YIELD MODELLING FOR MICRO INVERTER, POWER OPTIMIZER AND STRING INVERTER UNDER CLEAR AND PARTIALLY SHADED CONDITIONS

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ABSTRACT: Building Integrated and Building Attached Photovoltaic (BIPV, BAPV) systems may suffer from lower performance than predicted as a result of unwanted partial shading. New system architectures have been proposed to optimize performance. The common approach of these new architectures is to track the Maximum Power Point (MPP) of every solar module individually. A simulation model is developed to quantify the benefits and drawbacks of different PV system architectures. The model includes a shading evaluation of the installation with means of 3D modeling, irradiance calculations, PV cell modelling and finally an empirical power conversion model. The energy yield of three leading architectures is confirmed (string inverter, power optimizer, micro inverter) for clear and partial shading conditions by means of an outdoor field test. Results show that there is a clear benefit for MLPE systems at higher irradiance when partial shading is present. The analysis method can be used by PV installers and system designer to determine which is the optimal system architecture for maximum energy yield especially when partial shading is present.
Keywords: MLPE, BIPV, Power optimizers, micro inverters

1. Introduction

Penetration of solar photovoltaic (PV) systems in the Netherlands and worldwide has remarkably increased the past years and it is forecasted to keep growing in the future [1]. Particularly the application of BIPV and BAPV systems are projected to thrive in the following years as a result of increasing electricity prices for the residential sector and decreasing PV component costs. Residential and small commercial PV systems are typically installed in an urban environment. Roofs and terraces are often affected by shade coming from the close proximity of buildings, poles, antennas, dormers etc and thus introduce electrical and thermal mismatch losses between cells and modules. These are generally caused by manufacturing tolerance, heterogeneous irradiation conditions which are especially important for larger systems, panel degradation and thermal mismatch of the solar panels. Solar panels are connected in series and thus sharing the same current in a string. This topology is prone to power losses if the solar cells in the panel are not operating under the same conditions thereby reducing the current of the panel and consequently of the whole string. Partially shaded solar cells may become reverse biased because of the series connection and thus act as a load consuming the power that is generated by the unshaded cells. Two negative effects occur from partially shaded operation of a PV system: power loss and increased temperature of the shaded cells (hot-spot). By-pass diodes have been applied in solar panels to prevent power consumption from shaded cells and to prevent hot-spots by by-passing the shaded substrings of the solar panel. Most of the solar panels include one by-pass diode connected anti parallel per 16-24 cells [2].

The use of module level power electronic devices (MLPE) has been proposed to mitigate electrical and thermal mismatch losses [3-5] in the field by tracking the maximum power point of individual modules. In general MLPE devices consist of two main categories: micro inverters and power optimizers. In this paper micro inverters and boost power optimizers are considered.

Although modelling tools have been developed based on a variety of software platforms, most of them don't consider the system architecture. There are many available models which can be different in terms of mathematical sub-models and assumptions. Some models lack transparency and as a result project developers are expressing concerns regarding PV performance validity forecast, especially when shading is present. The key challenges of partial shading PV models is therefore to generate accurate yield predictions under heterogeneous irradiance conditions with reduced simulation time. In this paper a model is presented that considers cell shading fractions determined by a 3D model and applies an irradiance model to determine the effective irradiance on a partially shaded cell. Moreover, the model takes into consideration the system architecture and associated power electronics efficiency losses.

2. Correlations of shading fracture and power output at c-Si solar modules

A steady state solar simulator [6] was utilized for a series of shading experiments on a solar module with 60 series connected monocrystalline silicon cells. The module consists of 3 groups of 20 cells and each group is connected anti-parallel with a by-pass diode. An IV tracer was recording performance under standard test conditions (25 C, 1000w/m2 irradiance). Artificial shading was applied with two means: a) opaque masking with black cardboard and b) wire meshes with reduced transmittance as seen in figure 1. The reason of using two shading strategies is to represent field conditions where the beam B irradiance is obstructed and sky diffuse D remains relatively the same. For the analysis a 33 and 67% transmittance meshes were chosen to fit realistic D/G ratio.

Measurements were performed for cell shading percentages of: 10, 15, 20, 25, 30, 35, 40, 50, 75 and 100%. Twelve different cells were shaded for every shading fraction giving a total of 120 I-V curves per shading material in order to provide a distribution of the shade effect since the shading response is highly associated with shunt resistance of individual cells [8]. In figure 4 the relative power output in correlation with the shading fraction can be seen. As expected the opaque shading is causing the largest drop in power output. It is important to mention that even shading a very small portion of a single solar cell (10%-50%) leads to disproportional losses in power output. When shading as a fraction of a single solar cell's surface exceeds 50% then there is a total reduction of power at that cell's group due to the activation of the by-pass diode. Thus further shading of the specific cell or group of cells will not have any consequence in power output. These results are supported by similar work in the field [7].

