Grid Connected Photovoltaic Generation Plants.

Components and Operation

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Abstract— The main design objectives of photovoltaic (PV) systems have been for a long time to extract the maximum power from the PV array and to inject it into the AC grid. Therefore, the maximum power point tracking of a uniformly irradiated PV array and the maximization of the conversion efficiency have been the main design issues. But also, when the PV plant is connected to the grid, special attention has to be paid to the reliability of the system, the power quality and the implementation of protection and grid synchronization functions. Modern power plants are required to maximize their energy production requiring suitable control strategies to solve the problems related to the partial shading phenomena and different orientation of the PV modules towards the Sun. Moreover, the new policy concerning the injection of reactive power into the grid makes the development of suitable topologies and control algorithms mandatory. A general view of actual solutions for applications of the PV energy systems is presented. The paper covers some important issues such as the most reliable models used for simulation that are useful in the design of control systems, and the maximum power point tracking function, especially in distributed applications. The main topologies used in the PV power processing system and, finally, grid connection aspects are discussed, especially as far as synchronization, protections and integration are concerned.

Keywords: Photovoltaic, Renewable energies grid integration, Smart Grids.

I. INTRODUCTION

Governments and public organizations are nowadays concerned about the production of energy with technologies as clean as possible. As a consequence, the guidelines for future energy production are established according to the Kyoto protocol [1], which for European countries inspires the "20-20-20" target [2]. The energy production technologies based on hydro, wind, photovoltaic and geothermal energies can be considered to be clean and renewable alternatives to the non-clean conventional technologies based on fossil fuels and nuclear fission. Among the clean technologies, photovoltaic (PV) is the one that has experienced a great growth in the last years, close to 60% in Europe.

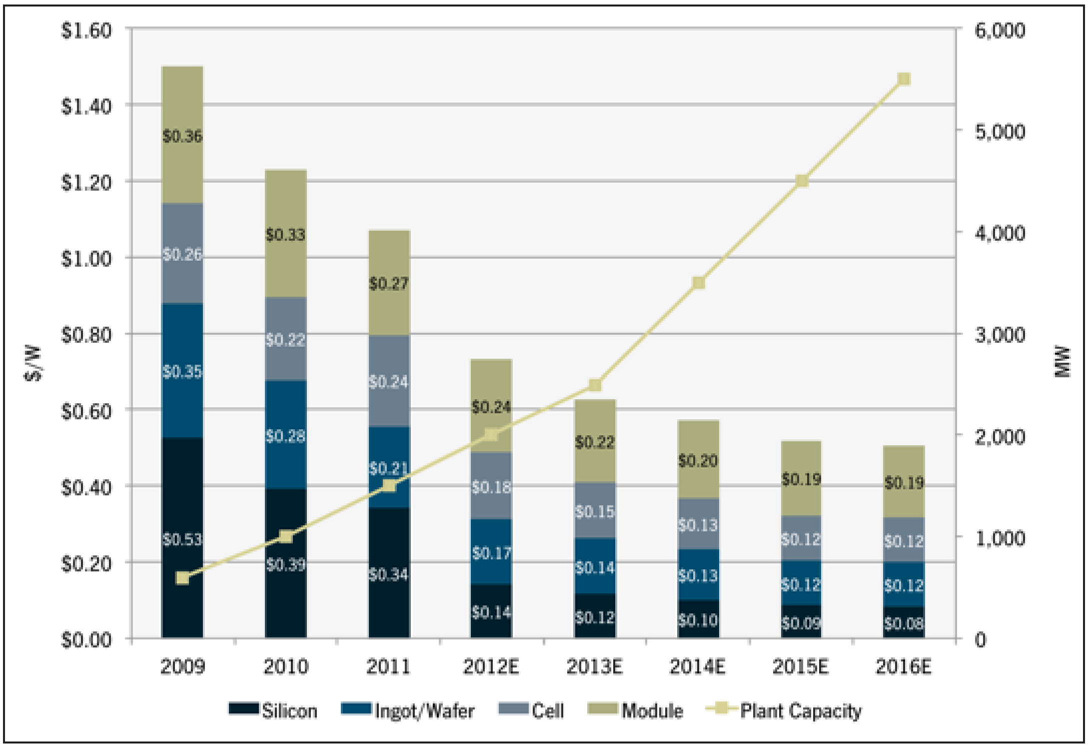
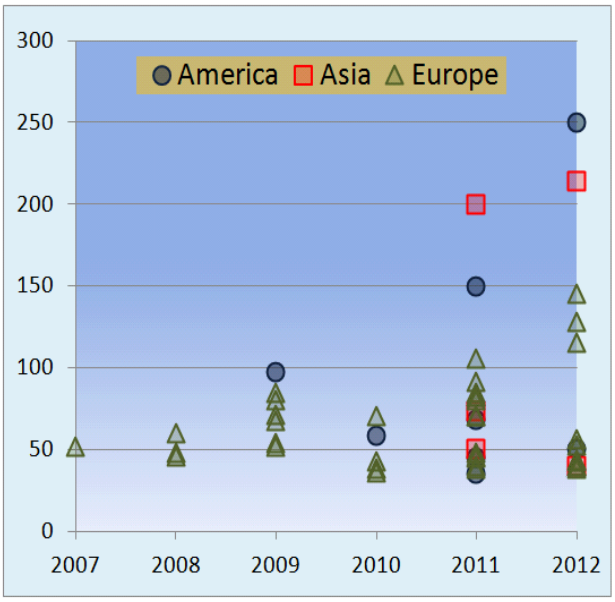


Fig. 1 All-In Module Cost (US dollars/W) and Plant Capacity evolution [3].

PV installations are no longer isolated from the grid, but connected to it, aiming to become part of the electric generation mix. In this context the cost (in US dollars) per watt of these plants has decreased from 1.5$/W in 2009 to 0.6$/W in 2013 (Fig. 1, [3]) and this decreasing tendency will continue. These plants are economically viable even without government subsidies, and the PV plant capacity is increasing significantly (Fig. 1). Therefore, the power generation of grid-connected PV plants is increasing continuously all over the world reaching values of hundreds of megawatts (Fig. 2, [4]), thus making these plants a crucial part of the future electric energy system and Smart Grids.



