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Stochastic Modeling of the Output Power of Photovoltaic Generators in Various Weather Conditions

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Abstract—The intermittency of solar-powered energy sources prompt the uncertainty of load management. The influence of shading (whatever the reason may be) directly diminishes the feasible output power of the photovoltaic (PV) generators. The major causes of shading are the weather condition changes like the clouds, storms, and rains. Thereby, the dispatchable power for a distinct weather condition at an explicit time frame needs to be quantified. The stochastic modeling of a practical PV system has been performed in this paper. A step-by-step MATLAB-based algorithm is developed for tracking of dispatchable power limit using the Monte Carlo Principle. The proposed algorithm describes the weather condition as a function of cloud presence. The prescribed characteristics consist of the solar irradiance and the ambient temperature. The impact of weather changes on the output power of a PV system is evaluated by this algorithm. The results of this research are concluded by realistic data analysis taken from the Australian bureau of meteorology.

Index Terms—Modeling, PV system, Insolation, Temperature.

NOMENCLATURE

MPPT maximum power point tracking
PDF Probability Density Function
PV Photovoltaic

Variables

a, b Beta distribution shape parameters for sunny condition
 B Beta distribution
 d, e Beta distribution shape parameters for cloudy condition
 FF Fill Factor
 $f(X)$ PDF for sunny condition
 $f(C)$ PDF for cloudy condition
 $f(R)$ PDF for rainy condition
 g, h Beta distribution shape parameters for rainy condition
 I_{mpp} Current at maximum power point [A]
 I_{sc} Short-circuit current [A]
 I_{sco} Short-circuit current in normal conditions [A]
 $I_{sc}(S)$ Mismatched short-circuit current due to shading [A]
 k_i Temperature coefficient of I_{sc} [A/°C]
 k_v Temperature coefficient of V_{oc} [V/°C]

m By pass diode ideality factor
 N_{cell} Number of cells connected in PV module
 nl Diode ideality factor [between 0 and 1]
 P_C Expected output power at cloudy condition
 P_R Expected output power at rainy condition
 P_X Expected output power at sunny condition
 q Charge on electron [Col]
 R_s Cell series resistance [Ω]
 R_{sh} Cell shunt resistance [Ω]
 S Shading factor
 T Cell temperature [°C]
 T_{amb} Ambient Temperature ($20 < T_{amb} < 48^\circ\text{C}$)
 T_O Nominal operating temperature (25°C)
 V_d Diode voltage [V]
 V_{mpp} Voltage at maximum power point [V]
 V_{OC} Open Circuit voltage [V]
 V_x Array voltage [V]

I. INTRODUCTION

The need to reduce global warming has promoted the adoption of new green energy policies that encourage the application of renewable energy systems to meet the growing electricity demand as well as reducing the greenhouse gas emissions. Among the considered renewable energies, solar is an abundant renewable source of energy that has low maintenance costs. Thus, solar systems are considered as an important building component of the future electric networks and microgrids. The levels of solar irradiance and the ambient temperature, on top of the internal characteristics of the photovoltaic (PV) cells, are the factors that affect the generated output power by a PV module. In addition, frequently moving clouds in the sky, which pass over the solar cells, strongly result in shading over the PV cells; and thereby, a frequent decrease/increase is observed in the amount of the instantaneous generated power by the solar cells.

A mathematical model of a PV cell is developed in [1] and the impact of the environmental factors is considered on its performance. The PV models that have been developed so far represent their output characteristics on the basis of solar insolation,

cell temperature, ambient temperature, and wind speed [2]. PV cells have a non-linear output voltage-power characteristic; and thereby, they are usually equipped with maximum power point tracking (MPPT) algorithms that modify dynamically the output voltage of a PV cell to extract maximum possible power from them. Different maximum power point tracking strategies are discussed in [3-4] while a global MPPT strategy is developed in [5] using a dynamic particle swarm optimization. However, ambient weather conditions have high influence on the exposed solar irradiance to the PV cells and their performance. The solar irradiance exposed to a PV cell is modeled as a probability density function in [6]. Other models developed in [7-8] defines the output power of a PV cell under different sets of metrological states, i.e. sunny and cloudy conditions etc. Moreover, it is discussed in [9-10] that a rise in the internal temperature of a PV cell can also cause losses in the output power and may also reduce its life span.

