Changing photovoltaic array interconnections to reduce mismatch losses: a case study

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***Abstract*- Partial shading of photovoltaic (PV) modules can affect a wide variety of plants ranging from utility-sized solar trackers to residential building-integrated PV, resulting in lower energy production yields. The traditional series-parallel interconnection scheme of solar arrays is sensitive to disparate solar irradiation levels on modules of the plant. By using alternative topologies, the effects of unavoidable partial shade can be decreased. In this paper, module interconnections inside a PV array are modified to reduce mismatch losses caused by partial shading. Results from a measurement campaign on a 2.2kW plant carried out on Jaén University's campus using various interconnection schemes are presented.**

I. INTRODUCTION

The global photovoltaic market has tremendously increased this past year throughout the world accumulating approximately 7.8 GW_p at the end of 2007. Certain countries have largely contributed to the expansion of PV generation, especially in Europe, such as Germany and Spain whom account for 73% of the new PV installations throughout the world [1]. In 2007, the Spanish photovoltaic market grew by 450% bringing its total installed PV power to 634 MW_p. As can be seen below, the Spanish photovoltaic ownership installation map shows that more than 65% of the grid-connected installations are utility-sized [2]. Most utility-sized installations, including those with solar tracking devices, are subject to partial shading during the early morning and sunset hours of the day.

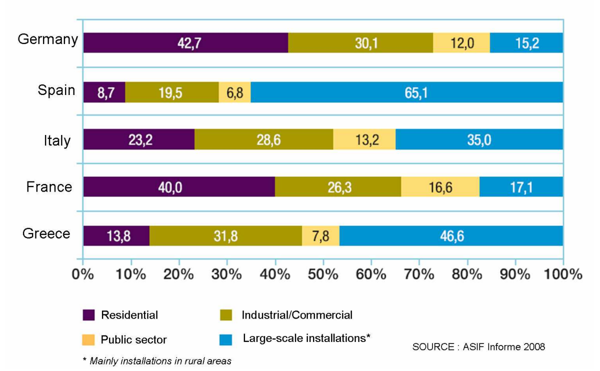

Figure 1 : Ownership of PV installation in selected European countries

Furthermore, utility-sized solar plants commonly use the centralized inverter topology, mostly for economical reasons, which consists of a single inverter having a large number of module strings connected in parallel. This topology, more commonly known as series-parallel (SP) topology, is sensitive to mismatch losses in the case of partial shading on the PV array. The series connections of modules, also known as PV strings, incur mismatch losses due to single current flow through modules with different characteristic parameters. Dispersion in PV module electrical properties can be due to manufacturing process tolerances, environmental alteration, or shadowing [3]. In partially shaded modules, light-induced current values are smaller because of lower irradiation levels received by shaded modules. This phenomenon has been partly addressed by introducing bypass diodes into modules to prevent deterioration of solar cells [4].

This paper proposes another way to reduce mismatch losses using alternative topologies of PV arrays. Measurement results carried out on a 2.2kW plant confirm the interest in modifying array interconnections.

II. ALTERNATIVE TOPOLOGIES FOR PV ARRAYS

Mismatch losses are almost always present in photovoltaic arrays, be it in PV modules or PV plants, simply because electrical characteristics in photovoltaic devices are not identical for each element of the array. The difference between the output power of the array and the sum of the output powers of its elements represent the amount of losses by element mismatch, better known as mismatch losses.

Previous research on modifying PV array interconnections of cells in PV modules [5][6] has shown promising simulation results of alternative cell interconnection schemes which reduced from 18% to 7% the amount of power lost in a module of 36 cells due to partial shadowing. In this paper, the alternative topologies will be used on an array of PV modules.

The total cross-tied (TCT) and bridge-link (BL) structures, shown on Figure 2, introduce additional connections in between strings of PV modules. The creation of loops in the array increases redundancy in the circuit which enables PV strings to have different currents values flowing through modules of a same string while respecting voltage constraints. In the TCT topology each module is in series and parallel with another one, whereas as in the BL topology half of the interconnections in the TCT topology are removed. The BL arrangement has the advantage of having fewer interconnections, thus reducing cable losses and wiring time

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of the installation. However, in larger installations the TCT arrangement can be easier to wire because of the simplicity of the pattern. It should be noticed that modifying array interconnexions does not affect inverter specifications; one single inverter has been used for the study of all three topologies.