TOP 5 BY POWER		
Power	Description and Location	Commissioned
250 MW	Agua Caliente Solar Project USA, Yuma County, AZ	2012
214 MW	Charanka Park, Patan district PV power plant India, Charanka	2012
200 MWp	Golmud PV power plant China, Golmud	2011
150 MW	Mesquite Solar I USA, Sonora desert, AZ	2011
145 MWp	Solarpark Neuhardenberg Germany, Neuhardenberg	2012
128 MW	Solarpark Templin, Germany.	2012
115 MW	Centrale solaire de Toul-Rosières, France.	2012
106 MW	Perovo I-V PV power plant, Ukraine	2011
97 MW	Sarnia PV power plant, Canada	2009
91 MW	Solarpark Briest, Germany	2011

Fig. 2 Nominal Power (in MW) of Photovoltaic Plants classified by the continent where they are installed [4] and top-ten large-scale PV power plants.

This paper gives a general description for new researchers and industrial electronic professionals of the electronic devices needed to connect these plants to the grid in an efficient and safe way, describing their components, mainly DC/DC converters and DC/AC converters, their structures, control algorithms and functions.

In Section II, the more reliable PV models for simulating mismatched arrays are recalled and compared in terms of accuracy and computational burden. These models aim to develop simulation models that can be used for testing and evaluating the performance of the electronic converter control algorithms. This Section also introduces the main problem related with associated PV cells that electronic converters have to solve (mismatching effect mainly due to shadowing).

Section III presents the main topologies used in the PV power processing system, as well as discusses their advantages and drawbacks.

Maximum Power Point Tracking (MPPT) system described in Section IV is a basic and main part of the control algorithm. This Section also describes the distributed MPPT that tries to improve the energy generation coping with the mismatching effect presented in Section II.

Finally, in Section V, the paper exposes issues related to the operation of these plants from the point of view of their smart integration into the grid, especially as far as synchronization, protection and integration are concerned.

II. PHOTOVOLTAIC CELLS AND ASSOCIATIONS

The main components of a PV plant are the PV cells, that are associated and complemented by auxiliary elements to guarantee the power and energy the PV plant will produce. The design of the PV field could be done by commercial solutions like PVSIST [5] which allow the prediction of solar energy production under various irradiance and temperature conditions, taking into account different PV technologies or sun tracker systems.

A reliable and accurate mathematical model that can be used in standard simulation packages (as MATLAB/SIMULINK, PSPICE or PSIM) is desired to design and test the control algorithms of the electronic devices.

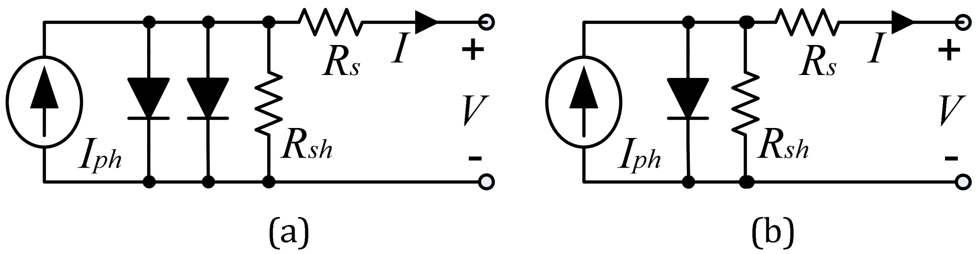


Fig. 3 Equivalent circuits of double-diode (a) and single-diode (b) model.

The equivalent circuits of PV generators proposed in prior studies can be categorized into two main types, double (DDM) [6-8] and single (SDM) diode models [9-13], which are illustrated in Fig. 3. The I-V characteristic for SDM can be expressed by (1). For the DDM, an additional current term shall be added to represent the second diode.

$$I = I_{ph} - I_s \left[e^{\left(\frac{q(V+IR_s)}{KTA}\right)} - 1 \right] - \frac{(V + IR_s)}{R_{sh}} \tag{1}$$

Electrical characteristics at standard test conditions (STC) cannot be usually measured. Therefore, PV modeling tends to use current-voltage data and curves given by cell or module manufacturers [14]. In this case, four conditions can be formulated using equation (1) corresponding to the known values for short circuit current I_{sc}, open circuit voltage V_{oc}, operating voltage and current at maximum power point (V_m, I_m), and the implicit information that the peak of P-V curve occurs at the voltage point (V_m) [12]. Although the equations that correspond to the application of the four conditions comprise a complex nonlinear equations system, they can be solved by using various mathematical approaches or numerical solvers [12, 15]. As pointed out in [14, 16], these four equations do not provide enough information to solve the five unknown parameters in a SDM including I_{ph}, I_s, A, R_s and R_{sh}, which are the photon current, diode saturation current, ideality factor, series resistance and shunt resistance, respectively. One possible solution is to fix one parameter value, e.g. the ideality factor [12] or the shunt resistance [16], and solve the remaining parameters accordingly. An ideal SDM (R_s = 0 and R_{sh} = ∞), as shown in [14], can be more accurate than the standard SDM parameterization. Moreover, the high-order model is very sensitive to the selection of initial conditions, and failing in it may lead to the reduction of model accuracy, which supports the use of the SDM. The DDM requires generally more pre-assumed parameters and iterative tuning cycles than the SDM parameterization, because if the initial condition is not correctly selected, the accuracy of the high-order model will be low, resulting in the opposite effect that is desired when using this model. Due to the modeling complexity and high computational burden, the DDM approach is not as popular as the SDM. Simplified SDM is highly recommended in [17] for complex grid-tied systems, real-time applications and long term simulations.

The measure of Normalized Root-Mean-Square Deviation (NRMSD) is proposed in [17] to quantify the modeling accuracy, because different solar cells can be compared under the same standard even if their power capacities are widely different. Usually short circuit current at STC is used as normalizing value, for example, to express the deviation between the measured data and the ones obtained from the mathematical model [17]. The single cell model can be easily aggregated to any size of PV array using the number of cells connected in series and parallel [17]. However, the approach cannot mimic partial shading or mismatching conditions that are unavoidable in real world applications.

