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Research Note

Modelling polycristallin photovoltaic cells using design of experiments

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Abstract. Photovoltaic energy has, nowadays, an increased importance in electrical power applications. However, the output power provided via the photovoltaic conversion process depends on solar irradiation and temperature. Tracking the Maximum Power Point (MPP) of photovoltaic (PV) systems is the most important part of the PV systems. In this paper, modeling and parameter extraction methods are proposed to describe the optimal current, voltage and power of the photovoltaic cells. The aim is to find a formula that considers these factors and to study the interactions between these various factors. The design of experiments is a powerful tool to understand systems and processes. Experiments are often run so that the effect of one factor is unknowingly confused with the effect of another factor. A brief comparison between classic modeling is presented. In order to model the optimal current, optimal tension and optimal power, a methodology of experimental design is presented. The obtained results show the merits of the proposed mathematical model, which makes the study of the interactions between various climatic factors possible.

1. Introduction

The consumption of fossil fuels has an environmental impact, in particular the release of carbon dioxide (CO_2) into the atmosphere. CO_2 emissions can be greatly reduced through the application of renewable energy technologies, and renewable energy resources are sufficient to meet world energy requirements. Photovoltaic systems have become increasingly popular and are ideally suited for distributed systems, as solar energy is the most abundant renewable resource.

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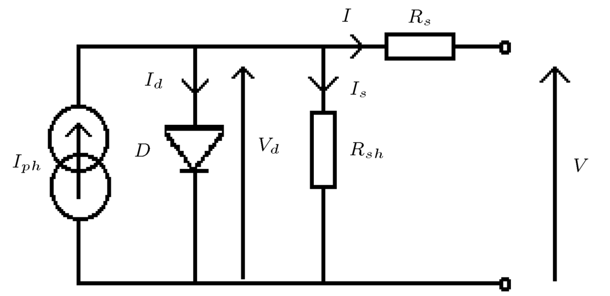
2. Photovoltaic characteristics

There are three classic parameters that are very important for PV characteristics, namely, short-circuit current (I_{cc}), open-circuit voltage (V_{oc}) and the maximum power point (I_{opt}; V_{opt}). The power delivered by a PV cell reaches a maximum value at the point (I_{opt}; V_{opt}). Solar photovoltaic (PV) arrays consist of many N_s cells connected in series to provide the required terminal voltage, and N_s cells, which are connected in N_p branches to provide the current ratings. PV power systems do not have any moving parts, they are reliable, they require little maintenance and they do not generate pollutants or noise [1-8].

The voltage- current characteristic of a solar array



I: output current;
V: output voltage;
R_s: series resistance;
D: diode;
I_{ph}: light-generated current;
R_{sh}: shunt resistance;
I_s: current flowing through R_{sh};
I_d: diode forward current;
V_d: diodes voltage.

Figure 1. An equivalent circuit of a real photovoltaic cell where V and I are the output voltage and current of the PV module, respectively; R_s and R_{sh} are the series and shunt resistances.

in Figure 1 is given by Eq. (1) [1-8]:

$$I = I_{ph} - I_o.\left[\exp\frac{V_d}{A.U_T} - 1\right] - \frac{V_d}{R_{sh}}, \tag{1}$$

with:

$$V_d = V + R_s.I, \tag{2}$$

where V and I are the output voltage and current of the PV module, respectively; R_s and R_{sh} are the series and shunt resistances of the module, U_T is the thermal voltage, I_{ph} is the light-generated current, I_o is the reverse saturation current, and A is an ideality factor. In this studied case, a photovoltaic module is constituted of 36 solar polycrystalline cells in series (Kyocera LA 361 K51), mounted 35° south.

$$P = V.I. \tag{3}$$

The simulation result of the output module characteristics ($N_s = N_p = 1$) using Eq. (1) and Eq. (3) is shown in Figure 2 [3-8]. V_{oc} and I_{cc} points are shown in Figure 2(a). The curve shows a MPP (Maximum Power Point), M, where the solar array operates more efficiently (Figure 2(a)), which corresponds to the optimal power, P_{opt}, shown in Figure 2(b).

