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Assessment and control of a photovoltaic energy storage system based on the robust sliding mode MPPT controller

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ABSTRACT

The energy produced by the photovoltaic systems is very intermittent and depends enormously on the weather conditions. As the output characteristic of a photovoltaic (PV) module is nonlinear and changes with solar irradiance and the cell's temperature, its maximum power point (MPP) is not constant. Therefore, a maximum power point tracking (MPPT) technique is needed to draw peak power from the PV module to maximize the produced energy under varying conditions. This paper presents an assessment and control of a stand-alone photovoltaic system with battery storage using the robust sliding mode MPPT control for DC/DC boost converter operating in continuous conduction mode; under varying meteorological conditions. Simulation results are presented to verify the simplicity, the stability and the robustness of this control technique against changes in weather conditions.

1. Introduction

With the increasing demand for energy due to the indiscriminate use of electrical power by the people and industries, fossil energy reserves are becoming depleted; however, the consumption of this kind of energy causes severe pollution and also endangering human health and natural life. Energy shortages and the need for sustainable energy systems have enforced the search for energy supplies based mainly on renewable energy resources. Many renewable energy technologies today are well developed, reliable and cost competitive compared with conventional fuel supplied generators, in particular photovoltaic solar energy. Photovoltaic systems have been widely utilized in various applications (Ghosh et al., 2015; Lajouad et al., 2014), such as battery charging, water pumping (Hamrouni et al., 2009), and home power supply to convert the solar energy, as one of the main renewable energy sources due to its advantage direct electric power form, to electrical power through the semiconductor devices called photovoltaic cells based on photovoltaic effect (Boukenoui et al., 2016). Due to such advantages as easy maintenance, availability of sunlight and environmental friendly (Fattori et al., 2014; Mavromatidis et al., 2015; Rasool Mojallizadeh et al., 2016), the demand of PV power generation systems have been increased in recent years. On the other hand, high installation cost of PV systems and low efficiency during rapid changing in environmental conditions may restrict the extensive utilization. To increase the efficiency of such systems, various investigations have been carried out in three main areas as (i) designing sun tracking systems (Mousazadeh et al., 2009), (ii) implementing effective power converter topologies, and (iii) developing MPPT algorithms (Kamarzaman and Tan, 2014). The first two strategies are commonly adopted in designing and implementing the new PV systems, whereas developing MPPT schemes can be easily incorporated into the both new and installed systems. In fact, the MPPT problem is to adjust the PV operating point such that the PV power, delivered by the PV system, is maximized. In the presence of modeling errors, electrical noise, external disturbances, and model parameter variations, the characteristic curve of a photovoltaic solar cell, which is the fundamental element of the PV system, exhibits a nonlinear current-voltage characteristic and then designing an effective MPPT scheme is inevitable to ensure robust accurate tracking.

Many MPPT techniques have been proposed in the literature; in both stand-alone and grid-connected PV systems. Each MPPT technique has its advantages and disadvantages. Examples are the Perturb and Observe (P&O) methods Femia and et al., 2005, the Incremental Conductance (IC) methods Lin and et al., 2011; Safari and Mekhilef, 2011, ripple correlation (Esram and et al., 2006), short circuit current (Noguchi et al., 2002) and open-circuit voltage (Dorofte et al., 2005), the quadratic maximization method (Ko and Chao, 2012; Moradi and Reisi, 2011), the Artificial Neural Network method (Rai and et al., 2011), the Fuzzy Logic method (Kyoungsoo

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and Rahman, 1998), the genetic algorithm (Messai et al., 2011; Chaouachi et al., 2010; Zagrouba et al., 2010) and evolutionary algorithms which due to its ability to handle non-linear objective functions (Ishaque and Salam, 2011; Ishaque et al., 2011; Ishaque and et al., 2012; Salam et al., 2013), envisaged with the MPPT difficulties effectively. These techniques vary between them in many aspects, including simplicity, convergence speed, hardware implementation, sensors required, cost, range of effectiveness and need for parameterization. The P&O and IC techniques, as well as variants thereof, are the most widely used. The P&O is the most widely used algorithm due to the simplicity of implementation practically. Its main advantages are simple structure and ease of implementation, with both stand-alone and grid-connected systems. But it has limitations that reduce efficiency of MPPT. In the lower solar irradiance cases, it is difficult to determine the exact location of MPP, and the output power is oscillating around the MPP reducing the generated power. In literature, IC method was determined to operate with more efficiency under randomly generated conditions (Roman et al., 2006). However, the cost of IC method is high due to requirements of high sampling compliance and speed control as a result of complex structure (Libo et al., 2007). Classically, P&O and IC methods that are the most widely used techniques have two major disadvantages. In these methods, decision-making speed increases in proportion to the step size of error. However, higher error step size reduces the efficiency of MPPT. The second major problem is the direction errors under rapid atmospheric changes especially in P&O algorithm (Kazmi et al., 2009). In this paper, the sliding mode control is applied to track maximum power of photovoltaic system. The advantages of this control are various and important such as, high precision, good stability, simplicity, invariance, and robustness (Slotine and Li, 1991; Chiu et al., 2012). It has powerful ability for the control of uncertain systems; therefore, the controlled system with sliding mode exhibits robustness properties with respect to both internal parameter uncertainties and external disturbances (Rasool Mojallizadeh et al., 2016).