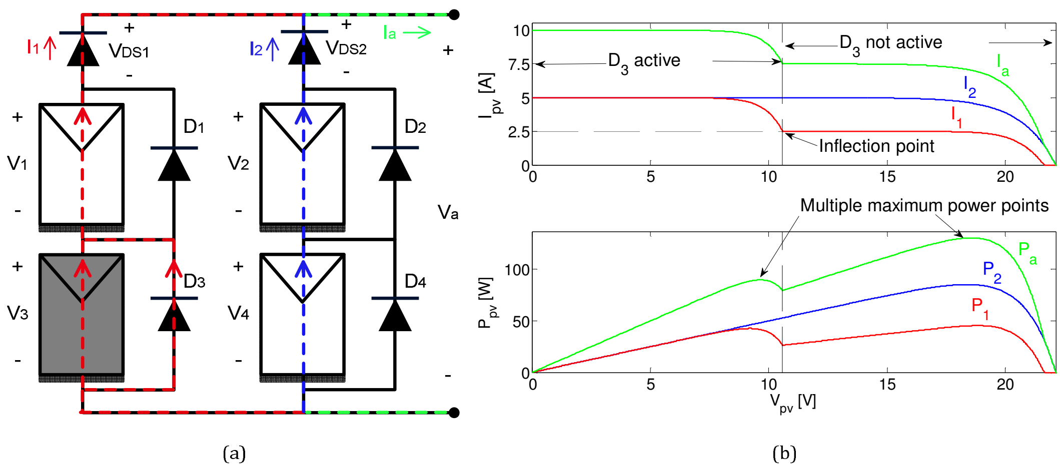


Fig. 4 Mismatching conditions and bypass diodes activation.

Different PV array topologies have been proposed [18-20] such as series-parallel, total cross-tied and bridge-linked, but the series-parallel topology, depicted in Fig. 4(a), is the most commonly used. It is based on series-connected PV modules, known as strings, which are connected in parallel to form the array [21]. The number of PV modules required in the string is determined to meet the voltage requirements of a grid-connected inverter, and the number of strings in the array determines the PV power level. Moreover, the series-parallel configuration must have blocking diodes in series with each PV string to avoid current flows from one string to another [22].

As an example, consider the case illustrated in Fig. 4, where an array composed of two strings of two modules each are shown, where each string has its corresponding blocking diode (Fig. 4(a)). Due to shading, construction tolerances, or even to different orientations, some of the PV modules in an array could experience different operating conditions, generating the mismatching phenomenon [21-23]. In such a condition the string current is limited by the lowest PV module current, degrading the power output of the PV modules with higher current. Bypass diodes are placed in anti-parallel with the modules as described in Fig. 4(a) to protect them by providing a path for the exceeding current to flow through [23-25]. In mismatching conditions, a bypass diode becomes active when the string current is higher than the current of the shaded PV module. For example, Fig. 4(a) represents a situation where the bottom PV module of the first string receives half the irradiance that the first module receives.

Fig. 4(b) shows the corresponding I-V and P-V curves (red traces I_1 and P_1) of such a string. Because the string current is higher than the short-circuit current of the second module (2.5 A), the associated bypass diode D_3 becomes active providing an alternative path through which the current exceeding the shaded module current can flow. Otherwise, if the string currents is lower than the short-circuit module current (2.5 A), the bypass diode D_3 is not active.

The shading affects the string current and power curves via the bypass diodes leading to the appearance of multiple maximum power points within the string [21, 26-28]. Fig. 4(b) shows the inflection point exhibited by the first string current, which also affects the array electrical characteristics. In contrast the second string, that operates at the uniform irradiation conditions, has a single maximum power point.

To predict solar energy production under mismatching conditions, the effect of the bypass diodes was studied in [19,20,23,25-27]. A mathematical model is proposed in [21], where each PV module is represented by a SDM and bypass diodes by Shockley equations. Such a model provides an accurate representation of the PV array by means of (N+1) non-linear equations with (N+1) unknowns (N PV voltages and blocking diode voltage) depending on the Lambert-W function. A different approach was proposed in [28], where the bypass diodes are modeled by ideal switches to calculate the inflection-point current and voltage. This approach allows the reduction of the computation effort required to predict the array current and power, because an array voltage lower than a given number of inflection voltages, e.g. K inflection voltages, implies (N-K) bypass diodes are active, where the associated PV modules have almost zero voltage and negligible power production. Therefore, the number of non-linear equations and unknown variables is reduced by K, requiring shorter computation time.

III. STRUCTURE AND TOPOLOGIES OF GRID-CONNECTED PV SYSTEMS

As shown previously, PV panels can be arranged in different configurations that affect directly the structure and topology of the electronic device. Usually this device includes a DC/DC converter and, as the PV plant is connected to the grid, it also needs a DC/AC converter. The combination of both types of elements, panels and converters, determines the cost, operation and efficiency of the whole PV system. Fig. 5 shows the schematic representation of the most common PV configurations following the classification established in [29]:

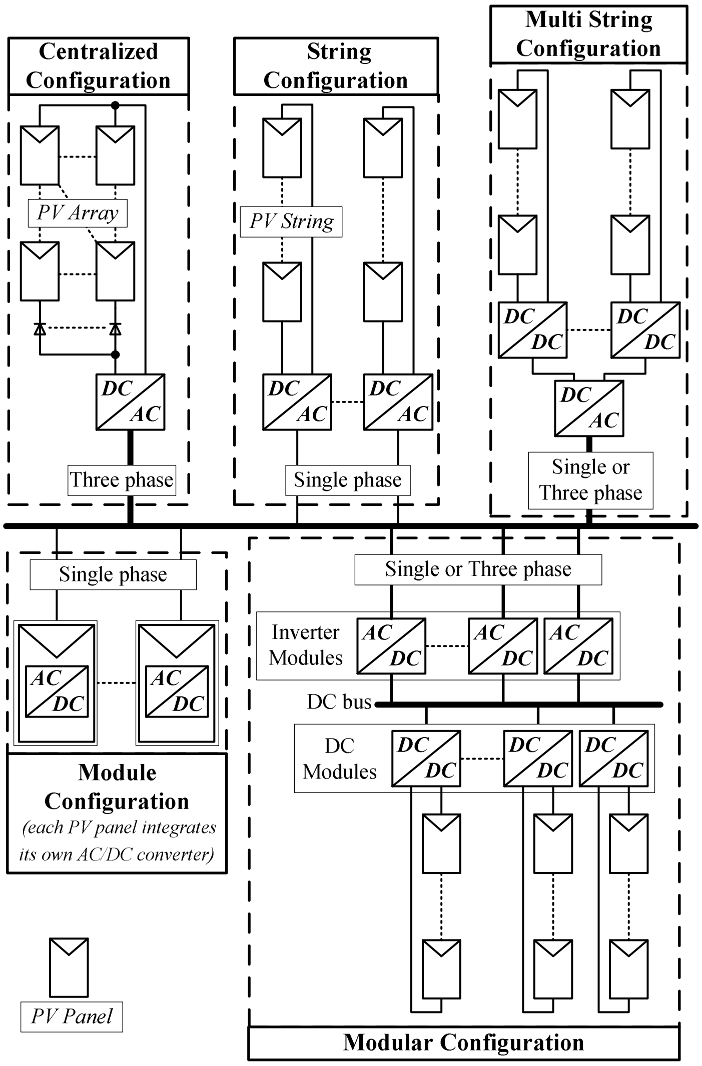


Fig. 5 PV system configurations.

