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Golden band search for rapid global peak detection under partial shading condition in photovoltaic system

Akbar Ahmad*, Archit Khandelwal, Paulson Samuel

Department of Electrical Engineering, Motilal Nehru National Institute of Technology, Allahabad 211004, Uttar Pradesh, India

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ABSTRACT

To harvest maximum power from a string operating under the partially shaded condition, it must work at its global power peak as the string characteristics follow changes in operating environment. The presence of multiple peaks in the power-voltage curve of a PV string increases computational complexity for the detection of the global power peak under rapidly changing climatic conditions. Traditional algorithms fail to operate satisfactorily under such dynamic changes and result in sub-optimal operation and higher power loss. In this paper, a novel algorithm is proposed for tracking of global maximum under rapidly changing solar radiation and temperature. The algorithm divides the search space into an optimal number of bands and then uses the golden search algorithm within each band to identify the local peaks and selects the global peak of the PV characteristics curve. The hardware in loop implementation of the proposed algorithm has been done using microcontroller by using Agilent E4360A for emulating the PV string characteristics and DC-DC boost converter resulting in various case studies. The comparison with the earlier proposed algorithm has been implemented on the same platform and the results obtained suggest that the proposed algorithm provides tracking of the global MPP with a fewer number of power perturbation steps. The hardware implementation with Arduino (Atmega 328) provides an economical and efficient solution. The practical results in conjunction with DC-DC boost converter show good agreement with the theoretical analysis, simulation and efficient tracking performance.

1. Introduction

The photovoltaic system consists of highly nonlinear characteristics of power-voltage and current-voltage curves, which are continuously changing with the variation in irradiation and change in temperature. The MPPT controller thus plays a critical role in sensing and acting in response to rapid shifts in the characteristics of the photovoltaic system thereby ensuring the extraction of the maximum power at all times. The effectiveness of an algorithm is classified by the speed of tracking, minimal oscillations, and accuracy to detect and operate at global maxima.

The PV source operates in linkage with the DC-DC converter, whose duty cycle is modulated with the tracking dynamics on maximum power point in the curve. The classification of the MPPT algorithm based on the uniform and non-uniform irradiation is analysed by Koutroulis and Blaabjerg (2015). Out of several schemes the first and foremost is the perturb and observe which is also termed as hill climbing algorithm (Mastromauro et al., 2012; Femia et al., 2005). The shortcomings of this technique were improved by the incremental conductance method as mentioned in Sera et al. (2013) and González-Morán et al. (2007). Due to the ease of implementing the techniques such as short circuit current (Walker, 2001), open circuit voltage, ripple correlation approaches were introduced. The improvement in tracking performance and efficiency of tracking is proposed as adaptive perturb and observe (Abdelsalam et al., 2011) and variable step size incremental method (Loukriz et al., 2016; Tey and Mekhilef, 2014; Abdourraziq Mohamed and Mohammed, 2014; Jain and Agarwal, 2004).

Artificial intelligence based MPP techniques such as fuzzy and neural network algorithms are applied for achieving the desired operation. The training method with a large set of input for real-time operation is required for such algorithms (Sheraz and Abido, 2014), as the model of the system is highly unpredictable hence it offers a huge disadvantage. The Fuzzy based logic control for the power converters as discussed in Rezvani et al. (2015) and Afghoul et al. (2013). The main advantage of the fuzzy logic based system is that the knowledge of the approximate model of the system is not necessarily required. However, for achieving the sufficient performance expert domain knowledge is needed for designing of membership function and its rule-based sets. The optimization techniques such as genetic algorithm and ant colony

* Corresponding author.
E-mail addresses: akbar7ahmad@gmail.com (A. Ahmad), archit.ee16@mnnit.ac.in (A. Khandelwal), paul@mnnit.ac.in (P. Samuel).

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strategy are applied for parameter tuning in Adly and Besheer (2012).

The effect of partially shaded condition occurring due to a nearby tree, building or structure with the integrated bypass diode can be seen with the unwanted presence of multiple local peaks in the I-V and P-V characteristics curve of the system under non-uniform irradiance (Patel and Agarwal, 2008; Romero-Cadaval et al., 2013; Alajmi et al., 2011). Around seventy percent of loss in power may be observed due to the improper detection of global peak location in I-V and P-V characteristics (Petrone et al., 2008). Under such conditions, the conventional MPP algorithm fails to track the global peak location further causing a significant increase in the power loss (Wang and Hsu, 2010). Several MPPT algorithms for dynamic irradiance for partial shading condition have been presented in the literature. Some of them propose hardware reconfiguration with changing shading sequence (Nguyen and Lehman, 2008; Velasco-Quesada et al., 2009), using a concept of distribution of MPPT on module level termed as DMPP (Petrone et al., 2012; Solorzano and Egido, 2014; Graditi and Adinolfi, 2011; Wu et al., 2012; Balato et al., 2011; Chen et al., 2014, 2011; Petrone et al., 2010; Femia et al., 2008a, 2008b; Jiang et al., 2012), a dedicated converter using series and shunt configuration (Sharma and Agarwal, 2014). All of these methods require external hardware circuitry which reduces the reliability of the system and increases the control complexity. However, some of the other techniques require optimization search algorithm easily implementable on the controller and preferably not increasing any control dynamics. Although some of them require a complex predictive control datasets to train a system and design membership function such as in Fuzzy logic control (Alajmi et al., 2011), Ant colony based system (Jiang et al., 2013), Fibonacci search based (Ahmed and Miyatake, 2008), global peak search (Patel and Agarwal, 2008), two stage tracking algorithm (Kobayashi et al., 2006), rectangle search method (Nguyen and Low, 2010). In Koutroulis and Blaabjerg (2012), a global search algorithm with constant power operation is suggested which becomes slow under small power differences among local peaks, also requires constant power from the DC-DC converter.

