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Shading Factor Estimation in Small-Scale PV Systems

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***Abstract*— In this paper we propose a method to accurately estimate effects of partial shading on a small-scale PV system. Current of each PV string is measured and along with the output voltage of the PV array are used in order to estimate the shading intensity and shaded area of the array. First, the string current variations are used to recognize partial shading condition (PSC) and estimate shading intensity. Later, using the output voltage variations, shading factor is calculated. The proposed system is then simulated under two scenarios and the method is verified by the simulation results. These findings help us find the best location for small-scale PV systems; a place where there is minimum shading.**

Keywords—photovoltaic systems (PV), partial shading condition (PSC), shading intensity, shading factor

I. INTRODUCTION

Nowadays due to environmental and economical reasons, the focus on renewable energy has increased rapidly. Photovoltaic (PV) energy is a kind of sustainable energy and works by converting the solar irradiation into electrical power. This technology has progressed over the last decades but still has some problems. Its nonlinearity and dependency on temperature and irradiation makes it difficult to extract maximum available power when the PV array is under partial shading condition (PSC) the problem becomes more complicated. PV modules are connected in a series-parallel configuration in order to produce a high enough voltage and a large enough power output. Therefore, when one cell is shaded or damaged, the overall power output of the PV array will be disproportionately reduced [1].

The impact of a partially shaded module can be significant- losses of 20-90% are possible with shading that affects as little as one row of cells within a module. Some amount of shading is unavoidable, but this does not minimize the importance of accurately predicting shading in order to reduce its effects over the life of the system. Determining actual shading is important to verify a shade-free installation as part of system commissioning; it should be periodically checked throughout the life of a PV system [2].

Since shadows change shape and intensity during the day estimating shading factor is very difficult. Several approaches have been proposed to study the shadow effects on PV arrays. In the numerical method [3], [4], the irradiation is modeled by real time data and then output power is calculated by solving differential equations. In this method, modeling partial shading for the long time is difficult and output power prediction is not accurate enough. In the photogram metric method [5], the position of obstacles and their shadow are estimated by using the triangulation with two photographs or more. Neural network methods used in [6], [7], [8] need PV system output data for training, thus, these methods are system specific and cannot be used for different systems. Also, running the system in different conditions to produce diverse enough training data causes noticeable power loss [9].

In some applications such as domestic or portable PV systems, it is common that they receive non-uniform irradiation which may be caused by clouds, trees or neighbor houses. Such PV systems are small, so, it is important that they receive the maximum irradiation possible and not be shaded by various obstacles. Therefore, choosing a proper location with minimum shading is substantial.

This paper proposes connecting a current sensor in series with each string of the PV array, in order to estimate the shading intensity and also calculating the shading factor which is defined as the ratio of the non-shade area to the total area of the PV array. The proposed method is especially useful for the small-scale domestic PV systems because the space is limited and it is important that the PV system is installed in a place where minimum numbers of modules are shaded.

II. THE PROPOSED METHOD

The basic idea of the proposed method is based on the variations of output current and voltage of a PV array under PSC. In order to calculate shading factor for each PV string individually, one current sensor is connected to each string and a voltage sensor is connected in parallel to the entire array. For estimating shading factor, the following sequences are applied.

A. Recognizing PSC

For simplicity, the single diode model of Fig. 1 is used in this paper. The operating equation of current-voltage characteristics of a solar cell can be derived as follows:

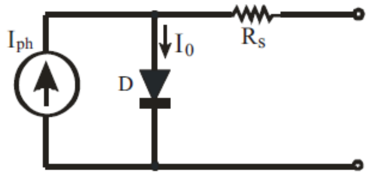

Fig. 1. Simplified single diode model of PV module

$$I = I_{PH} - I_0 \left[\exp\left(\frac{q(V + R_s I)}{AkT}\right) - 1\right] \tag{1}$$

Where V is the output voltage of the PV module, I_0 is the saturation current, A is the ideality factor, q is the electronic charge, k is the Boltzmann's constant, T is the junction temperature and R_s is the series resistance. I_{PH} is the photocurrent which depends linearly on solar irradiation

$$I_{PH} = \frac{G}{G_{ref}} \times I_{scn} \tag{2}$$

Where G is the solar irradiation on the array surface, G_{ref} is the nominal irradiation (1000 W/m^2) and I_{scn} is the short circuit current in the standard condition. Equations (1) and (2) show the PV output current is proportional to the irradiation. When shading occurs, the change of current is more noticeable than the change of voltage. The proposed method recognizes PSC when (3) is satisfied for any of the strings [10].

$$I_{pv} - I_{ref} \leq I_{SET} \tag{3}$$

Where I_{ref} is the maximum power point current at standard condition and I_{SET} is a predetermined value set by the user depending on the type of PV system.

