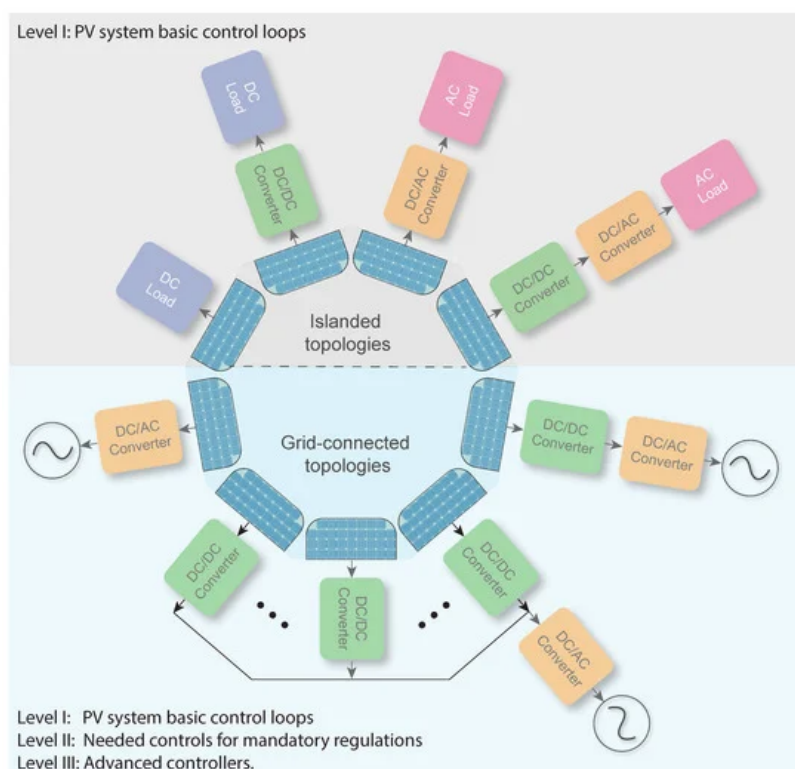# Control Techniques in Photovoltaic Systems

Complex control structures are required for the operation of photovoltaic electrical energy systems. In this paper, a general review of the controllers used for photovoltaic systems is presented. This entry is based on the most recent papers presented in the literature. The control architectures considered are complex hybrid systems that combine classical and modern techniques, such as artificial intelligence and statistical models. The main contribution of this paper is the synthesis of a generalized control structure and the identification of the latest trends. The main findings are summarized in the development of increasingly robust controllers for operation with improved efficiency, power quality, stability, safety, and economics.

1. Introduction

Solar energy is a renewable energy source. It is an attractive energy solution due to its inexhaustible supply source and it is non-polluting in character. The total amount of incident solar energy on the Earth is much greater than the current and anticipated energy needs of the world. Solar energy has the potential to satisfy all of the future energy needs if it is properly harnessed [1]. During its operation it does not emit greenhouse gas or toxic elements. Its use helps to reduce dependence on fossil fuels, contributing to the reduction of environmental impact [2]. Due to all its advantages, it is expected that in the 21st century solar energy will become the most important renewable source during the energy transition towards a sustainable development. These reasons justify why solar energy is a focus of such research interest.

The control of solar photovoltaic (PV) systems has recently attracted a lot of attention. Over the past few years, many control objectives and controllers have been reported in the literature. Two main objectives can be identified. The first is to obtain the maximum available PV power with maximum power point tracking (MPPT) control and the second objective is the PV power utilisation (application). Power can be obtained from the PV panels and then transformed to supply the load demand or to be injected into the electrical power network [3], as shown in Figure 1. According to the application, PV systems can be classified in two categories: (i) islanded systems, (ii) grid-connected systems.

Level I: PV system basic control loops
Islanded topologies
Grid-connected topologies

Level I: PV system basic control loops
Level II: Needed controls for mandatory regulations
Level III: Advanced controllers.

Figure 1. General scheme of photovoltaic (PV) systems topologies and their control levels.

The islanded system concept refers to systems that operate independent of the electrical grid. In islanded systems, ac or dc loads are directly supplied by the PV energy source. Usually the loads are AC, but with the DC power generation from renewable sources the number of DC loads has increased significantly [4]. Examples of potential DC loads are servers, data centers, lighting systems, electric drives for ventilation and air conditioning systems, electric vehicles and desktop computers [5]. In grid-connected systems, the power generated is injected into the electrical network and is used by any load or customer connected to the grid.

