Optimized Electric Networking of Photovoltaic Cells on Non Planar Surface

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Abstract:-This paper presents a study about the influence of electric combination of solar cells in the case of non-planar photovoltaic system. We first study the feasibility of a system which allows optimizing the association of these cells and after that, we show a method to do it. Then we analyze what assemblies can be advantageous over the commonly used series association, by varying the geometry of the whole system and the lighting on the cells. The results show that series combination is not always the best one. We show that, on one hand, for others arrangements than series combination, the order of cell association matters and on the other hand, the weaker the light is and the more variable the geometry of the surface is, the more the choice of another association is a good alternative.

Keywords: Photovoltaic Panel; Non-planar Surfaces; Electric Association of Cells; Series and Parallel Arrangement.

1. NTRODUCTION

Improvement of PV cells increases their efficiency and reduces their costs, encouraging more people to use this clean energy. Researches on cells and photovoltaic systems attempt to improve electrical performance of PV panels and reduce energy losses in PV installations. These researches are mainly conducted with plane systems (for instance the Maximum Power Point Tracking [3,5] and trackers installed for the complete module orientation[6]) but with new technologies it is becoming possible to create flexible continuous non-flat systems (cylindrical, spherical, toric, complex ...), and the problem of their optimization shows up.

Equations of such non-flat, flexible and continuous photovoltaic systems are not known, as theoretical analysis is not possible. In order to overcome the flatness of systems and thus to make a transition between flat systems and non-flat continuous and flexible systems, present study focuses on optimization of an assembly of flat cells displayed on a non-flat surface. Here it will be attempted to optimize an assembly of four cells placed in a non-flat surface.

PV systems are generally assembled in series because this structure allows greater power in the case of plane setting [1]. But when in a series assembly of photovoltaic cells, a cell receives a lower effective irradiance (due to shading or because of the inclination relative to incident light power), the power is greatly reduced because the current flowing in the system is determined by this cell, implying that other cells do not "provide" all the power they could provide (distance from maximum power point)[7]. In order to solve this problem and to always reach the maximum power for each PV cell, the optimization way chosen in the study is the wiring of cells and how they are linked to each other.

The study is concerning a system meant to determine the optimal wiring whatever is the shape of the surface on which the cells are distributed. This system is made of a matrix which selects the best combination among all possible combinations of association of four cells.

In order to show the results and the interest of such a system, they are displayed using Matlab/Simulink [4] for different possible combinations of cells placed on variable surfaces and different illumination, allowing to conclude on the importance of proper association of cells in this context.

2. MATERIAL ET METHODS

II.1 *Interest and Feasibility* : Optimizing a non-planar PV system requires understanding of the new parameters implied by its variable geometry. To conduct the study, the whole and complex system is divided in smaller parts and attention is here focused on the smallest units composing it. The knowledge of their behavior, according to these new settings, allows by generalization to reconstitute all initial system.

Analysis is made on a basic module consisting of four photovoltaic cells. In a configuration where the module is a planar one, it is generally agreed that the cells all receive (except in cases of shadows [2]) the same radiation regardless of sunlight incidence angle. Then, standard cells combination is the series, because it offers optimal performance and optimal power under usual conditions of PV panels use [1]. However in the case where module geometry is non-planar, the radiation distribution onto the module is variable. This distribution of irradiation raises the question of optimal performance provided by series connection of cells. Present study is thus devoted to analysis of possible influence of cells association as a function of irradiation distribution and to optimize the module based on these findings. In a broader sense this is a study of PV panel structure on its electricity production function. Interestingly, feedback type study of system structure on its function is the ultimate step in system evolution only accessible today to living systems, explaining their remarkable performances and adaptation for survival.

So the purpose here is, for the four studied working cells, to consider all possible electrical associations, and to look for a cell combination which for non-planar modules would be better than usual series association, and to what extent. Therefore the method is in the first step to identify every possible different combination of cells. Ten such associations can be identified, see Figure 1, and for each one there is also the order of the cells which can occur, up to 24 different orders.