- Centralized configuration. This configuration is mainly used in PV plants that have nominal power higher than 10 kWp, where a high number of PV panels are connected in series-parallel configuration (array). Each string has a blocking diode to prevent the energy reversion produced by the strings operating at different irradiance conditions, and by the existence of energy storage systems that operate during the night.

- String configuration. It is a simplified version of the centralized configuration, where each string is connected to one DC/AC converter. If the string voltage does not have the appropriate value, a boost DC/DC converter or a step-up transformer (that is usually placed in the AC side) is needed.
- Multi-string configuration. It is an evolution of the string configuration that unites the advantages of string and centralized configurations. Each DC/DC converter implements the Maximum Power Point (MPP) Tracking (MPPT) for the string. This configuration has a flexible design and improves overall PV plant efficiency.
- AC modules. In this configuration, each PV module incorporates a DC/AC converter that implements an "Automatic Control" that performs the MPPT control at module level. This topology operates like a Plug-and-Play system, having a PV-module-integrated converter. This configuration is more expensive and difficult to maintain, compared with other configurations, when the power of the plant increases.
- Modular configuration [30]. It is based on a modular design, with conventional DC/DC and DC/AC converters sharing a common DC bus. Each DC/DC converter is connected to a string and implements the MPPT algorithm. As many DC/AC converters are connected to DC bus and grid as are necessary to achieve the desired power level. The system reliability is high and it is easy to maintain, because only the damaged converter has to be replaced.

The typical structure can be deduced from the above presented PV architecture. In any of them, PV systems connected to the grid have to be provided with a DC/AC converter adapting PV panels' DC magnitudes to grid's AC ones. In addition to the DC/AC converter, a DC/DC converter can be used to adjust the DC voltage and to implement the MPPT algorithm (as will be discussed in Section IV). It is also important to determine if the galvanic isolation is needed, and where to place the corresponding transformer: either in the part of the system that operates at high frequency (having a high-frequency transformer, HFT), or in the part that operates at low frequency (having a low-frequency transformer, LFT, designed for 50 or 60Hz). Based on these criteria, the conversion topologies can be classified into the categories used in Table I [31], which also summarizes their characteristics and cited references that address their design and analysis.

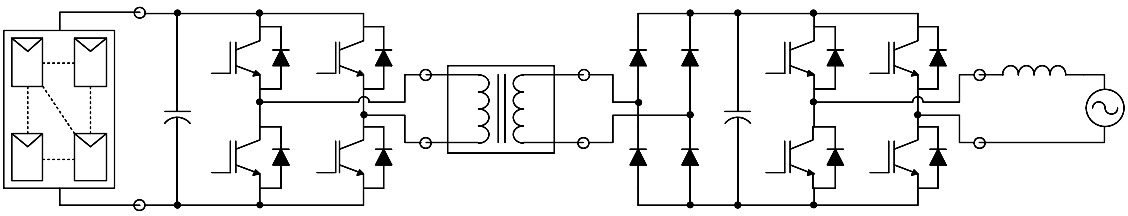
Nowadays, multilevel topologies (Fig. 6(d)) are of interest due to their lower harmonic waveform content and to the use of semiconductors in less stressing conditions. The number of commercial inverters that use this topology is increasing day by day. Also the use of high bandgap devices, mainly SiC and GaN [32], in inverters is an area of active research to improve inverter efficiency, but the cost of these devices are still high compared to conventional semiconductors.

Finally, a filter is needed between the DC/AC converter and the grid. L, LC or LCL are the most commonly used filter topologies [33,34].

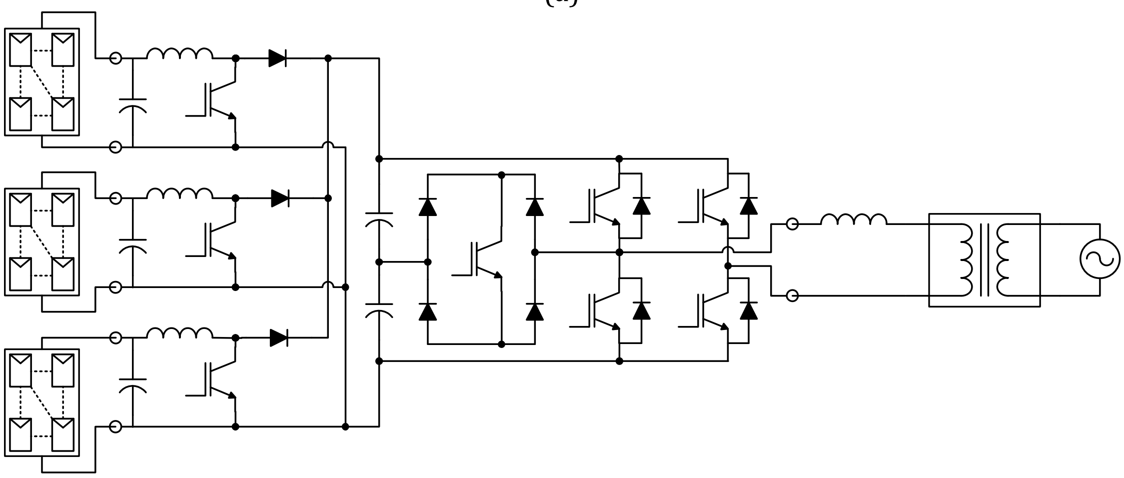
Table I – Classification of topologies for grid-connected PV systems [31]

	With DC/DC converter			Without DC/DC converter	
	With isolation		Without isolation	With isolation	Without isolation
Characteristic	DC/DC-DC/AC with HFT	DC/DC-DC/AC with LFT	DC/DC-DC/AC	DC/AC with LFT	DC/AC
Example and references	Fig. 6(a) [35,36]	Fig. 6(b) [37,38]	Fig. 6(c) [39,40]	Fig. 6(d) [41-45]	Fig. 6(e) [46-49]
Isolation	Yes	Yes	Leakage current through earth has to be controlled	Yes	Leakage current through earth has to be controlled
DC component in the injected	It has to be controlled	It is zero	It has to be controlled	It is zero	It has to be controlled

current					
Design	Complex	Medium	Medium	Simple	Simple and compact
MPPT	Implemented in DC/DC Converter	Implemented in DC/DC converter	Implemented in DC/DC converter	Implemented in AC/DC converter	Implemented in AC/DC converter
Power range	Medium-High	High	Medium-High	High	Low
Efficiency	Good	Medium	Good	Good	Very good
Transformer	Non conventional transformer. Low weight and volume.	Usual transformer. High weight and volume.	No	Usual transformer. High weight and volume.	No



