PVOPEL: A Scalable Opto-Electrical Performance Model of PV systems using Ray Tracing and PVMismatch

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Abstract - In this study, we introduce a novel Photovoltaic Energy Performance (PV) modeling framework "PVOPEL" to study performance of a PV array using a cell level resolution ray tracing technique and the resulting system level electrical response. Conventionally, PV performance modeling tools model the energy output of a given PV system for a unit, such as a single module or a row of modules, and make an approximation that the output of the system scales with the increasing system size. While some of the factors affecting the output of a PV system do scale linearly with the system size, other factors such as mismatch losses scale nonlinearly based on the shading scene and PV system. PVOPEL framework provides a first-of-its-kind, highly scalable and accurate solution for modeling annual energy output of PV systems. It is expected to shorten product development lifecycles, reduce uncertainty in design decisions, lower the burden on test campaigns, and reduce business risk for solar industry overall.

The case study presented here showcases the capability of this framework for assessing the performance impact of Module Level Power Electronics (MLPE) such as DC optimizers and Microinverters as compared to a traditional string inverter based PV system. The case study demonstrates that although the monthly energy impact of introducing MLPEs into PV systems can vary from 1.5% loss to up to 6% gain, the annual energy assessment for the given configuration presents a more realistic figure of up to 1% gain relative to string inverter based PV systems.. With the rapid growth of MLPE deployment, this case study demonstrates a tool that the solar industry can utilize to assess the technical value proposition of MLPEs in detail.

Index Terms- Photovoltaic systems, PVOPEL, PVMismatch, Ray Tracing, DC Mismatch loss, Module level Power Electronics (MLPE), Energy Modeling

I. Introduction

One of the crucial components of Photovoltaic (PV) performance models is converting optical availability of resource to electrical response. PV Modeling libraries such as pvlib provide a model chain of functions for calculating representative system response with support for select PV system layouts [1], but it does not provide support for calculating site-specific shading losses. PVSyst employs geometric projection based shade calculators with certain approximations for varied system layouts [2][3]. PVSyst also lets users study the module level electrical response by aggregating current-voltage (IV) curves, yielding shade impact factors with approximations for shade on sub-module level, but currently is not capable to extend the analysis to annual energy. Other tools such as Helioscope generate shade reports using 3D simulations at specific intervals without explicit treatment for electrical response [4]. Tools like SunSolve combines ray tracing and electric solvers for accurate characterization of intra-cell to module level response, but the model is not scalable to the system level [5]. Goss *et. al* [6] propose dividing the visible sky for PV array into a grid and determining if each unit of the grid will be shaded or not for the time duration of simulation to calculate annual irradiance loss due to shade. This method has no consideration for electrical response. Considering these modeling tools from a literature survey, there is a need for a fully-integrated, end-to-end opto-electrical PV energy modeling method.

This study introduces PVOPEL, a generalized framework for modeling annual energy yield of PV systems with complex shading scenes. Introducing a ray tracing model eliminates the highly instantiated geometric projection based models that require several limiting assumptions, such as infinitely long rows, a need to handle first row separately, and inability to model partially shaded cell strings, etc. Further, a cell level electrical model yields a more accurate estimate of system level compounded mismatch loss than approximate multipliers. Finally, the MPPT model lends users an ability to model system level dynamic behaviors such as global IV sweeps on inverters. The modularity in the framework draws immense benefits from formerly validated models and addresses aforementioned gaps in PV system energy modeling.

II. PVOPEL Modeling Framework

PVOPEL is an integration of various physics based models such as geometrical models that define PV array layouts, optical ray tracing models that calculate cell level effective incident irradiance, weather models that yield highly localized components of plane of array irradiance and cell temperatures and finally, electrical models that calculate the maximum power output of the PV system at any given set of conditions.

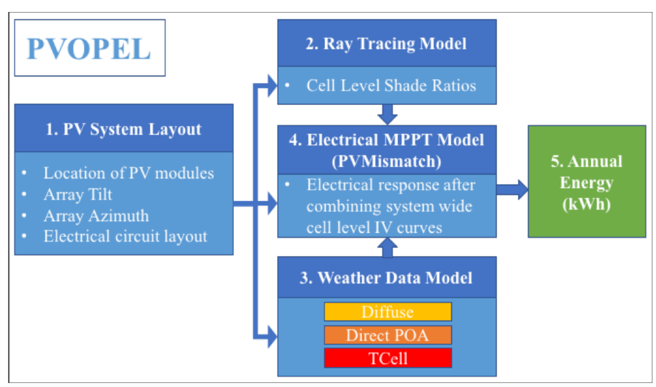

Fig. 1. PVOPEL architecture

The model chain is highly scalable for system size and can integrate desired interval of energy yield. Fig. 1 shows the architecture of PVOPEL model chain and the various component models that enable calculation of annual energy production.