Development of a suitable model of a PV system from which its output power can be determined is presented in this paper with respect to the changing ambient conditions. The developed technique can analyze and obtain the expected output power of a PV system for a specific metrological condition.

The rest of the paper is organized as follows: Section II describes the formulation and calculation of the output power of a PV module with respect to environmental conditions. Section III briefly explains the simulation and analysis method while some sample outcomes of the technique are presented in Section IV. Section V summarizes the main highlights of the research.

II. FORMULATION OF THE DEVELOPED MODEL

A PV cell can be modeled as shown in Fig. 1 [1]. In this scheme, the diode current-voltage characteristic is defined by

$$I_d = I_o \left(e^{\frac{V_d}{V_T}} - 1 \right) \quad (1)$$

$$V_T = \frac{kT}{q} \cdot nl \cdot N_{cell} \quad (2)$$

The series and shunt resistors in Fig. 1 not only affect this current-voltage characteristic of the cell but also affect its maximum output power [11]. In a well-designed PV cell, R_{sh} is quite large, while R_s is very small and ranges between 0 and 1 ohm approximately. The parameters of the solar cell used in this study are taken from the AU-Optronics PM-200 PV cell, as listed in Table 1 [12]. This PV model has been incorporated for the probabilistic treatment of solar irradiance data in this paper.

For modeling the cell temperature, a linear relationship between the ambient temperature, the insolation and the nominal operating temperature of the PV cell with respect to the solar irradiance is considered, as

$$T = T_{amb} + \frac{B (T_o - 20)}{0.8} \quad (3)$$

Fig. 1. Equivalent Circuit of a PV cell.

Table I. Design Specifications of a PV cell.

V_{oc}	30.35	k_t	0.078276
V_{mpp}	24.14	I_L	8.8169
k_v	-0.32069	I_o	7.2566E-11
N_{cell}	3000	nl	0.96434
I_{sc}	8.76	R_{sh}	1177.4122
I_{mpp}	8.38	R_s	0.32361

Where f represents the probability density function (PDF) of Beta distribution which is used to estimate the solar radiation discussed later in this paper. PDF is a function of considered weather condition and pair of shape parameters.

It is important to choose an appropriate distribution function to represent correctly the random phenomenon of the insolation. Although it is very difficult to discern; there are possibilities to find a suitable distribution empirically. Several distributions can be tested for finding the best fit as described in literature such as the normal, Weibull, and Beta distribution functions. An alternative solution is to consider a distribution function on the basis of the observed historical data. In many situations, histograms can also provide initial clue for proper selection of the distribution function, as explained in [13].

In this study, Beta distribution has been selected to express the insolation level at three conditions of sunny, cloudy, and rainy. Beta distribution can take variety of shapes depending on the values of its pair of shape parameters; i.e., (i) Mount shape, if both parameters are bigger than one; (ii) J-shape or reverse J-shape, if one parameter is larger than one while the other parameter is smaller than one, and (iii) U-shape, if both parameters are smaller than one [14]. The data of solar exposure, shading and rainfall can be taken from the original weather data of the bureau of metrology. The selected Beta distribution for sunny conditions (X) is given as

$$f(X|a, b) = \frac{1}{B(a, b)} X^{a-1} (1 - X^{b-1}) I_{(0,1)}(X) \quad (4)$$

where a and b are the shape parameters of the Beta distribution, and $a > 1$ and $b > 1$. The indicator function $I_{(0,1)}(x)$ ensures that values of x in the range of 0 to 1 have a nonzero probability [15]. As Beta distribution is bounded over two finite limits, it is able to replicate the random pattern of insolation levels for any given time (hour) of the day.

Shading of a PV module is a key point in this research as it has a great impact on the modeling parameters. For PV system, shading is classified into objective and subjective shading. Objective shading can be formed by various weather impacts such as clouds and haze, and will inevitably cause a reduction of overall sunlight intensity for the PV system. On the other hand, objects near or far from the PV can also block the sunlight and create solid shade shapes, which are considered as subjective shading [16]. Primordial stages for estimation of irradiance on a PV generator includes the case of subjective shading as explained in [17]. A dimensionless parameter, known as shading factor [18] is included in the developed model to deal with any causes of shading.

