STUDY AND MODELLING OF PV ARRAYS BUILT WITH NON-EQUIVALENT UNITS

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Abstract: Finding the most appropriate configuration of series-parallel connections of PV units to make a PV array is a key issue for obtaining a PV system with maximum generated power. In most cases, a PV array is constructed from a combination of standard PV units (solar cells or panels) connected in series and/or in parallel to obtain the desired power, voltage and current ratings. However, the non-linear behaviour a solar cells or panels exhibits as a function of internal physical parameters and optical irradiance and temperature makes accurate determination of the model parameters a difficult task. In addition to this, a precise determination of the internal physical parameters of cells and panels is not always possible and the different errors introduced on all the parameters during the extraction process induce non negligible errors in the models of the constructed panels. In this paper, the determination of PV array parameters from individual single cell/panel characteristics is developed for a two-diode device model and the effect of equivalent series and shunt resistances on the panels' characteristics and maximum power generation are studied. Simulation results obtained for simple case studies using Matlab/Simulink software are presented and discussed.

Keywords: Photovoltaic, PV system, Solar Cell, PV Array, Matlab, Simulink, Modelling, optimal connection.

1. INTRODUCTION

Photovoltaic (PV) systems have been used worldwide for the last three decades and their first applications were concentrated mainly in remote areas and in places were other types of energy are either very expensive or not feasible. However, with the progressive reduction in their fabrication costs, PV systems know a tremendous increase in different applications [1,2]. The maximum efficiency of utilization of solar panels is obtained at the maximum power operating point, which is a function of the panel physical characteristics, solar irradiation, and temperature. To design a PV-based system, an accurate model of the panel to be used in simulation is often required. Some PV cell/panel equivalent circuit approximations based on a single-diode model have been studied [3-7]. However, the simple models presented give acceptable results only for single crystalline cells. However, for some cost effective materials, the model presented is not accurate enough and the use of two-diode model gives better results [5]. In addition to this, a precise determination of the internal physical parameters of cells and panels is not always possible and the different errors introduced on all the parameters during the extraction process induce non negligible errors in the models of the panels.

In this paper, the electrical parameters of equivalent circuit models of solar panel/array are derived from basic cell/ panel models used to build the panel/array. The effect of temperature, solar irradiation, equivalent series and shunt resistances on the panel/array characteristics are studied on the light of connection approach to obtain maximum power operation of the PV system.

The considered approach is important as it deals with optimizing the layout connection of solar array through maximizing the generated output power. This will therefore minimize the surface to be covered by the solar units. This is the case for solar cars and many other PV applications where the surface to be used is of main concern. The effects the aforementioned PV array parameters on the units layout connections are demonstrated in this work through numerical simulations. Matlab/Simulink software is used for model evaluation, sensitivity analysis, and best connection layouts which give maximum output power.

2. MODEL OF PV PANELS AND ARRAYS

2.1. Analytical Model for Panel/Array

PV panels and arrays may be described in terms of a set of electric parameters that represent solar cell/panel physical properties. This is in addition to the numbers of cells/panels connected in series and/or in parallel. Most of solar cell/panel models available in the literature represent the solar cell by a single diode in parallel with a current source as shown in Fig. 1-a). Note that the current source, the diode, and the shunt resistance R_{SH} are connected to a series resistance R_S through which an electric load is fed [3-4]. However, in order to have more generalized model and obtain better accuracy in the simulation results, the two-diode equivalent circuit model shown in Fig. 1-b) has been developed [5-7]. This last model consists of an ideal current source, which represents the optical irradiation connected in parallel with two different diodes and a shunt resistance R_{SH}. All these elements are connected to a series resistance R_S. Note that diode D_1 models the generation photocurrent, which dominates the total current at small diode voltages whereas diode D_2 models the recombination photocurrent. The recombination photocurrent is dominant at large diode voltages.
The shunt resistance and series resistance are two important parameters in PV cells. This is because the shunt resistance mostly affects the panel power output and the series resistance affects mainly the efficiency and the fill factor [4],[8].

