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Full Length Research Paper

Behavior and performance of a photovoltaic generator in real time

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Solar photovoltaic is of great importance for developing countries like Mauritania and Senegal, without which many villages in these countries would still be facing lack of electricity services for many years to come. The use of solar energy can contribute to the improvement of the living conditions of these populations. This work presents the development of a simulation model for predicting the performance of a solar photovoltaic (PV) system operating under prevailing meteorological conditions at the site location. Mathematical equations developed for modelling the performance of the PV generator are based on power-voltage characteristic of the modules. The simulation model was validated with experimental data from a system installed at the University of Nouakchott, Mauritania. Simulated results from the model under the same operating and environmental climatic conditions are compared with those observed from the experimental tests. Good agreements between these results are obtained with a good correlation coefficient. The simulation model developed can be used not only for analysing the PV system performance, but also for sizing a PV system which is more suitable to the load requirements at any specified location provided that the local meteorological data is available.

Key words: Modelling, simulation, validation, Matlab, photovoltaic generator, meteorological conditions.

INTRODUCTION

Renewable energy resources (solar photovoltaic, wind) are of great importance for developing countries like Mauritania and Senegal. Many isolated villages in these countries do not have access to grid-based electricity services. In many cases, grid extension is impractical because of capacity storage and dispersed population resulting in high cost of grid extension. Thus, small off-grid stand-alone solar photovoltaic energy system is becoming an attractive and promising alternative for supplying electricity to remote villages. The advantages of using solar energy source to generate electricity include free pollution, silent operation, long lifetime and low maintenance requirement. Moreover solar energy is abundant, free, clean and inexhaustible. Stand-alone photovoltaic (PV) operating systems are widely used for electricity supply in isolated locations far from the grid distribution network. However isolated operation of these units may not be effective in terms of cost, efficiency and reliability, due to the fact that climatic conditions such as solar irradiance and temperature are always changing. Thus, there exist instability shortcomings for electricity production from a single energy source system (Alan and David, 2010; Mellit et al., 2007; Clastres et al., 2010; Chiemeka and Chineke, 2009; Kao-Feng et al., 2009; Mehmet, 2011; El Ouariachi et al., 2009a; 2009b; Shaahid and Elhadidy, 2003; De Soto et al., 2006; Zhou et al., 2007).

Despite being easy to set up, its general environmental friendliness and its low maintenance requirements, a photovoltaic system loses its advantage in cases of high energy demands. A thorough analysis is necessary to choose the most efficient and the most economical system. The performance of a PV system depends

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Figure 1. Generator photovoltaic of the CRAER.

Table 1. Characteristic of the photovoltaic generator.

Specification	ATERSA 1000 W/m^2 25°C AM 1.5
Series numbers	98090135
Total numbers panels	16
Model	AP-7105/A-75
Maximum power	75 W
Current of short -circuit Isc	4.8 A
Tension of open-circuit Vco	21 V
Optimal current Imp	4.4 V
Optimal tension Vmp	17 V
Dimensions	1,206 × 0,53 × 0,034m
Weight	8,2kg
Mode of connection	4 panels (//) of 4 in series
Surface used by the modules	8.6 m^2

The operational data provided by the manufacturer.

strongly on weather conditions, such as sunlight and temperature (Mellit, 2007; Ai et al., 2003; Elhadidy and Shaahid, 2003; Sukamongkol et al., 2002).

To generate energy continuously throughout the year, a PV system must also have an optimal size. To this end, we have developed a simple and reliable model that predicts the performance of a PV generator to a satisfactory level of accuracy for weather conditions that apply to our country. This model is validated by experimental data, measured over days on a PV generator that is located on our campus at the University of Nouakchott: The PV generator is used to drive a range of different electrical loads. The performances of the actual PV system and the model outcomes are compared.

PV system description

The photovoltaic generator shown in Figure 1 is used in this study. It is installed at the Faculty of Science of the Nouakchott University, Mauritania. The hybrid power generator system consists of a PV generator, a charge controller, a battery bank, other accessory, cables and loads. Sometimes the system loads also include one dump load for safety protection. It is monitored with a data-acquisition system in order to record different signals. The PV array employs 16 ARTESA (AP-7105/A-75) modules, which include 36 single crystal silicon cells each. The total power of the system is 1.2 kW (Figure 1). The operational data provided by the manufacturer are given in Table 1.

