Annual Yield Comparison of Module Level Power Electronics and String Level PV Systems with Standard and Advanced Module Design

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ABSTRACT: This study focuses on the partial shade-mitigating effects related to the insertion of additional ideal by-pass diodes in residential-scale photovoltaic (PV) systems. For this purpose, quantification of the resulting energy yield benefits is carried out in a representative residential environment. It is widely recognized that partial shading inflicts disproportional losses to the energy output of PV systems. Increased granularity levels in cell groups are perceived as a potentially promising measure to increase the shade-tolerance of photovoltaic devices. The past years, introduction of module level electronics promise to reduce further shading losses. The developed model includes a shading evaluation of the installation with means of 3D modeling, insertion of additional by pass diodes resulting in smaller cell groups, irradiance calculations, PV cell modelling and finally an empirical power conversion model. Results suggest that in the reference case of 3 by pass diodes the micro inverter system is performing the best under partial shading. By increasing the cell group granularity the string inverter systems seems to benefit due to the wide maximum power point voltage window.
Keywords: MLPE, BIPV

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 (BPD) 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 module. Most of the solar modules include one by-pass diode connected anti parallel per 16-24 cells [2]. Further increase of the granularity could potencialy result in additional power harvesting. On the other hand manufacturability of such module lay-outs is technically challenging and costly.

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 cell layout of the module and the number of BPDs. The PV system architecture and associated power electronics efficiency losses are also taken into account.

2 YIELD MODEL

The complete 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 Figure 1.

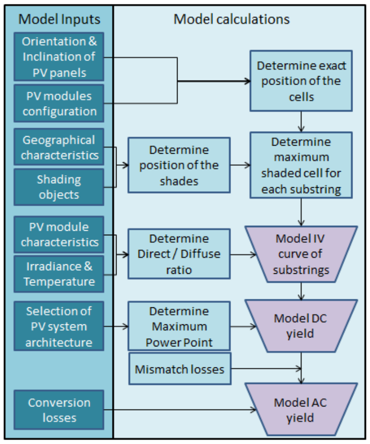

Figure 1: Building blocks of the simulation model presented in PVSEC 2015 with an oral presentation at session 5.AO 8.4

2.1 Shading Scenario

The partial shading conditions opted for in this research are set to match typical shading objects on a representative "reference" rooftop. The rooftop reference is determined for The Netherlands because the Dutch documentation on the housing stock is extensive. In terms of sensitivity, both the individual and aggregate effects of the shading object types are investigated. As this study is set to explore a realistic high-end range of the by-pass energy recovery potential under partial shading conditions, and by absence of average Dutch dormer dimensions, the shading scenarios are set relatively aggressively in the dormer-incorporating cases. Further chimney and exhaustion poles are situated in representative locations as seen in Figure 2.

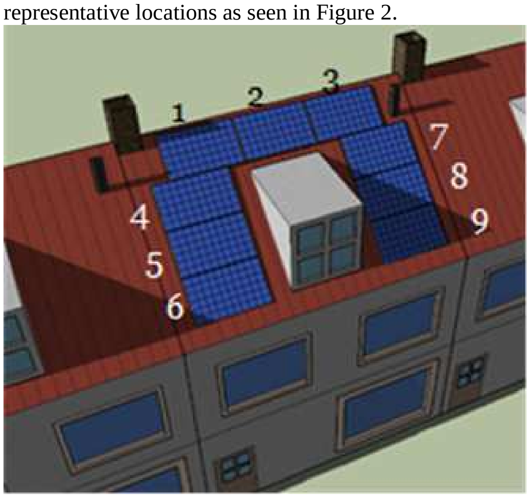

Figure 2: 3D impression of a typical row Dutch house. Dormers, chimneys and poles are usually present, causing obstruction shading to parts of the PV system

2.2 Module layout

A selection of 3 (reference), 6, 12 and 30 horizontally aligned BPD substring groups along with 5 and 10 vertically aligned BPD groups and the cell-wise case of 60 BPDs is assumed to be representative. These substring group selections can be seen in **Error! Reference source not found.**. This incremental approach is set out to evaluate the performance effect of stepwise BPD additions. As this research is set out for exploratory purposes, the BPDs modelled are assumed to be ideal smart by-pass diodes. This means that current leakages are neglected and that no voltage losses are assumed to occur when substrings are bypassed.