Therefore, the accuracy in determining these two parameters in particular and the knowledge of the errors involved in their determination is a key issue in simulating the panel/array characteristics. For instance the absolute values of R_{SH} are very important in cells qualification testing, module performance testing and failure analysis [8]. With reference to Fig. 1-b), for a generalized cell/panel/ array equivalent circuit, the *I-V* characteristics of solar cells/panels can be expressed in terms of the physical and electrical parameters as,

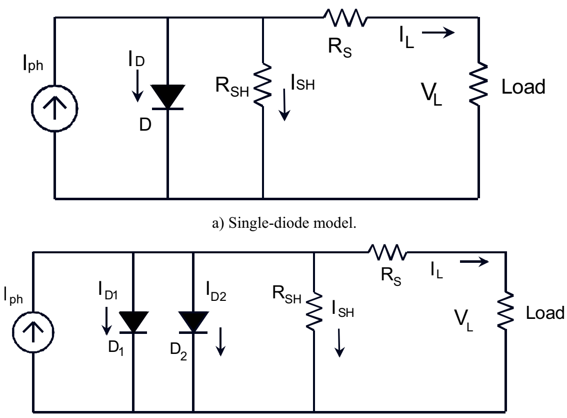
$$I_L = I_{ph} - I_{D1} - I_{D2} - I_{SH} \tag{1}$$

In the above equations, R_S and R_{SH} are the series and shunt resistances respectively, I_{SD1} and I_{SD2} are diffusion and saturation currents respectively, n_1 and n_2 are the diffusion and recombination diode ideality factors, k is the Boltzman's constant, q is the electronic charge, T is temperature in Kelvin, C_0 and C_1 are constants, and G is the irradiation in W/m^2.

Note that in case of a single-diode model shown in Fig. 1-a), either I_{D1} or I_{D2} must be removed from (1).

A typical connection scheme of cells and panels to form a PV array used for power system applications that might feed a resistive load is shown Fig. 2. For this typical array configuration with n_s horizontal units and n_p vertical units, the cells or panels connected in series are numbered as U_{i1} to U_{im} for a row i, where i varies from 1 to n_s, whereas, the panels or cells connected in parallel are designated for a given column j as U_{1j} to U_{nj} where j varies from 1 to n_p. Note that U stands for panel or cell unit.

As indicated above and as it has been reported in the literature, the extracted values of both the series resistance R_S and the shunt resistance R_{SH} have significant errors [8]. It is therefore important to count for this fact while considering and studying the effects of these two parameters on the panel/array characteristics.



a) Single-diode model.

b) Two-Diode model

Fig. 1 PV Cell/Panel/Array electric models. a) Single-diode model, b) Two-diode model

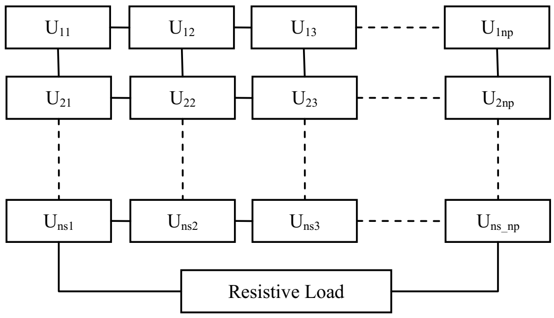


Fig. 2 Typical connections of PV units forming a PV array that feeds a resistive load

Based on the models developed elsewhere [3-5] and by taking into account the change of R_S and R_{SH} from one cell to another one, an improved panel model is proposed. The expressions to be used for the model together with (1) are given in (6-8) below. Typical figures for errors on the above two parameters have been suggested and their effects were studied by simulation using Matlab/Simulink software in [9].

