A new control system prototype for the energy production maximization of a unequally irradiated PV system

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Abstract: *This paper deals with the mismatch effect due to a unequally irradiation on a PV (PhotoVoltaic) system. The mismatch effect due to the partial shading of a PV module can be limited thanks to the installation of both bypass and block diodes. Unfortunately, this solution cannot fully solve the disvantages related to the mismatch effect. The Authors, in previous papers [1, 2], have theoretically demonstrated that the mismatch effect can be solved by changing the parallel/series connections of the modules of a PV system, taking into account each module radiating condition. This paper represents a first step of the experimental development of the above mentioned theoretical result. Specifically, the energy production maximization of the unequally irradiated PV system is obtained thanks to a Labview FPGA reconfiguration controller, designed by the Authors. This controller is able to detect the voltage values of all the modules and consequently to take the decision whether to change the connections of the modules or not in order to maximize the energy production of the PV system. This change of the connections is physically carried out by some commutation systems to which the FPGA electronic controller send the commutation pulses. The designed reconfiguration controller could be manufactured on a large scale and in a short time economically amortized thanks to the economical benefits related to the increase of the electric energy production.*

Keywords: PhotoVoltaic, mismatch, series/parallel connections, FPGA, controller

1. Introduction

The energetic crisis linked to the oil reserves decrease and to the increase of the world energy request have directed technologic improvements towards the exploitation of alternative energetic sources.
Solar energy is the most widespread alternative energetic source. It is available in a so large quantity as to theoretically cover the world energetic needs.
Anyway, solar energy employment has technical and economical difficulties connected to the following elements: low energetic density and uncertainty of the solar radiation, and low value of the conversion efficiency.
All the above mentioned elements represent the big gap between the theoretical and the practical utilization of the solar energy source.
Today, the technologic development has led to a significant cost reduction thanks to which it is now possible to build both low power and high power solar applications.
In the mid-term, thanks to the energetic efficiency increase and to the cost production decrease, the solar energy technology will stand. Anyway, up to today, the PV plants have high cost productions and low energetic efficiency. Moreover, current PV plants productions are strongly linked to the radiancy condition changes caused by sudden climatic changes.
In order to face the difficulties linked to the solar energy employment, the research has been directed not only towards efficiency maximization techniques and new MPPT algorithms but also towards new optimization algorithms. Particularly, these last deals with the change of the parallel/series connections of

the modules of a PV array, depending on each module radiating condition, in order to get the maximum value of the generated electric power. The reconfiguration of the PV system is obtained thanks to the use of electric contactors.
This paper deals with the mismatch effect due to a unequally irradiation on the PV modules and proposes a control system prototype thanks to which it is possible to get the reconfiguration of the PV system. This system allows to reconfigure the unequally irradiated PV array in order to maximize the energy production.
The designed prototype was conceived and built by SDES (Sustainable Development and Energy Savings) Laboratory, located in the Department of Electrical, Electronical and Telecommunications Engineering of University of Palermo. It is actually under test for its final characterization.

2. Mismatch effect in a unequally irradiated PV array

A PV cell is the elementary unit of a PV module, being this last the system able to transduce solar radiancy into electricity. A PV module is made of many connected cells. Since a PV module has low output voltage and current values then PV modules must be series/parallel connected in order to obtain the current and voltages values requested by the load.
Figure 1 represents an example of PV modules series/parallel connected.
A PV string is made of PV modules series connected. A PV plant is made of PV strings parallel connected.
The electric values of a PV plant depend on the number of series connected PV modules and on the number of PV strings parallel connected.
The mismatch term indicates the electrical maladjustment among the PV cells of a whole module or among the PV modules in series connected to set up a string.
The mismatch causes can be both internal and external.
The former are: the not homogeneous external characteristics of the cells (due to dissymmetric manufacturing), the degradation of the cell blooming layer, the manufacturing defects, the possibility of the cells breaking, the degradation of the materials used for the cells encapsulating.
The latter are: the dirt on the anterior part of the cells and the unequally radiation of the cells.
The mismatch leads to a reduction of the PV system performances because the power generated by a string is less than the sum of the powers generated by all the modules in series connected.

