

EFFICIENCY STUDY OF DIFFERENT PHOTOVOLTAIC PLANT CONNECTION SCHEMS UNDER DYNAMIC SHADING

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ABSTRACT

An important growth in the power of the photovoltaic systems connected to a grid has recently been observed. In spite of the advances in module technology, the problems in the system design increased, especially regarding the surface of the earth they occupy. In this work we propose a complete model for plant simulation with different wiring diagrams and under dynamic shading. Results obtained from simulations showed that the configuration with the lowest performance was that of only one serial-parallel group, whereas the highest efficiency corresponded to a design of groups of modules in parallel connected then in series. In general, a higher efficiency was obtained diminishing the quantity of modules in series and increasing their number in parallel. The simulation model proposed allows exploring different alternatives of wiring modules and finding the most efficient configurations for photovoltaic plants of medium and high power.

Keywords: Photovoltaic plant, simulation, efficiency, dynamic shading

1. INTRODUCTION

Among photovoltaic systems, stand-alone or isolated systems and those connected to an electrical grid can be distinguished. When the system connected to a network is a large power plant, there is a considerable number of constituent modules. The energy generated is a function of climatic variables such as radiation and temperature [1]. The search algorithms of the point of maximum power are generally based on the assumption that the power curve generated has a single peak [2]. Shading makes the output power of the panel array to present several maximum points, and the efficiency to fall significantly [3].

The choice of a wiring design maximizing the efficiency of modules and inverters, considering dynamic shading effect, is a scarcely studied aspect. Works referred to simulation of photovoltaic systems, without considering the shading effects can be found in the bibliography [4]. Other studies considered this effect but at the level of a single module [3, 5], or started from the equation of each panel in order to simulate the behavior of an array when affected by a cloud of static type [6], at the expense of a considerable calculation time. There are also studies which considered how to obtain the highest power, in an attempt to achieve optimum dimensioning of the system by means of the ratio between the installed peak power of the array and the rated power of the inverter, without taking into account shading [7].

This work proposes a new model for the simulation of photovoltaic plants formed by a great quantity of modules. This model allows not only studying the system behavior in the presence of static shading but also in the presence of shading varying in time. The model also considers the effect of the cloud at individual level on each panel. There follows the description of the model, as well as the efficiency measures used and the results and discussion for the different configurations.

Conclusions are summarized in the last section.

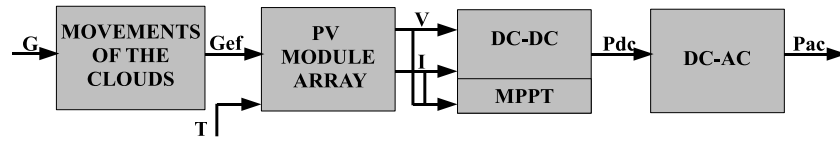


Figure 1. General design of the simulation

2. MODEL FOR SIMULATION

The proposed model for simulation can be represented in a block diagram as shown in Figure 1. In this figure those blocks corresponding to the influence of the cloud having radiation as input and effective radiation as output, the photovoltaic panel array having effective radiation and temperature as input, and tension and array current as output can be seen. Then, at the stage of conversion of power of continuous current the maximum power point tracking takes place and its output is the power curve and the MPP. Finally, the DC-to-AC converter has the current power as input and the alternating power as output. All input and output variables of these blocks are functions of time.

The cloud is modeled in a way that each panel receives a certain radiation in a given time. The degree of cloudiness exerts an influence as it decreases the radiation that is effectively received by each module independently.

$$G_e = G(x, y, t)n(x, y, t) \quad (1)$$

where $G_e(\cdot)$ is the effective radiation; $G(\cdot)$ is the total radiation and $n(\cdot)$ is the cloud influence. Coordinates (x,y) identify the position of each module in the array. Clouds are simulated with images moving in different directions in relation to the field of panels. Grey levels in the image are in a range of 0-255 and are normalized at the range of 0-1.

Effective radiation received by each module decreases proportionally with the grey level of the pixel corresponding to the cloud.