Assuming the errors on cell/panel parameters constant for all cells except for R_S and R_{SH}, and making an appropriate change of variables on saturation currents and ideality factors, expressions of equivalent resistances R_S and R_{SH} are suggested. This formulation is supported by practical considerations where the values of these two parameters are affected by the way external connections of cells/panels are done as well as by the aging process of the array. The change of variables has been done on the physical parameters of a single cell described by (1-5). Hence, if we designate by R_{SE} and R_{SHE} the equivalent series and shunt resistances of the whole panel/array respectively, it is possible to write [9],

$$R_{SE} = \sum_{j=1}^{n_p}\left(\sum_{i=1}^{n_s} R_{S_{ij}}^{-1}\right)^{-1}, R_{SHE} = \sum_{j=1}^{n_p}\left(\sum_{i=1}^{n_s} R_{P_{ij}}^{-1}\right)^{-1} \tag{6}$$

$$n_{1E} = n_s.n_1, \quad n_{2E} = n_s.n_2$$

$$I_{SD1E} = n_p.I_{SD1}, \quad I_{SD2E} = n_p.I_{SD2}$$

Thus, equations (2-5) can be extended to arrays as,

$$I_{D1} = I_{SD1E}\left[\exp\left(\frac{q}{n_{1E}kT}\left(V_L - I_L R_{SE}\right)\right) - 1\right] \tag{7}$$

$$I_{D2} = I_{SD2E}\left[\exp\left(\frac{q}{n_{2E}kT}\left(V_L - I_L R_{SE}\right)\right) - 1\right] \tag{8}$$

$$I_{sh} = \frac{V_L - I_L R_{SE}}{R_{SHE}} \tag{9}$$

$$I_{ph} = n_p \times \left(C_0 + C_1 T\right) \times G \tag{10}$$

Note that since the cell R_S and R_{SH} vary with both solar irradiance and temperature, and accordingly, the equivalent array series and shunt resistances R_{SE} and

R_{SHE} will also vary with irradiance and temperature. These two factors can easily be considered in simulations. A formulation of this dependency for one solar cell can be found in reference [10].

2.2. Matlab/Simulink Modeling and Simulation

A Matlab/Simulink program was implemented for simulating a six-unit PV array. Based on different configurations of series and parallel connections for the different units, several array topologies can be obtained. Fig. 3 shows one topology of the six-unit PV-array model as it is implemented with SimPowerSystem toolbox of Matlab/Simulink. Note that the PV units are denoted by U_{ij} where i and j refer to row and column numbers of the array, respectively.

Each PV unit is modeled by the Simulink block shown in Fig. 4 where the inputs to the cell model are the temperature T in ^oK and the solar irradiation G in W/m^2. The output is a voltage which is directly connected to a variable current load. The model of the panel was based on the implementation of equations (1)-(9).

The default PV-unit parameters used to study the suggested model are as follows: C_0=4.38x10^{-3} A.m^2/W, C_1=0 A.m^2/W/K, G=1000W/m^2, T=353K, n_1=39.6, n_2=76, I_{SD1}=4.8x10^{-9}A, I_{SD2}=11x10^{-5}A. The series and shunt resistances are kept variable for the reasons pointed out earlier to see their effect on the output power of the simulated arrays. However, their typical values were taken R_P=100 Ω and R_S=0.1 Ω. This makes PV units generating a maximum power of 72W, at 19V and 3.8A each.

The total current generated by the array can be varied by changing the load resistance or by just considering a variable-current sink-load. The advantage of using a variable-current sink-load is that the whole I-V characteristic of the array can be obtained easily at the end of each simulation run. Both voltage and current at the output of the array are measured and the maximum power point is determined from the I-V characteristic as follows.

$$P_{max} = \max(V \times I) = V_{opt} \times I_{opt} \quad (11)$$

Where, V_{opt} and I_{opt} are respectively, the optimum voltage and current operating point for the array.

2.3. Study Cases

The effects of having an array made of units having different irradiations, temperatures, series resistances, or shunt resistances, on the maximum power generated by the array, are investigated by considering several study cases.