PHOTOVOLTAIC GENERATOR MODELLING

For practical use, solar cells are electrically connected in various ways. This allows appropriate voltage and current for each application. They are also encapsulated between materials to protect them against the elements. Taken as a whole, cells, connections, protective parts, supports, etc., make up a photovoltaic generator (Ai et al., 2003; Sukamongkol et al., 2002).

A problem that design engineers frequently have to resolve is the prediction of the behaviour of a photovoltaic generator, from the information given by the manufacturer and from the local weather data.

In the work (Ai et al., 2003; De Soto et al., 2006; Sukamongkol et al., 2002), it is shown that the characteristic I-V curve of a solar cell can be expressed with sufficient accuracy using:

$$I = I_L - I_0\left[\exp\left(\frac{V+IR_S}{V_T}-1\right)\right]-\frac{V+IR_S}{R_{Sh}} \qquad (1)$$

Where $I_d = I_0\left[\exp\left(\frac{V+IR_S}{V_T}-1\right)\right]$

$$I_L = I_{SC}\left(G\left(\frac{W}{m^2}\right)/(1000)\right) \qquad (2)$$

I_0, I_L, R_S and R_{Sh} are the photo-generated current, the dark current, the series resistance and the parallel resistance, respectively. The voltage V_T equals $\frac{mkT}{e}$ (we recall that for $m=1$, $V_T \cong 25mV$ at $T=300K$).

The temperature of the cells depends exclusively on the irradiation and on the ambient temperature, according to the linear relation:

$$T - T_a = C_2 G \qquad (3)$$

where the constant C_2 has the value:

$$C_2 = \frac{NOC(°C)-20}{800W/m^2}$$

This assumption leaves aside the effect of wind velocity on T . In other words, heat dissipation from the cells to the environment is taken to be dominated by conduction through the encapsulation, rather than convection from the surface. There is substantial evidence to support this.

The value of NOC for modules currently on the market varies from about 42 to 46 $°C$, implying a value of the C_2 between 0.027 and 0.32 $°C/(W/m^2)$. When NOC is unknown, it is reasonable to approximate $C_2 \cong 0{,}32°C/(mW/m^2)$.

Short-circuit current

As seen from Equation 1, the greatest value of current with the cell as a generator (in the first quadrant) is obtained under short-circuit conditions, when V=0. According to Equation 1, the short-circuit current I_{SC} , is given by:

$$I_{SC} \cong \frac{I_L}{1+\frac{R_S}{R_{Sh}}} \qquad (4)$$

The short-circuit current of a solar cell depends exclusively and linearly on the irradiance. That is:

$$I_{SC}(G) = C_1 G \qquad (5)$$

Where the constant C_1 has the value:

$$C_1 = \frac{I_{SC}(1000W/m^2)}{1000W/m^2}$$

Open-circuit voltage

With I = 0, leads to the following expression for the open-circuit voltage:

$$V_{OC} = V_T \ln\left(-\frac{I_L}{I_0}\right) \qquad (6)$$

where

$$I_0 = I_L \exp\left(-\frac{V_{OC}}{V_T}\right) \qquad (7)$$

Substituting Equations 1 in 7, we obtain:

$$I = I_{SC}[\alpha - \beta\exp(y(V - V_{OC} + IR_S))] - \frac{V+IR_S}{R_{Sh}} \qquad (8)$$

where $\alpha = \frac{G}{1000}$, $\beta = 1+\frac{R_S}{R_{Sh}}$ and $y = \frac{1}{V_T}$

This equation was used to derive the characteristics of an

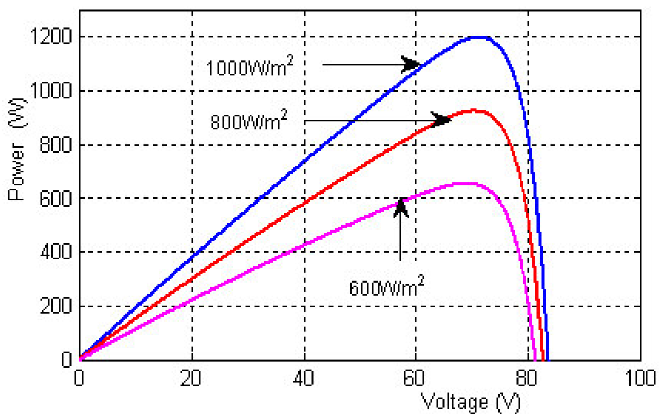

Figure 2. *P-V* characteristics for a module at 40℃, for several sunlight intensities.