A photovoltaic cell may be represented by an equivalent circuit [8]. This cell model may be extended to a module considering the type of connection and the number of its constituent cells. Fig. 2 shows curves V-I and V-P of a module obtained from the mathematical model given by the following equations:

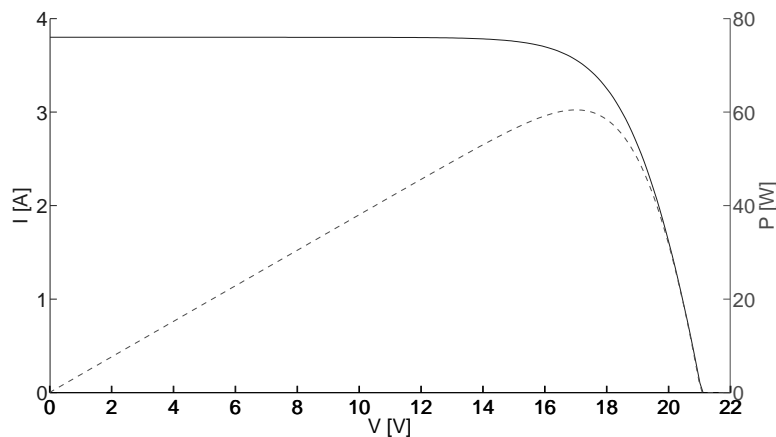


Figure 2. Curves V-I and V-P from a photovoltaic module

$$I = I_L - I_0 - \frac{V + IR_s}{R_{sh}}, \quad (2)$$

$$I_0 = I_{01} \left(e^{\frac{V + IR_s}{m_1 V_t}} - 1 \right) - I_{02} \left(e^{\frac{V + IR_s}{m_2 V_t}} - 1 \right), \quad (3)$$

where I is the electric current supplied by the solar cell; I_L is the photogenerated current; I_{01} and I_{02} are currents representing diffusion phenomena in neutral areas and recombination phenomena in the charge area, respectively; V_t is the thermal voltage ($V_t = kT/e$, being k Boltzmann constant, T temperature in Kelvin degrees and e the electron charge); m_1 and m_2 are factors representing diffusion and recombination phenomena [9, 10]; R_s is the series resistance; and R_{sh} the parallel resistance.

This model has seven unknown parameters which must be obtained solving a system of nonlinear implicit equations for each operating condition. It is important to notice that these conditions vary in time and, in addition, a large plant is constituted by thousands of panels, thus the resolution of the system increases the computational cost considerably.

2.1 Neural Model of the Panel

This work proposes modeling each module by a neural network in a way that the computational cost decreases, both at module and array level, thus obtaining useful results in an application in real time. The network is Multilayer Perceptron (MLP), which has two entries given by temperature and radiation variables, 9 neurons in the hidden layer and 40 nodes in the output layer (Fig. 3). The net output is a vector of 40 components, 20 of which form a voltage vector of the module and the other 20 components correspond to

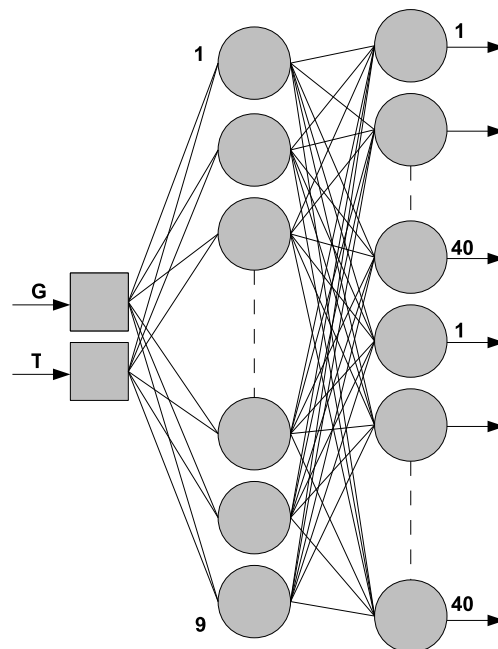


Figure 3. Neural model of the photovoltaic panel

a current vector. Each pair of components (v_k, i_k) gives the coordinates of the operating point of the panel for a particular charge. Functions of activation of neurons in the hidden layer are sigmoid and those in the output layer are linear. [11] Hidden neurons may be modeled as

$$h_j = g\left(\sum_{i=1}^I w_{ji}x_i + b_j\right) \quad j = 1, \dots, J \quad (4)$$

where $g(\cdot)$ is the sigmoid function, h_j is the output of the hidden neuron and b_j is the bias of this neuron.