2.3.1. Effect of units with different irradiations

The effect of having units with different irradiations G_{ij} is investigated first. For simplicity, only three pairs of units were considered having different irradiations. Ten different configurations can be considered from the connection of these six units as shown in Fig. 5. Note that when a parameter is varied, the other parameters of the cells are considered identical and equal to their default values (refer to section 2.2. above).

2.3.2. Effect of units with different temperatures

The effect of having units with different temperatures T_{ij} is also investigated. Here also, for simplicity reason, three pairs of units only were considered having different temperatures. Ten different configurations can be considered from the connection of these six units as shown in Fig. 6.

2.3.3. Effect of having units with different series resistances

To investigate the effect of cell internal equivalent series resistance R_s, ten other models are also built for the ten different configurations as shown in Fig. 7.

2.3.4. Effect of having units with different shunt resistances

To investigate the effect of cell internal equivalent shunt resistance R_{sh}, ten other models are also built for the ten different configurations. The configurations that were considered are similar to those shown in Fig. 7 with R_s replaced with R_{sh}.

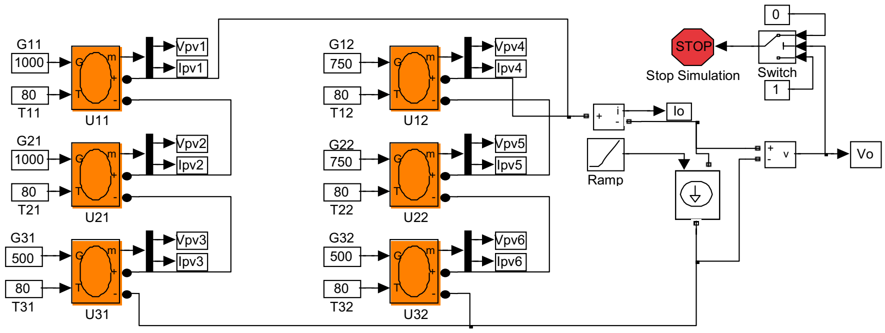


Fig. 3 PV array model implemented with SimPowerSystem toolbox of Matlab/Simulink

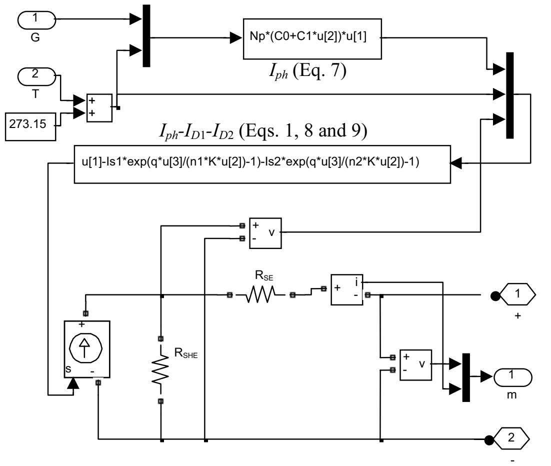


Fig. 4 Solar cell detailed model implemented with Matlab/Simulink

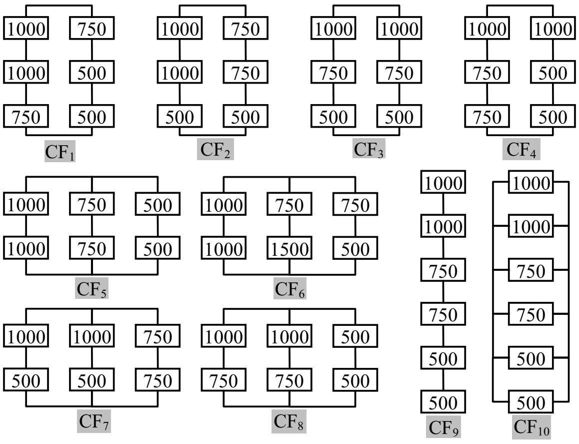


Fig. 5 The ten possible configurations for PV units with different irradiations

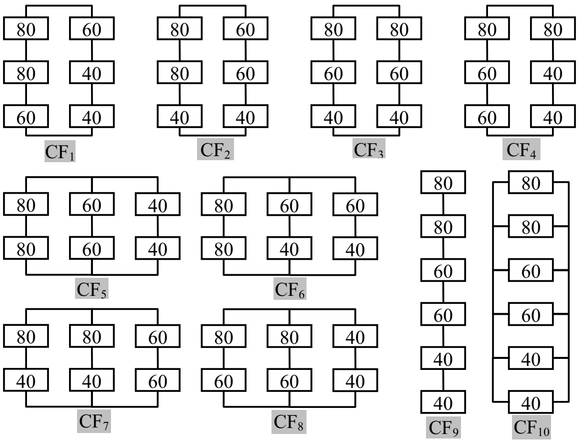


Fig. 6 The ten possible configurations for PV units with different temperatures

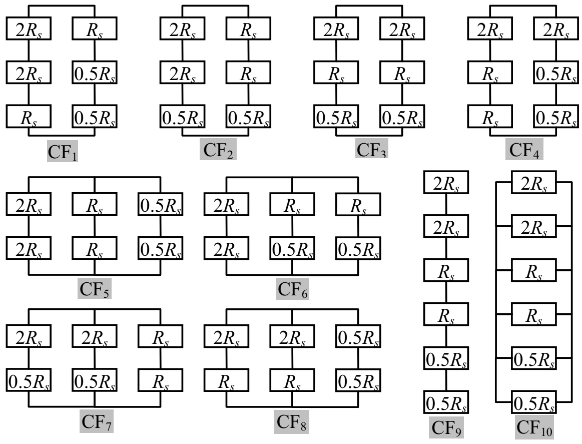


Fig. 7 The ten possible configurations for PV units with different series resistance

3. RESULTS

