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Design of a robust and efficient power electronic interface for the grid integration of solar photovoltaic generation systems☆

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ABSTRACT

Nowadays, the penetration of photovoltaic (PV) solar power generation in distributed generation (DG) systems is growing rapidly. This condition imposes new requirements to the operation and management of the distribution grid, especially when high integration levels are achieved. Under this scenario, the power electronics technology plays a vital role in ensuring an effective grid integration of the PV system, since it is subject to requirements related not only to the variable source itself but also to its effects on the stability and operation of the electric grid. This paper proposes an enhanced interface for the grid connection of solar PV generation systems. The topology employed consists of a three-level cascaded Z-source inverter that allows the flexible, efficient and reliable generation of high quality electric power from the PV plant. A full detailed model is described and its control scheme is designed. The dynamic performance of the designed architecture is verified by computer simulations.

1. Introduction

In the last years, interest in photovoltaic (PV) solar power generation is increasing worldwide and the installation of large grid-connected PV systems is accelerating because of distinctive advantages such as simplicity of allocation, high dependability, absence of fuel cost, low maintenance and lack of noise and wear due to the absence of moving parts. In addition to these factors are the declining costs of solar modules, an increasing efficiency of solar cells, manufacturing-technology improvements and economies of scale [1].

The grid integration of renewable energy sources (RES) based on PV systems is becoming today the most important application among PV solar systems, gaining interest over traditional stand-alone systems. This situation is mainly boosted by the numerous benefits of using RESs in distributed (aka dispersed) generation (DG) systems, including the strong support provided by governments of many countries, as investment subsidies and incentives [2,3].

The growing number of distributed PV systems brings new challenges to the operation and management of the power grid, especially when the variable and non-dispatchable energy source constitutes a significant part of the total system generation capacity. Under this scenario, the power electronics technology plays an important role in ensuring an effective grid connection of the PV system. Integration issues

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need to be addressed from both the distributed PV system side and from the utility side. In modern applications of grid-tied distributed PV generation, the power conditioning system (PCS) is the key component that enables to provide a more cost-effective harvest of energy from the sun and to meet specific electrical grid code requirements. This is especially significant for applications of DG in future smart grids.

In the literature, numerous topologies of PCSs, varying in cost and complexity, have been widely discussed for integrating PV solar systems into the electric grid. In modern PV systems designs with control of both, active and reactive power, the PCS is typically built using a full-scale power converter made up of a two-stage power conversion hardware configuration [4], as depicted in Fig. 1. This PCS design is composed of a DC/DC/AC power converter that permits to simultaneously and independently control the active and reactive power flow exchanged with the electric utility grid. In this sense, multi-level converters are increasingly preferred for medium- and high-power applications due to their ability to meet the increasing demand of power ratings and power quality associated with reduced harmonic distortion, lower electromagnetic interference, and higher efficiencies when compared with the conventional two-level topologies [5].

This paper describes the design and simulation of a robust and efficient electronic interface for the grid connection of distributed photovoltaic generation. A high performance PCS of a PV system and its control scheme for applications in DG systems is proposed. This PCS utilizes a simple and innovative structure that differs from the conventional ones in the use of a single-stage power conversion topology that offers significant advantages. Moreover, a new three-level control scheme is designed, capable of simultaneously and independently regulating both active and reactive power exchange with the electric grid. The dynamic performance of the designed architecture is verified by computer simulations.

2. Description of the PV system

2.1. Power circuit configuration

The main purpose of a grid-connected PV solar system is to transfer the maximum instant power harvested from the sun into the electric utility grid (usually with unity power factor). This goal imposes the necessity of being constantly operating the PV system near the maximum power point independently of the climatic conditions. Therefore, the use of an appropriate electronic interface with both maximum power point tracking (MPPT) capabilities and the ability of effectively connecting to the AC power grid is required [6]. The PCS permits to achieve this objective, by successfully controlling the active power flow exchanged with the electric system. Even more, with the appropriate configuration of the PCS and its control system design, the PV array is capable of simultaneously and independently performing both instantaneous active and reactive power flow control, as required by modern (and especially in future "smart") grid-connected DG applications.

