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Differentiation of multiple maximum power points of partially shaded photovoltaic power generators

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ABSTRACT

Partial shading conditions have a major effect on the electrical characteristics of photovoltaic (PV) power generators. In this paper, the effects of partial shading on maximum power points (MPPs) of a PV power generator have been systematically studied by using Simulink simulation model of a PV power generator composed of 18 series-connected PV modules. It is shown that the local MPPs can be classified into MPPs at low and high voltages based on the MPP operating point of the PV generator. The results also show that based on the MPP current and voltage it is possible to directly know if the MPP at high voltages is a local or a global MPP. The differentiation between local and global MPPs at high voltages is based on the voltage difference between the actual MPP voltage at high voltages and the theoretical MPP voltage under corresponding uniform conditions. This differentiation method was also tested to work correctly by utilizing experimental measurements of the Tampere University of Technology Solar PV Power Station Research Plant. By using this method, it can be identified if the system is operating at a local or a global MPP. This method can further be utilized to develop global MPP tracking algorithms.

1. Introduction

The operation of photovoltaic (PV) power generators is highly affected by the operating conditions such as irradiance and temperature of the PV cells [1]. Under uniform conditions, the nonlinear electrical characteristics of the generators have only one point at which the maximum power can be obtained, i.e. the maximum power point (MPP). Under non-uniform conditions such as partial shading, the operating point of individual PV cells of the generator is not at the MPP (although the generator might operate at its MPP) due to the interconnections between the PV cells in a PV module and between the PV modules of the generator. Partial shading conditions have a significant effect on the operation and energy yield of the generators [2–4].

Partial shading causes mismatch losses [5–7] and affects the operation of the generators in such a way that the electrical characteristics have multiple MPPs [8] because of the operation of bypass diodes connected in anti-parallel with the PV cells to protect the cells against hot-spot heating [9–11]. This will complicate the extraction of maximum available power, which is usually done using maximum power point tracking (MPPT) algorithms. Conventional MPPT algorithms that are based on hill climbing method are unable to recognize multiple MPPs and can easily operate at a local MPP instead of the global one [12–15].

Partial shading conditions can occur due to shading caused by static objects such as buildings, trees or by moving objects such as clouds and, therefore, affect all practical generators to some extent. The effect of partial shading on the electrical characteristics of PV power generators has already been studied in several papers, for example in Refs. [16–23]. In many of these papers, the effect of partial shading has been shown by using current–voltage (I–U) and power–voltage (P–U) curves when the generator operated under some specific operating conditions. In Ref. [23], more systematic studies have been conducted about the effects of all partial shading conditions with two irradiances affecting the generator.

This paper presents the effects of partial shading on the characteristics of MPPs based on a systematic and comprehensive simulation study. The characteristics of both local and global MPPs are presented under all partial shading conditions with two irradiances affecting the PV power generator. According to the results it is possible to estimate whether the present MPP at which the generator is operating is the global MPP or is there an MPP with more power available. This information could be used, e.g., to improve the operation of existing MPPT algorithms or even to develop completely new algorithms.