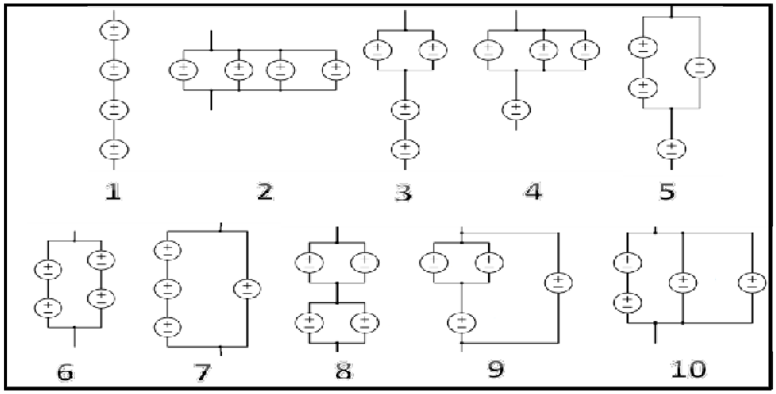


Figure 1. Identified Models of Cells Associations

For each association presented above, some cells orders in an assembly may be equivalent. For example in series (model 1) for four cells receiving a different value of irradiation, whatever is the cell order in the assembly, the power output is always the same (the influence of the order in an electrical assembly is shown later). However, in order to allow set the cells in 24 (= 4!) combinations for each model (which makes 240 possible combinations for the system) a general method will be followed here.

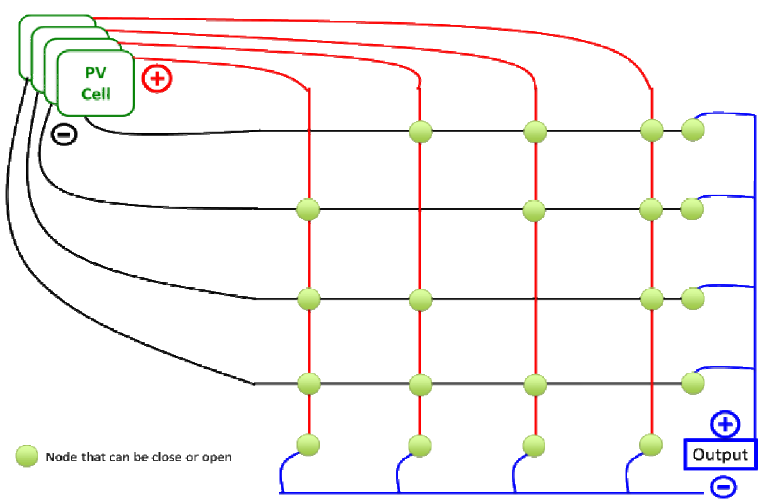


Figure 2. Matrix Representing the System

First the feasibility of such system which could behave like the identified 240 combinations is studied. The solution is a matrix for connecting cells in the same way for all associations shown in Figure 1 and in all possible orders. The connection is made by opening and closing the component nodes, and closing and opening different electrical entry and exit points. The nodes in particular allow the serial connection, and points of entry and exit permit parallel assembly of the cells.

The matrix shown in Figure 2 allows via its nodes the connection of the cells for all possible ways displayed on Figure 1 and in all orders. It is then possible, through self and smart control of switch nodes, to track in real-time the optimal connection model in order to always obtain the maximum power.

II.2 *Simulation* : The simulation of the system done here is based on the mathematical model equivalent to a PV cell, see Figure 3. The current produced by the cell evolving according to the illumination, is generated by ideal generator. The diode is used to model how the cell behaves in the absence of light. The resistor in series models the losses due to the resistance of cell material and the parallel resistor models the stray currents that can pass through[8].

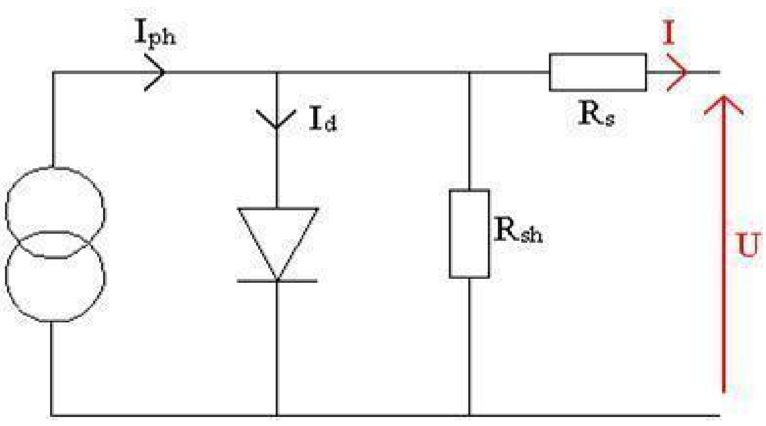


Figure 3. Equivalent Representation of PV Cell

The equation linking cell current and voltage is written in the form:

