range of uni-directional and bi-directional V2G chargers have been proposed in the literature. In [45] an on-board V2G charger with a bidirectional energy flow capacity is adopted, ensuring a transfer of the bidirectional AP and guaranteeing an improved power factor. In [46], authors have proposed a V2G charger with very reduced capacity in order to guarantee the charging and discharging of the EV battery and by generating an improved power factor. In [47], [48], the RP capability of the V2G charger has been adopted to strengthen the grid. These considerations lead to the design of RP control, power factor control and voltage control in the grid. The diversity of charger control options introduce the complication on the planning process for implementing V2G technology. In fact, it is important to study a V2G charger that integrates all the charger necessities and respond intelligently to the grid requirements. In [49], a multi-control V2G charger has been proposed, having a bidirectional power supply capacity. This allows charging and discharging of EV battery (AP control), Furthermore, RP compensation, power factor enhancement and grid voltage regulation.

3. Grid support

3.1. Frequency participation and synthetic inertia

By replacing the classical power plants with these PV power plants, participation of generators in frequency regulation is decreased dependly on overall inertia of the power system [50]. In [51], due to this variation, system inertia is regarded to be a vital parameter of the system and in the case of major imbalances among generation and consumption, the inertia of the rotating masses of synchronous generators defines the

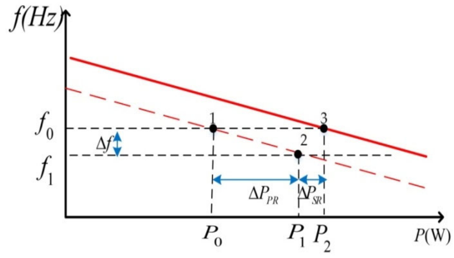

Fig. 5. *Primary and secondary control principle.*

immediate frequency response of the system. Thus, the dynamic performance of the primary frequency control and the enabling of under frequency load shedding schemes are both caused by the inertial phase of the system response. Therefore, PV units would decrease the capacity of the system to mitigate frequency deviations during important disturbances, affecting power system and frequency stability. Due to the comparatively low system inertia, this situation could be especially critical in the case of isolated power systems [52]-[53] and participate to reduce capabilities for frequency regulation [54], the system's ability is affected by both key factors to recover from a loss of generation. It is observed in figure 5 that the activation of primary and the secondary frequency control are directly realized after the load increase in the case of island mode of MG and due to the primary control, the power balance is restored. Then, the new steady state is at point 2. The frequency value is within the specified limits, however, it is not equivalent to its nominal value, so the frequency deviation is removed by the secondary control [55]. By the increasing the PV sources integration, some different control methods are adopted in researches in order to ameliorate the frequency control in the grid. It has been previously proposed that ESS like batteries or capacitors are added together with a PV unit and the coordination of control between the ESS and PV unit is very important for the optimization of the power output by the renewable and the frequency support. De-load or curtail PV unit is like the units work at a sub-optimal working point and a power reserve is performed, which as proposed in [56], can be used for frequency control. This approach has an advantage as the frequency control can be performed for a longer time period, and thus, it has the possibility of participating in primary and secondary control like the classical power plants. However, it is clearly kept as a reserve for renewable energy due to the negligible marginal costs and production support mechanisms [57]. Furthermore, due to the massive RESs integration, the complexity and nonlinearity of the power systems would increase. For that, the classical controller (proportional-integral (PI)) regulator will not be effective for a massive penetration. Therefore, a robust control scheme using intelligent techniques is required such as fuzzy logic control. In [56], a robust method is proposed based on a fuzzy logic controller that its main targets are frequency deviation and solar irradiance in order to define the reference power delivered by the PV inverter. A frequency regulation control technique for PV-diesel-battery island power system is proposed in [58]. To generate the command of the PV output power, this method uses a fuzzy logic controller with three inputs: frequency

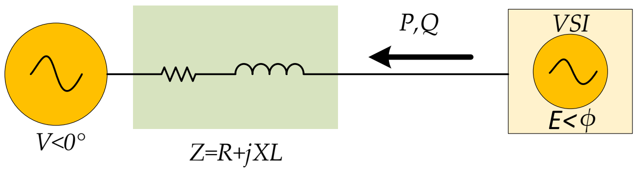

Fig. 6. *Power flow through a line.*

deviation of the isolated utility; average insolation; and change of irradiance to generate a power command for the PV-storage inverter. There are two inputs of fuzzy reasoning I. One is frequency deviation Δf_e, while the other is the average irradiance $\overline{Si}$. The average irradiance $\overline{Si}$ is given as [59]:

$$\bar{s}_i = \frac{1}{T}\int_{t=T}^{t} s_i dt \tag{4}$$

being T the integral interval, t being the present time, and *Si* the instantaneous insolation of the PV system. Second,fuzzy reasoning is performed. Frequency deviation Δf_e and the change of irradiance Δsi are employed as inputs of fuzzy reasoning II, such as Δsi is written [59]:

$$\Delta s_i = s_i(t-1) - s_i(t) \tag{5}$$

This method can be applied without energy storage when the operation of PV is below its maximum power point (MPP). And, it is proved that is effective in achieving frequency control and harvesting power close to the maximum PV power level.

With the massive penetration of RESs for future power system, some others studies must develop advanced, intelligent, as well as robust primary frequency (PF) regulation methods to guarantee the coordination between the PF control and frequency protection controller, for this, it will able to reach the adaptive frequency control.