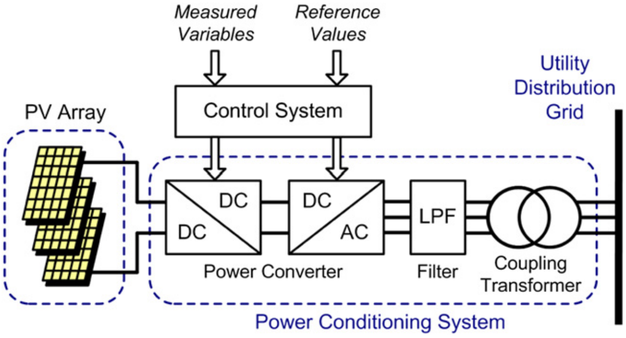

Fig. 1 – General scheme of a typical grid-tied solar PV generation system.

To this aim, a PCS hardware configuration of two cascade stages is the most common solution worldwide used, which offers an additional degree of freedom in the operation of the grid-connected PV solar system when compared with the classical single-stage topology. Hence, a three-phase DC/AC voltage source inverter (VSI) using IGBTs (Insulated Gate Bipolar Transistors) or MOSFETs (Metal Oxide Semiconductor Field Effect Transistors) is employed for connecting to the grid. The output voltage control of this VSI is generally achieved through pulse width modulation (PWM) techniques. As the VSI needs a fixed DC link in order to allow a decoupled control of both active and reactive power exchange with the electric grid, an extra conditioner utilized as interface in the DC side of the VSI is required. For this purpose, an intermediate DC/DC converter (or chopper) generally in a boost topology can be employed. Therefore, it allows linking the output of the PV solar array to the DC bus of the inverter and consequently permits to pursue various control objectives simultaneously and independently of the PV array operation without changing the PCS topology. However, this two-stage arrangement retains some disadvantages when compared to single-stage topologies.

- Lower power conversion efficiency, because of the two-stage configuration.
- Lower reliability because more fully controlled switches are used in this configuration with the addition of the chopper.
- Higher volume and weight, since the boost stage increases system size and weight.

In addition, the reliability of both configurations is reduced even more due to the potential existence of shoot-through states arising from gate-drive failures. Therefore, there is a motivation to deal with the aforementioned limitations.

2.2. Z-Source inverter

A potential solution to overcome these problems is the use of a novel inverter topology capable of coping with the output voltage variation of the primary energy source and still preserving a fixed higher voltage DC link, all in a modified single-stage structure. This structure utilized to realize both inversion and boost function in one stage is an impedance-source (or impedance-fed) power inverter (aka Z-source inverter) [7], which is shown in Fig. 2 (middle side). A unique impedance source (Z-source), consisting of a two-port network with a couple of inductors (or a split-inductor) and capacitors connected in X shape, is used for coupling the PV array output terminals to the standard three-phase inverter.

