Simulation of Power Generation for Mountainous Photovoltaic Power Plants

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Abstract

This study introduces a novel 3D simulation method for mountainous PV plants, combining high-resolution terrain modeling with cell-level shading and electrical analysis. By reconstructing detailed 3D site geometry, the approach calculates real-time irradiance distribution and shading effects at individual cell level, then simulates I-V curves based on cell physical characteristics. Power outputs are hierarchically aggregated from cells to modules, strings, inverters, and finally plant level, enabling precise energy yield prediction and quantification of intra/inter-string mismatch losses in complex terrains.

Validated using operational data from a 1 MW AC capacity (1.066 MW DC) PV array during October 10–18, 2024, the method demonstrated exceptional accuracy: correlation coefficient of 0.994, MBE of 4.20%, and MAE of 12.44% against measured data. The simulation successfully captured spatial power variations across strings and inverters, outperforming conventional methods in resolution and precision. These results underscore the method's potential to optimize design and operations of terrain-challenged PV systems through reliable energy yield forecasting.

Data

The data used for verification is from the No.8 array of a 20.21 MWp PV plant in the northeastern part of China (Figure 1). The detailed information of No.8 array is provided in Table1. Verification period is from 2024.10.10 to 2024.10.18.

Table 1: No.8 array information

Item	Detail information
Module	LONGi , Mono 285Wp, Full cell module
String	22 pcs module a string, 170 strings
Inverter	Sungrow, SG50KTL, 20 units, 3MPPT, 3 strings/MPPT
Capacity	1.0659 MWp (DC) / 1 MWp (AC)
Measurements	1-minute GHI (two Pyranometers) 5-minute DC & AC power measurements per inverter

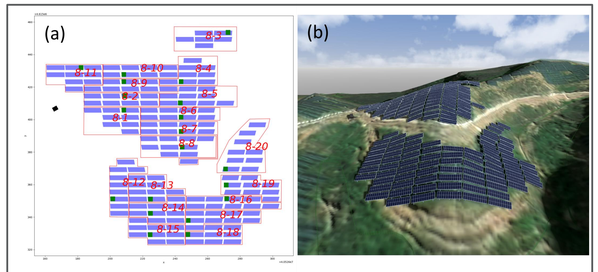


Figure 1: (a) Representation of the racks and inverters in No.8 array in 2D view; (b) 3D view of racks in No.8 array

Method

The simulation process mainly consists of the following several parts, as shown in Figure 2：

1. Three-dimensional modeling of PV plant, including terrain, PV modules, obstacles, etc.
2. Shade simulation based on ray tracing method. Beam shade ratios, diffuse shade ratios and albedo shade ratios of each rack/cell are calculated.
3. Shade ratios and weather data are used to calculate effective irradiance for each cell in PV modules across the system.
4. The DC model converts the effective irradiance values into I-V curves for each cell, aggregates them to the module, string, and MPPT levels, and calculates Pmp for each MPPT based on vectorized PVMismatch [1].
5. The AC model converts the DC power into AC power, thereby obtaining the power outputs of each inverter.
6. Power outputs of each inverter are then aggregated to PV plant level, obtaining the plant level net energy yield, equivalent full-load hours, performance ratio (PR) and loss details.