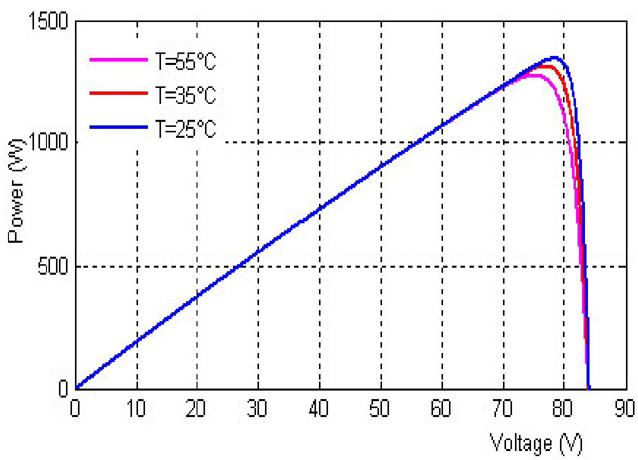

Figure 3. *P-V* characteristics of a module at different temperatures.

assembly of M_S modules joined in series and of M_P modules in parallel, as found in a photovoltaic generator, in the following form:

$$I = I_{SC} M_P \left[\alpha - \beta \exp\left(\frac{y}{M_P}(M_S(V - V_{OC})) + \frac{M_S I R_S}{M_P}\right)\right] - \frac{M_S V + \frac{M_S I R_S}{M_P}}{\frac{M_S R_{Sh}}{M_P}} \qquad (9)$$

The power delivered by a photovoltaic generator under given condition of operation is given by:

$$P = V \times I \qquad (10)$$

The energy-conversion efficiency of a photovoltaic generator is defined as the ratio between the maximum electrical power that can be delivered to the load and power P_L of the radiation incident on the photovoltaic generator (Ai et al., 2003; De Soto et al., 2006; Sukamongkol et al., 2002).

$$\eta_g = \frac{P_M}{P_L} \qquad (11)$$

The power P_L of the sunlight incident on the generator is the product of the light intensity and of the area of the PV surface.

SIMULATION RESULTS AND MODEL VALIDATION

Previous, we have shown the foundations of the mathematical model developed with the Matlab software. It was then validated using experimental data obtained from the PV generator located on the CRAER campus. This generator is made up of 16 modules (ATERSA), each containing 36 cells connected in series. The maximum power of the system is 1.2 kWc. Its optimal output voltage and current are of 68 V and 18 A, respectively, and surface area is 8.6 m^2.

At first, we present the results of simulations for a PV generator that combines M_S = 4 modules in series and M_P = 4 modules in parallel, based on the manufacturer's specifications of the series and parallel resistances: R_S = 0.177 Ω and R_{Sh} = 220 Ω. As the exposure intensities increase, the output power also increases and the peaks of the *P-V* curves shift to higher voltages, thereby allowing the generated current to deliver larger powers. The maximum power achievable for different exposure intensities at 40℃ (the cell temperature) occurs at voltages 68 to 72 V and is indicated in Figure 2. The maximum power of 1200 W corresponds to a sunlight intensity of 1000 W/m^2, in agreement with the manufacturer's specifications. The photocurrent is thus directly related to the incident sunlight intensity (Equation 2).

The temperature of a PV system is a crucial parameter but is often neglected. The *P-V* characteristics indicate that the output current increases rapidly with the cell temperature. The second term (I_d) in Equations 1 and 3 increases strongly with T, and the resulting that decrease in the voltage, of the order of a few mV per degree, can have a significant cumulative effect on the output power. The net result is a decrease in the maximum output power with increasing T, as shown in Figure 3. The larger the R_S value and the smaller the R_{Sh} value, the worse the performance of the PV cell.

Figure 4 shows the effect of R_{Sh} on the *P-V* characteristics. For different slopes of the curve, a decrease is observed on the right side of the maximum point where the photovoltaic generator effectively acts as a voltage source. The corresponding voltage drop follows that of the output power.

