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Designing a new robust sliding mode controller for maximum power point tracking of photovoltaic cells

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Abstract

This paper proposes a new sliding mode controller for maximum power point tracking of photovoltaic cells. By defining a suitable sliding surface, the proposed control law does not require reference voltage/current. The proposed system is based on the one-loop control schemes which makes its implementation easy. Stability of the proposed system is ensured using Lyapunov stability theorem. It is proved that the proposed control system is robust to system uncertainties. Moreover, a new state-dependent control magnitude is designed which suppresses chattering of the system. A traditional sliding mode controller is considered in order to compare the results of the proposed system. Simulation and experimental results are used to evaluate the robustness of the proposed system. It is shown that the proposed system is robust to system uncertainties, environment changes and load variations.

Keywords: Photovoltaics; Sliding mode control; Robustness; Maximum power point tracking

1. Introduction

Environmental problems and energy issues such as rising oil price are motivating research on the development of renewable energy sources (Ajanovic and Haas, 2015). Among renewable energies, photovoltaic (PV) has attracted a lot of interest with many important applications because it is free, abundant and environmental friendly (Mavromatidis et al., 2015; Fattori et al., 2014). Moreover, the cost of electricity from PV systems is close to that from conventional sources (Benda, 2015).

In order to extract the maximum electrical power from the PV cells under changing loads and environmental conditions, it is essential to provide PV systems with maximum power point tracking (MPPT) controllers. In this context, different MPPT controllers has been addressed in many literatures (Rezk and Eltamaly, 2015). In many PV systems a switching converter is usually connected between the PV modules and the load (Gonzalez Montoya et al., 2016). Due to nonlinear characteristics of PV modules and switching converters, nonlinear controllers have attracted considerable attention (Kim, 2007; Chu and Chen, 2009; Chiu et al., 2012; Zhang et al., 2015; Hamrouni et al., 2009; Lauria and Coppola, 2014; Liu et al., 2014; Valencia and Ramos-Paja, 2015; Mojallizadeh and Badamchizadeh,

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2016). Among nonlinear controllers, sliding mode control (SMC) has attracted a lot of interest due to the system order reduction, large signal stability, simple implementation, robustness to model uncertainty and disturbances (Young et al., 1999; Utkin, 2013). Sliding mode control is a nonlinear control strategy based on the variable structure theory. In a variable structure control system, the structure of the controller changes from one form to another (Utkin, 1993). Conventional sliding mode MPPT controllers are based on the following methods:

(1) The first method is based on the two-loop MPPT control approach (Kim, 2007; Chiu et al., 2012; Hamrouni et al., 2009; Lauria and Coppola, 2014; Liu et al., 2014; Lalili et al., 2013; Valencia and Ramos-Paja, 2015). In this method, the first loop is to find the reference voltage/current of the PV module and the second loop is to regulate the PV module voltage/current to the reference point. A terminal sliding mode MPPT controller was proposed in Chiu et al. (2012), which ensures the finite time convergence of the system. However, the chattering problem is not addressed in this controller. The main drawback of the first method is that the interaction between two loops needs to be addressed appropriately (dan Zhong et al., 2008).

(2) The second approach is based on the one-loop control method (Chu and Chen, 2009; Zhang et al., 2015; Yau and Chen, 2012; Valencia and Ramos-Paja, 2015). In this scheme, the controller does not need reference voltage/current. Therefore, its implementation complexity and calculation burden is relatively low. When the value of the sliding surface converges to zero, the PV power will be maximized. In Chu and Chen (2009), the sliding surface is defined as the derivative of the PV power with respect to PV current. In some other references Yau and Chen (2012) and Zhang et al. (2015), the sliding surface is defined as the derivative of the PV power with respect to PV voltage. In Zhang et al. (2015), a new strategy is proposed which reduces the requirement of voltage sensors. A new sliding mode controller for grid-connected PV systems is proposed in Valencia and Ramos-Paja (2015). This control system is based on the one-loop method. However, its chattering problem increases the voltage ripple of the PV module. Although these approaches are robust to environment changes and load variations, these controllers are not robust to system uncertainties.

The main challenges in designing MPPT controllers can be summarized as follows: The controllers should be able to track the maximum power point to maximize the extracted PV power. Many MPPT controllers suffer from chattering problem (Valencia and Ramos-Paja, 2015). This problem decreases the efficiency of system. Moreover, chattering may excite the high frequency dynamics which may lead the system into instability. Another challenge related to PV systems is the ease of implementation. One-loop schemes are usually easier to implement compared to two-loop schemes (Zhang et al., 2015).

The main motivation for the proposed controller presented in this article comes from the fact that robustness of the controller is important in PV systems where input voltage variations and parasitic elements are always present. The contribution of this paper is designing a new sliding mode controller for MPPT of PV modules. The proposed scheme is based on the one-loop control strategy. The robust stability of the proposed controller is assured by Lyapunov theory. Moreover, chattering amplitude of the controller is suppressed using a new state-dependent control magnitude (Levant, 2010). This paper is structured as follows. Modeling of the PV system is presented in Section 2. The proposed sliding mode controller and its robust stability are addressed in Section 3. Results of the simulations and experiments are given in Sections 4 and 5, respectively. Finally, conclusions are presented in the last section. Table 1 represents the nomenclature of quantities that are used in this paper.

2. Modeling of the photovoltaic system

A circuit schematic of the PV system is shown in Fig. 1. The system is composed of a PV module and a boost converter. The equations of the PV module and the boost converter are given in Sections 2.1, 2.2, respectively.

2.1. Model of the PV module

The voltage-current characteristic of the PV module can be written as Park and Choi (2015):

$$I_P = N_p\left(I_{ph} - I_{rs}\left(e^{\frac{qV_P}{N_s A K_0 T}} - 1\right)\right) \tag{1}$$

where I_P and V_P are the output current and voltage of the PV module, respectively. N_s and N_p are the number of the series and parallel cells, respectively. T denotes the PV module temperature, q is the charge of an electron, $A \in [1, 5]$ denotes the ideality factor, k_0 is the Boltzmann's constant, I_{rs} is the reverse saturation current and I_{ph} denotes the light generated current. Moreover, I_{ph} and I_{rs} depend on solar irradiance and PV module temperature and can be described by Eqs. (2), (3) (Park and Choi, 2015).

$$I_{rs} = i_r(T/T_{ref})^3 e^{\frac{qE_{go}}{K_0 A}\left[1/T_{ref} - 1/T\right]} \tag{2}$$

$$I_{ph} = \left(i_s + K_l(T - T_{ref})\right)\lambda/1000 \tag{3}$$

where, i_r denotes the reverse saturation current at the reference temperature ($T_{ref} = 298(K)$), i_s denotes the short-circuit cell current at the standard condition, E_{go} denotes the semiconductor band-gap energy, $K_l(A/K)$ is the temperature coefficient and λ denotes the irradiance in W/m^2. The PV module parameters are shown in Table 1. Power-current curve of the PV module is shown in Fig. 2. It can