Simulation results depicted in Table 1, show that the maximum power delivered by the array with different unit irradiations varies with the configuration of the units' connections.

Table 1 Simulation results for *G* effect

Configuration #	V_{opt}	I_{opt} (A)	P_{max} (W)
CF_{10}	18.93	16.65	315.09
CF_5	37.86	8.32	315.09
CF_8	38.78	7.61	295.05
CF_6	38.67	7.56	292.19
CF_1	58.93	4.83	284.87
CF_4	58.26	4.74	276.24
CF_7	39.15	6.58	257.65
CF_3	60.81	3.92	238.55
CF_9	121.64	1.96	238.55
CF_2	60.68	3.92	237.95

Note that the array configurations CF_{10} and CF_5 in Table 1 generate the highest maximum power. Based on this result, it is possible to conclude that it is preferable to connect in series only units exposed to similar irradiations. Thus, for every column *j* we should have:

$$G_{1j} \cong G_{2j} \cong \ldots \cong G_{n_s j} \tag{12}$$

Table 2 presents the results obtained when different temperatures are considered. Notice that the lowest maximum power is obtained for CF_{10} and the highest maximum power is obtained for CF_9. From Fig. 6, it is clear that the worst case scenario is to connect all units with different temperatures in parallel and the best case scenario is to connect all units in series. It is also noticed that when parallel connections are used like in CF_3 and CF_7, the sum of the temperatures per column should be similar. This leads to having:

$$\sum_{i=1}^{n_s} T_{i1} \cong \sum_{i=1}^{n_s} T_{i2} \cong \cdots \sum_{i=1}^{n_s} T_{ij} \cdots \cong \sum_{i=1}^{n_s} T_{in_p} \tag{13}$$

Table 2 Simulation results for *T* effect

Configuration #	V_{opt} (V)	I_{opt} (A)	P_{max} (W)
CF_9	107.76	3.76	404.63
CF_3	53.88	7.51	404.63
CF_7	35.92	11.26	404.63
CF_2	53.76	7.51	403.71
CF_4	53.76	7.51	403.71
CF_1	53.39	7.51	401.03
CF_6	35.59	11.27	401.01
CF_8	35.52	11.26	400.10
CF_5	35.44	11.27	399.24
CF_{10}	19.17	20.00	383.43

Table 3 lists the results obtained for the ten configurations presented in Fig. 7, where the effect of units with different series resistances is investigated.

