Renewable Energy 60 (2013) 202–214

Contents lists available at SciVerse ScienceDirect

Renewable Energy

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

Technical note

Adaptive fuzzy gain scheduling PID controller for maximum power point tracking of photovoltaic system

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A R T I C L E I N F O

Article history:
Received 24 November 2012
Accepted 26 April 2013
Available online

Keywords:
Maximum power point tracking
Adaptive fuzzy PID controller
Fuzzy gain scheduling
Adaptive scaling factors
Two-level control system architecture
Fuzzy logic system

A B S T R A C T

This paper proposes a methodology of designing a Maximum Power Point Tracking (MPPT) controller for photovoltaic systems (PV) using a Fuzzy Gain Scheduling of Proportional-Integral-Derivative (PID) type controller (FGS-PID) with adaptation of scaling factors (SF) for the input signals of FGS. The proposed adaptive FGS-PID method is based on a two-level control system architecture, which combines the advantages of fuzzy logic and conventional PID control. The initial values of the PID's gains are determined by the Ziegler–Nichols tuning method. During transient and steady states, the PID's gains are adapted by the FGS-PID to damp out the transient oscillations, to reduce settling time and to guarantee system stability and accuracy. Also, the conditioned input signals of the FGS-PID are tuned dynamically by gain factors which are based on fuzzy logic system (FLS). The FLS is characterized by a set of fuzzy rules which are fuzzy conditional statements expressing the relationship between inputs (error and change of error) and outputs. This approach creates an adaptive MPPT controller and achieves better overall system performance. The simulation results demonstrate the effectiveness of the proposed adaptive FGS-PID and show that this approach can achieve a good maximum power operation under any conditions such as different levels of solar radiation and PV cell temperature for varying PV sources. Compared to conventional methods (PID, perturb and observe method P&O), this method shows a considerable high tracking performance.

1. Introduction

A photovoltaic system directly converts solar radiation into electricity. The PV electric power generation has two limitations: a) very low conversion efficiency, especially under low irradiation and b) the power generation depends on atmospheric conditions (solar radiation and temperature), ageing and load conditions [1,2]. In order to reduce the cost of energy, it is ideal to maintain the PV operation at its maximum achievable efficiency at any time. However, this goal is complicated by uncertain nonlinear current–voltage (*I*–*V*) and power–voltage (*P*–*V*) characteristics due to changes in intrinsic and extrinsic factors. The maximum power point is a unique point on the *P*–*V* curves and at this point the PV system produces its maximum power. Although there are many factors influencing the energy conversion efficiency, the maximum power point tracking is the most vital aspect of control design for PV generation.

The MPPT is substantially a nonlinear control problem. This is due to the nonlinear nature of PV and the continuous changes of its parameters with the unpredictable variations of the environmental conditions. A significant number of MPPT algorithms have been presented in the literature such as the perturb and observe method and the incremental conductance method [3,4].

The P&O method is widely used because of its low implementation complexity [3]. The shortcoming of this method is that the operating point of the PV fluctuates around the MPP. Therefore, the available energy is decreased. Furthermore, if the solar irradiance changes rapidly, the P&O technique fails to track the real point of maximum power. This creates a slower tracking time response. The convergence speed is varied due to the slow trial and error process.

The incremental conductance MPPT method is based on comparing the instantaneous conductance to the incremental conductance. At the maximum power point, the values of conductance and incremental conductance are equal but with opposite signs. This method has medium implementation complexity compared to P&O [3]. The drawback of this technique is the oscillations around the MPP.

MPPT fuzzy logic controllers (FLC) have the advantage of being fast robust and of having quiet good performance (time response, stability, tracking speed, small oscillations) under varying atmospheric conditions. MPPT FLCs are more effective under sudden changes of atmospheric conditions compared to the traditional

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http://dx.doi.org/10.1016/j.renene.2013.04.014

algorithms. Our approach introduces more flexibility to the structure and design of MPPT algorithm. Flexible FLC means robustness against noise and parameter variations, simplicity and tolerance for imprecision [5].

However, the reliability depends on the knowledge of the control engineer who determines the fuzzy rule base and chooses with accuracy the fuzzy parameters such as error metrics, membership functions and scaling factors [6,7]. Therefore, the FLC design is implemented according to the trial and error method rather than a systematic methodology. Consequently, the FLC design is not optimum. To overcome these mentioned limitations, computational intelligence methods using fuzzy logic, neural networks, particle swarm optimizer (PSO) and genetic algorithms (GA) have been applied to optimize the FLC and to improve the tracking efficiency [2,8–12].

The literature shows a wide variety of methods for the development of fuzzy gain scheduling scheme of PID controllers [13–16]. Fuzzy logic reasoning is utilized online to determine the PID controller gain parameters. The main drawback of the FGS methods is that the determination of the scaling factors is based on the trial and error method. To overcome this problem the heuristic scaling factors are tuned online.

Patcharaprakiti developed an adaptive fuzzy logic controller that continuously tunes the membership functions and the rule base so that optimum performance is achieved [17]. Neural networks have been applied for implementing MPPT controller. Due to the fact that the majority of the PV arrays' characteristics change in time, the neural networks have to be regularly trained offline. However, a drawback of using neural networks is that they need a large number of environmental data for their offline training.