$$I = I_{ph} - I_{0d}.\left(e^{\frac{q.(U+R_s.I)}{k.T}} - 1\right) - \frac{U+R_s.I}{R_{sh}} \quad (1)$$

Simulation of cell behavior with Matlab/Simulink is based on equation (1). Cell specifications correspond to a cell having a short circuit current Isc = 3.8 A to an irradiance I_R = 1000 W/m² at 25°C, and an open circuit voltage Voc = 0.59 V. Cell characteristic is shown on Figure 4.

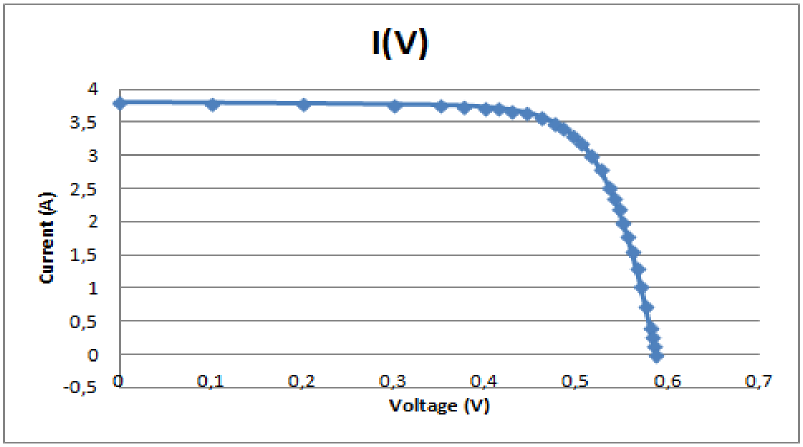


Figure 4. Cell Specification for Present Model

The simulation implements an incident light power of four adjacent cells on the surface of a sphere with variable curvature radius, see Figure 5. The angle α between two consecutive cells is variable. The objective is to define to what extent the combination of PV cells in series is or is not better than the other identified associations for a spherical surface.

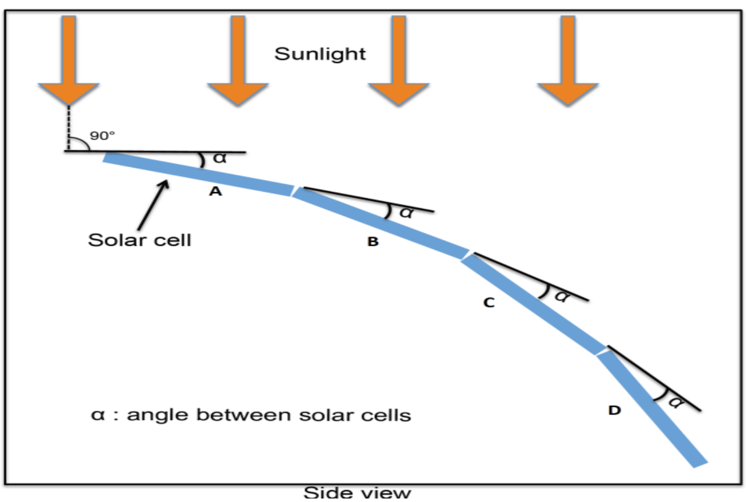


Figure 5. Description of Simulated Cell Distribution

The simulation has been made for each of the 10 association models and for each of the 24 order combinations, at irradiations from 50W/m² to 500W/m² with a step of 50W/m² by varying the angle α between 0 and 23 degrees (For α > 23°, the simulation cannot be made because cell D is completely out of light). The obtained power has been calculated as a function of these four parameters. For this the power obtained by varying the angle α between 0 and 23° for all possible orders has been first evaluated for a given irradiance and for a given model, then the calculation has been iterated with the next irradiance up to 500 W/m² and finally the operation has been repeated for the next model. The simulation of the variation of angle α is made from the relation between the incident angle of light rays on a cell and its yield R = sin(β) where β is incident light rays angle. Then one gets R = cos (i*α) where i = 1 for cell A, i = 2 for cell B, i = 3 for cell C, i = 4 for cell D,

