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Stady of a 100 kW Photovoltaic System Using the Sandia Array Performance Model (SAPM): Experimental Validation and Results Analysis

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Abstract. This paper discusses in modeling and simulating the Photovoltaic (PV) system using Sandia Array Performance Model (SAPM). The inputs consist of solar irradiance, ambient temperature, measured DC/AC currents, voltage, and power. The empirical model (SAPM) is used to predict the power output of DC power depending on cell temperature and solar irradiance. Results from simulations are compared to field measurements for validation, showing robust correlation between simulated and measured data. The mean error for the DC power was 42.12W. This study demonstrated the ability of the SAPM to predict the performance of large scale PV systems, as well as the different significant factors causing the energy production change. The results provide insights that can be useful to optimize PV systems, in terms of their energy yield.

Keywords: Photovoltaic system, Sandia Model (SAPM), simulation, performance, inverter, experimental validation.

1 Introduction

Photovoltaic (PV) systems contribute considerably to the worldwide energy transition because they provide a clean and renewable energy source [1-2]. PV systems operate under the influence of environmental factors, such as solar irradiance, cell temperature, and operating conditions, especially that of the inverter, which can significantly impact their performance [2]. To maximize energy output and ensure the feasibility of PV installations, reliable simulation models are needed to estimate system performance under real conditions.

SAPM (Sandia Array Performance Model) is one of the most used empirical models for predicting the energy produced by PV systems. It also takes into account changes in cell temperature and solar irradiance to determine the direct current (DC) output [3-4]. Involved with the integration of inverters and multi-string configurations the validation of this model for high-power systems, such as 100 kW installations has yet to be confirmed and is an area that remains active in research. This paper describes an extensive study of a full performance simulation of a 100 kW PV system using the SAPM.

Experimental data in the form of solar irradiance, ambient temperature and measured current, voltage and power (DC and AC) are used to validate the model. Simulation results are then compared with field measured data and a detailed analysis of discrepancies is conducted. The purpose of this study is to show how the SAPM can be used to predict the performance of large scale PV systems and identify key factors affecting their energy yield.

2 Description of the 100 kWp photovoltaic multi-technology pilot plant

The photovoltaic installation (PV) system to be selected for further study is a medium scale size solar power installation which is able to produce roughly 100kW of electricity under standard test conditions (STC). Such system is typical of commercial and industrial scale PV installations which are being deployed to meet energy demand, cut on energy costs, promote sustainability and help in the decarbonization of the global energy systems.

The system consists of several key components that play a critical role in maintaining high efficiency and safe operation of the system. The installation consists of 420 high efficiency monocrystalline solar panels with a rated power output of 245W for each panel. The panels are arranged into 21 strings, 20 panels connected in series per string. This configuration is optimized for voltage and current levels to maximize power generation and transmission (table 1).

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A 100 kW central inverter with a 97% efficiency rating transforms the direct current electricity produced by solar panels into alternating current electricity. The inverter uses maximum power point tracking (MPPT) technology to ensure optimal energy production across different levels of solar irradiance and temperature variations.

The installation includes a real-time monitoring system which monitors performance metrics including energy production and system efficiency. The monitoring system stores collected data in Excel files containing 6 columns and 360 rows.

Table 1. Electrical characteristics of monocrystalline silicon panels.

Characteristic	SOLARIA S6M-2G
Peak Power	245 Wp
Peak Power Tolerance	0 / +5 Wp
Module Efficiency	15%
Open Circuit Voltage	37.82 V
Short Circuit Current	8.52 A
Maximum System Voltage	1000V
Maximum Voltage (Vmpp)	30.33 V
Maximum Current (Impp)	8.08 A

3 PV module modelling approach

The performance of the photovoltaic (PV) system is modeled using SANDIA model, which accounts for the effects of irradiance and temperature on the current and voltage at the maximum power point (MPP). This model describes all electrical, thermal and optical behaviors and can be adapted with any PV technology even with large-scale PV arrays. Moreover, the SANDIA model can be used for the online prediction because of its simplicity. Equations (1-4) describe the evolution of Imp, Vmp and Pmp in this model [4-5].

