HIGH RESOLUTION SHADING MODELING AND PERFORMANCE SIMULATION OF SUNTRACKING PHOTOVOLTAIC SYSTEMS

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ABSTRACT

The present work describes a methodology and set of tools developed to increase the accuracy of energy conversion predictions for one and two axis vertical trackers. Focus resides on mutual shading losses considering 3D geometrical properties of complex terrain, mounting structures, and external obstacles. A dedicated energy conversion algorithm reduces the computational burden of a detailed electrical simulation (bypassed-cell-block level) to acceptable boundaries, while reproducing the complex behavior associated with partial shading of the PV array.

Effects of time step resolution, level of detail of the electrical model, and module connectivity on shading losses and energy conversion are presented for an existing 1.3MW, two-axis-tracking CPV plant, using 15min resolution satellite derived irradiance data.

1. INTRODUCTION

Solar energy developers and financing institutions increasingly push for high-level, reliable simulations for project approval and realization. State of the art tools for the prediction of large PV-array performance deal with shading and mismatch losses in semi-empirical ways [1], frequently requiring user-entered, ‘experience-based’ parameters [2] or even direct loss factors [3] which can noticeably affect simulation results.

State of the art simulation packages calculate string or module shading coefficients by interpolation of shading factors over a pre-calculated grid of solar positions. The errors induced by this approach if compared to a step-by-step shading calculation can be substantial, given the significance of shading losses in large plants. Further on, the electrical effects of non-uniform irradiance over the array are usually estimated by simplistic assumptions that fail to accurately reflect the electrical system behavior, thus precluding a realistic parametric study of e.g. tracker spacing and geometry.

Models that actually calculate the extent of shading effects by numerically solving non-linear circuit models have been proposed for small PV arrays and validated on laboratory-scale setups, e.g. [4], [5]. The applicability of these models, with small time-step resolution, to large photovoltaic systems becomes more challenging due to increased computational load and requires high performance computer resources.

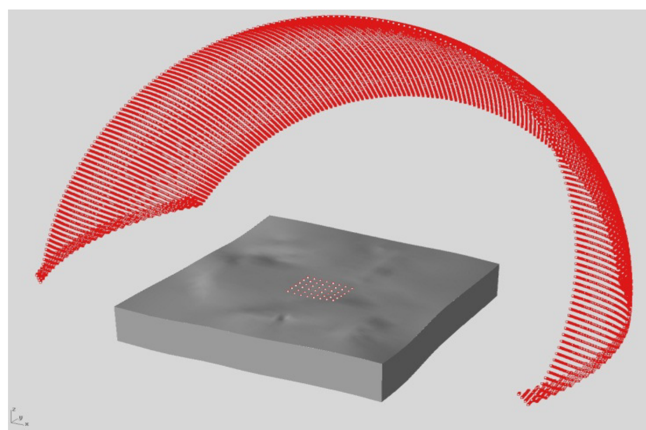

Fig. 1: 3D Site Model, surface with trackers grid and solar paths for a whole year.

2. SHADING ANALYSIS

A Shading Analysis Tool embedded in a CAD software environment provides enhanced, dedicated functions to treat aspects of geometry, module placement and string definition on the tracker. Three dimensional topographical aspects of the site are represented based on digital elevation model data and integrated as 3D surfaces for the tracker deployment in the shading analysis model.

Mutual shading calculations are performed at arbitrary time resolution steps (typically 5 minutes). Paths and time dependent solar positions at the required time intervals are computed through third-party algorithms [6] at the project location. The results are delivered as detailed shaded area fractions for any number of user-defined elements

