Electrical Power and Energy Systems 57 (2014) 250–260

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Power control for grid connected applications based on the phase shifting of the inverter output voltage with respect to the grid voltage

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ARTICLE INFO

Article history:
Received 13 May 2013
Received in revised form 4 November 2013
Accepted 1 December 2013

Keywords:
Grid connected photovoltaic inverter
Power control
Phase shifting
Digital SPWM control

ABSTRACT

In photovoltaic (PV) systems connected to the grid, the main goal is to control the power that the inverter injects into the grid. According to the grid demands, injected power does not only include the control of the active power, but also the control of the injected reactive power. This paper presents, a digital control strategy based on the phase shifting of the inverter output voltage with respect to the grid voltage, in order to control the power factor with a minimum number of Digital Sinusoidal Pulse Width Modulation (DSPWM) patterns and for a wide range of the inverter output current. This proposed method has been described, simulated and validated by experimental results.

The proposed control strategy requires few hardware and computational resources. As a result, the inverter implementation is simple, and it becomes an attractive solution for low power grid connected applications.

1. Introduction

Generally, the grid-connected photovoltaic (PV) system extracts maximum power from the PV arrays. The maximum power point tracking (MPPT) technique is usually associated with a DC–DC converter. The DC–AC converters inject sinusoidal current into the grid controlling the power factor. Therefore, the inverter converts the DC power from the PV generator into AC power for grid injection. A further concern in the operation of grid-connected system is that inverter topology design is often limited to the feeding of active power to the AC system without injecting reactive power. This design may deteriorate the power factor of AC source. To cope with this issue, the control of the active and reactive power supplied by photovoltaic systems through the inverter receives an increased interest nowadays [1,2].

Some key points have been identified in which significant improvements can be carried out in the design and implementation of the inverters connected to the grid: reduction of harmonic distortion, elimination of the DC component injected into the connected grid [3–10], and the digital implementation of the control [11–13]. Another very important aspect of the systems connected to the grid is to select a proper power factor according to the grid demands: active or reactive power. The most efficient systems are those which allow variation in the active and reactive power injected into the grid, depending on the power grid requirements [14,15].

The power quality injected into the grid and the performance of the converter system depend on the quality of the inverter current control. Moreover, the use of pulse width modulation (PWM) in conjunction with closed-loop current control [16–19], allows a sinusoidal input current to be achieved with a total harmonic distortion (THD) below 5% as suggests the International Standard IEEE Std 929-2000 [3]. Most of the control strategies were made based only to control the active power and the current injected into the grid with a power factor equal to the unity [20–26].

The proposed control strategy is capable to control, not only the current injected into the grid, but also the power factor, with a minimum number of DSPWM patterns. Varying the power factor, within a certain range, the injected reactive power (inductive or capacitive) can be dynamically changed and controlled, in order to obtain the high reliability of the inverter. The new proposed strategy control break the limitations of existing grid-connected system where the inverter topology is designed to supply only active power to the grid without injecting reactive power.

The basic idea of the control is to use a minimum number of PWM patterns previously calculated and tabulated applied to a constant DC bus voltage. Acting on the phase shift of the inverter output voltage as control parameter, the output current amplitude and the power factor can be controlled, and therefore the magnitude of the power injected to the grid, both active and reactive power.

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0142-0615/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijepes.2013.12.009

This paper describes the control strategy based on the phase shifting of the inverter output voltage with a minimum number of DSPWM patterns, this is followed by the presentation of the proposed control structure, and next the digital implementation is detailed. The simulation results are further discussed and finally, experimental results have been carried out demonstrating the validity and performance of this method.

2. Power factor and total harmonic distortion

In photovoltaic system connected to the grid, the current waveform injected into the grid is not a sinusoidal. The current quality depends on the harmonics contents. The real power factor can be calculated using the following expression [26]:

$$\mathrm{PF} = \frac{1}{\sqrt{1+\mathrm{THD}^2}} \cdot \mathrm{DPF} \quad (1)$$

where PF is the power factor; THD is the total current harmonic distortion; DPF is the displacement power factor; The displacement power factor (DPF) is equal to cos φ (DPF = cos φ).