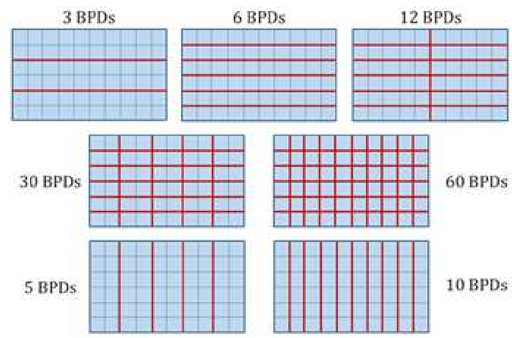

Figure 3: Substring granularities or variation of per-module BPDs investigated in this research. The 3, 6, 12 and 30 BPD cases are referred to as horizontally aligned substrings; the 5 and 10 BPD cases as vertically aligned substrings. Bypass diodes per cell are assumed in the 60 BPD case

2.3 Irradiance Model

The effective irradiance on a cell can be expressed as the area-weighted accumulation of its unshaded ($G_{U,k}$) and shaded ($G_{diff,k}$) irradiance-receiving fractions (where σ_P represents the cell shade percentage):

$$G_{cell,eff} = [(100-\sigma_P)\cdot G_{U,k} + \sigma_P \cdot G_{diff,k}] / 100 \qquad (1)$$

The effective irradiance on a substring (connecting cells in series) depends on the irradiance received by the cell receiving the least irradiance – the cell shaded most heavily in the case of this study:

$$G = G_{eff} = min(G_{cell,eff}) = G_{cell,eff}(max(\sigma_P)) \qquad (2)$$

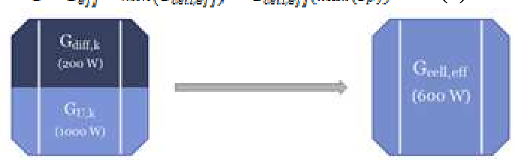

Figure 4: Principle of deriving the effective cell irradiance from its shaded and unshaded fractions. In this example, σP = 50%. Modified from previous similar work (Sinapis, et al., in press; Tzikas, 2015)

2.4 PV cell and conversion model

A mono-crystalline cell can be modelled with the equivalent electric circuit of a simplified double diode model developed by Ishaque [6] and shown in Figure 5.

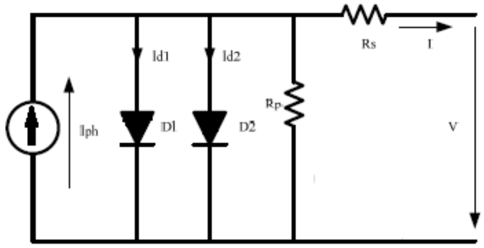

Figure 5: Double diode equivalent circuit for a PV cell

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 [7-8]. 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.

3 SIMULATION RESULTS

By using typical meteorological year**'s** irradiation data by Meteonorm [9], a full year simulation for unshaded and partially shaded scenarios has been performed. Meteonorm provides measured irradiance data for a variety of locations. Moreover, the data can be decomposed and trans-positioned by using known irradiance models. A constant albedo factor of 0.15 has been used for the simulations.

In Figure 6 the annual irradiance reduction due to shading can be seen. Modules around the dormer suffer the most while the chimney and poles have a small effect on the annual irradiance received by the cells.

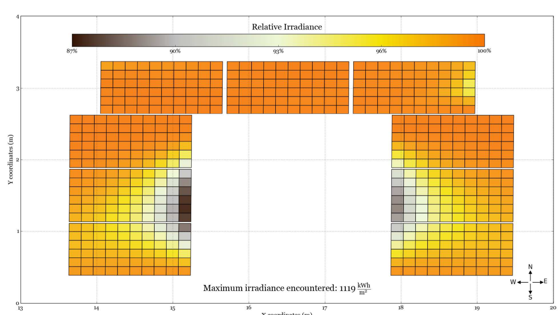

Figure 6: Annual irradiance reduction due to shading for the modelled roof

The effect of a triuangular shade on a PV module caused by the dormer situated in close proximity can be seen in *Figure 7* and *Figure 8.*

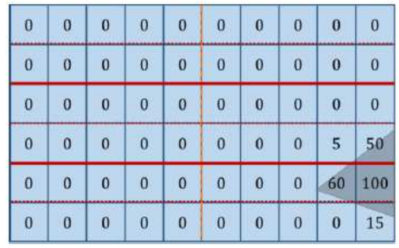

Figure 7: Partially shaded PV module with shaded cell percentages

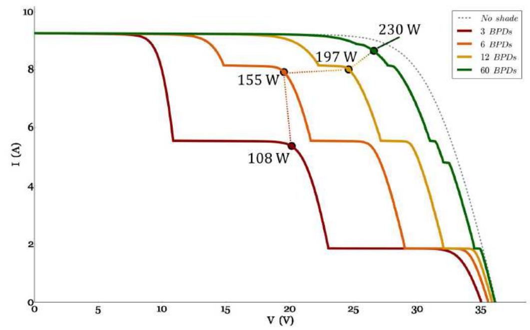

Figure 8: IV responses of example module under partial shading as in Figure 7. The cases of 3, 6, 12 and 60 per-module BPDs are shown. All increases lead to increases in extractable power, as can be seen from the highlighted MPP-values. The grey dashed line represents the IV curve in unshaded conditions. Total irradiance: 1000 W/m2; diffuse irradiance: 200 W/m2; Tmod: 40 °C