$$\mathrm{I_{mp}} = \mathrm{I_{mp\_STC}}(\mathrm{C_0}E_e + C_1E_e^2)(1 + \alpha_{mp}(T - T_{STC})) \quad (1)$$

$$\mathrm{V_{mp}} = \mathrm{V_{mp\_STC}} + \mathrm{C_2}\,\mathrm{N_s} \times \delta(\mathrm{T}) \times \ln(\mathrm{E_e}) + \mathrm{C_3}\,\mathrm{N_s}(\delta(\mathrm{T})\ln(\mathrm{E_e}))^2 + \beta_{mp}(T - T_{STC}) \quad (2)$$

$$\delta(T) = \frac{n \times k \times (T + 213.15)}{q} \quad (3)$$

$$\mathrm{P_{mp}} = I_{mp} \times V_{mp} \quad (4)$$

where, I_{mp_STC}, V_{mp_STC} and T_{STC} are the current in the MPP, the voltage in the MPP and the cell temperature under the Standard Test Condition (G=1000 W/m^2, T=25 °C),respectively. Ee is the effective irradiation, K is the constant of Boltzmann, q is the charge of electron, T is the cell temperature and δ(T)is the thermal voltage. α_{mp} and β_{mp} are the current and voltage temperature coefficients. C_0, C_1, C_3 and n are empirical parameters, which will be identified, in the dynamic study [6-7].

4 Validation

The simulation model underwent validation through a comparison between its calculated results and experimental measurements obtained from the photovoltaic system. The maximum power (P_{mp}), current at maximum power (I_{mp}), and voltage at maximum power (V_{mp}) calculated by the model were compared to their respective measured counterparts $P_{mp,mes}$, I_{mpmes}, and V_{mpmes}. The model received environmental data which contained irradiance (G) and temperature (T) as input variables. The Sandia model coefficients C_0, C_1, C_2, and C_3 were modified for alignment with the characteristics presented in PV module table (2). The study visualized the relationship between calculated power (P_{mp}) and measured power (P_{mpmes}) through graphical analysis by including a reference line (y=x) to determine model accuracy. The simulation results closely match the measured data values while displaying minimal variation from the reference line.

C_0	**C_1**	**C_2**	**C_3**	***α_mp***	***β_mp***
1.49	*-0.51*	*1.033*	*10.66*	*0.004192A/°C*	*0.0031V/°C*

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Table 2. The SANDIA parameters taken in program.

Fig. 1. Irradiation and temperature.

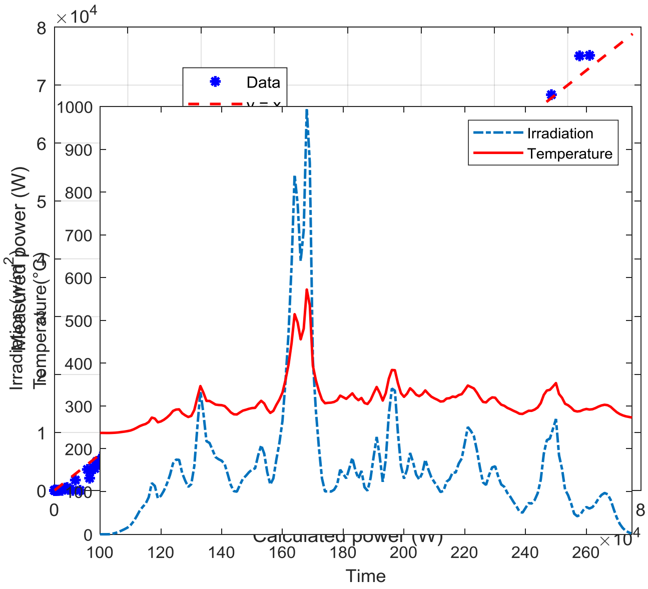

Fig. 2. Comparison of calculated and measured power.