The output function of the network is given by

$$z_k = \sum_{j=1}^J w_{kj}x_j + b_j \quad k = 1, \dots, K \quad (5)$$

The modeled panel is Solartec M75 and curve I-V data used in the training were obtained from tests carried out in our laboratory under different radiation and temperature conditions. Measurements of tension and current compliant with IEC-904 norm as to equipment used, measuring conditions and procedures were carried out. Cell temperatures of 25 °C to 65 °C in steps of 5 °C and radiations of 400, 500, 600 and 750 W/m² were used. Irradiance conditions and temperature determined and accepted as Standard Measuring Conditions (SMC) are given by an irradiance of 1000 W/m² and a temperature of 25 °C. With the aim of obtaining more data on the behavior of the module regarding other radiations that allow a better training of the net, data obtained experimentally are extrapolated. For extrapolation we use the IEC-891 international norm which describes the process of correction with the irradiance and temperature of the characteristic curve I-V of a photovoltaic device as long as the irradiance range to which correction is to be made falls within ±30 % regarding the measured range. According to this norm, the I-V characteristic of a photovoltaic device could be corrected to SMC or other conditions desired applying the following equations:

$$I_2 = I_1 - I_{SC}\left(\frac{I_{SR}}{I_{MR}} - 1\right) + \alpha(T_2 - T_1) \quad (6)$$

$$V_2 = V_1 - R_s(I_2 - I_1) - KI_2(T_2 - T_1) + \beta(T_2 - T_1) \quad (7)$$

where (I_1, V_1) are the coordinates of the points I-V measured; (I_2, V_2) are the corresponding coordinates of the points on the corrected curve; I_{SC} is the measured short-circuit current of the device tested; I_{MR} is the measured short-circuit current for the reference device; I_{SR} is the short-circuit current of the reference device under SMC or other conditions to which the curve I-V is to be extrapolated; T_1 is the measured temperature of the device tested; T_2 is the temperature under standard conditions or other conditions to which the curve is extrapolated; α is the coefficient of variation of the current with the temperature; β is the tension variation coefficient with temperature; R_s is the internal resistance of the test species; K is a correction factor for the curve. The values used for these parameters are $\alpha = 0,002$ [A/ °C], $\beta = -0,082$ [V / °C], $K = 0,004$ [V / °C A] y $R_s = 0,441$ [Ω], which were determined experimentally following the procedure described by IEC-891 norm. Applying the method mentioned above and with the measurements performed, 72 input patterns to train the neural net were obtained.

It is important to highlight that the architecture adopted by our neural network allows obtaining the output current and tension of a photovoltaic module in 1440 different situations given by radiation, temperature and charge born by the module.

The training method employed was error backpropagation, minimizing mean square error. Data used for training were partitioned into training data and validation data. Training by lot was carried out, adjusting weight matrixes w_{ji} and w_{kj} , and calculating training error and validation error at each iteration. Training was stopped when the net reached the generalization peak. The criterion followed was the early stopping. Subsequently, the neural net showing the best performance was selected.

2.2 Inverter and Maximum Power Point Tracking

The function of the inverter is to convert continuous current into alternating current. In this work the inverter is modeled in two steps. The first step consists of a converter DC-DC with a maximum power point tracking (MPPT), whereas the second step carries out the DC-AC conversion.

Coordinates (v_k, i_k) of the operating point of the module will be determined by the impedance seen by the module. This point is optimum when maximum power is reached (Fig. 2) and it is called point of maximum power (MPP).

The MPP can be found by applying numerical methods to solve the following equations:

$$P = V \left(I_L - I_0 - \frac{V + IR_s}{R_{sh}} \right) \quad (8)$$

$$\frac{dP}{dV} = 0 \quad (9)$$

Variations in climatic conditions such as radiation and temperature cause changes in the optimum operating tension and current, making a maximum power point tracking system (MPPTS) necessary. A MPPTS controls the switching of a DC converter (DC-DC) by means of a signal modulated by pulse width with a certain working cycle. Given the fact that the converter has an input impedance which is a function of the impedance of the load and the working cycle, the MPPTS algorithm has to find an appropriate working cycle so that the operating point of the photovoltaic array is optimum, i.e., is equal to the point of maximum power.