3.1 Annual Yield Results per system (NL)

The MI-type system provides the highest absolute system output if the amount of BPDs per panel is 3 or 6. However, the SI system with active shadow function (SI+) surpasses the specific yield performance of the MI-type system for other per-panel BPD amounts. The fact that either the MI or the SI+ system types come out on top can be rationalized. The reason is that SI and MI only require single-step conversion whereas the PO system requires two conversion steps: DC-to-DC followed by DC-to-AC. This two-step conversion leads to lower overall conversion efficiencies and therefore lower specific yield figures for the PO-type system. The MI performance advantage at low BPD amounts can be attributed to MPP optimization per panel instead of system-wise for the SI-type system. This leads to a flexibility advantage of MI-type systems over SI-type systems at low amounts of BPDs per module. The beneficial efficiency of the SI system combined with increased bypass flexibility of shaded module parts within the system makes it the best-performing system if the system bypassing flexibility is increased.

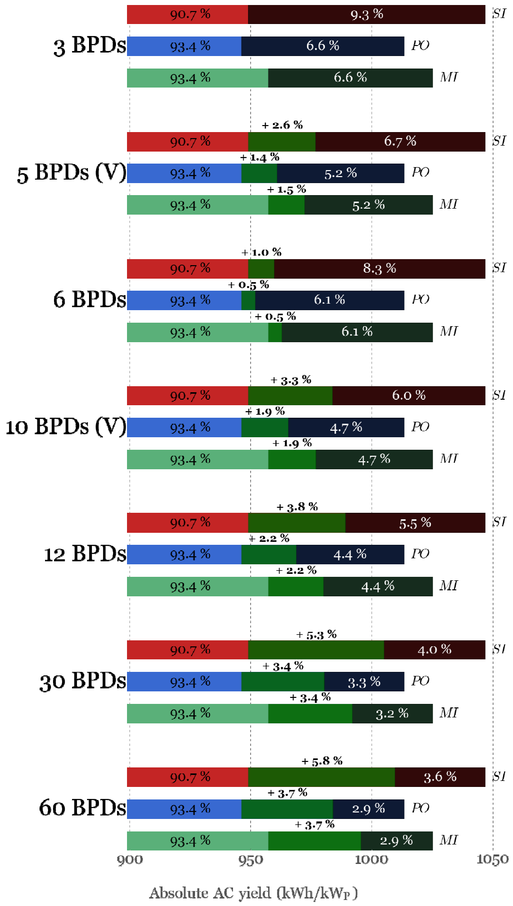

Figure 9: TMY AC yield results for SI(+), PO and MI systems. Shading index values and potential benefits when increasing the amount of BPDs per module in a stepwise fashion from 3 to 60 are illustrated

3.2 Geographic location sensitivity

Another crucial sensitivity component is the geographic location. This is because incident solar angles and direct-diffuse radiation ratios vary among different places on Earth. For this purpose an evaluation of three different representative locations have been investigated. The figure below presents the specific yield and the potential benefits in kWh/kW$_p$ for the reference case of 3 BPD and the potential improvement with 60 BPD. In Reykjavik and Eindhoven simulation runs, the MI system output exceeds those of the other system architectures when the amount of BPDs is 3. When the granularity of the cell groups increase to 60, the string inverter is able to recover significantly more yield.

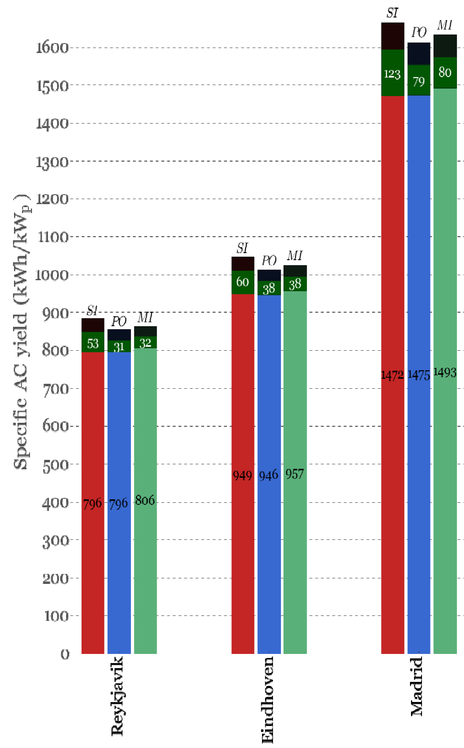

Figure 10: Specific AC yield results for SI(+), PO and MI systems placed in Reykjavik, Eindhoven and Madrid. The red, blue and light-green bars and the corresponding black text indicate the 3-BPD reference specific AC yield in kWh/kWp. The dark green bars and the corresponding white text indicate the potential benefits in kWh/kWp if 60 BPDs per module are used instead of three

4 CONCLUSIONS

In this paper we investigated the benefits of module level electronics and string inverters with various numbers of cell groups. Results suggest that the increased granularity can lead to higher performance under partial shading in almost all cases and locations. While the MI system is marginal better in the reference case of 3 BPD, the string inverter system is benefited the most when the granularity increases.

5 REFERENCES

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