Grid-Connected Photovoltaic System with Active Power Filtering Functionality

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Abstract: *Solar panels are an attractive and growing source of renewable energy in commercial and residential applications. Its use connected to the grid by means of a power converter results in a grid-connected photovoltaic system. In order to optimize this system, it is interesting to integrate several functionalities into the power converter, such as active power filtering and power factor correction. Nonlinear loads connected to the grid generate current harmonics, which deteriorates the mains power quality. Active power filters can compensate these current harmonics. A photovoltaic system with added harmonic compensation and power factor correction capabilities is proposed in this paper. A sliding mode controller is employed to control the power converter, implemented on the Compact RIO digital platform from National Instruments Corporation, allowing user friendly operation and easy tuning. The power system consists of two stages, a DC/DC boost converter and a single-phase inverter, and it is able to inject active power into the grid while compensating the current harmonics generated by nonlinear loads at the point of common coupling. The operation, design, simulation, and experimental results for the proposed system are discussed.*

Keywords: *frequency stability; grid integration; active power control; solar PV; frequency ride through; technical requirements; renewable control*

I. Introduction

Nowadays, with the increasing energy demand and its price increment, along with the scarcity of nonrenewable resources such as oil, natural gas, and coal, researchers are looking for new energy sources to meet the current energy needs. This has led to innovative solutions with desirable characteristics, such as greater efficiency, more power, and less pollution when generating energy . An important issue is power quality, which is influenced by the growing use of nonlinear loads by residential, commercial, and industrial consumers. This type of load generates high harmonic currents that interact with the grid impedance, causing harmonic voltages which affect all users connected to the same point of common coupling (PCC). Among the problems caused by the presence of harmonics are distortion of the AC mains voltage within the facilities, high currents flowing through the neutral conductor, overheating of transformers and conductors, poor operation of switches and fuses, erroneous operation of electronic equipment, life reduction in incandescent lamps, resonance risk in fluorescent lamps, and overheating of rotating machines. Active power filters have been proposed to compensate the current harmonics. Although they provide a good compensation system, their high cost is a considerable disadvantage. The growth of distributed generation (DG) has been favored by the use of renewable energies. The main power conversion stage in a DG system is the inverter, which is very flexible from a control point of view. This flexibility allows exploration of the possibility of injecting active power to the grid from a photovoltaic (PV) system while compensating current harmonics. Some papers have proposed the use of multifunctional inverters. Researchers in proposed the use of resonant tanks which are capable of effectively removing selected harmonics, but many resonant tanks are needed to remove the number of harmonics. Instantaneous reactive power theory has also been used in. However, this is only applicable to three-phase systems. In, the synchronous reference frame theory is used, usually applied to three phase systems, but it requires virtual signals when used in single-phase systems. In this paper, a PV system with active power filtering functionality and a controller based on sliding mode is analyzed, implemented, and tested. The authors have previously presented the simulation results of this proposal in, adding now experimental results, discussion on implementation issues, and a complete design and analysis of the system, which corroborates the conclusions of the previous work. The system consists of a single-phase two-stage converter. This converter is able to inject both active and reactive power and, additionally, to compensate the harmonic currents at the PCC. The sliding mode control brings the advantage of easy implementation with few computational resources compared to other techniques discussed above. In addition, it does not need an independent control loop as in to generate the reference signal. The paper is organized as follows: the power stage, the controller, and implementation are described, the simulation and experimental results are then illustrated, and finally, the conclusions are given.

2. Work Bench and Multifunctional System

The power stage consists of a DC/DC boost converter, an energy storage capacitor, a full-bridge single-phase inverter, and an output inductor connected to the grid (Figure 1). The switching devices used are a new generation of silicon carbide (SiC) metal-oxide-semiconductor field-effect transistor (MOSFET). The digital platform for the controller implementation is the Compact RIO from National Instruments Corporation (NI), together with LabVIEW software, which allows a flexible visual programming environment. modulation (PWM) pattern, in order to control the injected current to the grid. 2.1.1. Modelling the Power Stage. Considering the above simplification, the model of the system is

