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A Comparison Between Simulated and Measured IV Characteristics

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Partial shading of photovoltaic modules: a comparison between simulated and measured IV characteristics

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Abstract — **Photovoltaic (PV) technology is raising attention as a low-cost green energy source. It mainly finds applications in solar fields, on building facades and on rooftop. One of the main issues that can occur is the shading of solar cells inside the photovoltaic module which could affect the maximum power output of the PV panel and the lifetime of the cell itself. In order to predict the behaviour of PV panels in partial shading conditions, simulations and then measurements on two different photovoltaic modules have been carried out and compared. Data have shown that the maximum power output of the panels under 1sun illumination can be predicted by simulation with a 3% discrepancy from measured values, independently from the type of technology and interconnections of the PV module.**

Keywords: partial shading, simulation, modeling, photovoltaic

I. INTRODUCTION

Photovoltaic (PV) technology is used to convert solar light into electricity. It is a renewable energy source widely chosen for green energy production [1] thanks to its reduced levelized cost of generated electricity [2]. Photovoltaic panels find their application both in power plants or on rooftop where partial shading (PS) represents an issue. Solar cells in the photovoltaic panel can be shaded due to light-blocking objects like trees, buildings or chimneys and can experience issues due to reverse bias and high temperature [3]. In addition, partial shading causes a deterioration of the maximum power point (MPP) and sometimes generates multiple MPPs of the solar panel output making the maximum power point tracking (MPPT) system very complicated. In this scenario, it becomes necessary to predict the behaviour of solar panel in shading conditions by proper modeling. There exist several models in literature to simulate shading conditions on cells, panels and also on power plants [4].

In this work, the model proposed by Atia et al. [5] has been implemented in the Photovoltaic Materials and Devices Toolbox (PVMD Toolbox) [6] to predict the behaviour of two photovoltaic panels which differ for the type of interconnections. In order to validate the model and the simulation tool used, the two photovoltaic panels have been then tested under the typical AM1.5G 1sun condition, with different shading patterns.

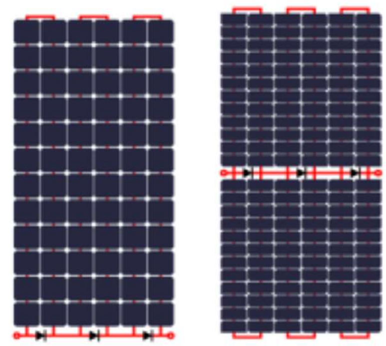

Figure 1: a) Standard module having 72 cells and 3 strings; b) butterfly module having 144 half cut cells divided in 6 substrings.

II. EXPERIMENTAL SECTION

Two different PV modules have been considered for both simulations and measurements. The first is a standard module composed by 72 M2 cells (individual cell area: 244.43 cm^2) connected in series. It can be divided into three strings each one connected to one bypass diode (Figure 1.a). The second one is a butterfly module and is made by 144 half M10 cells (individual cell area: of 165.35 cm^2). In this case, the bypass diode is placed in the middle of the string, forming two substrings connected in parallel (Figure 1.b). The IV curve of an individual cell of the module was calculated using a 1-diode model [7]. The model parameters saturation current (J_0), series resistance (R_s), shunt resistance (R_{sh}), and ideality factor (n_{id}) change with temperature and irradiance. For the model to work properly the shading factor was set to 99.5% instead of setting the incident irradiance to zero.

Standard module used for electrical measurements have been processed in EGP 3SUN factory in Catania and is made of heterojunction (HJT) solar cells. Butterfly module has been fabricated by Jinko and is made by Passivated Emitter and Rear Cells (PERC). Measurements at 1sun AM1.5G have been carried out in Enel Green Power under Pasan Solar simulator.

A. Shading patterns

For both the photovoltaic modules, the same shading patterns have been considered, meaning that two half-cut cells are shaded in the butterfly module for each whole cell in the standard module.

In Figure 2, four different patterns are represented: pattern 1 and 2 have been chosen to compare the effect of shading on a single string and on a single diode, while pattern 3 and 4 have been chosen to compare the effect of shading on two different strings connected on two diodes.

B. Electrical characterization

Simulation and measurements under 1 sun illumination have been carried out on 3Sun standard module and on Jinko butterfly module in order to study the effects of shading. Every IV curve of the shaded module has been compared with the electrical output of the unshaded module. In Figure 3 the simulated and measured IV characteristics under 1 sun illumination have been reported.