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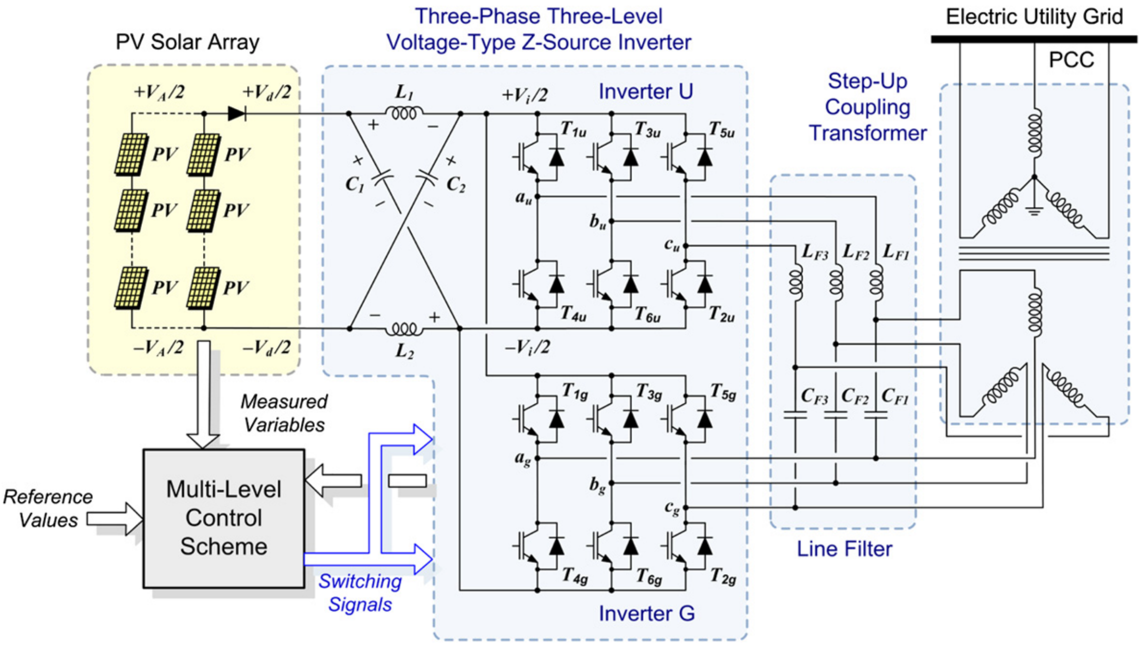

Fig. 2 – Configuration of the proposed grid-connected PV solar generation system.

In this way, with the proper design of the PWM scheme to the inverter, the voltage boosting (also bucking) function can be realized simultaneously and independently of the inverter operation, without affecting the voltage waveforms seen from the electric grid within a wide range.

The Z-source concept uses a modified PWM control technique based on introducing an additional switching state (or vector) to the eight states (six active and two null states) of the traditional three-phase voltage source inverter [8]. The traditional three-phase VSI has six active vectors when the DC link voltage is applied to the electric grid via the coupling transformers and two zero vectors when the transformer terminals are shorted through either the lower or upper three IGBTs. However, the three-phase Z-source inverter has one extra zero state when the transformer input terminals are shorted through both the upper and lower devices of any one phase leg (i.e., both devices are switched on), any two phase legs, or all three phase legs. This so-called shoot-through zero state provides the unique buck-boost feature to the inverter.

In summary, the Z-source inverter is chosen to be a good alternative to conventional inverter topologies due to its many merits. For instance, as previously mentioned, it has inherent voltage buck and boost capability using the shoot-through states in each phase leg of the inverter. Compared with the topology in Fig. 1, the proposed configuration has eliminated the DC/DC chopper and thereby simplified the system structure. The system operation reliability is also improved since there is no shoot-through risk in the VSI.

Multi-level inverters have found extensive applications in the industry and to date are increasingly preferred for medium- and high-power applications due to their many inherent advantages, like their ability to meet the increasing demand of power ratings and power quality associated with reduced harmonic distortion, lower electromagnetic interference, and higher efficiencies when compared with the conventional two-level topologies. In this way, in order to provide an effective multi-level topological alternative for the present Z-source inverter application, it is used a modified three-level cascaded Z-source inverter implemented using two three-phase two-level inverter bridges and supplied by one uniquely design Z-source impedance network [9], as depicted in Fig. 2. These three-phase bridges are series connected (cascaded) at their AC outputs using three single-phase step-up coupling transformers in order to create a dual Z-source inverter, whose secondary terminals are wye connected. This dual Z-source inverter can be controlled using different modulation approaches due to the availability of various additional redundant switching states within a phase leg comparing with other multi-level topologies. Particularly, using a modified phase-shifted-carrier (PSC) PWM scheme with shoot-through states inserted, it is shown that the dual inverter can efficiently be implemented using only a single Z-source network, with a significant saving in cost, while still achieving the correct switching loss equalization among the semiconductor devices. In addition, smaller DC ripple currents are expected to flow into the three-phase bridges, as compared to single-phase H-bridges of a traditional cascaded inverter.