(a)



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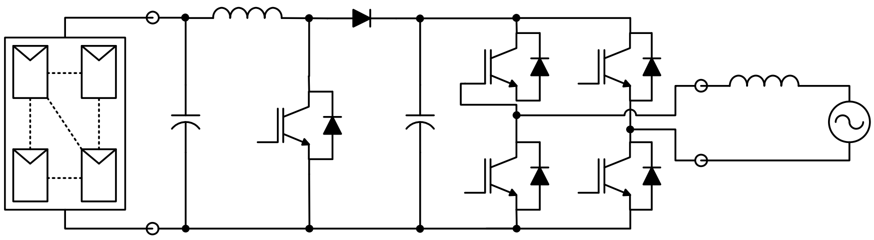

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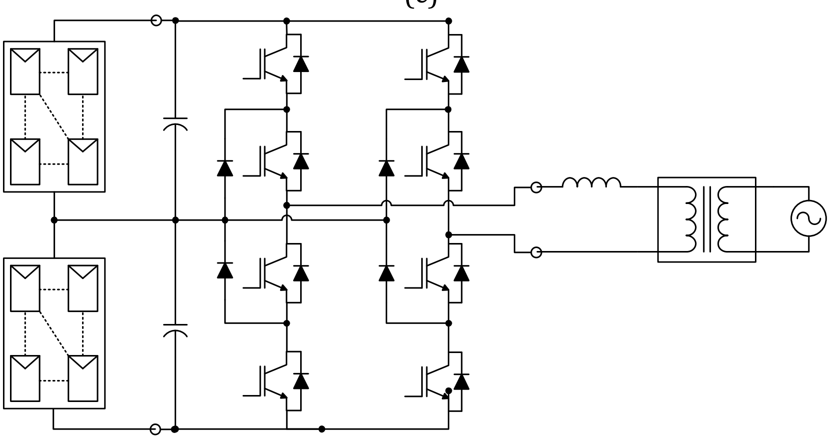

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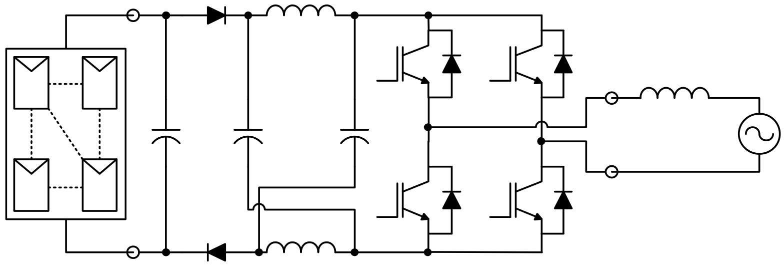


(e)

Fig. 6 Examples of topologies following the classification of Table I [31]

IV. MAXIMUM POWER POINT TRACKING SYSTEM

This efficiency maximization of PV power processing system is useless if the MPPT control does not ensure that the maximum power is extracted from the PV array both at steady state and under varying climatic conditions. In fact, the total efficiency of the power processing system is almost the product of the conversion efficiencies, which must be maximized by taking into account the extremely variable operating conditions throughout the day [50] as well as the MPPT efficiency.

There are multiple MPPT techniques [51] that could be compared using different criteria (Table II). The main techniques are *dP/dV* or *dP/dI* Feedback Control, Incremental Conductance (IncCond) and Hill-climbing (or Perturbation-Observation, P&O).

Table II – Major characteristics of MPPT techniques

MPPT technique	PV array dependent?	True MPPT?	Analog or Digital	Convergence Speed	Implementation Complexity	Sensed parameters
Hill-climbing / P&O	No	Yes	Both	Varies	Low	Voltage, Current
IncCond	No	Yes	Digital	Varies	Medium	Voltage, Current
Fractional V_{oc}	Yes	No	Both	Medium	Low	Voltage
Fractional I_{sc}	Yes	No	Both	Medium	Medium	Current
Fuzzy Logic	Yes	Yes	Digital	Fast	High	Varies
Neural Network	Yes	Yes	Digital	Fast	High	Varies
RCC	No	Yes	Analog	Fast	Low	Voltage, Current
Current Sweep	Yes	Yes	Digital	Slow	High	Voltage, Current
DC Link Capacitor Droop Control	No	No	Both	Medium	Low	Voltage
Load *I* or *V* Maximization	No	No	Analog	Fast	Low	Voltage, Current
dP/dV or *dP/dI* Feedback Control	No	Yes	Digital	Fast	Medium	Voltage, Current

A. MPPT operation and efficiency

Commercial products typically use perturbative approaches for tracking the MPP, determining, instant by instant, the voltage value at which the PV generator delivers its maximum power. Perturb & Observe and Incremental Conductance methods require an accurate parametric design [21] and usually control the reference signal of a feedback-controlled switching converter, generally a DC/DC regulator that matches the PV array voltage with the DC bus one, or that works as a battery charger.

Fig. 7 shows some examples of MPPT operation by employing a DC/DC converter: the outermost feedback cannot be taken either from the output-side signals without compromising the stability of the interfacing [52,53]. The MPPT operation usually acts on the PV voltage because of its logarithmic dependence on the irradiance level. Instead, an action based on the PV current would allow having a more prompt reaction to the irradiation variation: few examples of this approach have been recently proposed in literature [54,55] because of the intrinsic instability of the current control when irradiation drops occur.

