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Modeling and testing of two-stage grid-connected photovoltaic micro-inverters

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ABSTRACT

In this paper, the characteristics, design and control parameters of a 200 W micro-inverter, consisting of two conversion stages are presented; the first one is implemented by a push-pull converter, which provides galvanic insulation and adjusts the DC voltage from the photovoltaic panel to an appropriate voltage with the implementation of a current injected control. The second stage corresponds to a full bridge inverter SPWM with an average current control, which injects energy from the push-pull converter to the grid; it is synchronized with the grid and delivers the maximum power provided by the photovoltaic panel. Power is extracted through the Maximum Power Point Tracking Technique (MPPT). The micro-inverter is simulated and its behavior to irradiance variations is observed. Finally, the transient and stable responses of the implemented micro-inverter are presented. Stable and slightly underdamped output signals (voltage and current) are obtained under current panel variations.

1. Introduction

Currently, due to the increment of energy consumption, new generation sources from renewable energies such as solar energy, wind energy, fuel cells, among others, are being promoted [1]. Solar energy is one of the most promising and the renewable energy with the biggest impact on the future.

The technological developments of the last decades have led to a significant reduction in the costs of power electronic equipment (converters), digital processing equipment and photovoltaic panels, with the respective improvement in processing capabilities and a better power management. This has allowed the gradual imposition of photovoltaic systems.

Photovoltaic (PV) systems can operate in two ways; the first way is connected to the electric grid [2], where the aim is to deliver all the power from the panels to the grid. The second way is related to remote systems [3], where the key is to feed local loads offering appropriate power quality and reliability conditions.

Today, grid-connected photovoltaic systems are being used in many countries as complementary generation systems to the conventional generation [4], [5]. These systems in comparison with other ones based on renewable energies, have presented an accelerated growth from 40 GW installed in 2010 to 177 GW installed in 2014 [1]. Small-scale generation and installation of large photovoltaic parks with high generation capacity, usually connected to the medium voltage distribution grid, are among the most common applications.

PV systems are connected to the electric grid through converters. There are three basic topologies for connection of electronic converters to the power grid [6]. These are central inverters [7], string inverters [8] and micro-inverters [9].

The micro-inverter is characterized by using a single photovoltaic panel for each power converter equipment, so each converter manages between 50 W peak and 400 W peak. That topology improves the energy extraction from the panels since each micro-inverter has its own MPPT.

It is possible to find in the literature several proposals of micro-inverters, some of them are based on Boost topologies [10], with the problem of lack of insulation between source and load, or Flyback topologies [11,12], when managing a small power. However, when the management of a higher power and the provision of system insulation are required, Push-pull topology is the choice of suitable

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converter, since it has the advantage of operating switches with work cycles below 0.5, minimizing the ripple of the input current. Additionally, allows working with high output voltage levels with the consequent conduction losses reduction [13].

Based on the above, this paper focuses on the modeling and designing of the controllers for the two conversion stages of the 200 W micro-inverter. The first stage consists of a Push-pull converter, which provides galvanic insulation between the panel and the load. This converter is responsible for following the reference voltage imposed by the MPPT, which in this case uses the Perturb and Observe algorithm [14]. The controller implemented for the Push-pull was a current injection control (CIC) with double loop, the inner loop is a current loop which allows to control the peak current in each transistor in order to avoid saturation of the transformer, outer voltage loop was implemented through a PI controller, which sets the reference of the current loop and regulates the input voltage to the converter following the reference imposed by the MPPT.

This in order to deliver the maximum power available in the panels to the second conversion stage, which consists of an inverter that operates with Pulse-Width Modulation (PWM). The inverter has the functions of synchronizing its output current signal with the grid voltage through a Synchronous Reference Frame Phase-Locked Loop (SRF-PLL) [15], regulating the voltage of the DC input bus, and delivering the energy of the panels to the grid through the Push-pull. An average current controller with double loop is used, the inner loop is a current loop implemented with a controller P + Resonant, which have the advantage of applying a high gain to the frequency of the reference signal in order to counteract the grid disturbances, and an outer voltage loop implemented through a PI controller.