In order to compare the 10 cells association models, the order providing the maximum power for each angle is extracted from all obtained data and for each model. Thus, for each irradiation, 10 evolutions of power as a function of the angles have been obtained. Comparing these curves, it is possible to determine, for a given system (fixed geometry), the assembly providing the maximum power for a given irradiation.

3. RESULTS

As described above, the power delivered by the association of cells is simulated for all possible combinations of each model. This allows compare the different orders in which the cells are associated to find the maximum power values for installation, at each angle. To set an example the model 3 and its cells combinations are shown in Figure 6 for irradiance I_R = 200 W/ m^2.

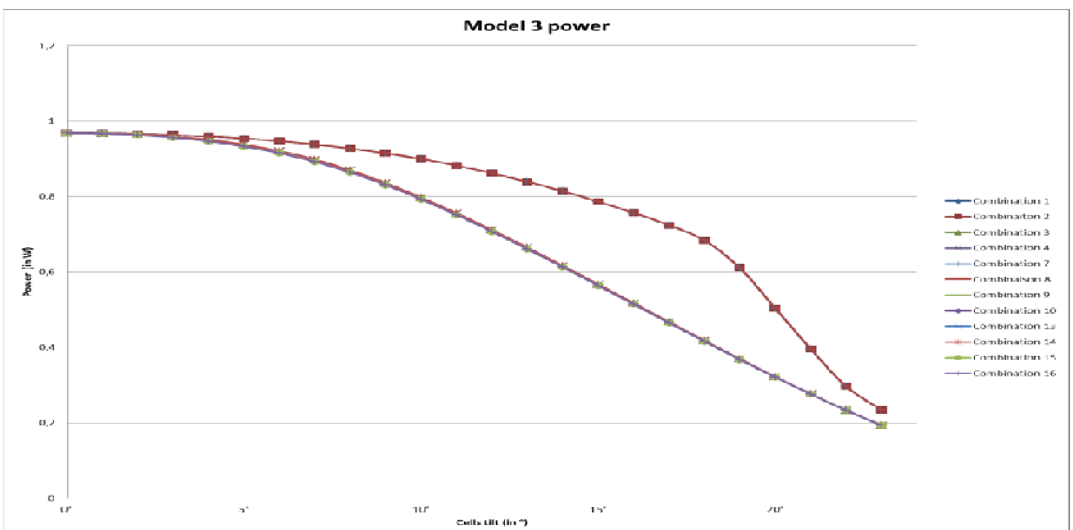
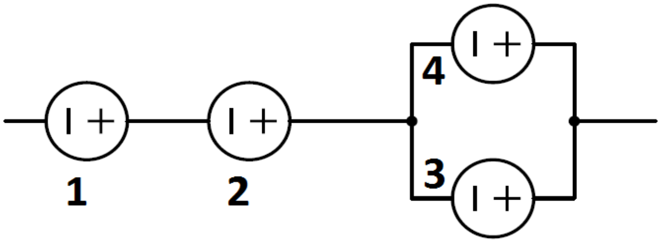


Figure 6. Power Evolution of Each Combination for Model 3 vs Incidence Angle α

Three distinct evolutions of power can be observed for model 3. In fact, there are actually 6 curves but 3 of them are very close (those for which the power is lowest), while 2 of them are very close (those of average power) and the first, which allows obtaining the maximum power, is a single curve. It is clear that 6 different curves can exist because there are $C_2^4 = 6$ different combinations in model 3 diagram, undifferentiated combinations are due to electrical properties of the assembly. Thus for each studied model a single or several orders delivering the maximum power can be found. In the case of model 3, the orders for obtaining the maximum curve are 1, 2, 7 and 8 corresponding to the cells in the following positions:



1: A1; B2; C3; D4 ; 2: A1; B2; C4; D3 ; 3: A2; B1; C3; D4 ; 4: A2; B1; C4; D3

Figure 7. Possible Cells Distribution with Corresponding Electric Linkage

This is equivalent to have the two most illuminated cells positioned in series with the two lowest ones which are in parallel.