B. Estimation of shading intensity

After PSC is recognized, the shading intensity must be estimated. Considering (2), in order to calculate shading irradiation, the photocurrent is obtained as (4) using (1) and (2):

$$I_{phsh} = I_{si} + I_0 \left[exp\left(\frac{q(V_{pv})}{AkT}\right) - 1\right] \tag{4}$$

Where $I_{phs\,h}$ is the photocurrent under shading, I_{si} is the string current of the ith string, and V_{pv} is the output voltage under PSC. Hence, shaded irradiation can be estimated:

$$I_{phsh} - I_{ref} \approx \frac{(G_{sh} - G_{ref})}{G_{ref}} \tag{5}$$

Where, I_{ref} is the reference current which is the short-circuit current at the standard condition G_{sh} is the shaded irradiation on the surface of the PV array.

The shading intensity is then calculated using (6) compared to a reference which is the standard condition. The higher the shading intensity, the darker is the shaded area of the array.

$$intensity = \frac{(1000 - G_{sh})}{1000} \tag{6}$$

C. Calculation of shading factor

After estimation of the shaded irradiation level, number of shaded modules in the ith string can be calculated using the voltage variations. The difference between the output voltage of the partially shaded array and the array reference voltage is divided by the difference between output voltage of one shaded module and module reference voltage. So, the number of shaded modules is obtained as follows:

$$n_{shade-i} = \frac{(N_s * V_{MPPn} - V_{pv})}{V_{MPPn} - V_{sh}} \tag{7}$$

Where, N_s is the number of series connected modules in a string, V_{MPPn} is the module MPP voltage at standard condition and the reference voltage, V_{pv} is the output voltage of the PV system and V_{sh} is output voltage of a module under the shaded irradiation which can be calculated [11] using (8)

$$V_{sh} = \frac{AkT}{q} \ln\left(\frac{I_{scn} G_{sh} - I_{si}}{I_0}\right) \tag{8}$$

Where, I_{si} is the current at the ith string.

Finally, the shading factor for the shaded string is easily obtained using (9)

$$shading\ factor\ i = \frac{N_s - n_{shade-i}}{N_s} \tag{9}$$

Where N_s is the number of series connected modules in a PV string.

In case more than one string is partially shaded, the voltage change is first divided in proportion to the shading intensity of each string as in (10):

$$dV_i = \frac{intens_i}{\sum_{i=1}^{N_p} intens_i} \times (N_s \times V_{ref} - V_{pv}) \tag{10}$$

Where $intens_i$ is the shading intensity on the ith string and N_{psh} is the number of parallel strings in a PV array that are shaded.

Therefore, shading factor of each string can be individually calculated using dV_i

$$n_{shade-i} = round\left(\frac{dV_i}{V_{mpp} - V_{sh}}\right) \tag{11}$$

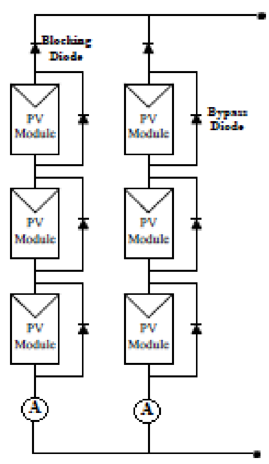

Fig. 2. Proposed system's structure

III. SIMULATIONS

The tested PV array is composed of 2 parallel strings, each consisting of 3 series modules as shown in Fig. 2. For simplicity, maximum power point tracking is not discussed in this paper and just the characteristic resistance of the array is connected, so, the system is working at the maximum power point under standard condition. The datasheet specifications of the module are shown in Table I. Simulation results are carried out using Matlab/Simulink to validate the performance of the proposed method.

The load which is the characteristic resistance of the PV array is calculated using (12)

$$load = \frac{N_s \times V_{mpp}}{N_p \times I_{mpp}} \tag{12}$$

Where N_p is the number of parallel connected PV strings. Therefore, the load value is calculated to be 2.96 ohm.

The proposed method is tested under two different conditions. First, each PV string is shaded separately and then, both strings are shaded simultaneously.

A. each string shaded separately

The PV system is tested under different irradiation levels. First, one module in string number 1 is shaded with 0.25 intensity from 0.5 s to 1 s and the rest of the array is under nominal irradiation. Then, one module is string number 2 is shaded with intensity level of 0.4 at 1.1 s and later at time 1.3 s another module in string number 2 becomes shaded with intensity level of 0.65.

From Fig. 3, the proposed method recognizes PSC and calculates the shading intensity as soon as it happens and Fig. 4 shows that the number of shaded modules is also correctly calculated. Therefore, shading factor is 1/3 for string 1 from 0.5 to 1 s and 1/3 for string 2 from 1.1 to 1.3 s and then 2/3 after 1.3 s.