Figure 1: Impression of the opaque and wire meshes used for the shading correlation experiments under a steady state solar simulator

From figure 3 one can determine the relative effective shading fraction by comparing the power output for the different transmittance materials. For example the power output with the 67% transittance mesh shading 100% of the cell is equivalent to 33% opaque shading. This transition can be better seen in figure 4. The results for all the three different transmittance materials fit perfectly leading to equation 1 which describes the effective equivalent irradiance of a partially shaded solar cell.

$$G_{eff} = (\text{unshaded fraction } \% * \text{Gtilt}) + (\text{shaded fraction } \% * D) \qquad (1)$$

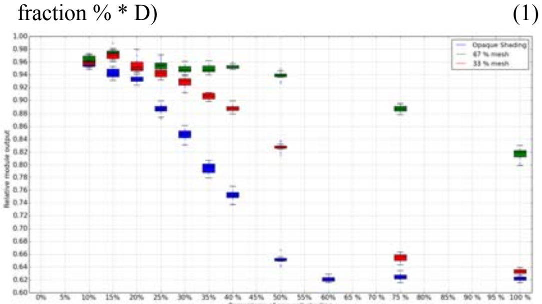

Figure 3: Relative power output for various shading percentages of a cell by using wire meshes and opaque cardboard

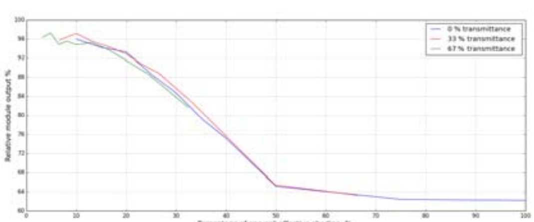

Figure 4: Relative effective shading fraction versus power output for three different shading materials

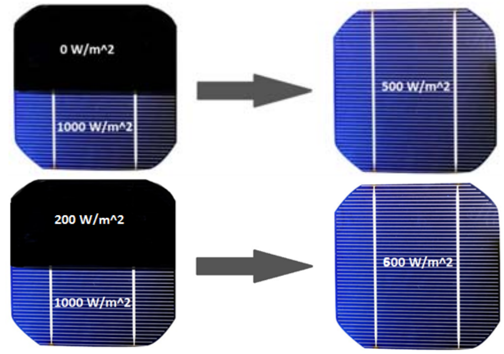

Figure 5: Application of equation 1 for direct and obstruction shading

3. Yield model

The complete MLPM yield model includes 5 different models integrated into one. Namely, it includes a 3D SketchUp model, a shade detection model, a radiation model, a DC and an AC simulation model. All the model inputs used in the complete model and the flow of simulation processes are shown in fig. 6. In the following sections, each one of the models will be separately presented along with all its specifics.

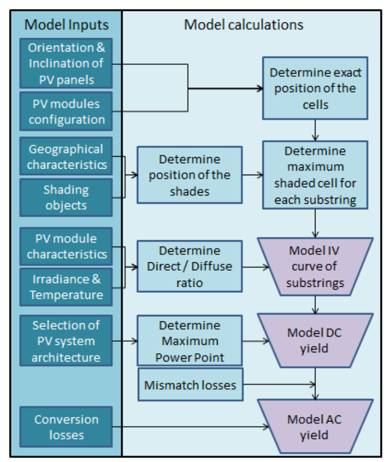

Figure 6: Yield model inputs and flow of simulation processes

3.1 3D Shading model and determination of shading fraction

To accurately predict the power output and behaviour of a partially shaded solar module, the shade coverage of the module's surface has to be known. For this reason, a computer-aided design tool is used to represent the installation site including the PV modules and the obstruction elements which cause the partial shading. There is a big variety of CAD software available in the market but for this study Google SketchUp [9] is used.