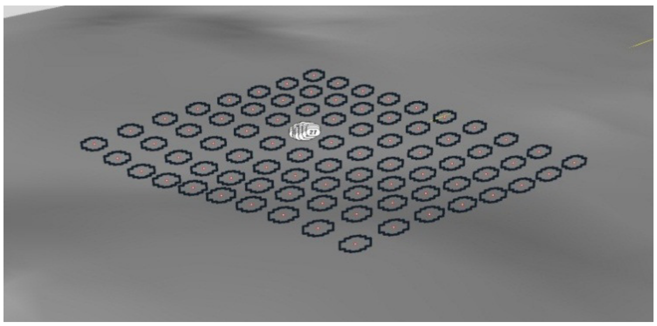

Fig. 2: Trackers matrix in near view

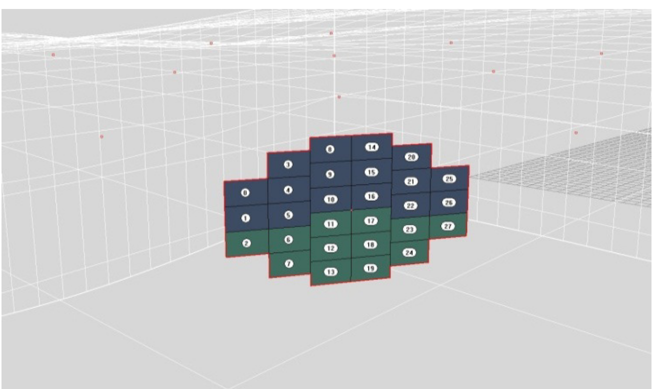

Fig. 3: Generic tracker geometry: modules and strings configuration

The shaded area fractions are obtained, at arbitrarily selected tolerance levels, through surface projection and intersection processing. Shadings effects caused by external objects and topographical terrain features are processed in the same way. Each tracker in the scene is singularly analyzed; therefore the simulation output provides shading factors regarding the chosen level of discretization (string / module / cell) separately for every tracker.

3. ELECTRICAL CONVERSION

The *PV Performance Modeling Collaborative* (PVPMC) defines nine modeling steps for the state-of-the-art performance prediction of a photovoltaic array [7]. For the sake of clarity and comparability, the structure of this section tries to adhere to these modeling steps. Differences in approach will be pointed out whenever necessary. The PVPMC also offers a comprehensive set of MATLAB® functions to support every step of the simulation [8], many of the functions were used either directly or for benchmarking of own algorithms.

3.1. Incident Irradiance (including shading)

Direct Normal- (DNI), Global Horizontal- (GHI), and diffuse horizontal irradiance are provided as raw data from a well-established satellite data provider [9]. Since the best resolution available is 15 minute intervals, variables were linearly interpolated for shorter simulation time steps. Functions for the transposition of irradiance into Plane of Array (POA) play a crucial role in the simulation of conventional PV plants, yet for the simulated 500-suns-CPV modules any diffuse and albedo irradiances were neglected.

Mean irradiance values for individual PV elements area calculated by superimposing POA array irradiance and the shading factors calculated by the Shading Analysis Tool.

3.2. Soiling and Reflection Losses

Spectral mismatch corrections are included as part of a Utilization Factor (UF) that will be described in detail in the following sections. Any angle of incidence deviations were neglected (perfect tracking assumed), and no soiling losses were considered.

3.3. Modeling Cell Temperature

The temperature model proposed in Gerstmeier et al. [10] was selected for comparability purposes. It describes heatsink temperature T_{hs} as a function of ambient air temperature T_a, absorptivity α, module efficiency η and wind speed v_w:

$$T_{hs} = T_a + \frac{\alpha \cdot DNI \cdot (1-\eta)}{U_c + U_w \cdot v_w} \qquad \text{Eq. 1}$$

Instead of using a correction value to estimate actual cell temperature (e.g. SAPM cell temp. model [3]), the module model parameters are 'tailored' to work directly with T_{hs}. Values for the two heat transfer coefficients U_c and U_w, ($10.6 Wm^{-2}K^{-1}$ and $0.6 Wm^{-3}K^{-1}s$ respectively) are also taken from [10]. Absorptivity is assumed to be independent of AM and equal to 0.9. Ambient air temperature values are provided along irradiance data, and were linearly interpolated whenever necessary. In the absence of reliable wind speed data a constant 2m/s value was used.

The detailed, full-IV-curve simulation approach brings out the possibility to reflect temperature differences among individual elements operating at different power regimes, i.e. $\eta_j = f(E_j, T_{hs,j}, V_j)$ and identify phenomena such as hot spot effects or diode thermal breakdown.

At this point, however, alterations in cell efficiency for elements operating outside MPP are not taken into account, i.e.

$$\eta_j \approx f\left(E_j, T_{hs,j}, V_{MP,j}\right), \; V_{MP,j} = f(E_j, T_{hs,j})$$

Including variability of efficiency (and not just a nominal value) requires the iterative solution of equation 1. To increase simulation efficiency the solution can be evaluated beforehand over a grid of T_a, v_w, and DNI values, and a 3D interpolation function created for use during the actual time-step simulation.

3.4. Module Characterization

For the study case, a one-diode-model as described by De Soto et al. [11] and implemented by Stein et al. [8] was utilized, and modifications applied according to Gerstmeier et al. [10], including an exponential dependency of R_{sh}, and a Utilization Factor $UF = f(AM, T_a, DNI)$ which is applied directly to DNI and accounts for the irradiance- and temperature dependent behavior of the concentrator-cell arrangement. Parameters for the model not included in [10] were estimated based on manufacturer datasheets.