3. Control of the PV system

The proposed multi-level control scheme for the three-phase grid-connected PV system is illustrated in Fig. 3. This control strategy consists of three distinct blocks with different hierarchies and their own control objectives, namely an external, middle and internal level [4].

3.1. *External level control*

The external level control (left side of Fig. 3) has the goal of rapidly and simultaneously controlling the active and reactive

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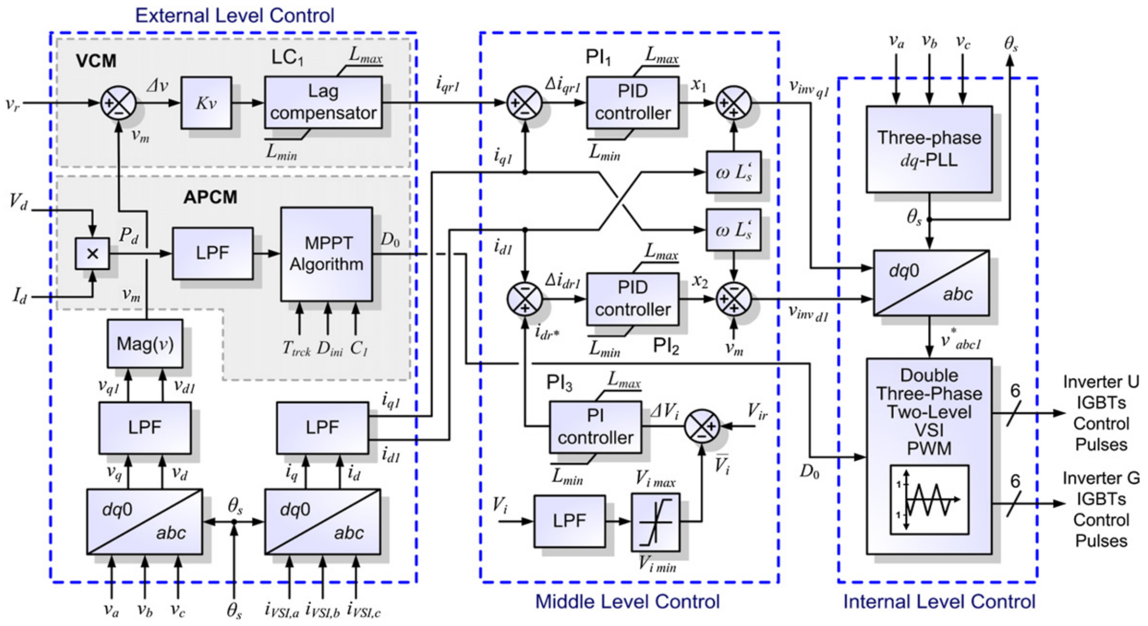

Fig. 3 – Control scheme of the three-phase grid-connected solar PV generation system.

power exchange between the PV system and the utility grid, through an active power control mode (APCM) and a voltage control mode (VCM), respectively.

The standard control block of major distributed energy resources is the VCM and consists of a voltage-droop strategy used to modulate the reactive component of the VSI output current, i_{q1} aiming at controlling the voltage at the point of common coupling (PCC) of the PV system to the distribution grid. This reactive power control loop employs a standard proportional-integral (PI) controller with droop characteristics (becoming the phase-lag compensator LC_1) for enabling a stable fast-response operation with more devices shunt-connected to the same feeder. In fact, this reactive power is locally generated exclusively by the inverter and can be controlled simultaneously and independently of the active power provided by the PV array.