This study demonstrates the use of PVOPEL framework using a case study approach. The optical ray tracing stage of the model is demonstrated using National Renewable Energy Laboratory's (NREL) SolTRACE tool [7]. SunPower's PV system simulation tool, PVSim [8], generates the required localized weather files derived inputs such as plane-of-array (POA) and diffuse irradiances using bankable solar data services. SunPower's PVMismatch library is utilized as the electrical and maximum power point tracking (MPPT) model that calculates the electrical response to given set of environmental conditions [9]. PVMismatch uses an implementation of the 2-diode model benefiting from former work by King *et. al* [10], Bishop [10], and Desoto *et. al* [11]. This study also utilizes newly added features in PVMismatch that allow users to configure cell string and bypass diode layouts on a PV module and to model PV modules equipped with Module Level Power Electronics (MLPE) such DC optimizers and microinverters.

A. *PVOPEL Architecture*

Elaborating the architecture in Fig. 1, users first define the PV System layout, including relative location at a site, tilt, azimuth, location and size of obstacles. Next, the ray tracing model uses this information to generate 3-dimensional (3D) site geometry, commonly referred to as a "scene", for ray tracing techniques to calculate the cell level shade ratios. Cell level shade ratios represent the variation of irradiance on a given PV cell, including obstacle and inter row shade. These cell shade ratios, along with Plane of array (POA) and diffuse irradiance, are used to calculate effective irradiance (*Ee*) for each cell in PV modules across the system.

Ee for each cell are used in the PVMismatch model chain by fitting a 2-diode equivalent circuit model on the cell level. The short circuit current (I_{sc}) is scaled using *Ee* and a Current-Voltage (IV) curve is calculated for each cell. The PVMismatch model chain aggregates the cell-level IV curves according to the electrical circuit configuration of the system by summing them in series and parallel combination. "Electrical circuit", for the purpose of this study, is defined as the series-parallel connection of PV cells and modules feeding into an MPPT channel of a PV inverter. The MPPT model is then used to determine the inverter-level maximum power point (MPP) to determine the Power at MPP, or P_{mp}. In the final stage of PVOPEL, P_{mp} values are aggregated over the desired time interval to calculate the energy yield of the PV system.

III. Data And Methods

This study demonstrates the PVOPEL framework's capabilities to calculate energy yield by simulating a case study with a PV system configuration as detailed in Table 1 for three PV module variants, namely 3-diode, DC optimizers and microinverters.

A 3-diode module is a conventional module with three cell strings and bypass diodes (one per cell string) isolating each of the cell strings. A DC optimizer module refers to a PV module equipped with a DC power optimizer per PV module (using a buck topology in this case study). DC optimizer is a voltage control circuit that finds the maximum operating power point of the PV module under given incident irradiance and reduces the output voltage of the PV module to match string current, correcting the module to module mismatch in the PV system. Finally, the collective output of DC optimizers is connected to a string inverter. A microinverter is an electrical circuit that finds the maximum power point of the PV module and further, converts the available DC power into AC power, directly integrating with the electric grid.

TABLE I

PVOPEL case study system configuration	
System Size (kW)	20
PV module	SunPower E20-327
Number of strings	6
Number of modules per string	10
Ground Coverage Ratio	0.85
Obstacle location	South West corner
Tilt Angle (Degree)	10
Azimuth (Degree)	0 (South)
Location	Richmond, CA

Fig. 2 shows an example of the shading scenes generated for the PV system. This particular scene demonstrates evening shade conditions on a typical winter evening. The inset of Fig. 2 shows an example of ray density across the PV module surface to its translation into equivalent I_{sc} for each cell of the PV module. The individual I_{sc} values for the entire PV system

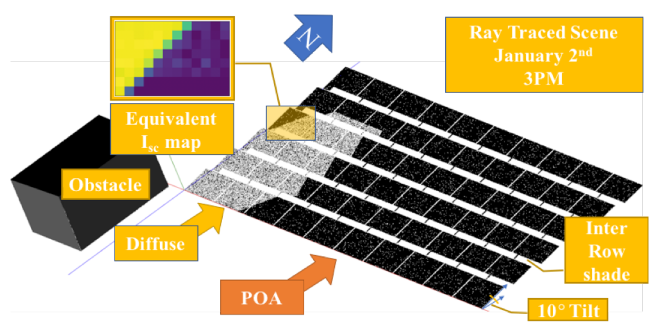

Fig. 2. Ray traced scene for the model 20kW PV system with an example of I_{sc} mapping

are passed to the electrical model to synthesize the PV system level Power-Voltage curve for the various module variants along with a reference unshaded case, as seen in Fig. 3.