TABLE I. PV ARRAY DATASHEET SPECIFICATIONS

Item	Value
Short circuit current (I_{sc})	19.1
Open circuit voltage (V_{oc})	40
Maximum power point voltage	34.4
Maximum power point current	17.4
Diode ideality factor (A)	1.6311

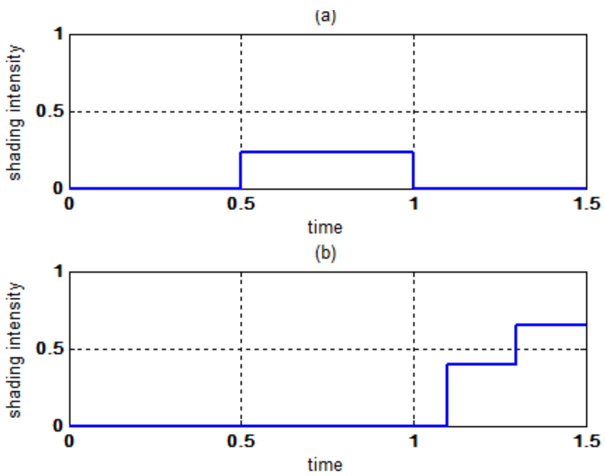

Fig. 3. Shading intensity in (a) string 1 and (b) string 2

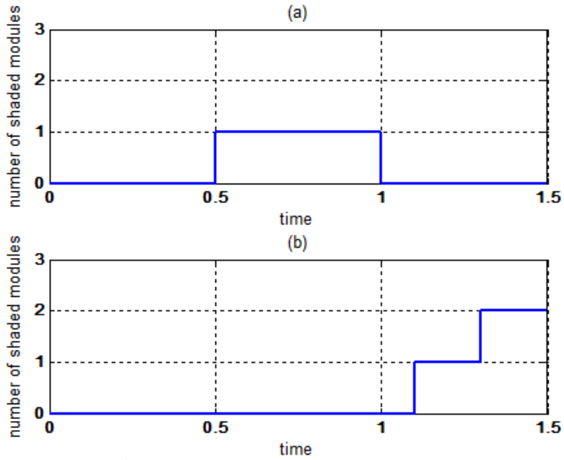

Fig. 4. Number of shaded modules in (a) string 1 and (b) string 2

B. both strings shaded together

In another condition, both strings are partially shaded simultaneously. One module in string 1 shaded with intensity level of 0.3 and two modules in string 2 are shaded with intensity level of 0.6 all at time 1 s.

In figs. 5 and 6 it is shown that both shading intensity and number of shaded modules are correctly calculated. Shading factor is 1/3 for string 1 and 2/3 for string 2 after 1 s. Although shading intensity estimation in this case is not completely accurate, but the error is minor and can be neglected.

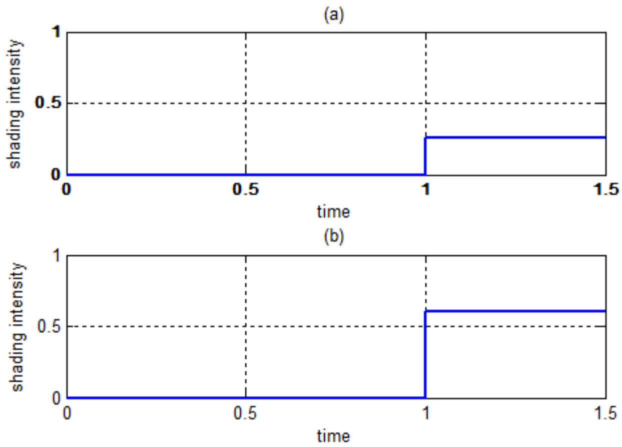

Fig. 5.Shading intensity in (a) string 1 and (b) string 2

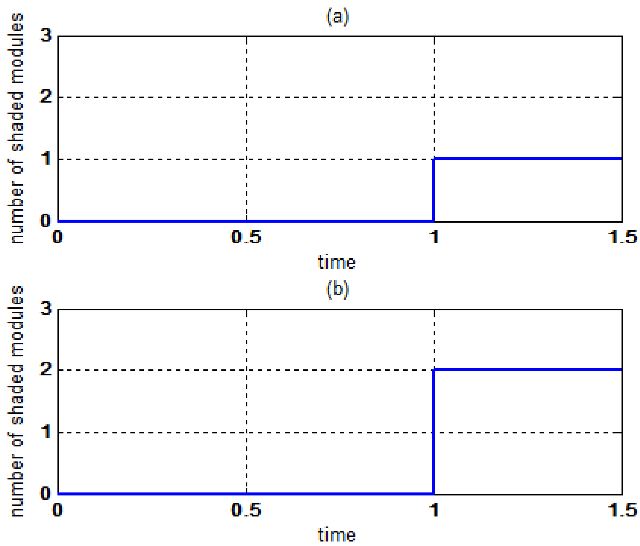

Fig. 6. Number of shaded modules in (a) string 1 and (b) string 2

IV. Conclusion and Discussion

In this paper, a method for estimation of shading intensity and shading factor of a partially shaded PV system is proposed. The proposed method is implemented by connecting a current sensor series to each string of the array. Current variations of each string are used for recognizing PSC and estimating shading intensity. Shading factor is also calculated using the voltage change and the shading intensity estimated before. Matlab/Simulink simulations of a partially shaded PV system are carried out to validate the proposed method. The results show that this method is able to estimate shading intensity and shading factor under different shading scenarios. The proposed method is fast, accurate and only requires the datasheet specifications. Therefore, it can be used for any PV system.

Future work will be focused on developing a more general topology in which several strings are connected to one current sensor, in order to reduce costs and simplify the method for larger PV systems. The method will also be more generalized and take the effects of temperature variations into consideration.

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