The middle blocks in Figure 1 are responsible for the energy conversion. This function is performed by power converters which are electronic circuits based on power switching devices. Power circuits employed in solar energy applications are: (i) DC-DC converters, (ii) DC-AC converters (inverters). Some possible system topologies for islanded and grid-connected systems are shown in Figure 1. Power converters are fundamental components in PV systems because they carry out the control actions. The control requirements of islanded and grid-connected systems are different. Current/voltage controllers and MPPTs algorithms are required in both cases. In islanded systems it is possible to implement additional controllers for the energy management of energy storage systems (ESS) and filters to improve the quality of power supplied to loads [6] [7].

2. First Level Controllers

2.1. Current and Voltage Control

For current and voltage control a two-loop control strategy is usually employed. A condition of this structure is the decoupling of the dynamic response between both loops. The inner loop must be faster than the outer loop. The common structure is to have a inner loop and a voltage outer loop. PI controllers are commonly used in both control loops, but they have disadvantages such as limitations on voltage regulation, conflicts between control loops and small regions of stability [8]. To improve the performance of two-loop strategy, robust non-linear controllers have been proposed. Recent work has addressed several control techniques in two-loop controllers such as: active disturbance rejection [9] and PI controllers [9] [10][11], passivity based control [8], predictive control [8][12], droop control [13] and adaptive controllers [14]. The description of the controllers used in inner and outer loops in this paper is shown in Table 3.

Table 3. Controllers employed in two-loop strategy.

Reference	Inner Loop	Outer Loop
[9]	PI algorithm for inner current loop	Active perturbation rejection in the outer voltage control
[10]	PI current control	Outer loop controller is used to voltage control
[11]	Inner current and voltage loops	Outer current loop
[8]	Finite control set-model predictive control as inner current loop	Interconnection damping assessment- Passivity based controller as outer controller
[12]	Vector oriented control as current controller	Model predictive control with multiple steps as voltage and power control
[13]	Inner loop current droop control	Outer loop voltage droop control
[14]	Non-linear current controller	Adaptive voltage controller with active disturbance injection

The two-loop control strategy can be replaced by a single control loop or independent control loops. This avoids complicated feedback loops. The control technique with the most potential to replace the inner and outer loop with a single loop is predictive control. In [15], a predictive controller is used to regulate the operation of a DC-DC converter and an inverter. An application of independent controllers it is a hybrid approach between predictive and sliding control applied in a grid-connected PV system, where the sliding governs the voltage fluctuations of the DC bus and the predictive control regulates the inverter's performance [16].

2.2. Maximum Power Point Tracking Methods

In order to obtain the maximum available power from a PV system and to enhance the installation efficiency, MPPT methods are used [17]. The most popular conventional MPPT in full methods are perturb and observe (P&O), incremental conductance, fractional open circuit voltage and fractional short circuit current [18]. These algorithms are very popular because of its simplicity and fast convergence [19]. In recent years, MPPT methods based on intelligent techniques such as particle swarm optimization (PSO), genetic algorithms (GA), fuzzy control, simulated annealing algorithm, neural networks and firefly algorithm have been reported [20]. Intelligent algorithms have drawbacks as complex implementation and the difficulty in initial point selection [21]. The current challenge is to introduce robust and reliable MPPT methods. The lines of research addressed in recent publications are focusing on partial shading condition and improved classical techniques [22].

2.3. Synchronization

Synchronization is fundamental in the control of the inverters connected to the grid. It consists of the connection of the generated signals with the same parameters of amplitude, phase and frequency of the power grid. In this process PLL techniques are generally used to perform the synchronization. The operation principle of the PLL is tuning the inverter's voltage with a reference voltage measured at the PCC. According to the technique employed, PLL algorithms can be categorized as: synchronous reference frame, second-order generalized integrator, quadrature PLL and enhanced PLL [23]. Another alternative are synchronization algorithms that do not measure grid voltage. These are based on virtual flow, power instantaneous and observer-based schemes [24].

Generally, classical PLL techniques do not achieve a good phase-angle detection when the voltage grids have large amplitude and phase variations [25]. Robust PLL techniques are required for weak-grid conditions. When there are not ideal conditions at the PCC techniques sensorless are suitable, although hybrid PLL algorithms may result in a good performance. Weak-grid is a challenge widely approached. Additionally, situations like unbalances and grid faults are studied in recent works. The most contributions are algorithms based on PLL [26][27][28][29][30][31]. In addition, synchronization techniques without PLL algorithms are presented in [25][24]. A brief description of recent literature is presented below.

- A PLL based on a decoupled double synchronous reference frame is presented in [26]. This structure is suitable for unbalanced grid and variable frequency conditions.