In general, in order to find the MPP, (8) and (9) are not solved. Instead, the point at which the first derivative is null by means of some simpler and faster algorithm is sought. The maximum power point tracking algorithm employed in this model is of the disturbance and observation type [2]. This algorithm increases or decreases tension at the terminals of the module, and if the derivative $dP/dV > 0$ (observation) continues disturbing in the same sense the operating point moving it closer to the point of maximum power, this process is repeated until $dP/dV < 0$, in which case the sense of the disturbance is changed to shift the operating point into the opposite direction.

The second stage of the inverter is the inverter itself, i.e., the inverter is in charge of transforming DC into AC (DC-AC). At this stage, inputs are V and I, and the output is the power generated. The efficiency of this inverter is given by the output power/input power ratio, but as this study is working on a simulation, the output cannot be measured for efficiency. Modeling of this converter was carried out taking into account efficiency variation in time, as a function of the rated power of the inverter and input power [12]. The method consists in thinking of power in alternating current as the difference between continuous current and the losses of power in the inverter. Thus, instant efficiency can be defined as:

$$\eta_{inv}(P_N, t) = \frac{P_N(t)}{P_N(t) + k_0 + k_1 P_N(t) + k_2 P_N(t)^2} \quad (10)$$

where $P_N = P_{dc}/P_{nom}$, with P_{dc} input power and P_{nom} rated power of the inverter; k_0 represents losses in the vacuum; k_1 is associated to the linear losses with the current due to tension drops in diodes, transistors and other components; and k_2 is associated to the quadratic losses with the current, mainly due to resistances.

The values of k_0 , k_1 and k_2 can be experimentally calculated by measuring the efficiency of the inverter for different values of the input power. In this work we take the parameters obtained by

a representative sample of commercial inverters of a high efficiency measured by the Institute of Solar Energy of the Universidad Politécnica de Madrid [13].

2.3 Connection Schemes

With the aim of finding an alternative representation for the wiring designs

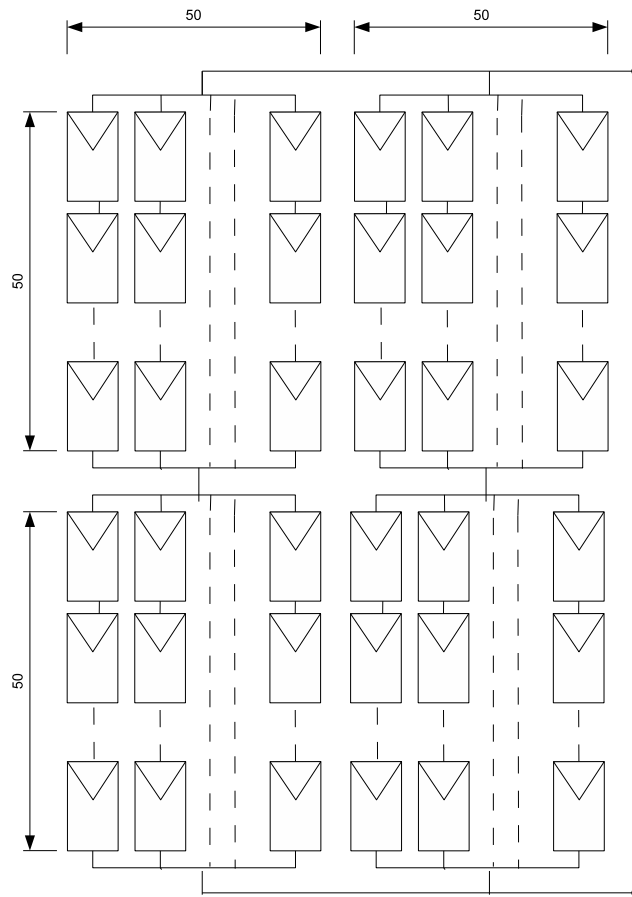


Figure 4. Wiring design for configuration 2

which allows expressing in a compact fashion the several configurations simulated, there follows a notation system specially designed for this case. The symbols (·) indicate that the group is level one, [·] represents level two groups, and the subscript refers to the group of the corresponding level.

