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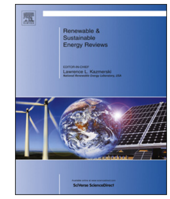

Comprehensive analysis on the role of array size and configuration on energy yield of photovoltaic systems under shaded conditions

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A B S T R A C T

Partial shading is a condition where, the panels in a photovoltaic (PV) array do not receive uniform irradiation. Shading causes mismatch in the electrical characteristics of the panels composing the PV array and results in significant reduction in the energy yield. The reduction in output is not proportional to the shaded area but depends on the extent of mismatch that in turn depends on other factors like array size, type of configuration chosen, position of the panels in the array and shading pattern. To reduce the severity of this issue and to improve the energy yield under shaded conditions, it is therefore necessary to analyze the role played by each one of the contributing factors in greater detail. This paper presents a detailed analysis focusing mainly on the role played by the array size, array configuration (interconnections among the panels) and the shading pattern on the energy yield under partial shading conditions.

Contents

1. Introduction

As the demand for energy is increasing day by day and the fossil fuels are getting depleted at a faster rate, the non conventional energy sources are gaining attention these days. Solar PV system is one such renewable source that is gaining popularity in the recent years. The efficiency of a Si–PV cell is in the range of (12–14)% and besides that, the output of PV cell is influenced by various environmental and climatic factors like the irradiation, temperature, air mass and length of the Sun shine hours [1,2]. Moreover, the electrical characteristics of a PV panel is nonlinear and the operating point is dictated by the load. To improve the efficiency of the PV system, it is necessary to operate the PV panels at their optimal power points so as to ensure maximum power extraction. Usually mechanical tracking to track the Sun and electrical tracking to track the optimal operating point are employed to improve the efficiency of the system. But, the actual power generated by a PV system is often found to be lesser than that of the designed or expected one. If this difference is not well thought out, it may result in under utilization or poor performance ratio.

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The key factor responsible for this difference is the losses associated with the mismatch in characteristics of the panels that compose the PV array. The mismatch can be either internal or external. While the internal mismatch is either because of the manufacturing techniques employed, poor soldering bonds or aging, the external mismatch is due to partial shading. This paper focuses only on the losses associated with external mismatches. Partial shading is more common in building integrated PV systems (BIPV) and other residential PV systems where panels are installed on the rooftops or facades of the building. PV panels in such installations may be shaded completely or partially by structures of the same building or nearby buildings. Though all the panels in an array are chosen to have similar electrical characteristics, under inhomogeneous irradiation condition, the characteristics differ and this mismatch increases the thermal stress on the heavily shaded panels. Increased thermal stress may result in hot spot development [3]. To prevent the PV panels from hot spot development, the panels are provided with bypass diodes [4]. These diodes are connected anti parallel to the PV panels and provide alternate path for the current flow when activated. However, bypass diodes introduce multiple peaks in the *V–P* characteristic curve making the maximum power point tracking difficult as conventional MPPT algorithms cannot differentiate between global and local maximum. Modified MPPT algorithms and many sophisticated MPPT algorithms have been proposed to track the global maximum. To mitigate the negative effects of shading and to improve the efficiency of the overall system, many researchers have analyzed the electrical characteristics (*V–I* and *V–P*) of PV array under partial or complete shading conditions [5–9]. The uncontrollable environmental factors make the practical shading analysis difficult and this has lead to the formulation of mathematical model. The negative effects of shading have been analysed in detail by simulating the partial shading conditions through computer based simulations [10–16].

The effect of shading is severe in series connected arrays as the shaded panels impose current limitations. With no such limitations, the parallel connected arrays remain robust. Hence for portable PV systems where the shadows change rapidly, parallel connected arrays are preferred [17]. However, high currents at relatively low voltage level demands proper power conditioning. In a typical PV system, the panels are connected in series (strings) and the strings are connected in parallel, called series-parallel (SP) configuration. The number of strings and panels per string are determined by the voltage and power specifications. This conventional SP configuration is sensitive to inhomogeneous irradiation conditions due to long strings and hence alternate configurations like total cross tied (TCT), bridge link (BL) and honeycomb (HC) derived from the SP have been proposed to improve the energy yield. These derived configurations includes cross ties and perform better than the series configuration as the cross ties offer alternate path for current flow when shaded [18–21]. Another important factor that influence the output is the shade pattern. The shade pattern changes rapidly if it is caused by passing clouds or other moving objects, while it remains fixed if it is cast by nearby structures. The reduction in the energy yield is not proportional to the shaded area but depends on the location of shaded panel and in turn on the shade pattern.