- Ref. [27] proposes a self adaptive controller to operate in both grid connected and islanding condition, with sure transfer between modes without reconfiguring control structure. The controller is designed on the basis of a PLL and two cascaded control loops.

- A SOGI based PLL technique that uses two interdependent loops one for frequency and the other one during the synchronization process is presented in [28].

- Ref. [29] proposes a PLL with second order approximation valid for steady state and transients. Compared with other PLLs, it is more accurate during large phase perturbation by cause of grid faults.

- A PLL based on a dual second order generalized integrator (SOGI) enhanced is presented in [30]. The algorithm realizes a harmonics cancellation before performing sequence calculations. Its application is weak grids.

- A novel PLL with an improved dual adaptive notch and multivariable filter is presented in [31] for unideal grid conditions.

- Ref. [25] proposes an extra function on the basis of direct phase-angle detection method to support asymmetrical grids.

- A novel grid synchronization technique with bumpless start is proposed in [24]. The method reduces the computational effort and can operate in an unbalanced and distorted weak grid.

3. Second Level Controllers

3.1. Power Quality

To achieve power quality according to specifications, control structures for inverters in PV systems must adopt harmonic compensation algorithms. IEEE Std 519 recommends a harmonic distortion of less than 5%. Harmonics are due to non-linear behaviour of elements connected to the power grid that produce undesired phenomena in both grid and connected loads. In order to attenuate these effects, control actions are implemented reducing the currents harmonics injected to the grid. The simplest strategy is to use passive filters designed for the frequencies to be eliminated. A more suitable strategy

is to use active filters which inject compensation currents to cancel the effect of the harmonics [32][33]. There are also filters that combine active and passive technologies known as hybrid filters [34]. There are two strategies for active compensation: methods based on harmonics detection in the load and selective harmonic compensation. In order to detect the harmonic content at the PCC, harmonic compensation strategies such as instantaneous power, conservative power theory and SOGI are used [35][36][37][34]. The second strategy is selective harmonic compensation, in which the controllers are tuned at the harmonic to be eliminated [38][39]. Discrete Fourier Transform (DFT) method is usually applied to detect the harmonic content to compensate. Additionally, first harmonics can be detected considering a compensation strategy and a low pass filter (LPF) [40][41]. Additional information about these contributions is given below.

3.1.1. Harmonic Detection in the Load

- In [32] harmonic components are obtained in synchronous rotating DQ frame, as a subtraction between instantaneous current and fundamental components.

- Instantaneous power theory is applied utilizing LPFs to detect the compensation currents [42][34]. Harmonics compensation is an ancillary service in a PV system under variable radiation [42] or a hysteresis band controller in the control loop [34].

- The unbalanced output power problem in single-phase cascaded H-bridge PV inverter is studied in [35][36]. This condition results in a higher harmonic content of the grid current. In [35], a novel harmonic compensation technique is proposed. In this strategy, harmonic components are obtained from DC-link average voltage calculated by means of a notch filter. In [36], multiples harmonics are injected in overmodulation and non-overmodulation regions, to extend the linear modulation range and compensate grid current harmonics.

3.1.2. Selective Harmonic Compensation

- Methods based on the traditional DFT are used to detect the load current harmonic content [38][39]. A sliding DFT is applied in a dynamic current saturation algorithm. Sliding DFT provides high computational efficiency in comparison with traditional algorithm [38]. An enhanced DFT is proposed. The controller provides a feedback for each harmonic being able to compensate different harmonics [39].

- A flexible method of selective compensation based on instantaneous power theory is presented in [37]. Compensation current is calculated according to THD index and power factor, injecting to grid active component or reactive component or both.

- A new technique to compensate second order harmonic component is proposed in [40]. This technique is based on cascaded LPFs and synchronous rotating DQ frame.

- Ref. [41] considers the current saturation problem and the compensation of the extra harmonics generated in this process. Two saturation techniques are proposed. Harmonic current components are detected applying SOGI based method.

3.2. Anti-Islanding Protection

Anti-islanding protection is a required function of grid-connected systems. The objective is to disconnect the solar modules during power outages of the grid. Disconnection isolates potential problems to avoid damage to PV components [43] and promotes safe conditions for performing maintenance [44]. The proposed techniques are classified as active or passive. In active techniques, a perturbation is applied to grid while in passive techniques, electrical variables are analyzed at the PCC. The most recent active and pasive techniques of anti-islanding detection methods are:

3.2.1. Active Techniques

- A method based on reactive power perturbation is presented in [45]. This islanding detection method poses a reactive power P&O anti-islanding method for indirect current control. The proposed algorithm introduces a small reactive power disturbance in the inverter output and detects the islanding by observing reactive power mismatch during the islanding condition.

