Simplified Calculation of Partial Shading Impact on PV Array Performance

1. Motivation and Requirements

Demand remains strong for residential and small commercial rooftop solar photovoltaic (PV) systems, driven in large part by improved technology and increased affordability. Building geometries and landscapes of PV systems in urban and suburban environments often create situations in which arrays are partially shaded during a portion of their operating hours. Partial shading, while not ideal, does not necessarily preclude the financial viability of a PV installation; the resulting energy losses may be mitigated by use of power electronics (microconverters or microinverters), or they may be insignificant , depending on the location and extent of the shading relative to the array. The impact of partial shading on a proposed PV system's performance must be accurately predicted to determine how it should be configured and installed for maximum value to the customer.

Partial shading is difficult to model in PV systems with standard, central inverter configurations, as shading effects are nonlinear, dictated by string voltage and current constraints. Some detailed PV simulation tools such as PV*SOL (1) and PVSyst (2) do include detailed shade modeling capabilities, but these can include long setup and run times, which are not cost effective for smaller projects or for simulating multiple scenarios to optimize system design. Simpler simulation tools, such as NREL's System Advisor Model (3) or PVWatts (4), use hourly or annual user-created shade loss derates, which enable faster simulations but do not capture the complexity of partial shading's performance impact. Discussions between NREL and solar company Sunrun (5) have indicated that there is a need for a solution which utilizes simpler PV modeling tools to account for the effects of partial shading on a PV array with reasonable accuracy, while adding only minimal simulation time.

This solution is to be implemented using a lookup table style database of shade impact results, encompassing a wide variety of shading scenarios. The shade impacts found in the table will be representative of most conventional crystalline silicon PV modules, with the possibility of a second table added for higher performance modules, such as those made by SunPower. Basic requirements and guidelines include the following:

- Table will include results for conventional (central inverter) PV systems configured in up to 8 parallel strings. String length and module orientation are assumed uniform across each system.
- Strings are shaded from 0-100% (increments of 10%) by area, with independent shading on each string.
- Light available in shade (diffuse fraction) ranging from 10-100% of the total plane-of-array irradiance, again in increments of 10%.
- At any given time the PV system is assumed to be operating under no more than two light levels, shaded and unshaded.

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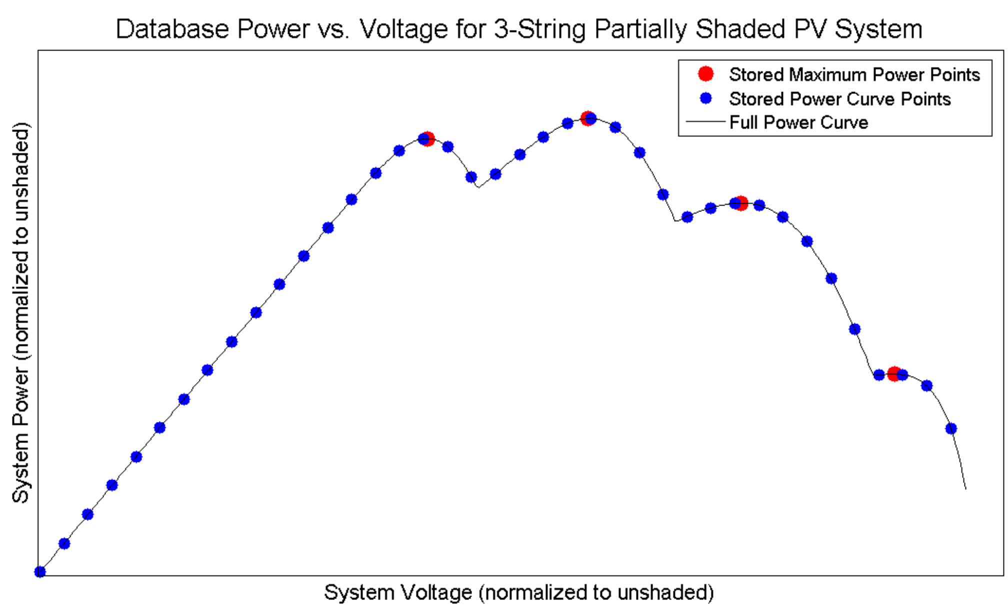
2. PV Shade Impact Database

The shade impact database is created as a structure in MATLAB, with its form shown as follows:

$$\text{Database Structure: } \mathrm{DB}\{NumStrings\}.\mathrm{d}\{DiffuseFrac\}.\mathrm{t}\{[MaxStrShade]\}\begin{bmatrix} maxVs \\ maxIs \\ voltages \\ currents \end{bmatrix}$$

In the database, the variables *NumStrings, DiffuseFrac,* and *MaxStrShade* are used to define and index an array's particular partial shading scenario. Variable *NumStrings* is the number of parallel strings in the PV system, which can range from 1-8. *DiffuseFrac* is the fraction of the total incident plane-of-array irradiance that is available to the shaded portions of the array, which can range from 1-10, corresponding to 10-100%. *MaxStrShade* is the maximum value in *ShadingFracs,* a user-input vector of length *NumStrings*, which indexes the fraction of each string that is shaded, sorted in descending order. These indices may range from 1-11, corresponding to 0-100%.