Power for the module variant with DC optimizers are calculated by applying their respective efficiency loss to the maximum power point power (P_{mp}) of the individual PV module. Efficiency for DC power optimizers is a function of the duty cycle (ratio of input current to output current) and input power. For each shade scene, for each optimizer, the duty cycle is calculated as the ratio of input current or I_{mp} and the maximum possible string current (output current for the optimizer) for the system level DC voltage at the system level maximum power point. Efficiency loss is calculated using duty cycle and input power. Applying these efficiency losses at each optimizer module yields an accurate assessment of power output of an optimizer enabled PV module.

For a microinverter based module, the efficiency depends on the input power level and input voltage to the microinverter. It also depends on other factors such as temperature and grid conditions but for the scope of this study, only the input voltage and input power were used as variables affecting the efficiency. This efficiency is finally multiplied at the module level power at MPP to get the net output of the microinverter PV module.

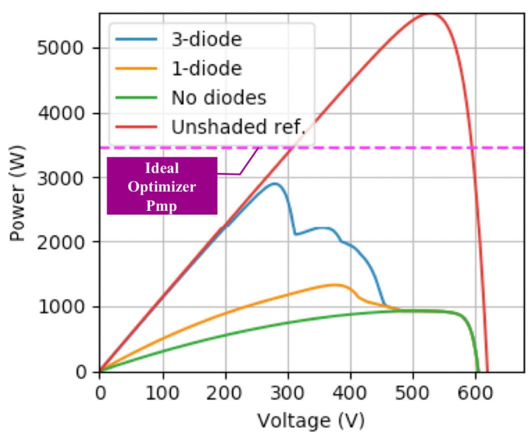

Fig. 3. MPPT model - System level aggregated Power-Voltage curves

Finally, the inverter MPPT model tracks the maxima of the system level Power-Voltage curves dynamically, taking into account effects of inverter-specific behaviors, and yields a system-level P_{mp} value to be integrated as energy value over desired time interval.

IV. Results

The results for this case study focus on a comparative analysis of performance impact of introducing power optimizers and microinverters in a PV system over a standard three bypass diodes configuration of PV modules. Fig. 4 shows the calculated power timeseries for a single winter day. The "Unshaded" case refers to the standard 3-diode case without any shading on the PV modules and thus follows the POA timeseries. The "Reference" case refers to the 3-diode case with the effect of shade on the PV system included. Whereas, "Optimizer" case refers to having DC optimizers on each of the PV modules in the system. "Microinverter" case shows the power timeseries for the microinverters on each PV module scenario. It is noteworthy that due to the higher GCR used in this scene, there is shade-induced power reduction at all hours of the day and significantly higher reduction into the afternoon and evening due to the South-West location of the obstacle and

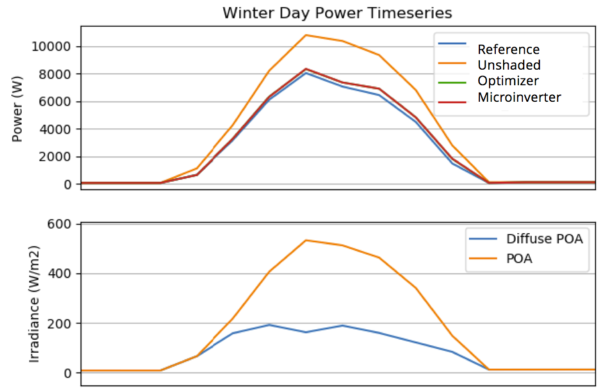

Fig. 4. Typical Winter day power timeseries

the northern hemisphere location of the site. Also, because of cell-level resolution of the study, the shade induced mismatch losses within the module are also taken into account, resulting in higher losses. Using an approximation that most commercially available modeling tools make, it would not be possible to study this particular detail of shade losses.

After running the simulation for the yearly weather file, Fig. 5 shows monthly energy aggregation of the scenarios under study in terms of monthly energy gain/loss with respect to the 3-diode case as a reference.