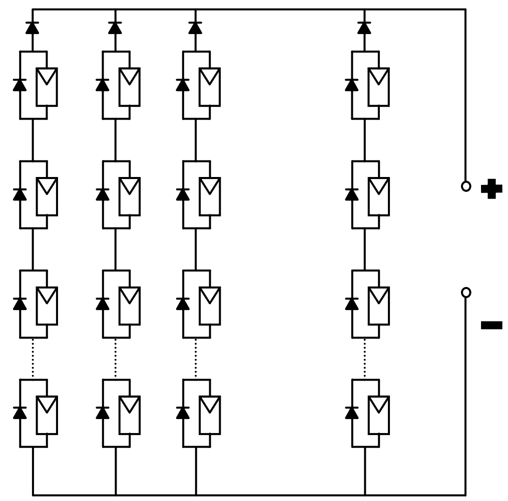

Fig. 1 – PV modules series/parallel connected

If all the modules of the same PV string are equally irradiated then they have the same V-I external curves. If all the strings of the same PV plant are equally irradiated then all the strings deliver the same values of the current to load (the inverter to which they are connected). If a single module of a PV string is less irradiated then the other modules of the same PV string then the string current decreases. If a module is fully shaded then it may even happens that the string current is null.
The mismatch effect due to the partial shading of a PV module can be limited thanks to the installation of both bypass and block diodes and to the adoption of suitable technical solutions. A widespread technical solution is the utilization of modular inverters (in order to limit the number of strings controlled by the same MPPT controller). Moreover, during the design stage, it is necessary to evaluate the optimal PV modules arrangement able to minimize both widespread and restricted shadings.
Unfortunately, these technical solutions cannot fully solve the disvantages related to the mismatch effect. The Authors, in two previous papers [1, 2], had theoretically demonstrated that the mismatch effect can be solved by changing the parallel/series connections of the modules of a PV plant. This result is confirmed by other authors [3-6].
This paper represents a first step towards the experimental development of the above mentioned theoretical result.

3. PV system under tests

The power generated by a PV plant strongly depends on its own configuration. Concerning this, the simulation results reported in [2] have shown that, in order to maximize the electrical energy produced by a PV plant, it is necessary to obtain symmetrical configurations. These last are realized through an equally distribution of the shaded modules among the parallel connected strings. The best condition is the one in which the number of shaded modules is multiple of the parallel connected strings. What said suggests the idea to reconfigure the PV plants where the modules are unequally irradiated with the aim of maximizing the produced energy. Anyway, the output values of the plant electric quantities must be suitable with the inverter MPPT ones.

In order to experimentally validate what theoretically demonstrated in [2], a test bench has been set up. With this aim, the PV plant under study has been that built by SDES Laboratory researchers at the Department of Electrical Electronic and Telecommunication Engineering of University of Palermo.

The PV plant is made of 2 PV parallel connected strings having each 3 series connected PV modules. The PV plant is depicted in Figg. 2 and 3.

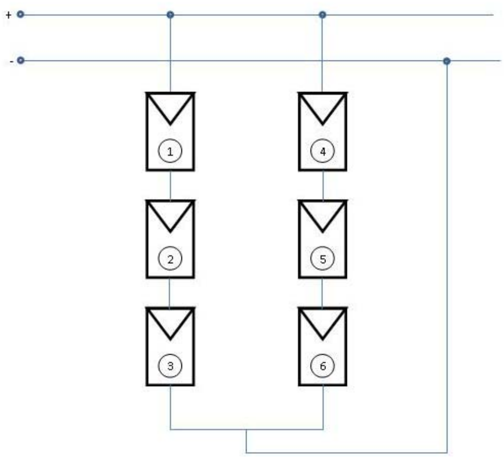

Fig. 2 - Two PV parallel connected strings having 3 series connected PV modules each

Fig. 3 – 2×3 PV plant (one module disconnected)

The PV plant chosen allows to study on a small scale the behaviour of big high power PV plants made of hundreds parallel connected PV strings having each up to 15-20 series connected PV modules.

In our case, the PV modules are of the E215P Conergy type. They are made of high efficiency polycrystalline cells able to produce 215 W maximum power. The rated values of the PV modules are reported in Table 1.

Tab. 1 – Rated values of the Conergy E215P PV modules

Maximum Power (PMPP)	215 W
Rated Voltage (VMPP)	28,27 V
Rated Current (IMPP)	7,59 A
Open Circuit Voltage (VOC)	36,37 V
Short Circuit Current (ISC)	8,21 A
Maximum System Voltage	1000 V
Above specification at STC: Insol. 1000W/m^2, AM 1,5, Cell T 25°C	

In the test bench, two amperometers and one voltmeter have been employed. The amperometers have been series inserted into the strings and the voltmeter has been parallel connected to the load (one resistor). An amperometer has been series connected to the resistor load as well. Finally, a pyranometer is used to measure the solar irradiation.

Fig. 4 shows the test bench, fig. 5 the measurement scheme.

The electrical quantities monitored have been the currents flowing in each string and the load voltage.

The measurements have been carried out with the aim of quantify how the PV plant production changes when the irradiation conditions changes as well. The change of the irradiation conditions are depicted in Fig. 6.