On the other hand, the main purpose of a grid-tied solar PV system is to transfer the maximum available power into the electric system. In this way, the APCM aims at continuously matching the active power to be injected into the electric grid with the maximum instant power capable of being generated by the PV modules, independently of the reactive power generated by the VCM. To this aim, the PCS and its controller must ensure the instantaneous energy balance among all the PV components. With this objective, an indirect approach which is very efficient and robust in tracking the maximum power point of solar PV systems is implemented.

The maximum power point tracking (MPPT) strategy proposed is based on directly adjusting the shoot-through duty ratio of the cascaded Z-source inverter and consequently the PV array voltage, according to the result of the comparison of successive output power measurements. The control algorithm uses a “Perturbation and Observation” (P&O) iterative method widely used in solar photovoltaic and thermal applications with good results [10].

3.2. *Middle level control*

The middle level control makes the expected output to dynamically track the reference values (i_{dr1} and i_{qr1}) set by the prior external level. This control, which is shown in Fig. 3 (middle side), implements a full decoupled current control strategy of the inverter in the synchronous-rotating *dq* reference frame. To this aim, a linearization of the state-space averaged model of the Z-source VSI in *d-q* coordinates (described in-depth in [11]) is employed to design a voltage cross-coupling elimination feed-forward arrangement with two conventional PI controllers (PI_1 and PI_2). In addition, another PI controller (PI_3) is used in order to eliminate the extra coupling resulting from the DC capacitors voltage V_i dual Z-source inverter as much in the DC side as in the AC side of the inverter. This is employed in order to eliminate the steady-state voltage variations at the DC bus, by forcing the instantaneous balance of power between the DC and the AC sides of the dual Z-source inverter.

3.3. *Internal level control*

The internal level (right side of Fig. 3) is responsible for generating the switching signals for the twelve IGBTs of the three-phase three-level dual Z-source inverter, using a phase-shifted-carrier (PSC) PWM scheme based on [9]. Using this PSC approach, the carrier-reference comparison is first used to produce an appropriate state sequence for controlling the upper VSI bridge (labeled as inverter U in Fig. 3) in the dual inverter, while the negation of the references and the same carrier are compared to produce another sequence for driving the lower VSI bridge (labeled as inverter G). The combined dual inverter output then gives the correct voltage average with three-level switching and the appropriate off intervals inserted for buck/boost control. This level is also composed of a line synchronization module, which uses a phase locked

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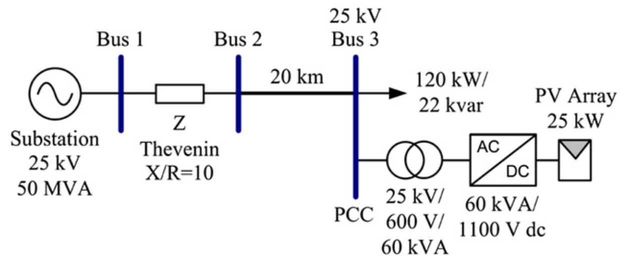

Fig. 4 – Test power distribution system with proposed PV solar system.

loop (PLL) designed in the dq frame. This circuit is a feedback control system used to automatically synchronize the VSI carrier-based switching pulses; through the phase θ_s, with the positive sequence components of the AC voltage vector at the PCC.