3.2. Voltage support

During the fault, voltage support (VS) is very necessary to optimize the voltage fluctuation and to guarantee a fast voltage recovery after fault in the grid. Thus, the stability of the power system is well ameliorated. A Dynamic Voltage Support (DVS) capability is proposed in [60], using both active power (AP) and reactive power (RP) injection in a coordinated way as a function of the voltage at the terminal to improve the short-term voltage stability. Moreover, this method can lessen the frequency drop after fault generated by an interruption in PV systems. In [61], an optimized control technique is proposed to realize the operation scenario acquired from the optimization process in terms of AP and RP control and to ensure the improvement of the quality of the medium/low voltage distribution power systems. In [62], the focus is on grid-tied PV system with integrated power-quality conditioning functionalities. The PV array connected to grid through a converter which provides AP to local loads and delivers RP into the grid providing VS at the fundamental frequency.

As shown in figure 6, a generic impedance is exist through the connection of distributed power generation systems inverter to the network, the AP and RP injected to the grid can be written:

$$\begin{aligned} P &= \frac{1}{z}\left[(\mathrm{EV}\cos\phi - \mathrm{V}^2)\cos\theta + \mathrm{EV}\sin\phi\sin\theta\right] \\ Q &= \frac{1}{z}\left[(\mathrm{EV}\cos\phi - \mathrm{V}^2)\sin\theta - \mathrm{EV}\sin\phi\cos\theta\right] \end{aligned} \tag{6}$$

being V the voltage of the grid, *E* the voltage of the voltage source inverter (VSI), and ϕ the phase angle between *E* and *V*. The line impedance is considering inductive $X >> R$, *R* is neglected, and (6) can be written as:

$$\begin{aligned} P &= \frac{EV}{X}\sin \\ Q &= \frac{EV\cos\phi - V^2}{X} \end{aligned} \tag{7}$$

In [63], an optimized method is proposed for a utility coupled to the community based PV system, which provide (AP) and reactive power (RP) compensation to the utility network and it participate in voltage and frequency regulation functions using the Smart Grid framework. Using Li-ion batteries with PV connected network through a helpful inverter. The both way communication between the grid and the PV power plant is assumed. The response of the system is almost momently and thus can participate in frequency and voltage regulation. For voltage variations processing, Carvalho et al. in [64] described strategies for central coordination and local voltage support. The first can generate VS using a real-time infrastructure for communication, supervision, and coordination of individual PV generators. Local methods by using RP for voltage control have been the frequently adopted up to now because they are implemented on each PV inverter that can operate autonomously [65]-[66]. Supervisory and communication control can be abandoned when RP methods are used because simple PV inverters can be adapted in real time. Whereas, the amount of RP increases with the PV penetration, thus storage is becoming necessary for voltage support [67]. Storage solutions are important, thus, having a stronger synergy between PV energy consumers and electricity consumers' needs storage for network support. In [31], the integration of energy storage contributes to the attenuation of voltage fluctuations in high-penetration PV in LV, power supply lines according to the quality requirements of the voltage in a high-voltage network. The cooperation of reactive energy with the storage methods

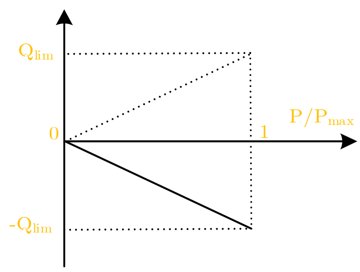

Fig. 7. *PFP control strategy.*

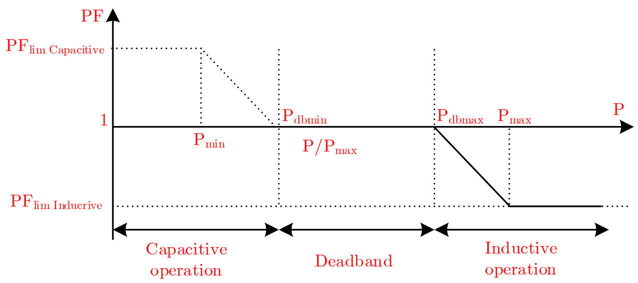

Fig. 8. *PF (P) strategy for reactive power control.*

leads to avoid the reinforcement of the network and the reduction of the active power.

Effective voltage control using RP control is primarily related to the grid features. In recent research, it is clearly demonstrated that using the capacity of the PV solar inverter to consume and deliver RP as well as AP seems to be an effective method of attenuating the increase in voltage of the distribution network. In the literature, there are various strategies for controlling RP proposed as solutions for increasing the voltage of the distribution network. These techniques are classified as follows: Fixed power factor (FPF) type control; Voltage dependent RP control; Power factor in terms of injected AP [30].

In the fixed PF strategy, the AP generation is dependent on the RP. Any weak solar irradiance generates a low AP production as well as RP absorption. However, a high PV integration leads to the maximum RP production or absorption by the generator. The description of the FPF control is illustrated in figure 7.

As shown in this latter, a weak solar radiation leads to a low RP absorption even a low AP production. With an energy production of around 100%, the maximum RP (Q_{lim}) is injected in inductive or capacitive form. A low energy generation is caused by the low solar radiation or the peak load, which neglects the risk of having a voltage increase in the grid distribution. In fact, additional losses in the network appear during the RP injection. This problem is solved through using the PF(P) strategy described in Figure 8.

In this figure, it is remarkable that for any voltage increase problem, the capacitive part of the curve is taken into account. Overall, this strategy provides significant voltage control even though the operation of each inverter [30].