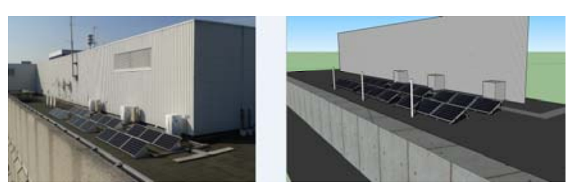

Figure 7: Impression of the field test (left) and impression of the 3D model (right)

Simulation Procedure:

- Design an accurate representation of the installation including the PV modules and all the obstruction elements (fig 7).
- In SketchUp the option is provided of exporting model elements x, y, z coordinates using the point cloud extraction function. This is done by selecting the cells and obstruction elements.
- A Python script is developed to virtually re-create the shading surfaces by using the x, y, z coordinates of the cells and the obstruction elements. Given the azimuth and altitude of the sun which is modeled depending on the location [10] at any particular time, simple trigonometric relationships can determine the relative X and Y offset co-ordinates of shadow points on a flat or inclined plane. Constructing the shadow of a complex 3D object is simply a process of translating each of its vertexes in turn to produce an outline on the ground or at a plane. The output of the model is a look up table with the shading fraction of the cells for any given azimuth and elevation angle of the sun. As a result, these look up tables can be used for various locations.

The shading fraction of each cell in the system is calculated with 0.5 degrees interval of the sun's azimuth and elevation angle. For higher accuracy the look up tables can be constructed with a range of azimuth and elevation intervals with an unavoidable consequence in simulation time. In figure 8 a graphic representation of a part of the look up table can be seen. Specifically the shadow extension of a pole situated at the south part of the system for three different times of the day is visible. Subsequently the heaviest shaded solar cell of a substring is determined and is used as an input for the next part of the simulation.

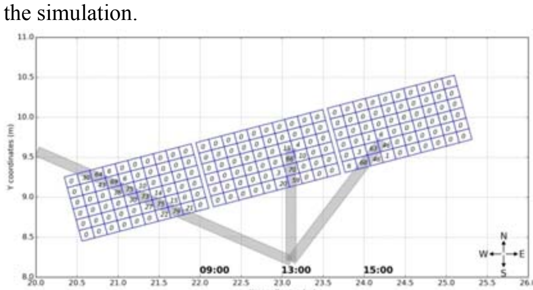

Figure 8: Graphic representation of the look up table for specific time and date produced by the shading model

3.2 Irradiance model for determination of direct and diffuse light components

After the determination of the shaded fraction of the cell, the diffuse and direct part of the irradiance has to be calculated with an irradiance decomposition model. A comparative review of the various irradiance models and their empirical validation has been presented by Loutzenhiser [11]. For this paper the Reindl 2 model [12] was chosen to estimate the diffuse part of irradiance using as input the clearness index, the global in-plane irradiance and the elevation angle of the sun.

3.3 PV cell and conversion model

A mono-crystalline cell can be modeled with the equivalent electric circuit of a simplified double diode model developed by Ishaque [13] and shown in figure 9.

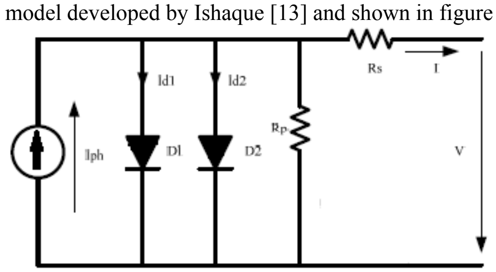

Figure 9: Double diode equivalent circuit for a PV cell

Nearly all modern inverters have more than 99% MPPT efficiency. While Perturb and Observe (P&O) is the most used algorithm new hybrid algorithms have been implemented by inverter manufacturers to boost performance at partial shading conditions [14-15]. This is achieved by frequent scans of the P-V curve of the solar modules which ensure that the inverter will detect the MPP even in the case of lumpy P-V curves. In this study the MLPE devices are using the hybrid P&0 algorithm while the string inverter system has the option to activate it. Note that the string inverter is delivered from the manufacturer with the shadow mode deactivated. The model assumes that the MPP of the solar modules is always found and kept when the hybrid algorithm is used, however the string inverter is modeled with the hypothesis that when the shadow mode is deactivated the solar modules are operated at a local maximum when partial shading is present.

4. Model validation by using real measured data

For the validation of the proposed yield model, measurements from 3 systems in Eindhoven [16] are used. The systems are oriented south-east with an inclination angle of 30 degrees. The systems architecture consists of a string inverter system, a power optimizer system and a micro inverter system, all with the same installed power (1.6 KWp). The electrical parameters are continuously monitored before and after every stage of power conversion including in plane global irradiance and module temperatures. For the model validation the measured irradiance from the field test has been used as input after having been decomposed in diffuse and direct components [17]. Moreover, module temperatures have been used by the measured data.

For obstruction shading, three shading scenarios that usually occur in pitched and flat roofs have been defined:

<u>Pole shading:</u> a pole with 1 m 70 cm height has been positioned on the south side of the systems.