It is to be highlighted that to minimize cracking, overheating and potentially burning due to possible hard-edged shading, bypass diodes are used in parallel with modules that conduct when the module is shaded. It is cost effective to provide a bypass diode across sub-string of cells instead of connection with individual cell and each sub-string will result in one module as shown in Fig. 2. Bypass diodes become active only when subjective shading effect appears in the system; otherwise, the bypass diode factor is zero.

Beta distributions for cloudy and rainy conditions are given as

$$f(C|d, e) = \frac{1}{B(d, e)} C^{d-1} (1 - C^{e-1}) I_{(0,1)}(C) \quad (5)$$

$$f(R|g, h) = \frac{1}{B(g, h)} R^{g-1} (1 - R^{h-1}) I_{(0,1)}(R) \quad (6)$$

where $d > 1$ and $e > 1$ are formed from shading factor and $g > 1$ and $h < 1$ are formed from rainfall duration and rainfall intensity components [19].

For a PV cell, the short-circuit current is calculated for the sunny, cloudy and rainy condition as

$$I_{sc}(X) = f(X|a, b) [I_{sc0} + k_i (T_x - 25)] \quad (7)$$

$$I_{sc}(C) = I_{sc}(S) [1 - f(C|d, e)] \quad (8)$$

$$I_{sc}(R) = I_{sc}(S) f(R|g, h) - k_i (T_{amb} - T_0) \quad (9)$$

while its open-circuit voltage is calculated for each condition as

$$V_{oc}(X) = V_{oc} - k_v T_x \quad (10)$$

$$V_{oc}(C) = V_{oc} + 2m V_t \log[1 - f(C|d, e)] \quad (11)$$

$$V_{oc}(R) = \frac{KT_{amb}}{q} \log\left(\frac{I_{sc}(S)}{I_0}\right) \quad (12)$$

which considers the shading factor due to objective shading caused by clouds. Thus, the voltage and current at the maximum power point under partial shading conditions can be calculated as [3]

$$V_{mpp}(S) = V_{mpp} + 2c_{1m \times v_t} \log[1 - f(C|d, e)] \quad (13)$$

$$I_{mpp}(S) = I_{mpp} [1 - f(C|d, e)] \quad (14)$$

From (7)-(14), the deviation of the current-voltage characteristic of a PV cell with respect to the ideal condition, denoted by

Fig. 2. Schematic illustration of a single PV module.

Fig. 3. Considered Beta distributions for sunny, cloudy and rainy condition.

fill factor, is determined as

$$FF = \frac{V_{mpp} I_{mpp}}{V_{oc} I_{sc}} \quad (15)$$

Thus, the output voltage and current of a PV module, consisting of strings of cells as shown in Fig. 2, can be calculated in every condition as

$$I_{out} = f(s|a, b) [I_{sc} + k_i (T - 25)] \quad (16)$$

$$V_{out} = V_{oc} - k_v T \quad (17)$$

Thereby, the total output power of a PV module in any condition can be defined from

$$P_{total} = I_{out} V_{out} FF \quad (18)$$

III. SIMULATION AND MODELING

The major purpose of the developed algorithm (shown schematically in Fig. 4) is to calculate the weather-based output power of the PV system. A stochastic modeling approach, which is a useful tool for estimations of probability distributions, has been used here as the simulation technique. The potential outcomes taken from the Beta PDF are allowed for random variation of one or more inputs, based on historical data for selected intervals using metrological year data. To this end, typical metrological data of 12 months has been captured for a site (i.e., Sydney, Australia). Multiple trial runs are performed in MATLAB using random variables, specified earlier in stochastic modeling stage.

Table II. Comparison of the expected output power of a PV system in different ambient conditions throughout the year.

