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Second-order fuzzy sliding-mode control of photovoltaic power generation systems

Mohammad Rasool Mojallizadeh, Mohammad Ali Badamchizadeh *

Faculty of Electrical and Computer Engineering, University of Tabriz, Tabriz, Iran

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ABSTRACT

In order to maximize the conversion efficiency of photovoltaic systems, it is usually essential to design a maximum power point tracking controller. In this paper, a new second-order fuzzy sliding-mode controller is designed for this purpose. Since the proposed scheme is based on the second-order sliding-mode control law, it can handle nonlinear dynamics of photovoltaic systems. Compared to previously introduced controllers, the proposed control law does not depend on model parameters and thus is robust to system uncertainties. The gain of the control signal is determined using a fuzzy gain tunning algorithm. Therefore, not only the robustness of the system will be improved, but also chattering amplitude will be suppressed. The proposed scheme does not require asymptotic observers, and thus its analysis and implementation are fairly simple. The performance of the proposed control system is verified through simulation and experiment. Compared to terminal sliding mode control system, the proposed system can increase the efficiency up to 1.5%.

1. Introduction

Duo to unstable price of conventional fuels, concern about global warming and air pollution, extensive attention have been focused on renewable energy resources (Ajanovic and Haas, 2015; Enteria et al., 2014). Among renewable energies, photovoltaic (PV) energy has received a lot of interest because it is clean and abundant (Pinto et al., 2016; Campos et al., 2016).

PV energy can be converted directly to electrical energy using PV cells. In order to maximize the efficiency of this conversion, a proper control system should be designed to drive the PV cells to their maximum power points (MPP). These control systems are usually based on the two-loop control scheme. In this scheme, control system consists of two loops, namely seeking loop and tracking loop (Chiu et al., 2012; Mojallizadeh and Badamchizadeh, 2016b). The seeking loop is to find MPP and the tracking loop is to track MPP.

A large number of extremum seeking algorithms have been proposed to find the MPP in the first loop (Gupta et al., 2016; Tang et al., 2016). Perturb and observe (PO) is one of the commonly used algorithms. Based on this algorithm, MPP can be found by perturbing the operating point of PV cells and observing the output power (Rezk and Eltamaly, 2015). Implementation of this algorithm is simple. However, its performance depends on the size of perturbations. Therefore, adaptive PO algorithms have been proposed to tune the step size based on the operating conditions (Enrique et al., 2010).

Incremental conductance (IC) is another algorithm which has been widely used in the first loop (Rezk and Eltamaly, 2015). This algorithm finds the MPP by calculating derivative of PV power (P) with respect to voltage (V) i.e., dP/dV. Modified IC methods are also introduced to improve the performance of the seeking loop (Tey and Mekhilef, 2014). Some other extremum seeking algorithms such as particle swarm optimization (Letting et al., 2012) and adaptive neuro-fuzzy approach (Khiareddine et al., 2015) have been proposed to improve the MPP searching performance. However, their implementations are expensive and complex.

MPP searching and tracking performances highly depend on the tracking loop. Therefore, design of an appropriate controller is essential to cope with the nonlinear dynamics of PV systems, uncertainties, disturbances and noises. In this context, several controllers have been proposed in many literatures. The proposed approaches are mainly based on the following methods:

- The first method is based on the linear control scheme. Linear controllers such as PI and lead-lag are widely used due to their straightforward and simple implementation (Letting et al., 2012). Linear control systems are usually designed around an

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* Corresponding author at: Faculty of Electrical and Computer Engineering, University of Tabriz, 29 Bahman Blvd., Tabriz, Iran.

E-mail addresses: mojalli@tabrizu.ac.ir (M.R. Mojallizadeh), mbadamchi@tabrizu.ac.ir (M.A. Badamchizadeh).

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Nomenclature

I_P	current of the module
V_P	voltage of the module
T	module temperature
λ	irradiance level
A	ideality factor
E	band-gap energy
i_{rr}	reverse saturation current
i_s	short-circuit current
K_T	temperature coefficient
K_B	Boltzmann's constant
T_r	standard temperature
N_s	number of series cells
N_p	number of parallel cells
L	inductor
C_1 and C_2	capacitors
R	load resistance
V_o	output voltage
V_D	voltage drop of diode
u	control signal
k	control gain
β	modulation factor
MPP	maximum power point
CA	chattering amplitude
SMC	sliding-mode controller
SOSMC	second-order sliding-mode controller
SOFSMC	second-order fuzzy sliding-mode controller
CGSOSMC	constant-gain second-order sliding-mode controller
TSMC	terminal sliding-mode controller
PO	perturb and observe
IC	incremental conductance

equilibrium point (Fialho et al., 2014). Since operating points of PV systems highly depend on the solar irradiance, temperature and load, these controllers may lead to a lack of robustness to operating condition.