Substituting DPF with cos φ in Eq. (1), it can be obtained:

$$\mathrm{PF} = \frac{1}{\sqrt{1+\mathrm{THD}^2}} \cdot \cos\varphi \quad (2)$$

To measure the distortion of the output current, the total harmonic distortion, THD is often used. Total Harmonic Distortion is a measure of the proportionality between the fundamental and the sum of all other frequencies in the current waveform. The THD content of the current injected into the grid is reported lower than 5%. Eq. (3) defines the THD used here:

$$\mathrm{THD} = \frac{\sqrt{I_{\mathrm{out}}^2 - I_{\mathrm{out1}}^2}}{I_{\mathrm{out1}}} \quad (3)$$

where I_{out} is the total current; (RMS) is the Root means square and I_{out1} is the fundamental current (RMS).

The main objective of this work is to develop a control strategy based on Eq. (2), where the total harmonic distortion is equal or near to zero (THD ≈ 0), in order to control the power factor, PF, with a minimum number of DSPWM patterns for a wide range of power injected into the grid, by shifting the phase of the inverter output voltage with respect to the grid voltage. In the following it is shown the development of this approach.

3. Inverter control description

In Fig. 1, is shown an electrical scheme of the single phase inverter connected to the grid in order to explain the key of the output current control of the inverter. In addition, an active and reactive power can be controlled.

The main specification of the inverter connected to the grid is that the current must be injected from a PV panel with a power factor within a certain range [4]. The equivalent electrical circuit is shown in Fig. 2.

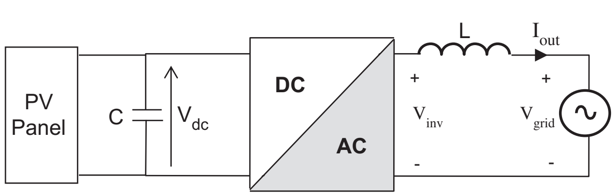

Fig. 1. Electrical scheme of the single phase inverter connected to the grid (inductive coupling).

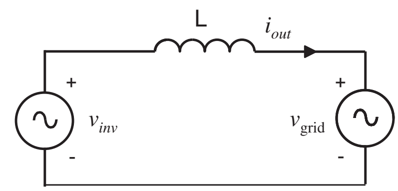

Fig. 2. Equivalent electrical circuit of the inverter connected to the grid.

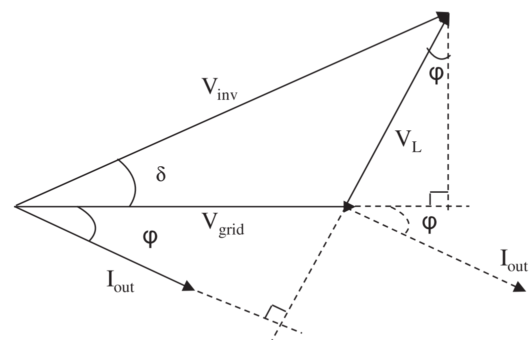

Fig. 3. Phase diagram with V_{inv}, V_L and V_{grid} voltage.

In order to explain the circuit characteristics, in Fig. 3, is represented the phase diagram for the RMS values of the fundamental component of the inverter output voltage (V_{inv}), the fundamental component of the inverter output current (I_{out}), the fundamental component of inductance voltage (V_L) and the fundamental component of the grid voltage (V_{grid}).

The phase shift between the grid voltage and the fundamental current component of inverter output current is represented by angle (φ). Moreover, the phase shift between the grid voltage and the inverter output voltage is represented by angle (δ). V_{inv} and I_{out} can be expressed as:

$$v_{\mathrm{in}} = \sqrt{2}\, V_{\mathrm{inv}} \angle \delta \quad (4)$$

$$i_{\mathrm{out}} = \sqrt{2}\, I_{\mathrm{out}} \angle \varphi \quad (5)$$

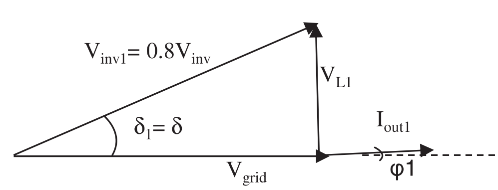

Fig. 4. Phase diagram with $V_{\mathrm{inv1}} = 0.8^{*} V_{\mathrm{inv}}$.

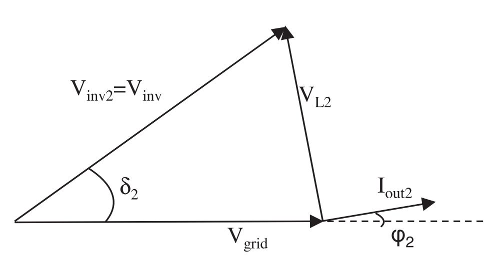

Fig. 5. Phase diagram with $\delta_2 > \delta$.