One can also, after extraction of maximum values for each level of cells, plot the power vs incidence angle, for the 10 models and for all irradiances. To set an example in model 3, we choose one of four combinations to obtain maximum power, orders 1, 2, 7 and 8 on the graph. Most real cells do not work for I_R < 100W/m², so starting from I_R = 100W/m² one obtains the curves displayed on Figure 8.

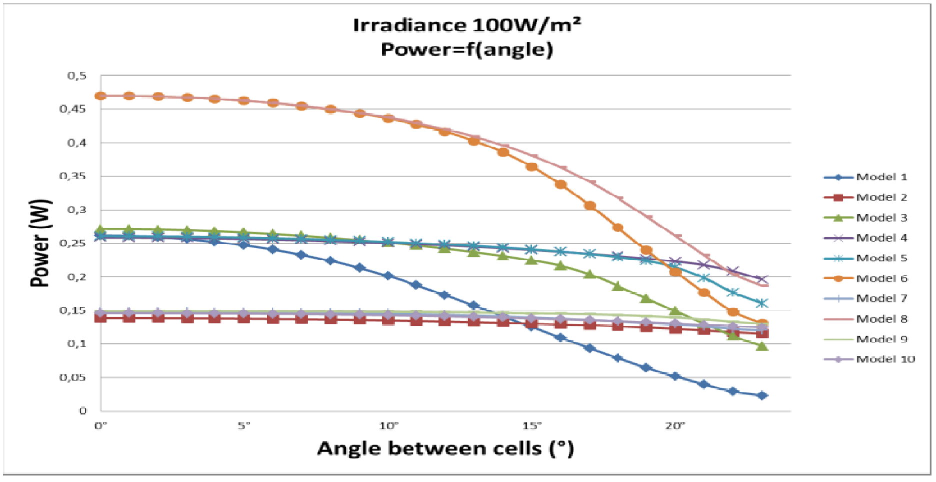


Figure 8. Power Dependence vs Angle between Cells at Irradiance of 100W/m²

It is observed that regardless of module geometry in our conditions, for a very low illumination, the series combination (curve "Model 1") does not provide the best performance. Thus it is seen that best models, in these conditions, are models 6 and 8, which is consistent because they are similar: model 6 is parallel combination of two cells in series so that model 8 is the series connection of two cells in parallel. When α increases, model 8 differs from model 6 and corresponds to better performance. Also for larger angles between cells (for α = [20:23]), models 6 and 8 become less attractive and thus model 5 has a better performance than model 6 and model 4 finally becomes more interesting than model 8 in terms of performance.