- The second method is based on the passivity-based control (PBC). PBC can modify damping characteristic of nonlinear systems. Therefore, it can handle nonlinear dynamics of PV systems. PBC exhibits fast and smooth responses. However, it requires a large number of voltage and current sensors, which increases the cost and footprint of the overall system (Tofighi and Kalantar, 2011). Hence, adaptive PBC is introduced to reduce the number of required sensors (Mojallizadeh and Badamchizadeh, 2016a). However, it requires a powerful processor to estimate the parameters.
- The third method is based on the input-output linearization (IOL) (Espinoza-Trejo et al., 2015) or feedback linearization (FL) (Lalili et al., 2013) schemes. This method generates a linear input-output relation for the PV systems. Afterwards, linear controllers can be used to control PV systems. Compared to linear control methods, global stability of this method can be ensured. The main drawback of this method is that cancelation of nonlinear dynamics requires the exact model of the PV system, which is not available in practice.
- The fourth method is the sliding-mode control (SMC). This method is based on the variable structure control theory, in which structure of the controller is variable. Among nonlinear control methods, SMC has attracted a lot of interest because of its robustness, ease of implementation and order reduction. The main drawback of the SMC is the chattering phenomenon. Chattering is caused by high-frequency oscillations of control signal, which may reduce the performance of systems and even lead those to instability (Utkin, 2013). Terminal SMC of PV systems is proposed in Chiu et al. (2012). In this approach, a nonlinear sliding surface is designed which ensures finite-time convergence of the system. However, this scheme requires an upper bound of uncertainties. Moreover, a trade-off has to be made between the robustness and chattering. One-loop sliding-mode control systems have been proposed in Chu and Chen (2009), Zhang et al. (2015), and Ghazanfari and Maghfoori Farsangi (2013), which do not require MPP reference. Since these methods are not robust to system uncertainties, a robust one-loop schemes has been proposed in Mojallizadeh et al. (2016). However, this approach suffers from the same drawbacks of the terminal SMC.
- Backstepping sliding-mode control of PV systems is presented in Dahech et al. (2017). This approach presents a good transition response. However, the robustness of this system is not addressed explicitly. Double-integral sliding-mode control for PV power generation systems is proposed in Pradhan and Subudhi (2016). A boundary layer is used around the sliding surface to suppress the chattering. However, utilization of boundary layer may lead to an unacceptable tracking error.

Second-order sliding-mode controllers (SOSMC) have been introduced to suppress the chattering amplitude (CA) of the control systems (Pisano et al., 2016; Bartolini et al., 1998, 1997; Boiko et al., 2007). However, without knowing a priori knowledge about the bound of uncertainties, these controllers cannot be designed. Therefore, many efforts have been made to estimate this bound. In this context, Levants differentiator has been widely used for estimation (Pisano et al., 2016). Since the separation principle is not valid for nonlinear systems, the interaction between controller and estimator should be analyzed, which is not possible in many cases.

The main motivation of this article is that existing PV control systems require a priori knowledge about the upper bound of the uncertainties. Since PV systems are highly uncertain, this upper bound may not be available. Thus, existing methods may not be suitable for practical PV systems.

The contribution of this article is in designing a new second-order fuzzy sliding-mode controller (SOFSMC) for PV systems. The control gain of the proposed controller is tuned using a fuzzy inference system. Therefore, the proposed system does not require a priori knowledge about the bound of uncertainties. As a results, no additional estimator is required, which makes the implementation easier. It will be shown that the proposed control system does not depend on parameters of the model. Thus, compared to many other schemes, the proposed control system is robust to uncertainties. The rest of the paper is organized as follows. PV power generation system is modeled in Section 2. Suboptimal second-order sliding-mode controller is introduced in Section 3. The proposed fuzzy gain tunning (FGT) is designed in Section 4. Simulation and experimental results are presented in Sections 5, 6, respectively. Finally, concluding remarks are presented in Section 7.

2. Photovoltaic power generation system

Diagram of the PV system is shown in Fig. 1. The system consists of a PV module and a boost converter. PV module converts