

Power Losses in Long String and Parallel-Connected Short Strings of Series-Connected Silicon-Based Photovoltaic Modules Due to Partial Shading Conditions

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Abstract—Configuration of a photovoltaic (PV) power generator has influence on the operation of the generator, especially if it is prone to partial shading. In this paper, the mismatch losses and the power losses due to failure in tracking of the global maximum power point of a long string of 18 series-connected PV modules and three short strings of six series-connected PV modules connected in parallel are investigated under different partial shading conditions by using a MATLAB Simulink simulation model. The generators with parallel-connected short strings are studied in case when they have the same operating voltage and when they operate as separate strings. The results show that long series connection of modules and parallel connections of strings via a single inverter to the electrical grid should be minimized to avoid losses in case of partial shading conditions. Under partial shading conditions, short strings operating separately have the lowest power losses.

Index Terms—Grid-connected photovoltaic power generator, mismatch losses, photovoltaic cells, photovoltaic systems, solar energy, solar power generation.

I. INTRODUCTION

GLOBAL warming and the limited resources of fossil fuels have increased the need for renewable energy [1]–[3]. Solar radiation is the largest source of renewable energy [4], [5] and the only one by which the present primary energy consumption can be replaced.

Photovoltaic (PV) power generators convert the energy of solar radiation directly to electrical energy without any moving parts. PV power generators can be classified into stand-alone and grid-connected generators [6]. In stand-alone systems, the energy storage has big influence on the design of the systems. In grid-connected systems, the grid acts as an energy storage into which the PV power generator can inject power whenever power is available.

The electrical grids have specific voltage levels. They are much higher than the maximum voltage of a single silicon-based PV cell. In order to interface PV power generators with the grid, the PV cells are connected in series to form PV modules. The

voltage of an individual PV module is normally still too low to be conveniently used as a grid-connected PV power generator. Therefore, the generators are built by connecting PV modules in series and in parallel in order to get a sufficient voltage level and to increase the nominal power of the generator.

The series connection of PV cells is prone to mismatch power losses if the electrical characteristics of the PV cells are not similar or the cells do not operate under uniform conditions. The PV cell with the lowest short-circuit (SC) current limits the current of the whole series connection [7]. SC currents of the PV cells can vary due to various technical or environmental reasons. Technical reasons can be minimized during the manufacture of PV modules and during system design phase, but environmental reasons are harder to avoid.

One major environmental reason for uneven SC currents is partial shading of the PV power generator due to clouds, trees, buildings, etc. Under partial shading conditions, for example, if one PV cell of the generator composed of series-connected cells is shaded, the SC currents of the non-shaded cells are higher than the SC current of the shaded cell. If then the current of the PV power generator is higher than the SC current of the shaded cell, the shaded cell will be reverse biased due to the other cells in the series connection. In this case, the reverse biased cell acts as a load in the series connection dissipating part of the power generated by the other cells leading to power losses. This can also lead to hot spots in the shaded cell and the cell can be damaged [8]. The worst situation is when the series connection is short circuited. Then, the shaded cell dissipates all of the power generated by the other cells in the series connection.

In order to prevent PV cells from damaging due to hot spots, manufacturers of PV modules have connected bypass diodes in antiparallel with PV cells [9]. There is a total amount of 54 series-connected PV cells in a typical PV module designed to be used in grid-connected PV power generators with three bypass diodes, each of them connected in antiparallel with 18 PV cells. When some of the PV cells of the PV module become shaded, they become reverse biased and the bypass diode connected in antiparallel starts to bypass the current exceeding the SC current of the shaded cells and limits the power dissipated in the shaded cells.

Under nonuniform conditions when a part of the bypass diodes starts to conduct, the power–voltage (P – U) curve of the PV module shows multiple maxima as illustrated in Fig. 9 in which there are P – U curves of a PV power generator called

Manuscript received June 22, 2011; revised October 19, 2011; accepted November 7, 2011. Date of publication December 13, 2011; date of current version February 17, 2012. Paper no. TEC-00308-2011.

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Digital Object Identifier 10.1109/TEC.2011.2175928

“Parallel strings generator” operating under partial shading conditions. In this case, extraction of maximum power from the PV power generator is not straightforward, because there is one local maximum power point (MPP) at low voltages and another at high voltages. Typically used maximum power point tracking (MPPT) algorithms are based on the hill climbing method [10], [11], which drives the operating point just to the nearest maximum of the $P-U$ curve. They can fail to track the MPP with highest power, the global MPP, when the generator is operating under partial shading conditions. In this case, in addition to mismatch losses, there are also losses due to tracking of a local MPP with lower power instead of the global MPP. Algorithms to track the global MPP in the case of multiple maxima have also been developed, e.g., in [12] and [13], but they tend to be complicated and many of them are unable to track the global MPP under all nonuniform conditions.