A real cell also includes an effective shunt resistance R_S (Figure 5), a by-product of the fabrication process. Its

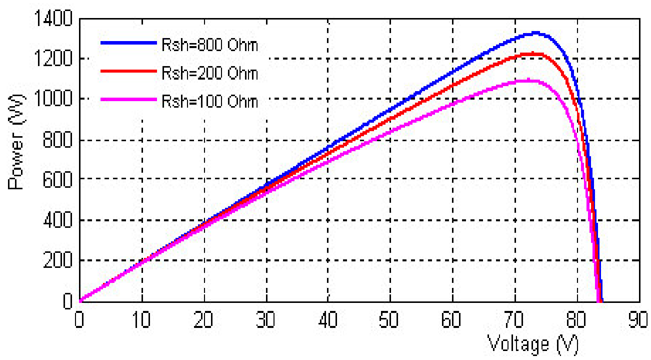

Figure 4. *P-V* characteristics of a module for different values of the shunt resistance R_{Sh}.

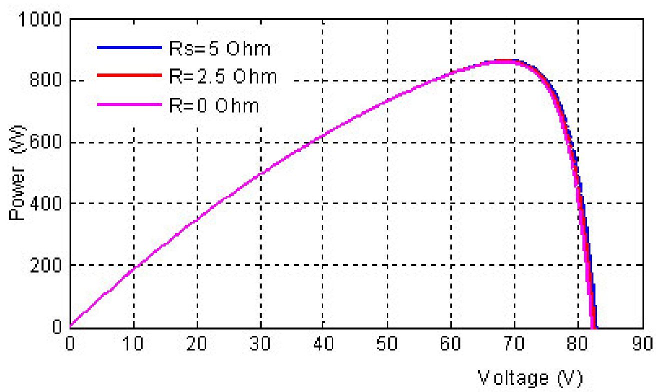

Figure 5. *P-V* characteristics of a module for different values of the series resistance R_S.

impact on the *P-V* characteristics becomes apparent when it is very small.

Our main goal is to determine whether or not the model can predict the performance of a real PV system. This was done by taking measurements on five typical days. Sunlight exposure and air temperature during these days are plotted in Figure 6. Temperature can fall to around 12°C at night, but it reaches between 22.5 and 38°C during the day, depending on the amount of sunlight.

We compared our simulation results with the measured data. There is good agreement for the data measured on the sunny days (Day 1, Day 3, Day 4 and Day 5), but somewhat worse agreement for the other day (day2). These discrepancies might be due to the inaccurate estimate of the cells' temperature in the model. As a result of air convection, of thermal inertia or of the thermometer being incorrectly placed, there can be time lag between the measured temperature and the actual temperature. Indeed, on the sunny day, the exposure and therefore in the air temperature, which can thus differ significantly from the measured temperature.

The simulated and measured data were compared quantitatively via a linear correlation coefficient R^2.

$$R^2 = 1 - \frac{\sum\left(X_i - \tilde{X}_i\right)^2}{\sum\left(X_i - \bar{X}\right)^2} \qquad (12)$$

The correlation coefficients for the five days are 0.95, 0.93, 0.97, 0.96 and 0.98, respectively (Figure 9). Although, the sunny days give the best correlation, the generally large values of R^2 for all days confirm the overall accuracy of our model.

Conclusion

Our study has yielded the following three main results:

1. The significance of the cell temperature, of sunlight exposure and of the values of the series and shunt resistances for determining the *P-V* characteristics of the photovoltaic generator was made apparent from the analysis performed using Matlab. The mathematical model developed using Matlab for predicting the system behaviour was also validated. The model's main appeal is its simplicity and convenience, using the technical specifications provided by the manufacturer.
2. The sunlight irradiation is a crucial parameter for predicting the electrical output of the PV system (Figure 6). A solar panel rarely captures sun rays at normal incidence, only seldom, as the sun's position changes continually. Furthermore, at least five types of weather conditions can also affect the performance (Figure 6). The output power of the PV generator, measured on five days under different conditions, is compared to the simulation results in Figure 7. There is good agreement between the measured data and the simulation for each day, which confirms the overall accuracy of our model.
3. The yield of solar panels has been constantly improving over the years, from around 10% in 2000 to between 12 and 15% presently. Figure 8 shows the yield for our solar panels as a function of time. The results closely follow the time course for sunlight exposure. The yield is close to 10% on the sunny day. These results will be useful for accurately predicting the behaviour of the PV generator as a function of time, on the basis of manufacturer specifications and given adequate sunlight, following Equation 11.
4. These three results are at the base of the steps used to demonstrate the strength of the model. The strength of the model lies in its simplicity of implementation using the technical data of the manufacturer. The purpose of the manufacturer's data (V_{OC}, I_{SC}, R_S and R_{Sh}) is to simulate the operations of photovoltaic generator under various conditions of sunlight irradiation and temperature (G and T_a).

