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New parameter for current-sensorless MPPT in grid-connected photovoltaic VSIs

Gamal M. Dousoky [a,*], Masahito Shoyama [b]

[a] Minia University, 61517, Egypt
[b] Kyushu University, 819-0395, Japan

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ABSTRACT

This paper a new quantity for current-sensorless power-angle-based MPPT for single-stage grid-connected photovoltaic voltage-source inverters (VSIs). The proposed tracker eliminates the use of the current sensor by using only the voltage sensor: The current sensor is substituted with a new quantity, which is the sine value of the power-angle (the phase angle between the inverter output voltage and the power grid voltage). A theoretical proof for this quantity is developed and is provided. Then the controller is designed and implemented using a digital signal processor (DSP). Algorithms are configured on a fixed point DSP TMS320F2812. Moreover, a breadboard has been built-up for testing the use of the proposed tracker with a single-stage grid-connected photovoltaic voltage-source inverter. Both of simulation and experimental results show that the proposed tracker attains a satisfactory performance. On the other hand, it requires a good control tool to accurately achieve the arithmetic calculations. A substantial part of the manufacturing cost and complexity burdens of MPPTs involves the use of current sensors. Considering this investigation saves cost, decreases complexity, and therefore increases the power density of the MPPTs.

1. Introduction

Photovoltaic (PV) panels' output power is highly depending on the atmospheric conditions: Solar radiation and temperature. Therefore a maximum power point tracker (MPPT) is an essential part of any PV system to extract the maximum available power from the PV panels (Dousoky, 2010; Dousoky et al., 2012a,b). Research trend in MPPTs is generally moves into two main directions: improving the performance of the tracker (Abdelsalam et al., 2011; Mei et al., 2011; Femia et al., 2005), and reducing its cost and complexity (Esram and Chapman, 2007; Urayai and Amaratunga, 2011; Pandey et al., 2007). Therefore, a satisfying tradeoff between both directions has to be made to ensure good performance at a reasonable cost. Operating principles of numerous PV MPPT techniques are extensively overviewed in Koutroulis and Frede (2015).

Single-stage grid-connected systems provide many advantages such as simple topology, high efficiency, high power density, and lower cost (Jain and Agarwal, 2007; Gonzalez-Espin et al., 2012; Kjaer et al., 2005; Azri et al., 2015; Jain and Singh, 2015). Comprehensive overviews of PV grid-connected systems are provided in Kerekes et al. (2015). Inverters must guarantee that the PV module(s) is operated at the MPP, which is the operating condition where the most energy is captured.

The power injection principle, described in Section 2, is usually used in short transmission line power transfer to enables active/reactive power control beside an MPPT function using a single-stage voltage source inverter (VSI) (Strzelecki and Benysek, 2008). The authors applied this principle to maximize the power produced by a grid-connected PV system in different schemes (Dousoky et al., 2013a,b). Furthermore, the authors introduced a dual-mode controller to improve the performance of maximum power point tracking in grid-connected photovoltaic inverters (Dousoky et al., 2013a,b). Their proposed method employs two independent control variables (load angle and inverter modulation index) into two control modes: Active power mode, and reactive power mode.

Simplifying PV systems and reducing their complexity, for the sake of low-cost, make such systems more competitive energy sources. In most of tracking algorithms, two sensors are necessary for periodic measurement of voltage and current (Xiao and

* Corresponding author.
E-mail address: dousoky@mu.edu.eg (G.M. Dousoky).

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Nomenclature

P_{ge}	active power
Q_{ge}	reactive power
δ	load angle, namely, the phase angle of the sinusoidal pulse-width modulation (SPWM) control signal (w.r.t. the power grid voltage phase angle)
m_i	inverter modulation index
E_{ge}	magnitude of inverter AC output voltage
e	actuating error
V_{PV}	PV panels output voltage
I_{PV}	PV panels output current
P_{PV}	PV panels output power
ΔP_{PV}	rate of change of the PV panels output power
$\Delta\delta$	step size perturbation for δ

Dunford, 2004). Hence, the PV power can be calculated and subsequently maximized. This paper proposes a current-sensorless tracker that eliminates the use of the current sensor, by using only the voltage sensor, as shown in Fig. 1. Getting rid of the current sensor has many merits such as saving cost, decreasing complexity, and increasing the efficiency and the power density of the tracker.

Digital controllers are flexible and attractive implementation tools. Their cost gradually decreases, and their speed is getting faster. Such competitive tools have made the application of many sophisticated control algorithms possible in this field (Xiao and Dunford, 2004; Dousoky et al., 2012a,b). The implementation of the proposed tracker has been accomplished by a fixed-point DSP.