The main aspects of the MPPT controllers are 1) ease of implementation, 2) the number of sensors required to implement MPPT, 3) the avoidance of multiple local maxima, 4) the low cost and 5) the suit application [18]. The most widely used controllers in the industrial control processes are the PID controllers due to their simple structure, ease of implementation, small cost and robust performance in a wide range of operating conditions. The selection of a PID as an MPPT controller satisfies most of the above aspects. The design of such a PID controller requires the determination of three parameters: proportional gain, integral time constant and derivative time constant. The Ziegler–Nichols (Z–N) tuning formula is perhaps the most well-known tuning method for selecting PID parameters. The PID controllers tuned by Z–N are simple, but cannot always have a good performance with changing parameters, and may need frequent online retuning.

Most of the preceding MPPT control unit design methods are based on single-level controllers, which means that the control system consists of the process and the local controller both connected in a single loop. Due to the complexity and diversity of real systems, such as the tracking of MPP on PV array, the single-level controller may not effectively achieve the control goal. In these systems, a multi-level control system turns out to be very helpful [19]. The multi-level control has been studied in the field of intelligent robotics [20]. In the proposed adaptive FGS-PID method, the MPPT structure is based upon the architecture of a two-level fuzzy PID control system. In this paper, a rule-based scheme is developed for fuzzy gain scheduling of PID controllers with online adaptation of the scaling factors for MPPT control. The scheme utilizes fuzzy rules and reasoning to determine a) the controller parameters and b) the input scaling factor values in order for the PID controller to generate the appropriate control signal. The PID and the scaling factor gains can be determined online based on the error signal and either the change of error or the time derivative of error. The simulation results demonstrate the effectiveness of the proposed method and show that this approach can achieve a better maximum power operation under any atmospheric conditions compared to the other techniques such as simple PID controller, FGS-PID controller and classic MPPT methods like P&O.

2. Photovoltaic system

2.1. PV model characteristics

The equivalent circuit of a PV cell is using a photovoltaic power source, as depicted in Fig. 1.

The current source corresponds to the photocurrent that takes place at the diode due to sunlight. This current depends on the spectrum and the intensity of the sunlight, as well as the temperature of the cell and it is equal to the short circuit current I_{sc}. The current which produced by the current source is described in Eq. (4). I_o is the reverse saturation current, I_{sc} is the short circuit current of a PV cell, V_{pv} is the voltage across the PV source, k is the Boltzman's constant, q is the electron charge, A is the quality factor ($A = 1.3$), T is the temperature on the photovoltaic surface and G is the solar irradiance that incidents at the photovoltaic surface. The factors n_s and n_p are related to the number of the cells that are in series and in parallel connection respectively. The n_s factor multiplies every term related to voltage and the n_p multiplies every term related to current [21]. In this model, it is considered that the value of the parallel resistance is very high and has no effect in the model. It is also assumed that the value of the series resistance is constant and equals to the series resistance at the maximum power point of 25 °C and 1000 W/m^2 Eq. (3) where I_{mpp} and V_{mpp} are the current and the voltage at the maximum power point respectively. The current produced from the photovoltaic cell can be described as follows [22]:

$$I_{pv} = I_{sc} - I_{sc}e^{\frac{V_{pv}-I_{pv}R_s-V_{oc}}{nV_T}} \tag{1}$$

where $V_T = kT/q$ and the factor $I_{sc}e^{-V_{oc}/nV_T}$ is the reverse saturation current I_o. This arises from the open circuit point, where the $I_{sc} = I_d = I_o e^{(V_{pv}-I_{pv}R_s)/nV_T} = I_o e^{V_{oc}/nV_T}$.

At the Maximum Power Point it is known that:

$$\frac{dP_{pv}}{dV_{pv}} = I_{pv} + V_{pv}\frac{dI_{pv}}{dV_{pv}} = 0 \tag{2}$$

Combining Eqs. (1) and (2) by using the computational software Wolfram Mathematica arises:

$$R_s = \frac{AKT\ln\left(\frac{I_{sc} - I_{mpp} + I_o}{I_o}\right) - qV_{mpp}}{qI_{mpp}} \tag{3}$$

The relation of I_{sc} with the solar irradiance is almost linear and can be found in Ref. [22]. Furthermore, the relation between the solar irradiance and the V_{oc} can be found through the $I_{sc} = I_o e^{-V_{oc}/nV_T}$. The reverse saturation current I_o mainly depends

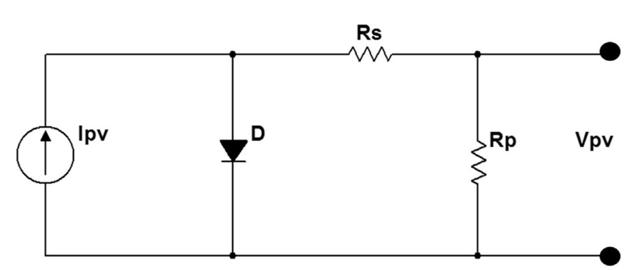

Fig. 1. Equivalent circuit for general PV cell model.