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Maximum power point tracking of large-scale photovoltaic array

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ABSTRACT

In partial shading conditions, reverse voltage may impose on the shaded photovoltaic modules and cause the "hot spot" problem. In this paper, a novel topological structure of photovoltaic array is proposed for operational safety and efficiency in possible partial shading, and the maximum power point tracking (MPPT) is also implemented on each photovoltaic module. This new structure consists of the photovoltaic module control device (PMCD) and branch voltage stabilization device (BVSD), which differentiate the MPPT at levels of each photovoltaic module (PVM-level MPPT) and minimum control unit (MCU-level MPPT). The MPPT of large-scale photovoltaic system can be formulized as a large-scale global optimization (LSGO) problem. Therefore, a novel multi-context cooperatively coevolving PSO (CCPSO-m) algorithm is proposed for solving the LSGO. Numerical result shows that the CCPSO-m outperforms some state-of-the-art algorithms evidently, and each photovoltaic module works on its own maximum power point effectively in the proposed structure of PV array. Finally, the large-scale photovoltaic system can achieve PVM-level (or MCU-level) MPPT, conquer the "hot spot" problem, and improve output power under complex environmental conditions significantly.

1. Introduction

The increasing interest in greenhouse effect and other environmental issues, has asked for the development and installation of renewable energy systems, which could generate clean power with less cost and pollute emission. Some sustainable sources, e.g., wind, tidal, geothermal and solar energy, have become extremely important for replacing the fuel generation and improving the performance of energy supply, and some advanced control methods are also adopted in the process of power generation and utilization as well (Yin C. et al., 2014; Yin C. et al., 2015; Lai J.G. et al., 2016). For exploring the solar energy, the photovoltaic modules which are composed of several cells in series and parallel connections, are widely used in aerospace (Girish et al., 2007; Lee et al., 2015), architecture (Kibria et al., 2016; Wu and Xia, 2015), electric power generation (Choi and Lai, 2010; Kaabeche and Ibtiouen, 2014), and other applications (Atmaca, 2015; Vinnichenko et al., 2014). However, due to varying environmental conditions, e.g., irradiance and temperature, photovoltaic module is usually regarded as an unstable power supplier (Pierro et al., 2015). It is necessary to develop control methods of these photovoltaic modules in an attempt to ensure the security and efficiency of photovoltaic system.

In a solar generation system, the energy harvesting component is the photovoltaic array, which is usually composed of several modules in series and parallel connections. Under uniform irradiance condition, current and voltage of each photovoltaic module are almost the same, and the whole system works in good performance. However, when the irradiance becomes non-uniform, shading of even a single module can reduce the efficiency of the entire system significantly, and possibly cause permanent thermal damage (Maki and Valkealahti, 2013; Sullivan et al., 2013; Dein et al., 2013). Partial shading (or "non-uniform irradiance") would also cause the so-called "hot spot" problem (Moreton et al., 2015). Shading modules in series branches may be imposed on reverse voltages and served as loads of photovoltaic system. As a result, these modules absorb power, and their surface temperature increases rapidly, which will cause permanent thermal damage of these shading branches. The gap of terminal voltages between different branches may also cause damage of the entire system. To conquer this "hot spot" weakness, the conventional method is to add bypass diodes across each module in parallel connections reversely, and to add blocking diodes in series connections at each branch (Ziar et al., 2014; d'Alessandro et al., 2014; Pennisi et al.,

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2011). This method can ensure operational safety of the photovoltaic system, however, it also presents a significant reduction of the power output.

Suffering from the varying irradiance and temperature, effective control of currency or voltage is necessary to introduce the maximum power output, which is defined as the maximum power point tracking (MPPT) problem. The conventional MPPT algorithms can be classified in two categories: online algorithms and offline algorithms. Online MPPT algorithms include the perturbation and observation method (P&O) (Piegari and Rizzo, 2010), the incremental conductance method (INC) (Tey and Mekhilef, 2014), and other P&O or INC variants (Petrone et al., 2011; Zan et al., 2013; Radjai et al., 2014). Offline MPPT algorithms are usually based on the mathematical model or empirical data of photovoltaic module, e.g., artificial neural networks (ANN) based MPPT algorithm (Kulaksiz and Akkaya, 2012), support vector machine (SVM) based MPPT algorithm (Chen et al., 2013), particle swarm optimization (PSO) based MPPT algorithm (Renaudineau et al., 2015), genetic algorithm (GA) based MPPT algorithm (Nafeh, 2011). In the existing online MPPT algorithms, e.g., the P&O, a perturbation is given to trigger the system, and then the feedback information is obtained for the MPPT control. Obviously, the repeated perturbation may cause system instability. In contrast, in the existing offline MPPT algorithms, no perturbation is required. The control input is computed beforehand, and the MPPT is usually implemented on each photovoltaic branch but not each module, so the resulted point cannot be the ideal maximum. Furthermore, when the photovoltaic array is really large (e.g., with thousands of modules), most algorithms show their inabilities to achieve the MPPT of each photovoltaic module (PVM-level MPPT). They fail to find the acceptable solution close to the global optimum.