According to the maximum power transfer theory, the power P delivered to the load is maximum when the source internal impedance matches the load impedance in a direct coupling. The peak P_{opt} in Figure 2 is provided by solving (4) [8]:

$$\frac{dP}{dI} = -2.R_s.I + A.U_T.\ln\left[\frac{I_{cc} - I + I_o}{I_o}\right] - \frac{A.U_T.I}{I_{cc} - I + I_o} = 0. \tag{4}$$

The current I_{opt} is the solution of Eq. (5):

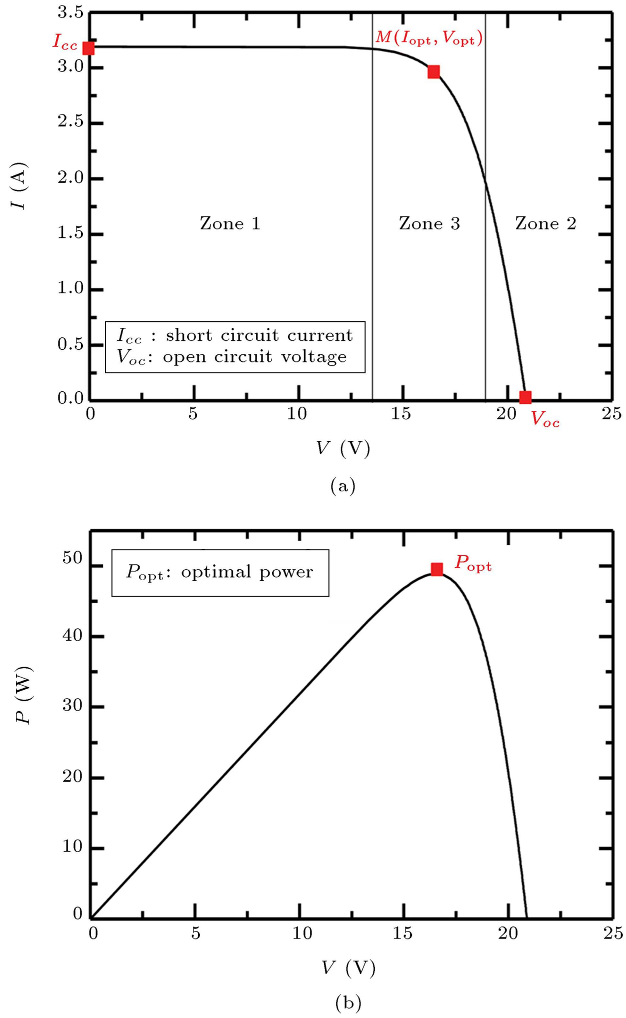


Figure 2. Electrical characteristic of the module at solar radiation, $E_s = 100\%$ and temperature, $T = 25°$C: a) $I-V$ characteristic; and b) $P-V$ characteristic.

$$I_{cc} = I_{\text{opt}} + I_o.\left[\exp\left[\frac{(2.I_{\text{opt}}.R_s)}{A.U_T} + \frac{I_{\text{opt}}}{I_{cc} - I_{\text{opt}} + I_o}\right] - 1\right]. \tag{5}$$

The simulation results are shown in Figures 3 and 4. Figure 3 shows the characteristic curves at different irradiances, E_s, for a constant temperature. The characteristic curves at different temperatures for a constant E_s, is illustrated by Figure 4. Both figures demonstrate that the output characteristic of a solar module is crucially influenced by solar radiation, E_s, and temperature, T, conditions.

Due to the high cost of the photovoltaic generator, it is important to operate the modules close to their maximum power. So, in order to assure maximum power transfer, the objective is to obtain the maximum power point: I_{opt}, V_{opt}, P_{opt} [8-13].

I_{opt}: optimal current; V_{opt}: optimal voltage; P_{opt}: optimal power.