- An approach based on the periodical injection of a second order harmonic current component and evaluates grid response through a new cross-correlation anti-islanding detection is proposed in [46]. This approach is focused in module integrated converters with pseudo dc-link.

- Ref. [47] proposes a hybrid method for islanding detection. The proposed scheme injects a low frequency sinusoidal perturbation signal into the d-axis current control loop.

- A comparative analysis of active anti-islanding techniques based on the frequency drift is presented in [44]. These techniques are the classic active frequency drift (AFD), AFD with pulsating chopping factor and AFD with positive feedback.

- An hybrid islanding detection strategy that exploits Gibbs phenomenon on the interpolation of two voltage sinusoidal functions is described in [48]. The proposed technique combines active and passive methods of frequency rate of change at a given moment while the voltage THD is monitored.

3.2.2. Passive Techniques

- A detection scheme based on support vector machine is presented in [49]. This method exploits powerful classification capability. Algorithm collects measures of current, voltage, power, frequency and THD.

- Ref. [43] proposes a scheme based on the detection of voltages and frequencies higher and lower than the admissible values. This method reduces the non-detection zone of passive islanding techniques.

- A passive method with an adaptive algorithm is presented in [50]. This paper proposes a new islanding detection strategy based on the combination of an adaptive neuro-fuzzy inference system (ANFIS) approach and passive monitoring techniques of system variables. The method exploits the pattern recognition of ANFIS approach to detect the islanding condition.

3.3. Grid Support

Practical experience indicates that with a large penetration of PV generation in a power grid more challenges and problems appear [51][52][53]. Therefore, it is necessary to implement grid support functions in the control loops. Grid-connected PV systems must satisfy several requirements to contribute to normalize the grid operating under perturbations. The minimal requirements are voltage, frequency and reactive power conditions. These regulations are imposed by grid codes to maintain stability and reliability of the power grid. In line with grid codes, PV systems have to be able to stay connected and have fault ride-through capabilities. Different robust control schemes for frequency and voltage have been proposed to deal with the dynamics issues of the grid [54]. The effect in the grid is the flexible injection of active and reactive power according to the grid conditions [55].

3.3.1. Frequency Support

Nowadays, it is still found that some classes of PV converters and their controls can generate transient events completely opposite to the responses of a grid with inertia, which contributes a destabilizing effect on the power grids [56]. This is one of the reasons why PV systems can provide virtual inertia (through their control strategies) to the grid [57][58][59][60]. Although most of the virtual inertia strategies need energy storage [57], it is possible to use the energy reserve in the PV systems to generate the desired response, without the need for storage [61]. It is important to recognize that the strategies that provide virtual inertia (or virtual synchronous generation) are not the only scheme that can contribute to frequency support. In general, if the PV system has battery storage or even hybrid storage, a system with droop control may be sufficient to support the frequency [62][51].

3.3.2. Voltage Support

Solar plants inject generally reactive power components for voltage support. In [63], reactive power is injected to support line-to-ground and three line-to-ground faults. In [64], the effect of injecting negative sequence reactive current into the grid in case of asymmetrical faults is investigated. To support the grid, negative sequence reactive current is injected suppressing the negative sequence voltage. However, active and reactive currents can be injected simultaneously to support the grid. In [65][66], the asymmetrical faults problem is approached. The proposed strategy in [65] employs dual vector current control to ensure optimal current injection and low voltage ride through. In [66], a new voltage-support technique by using a negative sequence voltage at PCC is presented. This strategy helps to improve the short-term voltage stability and regulate the phase voltages within the margins.

4. Third Level Controllers

4.1. Active Power Limiting

Limitating active power helps to overcome the frequency and voltage fluctuations as a result of the large penetration of the PV. According to operation point, the control algorithms limits the maximum power that PV system can inject into grid. The techniques used are direct power control, current limiting and modified MPPT methods [67]. In direct power control and

current limiting methods, PV systems must be provided with reserve capability. ESS contribute to flexible operation to store or release power energy.

Direct power control method is based on power settings, in which the limit power is tracked by power controllers. Similarly, a PV generation regulation can be implemented through a current control loop with a current reference proportional to limit power. This method is known as current limiting. Direct power control and current limiting methods operate independently of the MPPT methods. But, modified MPPT methods can also limit active power. Nodaways, this alternative is a major focus of attention. These control schemes can operate at MPPT or constant power generation mode. For instance, an adaptation of the P&O method is presented in order to track a reference of active power [68]. The same MPPT algorithm is modified in [69] for power regulation, moving the operation point to the left side of MPP with a consideration of stability.