Significant effects of partial shading on the electrical characteristics and the energy yield of PV power generators in different generator configurations have been reported by several authors [14]–[25]. In many of these papers, the focus has been on the development of a simulation model for series-connected PV modules and, therefore, only a few current–voltage ($I-U$) or $P-U$ curves have been provided in order to give an idea of the operation of the simulation model and the PV power generator in specific nonuniform conditions. Comparably, in many papers, the focus has been on studying the operation of an MPPT algorithm or an interfacing device. Therefore, we are still short of a comprehensive knowledge about the effects of nonuniform conditions on different PV power generator configurations.

In this paper, the mismatch losses and power losses due to the tracking of a local MPP instead of the global one have been studied. A long string of 18 series-connected PV modules and three short strings of six series-connected PV modules connected in parallel are investigated under different partial shading conditions by using a MATLAB Simulink simulation model. The operation of short strings has been studied in case when strings are connected in parallel and have the same operating voltage and in case when they operate as separate strings. In the simulations, the number of shaded modules and the shading strength have been varied from 0% to 100%.

Typically, the configurations of PV power generators have been named based on the interfacing device used to connect the generators to the electrical grid [25]–[27]. In this paper, the Long string generator corresponds to the string inverter configuration, the Parallel strings generator to the central inverter configuration, and the Multi-string generator to the multi-string inverter configuration.

II. SIMULATION MODEL

The model of a PV module presented by Villalva *et al.* [28] has been used to simulate the operation of a PV power generator. The model is based on the well-known one-diode model of a PV cell [29] shown in Fig. 1. It provides the following relation between the current I and the voltage U of a PV cell:

$$I = I_{ph} - I_0 \left[\exp\left(\frac{U + R_s I}{AU_t}\right) - 1 \right] - \frac{U + R_s I}{R_{sh}} \quad (1)$$

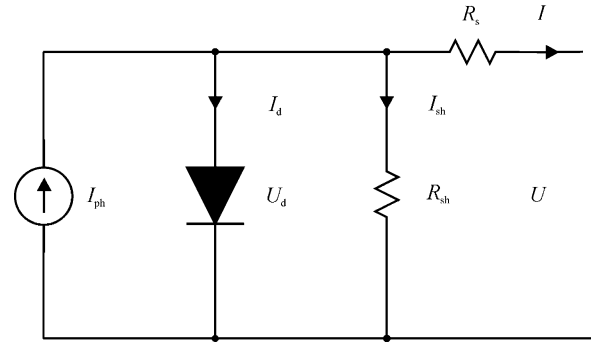


Fig. 1. One-diode model of a PV cell.

where I_{ph} is the light-generated current, I_0 is the dark saturation current, R_s is the series resistance, R_{sh} is the shunt resistance, A is the ideality factor, and U_t is the thermal voltage of the PV cell. I_d and U_d in Fig. 1 are the current and voltage of the diode, respectively. I_d represents the second term in the right-hand side of (1) and $U_d = U + R_s I$. The last term in the right-hand side of (1) is the current through the shunt resistance and is marked with I_{sh} in Fig. 1.

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

It can be seen in Fig. 1 that the light-generated current I_{ph} can be obtained as a function of SC current in any environmental conditions by current division by assuming that in SC condition the diode current I_d is negligible and almost all of the light-generated current flows to the terminals of the module. Accordingly

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

where $I_{SC,STC}$ is the SC current in standard test conditions (STC), K_i is the temperature coefficient of the SC current, G is 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 spectral conditions are AM1.5, the module temperature T_{STC} is 25 °C, and the irradiance G_{STC} 1000 W/m².

The dark saturation current I_0 depends on the temperature, structure, and material of the PV cell. It is obtained by solving (1) in open-circuit (OC) condition. When the effect of temperature on the OC voltage is added, the dark saturation current is given by

$$I_0 = \frac{I_{ph} - (U_{OC,STC} + K_u \Delta T) / R_{sh}}{\exp((U_{OC,STC} + K_u \Delta T) / (AU_t)) - 1} \quad (3)$$

where $U_{OC,STC}$ is the OC voltage in STC and K_u is the temperature coefficient of the OC voltage.

The temperature of the PV module is assumed to depend linearly on irradiance

$$T = T_{amb} + K_t G \quad (4)$$

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