The RP strategy uses information from the local voltage obtained through the energy production and consumption. A reference voltage Vref is chosen based on the nominal PCC voltage and the LV distribution transformer tap changer position. The Q (V) technique

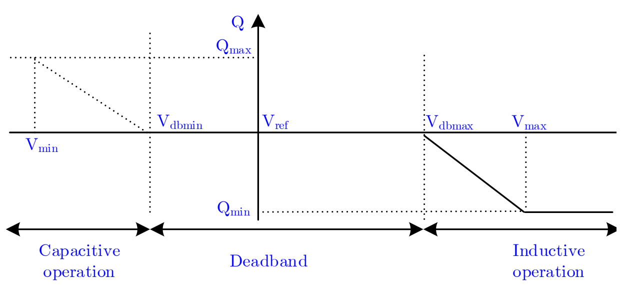

Fig. 9. *Q(V) strategy for reactive power control.*

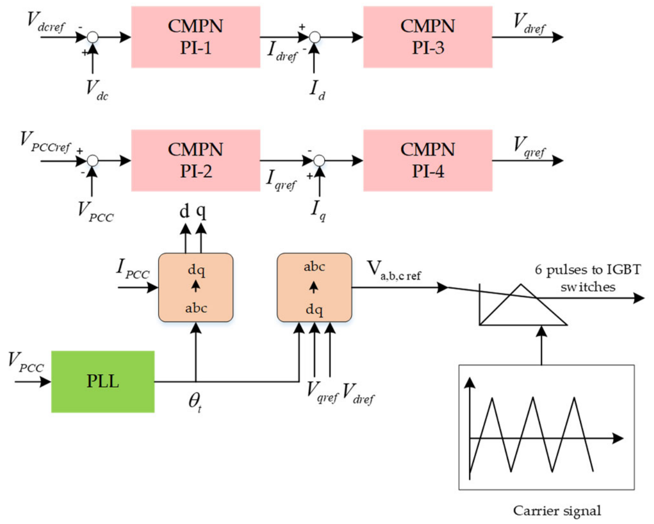

Fig. 10. *Control scheme of the grid-side inverter with LVRT capability.*

shows the relationship between RP and voltage. This relationship is described by a linear curve as shown in figure 9, which shows the use of a set of parameters as Vmin, Vdbmin, Vmax, Vdbmax, Vref, Qmin, and Qmax [30].

4. Fault ride through

4.1. Low voltage crossing

With PV generation increasing through the network, a big problem to the operators is represented to maintain the grid stability and reliability. For this, according to the grid code, the capability named low voltage passage capacity imposes that the photovoltaic system must be connected to the network during the voltage dips. To analyze, and improve the LVRT capability of the PV systems, several methods have been used in [68] for LVRT capability of single phase network connected to PV. In this method, depending on the actual and reactive power control of the photovoltaic system, a control method is proposed. Some researches works are extended in [69] to adopt the same control technique to transformerless PV plants. In [70], the effect of dynamic PV system performance on short-term voltage stability has been observed. Control of the grid side inverter is based on a proportional integration (PI) cascade control scheme. In addition, the PI controller is used in many studies to improve PV systems connected to the network by long-term processors [71]. However, in many previous studies, to design the PI controller, the proposed method is based on the trial and error method, which depends on the experience of the designer. Although the robustness of the PI controller and its use in industrial applications, it suffers from sensitivity to parameter variations and nonlinearity of dynamic systems. Presently, various optimization techniques have been imposed to address this issue [72]-[73]. These methods are known by the good efficiency at the processing level of such non-linear systems, for this they need complex calculation procedures, long periods and significant efforts. This represents a major motivation for authors to adopt the adaptive PI controller based on the CMPN algorithm (P-Norm Mixed Continuous) to increase the LVRT capacity of PV plants connected network. Using CMPN algorithm allows adaptive filtering (AF).

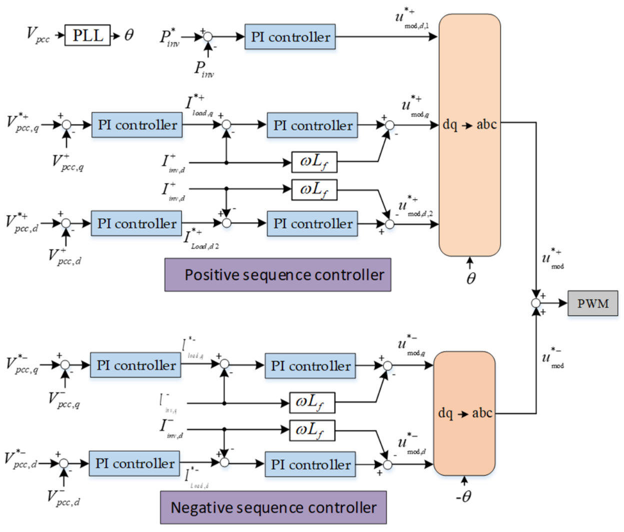

Fig. 11. *Positive and Negative Sequence Controller.*

The LVRT capability of grid-connected PV plants is improved when an application of the CMPN algorithm is used, this proposed method is based on adaptive control [74], it is applied to the DC-DC boost converter. This method leads to generate a MPPT operation based on the fractional open circuit voltage method and to monitor the DC voltage Vdc and terminal voltage at the PCC (Vpcc) for the grid-side inverter as illustrated in figure 10.