In this study, a novel topological structure of photovoltaic array is proposed in an attempt to conquer the "hot spot" problem and achieve PVM-level MPPT. On one hand, a bidirectional Cuk converter as the "photovoltaic module control device (PMCD)" is utilized to control every two photovoltaic modules in a series branch. On the other hand, a boost converter as the "branch voltage stabilization device (BVSD)" is utilized to control terminal voltage of each parallel branch. In the new topological structure, each module in series is not required to work in the same current and each branch in parallel is not required to work in the same voltage either. Under the condition of uniform irradiance or partial shading, the PVM-level MPPT is applicable based on the proposed structure. Furthermore, the large-scale photovoltaic array with thousands of modules is studied to control each module's operating point, which is a large-scale global optimization problem. To solve this LSGO problem, a novel multi-context cooperatively coevolving particle swarm optimization (CCPSO-m) algorithm is also proposed in this paper. Numerical result shows that the CCPSO-m outperforms some state-of-the-art PSO variants on most of the test functions, and can solve the large-scale MPPT problem effectively.

The main contributions of this paper include three folds. Firstly, a novel topological structure of photovoltaic array based on PMCD and BVSD is proposed to conquer the "hot spot" problem. Secondly, a new MPPT method of large-scale photovoltaic array is studied in the approach of large-scale global optimization, in which the PVM-level (or MCU-level) MPPT is formulated into a LSGO problem. Thirdly, a new CCPSO-m algorithm is proposed in an attempt to improve the performance of some existing PSO variants on solving LSGO problems.

The rest of this paper is organized as follows: Section 2 presents an overview of some related works, including the conventional topological structure of photovoltaic array and some existing MPPT algorithms. Section 3 studies the structure and operational principle of PMCD and BVSD, and proposes a new topological structure of large-scale photovoltaic array. In Section 4, the large-scale MPPT optimization problem is studied in terms of the related variables and fitness function. Section 5 studies the CCPSO-m algorithm, and gives some numerical results and analysis. Section 6 simulates the new structure of large-scale photovoltaic array and CCPSO-m based MPPT algorithm. Finally, this paper is concluded in Section 7.

2. Related work

2.1. Topological structure of photovoltaic array

It is well known that the output power of a single photovoltaic cell is relative small (only several Wp per cell). Therefore, a photovoltaic module is usually composed of several cells in series and parallel connections, and a photovoltaic array is also composed of many modules in series and parallel structures as well. The electrical characteristics of a photovoltaic cell can be analyzed via a well-established model (Laudani et al., 2014), which can be approximated by an equivalent circuit as shown in Fig. 1.

Shown as Fig. 1, I_{SC} denotes the current generated through a photovoltaic effect; I_D denotes the flowing-through current of the PN junction across the cell; R_s and R_p denote the series and parallel resistance of the model respectively; I_{sh} denotes the leakage current; V and I are the output voltage and current of the cell.

As photovoltaic array is composed of many modules in series and parallel connections, shading of even a single module can reduce the output power of the entire system significantly. Shading, especially partial shading is extremely harmful for photovoltaic system. Shown as Fig. 1, if the photovoltaic cell is totally shaded, the current source I_{SC} will be zero and the diode will become reversely biased. As connected in series with other cells under full irradiance condition, the current I flowing through the module will then travel through R_p. This leads to a voltage drop across R_s and R_p. Thus instead of generating power, this shaded cell will actually consume power and get hot, which will cause the "hot spot" problem. Furthermore, in terms of the branches in parallel, terminal voltage of the shaded branch will decrease immediately. Then, if the terminal voltage of full irradiance branch is larger than open circuit voltage of the shaded branch, the gap of terminal voltage between these branches may also cause a reverse current flowing through the shaded branch, which will cause the thermal damage to photovoltaic modules.

A widely used method to conquer the aforementioned problems is to utilize bypass diode and blocking diode. In this fold, a typical structure is given in Fig. 2. On one hand, a bypass diode is added in parallel with each photovoltaic module reversely. When a module is shaded to a certain degree, voltage drop of the shaded module will be larger than 0.7 V and the bypass diode will be turned on. In this way, the shaded module is protected by the bypass diode.

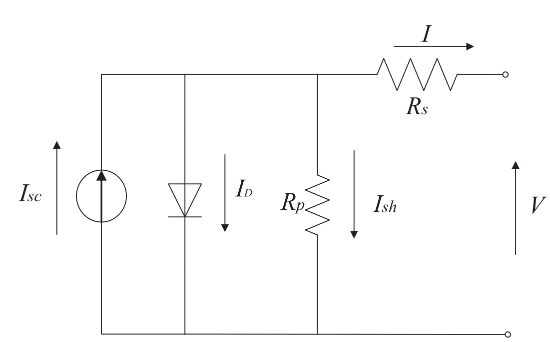

Fig. 1. Photovoltaic cell equivalent circuit.