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Improved performance of Dynamic Photovoltaic Array under repeating shade conditions

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ABSTRACT

This paper proposes a new strategy for implementing the Reconfigurable Solar Photovoltaic array or Dynamic Photovoltaic array under repeating shade conditions. The repeating shades are mainly caused by the civil structures, buildings, poles, etc., present in the vicinity of a Dynamic Photovoltaic array. This paper presents a new algorithm to minimize the processing time in case of repeating shades. According to which, the controller does not have to perform the exhaustive calculations at each shade condition. Instead, the algorithm compares the present shade response with the previous shade responses. Simulation of 4-by-4 size Dynamic Photovoltaic array has been carried out. Experimental tests of a Dynamic Photovoltaic array under resistive load conditions have been conducted. A switch-network of double pole double throw switches has been proposed and is used in the Dynamic Photovoltaic array experimental test. Switch-count of the proposed switch-network is one-third and significantly less compared to the conventional semiconductor switch-network.

1. Introduction

A Solar Photovoltaic System (SPVS) installed in urban locality generally faces a peculiar problem called Partial Shade Condition (PSC) [1]. During which, a section of PV modules receive less irradiance than others. It is mainly caused by the neighboring buildings, street poles, trees, other structures present in the close proximity of the SPVS plant [2]. In some cases, where the net area of PV modules is greater than available roof area, the PV modules will be installed close to each other. It causes few modules to receive shade of neighbor PV modules on a day-to-day basis. Under the PSC, PV plants produce a reduced power output [3].

A section of SPVS array getting shaded by the neighboring structures is shown in Fig. 1. Many novel techniques to minimize the effects and improve the performance of the SPVS under PSC have been reported. Few focus on detecting the PSC and other on improving the performance. In [4], voltage window based methodology to detect PSC and other faults of the PV array is reported. In [5], a fast sweeping technique to obtain the Current vs. Voltage (I-V) curve is proposed, which can be used for detecting the PSC. In [6], a Maximum Power Point Tracking (MPPT) technique for detecting the global MPP and improving performance of partially shaded PV array has been reported.

Reconfigurable Photovoltaic Array (RPVA), or, Dynamic Photovoltaic Array (DPVA) is one of the promising techniques to improve the SPVS performance under PSC [7]. In which, PV modules connections and configurations are changed to improve the performance [8]. This will be achieved by integrating a network of switches called Switching Matrix (SM) into the PV array [9]. For understanding purposes, consider 2-by-2 size Total Cross Tied (TCT) PV array as shown in Fig. 2. Assume, four modules are receiving different irradiance (W/m^2) as shown in Fig. 2a due to the PSC. In which, an imbalance among the tier-irradiances [1900 1400] results in reduced output power, which is proportional to the least tier-irradiance. After reconfiguring 600 W/m^2 and 900 W/m^2, a new PV array configuration as shown in Fig. 2b can be obtained. This reconfigured PV array produces more power due to an improved balance among the tier-irradiances [1600 1700]. Moreover, Power vs. Voltage (P-V) curve of problem and solution PV arrays are shown in Fig. 2c. In which, the multi-peak curve of problem PV array can trap the MPPT converter at a Local Maximum Power Point (LMPP) and produces less output power [10]. Whereas, the single-peak curve of the reconfiguration solution helps the MPPT converter to track the single MPP and harness more power.

According to the reconfiguration technique, PV array modules are re-arranged, such that, PV array shows greater balance and produces greater output power. In this case, exchanging the PV modules marked 600 W/m^2, 900 W/m^2 gives a new configuration as shown in Fig. 2b and produces more output.

For identifying the solutions and improving the performance of higher size PV arrays, many DPVA techniques have been reported. All

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Nomenclature

α	PV array current temperature coefficient (in A/°C)
β	PV array voltage temperature coefficient (in V/°C)
$\frac{dP}{dV}$	rate of change of power with respect to voltage (W/V)
G	PV plant normal irradiance (W/m^2)
G_{IP}	m-by-n size input irradiance matrix
G_{OP}	m-by-n size output irradiance matrix
$I_{mpp_{stc}}$	PV array STC MPP current (A)
I_{PV}	PV array current (A)
$I_{theo\,mpp}$	PV array theoretical MPP current (A)
$P_{actl\,mpp}$	PV array actual MPP power (W)
$P_{AR}(k)$	after-reconfiguration MPP power (W) at a k^{th} PSC
$P_{BR}(k)$	before-reconfiguration MPP power (W) at a k^{th} PSC
P_ε	allowable loss of MPP power (W)
$P_{theo\,mpp}$	PV array theoretical MPP power (W)
$V_{mpp_{stc}}$	PV array STC MPP voltage (V)
V_{PV}	PV array voltage (V)
$V_{theo\,mpp}$	PV array theoretical MPP voltage (V)