Table 3 Simulation results for R_s effect

Configuration #	V_{opt} (V)	I_{opt} (A)	P_{max} (W)
CF_3	56.63	7.48	423.29
CF_9	113.27	3.74	423.29
CF_7	37.74	11.21	423.12
CF_4	56.61	7.47	422.97
CF_2	56.58	7.46	422.02
CF_8	37.66	11.17	420.77
CF_1	56.52	7.44	420.48
CF_6	37.73	11.12	419.60
CF_5	37.70	11.12	419.14
CF_{10}	20.31	20.00	406.17

Notice that, for units with different internal series resistances, the maximum power is obtained when columns with similar total equivalent series resistances are connected in parallel (configurations CF_3, CF_7, and CF_9).

Based on these results, it is possible to conclude that it is preferable to form parallel connections of columns with similar total equivalent series resistances.

$$\sum_{i=1}^{n_s} R_{si1} \cong \sum_{i=1}^{n_s} R_{si2} \cong \cdots \sum_{i=1}^{n_s} R_{sij} \cdots \cong \sum_{i=1}^{n_s} R_{\sin_p} \quad (14)$$

Table 4 shows the results obtained when the effect of the internal equivalent shunt resistance is investigated using the ten configurations shown in Fig. 7 except that R_s is replaced by R_{sh}. Notice, that the shunt resistance has no significant effect for all configurations except when all cells are connected in parallel (configuration CF_{10}). Notice also that the results obtained in Table 4 reflect the same conclusion as for the case of series resistance (Table 3).

$$\sum_{i=1}^{n_s} R_{shi1} \cong \sum_{i=1}^{n_s} R_{shi2} \cong \cdots \sum_{i=1}^{n_s} R_{shij} \cdots \cong \sum_{i=1}^{n_s} R_{shin_p} \quad (15)$$

The units with lower shunt resistances tend to absorb more current from other units in their shunt resistances instead of allowing the current flows to the load. This has to be avoided because it creates circulating currents within the units and, hence, decreases considerably the efficiency of the PV array.

Table 4 Simulation results for R_{sh} effect

Configuration #	V_{optx} (V)	I_{opt} (A)	P_{max} (W)
CF_5	38.21	11.17	426.69
CF_8	38.22	11.16	426.51
CF_1	57.35	7.43	426.13
CF_6	38.24	11.14	425.99
CF_4	57.38	7.42	425.63
CF_7	38.28	11.11	425.12
CF_2	57.44	7.40	425.00
CF_3	57.43	7.40	424.95
CF_9	114.88	3.70	424.95
CF_{10}	20.57	20.00	411.37

4. CONCLUSION

The effects of connecting PV units, with non identical parameters, to make an efficient PV array were investigated by simulation. Matlab/Simulink models of PV units and different configurations of PV arrays were built for this purpose. The simulation results show that the unequal parameters of the PV units such as solar irradiation, PV temperature, and series and shunt equivalent circuit resistances, affect the maximum output power generated by the array.

It is well known that the efficiency of PV cells/panels/arrays is a very critical issue in the wide-spreading of the PV system applications. Therefore, it is important to find the optimum configuration for connecting the units in series and parallel in order to maximize the PV array generated output power, hence, reaching its maximum efficiency.

The proposed analysis will be very useful for designers of PV systems to select the optimum connection of their PV units to generate the maximum possible power form the arrays. In addition to this, it will minimize the surface to be covered by the solar units as their total surface is of critical importance for several PV applications such as solar vehicles and other PV mobile systems.

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