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Voltage band analysis for maximum power point tracking of stand-alone PV systems

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ABSTRACT

This paper introduces an analysis and calculation method to determine voltage bands, which are voltage regions of possible global maximum power points (GMPPs) for stand-alone photovoltaic (PV) systems under non-uniform irradiance conditions. Non-repeated irradiance cases is analyzed to obtain GMPPs according to electrical characteristics of a series-parallel-connected PV array. A clustering method is used to process these points to build voltage bands. Slope coefficients compensate for the influence of the temperature. Simulation results shows the influence of the PV array configuration and the PV module type on the voltage band method. The proposed method can be applied in designing global maximum power point tracking methods and analyzing the approximate regions of GMPPs.

1. Introduction

Conventional power generation based on fossil fuels has drawn serious concerns due to limited sources, greenhouse gases and other polluting gas emissions (Hong et al., 2015). Renewable energy resources, such as solar, wind, geothermal and tidal, have received considerable attention as promising solutions in terms of energy and environmental sustainability (Deshkar et al., 2015). In particular, solar energy is considered to be an efficient and well received renewable source, since it is safe, highly reliable, abundant, environmentally friendly and freely available (De Brito et al., 2013). As electrical power can be generated on-site by a PV array, solar energy is extremely well suited to stand-alone applications, such as solar lamps, water pumps, automobiles, unmanned aerial systems, mobile devices, wireless sensors, and wearables. PV arrays can be readily integrated into these devices to form self-powered PV systems.

The PV system exhibits only one maximum power point (MPP) on the power-voltage (P-V) curve. Its output features nonlinear current-voltage (I-V) and P-V characteristics, which vary with irradiance, temperature and other environmental conditions (Rezk and Eltamaly, 2015). In order to maximize utility and efficiency of PV systems, there have been intensive efforts to develop various control strategies to achieve the maximum power point tracking (MPPT) in real time (Kinattingal et al., 2016). Numerous conventional MPPT methods have been proposed and developed. Some of them are offline and model-based such as open-circuit voltage and short-circuit current. Most MPPT methods, such as perturbation and observation (Killi and Samanta, 2015), incremental conductance (Tey and Mekhilef, 2014), fuzzy logic control (Guenounou et al., 2014) and extremum seeking control (Li et al., 2013), are online and model-free, which operate basing on online measurements of voltage and current (Fathabadi, 2016). Algorithms vary in efficiency, speed, adaptation to environmental changes, complexity, sensor requirements and cost of implementation (Reza Tousi et al., 2016).

A PV array is normally composed of several PV modules connected in series and/or parallel. MPPT for a PV array faces a significantly greater challenge than for a single PV module, especially in some stand-alone PV systems. In practical operation, PV modules in an array may be subject to non-uniform irradiance conditions due to different installation angles or partial shading conditions (PSCs) caused by clouds, trees or buildings (Wang et al., 2016). Consequently, the P-V characteristic of a PV array may exhibit multiple peaks (Balasankar et al., 2017), i.e. multimodal performance index for the underlying real-time optimization problem. The local-optimization nature of conventional MPPT methods cannot tackle the global optimization problem for PV arrays under such non-uniform irradiance conditions, resulting in significant loss of power (Ishaque and Salam, 2013).

Much research has been carried out to address the non-uniform irradiance effect by improving the conventional MPPT or using intelligent algorithms such as artificial neural network (Rizzo and

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Nomenclature

I	current	N_s	series number of PV array
I_0	reverse saturation current of diode	R_{sh}	shunt resistance
I_{ph}	light current	R_s	series resistance
I_{sc}	short-circuit current	S	irradiance level
n	diode ideality factor	T_m	temperature of PV module
N_{gr}	number of irradiance groups	V	voltage
N_{ic}	number of different irradiance cases	V_{mpp}	voltage of maximum power point
N_{lv}	number of irradiance levels	V_{oc}	open-circuit voltage
N_p	parallel number of PV array		