4. Digital simulation results

In order to investigate the effectiveness of the proposed developments, digital simulations were implemented using SimPowerSystems of MATLAB/Simulink environment [12]. For validation of both control strategies, i.e. APCM and VCM, two sets of simulations were performed using the test distribution system sketched in Fig. 4. Under this scenario, a 25 kV/50 MVA

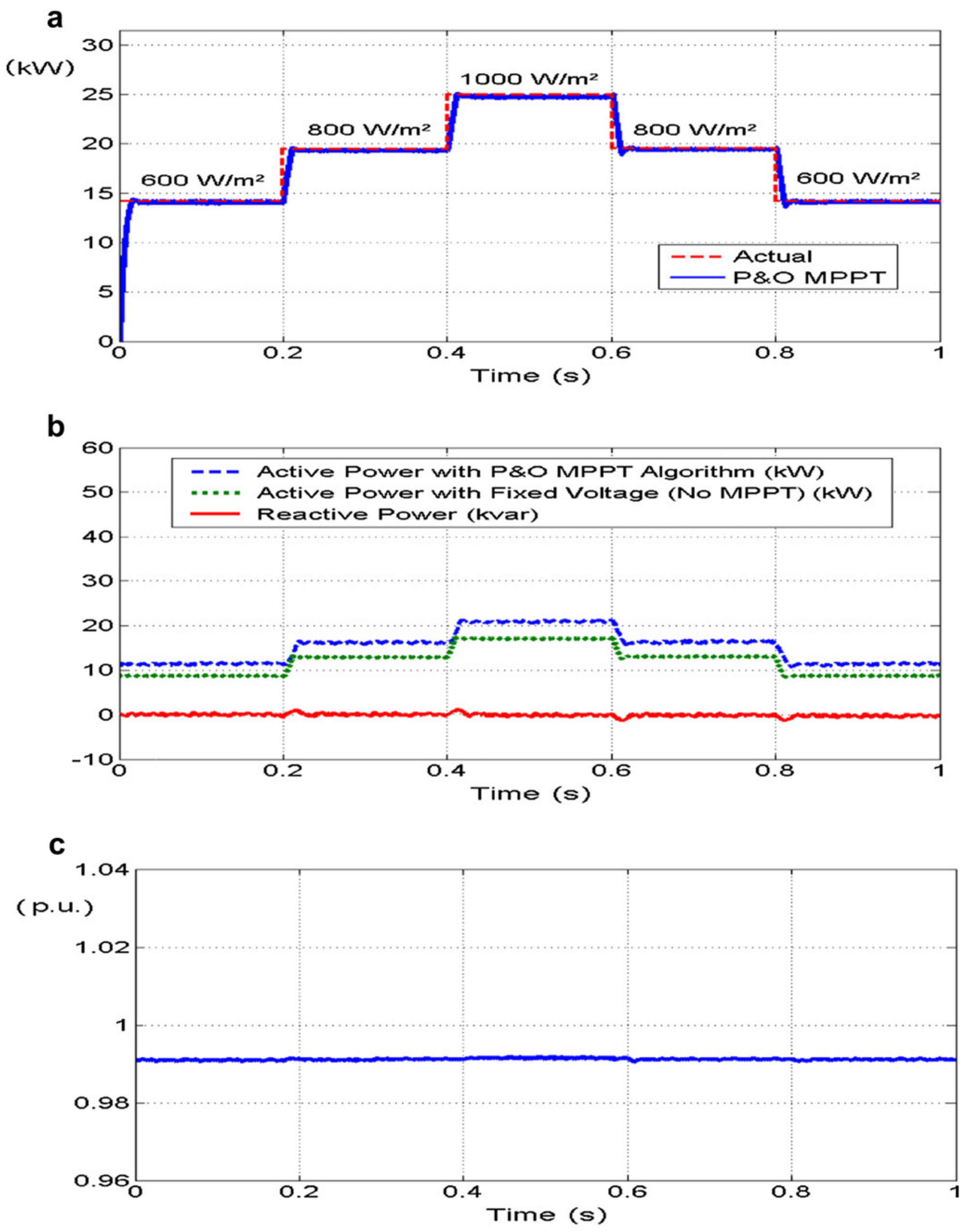

Fig. 5 – Simulation results for active power exchange with the utility grid (APCM): (a) PV system total absorbed solar radiation and output power. (b) Inverter active and reactive power. (c) PCC (bus 3) terminal voltage.