The PV plant configurations under study are as follows:

1) Fully irradiated PV plant;
2) One shaded module;
3) Two shaded modules in the same string;
4) Two shaded modules in two separate strings;
5) Three shaded modules in the same string;
6) Three shaded modules in separate strings

Fig. 4 – test bench

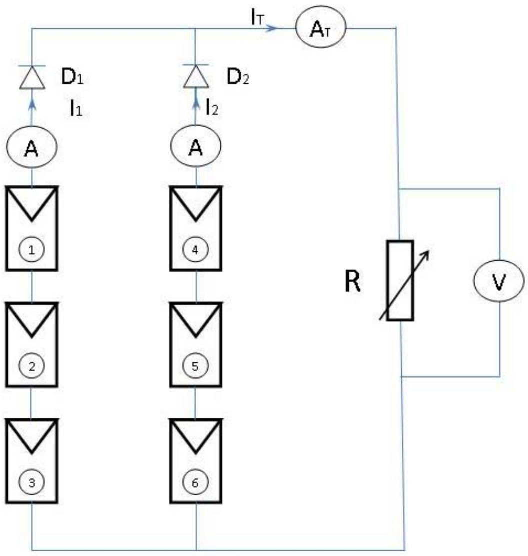

Fig. 5 – measurement scheme

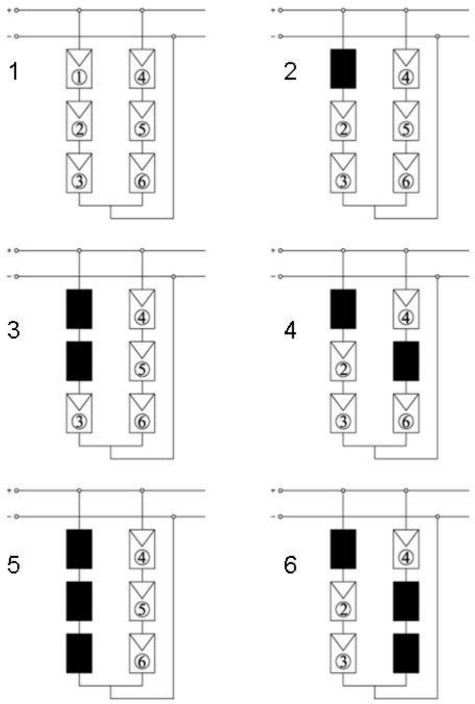

Fig. 6 – PV plant under changing irradiation conditions.

Measurements have been carried out using a pyranometer when solar irradiation was equal to 960 W/m2.
The experimental research has validated the theoretical results reported in [2]. In the PV plant where each module has its own bypass diode and each string has its own block diode, the power generated value depends on the number of shaded modules and on the value of the solar irradiation on the non-shaded modules. Moreover, even if the number of shaded modules and the value of the solar irradiation on the non-shaded modules do not change then the power generated value depends on the exact position taken by the non-shaded modules inside the PV plant. It means that in order to maximize the power generated by a unequally irradiated PV plant it is necessary to conceive a control logic to re-configure the series/parallel connection of the PV modules. Moreover, the control logic must take into account the need that the PV strings output values must be suitable with the MPPT range ones.
The experimental research has brought out that in order to maximize the output power of the PV plant, the shaded modules must belong to separate strings. In this sense, in Fig. 6 configuration 4 is better than configuration 3 and configuration 6 is better than configuration 5. It means that when the shaded modules of the PV plant are as in configuration 3 and 5 then the control logic must change the modules connections in order to achieve configurations 4 and 6 respectively.

4. The reconfiguration system for the energy production maximization.

Taking into account what stated in [2], a reconfiguration system has been conceived and set up (Fig. 7).
When two or more modules of a PV plant are shaded then the reconfiguration system changes the series/parallel connection between the modules in order to maximize the output power. Fig. 8 shows the block scheme of the designed reconfiguration system.

The main parts of the system are:
- the controller
- the input electronic interface
- the acquisition board
- the command board
- the output electronic interface
- the electro mechanic switch

Thanks to a control system and a management software developed by the Authors, the reconfiguration system is able to supervise each single module. Particularly it is able to detect if some modules are shaded and, in this case, to enforce the reconfiguration of the series/parallel connections between the PV plant modules.
In order to detect the working condition of each module, the reconfiguration system monitors in real time the module voltage output value, which depends on the solar radiation.
The voltage values are sent to an acquisition board and then processed by a controller.