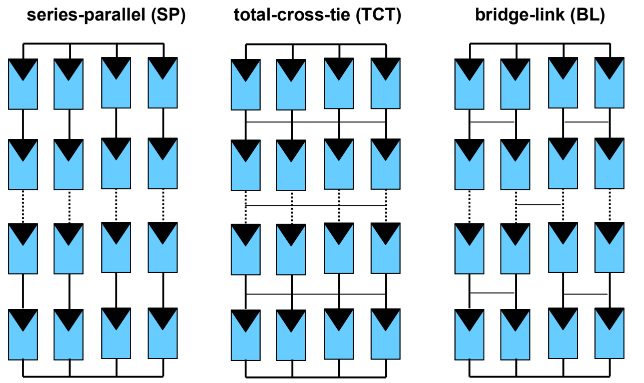

Figure 2 : Diagram showing series-parallel, total-cross-tie, and bridge-link array topologies

III. CASE STUDY : PERGOLA 5 ROOFTOP PV PLANT

The Universidad Verde (UNIVER) project on Jaén University's campus (Spain) consists of a 200kW plant made up of mono-Si and poly-Si technologies. Measurements were carried out on the 2.2 kW_p Pergola 5 (P5) plant which consists of 20 Isofotón I-106 modules. The I-106 modules are of mono-Si technology and are equipped with a total of two bypass diodes. Additional technical characteristics of the modules are shown on Table 1.

The P5 plant has been equipped with a Module Connection Box (MBC) enabling the user to rapidly change the interconnection scheme of the 20 module array. The MBC gathers both positive and negative poles of each module, enabling the user to wire the plant into the desired topology in a short time span. In order to directly interpret measurement results it is important to rapidly change topology wiring from one to another so that the incoming solar irradiance and plant temperature remains similar for all array structures. In the measurement campaign each topology had been manually changed in less than fifteen minutes with the MBC.

Isofotón I-106 Module		
Electrical Characteristics		
Standard Test Conditions : 1000 W/m², 25ºC, AM=1,5		
Nominal Voltage (V_n)	12	V
Maximum Power (P_{max})	106	W
Short Circuit Current (I_{sc})	6,54	A
Open Circuit Voltage (V_{oc})	21,6	V
Maximum Power Point Current (I_{max})	6,1	A
Maximum Power Point Voltage (V_{max})	17,4	V

Table 1 : Electrical characteristics of Isofoton I-106 module

Moreover, plant topologies have been carried out in two different configurations: 4-5 and 2-10 configuration. The first configuration consists in 4 strings of 5 series connected modules, bringing an open circuit voltage of 98 V. The second configuration consists in 2 strings of 10 modules was used for grid-connection and energy production measurements presented in the last part of this paper.

Static partial shading of the PV modules was achieved by placing plastic film on the modules. The film used on the P5 plant modules reduces by 30%-50% the incoming solar resource depending on the number of layers of film used and solar irradiance level. The first series of measurements uses the static partial shading technique to obtain current-voltage characteristics of topologies.

Furthermore, the P5 plant is exposed to natural partial shading at the end of the day, due to a nearby building, which progressively covers the plant as the sun sets. The impact of alternative plant architectures on energy production caused by the nearby building shade will be addressed in the second series of measurement results.

A. Effect of alternative array topologies in normal operating conditions

First of all, it is important to determine if the TCT and BL topologies do not reduce power production in normal operating conditions, that is to say without shade, when compared to the traditional interconnection scheme. The P-V characteristics of the traditional and alternative topologies are presented on Figure 3. Results show that all three array structures have one single power peak and similar maximum power point values. The mismatch losses due to dispersion of electrical properties of the modules composing the plant can explain the differences in the plants' maximum power values, however in this case TCT and BL topologies have a 0.3 % maximum power increase, which can be considered as negligible.

Consequently, under normal operating conditions SP, BL, and TCT topologies have equivalent power production. The cable losses due to the additional connectivity can therefore be considered negligible.

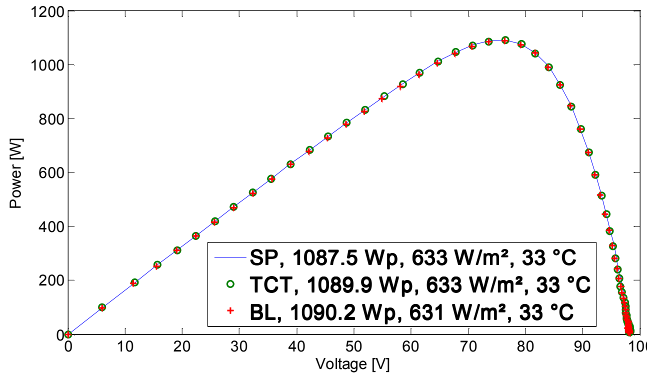

Figure 3 : Power-voltage characteristic carried out in 4-5 configuration normal operating conditions

B. Effect of partial shade on PV arrays

Partial shading of the traditional SP topology, which will be considered as our reference topology, generates mismatch losses. These amounts of losses vary with the operating point of the PV array. Indeed, when module voltage is too low the bypass diodes short-circuit the module in order to maintain proper operation of the entire string and protect the shaded module from solar-cell heating [4]. In many cases, PV modules are equipped with two bypass diodes: one for each 18 solar cell string. Module mismatching can be observed on the power-voltage characteristics with the multi-power peaks. These peaks have the inconvenience of having multiple maxima which mislead most Maximum Power Point Tracking (MPPT) algorithms [7].