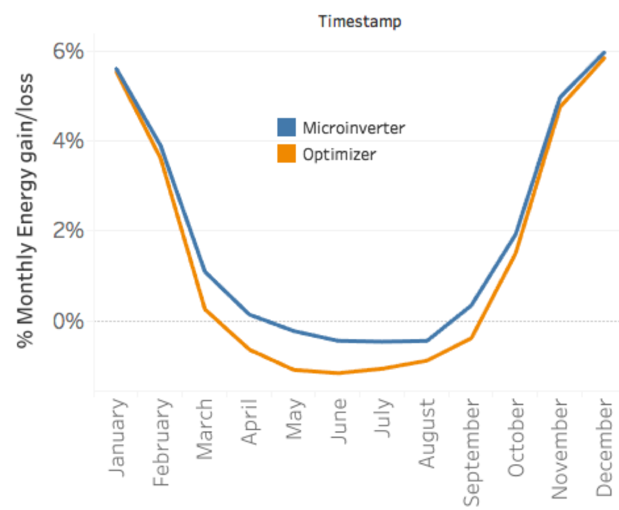

Fig. 5. Monthly energy impact of MLPEs with reference to 3 diode modules case

Gains in energy over the reference case can be interpreted as the energy recovered by the MLPE device by correcting mismatch in the PV electrical circuits minus the efficiency loss. Losses relative to the reference case are due to energy consumed by the MLPE devices for their operation, notably higher in summer months due to lack of shading for the PV system in this case study. Figure 5 shows that using MLPEs in a shade constrained PV system can yield up to 6% more monthly energy during winter months, But during summer months the efficiency losses of the MLPE devices can result in a relative monthly energy loss of up to 1.5%.

For PV applications, annual energy is a crucial metric for assessment of financial viability, since it directly influences the project economics. Aggregating the monthly results from this study into an annual basis shows the net gain or loss for the module variants under study, as shown in Fig. 6. The significant difference between the monthly and annual aggregations of results show the importance of proper weather-based weighting of the seasonal impacts. Furthermore, achieving cell-level resolution for studying shading loss enables performance comparisons for critical business decisions where the differences would have otherwise been lost in the margin of error, thus reducing the burden on resource intensive field tests. The framework presented in this study shows the importance of modeling PV systems in detail and calculating annual energy impact before wide-spread adoption of new technologies in a PV system. The case study presented in this paper demonstrates how to accurately determine the impact of introducing MLPEs in to a PV project and enables assessment of various control topologies of MLPEs.

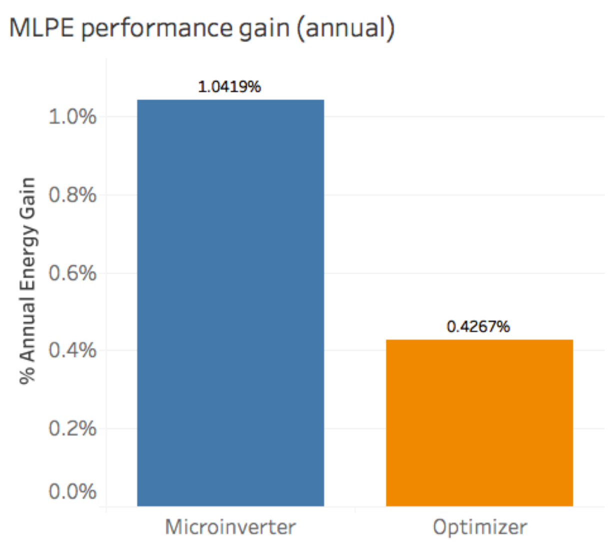

Fig. 6. Annual energy performance impact of MLPEs

V. DISCUSSION

It should be noted that this study was carried out with certain assumptions that make the magnitude of results specific to the case study demonstrated here. The annual performance of PV systems depends significantly on location and design of a PV system and thus, depending on the variability of weather at a specific location, the performance impact of MLPEs as discussed in this study could vary in magnitude. However, it is expected that the trend of higher seasonal than annual impacts observed in this study should be consistent.

It is also worth noting that DC optimizers are typically suited for smaller PV systems since they are susceptible to PV string to string mismatch. The PV system layout demonstrated in this case study shows balanced PV strings and thus the impact of possible string to string mismatch is minimal. In a scenario where the constraints of a roof do not allow for balanced string lengths, it is expected that the annual energy loss could increase for the optimizer case.

VI. CONCLUSIONS

Through a case study approach, it was successfully demonstrated that PVOPEL can be used to assess performance impact of introducing new technologies such as MLPEs in PV systems. For the shade constrained PV system described in the case study, using MLPEs can help recover up to 6% energy in winter months and in total 1% of annual energy.

Modeling PV systems with PVOPEL framework can benefit the solar industry at every stage of the business value chain: new technology R&D, improved fleet diagnostics, boosted confidence in pre-sales support, improved bankability and ultimately its contribution towards lowering levelized cost of energy.

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