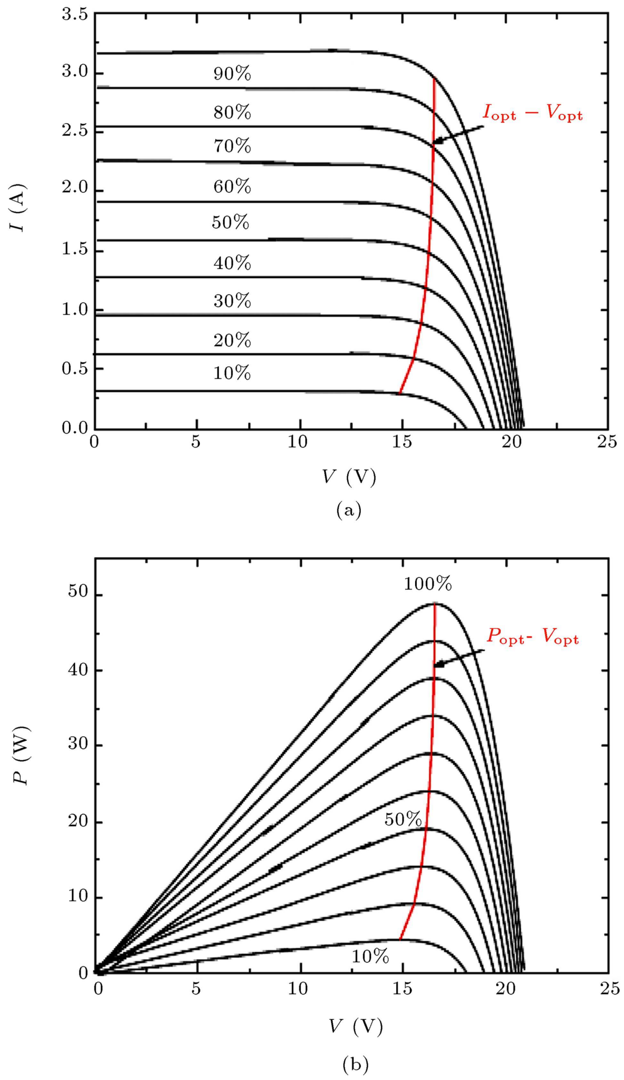


Figure 3. $I-V$ and $P-V$ characteristics of a solar module under varied solar irradiance and constant temperature: a) $I-V$ characteristic; and b) $P-V$ characteristic.

3. Experimental design methodology and development of the method

The methodology of the experimental designs allows one to determine the number of experiments to be achieved according to a well defined objective, to study several factors simultaneously, to reduce dispersion related to measurements, to appreciate the effects of coupling between factors, and, finally, to evaluate the respective influence of the factors and their interactions [7-10].

Finding mathematical models of good quality with minimum effort depends on how input factor intervals are selected. This method can be used, as follows [14-19]:

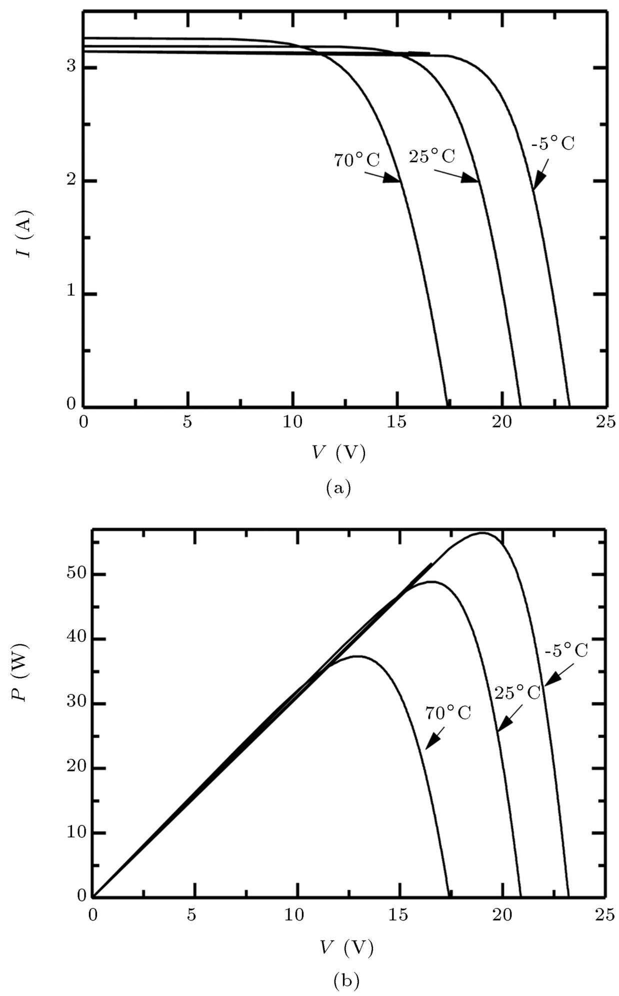


Figure 4. $I-V$ and $P-V$ characteristics of a solar module under varied temperatures and constant irradiance: a) $I-V$ characteristic; and b) $P-V$ characteristic.