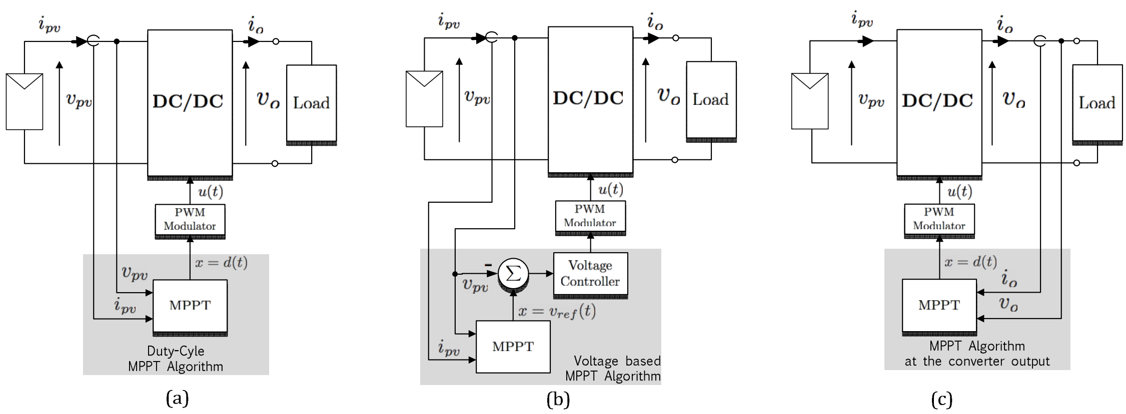


Fig. 7 Different ways of implementing the MPPT operation by means of a DC/DC

converter: by acting on the duty cycle value (a) or on a reference signal (b). The output power can be observed instead of the input one (c).

The MPPT performances are mainly affected by two types of disturbances: an endogenous one, that is the noise unpredictably moving the PV operating point away from the MPP, and an exogenous one, that is the inhomogeneous irradiance received by the modules of the PV array. The effects of the former source must be minimized by a proper control action, e.g. [21], without using any passive filtering that could affect the conversion efficiency. The mismatched operation of the PV array requires very sophisticated MPPT techniques. Indeed, perturbative methods are able to perform a local, not global, maximization of the PV power, thus not ensuring that the absolute MPP of the multi-modal PV characteristic resulting from the mismatched operation (see Fig. 4(b)) is tracked. Some real time global optimization methods have been presented in literature, e.g. [27], but they are usually very complicated, so the leading companies operating in the field have preferred to offer the possibility of doing a periodical sweep of the PV curve in order to discover where the absolute maximum power point really is [56]. Needless to say that a frequent sweep analysis improves the power production in daylight hours when a shadow affects the PV array, but reduces the power the system is able to produce when it works in homogeneous conditions. During the last five years, a large number of papers have been dedicated to the so-called Distributed MPPT control and to the dynamical reconfiguration of the PV arrays [57]; both solutions allow the increase of the power production in presence of mismatching effects but, of course, show some drawbacks.

B. Distributed MPPT Schemes

The long PV strings are very sensitive to the partial shading effects caused by the nearby obstacles such as buildings, trees, chimneys, flag poles, and even the passing of clouds due to the current-source nature of the individual PV cells [58,59]. To reduce the detrimental effect of shading on the energy production, the PV modules are usually equipped with bypass or shunt diodes (as shown previously), but these alone will not give the desired results of maximizing the energy output of the PV generator. Other actions are needed such as providing each PV module or its submodules with a dedicated MPP-tracking converter [60-66], so that the detrimental effects of mismatching remain limited to the penalized modules and the MPPT algorithms almost operate on single-peak current-voltage characteristics. Such arrangements are known as distributed or granular MPP-tracking schemes. In [63] is estimated that the module-integrated MPP-tracking can improve the energy captured in shaded conditions by 16 % compared to string-based MPP tracking. If the granularity is extended to cell level, the improvement could be as high as 30%.

The module level distributed MPP-tracking can be basically implemented either by connecting the output terminals of the DC/DC converters in parallel, Fig. 8(a) [64], or in series, Fig. 8(b) [65]. In grid-connected applications, the DC-link voltage is in the order of the peak or twice the peak of the grid voltage. Therefore, the parallel-connected scheme requires the use of DC/DC converters having transformer isolation and quadratic conversion ratio as well as high-voltage-rated components [64]. It is assumed that the cascade-connected scheme can be implemented by using non-isolated DC/DC converters with low-voltage-rated components yielding superior efficiency and reliability performance over the parallel-connected scheme. The output-terminal voltage of the cascade-connected converter is highly dependent on the power the converter supplies and the DC-link voltage. As a consequence, the buck-boost-type converter has to be utilized for the cascaded system to work properly [68]. In addition, the conditions for low voltage may not be valid, requiring the use of components with a greater capacity to withstand higher voltage [68]. The terminal voltages can be balanced by connecting at the output terminals of the converters an additional converter known as string-current diverter as explained in detail in [69]. The same technology is also the basis for the submodule-integrated distributed MPP-tracking schemes. The output-terminal voltages are also prone to disturbances during the changes in the irradiation condition [62,65] necessitating the use of feedback control for eliminating them [62]. The parallel-connected arrangement does not suffer from such disturbances.

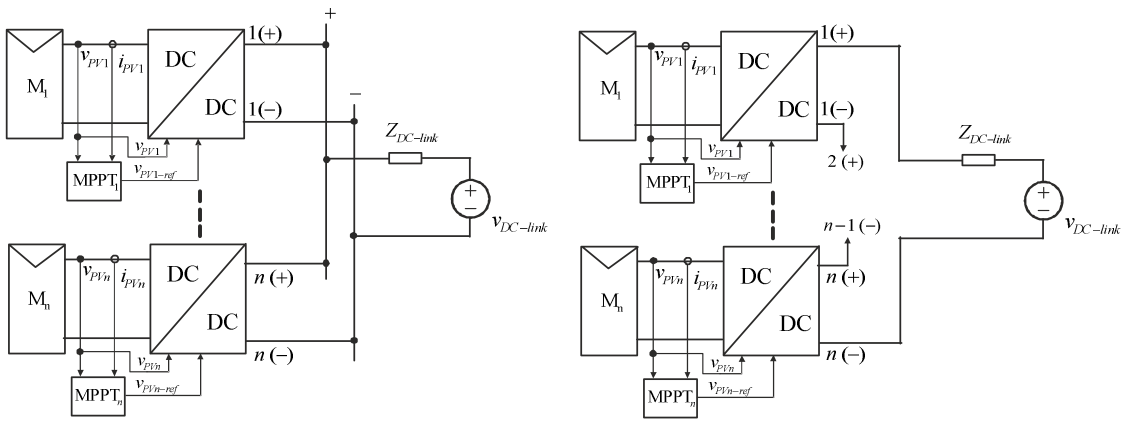


Fig. 8 PV module-integrated distributed MPP-tracking arrangement, using parallel-connected (a) and series-connected (b) DC/DC converters.