For the standard module, the output IV curves given by Patterns 1 and 2 are overlapping since cells are connected in series. This means that covering one cell of the string or the whole string gives the same output IV curve. In Patterns 1 and 2 the open circuit voltage (V_{oc}) of the shaded module is equal to 2/3 of the $V_{oc,unshaded}$ since only 2/3 of the PV module is actually working and the maximum power (P_{max}) is 64% of $P_{max,unshaded}$ (Table 1). Also for Patterns 3 and 4 the IV output curves are overlapping independently from the covered area. In this case, the Voc of the shaded module is 1/3 the $V_{oc,unshaded}$ and the P_{max} is 27% of $P_{max,unshaded}$ (Table 1). Looking at the IV output curves of the butterfly module, a difference with respect to the standard configuration can be appreciated: Patterns 1 and 2 do not give rise to the same output. Indeed, in the case of parallel connection of the string, current keeps flowing into the unshaded substring [8]. In Patterns 1, 3 and 4 where the string is not totally covered, the IV curve has a hump which generates a double P_{max} peak (a global and a local P_{max}). Even if there is this P_{max} double peak, for Patterns 1 and 2 the global P_{max} is the same and corresponds to 64% of $P_{max,unshaded}$ (Table 1) as for the standard module.

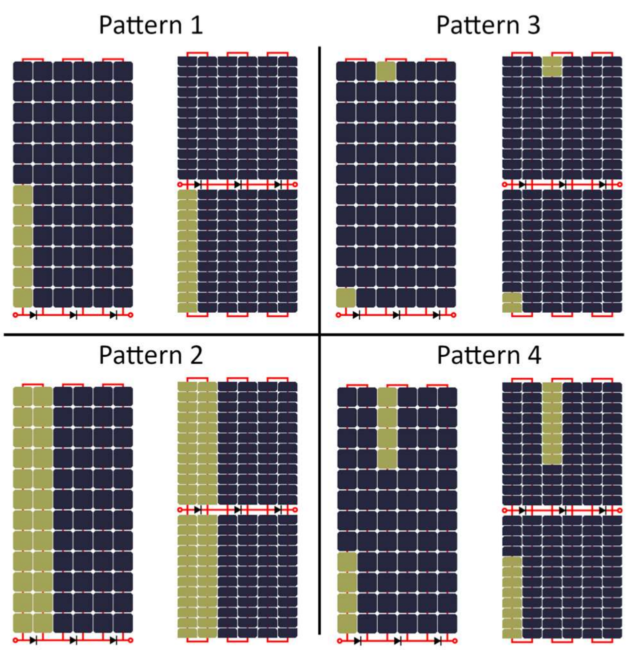

Figure 2: Shading patterns reported for both standard and butterfly module. Pattern 1 and 2 affects one only bypass diode while pattern 3 and 4 affect two bypass diodes.

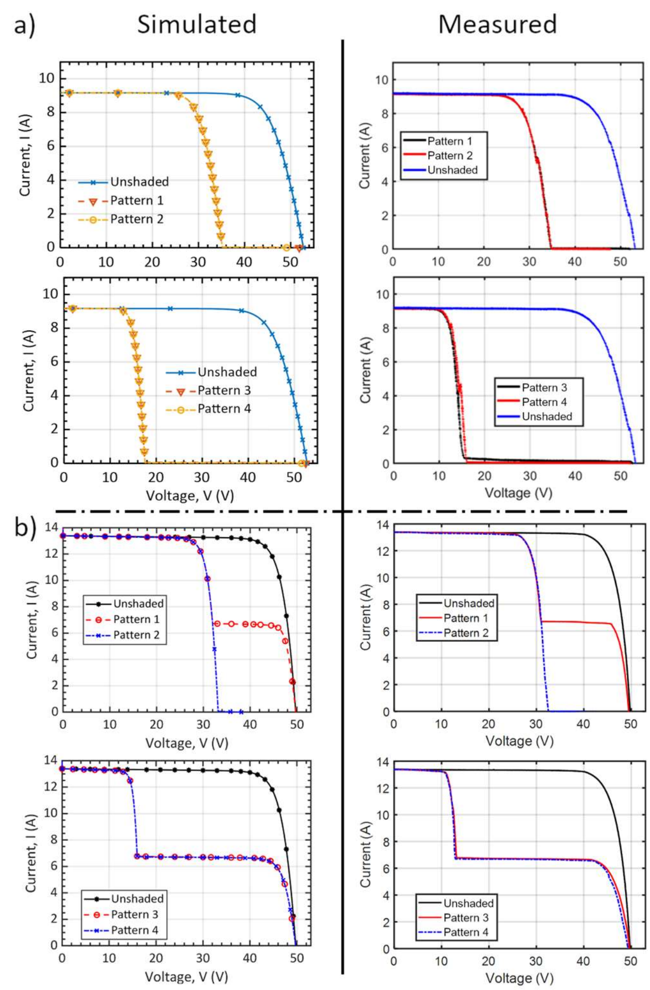

Figure 3: simulated and measured IV characteristic curves under 1 sun illumination for a) standard and b) butterfly modules.