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Nomenclature

α	absorptivity of PV module
ΔT	temperature difference (K)
ε_{back}	back surface emissivity
ε_{front}	front surface emissivity
σ	Stefan–Boltzmann constant (W/m^2 K^4)
τ	time step (s)
A	ideality factor
A_{bypass}	ideality factor of bypass diode
A_{mod}	surface area of PV module (m^2)
C_{mod}	heat capacity of PV module (J/K)
F_{fr}	view factor from front to roof
F_{fs}	view factor from front to sky
G	irradiance (W/m^2)
G_{STC}	irradiance in standard test conditions (W/m^2)
h_{conv}	convection heat transfer coefficient of PV module (W/m^2 K)
I	current (A or p.u.)
$I_{MPP,STC}$	current at MPP in standard test conditions (A)
I_o	dark saturation current (A)
$I_{o,bypass}$	dark saturation current of bypass diode (A)
$I_{o,STC}$	dark saturation current in standard test conditions (A)
I_{ph}	light-generated current (A)
$I_{ph,STC}$	light-generated current in standard test conditions (A)
$I_{SC,STC}$	short-circuit current in standard test conditions (A)
k	Boltzmann constant (m^2 kg/s^2 K)
K_i	temperature coefficient of short-circuit current (A/K)
K_t	temperature-rise coefficient (K m^2/W)
K_u	temperature coefficient of open-circuit voltage (V/K)
N_s	number of series-connected cells in a PV module
P	power (W or p.u.)
$P_{MPP,STC}$	power at MPP in standard test conditions (W)
P_{out}	electric power produced by PV module (W)
q	elementary charge (C)
q_{in}	incoming solar radiation to PV module (W)
q_{loss}	heat transfer losses from PV module to environment (W)
R_s	series resistance (Ω)
$R_{s,bypass}$	series resistance of bypass diode (Ω)
R_{sh}	shunt resistance (Ω)
t	time (s)
T	temperature of a PV cell/module (K)
T_{amb}	ambient temperature (K)
T_{rack}	mounting rack temperature (K)
T_{roof}	roof temperature (K)
T_{sky}	sky temperature (K)
T_{STC}	PV module temperature in standard test conditions (K)
U	voltage (V or p.u.)
U_{GMPP}	global MPP voltage (V)
$U_{MPP,diff1}$	relative MPP voltage difference between the highest MPP voltage and estimated MPP under uniform conditions (%)
$U_{MPP,diff2}$	relative MPP voltage difference between the second highest MPP voltage and estimated MPP under uniform conditions (%)
$U_{MPP,STC}$	voltage at MPP in standard test conditions (V)
U_{MPP1}	highest MPP voltage (V)
U_{MPP2}	second highest MPP voltage (V)
$U_{MPP1,est}$	estimated MPP voltage under uniform conditions based on MPP with highest voltage (V)
$U_{MPP2,est}$	estimated MPP voltage under uniform conditions based on MPP with second highest voltage (V)
$U_{OC,STC}$	open-circuit voltage in standard test conditions (V)
U_t	thermal voltage (V)

2. Research method and approach

2.1. Simulation model of the photovoltaic generator

The model presented by Villalva et al. [24] has been used in this paper to simulate the operation of the PV power generator. The model is based on the well-known one-diode model of a PV cell [25,26]. According to the one-diode model including parasitic resistances, the current I of a PV cell is

$$I = I_{ph} - I_o\left[\exp\left(\frac{U+R_sI}{AU_t}\right)-1\right] - \frac{U+R_sI}{R_{sh}}, \tag{1}$$

where I_{ph} is the light-generated current, I_o the dark saturation current, U the voltage, R_s the series resistance, R_{sh} the shunt resistance, A the ideality factor and U_t the thermal voltage of the PV cell. The series and shunt resistances as well as the ideality factor represent non-idealities in a PV cell.

The simulation model of a PV module can be obtained by scaling the parameter values used in the one-diode model for a PV cell by the number of PV cells in the module. The thermal voltage of the PV module is then defined by $U_t = N_s kT/q$, where N_s is the number of cells in the module, k the Boltzmann constant, T the temperature of the module and q the elementary charge.

Light-generated current I_{ph}, which is assumed to be directly proportional to irradiance, can be obtained as a function of short-circuit (SC) current from the one-diode model in any environmental condition by neglecting the product of I_o and the exponential term subtracted by one in (1) at SC ($U = 0$ V) which yields

$$I_{ph} = \left(I_{SC,STC} + K_i\Delta T\right)\frac{G}{G_{STC}}\frac{R_{sh}+R_s}{R_{sh}}, \tag{2}$$

where $I_{SC,STC}$ is the SC current in standard test conditions (STC), K_i the temperature coefficient of SC current, G the irradiance reaching the surface of the module and $\Delta T = T - T_{STC}$, where T is the temperature of the PV module. In STC, the module temperature T_{STC} and the irradiance G_{STC} are 25 °C and 1000 W/m^2, respectively. The spectral conditions in STC are AM1.5.

The dark saturation current I_o is obtained in open-circuit (OC) under all operating conditions as

$$I_o = \frac{I_{ph} - \left(U_{OC,STC} + K_u\Delta T\right)/R_{sh}}{\exp\left[\left(U_{OC,STC} + K_u\Delta T\right)/(AU_t)\right] - 1}, \tag{3}$$

where $U_{OC,STC}$ is the OC voltage in STC. The effect of temperature on OC voltage has been taken into account by the temperature coefficient of OC voltage K_u. The effect of temperature and irradiance on light-generated current has been taken into account by (2).

A method to obtain the series and the shunt resistances by iteratively matching the I–U and P–U curves to the values in STC is also introduced in Ref. [24]. It is based on three points in the electrical characteristics of the PV module: the OC voltage, the SC current and the MPP voltage and current. The ideality factor A of 1.3