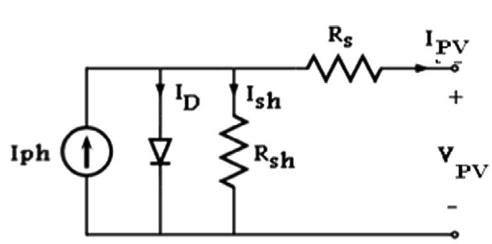

Fig. 1. Single diode model.

Though the performance of different PV array configurations has been analysed by different researchers, the configuration of interest differs. Few researches have analysed only basic configurations (series and parallel) while the others have chosen only TCT. The shading pattern considered for analysis was either random shade pattern or fixed shade pattern. Despite these reported works, there is still a need for a comprehensive analysis that analyses the role of the interconnection schemes, array size and shading type/pattern (fixed and random) on the characteristics and in turn on the energy yield of the PV system to gain better knowledge about the negative impacts of shading.

A generalized Matlab based tool that has the flexibility to model array of any size, configuration and shade pattern has been developed and the simulation analysis is done on an array with 36 panels [22]. Each of the panel is provided with single bypass diode. It is possible to arrange the 36 panels in different array sizes as 1×36, 2×18, 3×12, 4×9, 6×6, 9×4, 12×3, 18×2, and 36×1. The analysis is carried out by subjecting all possible combinations of array size and configurations to different types of shading (complete, partial, fixed and random shading) and the results and inferences are presented in the following sections.

2. Mathematical model of photovoltaic panel

Mathematical model that would mimic the actual behaviour of the panel is necessary, as it is difficult to maintain the same irradiation condition throughout the practical shading analysis. The single diode model of PV panel is presented in Fig. 1.

The governing Eq. (2) that are used to develop Matlab based model for a $37W_p$ Solkar PV panel with an open circuit voltage of 21.24 V and a short circuit current of 2.55 A are given from (1) to (9).

$$I_{PV} = I_{ph} - I_r\left[\exp\left(\frac{V_D}{V_t}\right)-1\right] - \frac{V_D}{R_{sh}} \tag{1}$$

$$I_{ph} = G \times I_{sc} \tag{2}$$

$$I_{sc} = I_{scn}\left[1+K_i\, dT\right] \tag{3}$$

$$I_r = \frac{K_i dT + I_{scn}}{\exp\left[(K_v dT + V_{ocn})V_{ta}\right]-1} \tag{4}$$

$$V_D = \frac{N_{ss}}{N_{pp}} I_{meas}R_s + V_{meas} \tag{5}$$

$$V_t = \frac{q}{nKN_sT} \tag{6}$$

$$I_0 = I_r\left[\exp\left(\frac{V_D V_t}{N_{ss}}\right) - 1\right] \tag{7}$$

$$I_m = N_{pp}\left[I_{ph} - I_0\right] \tag{8}$$

$$V_D = I_{PV}R_{se} + V_{pv} \tag{9}$$

where $I_{PV}$is the PV current, V_D is the voltage across the diode, V_{PV} is the PV voltage, R_{se} is the series resistance, R_{sh} is the shunt resistance, I_{ph} is the photon generated current, I_r is the reverse saturation current, I_o is the diode current, K_v and K_i is the voltage and current temperature constants, G is the Irradiation, V_t is the Thermal voltage, V_{ocn} and I_{scn} is the voltage and current at STC ($G=1000$ W/m^2 and $T=25$ °C), N_{ss} is the number of panels in series, N_{pp} is the number of panels in parallel, V_{meas} and I_{meas} is the feedback parameters for solving the transcendental equations.

These governing equations signify that the PV panel current (I_{PV}) depends on the environmental factors like insolation and