As shown on Figure 4, partial shading induces a second power peak on the plant I-V curve. The local maximum is located between 30 V and 40 V whereas the global maximum is located at 72 V. Since irradiance and temperature levels during all three curve tracings are similar direct interpretation of results can be carried out. Two main interests in altering module interconnections can be brought to the light with these measurements:

- multi-peak shedding
- increase in maximum power output

First of all, alternative array topologies increase the maximum power point (MPP) value by 2.3% and 3.8% for BL and TCT topologies respectively. Moreover, as mismatch losses vary with environmental conditions we can expect larger maximum power increases with higher solar irradiance values at constant temperature levels.

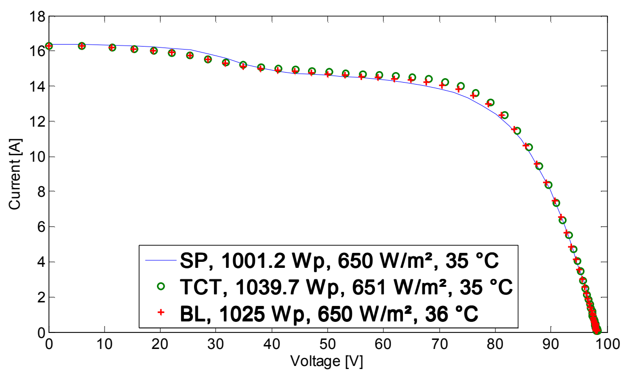

Figure 4 : Current-voltage characteristic of measurements with artificial static shading in 4-5 configuration

Secondly, BL and TCT topologies have lower local maximum peaks when compared to the traditional array structure. The additional redundancy in the circuit reduces the impact of degraded modules on normally operating modules throughout the array.

C. Study on energy production of alternative topologies

Previous experiments have shown greater maximum power values with static artificial shadows on the P5 plant. Since a natural shadow appears on the P5 plant, the experiment consisting in recording plant energy production and incoming solar energy has been carried out for each of the array architectures.

Due to the uncontrollability of outdoor environmental conditions, performance comparison of these topologies has been carried out by using an Energy Production Ratio (EPR). The EPR is a ratio expressing the incoming solar energy and the grid-fed energy produced. This indicator is, during normal operating conditions, the sun-to-grid efficiency of the solar plant. Experimental results are shown on Figures 6-8.

Results show that alternative topologies extend the energy production period in partially shaded conditions. Indeed, on Figure 5 partial shading occurs around 15:30 which is also visible with the EPR peak. In the TCT and BL topologies the partial shade peaks are wider and have larger amplitudes with respect to the SP arrangement. Furthermore, the top-right boxes on Figures 6-8 show a zoom on the graphs when partial shading appears. In the case of the SP topology, grid-fed energy (in blue) decreases rapidly when partial shading appears, whereas alternative topologies continue to feed the grid even after partial shading of the plant. The high EPR values are surprising at first since the EPR is sensibly close in definition to the efficiency of the solar plant, yet a distinction is necessary. The incoming solar energy is measured by an irradiance sensor located on the top-right side and at the same inclination angle as the modules of the plant. It has been observed that the building shades the P5 plant beginning from the top and progressing downwards as the sun sets. Therefore, the irradiance sensor is shaded before the entire P5 plant. Hence, the irradiance sensor does not systematically reflect the irradiance received by the entire solar plant due to its limited surface and location, especially in partial shading cases. Such high EPR values can be explained by the difference between the actual solar energy received by modules and the information delivered by the solar irradiance sensor.

The EPR indicator may help point out variations between irradiance sensor measurements and real solar energy received by the PV array. Indeed, in normal operating conditions the sun-to-grid ratio varies slowly. The detection of EPR peaks may help observe brutal changes in real solar plant irradiance and identify partial shading on the solar plant. For example, on Figure 7 shade has temporarily affected the irradiance sensor at midday. We can see an EPR peak rising with a small value at the same time while the energy production remains constant. The shade phenomenon does not affect the energy production therefore error on plant irradiance can be concluded.