List of abbreviations

BW	Best Worst
COI	Configurations of Interest
DPDT	Double Pole Double Throw
DPVA	Dynamic Photovoltaic Array
I-V	Current vs. Voltage
IC	Integrated Circuit
IDE	Integrated Development Environment
LMPP	Local Maximum Power Point
MPPT	Maximum Power Point Tracking
P-V	Power vs. Voltage
PSC	Partial Shade Condition
RPVA	Reconfigurable Photovoltaic Array
SM	Switching Matrix
SN	Switch Network
SPDT	Single Pole Double Throw
SPST	Single Pole Single Throw
SPVS	Solar Photovoltaic System
TCT	Total Cross Tied

the techniques reported in literature can be classified into two categories: greater-output, faster-response reconfiguration techniques. In greater-output technique [11], a solution configuration will be identified after checking each one of the possible solutions. This approach ensures the best output, but takes more time. In faster-response reconfiguration [12], the solution configuration will be identified through a logical approach. In the literature, many logical-approach based algorithms have been reported. In which, they apply different algorithms and perform mathematical operations to identify the solution. The simplest and easily implementable Best-Worst [13] algorithm reconnects all the PV modules in the decreasing order of the irradiance, such that, the difference among the tiers is minimized. This approach may not ensure the best-output power. Moreover, it is not concerned about the minimization of number of relocations. The Genetic algorithm [14] offers a generalized approach to identify the best configuration of the PV modules. However, effectiveness of this approach is depended on the inclusion of number of parameters, formulation of the objective function and the population size. The Particle Swarm Optimization (PSO) [15] based reconfiguration algorithm identifies a better configuration at the end of each iteration. However, the best output configuration and the number of iterations to be computed depends on the population size, mutation and cross over considered. The deterministic re-configuration algorithm [16] collects the I-V characteristic curve of each PV module. Then, the modules with same Maximum Power Point (MPP) are reconfigured across a string. In this approach, PV modules with low MPP power are isolated, which is a drawback. Due to the logical nature, these algorithms can be applied to higher size PV arrays. Moreover, these logical algorithms take few ns to ms time to identify the solution but, may not guarantee the best output.

Fig. 1. A section of a PV plant getting shaded every day during evening hours due to neighboring structures.

In addition to the electrical reconfiguration methods, one-time reconfiguration [17] algorithms are reported in the literature. In this approach, electrical connections of the PV modules remain intact. But, the modules are physically relocated. This approach does not require any hardware, sensors and switch-network. However, requirement of lengthy wires is a drawback of this approach. The Su Do Ku algorithm [18] physically realigns the modules of a 9-by-9 size PV array, such that, each 3-by-3 cell of the PV array has one module belonging to the each tier.

In addition to above, many techniques have been reported to sense, measure the irradiance falling on each of the modules of PV array. In [19], a low-cost irradiance measuring sensor was developed. However, high error in measuring low irradiance values is a drawback to it. In [20], voltage and current of each module were measured to ensure high accuracy data. This method requires the installation of voltage, current measuring sensors to each PV module, which increases the cost and complexity of operation. In [21], a high pixel image of the PV array was periodically collected to estimate the irradiance of each PV module. However, requiring a high pixel camera increases the cost of investment. In [22], a novel approach to measure the irradiance of each PV module using a reduced number of voltage sensors was proposed. Compared to previous approaches, this method requires less number of sensors and reduced investment.

In addition to the development of algorithms, few research works have focused on improving the SM design through minimization of switch count and operational complexities. It should be noted that, SM is the main component of Dynamic PV array. Many types of switch-networks designed using semiconductor or electrical relays have been reported [23]. A relay has less conduction losses. Moreover, galvanic separation between the control and power paths makes it an advantageous compared to a semiconductor [24]. Since, separate isolation arrangements may not be necessary. However, in terms of switch sizes, the relay is a big size switch, which is a drawback. In [24], Single Pole Single Throw (SPST) relay based switch-network has been used. Compared to semiconductor-network, low conduction resistance is an advantage of it. However, higher switch-count is a drawback to it. In [25], Single Pole Double Throw (SPDT) based switch-network has been reported. Reducing the conventional switch-count is an advantage of it. However, the proposed switch-network is limited to a four module PV array. In [26], SN of Double Pole Double Throw (DPDT) switches is presented for variable configuration of a six module PV array. The drawback of this SN is, it cannot produce the TCT connections of the PV array.

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