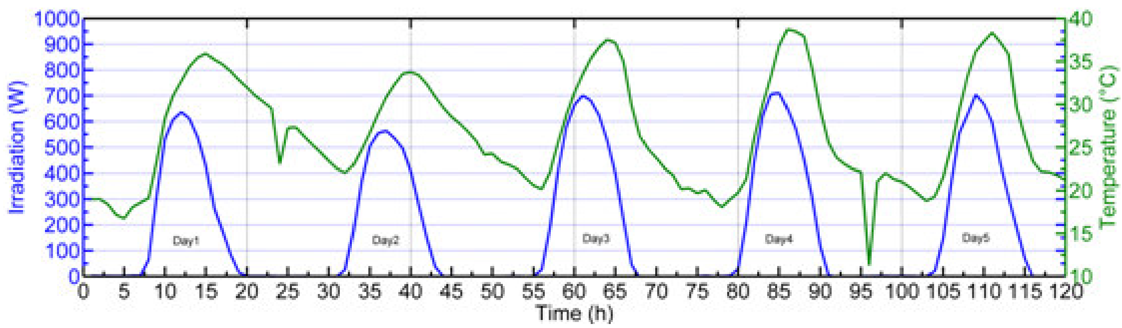

Figure 6. Time course of sunlight exposure and temperature on five different days.

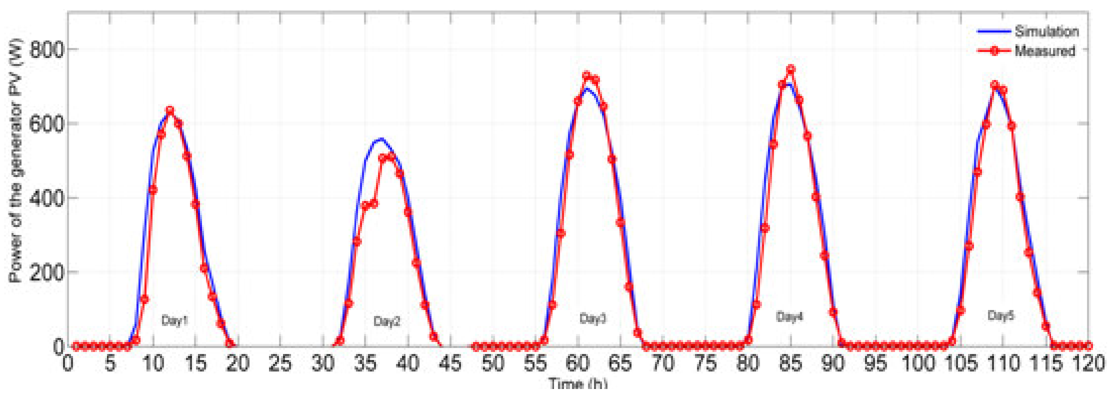

Figure 7. Comparison of measured output power (red) and simulation results (blue).