For the configuration shown in Fig. 4, the expression

$[(50_s50_p)_1 S(50_s50_p)_{2|1}] // [(50_s50_p)_3 S(50_s50_p)_4]_2$ indicates that there are four groups level 1 formed by 50 branches in parallel with 50 modules in series for each branch, and there are two level 2 groups wired in parallel, consisting in level 1 groups wired in series. Parallel wiring of level two groups is shown as //, and their wiring is expressed as S.

3. RESULTS AND DISCUSSION

In simulations we consider that the time behaviour of radiation and temperature present a typical curve shape along a day, and that data show time frequency. There follows the performance analysis of the various configurations of the array faced with different shading conditions.

3.1 Efficiency Measure

In the analysis of different configurations, performance rate PR is used as a measure of performance, calculated as

	Wiring design	PRh	PRv
1	(100s100p) ₁	0.19	0.33
2	[(50s50p) ₁ S(50s50p) ₂] ₁ // [(50s50p) ₃ S(50s50p) ₄] ₂	0.41	0.44
3	(50s100p) ₁ S(50s100p) ₂	0.24	0.32
4	(100p) ₁ S(100p) ₂ ...S(100p) ₁₀₀	0.77	0.56
5	[(50s50p) ₁ S... (50s50p) ₁₀₀] ₁ // [(50s50p) ₁₀₁ S... (50s50p) ₂₀₀] ₂	0.68	0.67
6	(100s50p) ₁ // (100s50p) ₂	0.44	0.3
7	(75s100p) ₁ S(25s100p) ₂	0.49	0.52
8	[(75s50p) ₁ S(25s50p) ₂] ₁ // [(75s50p) ₃ S(25s50p) ₄] ₂	0.45	0.29
9	[(50s100p) ₁] ₁ S [(100p) ₂ S... (100p) ₅₁] ₂	0.56	0.48
10	[(75s100p) ₁] ₁ S [(100p) ₂ S... (100p) ₂₆] ₂	0.53	0.51

Table I. Configurations with an inverter

$$PR = \frac{\int P_{ac}(t)dt}{\eta_{SMC} \int G(x, y, t)dAdt} \quad (11)$$

where P_{ac} is power in alternating current; G is radiation; A is the area and η_{SMC} is the efficiency of the module under standard measurement conditions. PR is understood as the ratio between generated energy in alternating current and that which would be delivered by an ideal system, i.e., without losses and with the modules working under standard measurement conditions. Since a heterogeneous and dynamic shading condition was considered, each panel receives different and variable energy in time. For this reason, in the (11) denominator energy is calculated by spatial integration.

3.2 Photovoltaic Plant Efficiency

Different forms of interconnecting modules constituting the photovoltaic plant and the use a single inverter were considered in the simulations. The results of the simulations carried out for the different wiring schemes with clouds moving in horizontal (PRh) and vertical (PRv) positions regarding the photovoltaic field are shown in Tabla I. The resulting PR shows that configuration 1, with a single group of panels associated in series and these series in parallel, is the configuration of the lowest efficiency. Configuration 4 shows the best performance, of a PRh=0.77, but it evidences a strong dependence on the shading condition which can decrease its PR up to 0.56. On the other hand, configuration 5, with a PR between 0.66 and 0.68 has a good efficiency and in addition, its performance is independent from the shading condition. This means, in general, that many modules in series decrease their PR and also that the increase in modules in parallel favours a higher efficiency. However, using too many modules in direct parallel leads to a less robust configuration regarding changes in the shading conditions. Particularly, shading in the direction of the resulting series would cause its greater imbalance with respect to the case of perpendicular movement of the cloud due to a greater influence of the currents of each group of parallels.

4. CONCLUSIONS

A simulation model of photovoltaic plants was implemented, allowing the evaluation of the global efficiency for all the system. Simulations considered heterogeneous shading conditions of the array, being each module affected by the cloud independently. The behaviour of the cloud was considered to be static or varying in time. Besides, different wiring designs may be simulated, as well as different directions of cloud movements. Results show that the grouping of the highest number of modules in parallel may benefit the global efficiency and that these configurations are not necessarily the most robust ones when changing the direction of shading. The simulation model proposed is useful to study different variants and to find photovoltaic plants with configurations of a higher efficiency.

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