Each partial shading scenario has four items stored in an array of integers in the database, giving full information about the PV system performance. *maxVs and maxIs* are the system-level local and global maximum power point voltages and currents, respectively, normalized to unshaded conditions. It is possible for these maximum power points to fall outside of the central inverter's maximum power point tracking (MPPT) range, depending on system design, so the database also includes variables *voltages* and *currents*, which are 40 evenly-spaced (in voltage) points on the partially shaded system-level I-V curve, scaled to the unshaded I-V curve. Inclusion of these points allows the database to better track realistic inverter performance. An example of the stored I-V curve data is found in the following figure. Note that all of the voltage and current information in each scenario's stored array is multiplied by a factor of one thousand so that they may be stored as integers (less memory intensive).



The database is based on a 250W polycrystalline module, Trina module TSM-PA05, chosen because it has performance characteristics that are typical of crystalline silicon modules used in residential PV arrays. Each string is made up of 10 PV modules so that a string's shaded fraction (0-100%) applies to shading of entire modules; bypass diode configurations are not considered. Shaded and unshaded module I-V curves are generated using the standard 5 parameter single diode model (6) for each diffuse fraction, with unshaded conditions assumed to be standard test conditions (STC -- 1000 W/m^2 and 25°C) and shaded modules receiving the dictated irradiance fraction, also with a temperature of 25°C. Module level curves are used to build PV system curves with a validated, detailed simulation tool (7) that accounts for current and voltage constraints related to the system's series and parallel string wiring under partially shaded conditions.

When the database as described above is fully populated from 1-8 strings, its MATLAB-compressed size is 10.5MB. If each partial shading scenario is stored with just the system-level maximum power points (not the 40 points along the power curve), the size decreases by a factor of approximately four. However, as will be shown in the validation section, this may compromise the accuracy of the performance prediction for some PV systems.

3. Database Access

Accessing the database is done using a function called GetShadeLoss, which returns the fraction of the PV system's unshaded energy potential that is lost to partial shading. The output is intended to be used as a shade loss derate factor in hourly simulations. GetShadeLoss requires the following basic inputs:

- *G* -- the total plane of array (POA) irradiance on unshaded portions of the array
- *D* -- the diffuse fraction of the POA irradiance, which is incident on shaded portions of the array
- *Tc* -- the cell temperature (assumed to be the same for shaded and unshaded)
- *ModsPerString* -- the number of modules per string in the PV system (parallel strings are assumed equal in length)
- *StrShade* -- A vector with length equal to the number of strings in the PV system. Vector elements correspond to each string's shaded fraction, given as 12, 34, 55, etc. For maximum accuracy, the string shading may be given in terms of the fraction of bypass diode substrings shaded in a string.
- *VMaxSTCStrUnshaded* -- the module's unshaded maximum power point voltage (V_{mp}) under standard test conditions (STC). This may be obtained from the module datasheet.
- *VStrMPPT* -- a two element vector giving the minimum and maximum DC input voltages for central inverter maximum power point tracking.
- *ShadeDB* -- a pointer to the partial shading performance impact database