A two-level, three-phase, six IGBT switches inverter is used in this work. The use of a phase locked loop (PLL) lead to detect the transformation angle θt from the 3 phase voltages at the PCC. The output signals of the control scheme (Vqref and Vdref) are converted to 3 phase sinusoidal reference signals *Va,b,c-ref*, which are compared with a triangular carrier signal of 10-kHz in order to provide the firing pulses of the IGBT switches. The CMPN algorithm can be given by:

$$j(k) = \int_1^2 \varepsilon_k E\{|e(k)|^p\}dp \tag{8}$$

Where *εk* is a probability density. Its limit can be expressed by:

$$\int_1^2 \varepsilon_k(p)dp = 1 \tag{9}$$

Focusing on (8), the adaptive of the weight vector of the CMPN AF algorithms can be given by:

$$\omega\ (k+1) = \ \omega(k) - \mu\ \sigma_k J(k) \tag{10}$$

μ is the step size and σ_k *α*(*k*) *J*(*k*) is the momently gradient of *J*(*k*) respected to *ω*(*k*). This can be defined by:

$$\frac{\partial j(k)}{\partial w_i(k)} = \int_1^2 \varepsilon(p) \frac{\partial}{\partial w_i(k)} \{|e(k)|^p\}dp \tag{11}$$

E{e(k)} can be referred to *e*(*k*) and after carrying out a simple calculation, (10) is rewritten after modification:

$$\omega\ (k+1) = \ \omega(k) - \theta_k \alpha(k)\ sign\ (e(k))x(k) \tag{12}$$

$$\theta_k = \int_1^2 p\varepsilon(p)\,|\,e(k)\,| \tag{13}$$

where, *θk* is the available step size, which is based on *e*(*k*). If *ε*(*p*) equals unity, *θk* can be obtained by this expression:

$$\theta_k = \frac{(2\,|\,e(k)\,|-1)-1)\ln(e(k)) - |\,e(k)\,|-1}{(\ln(e(k)))^2} \tag{14}$$

4.2. Unbalance voltage control

With the increasing of PV integration, some effects are caused as unbalanced voltages on the power system. For this, this one is likely to suffer serious and this will lead to instability in unbalance condition. Series active power filter are used with the distribution line through generation of negative sequence (NS) voltage in series for compensation of voltage unbalance [75]. Some others researches concentrate on shunt compensations [76]-[77]. Proper control strategies proposed in [78], lead to compensate for power quality problems. Some approaches are presented in [79]-[80] based on connection of two-inverter structure, a parallel filter is controlling the AP and RP flow and the series filter connected to the network balances the currents line and the voltages across sensitive loads, despite an unbalanced network voltage. The form of injecting is NS voltage. In [81], a stationary-frame control method for voltage unbalance compensation is used to compensate voltage unbalance, this method adopted Interline Photovoltaic (I-PV) power system knowing that the basic idea in this method is to provide the NS currents caused by unbalanced load using I-PV power plants. This controller is composed by positive and NS loops. The main role of the positive sequence (PS) controller is to restore balanced voltage, while the main role of the NS is to mitigate the unbalanced voltage.

The PS and NS controllers for I-PV power plants are illustrated in figure 11. The PS controller is adopted to provide the reference AP P_{inv} from PV into the network and to ensure regulation voltage V_{PCC} at the PCC. The NS controller is used to provide the NS current Iload needed by the unbalanced load using the PV inverter.

5. Power quality and harmonics

Power pollutions are major causes of PV generation into power systems without a proper functioning of active power filters (APF). Providing power quality is an important issue of grid connected PV system. Maintaining the power quality by the introduced system is influenced by the intermittent irradiation [82], the used power electronic inverters [83], and nonlinear loads.

In [84], authors present a shunt (SAPF) based on a two-level voltage source inverter (VSI) for grid-connected PV systems. This power filter injects PV power into the grid to eliminate the current harmonics and absorb the RP produced by the nonlinear loads, a boost converter controlled by a Fuzzy logic (FLC) algorithm for MPPT can be used to ensure PV power injected in grid. The SAPF system is P-Q theory used for currents harmonic references extraction. SAPF or alternatively UPQC can reduce power quality problems affected by PV integration. The SAPF is suggested in [85] for harmonic suppression using series active filter and SAF. It absorbs RP, harmonics and maintains dc voltage.

Currently, available filters are enabling to suppress harmonics and distortions. For this, an AUPQS is adopted in [86] to interface PV plants to network. An improved series active filter is designed in the interfaced system, it generates output voltages for compensation of all the voltage source deficiencies , Further, it suppress current harmonics and distortions, also under unbalanced non-linear load conditions. Even, an independent single-phase inverter is suggested at the load side instead of the source side to regulate the dc voltage, distortions and harmonics provided by this inverter are compensated by the AUPQS.

Chen et al. [87] proposed a control system that combines PV generation connected to grid and power quality managements. The structure has a good dynamic performance, as it can realize PV generation, harmonics elimination and RP compensation, eliminate voltage sags, it can also power quality issues regarding mitigation instantly power interruption problems. An adaptive predictive MPPT algorithm lead to ameliorate the efficiency of PV generation as shown in fig 12 [87].

$$\begin{Bmatrix} p(n-1) = [p(n-1), p(n-2), ..., p(n-N)] \\ p(n) = p(n)n(p(n-1), ..., p(n-N+1)] \end{Bmatrix} \quad (15)$$

Where p(n) is the voltage of the PV array and p(n-1),…,p(n-N+1) are the historical voltages, p(n) is the actual output power at the current sampling moment, $\hat{y}(n)$ and $\hat{y}(n+1)$ are the predictive output powers at the current sampling moment and next moment respectively. The error is written as [87]:

$$e(n) = y(n) - \hat{y}(n) \quad (16)$$

Based on the finite Impulse Response model, the expression of adaptive prediction can be given by:

$$\hat{y}(n+1) = \sum_{k=0}^{N} f_k p(n-k) = F'P(n) \quad (17)$$

Where F'=[f_0, f_1,.. f_{N-1}] being the adaptive predictive coefficient matrix. Based on the Least Mean Square criterion, the main goal of adaptive adjustment algorithm is to solve the optimum f_k=[0,1,…,N-1] by minimizing the mean square error of $e(n)$.