Use of the Lambert-W-function was implemented to solve the implicit one-diode-model [12]; yet for the extensive use of the curves that the detailed simulation approach requires, this solution is still too slow to be practical. Piece-Wise-Linear (PWL) approximations, as inspired by the work of Wang and Hsu [13] are used instead, although as will be discussed below, the solution approach differs considerably.

Besides improving simulation speed, the use of PWL models allows the solution algorithm to be model-complexity-independent. N-diode models, or the Sandia Array Performance Model as proposed by King et al. [3] (extended by Barker and Norton [14] to yield a complete IV curve) would probably yield better simulation results [15], as long as an appropriate set of parameters is available.

A piece-wise-linear approximation to an ideal diode model is also used to accurately model bypass diodes in cell blocks, as well as string blocking diodes.

3.5. Circuit Solution (DC and Mismatch Losses)

Each tracker in the simulated PV plant consists of 144 modules of 200 cells each. If a bypassed-cell-block level of detail is to be achieved, with 20 cells per block, a strongly-non-linear system of equations on 1440 unknowns is to be solved for each simulation step; needless to say that the time complexity of this approach is prohibitive.

The developed algorithm takes advantage of the regular series-parallel arrangement of the circuit elements and calculates a full array IV curve by simple addition of PWL curves. The accuracy of the method is controlled by dynamically adjusting the number of breakpoints in the curves. The solution per time step of a partially shaded1440 element tracker takes about 1.9s in a single core workstation.

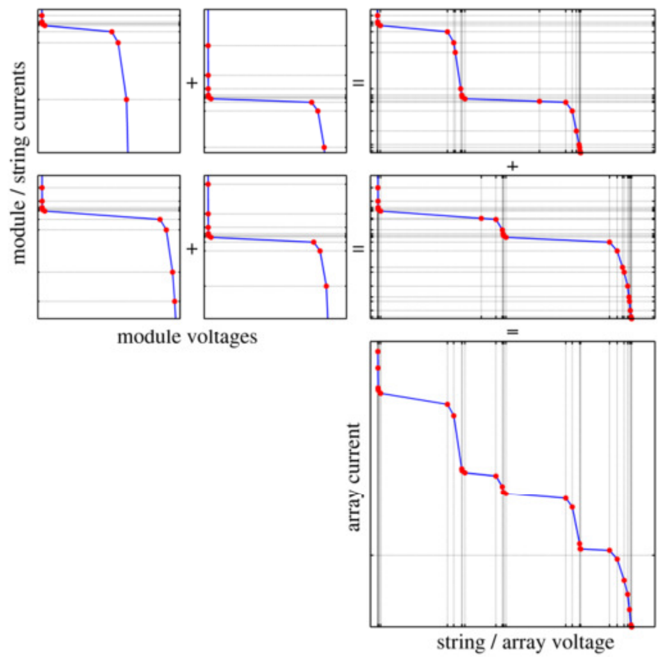

Fig. 4: Solution of electrical system by addition of PWL curves.

3.6. MPP tracking, Inverter Performance and AC Losses

Once a PWL array IV curve has been calculated, finding the true array MPP is straightforward. Variations in V_{MP} due to partial shading, which affect inverter performance yet are ignored by commercial packages, can be easily considered. Limitations in MPP tracker can also be quantified in detail.

4. RESULTS

For the selected PV plant sample a series of simulation for significant days of the year has shown noticeably differences in the shading factors values. The difference in the factors to be used for energy production evaluation for the simulated plant is quantified in 1.2% on yearly basis.