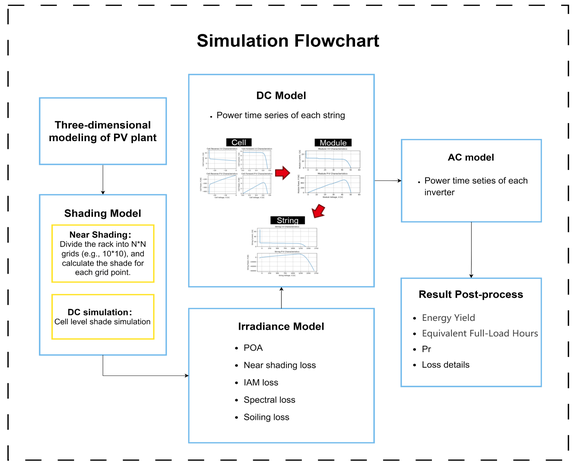


Figure 2: Simulation flowchart

Result

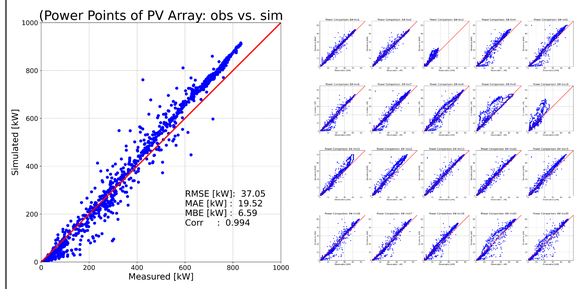


Figure 3: Scatter plots of simulated and operational DC power (left: whole array, right: each inverter)

Table 2: Comparison of 2D and 3D simulation

Item	2D Sim	3D sim	Reduction
RMSE [%]	31.85	23.62	-25.8%
MAE [%]	16.47	12.44	-24.4%
MBE [%]	5.14	4.20	-18.2%

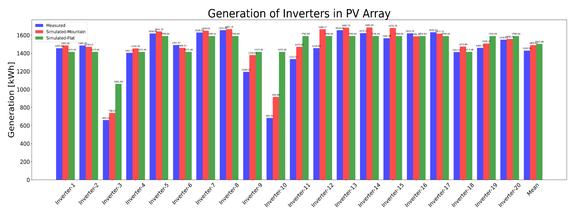


Figure 4: Bar plot of simulated and operational DC power (bule: measurements, red: 3D simulation, green: 2D simulation)

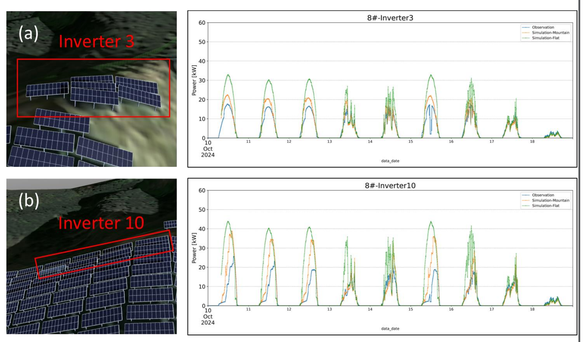


Figure 5: Time series of simulated and operational DC power: (a) inverter 3 and (b) inverter 10 (bule: measurements, orange: 3D simulation, green: 2D simulation)

The array level scatter plot indicate a high correlation coefficient of 0.994 between simulation results and operational data.

Furthermore, the mountainous PV power generation simulation demonstrates normalized error metrics of 4.20% for MBE, 12.44% for MAE, and 23.62% for RMSE. Compared with conventional 2D simulation, these errors are reduced by 18.2%, 24.4%, and 25.8% respectively (Table 2).

The bar chart reveals a consistent trend (Figure 4), showing that the 3D model achieves better agreement with actual operational data than 2D simulation for most inverters.

The improvement is particularly pronounced for severely shaded inverters (e.g., #3, #10, and #11), where the 3D simulation more accurately captures mismatch losses caused by non-uniformity irradiance due to shade effects. In contrast, the 2D simulation requires user-defined input for mismatch loss estimation, which often leads to underestimation in heavily shaded areas.

Conclusion

Through a case study, it was successfully demonstrated that the new method offers superior simulation performance and higher accuracy in complex terrain PV systems compared to conventional approaches. It has significant advantages in the following aspects：

1. More precise shade simulation and irradiation components calculation on the module surfaces.
2. It can automatically simulate the intra/inter-string mismatch loss which is significant for complex mountainous power plants. In contrast, 2D simulations do not support automatic mismatch simulation and treat it as an input parameter.

References

[1] Mark Mikofski, Bennet Meyers, Chetan Chaudhari (2018). “PVMismatch Project: https://github.com/SunPower/PVMismatch". SunPower Corporation, Richmond, CA.

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