For optimal performance of ESS, energy management strategies must be included.

4.2. Energy Storage Systems

Additional energy can be stored during the day and used at night to supply critical loads or for grid support. Stored energy is important in the flexible control of power flow, because used appropriately it reduces losses, power in distribution lines, reverse energy flow and supports voltage and reactive power [70]. In recent publications can be identified two principal objectives about ESS. The first one consists of the optimal sizing. This purpose is approached in [71], where optimal designs using real-world data are discussed. Additionally scheduling of charge/discharge is minimized. Optimal control of charge/discharge of ESS is the second objective. In general, restrictions must be implemented in the control laws to limit the charge/discharge of ESS and to increase its life span. It should consider that the investment cost of ESS is high and it is a priority to extend the operating time. Usually, PI controllers have been used to charge/discharge control of ESS. But a cause of their disadvantages, nonlinear controllers have been proposed.

4.3. Photovoltaic Monitoring

To achieve better performance from PV systems and increase equipment life time, the use of monitoring and control software has become popular. Software tools are responsible for acquisition, visualization and data storage [72]. This software can include smart functions to diagnose and estimate degradation of solar panels. Data processing techniques and intelligent algorithms are used in the diagnostic process.

Data processing techniques commonly used in PV systems monitoring include neural networks and machine learning. For example, a novel real-time monitoring tool considering a neural network is presented in [73]. The algorithm predicts the power generation of a PV panel in normal operation under changing environmental conditions. These results allow to identify if the solar panel exhibits degradation by cause of fault conditions. In [74], a method of monitoring solar panels for the identification of degradation based on machine learning techniques is presented. The development of the model and its validation are based on panel and weather data.

In previous cases data was obtained from the normal operation of the solar panel. Also, active procedures that perturb the system can provide data for the PV diagnostic tool, an example is presented in [75]. The proposed system consists of data acquisition and control units. For testing the solar panels, it is injected large-signal perturbations into their panel voltages. After that, voltage and current are sampled, thus it is obtained the current-voltage characteristics of the solar panel. Then, a genetic algorithm extracts the parameters of the curve. Finally, panel degradation is observed according to the parameter's variation.

4.4. Power Forecasting

PV power generation is highly dependent on weather conditions [76]. Then, prediction techniques are essential to reduce the unbalance between expected power and real power generation, and support power system operation [77][78]. Forecasting models can be classified in two categories: indirect and direct models. In indirect forecasting models a weather prediction is the input of PV simulation softwares, which provide the power prediction. Meanwhile, direct models use directly historical data of weather and PV power generation to get the prediction [76].

The most common predictions methods for PV generation are artificial intelligence based models [79][80]. Several artificial intelligence techniques are artificial neural network (ANN), support vector machine (SVM), machine learning (ML) and regressive methods. Additional categories are statistical [81], physical models [82] and hybrid models [82][83][84].

- Two artificial intelligence techniques are proposed in [79]: auto-regressive integrated moving average model with an ANN model considering weighing factors computed periodically by means of least squares method.

- Ref. [80] analyzes the performance of different machine learning models that predict the PV power generation. The forecasting models are developed by using historic data of PV power and weather predictions.

- A model uses historic PV generation and weather data is presented in [81]. A Bayesian network performs data inference. The approach also incorporates spatial similarity and temporal correlation to support the power prediction.

- A novel solar generation forecasting proposal based on exploring weather factors from PV model is presented in [82]. The method is performed at three stages: PV systems modeling, machine learning methods for mapping weather features with solar power and forecast adjustment.

- In [76] PV generation estimation is achieved by using numerical weather prediction (NWP). Historical data is processing in NWP products.

- A PV output forecast based on weather prediction is presented in [83]. K-means clustering algorithm is employed to classify historical generation data and the correlation analysis method reduces the dimension of the inputs. Prediction model is solved by considering the long-short memory neural network combined with attention mechanism.

- In [84] a forecasting method based on the ANFIS approach is presented to optimize peak load reduction. The forecasted results are used to calculate the BESS capacity and a FLC considering BESS capacity and PV power determines optimal BESS usage for the sake of power peak curtailment.

An improved PV generation prediction can be obtained incorporating a forecast adjustment stage. Thus, an additional term is included to improve the results. This function is implemented in [78][82]. In [82], the errors are reduced with a term result of a deviation analysis by using the cross-validation for historical data. In [78], a method for adjusting the solar radiation forecast from a numerical weather prediction model is presented, based on the tendency of past error occurrence.

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