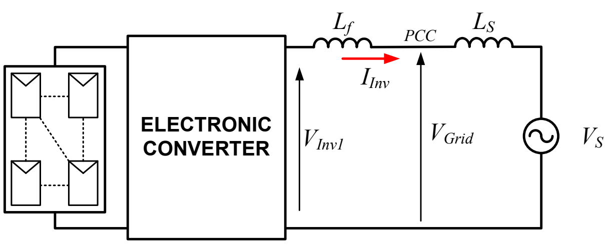
It is well proven that the distributed MPP-tracking arrangement can substantially increase the energy capture of a PV generator when subjected to severe shading conditions. The parallel-connected arrangement may eventually be the best choice even if the series-connected arrangement is commonly assumed to be superior in terms of cost, efficiency, and reliability over the parallel-connected arrangement. The feasibility of the submodule-integrated solutions has to be studied case-by-case.

V. GRID CONNECTION

The operation of inverters when they are connected to the grid, compared to inverters that operate in isolated installations, needs the implementation of additional functions, such as synchronization and protection functions. The energy storage function usually needed in isolated PV installations, is not so important in grid-connected systems. However, energy storage is becoming more important nowadays for achieving a smart integration into the grid, as a consequence of increasing the nominal power of PV plants.

A. Synchronization

Most inverters operate as current sources injecting a current that is sinusoidal and in phase with the grid voltage, with a power factor equal or very close to unity. It is required that the inverter synchronizes with the fundamental component of the grid voltage, even in the cases when the grid voltage is distorted or unbalanced, or even when the grid frequency varies.



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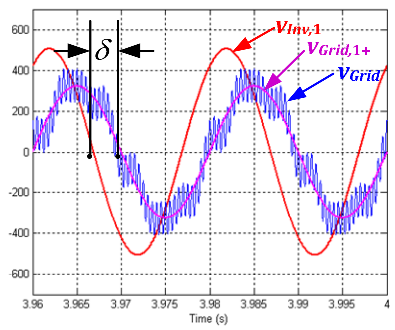

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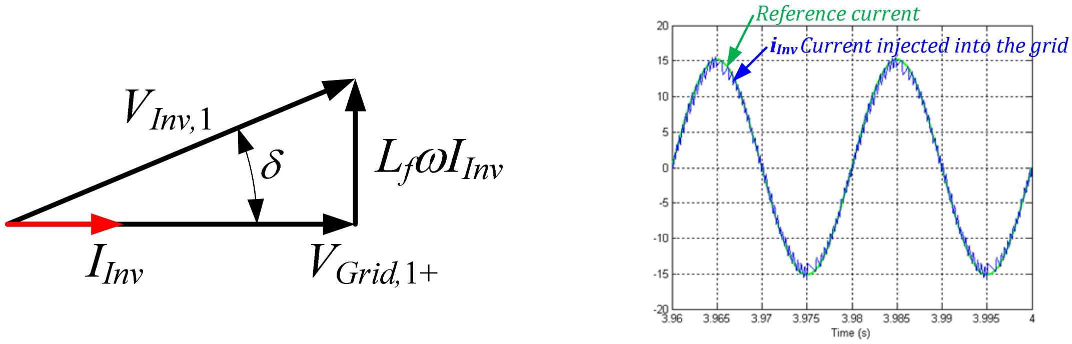

(b) (d)

Fig. 9 Example of waveforms synchronization for achieving a Unity Power Factor operation.

An example of synchronization in steady state for a single-phase system is shown in Fig. 9, where it can seen that even when the grid voltage, v_{Grid}, is distorted, the synchronization system is able to extract its fundamental and positive sequence component, $v_{Grid,1+}$, which is used for determining the fundamental voltage component the inverter has to generate, $v_{Inv,1}$, to ensure that the current injected into the grid, i_{Inv}, is in phase with the fundamental grid voltage. In this way, the active power flowing to the grid can be controlled; this power, assuming that the power factor is equal to unity, is given by the following expression

$$P_{Grid} = V_{Grid,1+} I_{Inv} \,. \qquad (2)$$

To obtain the fundamental and positive component of the PCC voltage is not a simple task. This voltage could present disturbances, due to harmonics or unbalances that exist on the grid or due to the resonance at the switching frequency between the passive elements of the inverter and the grid impedance (this is the case of the voltage shown in the example of Fig. 9c). Furthermore, the synchronization system has to guarantee the required filter with the desired dynamic and steady responses. It has to be also taken into account the start-up time that the synchronization system requires for being operative and for the inverter to start to inject energy.

Several techniques have been introduced in the literature for implementing the grid synchronization paying attention to the issues described above [70,71], that can be classified according to [72] as follows: Zero Crossing Detector (ZCD), Phase Locked Oscillator (PLO), Based on Digital Fourier Transformer (DFT), Adaptive Notch Filter (ANF), Based on Kalman filters (KF), Weighted Least Squares Estimation (WLSE), Artificial Neural Network (ANN), Usual Phase Locked Loop (PLL), Enhanced PLL (EPLL), Adaptive PLL (APLL), Synchronous Reference Frame PLL (SRF-PLL), and combining SRF-PLL with LPF (SRF-PLL LPF), Moving Average Filter (SRF-PLL MAF), DFT (SRF-PLL DFT) or using symmetric components (SRF-PLL SC). The comparison of these methods is presented in Table III.

Table III – Comparison of main Synchronization methods used in PV systems

Synchronization method			Distortion Immunity	Adaptation to frequency	Unbalance Robustness	Dynamic response	Computational Cost	Complexity
Single phase [1]	AM	ZCD	Low, it suffers from harmonic instability	Medium	-	Slow, it reacts with the next cero crossing	Low	Low
	OLDM	DFT	High	High, with variable frequency platforms	-	Slow	High	High
		ANF	Medium	Medium	-	Very slow	High	High
		KF	-	Medium-High	-	-	Very high	Very high
		WLSE	-	Medium-High	-	-	Medium	Medium
		ANN	-	Medium-High	-	Medium-Fast	Low	High
	CLDM	PLL	Medium, it depends on the band width	Medium, due to the internal 2nd harmonic	-	Medium, it depends on the band width	Low-Medium	Low, it can be linearized to a servo transfer function
		EPLL	High	High, it eliminates the internal 2nd harmonic	-	Medium-Slow	Medium	Low-Medium
		APLL	Medium	Medium-High	-	Medium-Fast	Medium	Medium
		SRF-PLL	High	High, they can be frequency adaptive	-	Medium	Medium-High	Medium-High
Three phase	AM	PLO	Medium	Medium	Medium	Variable	Medium	Very high, synchronization in the control loop
	LD	LPF	High	Low, very sensible	Low, Clarke transformation	Medium	Medium-Low	Medium-Low