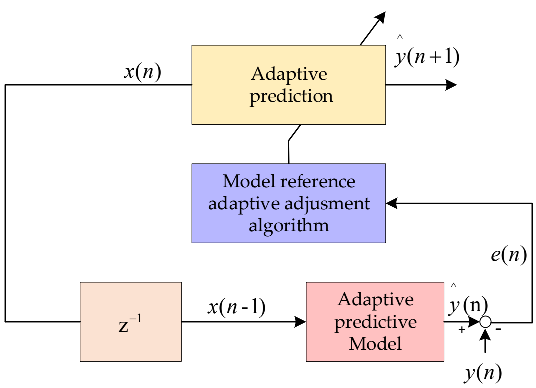

Fig. 12. *Adaptive predictive control of output power of PV array [78].*

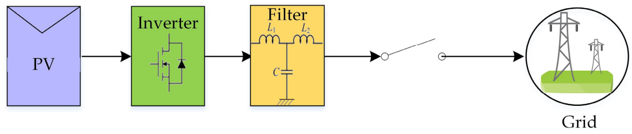

Fig. 13. *A sample of microgrid model.*

In [88], with new technologies, the power distribution system is being monitored automatically over the last 50 years. The monitoring system makes it possible to identify and correct faults in a relatively short time. For example, a Malaysian operators company has implemented a power quality control in some sites to detect and record power quality events. This makes it easy to take action corrective action as soon as possible. Because power monitoring is a necessary parameter to mitigate power quality events, Kilter et al. [89] establishes guidance for monitoring the quality of energy. However, many efforts are needed to finish it. In [90], authors have involved that in Data Integration, supervisory control and data acquisition (SCADA) and AMR, EQMS and Electric Vehicle Management System as an implemented IPQMS to control distribution system. It has been proved facilities control of electricity networks via IPQMS.

6. Islanding and microgrid operation

With the rapid increasing of penetrating DG, the problem that is built into island mode for the protection of the media gateway is the detection of the occurrence of an island. Two types of modes can appear: intentional or accidental depending on its occurrence. The intentional creation of an islanded microgrid to supply the load with shedding and maintenance operation is referred as “intentional islanding,” while the unintentional islanding is done due to a grid failure or failure of the equipment.

The unintentional presence of islets poses a significant challenge in the functioning of MG, which in turn leads to serious safety problems and technical problems. This raises major problems, in particular: the voltage and frequency are maintained within acceptable limits, danger for safety line workers by the DG units supplying the loads, reclosing out of phase DG unit following an instantaneous reclosing. Therefore, the need for detection of the occurrence of an island is mandatory in the power system. Figure 13 illustrates the island mode of DG in the case of opening CB main breaker due to the occurrence of a fault on the network side. Relay intervention should exist for instantaneous DG isolation within 2 seconds of island formation in accordance with the IEEE standard. 1547-2003.

6.1. Islanding detection

According to the literature, the techniques for islanding detection operation can be classified into 2 types remote and local. The remote methods need a communication including supervisory control and data acquisition (SCADA) to ensure the islanding detection, whereas local methods require simple information. Remote methods are known by the best reliability but at the same time, having small non detection zone (NDZ) [91] compared to local methods. Moreover, its installation is complex and expensive because it requires the implementation of the protection system where the protection scheme is reconfigured every time new components are needed to be added to distribution network. Therefore, the most simple and applicable technique is the local method which is considered to be more profitable in practice compared to the remote method. For the local technique there are 3 types: passive, active and hybrid. The system parameters controlled in the PCC for the passive technique [92] are voltage, frequency, harmonic and current distortion in order to ensure the detection of islanding events. These techniques have many advantages such as flexibility and the reasonable implementation cost due to their traditional measurement and protection devices to detect islanding. However, these methods have a major drawback related to a large NDZ. This problem leads to the poor islanding detection in the power balance event between the load and the produced energy. In active detection techniques, the disturbances are intentionally injected into the network and the island is then detected according to the system responses to the faults. These methods not only have much negligible NDZ than passive methods, but they have also the highest impact on the PQ and implementation costs. Therefore, in [93], various studies concentrate on NDZ optimization in order to minimize the maximum of it. In [94], some of the most popular active methods are high frequency signal injection, RP, active current disturbance.

In [95], active and passive techniques are combined together, knowing that the active technique is only applied if islanding is not detected on the basis of the passive technique. This technique is called hybrid. The most economical and efficient technique for islanding detection is the combination between the passive technique and artificial intelligence, where advantage of this method is less complex, very reliable and has more efficient degree in calculation with best precision. This method has minimal negative disadvantages. It seems that the NDZ is completely covered, while a lot of obstacles are appeared when combining active and passive techniques. Therefore, involving more parameters. New intelligent methods have adopted in some researches as in [96] artificial intelligence techniques are adopted in detection islanding mode.