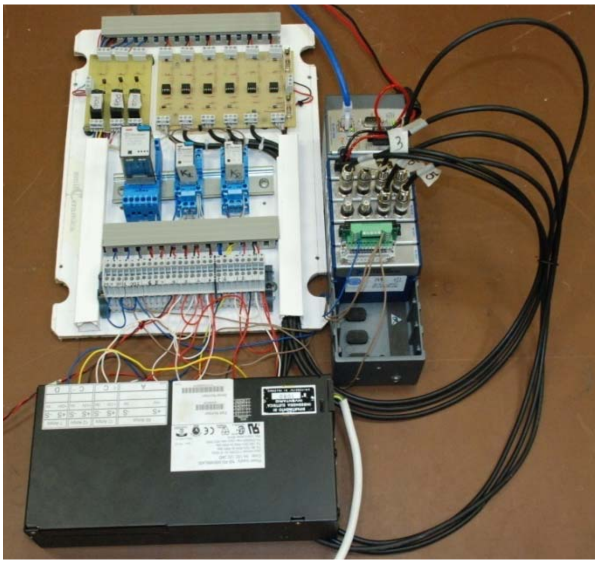

Fig. 7 The designed reconfiguration system

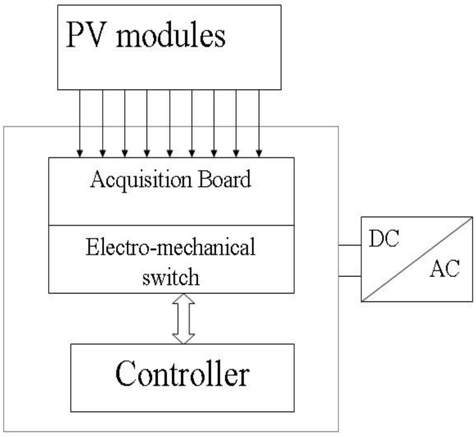

Fig. 8 block scheme of the designed reconfiguration system

This latter generates the output signals sent to the command board. Finally, the command board generates some signals which are amplified and which carry out the electro-mechanic actions in order to re-configure the PV modules connections. The reconfiguration algorithm, loaded on the controller, has been written in Labview for FPGA.

The algorithm control strategy is based on the early and cyclical modules output voltage values acquisition. The FPGA elaborates the voltage signals in order to detect each module working condition. The diagnosis strategy has been conceived and validated in the experimental tests carried out.

Particularly, in order to detect the working condition of each module, the reconfiguration system monitors in real time the module voltage output value compared with a threshold value. Moreover it also compares the output voltage values of all the modules of the same string.

If a working anomaly occurs, then command board generates the signals which are amplified and which carry out the electro-mechanic actions in order to re-configure the series/parallel connections within the PV plant. As an example, in the 2x3 PV array where the reconfiguration system takes place, if conditions 3 and 5 of Fig. 6 occur then the command board carries out the electro-mechanic actions in order to re-configure the PV array as in conditions 4 and 6 of Fig. 6.

In the case of a temporary shading condition, the anomalous working condition is off. So, the command board carries the PV array back to the previous configuration.

If one only module is shaded, no symmetrical configuration of the PV plant can be obtained and so the command board does not carry out any control action on the PV array. However, if this is a lasting condition then a malfunction signal can be sent to the information room. This allows to detect single module malfunctions due to lasting shadings caused by plastic bags, bird excrements etc and allows also to minimize the malfunction period.

5. Conclusions

By analyzing the experimental results carried out thanks to the test bench built by SDESLAB Laboratory, it has been possible to detect the PV plant under unequally radiation conditions.

Particularly, each module output voltage has been chosen as the key indicator of its working condition.

A threshold strategy has been conceived and the threshold values have been defined.

Finally, the comparison between each module output voltage and the threshold one has allowed to detect anomalous working conditions.

Thanks to the experimental researches carried out, a new control system prototype for the energy production maximization of a unequally irradiated PV system has been conceived and built.

Under shading conditions, the reconfiguration system changes the series/parallel connection between the modules in order to maximize the output power.

The tests carried out in order to set up the reconfiguration system, show that this latter is a flexible tool able to:

- increase the PV plant efficiency, thanks to the mismatch effect reduction;
- reduce the maintenance time and the time in which the PV plant does not produce energy cause of the mismatch effect thanks to the possibility of diagnose each module working condition.

Thanks to its simple architecture, the reconfiguration control system, if on a large scale manufactured, could have a negligible cost compared with the plant one. Moreover, the reconfiguration control system cost would be amortizable in a short time thanks to the benefits connected to the increase of the electric energy production.

The reconfiguration controller could be used in high power PV plants in which the decrease of electric energy production, due to the mismatch effect, can reach considerable values.

Other tests are in progress in order to optimize the prototype operating conditions. The results of these tests will be shown in a next paper.

Acknowledgement

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