- Selection of the most interesting and influential factors;
- Determination of maximal, minimal and average values of each factor;
- Carrying out a matrix of experiments with all possible states and their corresponding responses.

Before starting the experiments, it is necessary to set the best and suitable design which can model the process with the most possible precision. In this paper, the Centred Faces Composite design (CCF) is chosen which allows the use of Response Surfaces Modelling (RSM). It is possible to determine a quadratic dependence between the output function to optimize (response) and the input variables, u_i $(i = 1, \cdots, k)$:

$$y = f(u_i) = c_0 + \sum c_i u_i + \sum c_{ij} u_i u_j + \sum c_{ii} u_i^2. \quad (6)$$

Knowing that Δu_i and u_{i0} are, respectively, the step of variation and the central value of factor i, the reduced centred values of input factors may be defined by the following relation:

$$x_i = (u_i - u_{i0})/\Delta u_i. \quad (7)$$

With these new variables, the output function becomes:

$$y = f(x_i) = a_0 + \sum a_i x_i + \sum a_{ij} x_i x_j + \sum a_{ii} x_i^2. \quad (8)$$

The coefficients can be calculated or estimated by a data-processing program in such a way as to have a minimum variance between the predictive mathematical model and the experimental results.

4. Software Modde 5.0

The software MODDE 5.0 (Umetrics AB, Umea, Sweden) was used, which is a Windows program for the creation and evaluation of experimental designs [20]. The program assists the user for interpretation of the results and prediction of the responses. It calculates the coefficients of the mathematical model. In fact, it draws the surfaces of response (RSM) and identifies the best adjustments of the parameters for process optimisation.

Moreover, the program calculates two significant statistical criteria, which make it possible to validate the mathematical model or not:

- The predictive power is given by Q^2. This is a measure of how well the model will predict the responses for a new experimental condition.
- The goodness of fit parameter is given by R^2.

A good mathematical model must have criteria Q^2 and R^2, whose numerical values should be close to unity.

5. Results

The analysis of electric power, current and voltage were achieved using a CCF experimental design with two factors. In the experiments site in ORAN, used in this work, the domain of variation of each factor is:

- Solar radiation, E_S: $E_{S\min} = 10\%$, corresponding to 100 W/m^2, and $E_{S\max} = 100\%$, corresponding to 1 KW/m^2;
- Temperature: $T_{\min} = 20°$C and $T_{\max} = 50°$C.

Measurements of the three responses, i.e. power, P_{opt}, current, I_{opt}, and voltage, V_{opt}, obtained according to a CCF design, are given in Table 1.

Once the experimental values of the responses are measured, software MODDE.05 checks whether experimental results are "reasonable". It detects any "doubtful" measurement result.

Table 1. Obtained results.

Experience $n =°$	E_s [%]	T [°C]	P_{opt} [W]	V_{opt} [V]	I_{opt} [A]
1	10	20	4.38	14.836	0.295
2	100	20	49	16.528	2.957
3	10	50	3.62	12.476	0.29
4	100	50	42.5	14.525	2.926
5	10	35	4.07	13.904	0.293
6	100	35	46.3	15.723	2.947
7	55	20	27.298	16.737	1.631
8	55	50	22.882	14.2	1.611
9	55	35	25.107	15.467	1.623
10	55	35	25.107	14.467	1.623
11	55	35	25.107	14.467	1.623

The statistical tests achieved with MODDE.05 lead to a valid mathematical model, since R^2 and Q^2 reach higher values ranging between 0.991 and 1.000. The models suggested by MODDE.05 are:

- For power, P_{opt}:

$$P_{\text{opt}} = 25.17 + 20.96E_s^* - 1.95T^* - 0.07(E_S^*)^2 - 0.17(T^*)^2 - 1.44(E_S^* T^*). \quad (9)$$

- For voltage, V_{opt}:

$$V_{\text{opt}} = 15.51 + 0.93E_S^* - 1.15T^* - 0.77(E_S^*)^2 - 0.12(T^*)^2 - 0.09(E_S^* T^*). \quad (10)$$

- For current, I_{opt}:

$$I_{\text{opt}} = 1.62 + 1.32E_S^* - 0.009T^* - 0.003(E_S^*)^2 - 0.02(T^*)^2 - 0.06(E_S^* T^*). \quad (11)$$

6. Discussions

The values of the coefficients associated with the factors show the degree of the influence of each factor. The signs indicate how much the response is influenced. The coefficients could also be plotted as shown in Figure 5. The latter shows that the E_S effect is more significant than all the others. It arises from mathematical models that within the variation limits of the selected intervals, E_S is the most effective. This was confirmed by iso-responses surfaces shown in Figure 6, where it could be verified that factor E_S is more significant than temperature. Furthermore, as expected, the influence of E_S is positive and the one of T is negative.