where iL is the inductor current, vc is the capacitor voltage, iPV represents the energy provided by the PV panels and the boost converter, ux is the control signal for switch Sx (1 = on, 0 = off), and vs is the AC mains voltage. The switches of the same branch are complementary; hence, For a model of the PV panel, see that proposed in. Design of the Power Stage. The capacitor is calculated considering the stored energy and the low-frequency component of the capacitor voltage ripple. The following equation is first used: where ΔE is the energy stored in the capacitor and vcf and vco are the capacitor voltages due to the ripple. The low frequency of the capacitor voltage ripple is twice the grid frequency. Considering that the stored energy handled by the system in each half of the AC mains period is 10% of the nominal output energy and that the capacitor voltages due to the ripple are vcf = vc + Δvc /2 and vco = vc – Δvc /2, is obtained C = 0 1 P 2vcΔvc f o , where Δvc is the desired ripple at the capacitor voltage, f o is the AC mains frequency, and P is the nominal output power. If vc = 250 V, f o = 60 Hz, P = 200 W, and Δvc = 1%, a value of C = 266 µF is obtained. It is approximated to the next highest commercially available value of 330 µF. For practical purposes, an electrolytic type capacitor was selected. The output inductor can be calculated with where ΔIL is the desired current ripple at the inductor, f s is the switching frequency of the inverter, VL is the voltage at the inductor, and D is the equivalent duty cycle of the inverter. Considering a worst-case design for the duty cycle, the zero crossing the grid voltage, a duty cycle of D = 0 5 was selected. If f s = 90 kHz, VL = 250 V, and an allowed current ripple ΔIL = 10%, a value of L = 3 96 mH is obtained. The design of the DC/DC boost converter can be calculated as a classical one, so it is not discussed in this paper. 2.2.1. Controller Stage. There are several MPPT algorithms reported in the literature that can be used for the DC/DC boost converter. A classic perturb and observe (P&O) method has been used in this work. For the inverter, a sliding mode control has been considered. It provides advantages like stability at large variations in load and voltage, robustness, good dynamic response, and easy implementation. The sliding mode controller is based on the theory of variable structures, so power converters are good candidates for this type of control, since they naturally operate in this way. The controller design begins with the definition of a sling surface, toward which the system must be attracted and must remain in it . The sliding surface can be a line or a plane in the generalized form. The conditions of existence and stability of the sliding mode control assure its proper operation Since the converter is intended to operate as an active power filter in addition to the power injection, the grid current is must be sinusoidal and in phase with the voltage source vs, regardless of the existing nonlinear loads connected at the PCC at the grid. Then, the AC current must be is = kvs, 6 where k determines the actual power demanded by the load plus the energy available at the PV panels. The proposed sliding surface is σ = is − kvs, 7 and the control laws considered are u1 = 1, for σ > 0, 0, for σ < 0, u3 = 1, for vs < 0, 0, for vs > 0 8 2.3. Existence of the Sliding Mode. The existence condition ensures that the equation system will be maintained in 2.4. Other Controller Blocks. For the proper operation of the system, other important control blocks must be taken into account, that is, the MPPT algorithm, the grid synchronization algorithm, and the voltage reference generator to control the capacitor voltage. The constant k for the control of the capacitor voltage is determined by a PI controller, as in. To ensure a good steady-state operation of the system and thus a high-power factor, this controller is tuned for a slow response. The SOGI-FLL is considered for the synchronization with the grid. This algorithm is capable of generating a good reference under distorted grid conditions. Finally, other blocks, like blanking time and protections, are considered in the final implementation. Digital Platform. As mentioned before, the platform considered for the control implementation is the Compact RIO from NI, together with the LabVIEW visual programming software. There have been programmed system protections and controllers for the entire system. Figure 3 shows the control panel. The user can select several waveforms to be graphed in real time. Also, the FFT can be obtained, by selecting the appropriate tab on the control panel In some of the controllers implemented are shown. Specifically, the MPPT algorithm based on the P&O method is shown in , and the SOGI-FLL controller employed for the synchronization with the grid As part of the protections, overvoltage and overcurrent detection is included, but the blanking time of the inverter branch is also included in the program.

3. Simulation and Experimental Results

The system shown in Figure 1 was numerically simulated and physically implemented. The PSIM software was selected for simulations because of its ease of use and versatility. It also includes models for the PV panels. For the implementation of the switches, SiC devices were used. the parameters considered for the system. The nonlinear load considered is a traditional single-phase full-bridge diode rectifier plus a capacitive filter; the total harmonic distortion of this current is above 100%. 3.1. Simulation Results. The steady-state operation of the proposed system is illustrated. In this test, the load demands a high harmonic current content and the PV panels deliver more power than that absorbed by the load, so energy is injected to the grid. the current demanded by the nonlinear load is shown the low distorted grid current can be observed; in this case, it should be noted that this current is 180 degrees out of phase with the load current. the inverter current is shown, where it can be observed that it is injecting both active power and harmonic currents. The power factor at the PCC is 0.99. The operation of the system without nonlinear load In this case, the converter operates as a traditional grid-connected PV system. Only active power is injected into the grid. The current is 180 degrees out of phase with the grid voltage. Additionally, the proposed system has the advantage of operating as a conventional active filter,. In this case, the power from the PV panels is null. the distorted load current can be observed the low distorted grid current is shown, which is in phase with the grid voltage. the compensating current from the inverter can be observed. Experimental Results. The steady-state operation of the proposed system is shown in Figure 8. In this test, the load demands a high harmonic current content and the PV panels provide more power than that absorbed by the nonlinear load, so energy is injected to the grid. At the top of the figure, the high distorted current demanded by the nonlinear load is shown (THD = 164%). At the bottom of the figure, the low distorted grid current can be observed (THD = 4.34%). Note that this current is 180 degrees out of phase with the nonlinear load current, as expected. At the center of the figure, the inverter current is shown, where it can be observed that it is injecting both active power and harmonic current components. The power factor at the PCC is 0.99. The operation of the system without load In this case, the converter operates as a traditional grid-connected PV system. Only active power is injected into the grid. The current is 180 degrees out of phase with the grid voltage. Additionally, the proposed system has the advantage of operating as a conventional active filter, as shown in Figure 10. In this case, the power from the PV panels is null. At the top of the figure, the distorted load current can be observed. At the bottom of the figure, the grid current is shown, which is in phase with the grid voltage. At the center of the figure, the compensating current of the inverter can be observed.

4. Conclusion

Grid-connected PV systems usually inject active power energy to the grid. They are mainly used to avoid the dependence of fossil fuels. Since the power stage used in grid connected applications is an inverter, the functionality of this stage may be increased, acting as an active power filter and a power factor corrector. In this paper, a multifunctional grid-connected PV system is analyzed and tested. The power stage consists of DC/DC boost converter and a single-phase inverter. The converter's protections and controllers are implemented in the Compact RIO digital platform from NI, which allows user friendly and easy tuning of the system. A sliding mode controller is employed that permits good operation in different modes: when the system delivers energy and compensates harmonics, when it only injects energy, or when it only acts as an active power filter. The operation, design, and implementation of the system are presented. The simulation and experimental results confirm the feasibility of the proposal.

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