Scelba, 2015), differential evolution (Ramli et al., 2015) and particle swarm optimization (PSO) algorithm (Sarvi et al., 2015). The majority of global maximum power point tracking (GMPPT) algorithms start by identifying non-uniform irradiance conditions. Various kinds of global scanning strategies are then used to search for the global maximum power point (GMPP). Scanning strategies vary from simple to sophisticated (Ishaque and Salam, 2013). Shah and Rajagopalan, 2016 scanned the entire P-V curve in larger steps to determine the approximate location of the MPP. Wang et al., 2016 used a searching and skipping process to reduce the range of voltage scanning. Boztepe et al., 2014 and Liu et al., 2014 only scanned some points with fixed steps to determine the approximate location of the GMPP in a short scanning time. Jiang et al., 2015 adopted artificial neural network (ANN) to predict the GMPP region, and then used the conventional MPPT method to search for the GMPP within the predicted region. Ding et al., 2014 used a voltage interval of $0.9V_{oc}$ to skip voltage region, thus reducing the scanning range. Gokmen et al., 2013 proposed the voltage band based GMPPT method. They used 1000 random non-uniform irradiance conditions to calculate the GMPPs and found that voltage values at GMPPs can be divided into different clusters. However, only the value of voltage bands' centers is taken into consideration in this paper, and the authors did not analyze the situation in a parallel-connected PV array. Sudhakar Babu et al., 2016 also used the concept of the voltage band. But this voltage band contains only a single continuous voltage region.

To speed up global scanning, it is widely assumed that peaks are located at multiples of $0.8V_{oc}$. Many researchers, such as Patel and Agarwal, 2008; Ramli et al., 2015 and Chen et al., 2016 have made this critical assumption to develop novel GMPPT methods. Hajighorbani et al., 2016 assumed that the minimum length between two sequential MPPs is $0.8V_{oc}$. Further, Ahmed and Salam, 2015 suggests a simple relationship other than the $0.8V_{oc}$ model to predict the position of peaks.

In this paper, an analysis, calculation and preprocessing method rather than a complete MPPT method is proposed to determine voltage bands of possible GMPPs in any irradiance and temperature condition. Non-uniform irradiance cases are further analyzed. The model of the PV array and clustering method is used to calculate voltage bands with the consideration of possible irradiance and temperature conditions. The effect on the voltage band range caused by the PV array configuration and the PV module type is discussed. All the work is done offline, but various kinds of online GMPPT algorithms, including improved conventional MPPT and intelligent algorithms, can use this analysis method to reduce the scan range. This method can also be utilized to further discuss the problem of the $0.8V_{oc}$ model.

2. PV array model

The typical PV array is composed of several PV modules connected in series and/or parallel in order to obtain a required output power level. The most widely implemented interconnection scheme of PV modules is the series–parallel configuration (Qi et al., 2014), as shown in Fig. 1. A PV array consists of a group of parallel-connected PV strings, each consisting of several series-connected PV modules with one or more parallel bypass diodes to prevent hot spot (Batzelis et al., 2015). Blocking diodes are connected in series with each PV string to prevent reverse current (Fathabadi, 2015).

The model used to determine the output behavior of the PV array is necessary, as the proposed method is a model-based method for analyzing maximum power points in different irradiance and temperature conditions. An accurate PV array model is crucial, but it often results in complex computations. In this section, the PV array model used to meet computational speed and accuracy requirements is presented.

2.1. PV module model

A PV module can be modeled by the single diode equivalent circuit model by which each module is modeled as a current source connected to a parallel diode with series and shunt resistors (Villalva et al., 2009), as shown in Fig. 2. The single-diode model is widely used for its good compromise between accuracy and simplicity (Cristaldi et al., 2014).

The relationship between output current and voltage is given by the nonlinear implicit Eq. (1).

$$I = I_{ph} - I_0\{\exp[q(V + IR_s)/nKT_m] - 1\} - (V + IR_s)/R_{sh} \tag{1}$$

where I_{ph} is the light current, I_0 is the reverse saturation current of diode, n is the diode ideality factor, R_s is the series resistance and R_{sh} is the shunt resistance. T, q and K denote the module temperature, the charge of an electron and the Boltzmann constant, respectively.

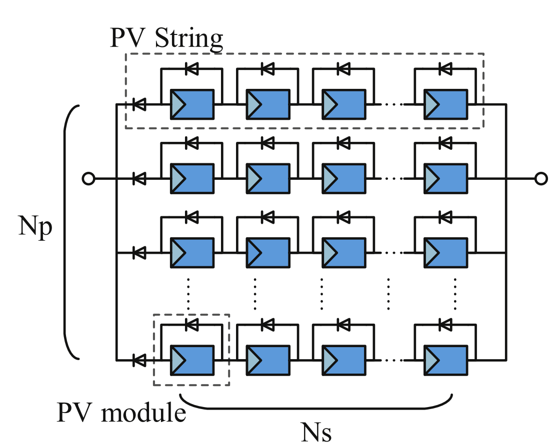

Fig. 1. Interconnection schemes of PV modules.