Removing some drawbacks of the previous works, the main contributions of this investigation are, (i) reducing the required sensors by estimating the output voltage by an adaptation mechanism, (ii) the bound of system uncertainties and environmental disturbances are not required to be known in the design procedure, and (iii) robust tracking performance is ensured, as shown analytically by using the Lyapunov stability theorem. The rest of this paper is organized as follows. The PV system description is presented in Section 2. Section 3 describes the robust MPPT method. In Section 4, the analysis based on the simulation results is conducted. The concluding remarks and some ideas for the future investigations are given in Section 5.

2. System description

The complete studied system is schematically shown in Fig. 1. In our analysis, we consider a photovoltaic module supplying a DC load, e.g. a battery through an adaptation stage considered by boost converter, driven by a MPPT assuming the maximum efficiency for the energy transfer. T and G are the input signals of the system, and are respectively the solar cell temperature (in K) and the solar irradiance (in W/m^2) on the surface of PV module.

2.1. Mathematical modeling of PV module

The direct conversation of the solar energy into electrical power is obtained by solar cells. And as the PV module is composed of group of cells, its model is based on that of a PV cell, associated in series and/or parallel. The equivalent circuit of the photovoltaic cell is shown in Fig. 2 (Yu et al., 2004; Cuce and Cuce, 2014; Picault et al., 2010). R_s: mainly due to losses by Joule effect through grids collection and to the specific resistance of the semiconductor, as well as bad contacts (semi conductor, electrodes). R_{sh}: Parallel resistance comes from the recombination losses mainly due to the thickness, the surface effects and the non-ideality of the junction.

The nonlinear current-voltage characteristic of a PV cell with 5 parameters is governed by the following equation, (Reisi et al., 2013; Zhao et al., 2015; Yıldıran and Tacer, 2016):

$$I_p = I_{ph} - I_d - I_{sh} = I_{ph} - I_0\left[\exp\left(\left(\frac{q}{aKT}\right)(V_p + I_pR_S)\right) - 1\right] - \left(\frac{V_p + I_pR_S}{R_{sh}}\right) \quad (1)$$

where

$$I_{ph} = [I_{SCR} + K_i(T - T_r)]\left(\frac{G}{1000}\right) \quad (2)$$

$$I_0 = I_{rs}\left[\frac{T}{T_r}\right]^3 \exp\left[\left(\frac{qE_{g_0}}{aK}\right)\left(\frac{1}{T_r} - \frac{1}{T}\right)\right] \quad (3)$$

where

I_{ph}: generated photocurrent (A); it depends mainly on the radiation and cell's temperature.
I_0: reverse saturation current of diode (A), it is influenced by the temperature.
V_p: output voltage of the PV cell (V).
I_p: output current of the PV cell (A).
I_{scr}: short-circuit current at reference condition (A).
K_i: short-circuit temperature coefficient.
T_r: reference temperature (K).
G: solar irradiance (W/m^2).
I_{rs}: saturation current at reference temperature (A).
q: electron charge ($1.60217 * 10^{-19}$ C).
K: Boltzmann constant ($1.38 * 10^{-23}$ J/K).
a: diode ideality factor.
T: temperature (K).
R_s: series resistance of cell (Ω).
R_{sh}: parallel resistance of cell (Ω).

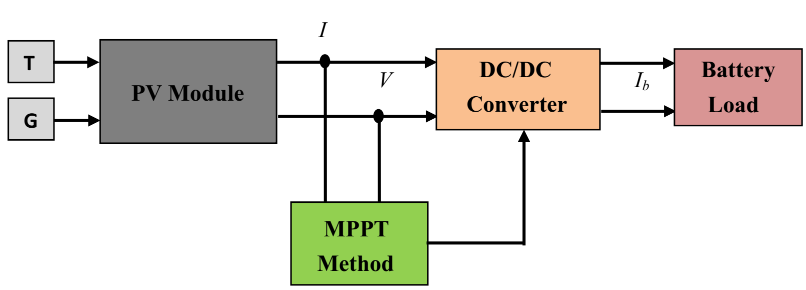

Fig. 1. Block diagram of the stand-alone PV system with storage battery.