This paper proposes a Section based golden search MPP algorithm which uses the open circuit voltage of the array and band limit as the search variables. The algorithm shows some distinct advantages like fast convergence and less oscillation and high accuracy in tracking in global maxima. The MPP algorithm is developed with limiting parameters and implemented using Atmega 328 microcontroller (Evans, 2008; Bayle, 2013), offering the economical solution to the issue. The details of the algorithm are explained in the later section of the paper. The experimental parameters are discussed and verified in the simulation and discussion section.

2. Modelling of photovoltaic system

Most commercially available solar cells are constructed with p-n junction fabricated on a thin wafer of semiconductor. In a single-junction PV cell, when the junction is exposed to light, the semiconductor absorbs the photons with energy greater than the bandgap energy and generates electron-hole pairs although the multi-junction PV cells can increase the conversion efficiency with working ability below the bandgap as well. The electron crosses the band gap of the p-n junction and generates the electric power. The semiconductor materials perform energy conversion between sunlight and the electronic circuit, and their characteristics differ with the amount of irradiance and temperature. The solar cell is modelled as a current source connected in parallel with a diode. The output of this current source is directly proportional to the light falling on the cell. The diode illustrates the nonlinear stochastic nature of the I-V characteristics of the solar cell. Fig. 1 shows the equivalent circuit of the PV cell with linear and nonlinear components.

The equivalent circuit of the PV cell consists of ideal current source and diode with shunt resistance. The cascaded connection of the current and voltage sources is made to define the nonlinear curve of the PV cell. Furthermore, various series and parallel connection of these cells are

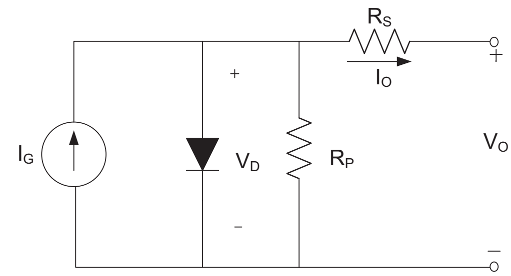

Fig. 1. Equivalent circuit of the PV cell.

done to increase the current and the voltage rating of the PV array (Yeung et al., 2014). For the steady state mathematical analysis of a PV cell, the Kirchhoff's voltage and current laws are applied to the circuit (Masoum et al., 2002; Selvamuthukumaran et al., 2016).

The load current (I_o) of the PV cell is equivalent to subtraction of the diode (I_d) and shunt branch resistance current (I_{sh}) from the current developed by photodiode mentioned in Eq. (1).

$$I_O = I_G - I_d - I_{sh} \tag{1}$$

$$I = I_G - I_R\left(e^{\frac{V_d}{\eta\times V_t}} - 1\right) - I_{sh} \tag{2}$$

$$I = I_G - I_R\left(e^{\frac{q\times Vd}{\eta\times KT}} - 1\right) - I_{sh} \tag{3}$$

The diode current parameter comprises of the voltage across the diode (V_D) and charges developed through the photovoltaic cell (q), an ideality factor of the diode (n), the temperature of the device (T) and the Boltzmann's constant (K). The thermal voltage (V_t) of the diode is equivalent to the multiple of the Boltzmann's constant (K) and the temperature of the diode (T) to the charge developed across the diode (q), reverse bias saturation current (I_R) expressed in Eqs. (2) and (3).

The photocurrent (I_G) represented regarding short circuit current (I_{SCR}), the reference level of irradiance (G_R), instantaneous irradiance (G), the temperature coefficient of the PV cell (α_T), reference temperature (T_{CR}) and instantaneous temperature (T_C) related and shown in Eq. (4).

$$I_G = I_{SCR}\frac{G}{G_R}[1 + \alpha_T(T_C - T_{CR})] \tag{4}$$

The initial dark current developed in the PV cell can be expressed by the Eq. (5). This is directly proportional to the ratio of instantaneous temperature to a reference temperature and dark current at a reference temperature.

$$I_{Dark} = I_{OR}\left(\frac{T_C^3}{T_{CR}^3}\right)e^{\left[\frac{1}{T_{cr}} - \frac{1}{T_c}\right]\frac{qeg}{\eta k}} \tag{5}$$

The shunt branch current of the PV cell consists of the voltage across the load, voltage across the series resistance of the PV cell and resistance of the shunt branch expressed in Eq. (6).

$$I_{sh} = \frac{V + IR_s}{R_P} \tag{6}$$

The PV panel exhibits highly nonlinear characteristics which depend on the level of solar irradiation and temperature. Fig. 2 shows the simulated P-V and I-V characteristics curves with variation in irradiance for a single operating module to display the change of power and current. The change in the open circuit voltage is affected by the change in PV module temperature. The output characteristics under different temperature can be found in Lineykin et al. (2014). The module has approximately constant current on the left side of the MPP and the approximately constant voltage on the right hand. The current and voltage at peak position (I_{mp} and V_{mp}) are analysed and expressed as (Masoum et al., 2002)