Month	$f(X)$	P_X [MW]	$f(C)$	P_C [MW]	$f(R)$	P_R [MW]
January	0.30	4.7	0.39	2.92	0.77	1.72
February	0.42	8.9	0.23	4.90	0.99	1.12
March	0.32	5.1	0.67	2.48	0.51	1.83
April	0.32	5.3	0.53	2.50	0.90	1.30
May	0.31	4.3	0.21	4.0	0.79	1.70
June	0.29	4.6	0.54	2.48	0.78	1.71
July	0.40	7.2	0.69	2.15	0.94	1.85
August	0.32	5.1	0.22	4.07	0.81	1.22
September	0.39	7.7	0.39	2.80	0.71	1.91
October	0.35	5.9	0.35	3.25	0.96	1.18
November	0.31	4.3	0.54	2.59	0.67	1.96
December	0.40	7.7	0.17	5.87	0.61	2.16

It is assumed that a sunny condition does not have any clouds; light clouding are considered for cloudy condition, and heavy clouding is considered for rainy condition. Thus, it is thought that a sunny condition does have 0% shading, a cloudy condition has 15-40% shading while 45-75% shading is considered for a rainy condition. This assumption is based on input parameter values of Beta distribution.

The required computational procedure is as below:

- Step-1: Select the month for which the expected output power is needed.
- Step-2: Perform statistical analysis to determine Beta PDF from the input metrological data.
- Step-3: Compute the ambient and cell temperature for that particular time of the year.
- Step-4: Solve equations of current and voltage for PV module under consideration (objective shading assumptions made earlier should be taken in account).
- Step-5: Calculate the fill factor to see the deviation from original voltage-current characteristic.
- Step-6: Calculate the output power of the PV system for a sunny, cloudy and rainy condition.

The flow chart of Fig. 5 illustrates schematically the computational procedure in more details.

IV. PERFORMANCE EVALUATION

The performance of a PV System with the developed algorithm is evaluated by considering one year data, and is tabulated in Table II. First, $f(X)$ has been computed using (4) where parameters $a, b < 1$ so the Beta PDF obtained for sunny condition is U-shaped as shown previously in Fig. 2. After this, the corresponding temperature is calculated while normal operating temperature is set at 25°C. The short circuit current obtained using (7) for 12 months is in the range of 1.05 to 1.28 A while the open circuit voltage is in the range of 22.04 to 22.08 V. The fill factor value is 0.7 for sunny weather. Finally, P_X values are calculated which show that the expected output power is maximum

Fig. 4. Assumed System topology.

Fig. 5. The algorithm flowchart.

Fig. 6. The expected output power of the considered PV system under different ambient conditions throughout the year.

(approximately 8.9 MW) for February due to the highest expected insolation level while lower values of 4.3 MW are expected for May and November because of the lower expected exposure to sunlight.

When the evaluation is carried out for a cloudy weather, the shading factor is involved in the composition of $f(C)$ so high value of shading will cause lower power output, and the PDF has a mount-curve shape. The expected output power of the consid-

ered PV system in rainy conditions (P_C) is 5.87 MW for December while it reduces to 2.15 MW in July because of the larger expected shadings.

Beta-PDF for rainy condition is made from rainfall duration and rainfall intensity factors and inclusion of shading effect is obvious in this case. The PDF has a J-shape curve. The expected output power of the considered PV system in this condition (P_R) is expected to generate 1.85 and 1.22 MW for July and August.

Fig. 6 illustrates the expected output power of the considered PV system in these three conditions throughout the year. The stochastic analysis shows a reduction of respectively 25-40 % and 60-70 % in the expected output power of the considered PV system for cloudy and rainy conditions in comparison to a sunny condition.

V. CONCLUSION

This paper presents a new model to calculate the output power of a PV system for selected weather condition with respect to its ambient conditions which affect the solar insolation. In the developed model, first, a practical PV module is designed. The numerical analysis by the developed technique illustrate that, as expected, the maximum output power is obtained under sunny condition while shading will drastically reduce the output even by 75%, in rainy conditions. The proposed method is useful when estimating the power generation capability of a PV system, with respect to the historical ambient data and the meteorological conditions. The developed technique can also be used for evaluating the self-adequacy of standalone power systems or microgrids, composed of a PV system. The results may be very useful for designing dispatchable microgrids.

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