The paper is organized as follows: Section 2 presents a theoretical framework and describes the proposed grid-connected PV system. Simulation results and digital implementation are addressed in Section 3. Section 4 provides the details of the experimental investigations and discussions. Finally, conclusions and future work are presented in Section 5.

2. Theoretical framework and description

2.1. Power injection principle

In the case of a connection of an alternate current (AC) generator to the power grid, the generator output is equal to the grid voltage and the generator is the source of active power (P_{ge}) and reactive power (Q_{ge}). Fig. 2 explains the power injection principle from a generator into the power grid (Strzelecki and Benysek, 2008), as an equivalent diagram of a grid-connected generation system shown in Fig. 1.

The active power, provided by the generator can be calculated as follows:

$$P_{ge} = E_{ge}V_{gr}\sin(\delta)/X_g \quad (1)$$

and the reactive power:

$$Q_{ge} = [(V_{gr})^2 - E_{ge}V_{gr}\cos(\delta)]/X_g \quad (2)$$

where the voltages are expressed in rms values.

If we have a system as shown in Fig. 1, the Photovoltaic output power can be calculated as follows:

$$P_{PV} = V_{PV} \times I_{PV} \quad (3)$$

Considering a fixed hardware setup (X_g = constant), constant power grid voltage (V_{gr} = constant), and at the same inverter modulation index (m_i = constant, which leads to $E_{ge} \propto V_{PV}$), the following proportionality is applicable:

$$P_{ge} \propto [V_{PV} \times \sin(\delta)] \quad (4)$$

Accordingly, to maximize the power injected into the grid (thus maximizing the PV output power, namely $P_{PV} \propto P_{ge}$), the current can be replaced by the sine value of the power-angle (sin (δ)). This is explained in the following section.

2.2. Current-sensorless MPPT algorithm

Incremental-conductance (INC) method (Hussein et al., 1995) is based on the fact that the slope of the PV array power curve versus voltage is zero at the MPP. The INC MPPT algorithm usually has a fixed iteration step size determined by the requirements of the accuracy at steady state and the response quickness of the MPPT. Thus, a tradeoff between dynamic and steady-state responses has to be investigated at the corresponding design.

The primary rules for INC MPPT algorithm are deduced as follows: the power curve of the PV module shows that the derivative of the PV module power P_{PV} with respect to its voltage is positive before reaching the MPP, zero at the MPP, and negative after passing the MPP as shown in Fig. 3. The derivation of P_{PV} is given in (5), which leads to the actuating error (e) in (6), as follows:

$$\frac{dP_{PV}}{dV_{PV}} \propto \left[\frac{d(V_{PV} \times \sin(\delta))}{dV_{PV}}\right] \propto \left[\frac{d(\sin(\delta))}{dV_{PV}} \times V_{PV} + \sin(\delta)\right] \quad (5)$$

$$\Rightarrow e = \frac{d(\sin(\delta))}{dV_{PV}} + \frac{\sin(\delta)}{V_{PV}} \quad (6)$$

Therefore tracking the maximum power point is achieved by watching the actuating error, then applying the following rule:

$$\left.\begin{array}{lll} e \geqslant 0 & \Rightarrow & \delta(n) = \delta(n-1) - \Delta\delta \\ e < 0 & \Rightarrow & \delta(n) = \delta(n-1) + \Delta\delta \end{array}\right\} \quad (7)$$

The schematic diagram of the proposed current sensorless MPPT is shown in Fig. 1(b).

2.3. Brief description of a single-stage grid-connected PV system

Fig. 1 presents a schematic diagram of the proposed single-stage grid-connected PV system. This system can be briefly described in the following points:

- The power-angle δ is employed to achieve MPPT: Extract the maximum available power from the PV panels.
- The control signals generator generates the reference signals at the desired δ and the desired m_i.
- The digital pulse-width modulator (DPWM) generates the gate signals corresponding to the reference signals and the internally-generated triangular wave.
- The synchronizing unit is employed to connect to the power grid only when the synchronization conditions are fulfilled.

3. Simulation results and digital implementation

To investigate the performance of the proposed tracker using the INC method, a simulation model is developed for the overall system (shown in Fig. 4). It consists of PV model, dc-ac six switches inverter, power grid, step-down transformer, and a controller. The controller employs ADC's, INC MPPT, reference signal generator, triangular generator, and SPWM. The INC MPPT is designed to track