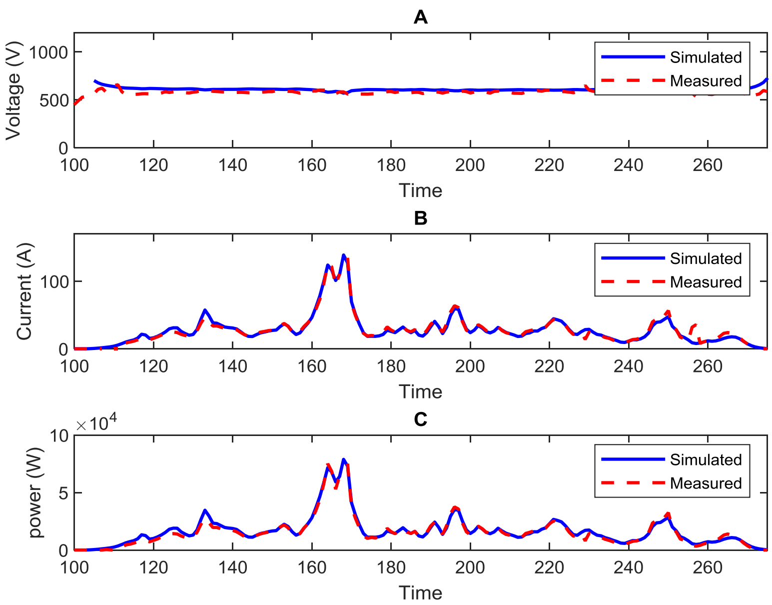

Fig. 3. A) Voltage at MPP, B) Current at MPP, C) Power at MPP.

Comparing the model's obtained results with those measured under extreme conditions, Figure 2 illustrates the estimated daily DC power alongside the measured values. The figure demonstrates a very symmetrical pattern. Figure 3(a, b, c) represents the comparison between measured and estimated performance parameters (Imp, Vmp, and Pmp). The obtained results with SPAM indicate good agreement for the PV module current. A lower difference is observed in the calculation of the PV voltage (Vmp), which can be attributed to an incorrect temperature coefficient estimation.

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The model's performance was quantified through the calculation of statistical metrics including Root Mean Square Error (RMSE) and Mean Absolute Percentage Error (MAPE) Equations (5 and 6). The model demonstrates accurate performance predictions of the PV system across different environmental conditions through its low RMSE and MAPE values. The validation process shows how sturdy the model is while also proving its valuable role in photovoltaic system analysis and optimization.

$$RMSE=\sqrt{\frac{1}{N}\sum_{I=1}^{N}(Y_{exp}-Y_{modeled})^2} \quad (5)$$

$$MAPE=\frac{100\%}{N}\sum_{I=1}^{N}\left|\frac{Y_{exp}-Y_{modeled}}{Y_{modeled}}\right| \quad (6)$$

Where :
Y_{exp} Actual value (measured) it can be (voltage, current, or power)
$Y_{modeled}$ Predicted value (from the model), It can be (voltage, current, or power)
N = Number of data points.

	V_{mp}	I_{mp}	P_{mp}
RMSE	3.1749 (V)	0.0368 (A)	42.1252 W
MAPE (%)	0.0291%	0.0114 %	0.0249 %

5 Conclusion

In conclusion, this study has demonstrated the ability of the Sandia Array Performance Model (SAPM) to reliably predict the performance of large-scale photovoltaic (PV) systems. By comparing simulation results with field measurements, a strong correlation was observed, with a mean error of 42.12W for DC power. These results highlight the importance of considering significant factors such as solar irradiance and cell temperature to optimize the energy yield of PV systems. By validating the SAPM for large-scale installations, this study provides valuable insights to enhance the energy performance of PV systems, thereby contributing to the global energy transition towards clean and renewable energy sources.

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