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distribution utility feeds a 120 kW/22 kvar load via a 20 km line. The PV array consists of 10 strings of 50 Solartec KS50 modules, making up a peak installed power of 25 kW, linked to a 60 kVA three-level cascaded Z-source inverter. The connection of the VSI to the utility grid is made through a 600 V/25 kV step-up transformer.

Simulations depicted in Fig. 5 show the case with only active power exchange with the utility grid, i.e. only the APCM is activated all the time. The solar radiation is forced to vary quickly in steps every 0.2 s as described in Fig. 5(a); thus producing proportional changes in the maximum power that can be drawn from the PV array (MPP actual power shown in red dashed lines). The true maximum power point for each solar radiation condition is given by the actual produced power, which is rapidly and accurately tracked by the P&O MPPT method (blue solid lines). As can be noted from Fig. 5(b), all the active power generated by the PV array is injected into the electric grid through the three-level cascaded Z-source inverter, except losses, with very small delays in the dynamic response (blue dashed lines). It can also be seen the case with fixed voltage control of the PV array, i.e. with no MPPT control (green dotted lines). In this case, the power injected into the electric grid is much lesser than with MPPT, about up to 25% in some cases. Eventually, no reactive power is exchanged with the electric grid since the VCM is not activated (shown in red solid lines). In this way, as can be observed in Fig. 5(c), the instantaneous voltage at the PCC to the AC grid is maintained almost invariant at about 0.99 p.u. (per unit of 25 kV). It is also verified a very low transient coupling between the active and reactive (null in this case) powers exchanged by the grid-connected PV system due to the full decoupled current control strategy in *d*-*q* coordinates.

