Temperature Dependency of Partial Shading Effect and Corresponding Electrical Characterization of PV panel

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***Abstract*—Partial shading of PV array occurs when it gets covered by some passing clouds, buildings or nearby modules. Analysis of electrical behavior of PV array in case of partial shading done so far considers only the fall of different solar irradiance on different modules with working temperature of all PV panels same as ambient temperature. This paper presents the mathematical formulation of cell working temperature which is different from ambient temperature. Partial shading effect under different cell working temperatures and solar irradiances is analyzed and presented through MATLAB based simulation.**

***Index Terms*—Ambient Temperature, Irradiance, Partial Shading**

I. INTRODUCTION

Solar photovoltaic cell is a semiconductor device which generates electrical energy when photons strike against it [1]. A series or parallel connection of such PV cells provides a desired rating of current and voltage of the panel prepared. Current generated depends upon the solar irradiance received and temperature of the PV cells. Under uniform solar irradiance fall, all PV cells conduct in forward biased condition, but when different PV cells receive different solar irradiances, some of the PV cells becomes reverse biased and dissipates power in the form of heat. Manufacturer provides bypass diode to avoid this hot spot formation [2]-[3]. Due to presence of bypass diode, PV panel electrical behavior is found to be complex with multiple peaks in power curve [4].

Analysis of partial shading condition and its effect on electrical characteristics of PV panel is discussed in literature. In [5], a MATLAB based modeling is presented to study the partial shading effect on PV panel characteristics. Both simulation and experimental results verify the presence of multiple peaks in power output of PV panels. In [6]-[7] a simplified formula for calculating maximum power point (MPP) is derived.

All these works available in literature present partial shading effect using a common ambient temperature for all PV panels involved in analysis. Under the effect of continuous solar radiation fall, internal processes take place within semiconductor material and large amount of solar radiation flux that degraded at the surface increases the working temperature of the PV panel [8]. This paper has introduced this effect in analysis of partial shading effect on electrical behavior of PV panel. The paper is organized as follows. Section II presents mathematical formulation of relation between ambient temperature and PV cell working temperature. Section III presents partial shading effect based on actual working temperature. Simulation and results are presented in section IV.

II. PV CELL WORKING TEMPERATURE

Operating temperature of PV module has dependency on its thermal and physical properties, solar irradiance and wind speed. Heat transfer mechanisms like conduction, convection and radiation govern the heating of front and back side of the module. Electrical characteristics of PV panel are found to be governed by the temperature of the p-n junction. This temperature which is different from the ambient temperature is called operating cell temperature and is represented by T_C. Under steady state energy balance condition, a relation between operating temperature T_C and ambient temperature T_a is given as (1),

$$\eta_c G_T = (\tau\alpha)G_T - U_L(T_C - T_a) \tag{1}$$

Where,

η_c = Module electrical efficiency

G_T = Instantaneous solar irradiance in W/m^2

τ = Transmittance of glazing

α = Solar absorptance of PV layer

U_L = Overall thermal loss coefficient in W/m^{2}K

With simple rearrangement (1) can be written as,

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$$T_C = T_a + (\tau\alpha)\left(\frac{G_T}{U_L}\right)\left[1 - \frac{\eta_C}{\tau\alpha}\right] \quad (2)$$

Manufacturer's datasheet for PV panel provide rated electrical parameters at nominal operating cell temperature (NOCT) which is 25^0 C cell temperature, 1000 W/m^2 solar irradiance, 20^0 C ambient temperatures, 1m/s average wind speed and zero electrical load. Extending equation (2) for NOCT conditions, η_c=0 because of zero electrical load condition, we obtain the relation for thermal loss coefficient as given below,

$$U_L = \frac{(\tau\alpha)G_{NOCT}}{T_{NOCT} - T_{a,NOCT}} \quad (3)$$

Substituting (3) into (2), we get a final relation for operating cell temperature as,

$$T_C = T_a + \left(\frac{G_T}{G_{NOCT}}\right)\left(T_{NOCT} - T_{a,NOCT}\right) \quad (4)$$

III. PARTIAL SHADING EFFECT

Electrical equivalent circuit of PV cell is given in fig. 1. Fundamental equations governing the electrical characteristics of PV cell with cell operating temperature included is given below,

$$I_{pv} = I_{ph} - I_D - \frac{V_D}{R_{sh}} \quad (5)$$

$$I_{ph} = I_{sc} + K_1(T_c - T_{NOCT})\frac{G_T}{G_{NOCT}} \quad (6)$$

$$I_D = I_0\left(e^{\frac{V_D}{V_T A}} - 1\right) \quad (7)$$

A solar panel consists of number of PV cells connected in series and parallel. Under partial shading condition, different PV cells receive different solar irradiances. A PV cell is bound to allow current only less than its short circuit current for a given value of solar irradiance. If two PV cells connected in parallel receive different irradiances, only those cells whose short circuit current at that specific irradiance is higher than current flowing through array conducts. This results in reverse bias operation of some of the PV cells which leads to hot spot formation in PV panel. In order to avoid the hot spot formation, bypass diodes are provided as shown in fig. 2. When a current more than that of short circuit value flows through the PV cell, bypass diode operates and short circuit the respective PV cell terminal making its voltage contribution zero. This causes multiple peaks in power curve. Electrical characteristics of PV panel under partial shading condition hence differ from that of uniform solar irradiance fall.