TABLE I

MEASURED MAXIMUM POWER POINT

	$P_{max,STD}$ [W]	$P_{max,BUTTERFLY}$ [W]
Unshaded	364.9	543
Pattern 1	233.7	351
Pattern 2	233.7	351
Pattern 3	99.4	279
Pattern 4	102.1	277

TABLE II

SIMULATED MAXIMUM POWER POINT

	$P_{max,STD}$ [W]	$P_{max,BUTTERFLY}$ [W]
Unshaded	364.2	543.4
Pattern 1	242.8	362.3
Pattern 2	242.8	362.3
Pattern 3	121.4	284.7
Pattern 4	121.4	282.4

In Patterns 3 and 4, the presence of the hump in the IV curves gives an output P_{max} equal to the 51% of the $P_{max,unshaded}$ (Table 1) which means that, if MPPT capable in finding the global P_{max} is present, the butterfly configuration is more convenient in case of PS of the string.

Comparing the measured and simulated IV curves for both standard and butterfly modules it can be noticed that with the chosen model, the behaviour of the PV panels can be predicted in a reliable way. Simulated and measured IV curves are in accordance and for the four presented patterns they differ of about 3% in terms of maximum power since there is a slight overestimation of the voltage at the maximum power point (V_{mpp}).

III.CONCLUSIONS

In this work, an experimental investigation of partial shading influence on PV panels has been performed and then compared to simulated results. Measurements under 1sun illumination have been carried out on two different PV modules: a standard module with HJT cells and a butterfly module with PERC cells. Measured and simulated IV characteristics were in accordance for both the PV panels independently from the kind of connections and the cells technology and a difference of around 3% in the P_{max} has been calculated.

REFERENCES

[1] A. G. Olabi and M. A. Abdelkareem, "Renewable energy and climate change," *Renewable and Sustainable Energy Reviews*, vol. 158, Apr. 2022, doi: 10.1016/j.rser.2022.112111.

[2] M. A. Green, "Photovoltaic technology and visions for the future," *Progress in Energy*, vol. 1, no. 1. Institute of Physics, Jul. 01, 2019. doi: 10.1088/2516-1083/ab0fa8.

[3] M. Dhimish, V. Holmes, P. Mather, and M. Sibley, "Novel hot spot mitigation technique to enhance photovoltaic solar panels output power performance," *Solar Energy Materials and Solar Cells*, vol. 179, pp. 72–79, Jun. 2018, doi: 10.1016/j.solmat.2018.02.019.

[4] F. Bayrak and H. F. Oztop, "Effects of static and dynamic shading on thermodynamic and electrical performance for photovoltaic panels," *Appl Therm Eng*, vol. 169, Mar. 2020, doi: 10.1016/j.applthermaleng.2020.114900.

[5] A. Atia, F. Anayi, and M. Gao, "Influence of Shading on Solar Cell Parameters and Modelling Accuracy Improvement of PV Modules with Reverse Biased Solar Cells," *Energies (Basel)*, vol. 15, no. 23, Dec. 2022, doi: 10.3390/en15239067.

[6] M. R. Vogt *et al.*, "Introducing a comprehensive physics-based modelling framework for tandem and other PV systems," *Solar Energy Materials and Solar Cells*, vol. 247, Oct. 2022, doi: 10.1016/j.solmat.2022.111944.

[7] M. A. Koondhar, M. I. Jamali, A. S. Channa, and I. A. Laghari, "PARTIAL SHADING EFFECT ON THE PERFORMANCE OF PV PANEL AND ITS DIFFERENT CIRCUIT TOPOLOGIES BASED MITIGATION TECHNIQUES: A REVIEW," *Article ID: IJARET_12_04_003 International Journal of Advanced Research in Engineering and Technology (IJARET)*, vol. 12, no. 4, pp. 15–23, 2021, doi: 10.34218/IJARET.12.4.2021.003.

[8] R. G. Vieira, F. M. U. de Araújo, M. Dhimish, and M. I. S. Guerra, "A comprehensive review on bypass diode application on photovoltaic modules," *Energies*, vol. 13, no. 10. MDPI AG, May 01, 2020. doi: 10.3390/en13102472.