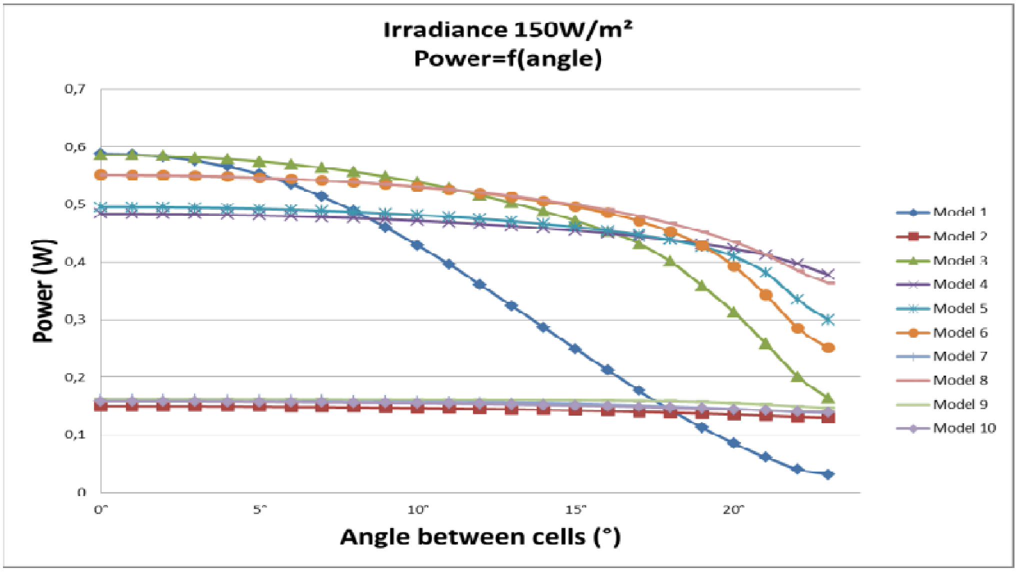


Fig 9. Power depending on the angle between cells at an irradiance of 150 W/m²

When irradiance increases to 150 W/m², it is observed as expected that series association ("Model 1") is the best solution in flat case (α = 0 to 3). When inclination angle between cells increases, this is no longer the case. Indeed model 3, consisting of two cells in parallel connected in series with two other cells in series, becomes more interesting until α = 12°. When α > 12°, the situation is similar to previous position of illumination (100 W/m²), and best performance models 6 and 8 are found as above and then at the end of the model 4.

The combination of cells in series is now seen as preferable for planar modules when irradiance increases, but when α increases and becomes significant, this association is not the best, and model 3 appears as a good alternative when cells association is ordered to obtain maximum power. Other models than models 3 and 1 appear to lose interest with increasing irradiance; however this cannot be generalized yet, actual results are also obtained with prescribed cell parameters and specific network parameters (fixed circuit load, homogeneous surface, temperature condition). The results are as shown in Figure 11.