				maintains inverse sequence data			
	SVF	High, if well tuned	Low, sensible	Low, Clarke transformation maintains inverse sequence data	Medium-Slow	High	Medium-High
	KF	High	Medium	Medium	Medium	High	High
	WLSE	-	Medium, it is slow	High	Fast	High, it present some problems	Medium
CLDM	SRF-PLL	Medium	Medium, due to the 2nd harmonic of d-q components	Medium, due to the 2nd harmonic of d-q components	Fast	Medium	Low, easy linearization
	SRF-PLL LPF	Medium-High	Medium-High	Medium-High	Medium	Medium	Medium-Low
	SRF-PLL MAF	High, it eliminates the 2nd harmonic	Medium-High	High, it eliminates the 2nd harmonic	Slow	Medium	Medium
	SRF-PLL DFT	High, it eliminates the 2nd harmonic	Medium-High	High, it eliminates the 2nd harmonic	Medium-Slow	High	High
	SRF-PLL SC	High, it extracts the positive sequence	High	High	Medium	Medium-High, except the ones based on neural networks	Medium-High

AM: Analog Method, OLDM: Open-loop Digital Method, CLDM: Closed-loop Digital Method

B. Protections

Most national and international grid codes, that regulate the PV plants connected to the grid, require having maximum and minimum voltage and frequency protections. If the grid RMS voltage and/or frequency are outside of the pre-defined operating range, the PV plant has to be disconnected from the grid.

Another protection that is commonly implemented in grid-connected inverters is the anti-islanding protection, which prevents the inverter from continuing to work when the grid is not energized (due to a fault or a maintenance activity in the electrical system). There are multiple methods that try to detect the absence of grid voltage [24,73-74] and they can be classified in two main groups: local, implemented at inverter level, that could be passive, active or hybrid; or remote, implemented at grid level or based in communication systems.

The main characteristics of the most relevant anti-islanding methods are summarized in Table IV. These anti-islanding methods are as follows: Reactive Power Variation (RPV), Active Frequency Shift (AFS), Slip-Mode frequency Shift

(SMS), Active Frequency Drift with Positive Feedback (AFDPF, Sandia Frequency Shift), Active Frequency Drift with Pulsating Chopping Factor (AFDPC), General Electric Frequency Scheme (GEFS), Grid Impedance Estimation by Harmonic Injection (GIEHI), Grid Impedance Estimation using External Switched Capacitors (GIEESC), Based on Communication Systems (BCS).

Table IV – Characteristics of the most relevant anti-islanding methods

Anti-Islanding method	Reliability NDZ[1]	Power Quality PQ	Multiple inverter integration	Standardization possibilities
RPV	High, NDZ could be eliminated	High, without harmonics but reduces the PF[2]	Low	Low, due to the parallel problems
AFD	Medium, Does not eliminates NDZ	Low, it introduces low order harmonics	Low, it cannot manage concurrent detections	Low
SMS	Medium, Does not eliminates NDZ	Medium, it affects the PF	Low, it cannot manage concurrent detections	Low
AFDPF	High, NDZ could be eliminated	Medium, PQ could be affected by continuous shifts	Medium, it can work with parallel inverter, but affects the PQ.	Medium
AFDPCF	Medium-High, with controlled stability	High, it introduces harmonics but controls the THD	High, but limited	High, stability and THD could be controlled
GEFS	Very high. It eliminates NDZ and controls stability	Very high, THD changes very few	High, but limited	High, it does not degrades the THD
GIEHI	High, NDZ could be eliminated	Medium, it depends on the frequency of injected harmonics	Low	Low
GIEESC	High, NDZ could be eliminated	Low, it introduces low order harmonics	Low	Low
BCS	Medium-High, if communication quality is good	High, it does not influence on the PQ	High, it depends on the communication reliability	High, a large term due to cost

[1]NDZ: Non-Detection Zone, [2]PF: Power Factor

C. Grid integration

Several regulations (grid codes) have been established to avoid problems of connecting a large number of PV installations into the grid. These problems are mainly due to unmanageable behavior (the produced energy cannot be controlled because it depends on the weather conditions, mainly irradiation and temperature), to the injection of current harmonics and to its operation under abnormal grid states [75-79] (usually produced in after-fault or re-connection grid scenarios).

Some of the existing regulations related to harmonic injection, could equally be applied to PV installations (for example, IEC 61000 [78] or IEEE Std 519-1992 [76]). These norms mainly define limits for the total and individual harmonic distortion ratios the injected current can have, depending on the nominal power or current of the inverter.

Another major issue, when connecting photovoltaic installations to the grid, is related to the ability to control reactive power in both transient (under abnormal situations) and steady conditions. The inverter has to control the phase of currents to inject or demand a pre-established reactive power, that is imposed by the Electric System Operator (to guarantee the manageable behavior of the plant), or that is determined by the inverter itself, depending on the magnitudes measured from the grid.

The association of Energy Storage Systems (ESS) with PV installations is also a key factor to be solved in the future. It has to be determined when and how to charge and discharge the energy, taking into account the prices of produced and consumed energy, as well as the ESS size optimization. It is known as Smart Energy Storage and there are some commercial solutions already available on the market [80,81].

VI. CONCLUSIONS

Photovoltaic power processing plants connected to the grid are increasing both in the number of installations and also in the rated power of each plant, and will cover a significant percentage of the electric generation mix. In this paper, a comprehensive overview of grid-connected photovoltaic power processing systems is presented with the aim of giving the clues for future improvements and research activities in the field.

There are different techniques and architecture that can reduce the effects of control problems related to the non uniform operation of the modules the PV array is made of. Some solutions to these problems are related to the structure of the array itself and involve the use of block and bypass diodes, and others are related to how to apply the MPPT algorithm, covering distributed control and its integration in dedicated DC/DC converter.

The different single-stage and multiple-stage conversion topologies proposed in recent literature can be compared in terms of their main issues related to the grid connection, determining their pros and cons. Most of these comparisons have been done in this paper.

Finally, it has to be determined the synchronization, power (active and reactive) control and protection functions that the inverter has to implement to achieve a smart integration into the grid, taking into account their main characteristics.

In the near future, Industrial Electronic Researchers will have to solve the emerging problems associated with Smart Grids, as for example, the ones related to control of multiple distributed generation plants integrated within the houses, and to develop Smart Energy Storage systems.

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