6.2. Voltage and frequency controls (islanded mode)

MG may operate in two modes, grid-connected and islanded modes, but the difficulty in MG research is the problem of control the system in islanded mode. Thus, it is necessary to adopt a reliable control method in order to

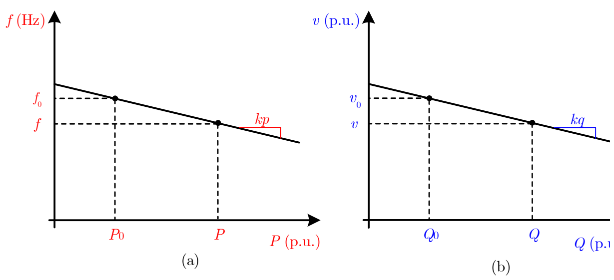

Fig. 14. *Droop control characteristics: (a) P – F control (b) Q – V control.*

adjust the system V-F under the islanded operation. Different control methods exist in the literature to ensure control of islanded operation in MG. The classical method to control islanded MG is the droop controller [97]-[98]. The droop controller is the most effective method of control, which is using to restore the V-F system in islanded MG. Voltage and frequency references are provided for the voltage and current control depending on the required power of the MG using P - F and Q - V droops to restore the system V-F in islanded operation. Whereas, there are many parameters in the traditional droop controller that need to be optimized for better control performance [99].

In [100] a robust control technique proposed based on the H∞, which can be combined with droop control in order to obtain better V-F in the islanded mode. The V-F control in island mode is a complex method, so variations in output or load power lead to many variations in system V-F, therefore a smart and reliable method must be applied for the control of MG in this case.

For instance, H infinity (H∞) is a repetitive control of the DC-AC converters in the MG which is adopted to ensure the correct operation as the controller with the generation and load changes. It is used to synthesize the controller in order to generate stabilization with better performance. It has the advantage of being able to fix and optimize multi-objective and multivariate systems. For applying this method, the control problem must be transferred to a mathematical optimization problem to obtain the solutions of this optimization [101]-[102]. In [101], H∞ control method is applied and the proposed controller aims to inject pure sinusoidal current specific to the utility, even the presence of non-linear loads. Using this controller leads to a weak total harmonic distortion and improved tracking performance. In [103], the authors use the H∞ algorithm to minimize the V-F deviations, and it is proved that the V-F deviations meet the rate values. This article presents a proposal for modified V-F droop MG control method in islanded mode. This method applies H∞ with the droop controller to adjust the system V-F at their rate values. Under this condition, the MG is responsible for providing the AP and RP which is used to control the system. Accordingly, it regulates the V-F droop coefficients that determined by V–F controller.

Figure 14 shows the principle of the droop control (P-f, Q-V). If the generated AP increases from P0 to P, then the frequency should be decreased from (f0) to (f). Hence the characteristic must be shifted up to maintain the nominal frequency f0 as described by figure. 14a. On the other hand, if the RP rises from Q0 to Q, then the voltage should be dropped from V0 to V as described in figure. 14b. Hence, the features must be increased up to keep the rate voltage V0.

To guarantee the functioning of DG in a micro-grid environment, it is essential to involve the central micro-grid controller (MGCC) to ensure coordination between operations. The MGCC monitors the systemic status and commands the local micro-source controllers (MC), ensuring system stability. Also, collecting an information database facilitates the execution of secondary and tertiary control functions, these control levels are mainly integrated in MGCC [104], [105], and [106] between the DGC and the MGCC, it is necessary to add the communication devices for the link between them, on the other hand. The choice of the model and the bandwidth of the communication must be precisely designed depending on the control requirements [107]. In [108], MCCG is developed for an inverter based intelligent MG in order to restore the frequency and voltage unbalance compensation. The complete control system adopted based on the hierarchical control scheme for MG, including primary, secondary and tertiary control.

6.3. Smooth transition between the grid connected and islanded modes

An advanced control technique acts on the MG gateway to guarantee seamless transfer (ST) separating network and island scenarios, this flawless transfer technique must be used in the MG for a purpose that leads to the minimization of transients on local loads during transitions [109]-[110]. Thus, this flawless transfer technique is considered one of the critical mechanisms of MG, and as a result, recently, extensive works have devoted various types of ST techniques. In [111], a transfer technique that is proposed, homogeneous, it succeeds in improving system robustness during scenario transfer separating island modes and its connection to network. The smooth transition is reached by modifying the monitor algorithm according to the operating scenario of MG. By selecting the voltage control loop for inverter control in standalone scenario, if not the selection of the feedback control loop helps to control inverters in network connected scenario. Usually, this control structure can be divided as shown in figure15 into three parts: First is islanded mode control, second is grid-connected control and at last ST between scenarios (mode selection).

The MG contains DG units. The control of each of them is based on the technique of voltage control in island mode, while in connected mode, the control technique used is direct feedback current. This technique ensures a smooth transition. In addition, the technique applied for parallel converters is slump control to ensure the generation of the desired power to local loads in island scenario. Opposed to islanding, in [112] the transition from the two mode of islanded to grid-connected scenario applied knowing that before the transition, the phase angle and the rms value of the PCC voltage at MG and utility side may differ. The operation of the MG and utility network can be done at different values of frequencies, because the droop controllers in networks do not force the frequency to its nominal value. Therefore, closure of the PCC switch without synchronization would introduce the large transients as a result of a sudden voltage and current changes. A synchronization procedure is required to achieve a smooth mode transfer; therefore, the voltage-based Droop (VBD)