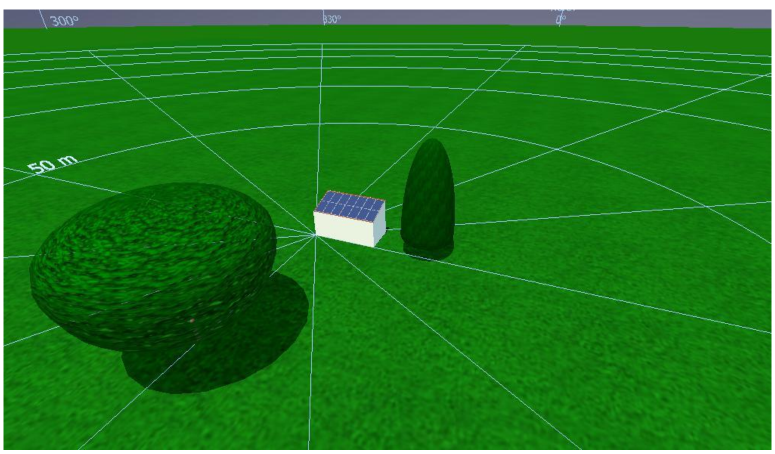
First, *StrShade* and the diffuse irradiance fraction are rounded to their nearest 10%, and these are used to obtain the most relevant set of current and voltage information from the database. Next, one must determine the string voltage within the PV system's inverter MPPT range that maximizes the power output. For unshaded arrays this is usually just the standard maximum power point voltage $V_{mp,}$ but in partially shaded systems the global maximum may not be in the inverter's range and another operating point must be chosen. As the database voltage values are relative to STC, they are adjusted internally to the script by multiplying them by *VMaxSTCStrUnshaded* and then converting to the actual conditions of incident irradiance and cell temperature. The Sandia array performance model (8) gives a method for adjusting V_{mp} based on irradiance and temperature, using empirical constants and module properties. Empirical constants are available in the Sandia PV modeling database for the Yingli 230 module, which is similar to the Trina PA05. Once string voltages are calculated under actual operating conditions, it is simple to select the operating point that yields the highest power and has a voltage falling within the inverter's maximum power point tracking range, *VStrMPPT.*

4. Validation

Validation is carried out by comparing the annual performance predictions of the detailed Matlab simulation tool described in Section 2 and the simplified shade impact database method.

Small PV System (~3kW)

An existing PV system in Denver, Colorado is chosen as a validation test case for a typical, partially shaded residential installation. The system is configured in two strings of seven polycrystalline silicon modules, with shading obstacles (two large trees) shown in the figure below. The string length in this system is slightly undersized in comparison to the central inverter's maximum power point tracking range; under partially shaded conditions the array's maximum power point is occasionally outside the inverter's MPPT input window. This PV system experiences significant shading from the trees, losing approximately 20% of its potential available light annually.



Shading is mapped onto the array on an annual, hourly basis using a simple ray tracing algorithm. Irradiance and PV cell temperature are determined from the Broomfield/Jeffco [Boulder] TMY3 dataset. During mapping, any bypass diode substring that is touched by shade is considered fully shaded; this simplified shade mapping method has been shown to give nearly the same results as very detailed cell level light mapping (9). The resulting annual, hourly operating conditions are used by both the detailed and simplified models to generate annual performance predictions.

The shade impact database predicts **0.9%** more energy production than the detailed simulation tool on an annual basis when using the database that includes full I-V curves. Runtime for database access for all daylight hours (~4300 hours) is approximately 1 second, which meets the goal of a very fast simulation time. Given the rounding of the degree and position of shading in the shade impact database, this is an excellent agreement between the results. The shade impact database without full I-V curves (just global and local maximum power points) predicts 4.5% less energy production than the detailed simulation. This is attributed to the fact that this test array was designed with fairly low string voltage as compared to the inverter's operating range; the system often operates at the inverter's lower voltage MPPT limit rather than a maximum power point. It is especially important in systems like this to include the entire I-V curve in the shade impact database.

Large PV System (~18kW)

Validation of a larger PV system is carried out using a simulated PV system configured in six strings of twelve polycrystalline silicon modules. The system is again located in Denver, Colorado and is mounted in six rows of twelve modules each (each row=1 string), at latitude tilt, similar to the system pictured below. There are no shading obstacles around the system, but it experiences a fairly regular pattern of self-shading between rows during the winter months, as the rows are positioned just several feet apart. This simulated PV system experiences mild shading, losing approximately 5% of its potential available light annually.

Shading is mapped onto the array as described in the small system validation case, and the resulting annual, hourly operating conditions are again used by both the detailed and simplified models to generate annual performance predictions. The shade impact database predicts **0.9%** more energy production than the detailed simulation tool on an annual basis when using the database that includes full I-V curves; results with the database with just maximum power points are identical. This indicates that for a PV system with strings well-sized to interface with the central inverter, the 40 point I-V curve in the database is likely unnecessary.

5. Ongoing Work

The following activities are being considered for an extension of this work. Input from Sunrun is welcome to determine what would have the highest impact:

- Develop and run a validation case for SunPower modules, to determine whether second database is necessary for crystalline silicon modules with a higher fill factor?
- Develop method to extend application of database to PV systems with more than 8 strings?
- Further tool validation using Sunrun irradiance and/or performance data?
- Implementation of the database method within NREL's System Advisor Model tool?

6. References

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