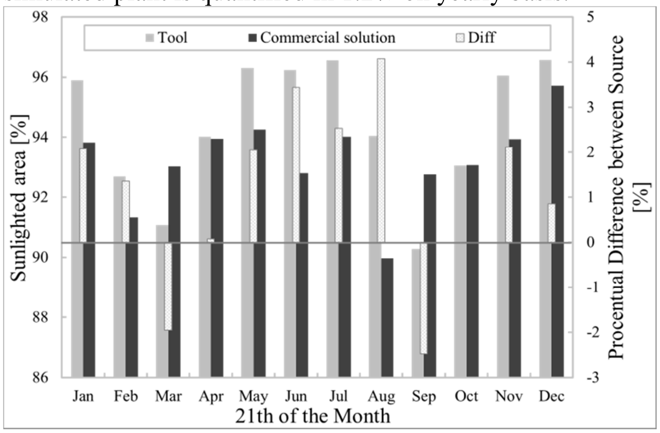

Fig. 5: Calculated shadings factor for the considered CPV plant

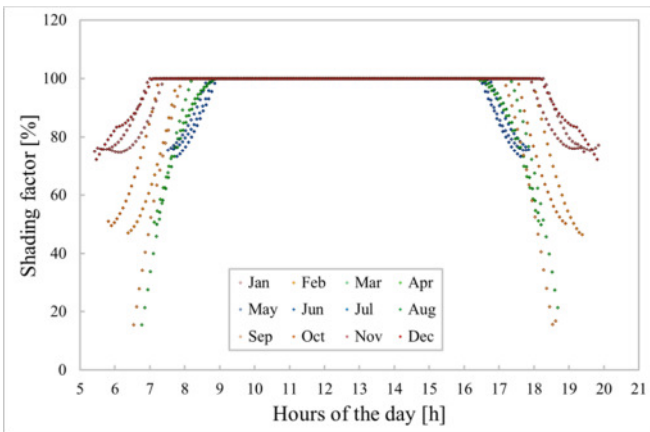

Fig. 6: Shading factor evolution through the day for the considered CPV plant

The electrical effect of the irradiance shading factors was calculated based on the solution of the electrical circuit, using different levels of detail and array connection patterns. The results were compared with state-of-the-art methods that perform estimations based on empirical rules.

An upper bound for energy losses is usually calculated by considering that any strings shaded over a certain threshold (usually the equivalent of one cell) as completely unproductive.

$$1 - \frac{P_{sh}}{P_{nsh}}\Big|_{max} = 1 - \frac{N_{ss}}{N_{ts}}$$

Where N_{ss} is the number of strings which are shaded, and N_{ts} is the total number of strings. A lower bound for energy losses is given by the linear case

$$1 - \frac{P_{sh}}{P_{nsh}}\Big|_{min} = F_{GS}$$

The two values are usually weighted by a *strength* parameter to achieve a 'realistic' result. Simulation results suggest that if this parameter value is chosen appropriately, the method can yield very accurate results, yet clear guidelines for its selection are not available.

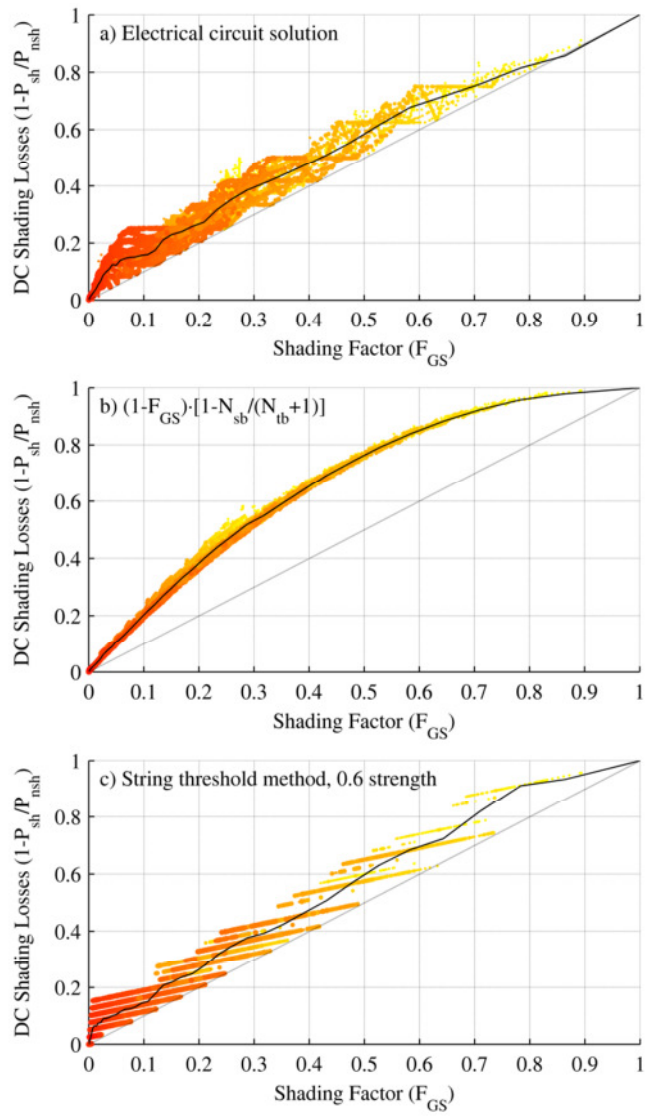

Fig. 7: Estimation of electrical effect of partially shaded array by different methods. a) represents the proposed detailed simulation approach; b) refers to the work of Martínez-Moreno et al. [1]; and c) is the algorithm used by state-of-the-art programs.