<u>Row to row shading:</u> A wall situated on the south side of the systems (fig.7), homogenously shades all three systems during winter months. Additionally because of the module spacing there is row to row shading

In figure 10 the irradiance, the measured and simulated AC power of the three systems can be seen for a clear day without any shading elements. The simulation measurements follow the measured data with high accuracy except early morning and late evening hours when the pyranometer and parts of the PV modules are covered from shade from neighboring buildings. While the system's daily yield is very close for all three systems, the micro inverter seems to outperform the power optimizer and string inverter system by 4.3% and 2.3% respectively. Deviation between measured and simulated daily yield lies below 1% for the power optimizer and micro inverter while it reaches almost 2% for the string inverter system. This occurs partially due to the unavoidable shading late in the evening and because of the increased mismatch losses at high irradiances. When shading is not present hence the mismatch losses are low, the performance of the systems highly depends on the converting efficiency of the power electronics. This issue has been discussed before [16] and results showed that the converting efficiency of the string inverter especially in low power is superior to the MLPE devices examined in this work.

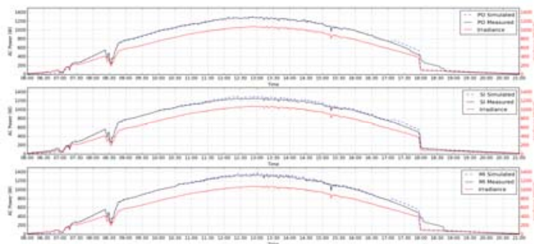

Figure 10: Irradiance, measured and simulated AC output of the three systems for a clear day

In figure 11 partial shading by a pole has been introduced for the three systems. The simulated and measured AC outputs seem to overlap for the most part of the day. The micro inverter and power optimizer systems outperform the string inverter system both in the measured and simulated daily yield data by 7-9 %. Small variations occur from the measured data due to the shading fraction detection from the 3D model and the MPP tracker. Specifically for the string inverter system, it is visible how the MPPT is losing the global maximum 3 times during the day and thus reducing the system yield. The detection of this behavior from the simulation model is not possible due to the fact that the tracking algorithm is not known. Measured and simulated daily yield has a deviation of 2.5-3.5% for the MLPE and around 6% for the string inverter system.

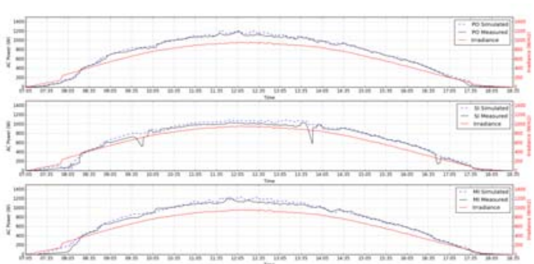

Figure 11: Irradiance, measured and simulated AC power for partial shading by a pole

In figure 12 the AC output and irradiance during a clear winter day can be seen. During winter months row to row shading is present due to the wall situated at the south of the systems and because of the distance between the two rows of modules. The systems are gradually free of shade with the power optimizer performing better due to the fact that it can detect the global MPP even at low voltage inputs (up to 8V). The string inverter system cannot detect the MPP when the voltage input becomes less that 110-120V and thus operates the PV modules at a local maxima. Therefor the MLPE retrieve 10-11% more energy yield for this specific day. Deviation of simulated and measured data range from 0.5 to 2.5% for the MLPE and around 4% for the string inverter system.

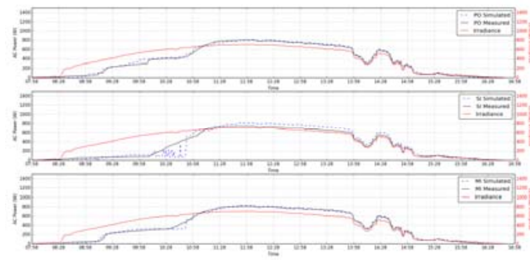

Figure 12: Irradiance, measured and simulated AC power for row to row shading

5. Conclusion

In this paper an effort was done to assess the shade response of typical c-Si solar modules and different PV system architectures. The shading impact has been proven to be nonlinear for c-Si solar modules. Shading of half a cell has a power impact of 40 times the shade's physical size. Based on these results an effective irradiance equivalent was used to describe operation of solar cells under partially shaded conditions. Furthermore a model was developed to predict the shading fraction of cells and modules throughout the year and correlate that with yield output. The model was calibrated by using real measured data from three systems installed in Eindhoven.

Results suggest that MLPE systems produce more energy in certain irradiance and partial shadding conditions. Future work will include simulations for a typical meteorological year with various irradiance profiles from Central and Southern Europe.

6. Achnoledgements

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