Analysis of partial shading effect on electrical characteristics done so far is based on assumption that the cell working temperature same as ambient temperature. This paper

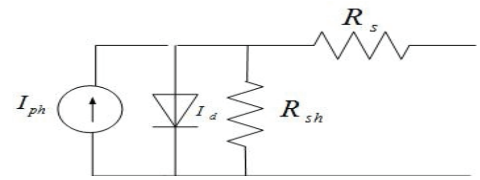

Figure 1. Electrical equivalent circuit of PV cell

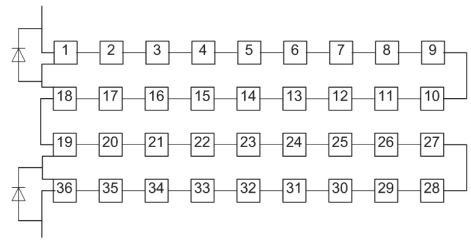

Figure 2. Configuration of Bypass diode in a PV panel

introduces cell operating temperature as the working temperature for PV panel. Analysis based on this formulation produces electrical characteristics which are compared with the earlier analyses.

IV. SIMULATION AND RESULTS

Simulation carried out in this paper is based on MATLAB/Simulink platform. Three PV panels of the same ratings are considered to be connected in series. The net voltage contribution of any PV panel depends upon the state of operation of bypass diode connected to it.

One of the most popular manufacturing configurations is to provide one bypass diode covering 18 solar cells [2]. This study uses a PV panel having 116 solar cells in series. Each PV panel includes 7 bypass diodes covering for 116 solar cells. When required, all 7 bypass diodes operate simultaneously and isolate the respective PV panel.

Three different cases are compared in this paper. Case I considers that all PV panels receive same magnitude of solar irradiance and operate at same ambient temperature. Case II presents the partial shading effect when all PV panels receive different solar irradiance but operate at same ambient temperature. Case III incorporates the operating cell temperature corresponding to different solar irradiances. Operating cell temperature is calculated from (4) corresponding to given NOCT conditions. Table I presents the PV cell rating used for simulation in this paper. The data required for three different cases considered in simulation as follows,

Case I: $G_1=G_2=G_3=1000$ W/m^2, $T_a=T_c=30^0$ C

Case II: $G_1=1000$ W/m^2, $G_2=600$ W/m^2, $G_3=400$ W/m^2, $T_a=T_c=30^0$ C

Case III: $G_1=1000$ W/m^2, $G_2=600$ W/m^2, $G_3=400$ W/m^2, $T_{a1}=T_{a2}=T_{a3}=30^0$ C, $T_{c1}=35^0$ C, $T_{c2}=33^0$ C, $T_{c3}=32^0$ C

I-V and P-V characteristics for different cases are presented and compared in this paper. Results show the variation in electrical characteristics under different cases. Since case III considers most of the practical condition out of Three cases, results obtained for case III can be considered as most accurate one.

TABLE I. PV PANEL DATASHEET

Electrical Parameters	Rating
Rated Power	70 W
Open circuit voltage	88 V
Short circuit current	1.23 A
Current at MPP	1.07 A
Voltage at MPP	65.5 V
Temperature coefficient for current	0.0004
Temperature coefficient for voltage	-0.0025
No of cells in series/parallel	116/1

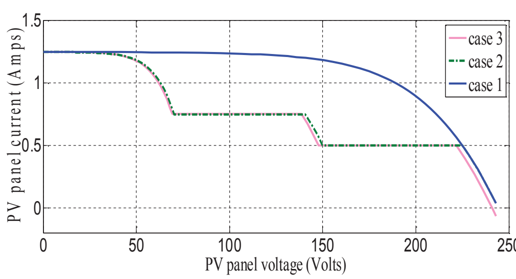

Figure 3. I-V characteristics of PV panel for different case studies

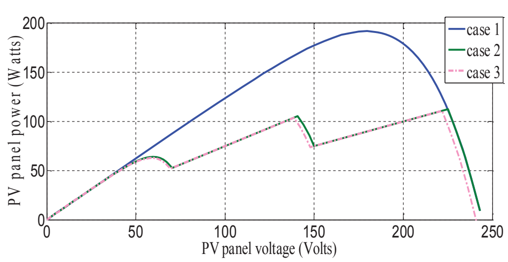

Figure. 3. P-V characteristics of PV panel for different case studies

CONCLUSION

Mathematical formulation is presented in this paper for obtaining actual operating cell temperature. So far the analyses have considered the ambient temperature as the working temperature of PV cells for the partial shading analysis. This work presented the electrical characteristics of PV panel under partial shading with actual operating temperature of the cell calculated from the physical and thermal properties of PV cells.

Results show that the I-V and P-V characteristics differ from earlier analyses. Maximum power point (MPP) in case of partial shading and actual cell operating condition considered appears at a different voltage. Also maximum power that can be fetched from the PV panel is reduced. So the results in actual scenario are pessimistic. This work can help in calculating actual power generation from a solar based power plant under partial shading condition.

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