Martínez-Moreno et al. [1] propose a similar approach, but working at cell-block level and including empirical correction factors:

$$1 - \frac{P_{sh}}{P_{nsh}} \approx (1 - F_{GS}) \cdot \left(1 - \frac{N_{sb}}{N_{tb} + 1}\right)$$

Where F_{GS} is the irradiance shading factor for the complete array, and N_{tb} and N_{sb} are the total and shaded number of cell-blocks, respectively. For the particular case simulated, this method appears to over-estimate the electrical effect of shading, especially at high shading fractions.

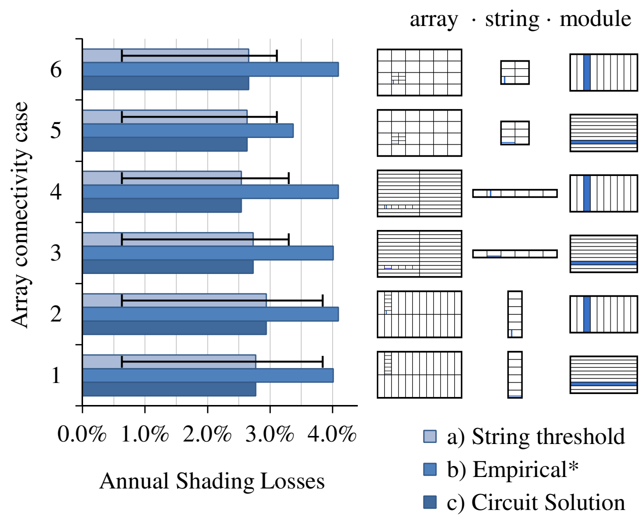

Fig. 8: Effect of electrical connection layout in annual energy losses, under identical shading conditions. *[1]

The detailed electrical circuit solution allows for a realistic parametric study of array connectivity to optimize energy production. As Fig. 8 demonstrates, subtle differences in array performance can be overseen by simpler simulation approaches.

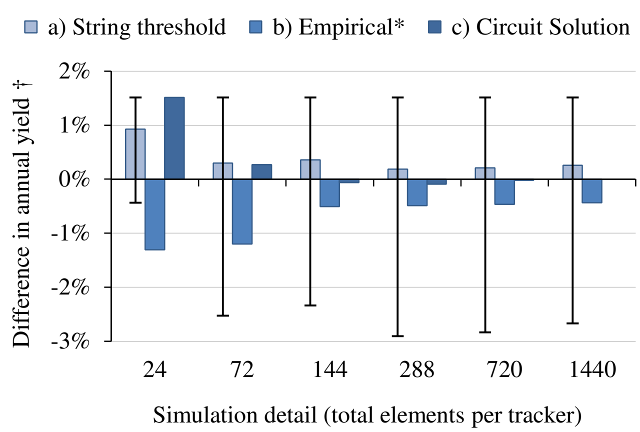

Fig. 9: Effect of PV area discretization in simulation results by the three considered methodologies. *[1], † reference case is the electrical circuit solution with 1440 elements.

The level of detail of the electrical model and area discretization for shading analysis have a strong influence in simulation accuracy up to a certain element resolution, above which no significant improvements can be observed. A similar tendency can be observed with time-step resolution. Differences in the order of 0.5% annual energy yield are achieved among hourly and 5min-step simulations.

5. CONCLUSIONS

A methodology and software environment for the modeling of diverse PV (CPV) systems has been developed. Delivered numerical results for the computation of electrical performance under shading effects demonstrate flexibility to adapt to the electrical complexity of the PV array. The system supports diverse module array geometries and integration in 3D site-models which can increase the impact on accurate performance prediction. The development of the system will transition now to a validation phase to correlate numerical and experimental results.

6. NOMENCLATURE

GHI – Global Horizontal Irradiance
DNI – Direct Normal Irradiance
AM – Air Mass
POA – Plane of Array
Ta – Ambient temperature
E – Irradiance
T_{hs} – Heat sink temperature
UF – Utility Factor
DNI – Direct Normal Irradiance– Absorptivity
v_w – Wind Speed
α – Absorptivity
U_w – Wind dependent heat transfer coefficient
U_c – Constant heat transfer coefficient
η – Module efficiency
P_{sh} – Power of shaded array
P_{nsh} – Power of not-shaded array
F_{GS} – Irradiance shading fraction
N_{sb} – Number of shaded cell blocks
N_{tb} – Total number of cell blocks
N_{ss} – Number of shaded strings
N_{ts} – Total number of strings

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