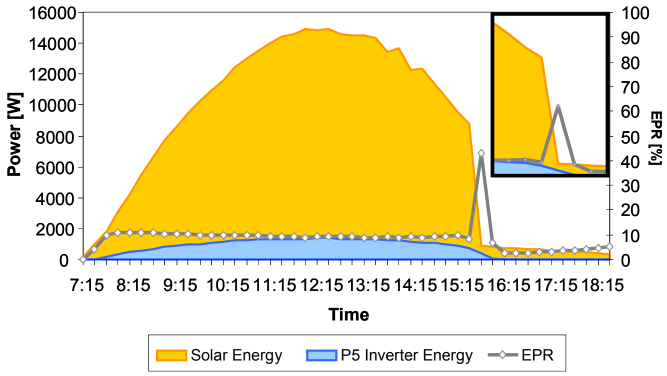

Figure 5 : Energy production and EPR evolution of P5 plant with SP topology on March 20th 2009

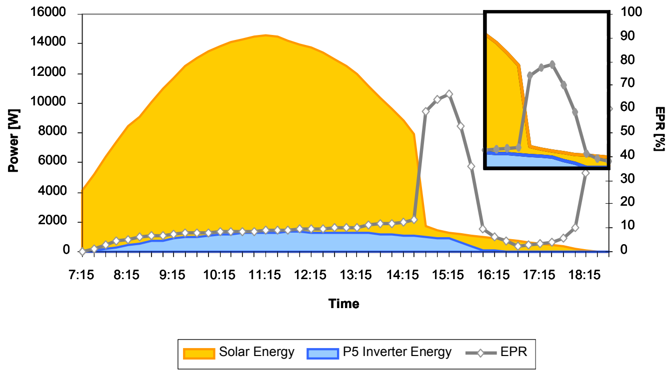

Figure 6 : Energy production and EPR evolution of P5 plant with TCT topology on March 25th 2009

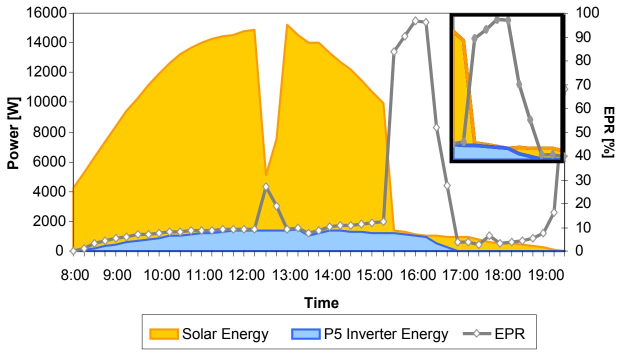

Figure 7 : Energy production and EPR evolution of P5 plant with BL topology on April 3rd 2009

IV. Conclusion and Perspectives

Partial shading and electrical characteristic dispersion of PV modules have been accounted for 4.8% of losses in PV arrays [2]. Such losses can be lessened by using alternative connection schemes which reduce mismatch losses and consequently grants the PV plant owner with supplementary photovoltaic generation. Adding redundancy in PV array wiring can help lower mismatch losses by allowing shaded panels to have less influence on the entire plant's energy yield. Alternative topologies of centralized inverter plants have been discussed and experimental results have shown beneficial qualities of modifying module interconnections: additional maximum power output, longer power production periods, and multi-peak shedding. Experimental results show that the TCT topology seems to be the most efficient for lessening mismatch losses during PV array shading without penalizing the overall efficiency of the plant in non shaded scenarios.

Further work will consist in characterizing these interconnection schemes with various shade scenarios in order to determine the most performant.

Although topology modification appears to be a solution to fight against mismatch losses, an evaluation of the supplementary wiring and maintenance of the plant should be addressed to entirely establish the cost-effectiveness of changing traditional array designs.

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References

[1] International Energy Agency Photovoltaic Power Systems Programme (IEA-PVPS), *Trends in Photovoltaic Applications : Survey report of selected IEA countries between 1992 and 2007*, available at http://www.iea-pvps.org/

[2] Associacion de la Industria Fotovoltaica (ASIF), *Informe annual 2008*, available at http://www.asif.org

[3] N.D. Kaushika and A.K. Rai, *An investigation of mismatch losses in solar photovoltaic cell networks*, Energy 32 (2007) 755-759

[4] A. Abete *et al.*, *Analysis of photovoltaic modules with protection diodes in presence of mismatching*, Photovoltaic Specialists Conference, 1990., Conference Record of the Twenty First IEEE Volume , Issue , 21-25 May 1990 Page(s):1005 - 1010 vol.2

[5] N.D. Kaushika and N.K. Gautam, *Energy Yield Simulations of Interconnected Solar PV Arrays*, IEEE Transactions on Energy Conversion, Vol. 18, No. 1, March 2003

[6] N.K. Gautam and N.D. Kaushika, *An efficient algorithm to simulate the electrical performance of solar photovoltaic arrays*, Energy 27 (2002) 347-361

[7] H. Patel and V. Agarwal, *MATLAB-Based Modeling to Study the Effects of Partial Shading on PV Array Characteristics*, IEEE Transactions on Energy Conversion, Vol. 23, No.1, March 2008