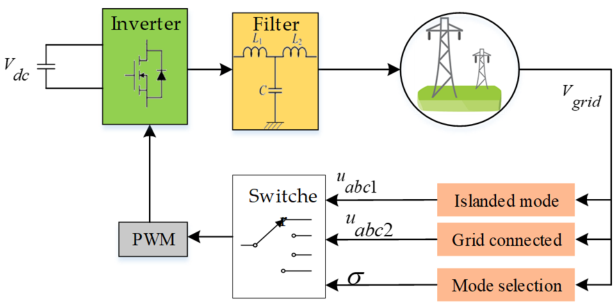

Fig. 15. *The proposed control structure of seamless transition.*

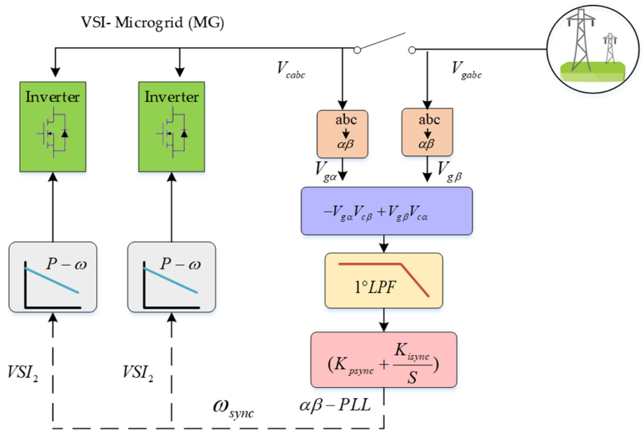

Fig. 16. *Synchronization control loop of a droop controlled MG scheme.*

control strategy is modified to synchronize the utility and MG side rms voltage, phase angle, and frequency before the connection of the MG to the utility. The synchronization procedure is operating slower than the primary VBD control. The PCC voltage is measured and communicated to the synchronizing DG unit that uses a PLL in order to obtain the voltage rms and its phase angle. In [113], the strategy used for the modeling and control of a single phase VSI with LCL filter, adapted to PV .This technique is able to operate in both scenarios: in network connected mode and in island mode. Robust controllers are designed using linear matrix inequality (LMI) methods, considering the uncertainty in the model as the existence of disturbances, where the stability of the system and the desired operation were the main targets.

6.1. Microgrid Synchronization

In [114], the synchronization of the MG is adopted in the two modes using an important control strategy based on modifying the VBD, which permit a ST between the two modes islanded and the grid-connected of the MG. Also, the operation of VBD control is available in two scenarios.

During the transition from islanded to grid-connected scenario is activated, synchronization of the MG voltage to the grid voltage is needed. Several researches are concentrated on Phase detection schemes for the synchronization techniques [115] including PLL methods such as the Single PLL, Enhanced PLL, Quadrature PLL and Synchronous Reference Frame PLL and Adaptive Notch Filtering (ANF). This model has been tested and discussed in this method and detection of a faster frequency is easier than other phase detection techniques, so that an input signal is distorted and loads are unbalanced. In addition, the required parameters and characteristics are generated by the ANF for synchronization and based on phase detection procedure. For this, the ANF is considering more reliable power signal processor. Using the droop control in islanded and grid-connected modes, a synchronization control loop in the abc frame is proposed in [114] to synchronize all the VSI of the MG are shown in Figure 16.

The two variables $V_{g\alpha\beta}$ and $V_{c\alpha\beta}$ are used as the α-β components of the grid and the VSI voltages for synchronization and when voltages are synchronized, it can be assumed that:

$$\left\langle V_{g\beta}V_{c\alpha}-V_{g_\alpha}V_{c\beta}\right\rangle=0 \tag{19}$$

Where <x> is the average value of the variable x over the line frequency. Then, the drift of the PLL structure becomes simpler, including in this product, a low-pass filter and a PI controller:

$$\omega_{sync} = (V_{g\beta}V_{c\alpha} - V_{g\alpha}V_{c\beta})\frac{\omega_c}{\omega_c + s}\frac{k_p s + k_i}{s} \tag{20}$$

ki and *kp* are control parameters of the PI, and ω_{sync} is the generated signal of the coordinated PLL to be transmitted to each VSI.

7. Solar irradiation forecasting

Solar energy constitutes one of the most basic sources of renewable energies which has undergone rapid evolution for the last decade, but its intermittence and its variability can appear as problems in the generated solar energy [116]. It is necessary to have accurate forecasts of solar power to mitigate the negative impact affected by the uncertainty of PV output power in the system with the increasing of solar PV generation. In [117]-[118] different proposed strategies are used to predict PV irradiation using previous basically data, digital meteorological measurements, and cloud satellites images. In [119], the probabilistic forecasting of radiation was carried based on a non-parametric approach and the application of the k-nearest neighbor regression model, which ensure the calculation of prediction intervals. In [120]-[121], an analog set method is applied based on the probabilistic forecast of solar radiation. The total daily forecast of future spatial and temporal radiation using the ensemble forecast based on empirical bias was proposed in [122]. In [123], a method of forecasting solar irradiance in sub five minutes is proposed using a monitoring network. In [124], k-nearest neighbors and support vector machine are carried to reveal the effect of weather classification on solar radiation data. A solar radiation forecasting method was proposed in [125] using the combination of empirical mode decomposition, local mean decomposition, least squares support vector machine and Volterra algorithms. Deep learning was applied to predict solar radiation using a six-month UTSA sky imager data set in [126]. One hour in advance, solar radiation is predicted using gated recurrent units (GRU) [127].

All of these methods relate to short-term forecasts ranging from a few hours to several days. Also, long-term solar radiation forecasting makes it possible to estimate the energy potentials influenced by the rate of degradation of photovoltaic panels.

