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Bat algorithm based maximum power point tracking for photovoltaic system under partial shading conditions

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ABSTRACT

This paper presents a maximum power point tracking (MPPT) method for photovoltaic system under partial shading conditions using bat algorithm (BA). The bat algorithm is a swarm intelligence based method which was inspired by the echolocation behaviour of bats. BA have a high accuracy in the global optimisation and it can provide good dynamic performance and very quick convergence rate by automatically switching between exploration and exploitation stages during the MPPT process. To verify the performance of the proposed method, several simulations have been carried out in Matlab/Simulink environment for various shading patterns. The simulations results highlight the accuracy of the proposed scheme for optimal management of the energy available at the output of the photovoltaic panels. In addition, the comparison with the P&O and the PSO methods shows that the proposed method outperforms them in term of global search ability and dynamic performance. To verify the practical implementation of the proposed method, a modular reconfigurable architecture is designed using very high speed integrated circuit hardware description language (VHDL) and implemented on Xilinx Virtex-5 (XC5VLX50-1FFG676) Field Programmable Gate Array (FPGA). The use of FPGA for designing the MPPT controller provides high performance, increases the robustness and makes the hardware implementation more flexible. The algorithm is tested in real time application on a buck-boost converter using a real photovoltaic panel. Experimental results confirm the efficiency of the proposed method in the global peak tracking and its high accuracy to handle the partial shading.

1. Introduction

Renewable energy resources have enormous potential and offer many advantages over conventional energy resources. Renewable energy comes from several resources like solar, wind, geothermal, biomass and water. They can produce electricity in large quantities over a long term without too emit greenhouse gases. The renewable sources of energy derived from the sun can be used both directly and indirectly. The direct use of solar energy by means of sensors is related to two distinct technologies: the first produces calories, it's solar thermal energy, and the second produces electricity through the photovoltaic effect. Photovoltaic (PV) technology is one of the most promising renewable energy technologies. Photovoltaic systems are configured as stand-alone, grid-connected and hybrid systems (Mellit et al., 2009).

Various configurations are used for the PV modules interconnection to meet the voltage-current requirement (Belhachat et al., 2015). The overall characteristics of photovoltaic generators are varying and depend on several factors, especially the meteorological conditions such as solar radiation, ambient temperature and wind speed, the aging of photovoltaic cells and partial shading or inhomogeneity of the illumination. When PV modules receive a uniform sunlight, the resulting *P-V* characteristic is uni-modal and characterized by a single point of maximum power. When part or the entire module receives a non-uniform illumination, some cells (dimly lit) become reversed bias and turn into receiving elements. This phenomenon is called "hot spot" and can result in the destruction of these cells. To remedy this problem, the photovoltaic modules are equipped with bypass diodes which function is to protect the cells that become passive (Woyte et al., 2003). The integration of bypass diodes in solar module has as consequence the changing of the *P-V* characteristic which becomes multimodal when the partial shading occurs (Karatepe et al., 2007). The *P-V* characteristic is then characterized by the appearance of several maxima: several local maximum power points (LMPPs) and one global maximum power point (GMPP). The number of maxima depends on the type of shading (uniform or partial), distribution of the illumination on the photovoltaic generator and the number of bypass diodes incorporated in each photovoltaic module.

Despite efforts to improve the technology of photovoltaic cells, the

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electrical efficiency is still low (Bhatnagar and Nema, 2013). Also, partial shading has dramatic consequences on the electrical power delivered (Dolara et al., 2013; Eke and Demircan, 2015). To reduce losses caused by partial shading and increase the efficiency of photovoltaic panels, several approaches are presented in the literature. These approaches include system architectures, converter topologies, PV array configurations and maximum power point tracking (MPPT) techniques (Bidram et al., 2012). Despite the improvements that can be achieved by the first three approaches, additional material increases the complexity of the system which becomes more expensive. So a good compromise cost-efficiency can be achieved by development of MPPT techniques which can handle the partial shading.