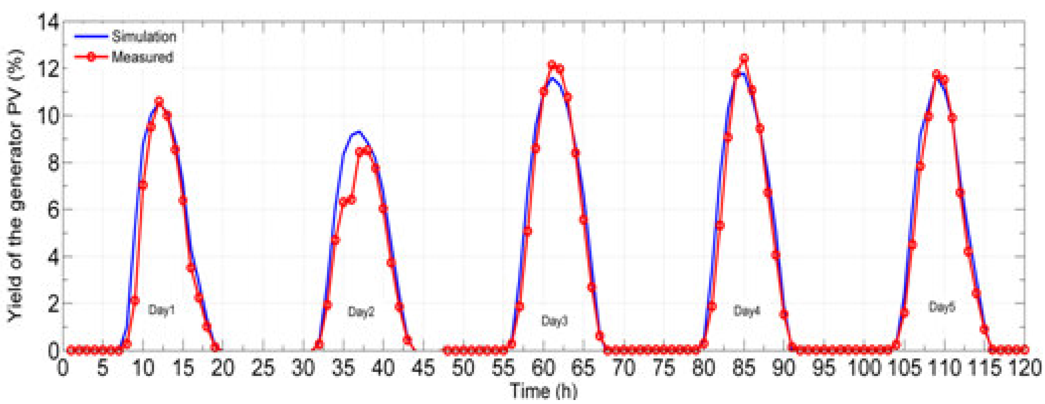

Figure 8. Yield of the PV generator.

Thus, these parameters were introduced to take in to account the physical phenomena of photovoltaic generator and to emphasize its performance (produced power and yield). In the same way, a comparison with the experimental data made it possible to show the degree of accuracy of the model under different weather conditions.

In addition, five days of typical weather conditions in Nouakchott were studied. Indeed, in each case, the simulation model was verified using data for sunny and cloudy states. The results show an acceptable precision

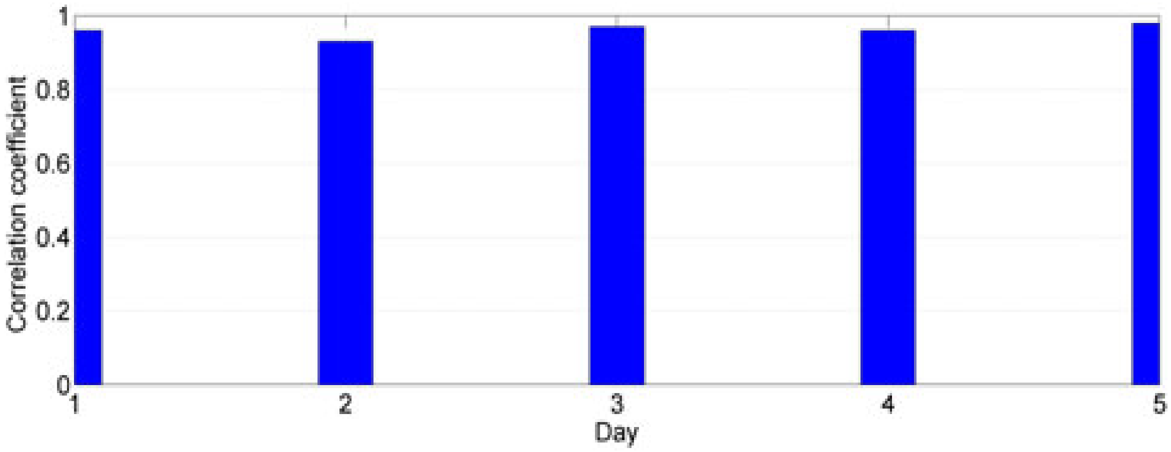

Figure 9. Correlation coefficient.

for the modeling of the behavior and the performance of a photovoltaic generator in real time.

Finally, our approach allows the overall behaviour of the system to be analysed and optimised for different loads, depending on local weather conditions, thereby providing a better general understanding of stand-alone PV systems.

Nomenclature : I **,** The current of the module (A); I_L **,** photo generated current (A) ; I_{SC} **,** short circuit current of the module (A); I_0 **,** diode reverse saturation current (A); **k,** Boltzmann's constant ($1.38\times10^{-23} J/K$); **(**C_1, C_2**),** constant ; R_{Sh} **,** module shunt resistance (Ω) ; R_S **,** module series resistance (Ω) ; q **,** electron charge ($1.6\times10^{-19} C$) ; usually ideality factor (m) ; P **,** the power of the PV generator (W); P_L **,** the power of the sunlight incident (W); R^2 **,** correlation coefficient ; T **,** cell temperature (°C); V_{OC} **,** module open-circuit voltage (V); V_T **,** thermal voltage (V); α , linear variation coefficient for the I_{SC} ; β **,** PM module parameter; G **,** total sunlight exposure (W/m^2); M_S **,** number of modules in series; M_P **,** number of modules in parallel; nominal operating cell temperature" (NOC); P_M **,** the maximum power of the PV (W); η_g **,** yield of the PV generator; X_i **,** is the measured output power.

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