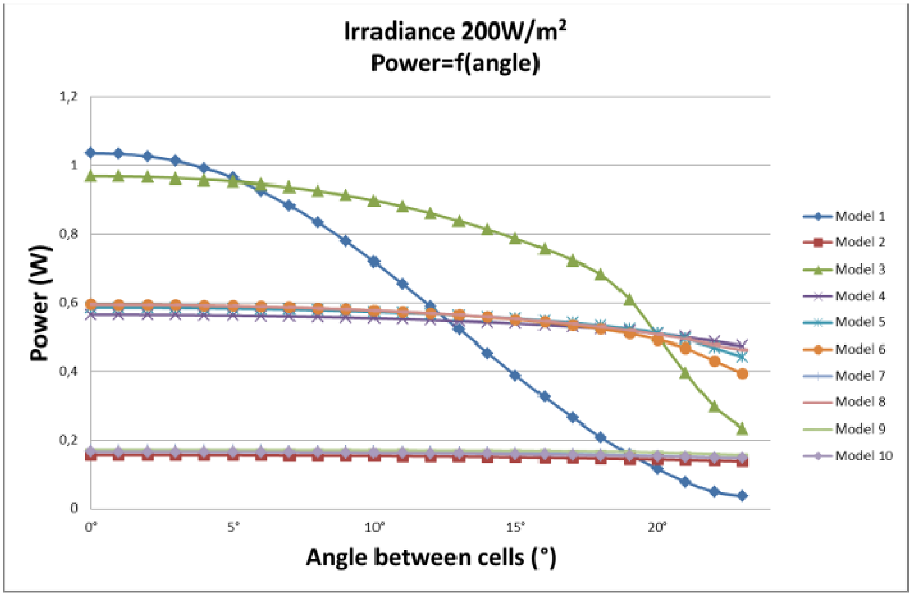


Fig 10. Power depending on the angle between cells at an irradiance of 200 W/m²

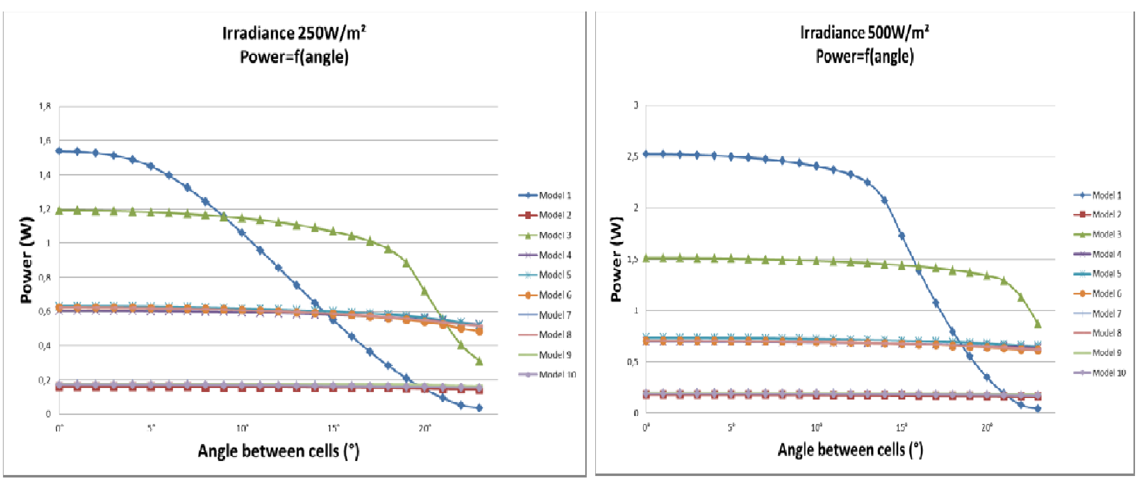


Fig. 11. Results Evolution with Increasing Lighting

These results show that in present test conditions, with low irradiation of cells, the series model is not the most efficient model and is even a worse choice when irradiance is low and cell surface geometry is variable. When irradiance increases, the series corresponds to maximum power up to a certain angle above which model 3 is superior (this angle can be called "limit angle"). Around 20°

tilt between each cell, the series arrangement is not a good choice in real lighting conditions, see Figure 12.

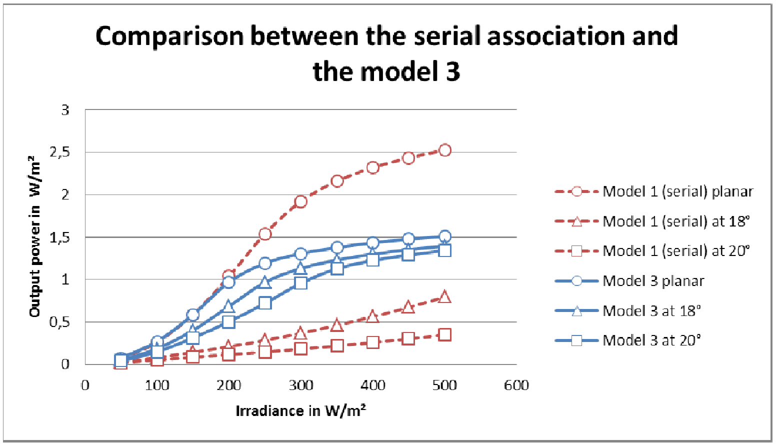


Fig. 12. Comparison between Model 1 and 3

The comparison in Figure 12 highlights the fact that series combination is advantageous in the case where the module is flat, but not in the case of highly curved module and for every real lighting. It is clear that the power obtained with model 3 is higher than with model 1 when angles are sufficiently large, which means when surface curvature is significant. The value of limit angle increases with received irradiance. Thus there is an irradiance value for which the series circuit is superior to all other associations. However this value is probably only achievable by modeling and not in actual illumination conditions. This strongly suggests that when irradiance is high enough series association is "superior" because the cells are "supercharged" in light energy and even the most inclined cell provides maximum power. Indeed cells cannot provide an infinitely large electric power even if light input is infinitely large. Based on this information, it is then possible for a non-planar module in an appropriate geometry to be more efficient than a serial plan module for a range of radiations.

4. CONCLUSION

The results obtained in present study are showing that performance of non-planar PV structure can be optimized through a better association of cells or modules composing it. It is shown that a series combination does not always correspond to best power depending on illumination conditions and solar panel geometry. An intelligent management of cells network taking into account the irradiance received by the system, would be interesting by allowing it to switch from a circuit structure to another one. Furthermore, the results show that a large angle variation between cells offer a better possibility of optimization by using present method. This idea is enforced by the fact that highly deformable PV surface will have uneven and fluctuating irradiation distribution, depending on the position of light source changes over time. A prototype is being developed in order to confirm the results and to check corresponding system reliability, in particular, the optimization of system output by power feedback on its structure.

5. AKNOWLEDGMENTS

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