Several MPPT techniques are presented in the literature to handle the multimodal *P-V* characteristic in partial shading conditions. These methods vary in complexity, in the types and the number of sensors used and the equipment used for the implementation. Kouchaki et al. (2013) proposed a two stage MPPT algorithm for tracking the GMPP. The authors introduce an analytic condition to distinguish partially shaded conditions from normal conditions. This condition is based on the comparison of the sensed photovoltaic current around $(0.8 \times N_{SS} \times V_{oc})$ and a reference value calculated at uniform insolation conditions with $G = 1000\ \mathrm{W/m^2}$, where N_{SS} is the number of series photovoltaic module and V_{oc} is the open circuit voltage. When the region of GMPP is located, the algorithm calls a hill climbing subroutine to reach the GMPP. However, in the first stage, $(N_{SS} + 1)$ points should be tested each time the partial shading conditions are detected before calling the hill climbing algorithm to locate the GMPP. This method will become time-costly if the number of series module is large (Ahmed and Salam, 2015). In addition, temperature sensors must be used to determine the open circuit voltage. Another two-stage search method is proposed by Liu et al. (2014) for locating the GMPP. The first stage involved using a fixed spacing method to divide the *P-V* characteristic curve into various segments and to obtain the block in which GMPP is located. During the second stage, a variable step-size perturb and observe (P&O) method is used to locate the precise location of the GMPP. The authors recommended using $(N_{SS} + 1)$ segments at the first stage to enhance the tracking performance, where N_{SS} denotes the number of PV modules serially connected. It is shown in Nguyen and Low (2010) that the function describing the PV power as a function of the PV voltage is a Lipschitz function. Therefore, Nguyen and Low (2010) adopted the dividing rectangles (DIRECT) algorithm to search for the GMPP. Although the presented experimental results showed the efficiency of this method in tracking the GMPP under partial shading conditions, an appropriate choice of the first sampling interval is primordial for the GMPP tracking performance (Lian et al., 2014). Kim and Kim (2013), Alajmi et al. (2013) and Boukenoui et al. (2016) employed two-stage search methods to track the GMPP, which first scanned the *P-V* characteristic curve and then recorded the GMPP. In the second stage, these methods applied either the P&O method (Kim and Kim, 2013) or fuzzy logic control (Alajmi et al., 2013; Boukenoui et al., 2016) to maintain the operating point at the GMPP. Evolutionary algorithms (EA) have attracted special attention by the academic community in recent years. Indeed, several articles have appeared in scientific journals, highlighting the effectiveness of these algorithms in the tracking of maximum power point in partially shaded conditions. Thanks to its simple structure, the particle swarm optimisation (PSO) algorithm is developed and improved by many researchers. Miyatake et al. (2011) used conventional PSO algorithm to control several PV arrays with one pair of voltage and current sensors. In Ishaque et al. (2012), the authors used the PSO technique for the tracking of GMPP using direct duty cycle control method. PI control loops are eliminated and the duty cycle of the Pulse Wide Modulation (PWM) signal is adjusted directly by the MPPT algorithm. In Ishaque and Salam (2013), the authors have improved their algorithm (PSO) by removing random factors from the velocity equation. The proposed algorithm becomes deterministic and its structure becomes simpler. However, a restriction is imposed on the maximum of particle velocity to not fall into a LMPP. Lian et al. (2014) combined P&O and PSO to form a hybrid method to reduce the search space of the PSO. Initially, the P&O method is employed to identify the nearest local maximum. Then, the PSO method is used to search for the GMPP. Experimental results show that this method has a faster convergence time and better dynamic response than the conventional PSO algorithm. Adaptive approaches are reported in Liu et al. (2012) and Chao et al. (2015) to tune the PSO algorithm control parameters to increase the efficiency and performance of the GMPP tracking. In Liu et al. (2012), the authors proposed to adjust these parameters in linear way whereas the authors in Chao et al. (2015) suggested varying them in exponential form. Despite improvements provided by these approaches, the structure of the algorithm becomes more complex and parameter selection task becomes more difficult (Ahmed and Salam, 2015). Tajuddin et al. (2013), Tey et al. (2014) and Ramli et al. (2015) tracked the GMPP using differential evolution (DE) algorithm. The conventional DE is used in Tajuddin et al. (2013) whereas modified mutation strategy are adopted in Tey et al. (2014) and Ramli et al. (2015) to improve the convergence speed. Ramli et al. (2015) proposed to remove the random numbers from the algorithm, and then the donor vectors (generated by the mutation) are used directly as a trial vectors. Experimental results of ten shaded patterns show that this method outperforms the PSO method in terms of global tracking capability and convergence time. Ahmed and Salam (2014) proposed a maximum power point tracking (MPPT) for PV system using cuckoo search method (CS). CS is a population based algorithm and its concept is similar to PSO. The main difference between CS and PSO is the manner to update the step sizes. In fact, the step sizes in CS are performed by Lévy Flight. The results shows improvements compared to the PSO technique in terms of convergence speed and transient fluctuations, but the structure of the CS algorithm is more complex. Sundareswaran et al. (2014) presented a MPPT algorithm based on a colony of flashing fireflies for tracking GMPP in partially shaded PV arrays, and compared it with PSO algorithm. The published results indicate that the firefly algorithm based tracking outperforms the PSO method in terms of tracking speed and dynamic behaviour. Seyedmahmoudian et al. (2015) proposed a hybrid method called DEPSO, a combination of PSO and DE. The PSO algorithm is used in odd iterations and the DE algorithm is performed in even iterations. Although this algorithm can track the GMPP, the presented results show that DEPSO requires a lot of iterations to converge, producing large fluctuations in the power before reaching the steady state (Seyedmahmoudian et al.,2016).

The main drawback of the mentioned EA based MPPT is that the tradeoff exploration-exploitation is low, which may result in large fluctuations in the operating power of the PV array during the optimization process, or to fall in LMPP in some partial shading configurations. Yang (2010) has developed a new metaheuristic method, the Bat Algorithm (BA), which is inspired on the echolocation behaviour of microbats. BA uses a frequency-tuning technique to increase the diversity of the solutions in the population. As a result, the search space is excellently explored. Moreover, this algorithm provides a mechanism of automatic switching between explorative moves and exploitation during the MPPT process. This feature allows to the algorithm to have a quick convergence rate towards the GMPP without falling into the trap of premature convergence. In addition, the combination of exploration (global search) and exploitation (local search) during the tracking process also allows to the algorithm to present good dynamic behaviour and less oscillations before reaching the GMPP.

Recognizing these benefits, this paper proposes bat algorithm based MPPT to track GMPP under partial shading conditions. The remainder of this paper is structured as follows. Section 2 presents the modelling of the photovoltaic system and the behaviour of the photovoltaic panel under partial shading condition. Section 3 discusses the key features of