The paper has been organized as follows: Section 2 and 3 describe the implemented micro-inverter and the used control structure, respectively. Section 4 presents the modeling and control for the conversion stages of the micro-inverter and in Section 5 the operation of each stage is validated through the simulation performed in PSIM [16]. In Section 6 experimental results are shown. Finally, conclusions are presented.

2. Description of the implemented micro-inverter

Fig. 1, the selected two-stage conversion scheme to implement the micro-inverter is observed.

In the first stage, a Push-pull DC-DC converter was selected, which is responsible for converting the energy from the panel (200 W @ 24–37.6 V) and delivering it to the inverter at a higher voltage (200 W @ 380 V). Push-pull converter only needs two power transistors to operate in comparison with the Bridge DC-DC converter, and does not need a capacitive voltage divider in order to withstand high RMS currents when compared with the Half-Bridge DC/DC converter. However, the main problem with the Push-pull topology is that the transistors have to withstand high input voltages, which is not a problem for this application, since the converter operates with photovoltaic panels at low voltage. As mentioned in the Introduction, Push-pull topology provides high frequency galvanic insulation, therefore the transformer used is small in comparison with the transformers that operate at low frequency.

When adequate voltage levels are achieved using the Push-pull, the DC signal is converted to an AC signal through an H-Bridge inverter with Bipolar Sinusoidal Pulse Width Modulation (SPWM) [17]. This aims to deliver the energy from the panels to the grid. In Table 1 the main parameters of the implemented micro-inverter are presented.

3. Description of the control structure of the micro-inverter

Fig. 2 shows the complete control structure proposed for the micro-inverter. The goal of the Push-pull converter is to regulate the output current and the input voltage. This input voltage has as reference the signal established by the MPPT selected technique. The type of control chosen for this application is the current injected control (CIC) [18]. This in order to prevent the saturation of the transformer due to small differences in the switching times of the electronic switches, which results in a significant difference of peak current in each transistor. Although the regulation of the input voltage to the converter using a control loop may seem obvious, it is a relatively recent practice as described in Refs. [19,20].

The second conversion stage comprises a Full bridge inverter SPWM, which aims to inject energy to the grid from the Push-pull converter and regulate the DC input voltage to the inverter. Since a double control loop is needed, an Average Current-Mode Control (ACC) will be used [21]. This control has the advantage of presenting less distortion than the CIC control when operating in AC and providing better response (flatter) of the transfer function for the current in the inductor on the reference voltage, which is ideal when the operation of the inverter as a regulated current source is required.

Since the inverter must be able to deliver the maximum power extracted from the panel, it is necessary that the output current signal of the inverter be in phase with the grid voltage signal. One way of achieving this objective is by implementing a PLL. This scheme has been widely used in three-phase systems for synchronization of the current with the grid voltage by using a Synchronous Reference Frame (SRF) [22]. For single-phase systems, it is necessary the creation of a quadrature component of the grid voltage signal, this in order to apply the Inverse Park Transformation. For this application, the PLL in the Synchronous Reference Frame (SRF- PLL) [15] has been developed following the steps indicated in Ref. [23].

For the design of the controllers, it is necessary to identify the transfer functions of the variables to control. The transfer functions are extracted from the dynamic models obtained from the Push-pull and from the inverter. The technique used for this purpose is the modeling of the PWM switch [24], which has the advantage of modeling the converters, operating in continuous conduction mode and discontinuous conduction mode, obtaining close to reality results in comparison with other methods [17], [25]. In the next section, the mathematical models to obtain such transfer functions are presented.

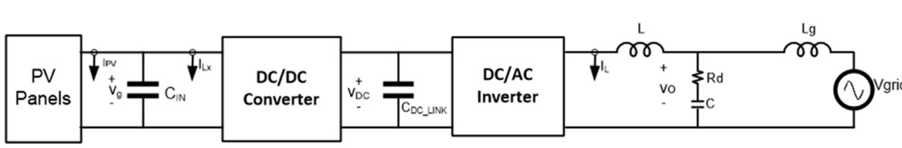

Fig. 1. Two-stage conversion scheme used in the implemented micro-inverter.