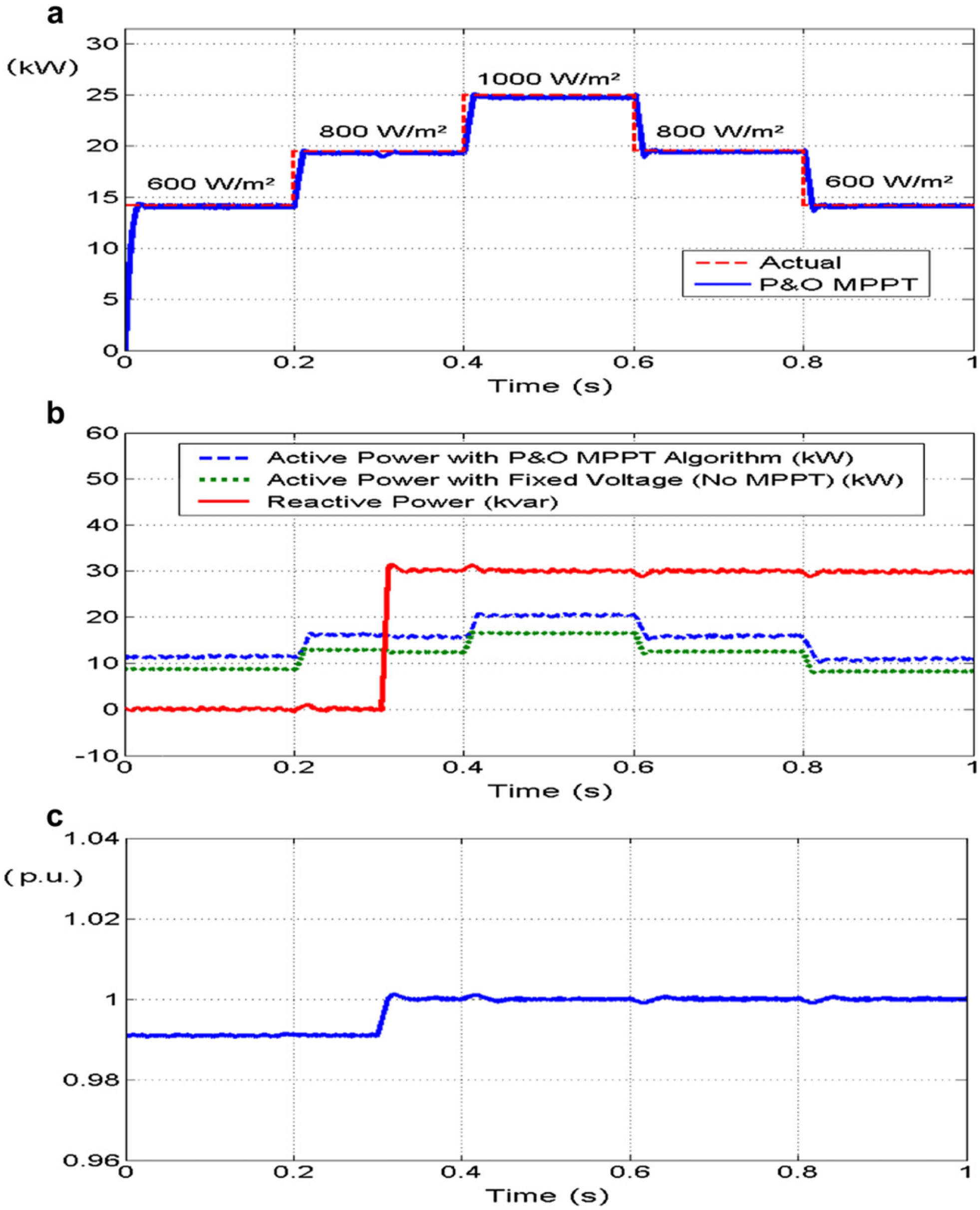

Fig. 6 – Simulation results for active and reactive power exchange with the utility grid (APCM and VCM): (a) PV system total absorbed solar radiation and output power. (b) Inverter active and reactive power. (c) PCC (bus 3) terminal voltage.

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Simulations of Fig. 6 show the case with both, active and reactive power exchange with the utility grid, i.e. the APCM is activated all the time while the VCM is activated at $t = 0.3$ s. The PV system is now subjected to the same previous profile of solar radiation variations, as described in Fig. 6(a). As can be observed, the maximum power for each solar radiation condition is rapidly and accurately drawn by the P&O MPPT method in the same way as in the preceding case study. This power is injected into the electric grid, except losses, as shown in blue dashed lines in Fig. 6(b). These losses are increased with the injection of reactive power, causing a slightly lower exchange of active power than the previous case studied with both controls of the Z-source inverter (with and without MPPT). As shown in Fig. 6(c), the rapid injection of almost 30 kvar of reactive capacitive power into the electric utility system (red solid lines) when the VCM is activated aims at controlling the magnitude of the instantaneous voltage at the PCC around the reference voltage of 1 p.u. (or 25 kV). Here it is also verified a very low transient coupling between the active and reactive power injected into the AC grid.

5. Conclusion

An improved power conditioning system and the control strategy of a three-phase grid-connected solar PV generation system to simultaneously and independently control the active and reactive power flow in the distribution grid has been studied. A real detailed model and a novel multi-level control scheme based on a full decoupled current control of the inverter in *d-q* coordinates with an MPPT control of the PV system were proposed. Dynamic system simulation studies demonstrate the effectiveness of the proposed developments. The fast response of power electronic devices and the enhanced performance of the control allow taking full advantage of the solar PV system as a DG system. The presented single-stage PCS topology with self-boost capabilities offers a simple and effective alternative over the conventional two-stage one for interfacing the PV devices with the AC utility grid. The advantages of this topology include a better power conversion efficiency, higher reliability, reduced harmonic distortion, inherent short circuit protection and a reduction of the volume and weight of the entire system, while permitting to use all standard PWM techniques. The improved capabilities of the grid-connected PV system to rapidly exchange active power with the electric system, and to generate locally reactive power, allows greatly enhancing the operation and control of the electric system.

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