In [128], a comparative study of the different deep learning (DL) approaches is applied to predict hourly and daily solar radiation one year in advance. Advanced DL and machine learning architectures such as GRU, long short term memory (LSTM), recurrent neural network (RNN), feed- forward neural network (FFNN) and support vector regression (SVR) are compared in this work, historical data of solar radiation and global horizontal irradiance (GHI) of the clear sky are used. Knowing that all the models work well, GRU considers itself the most efficient compared to the other models.

The quantity of current needed is decided by the input gate of LSTM, which is expressed in this equation:

$$i_t = \delta(x_t u^i + h_{t-1} w^i) \tag{20}$$

The detail needed to be forgotten from the last state is decided by the forget gate and it is given as follows:

$$f_t = \delta(x_t u^f + h_{t-1} w^f) \tag{21}$$

The output gate introduces the internal state information required to be transmitted is defined as follows:

$$\delta_t = \delta(x_t u^0 + h_{t-1} w^0) \tag{22}$$

LSTM and GRU are similar on having 2 gates, for the GRU, the reset gate is defined as follows:

$$c_t = \delta(x_t u^c + h_{t-1} w^c) \tag{23}$$

The update gate is expressed as follows:

$$y_t = \delta(x_t u^y + h_{t-1} w^y) \tag{24}$$

The proposed models are also compared to conventional methods for long-term prediction of solar radiation and they proved their efficiency compared to conventional methods. In [129] different deep learning models are used to forecast hourly and daily solar radiation over a period of one year. The proposed method is a new approach in terms of data management and the application of DL approaches for the prediction of solar radiation at one year. This method uses the historical data of the solar radiation and the global horizontal irradiance (GHI) of the clear sky.

8. Conclusion and future prospects

This paper presents the state of the art review on the impact of the large-scale PV penetration in the electrical distribution networks and its different technical solutions. The paper encompasses active power curtailment, reactive power injection, and energy storage and power flow control methods. Ancillary services provided by PV power plants for grid support are presented, such as frequency and voltage support, synthetic/virtual inertia, fault ride through (including low voltage and unbalance voltage control). Power quality and harmonics are also analyzed, which is also a strong impact especially in PV power parks. Another important issue is islanding and microgrid operation, including islanding detection, voltage and frequency control in islanded mode, smooth transition between grid-connected and islanded modes, and synchronization. Finally, solar irradiation forecasting methods are also reviewed.

Current power systems are not designed to support the massive integration of PV and to respond to the grid codes. The application of intelligent and online control methods for better coordination between all parts of modern electrical systems is very important. Also, the ancillary service of the EVs like reactive power control and simultaneous active and reactive power control in ESS and V2G parts have been discussed.

With the penetration of high PV sources, the detection of the occurrence of island mode becomes one of the primary issues in MG protection. Two different techniques as local and remote islanding detection methods are presented and compared in this paper. Moreover, various techniques are discussed in order to adjust the system voltage and frequency under the islanded operation. Also, different control methods which ensure a smooth transition between the two operation modes, along with synchronization between the two modes are also presented. Furthermore, the feasibility of a MGCC for operation of MG is well introduced. It is obvious that MGCC plays an important role for the maintain system stability.

Finally, it is obvious that the increase of PV sources needs ancillary services, for this, some works are focusing on ancillary services connected to the system in order to maintain the robustness in the network. Since the available level of inertia of the grid decreases considerably. This question becomes a critical challenge for this paradigm of control of emerging modern electrical systems which should be properly discussed.

In future research is required as:

1) to develop virtual inertia control strategies that allow the resolution of the problems encountered
2) Applying battery-based hybrid ESS and super capacitor in next research in order to address the issue of synthetic inertia control and several more faced issues. Developing an intelligent, robust, and advanced methods, and fast communication technologies to realize the inertia and frequency regulation.
3) A control strategy of ESS can be developed to effectively smooth the fluctuating output from PVs and to maintain the DC-bus voltage. Also, other control methods for distributed inverters by using MPC that can operate in islanded mode, grid synchronization and grid-connected mode with high grid support capability.
4) To develop a multi-control V2G charger adopting bi-directional AP and RP for grid support.

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10. Abbreviations

The following abbreviations are used in this manuscript:

AGC automatic generation control
AP active power
AUQS advanced universal power quality conditioning system
AMR automated meter reading
ANF adaptive notch filtering
BESS battery energy storage system
CAES air energy storage
CMPN p-norm mixed common
DSC distributed secondary control
DVS dynamic voltage support
DL deep learning
EQMS energy quality monitoring system
EVS electrical vehicle storage
ESSs energy Storage System
ES energy storage
FRT fault ride through
FFNN feed forward neural network
GRU gated recurrent units
GHI global horizontal irradiance
IPQMS electric vehicle management system
LVRT low voltage ride through
LMI linear matrix inequality
LSTM long short term memory
MG microgrid
MPC model predictive control
MGCC microgrid central controller
MPPT maximum power point tracking
NDZ non detection zone
PHS pumped hydraulic storage
PF primary frequency
PI proportional integral
PV photovoltaic
PVPP photovoltaic power plants
PCC point common coupling
PQ active and reactive
PLL Phase Locked Loop
RESs renewable energy sources
REMS energy management system
RP reactive power
RNN recurrent neural network
SCADA supervisory control and data acquisition
ST smooth transition
ST seamless transfer
UPQC unified power quality conditioner
SVC supervisory voltage control
VBD voltage bsed droop
VS voltage support
VSI voltage source inverter
VFC voltage frequency controller
V-F voltage and frequency

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