According to this power model, the operation set point, i.e. the optimum of the process corresponding to

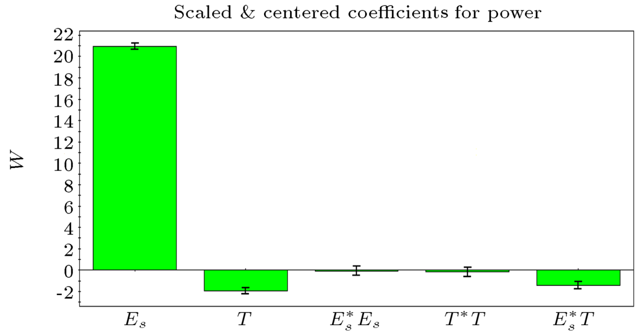


Figure 5. Plotted coefficients of the model.

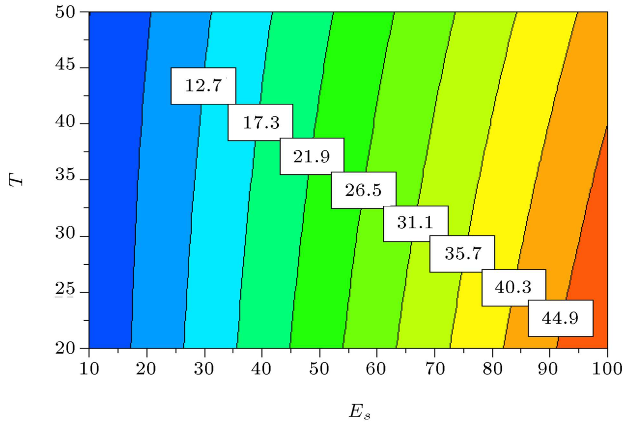


Figure 6. Iso power contours $P(W)$ plotted by Modde 5 based on the data of Table 1.

the maximum power, should be obtained for $E_S = 100$ and $T = 20°$C.

The design of the experiment model shows directly the relationship between the climatic data: solar radiation, E_s, temperature, T, and response, P_{opt}. It shows also interactions between these climatic factors.

7. Conclusion

In this work, we provide an approach to find optimal power, optimal current and optimal voltage in order to find the MPP. The control variables considered for the optimization include solar radiation and temperature. The aim is to show interactions between these various factors. This method can be applied to control a DC-DC converter device. An experimental design methodology was employed for determining the optimum value of each variable, using commercial software (MODDE, Umetrics, Sweden).

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Biographies

Fatima Zohra Zerhouni obtained her MS and PhD degrees in electrical engineering from the University of Science and Technology, Mohamed Boudiaf, Oran (USTOMB), Algeria, where she is currently Professor and researcher, and also member of the Microsystèmes et Systèmes Embarquès Laboratory. She began her studies in the field of power electronics and changed to environmental friendly production of energy. She has had a number of papers published in international journals and presented at international and national conferences, and was awarded by CDER and the Ministry of Higher Education and Scientific Research, Algeria, for the best publication of 2010. Her research interests include renewable energy, fuel cells, power electronics, electrical storage systems and soft computing control.

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Mohammed Tarik Benmessaoud received BS, MS and PhD degrees in engineering and electronics from the University of Science and Technology, Oran (USTO-MB), Algeria, in 2000, 2006, and 2012, respectively. He is currently Professor in the electrical and electronics engineering faculty, as well as member of the Materials and their Applications in Electrical Engineering Laboratory, at the same institution.

His research interests include electronics, renewable energy, solar cells, fuel cells, desalination, materials and their applications in electrical engineering, theoretical and computational mathematical concepts with applications in electrical engineering, neural networks, genetic algorithms and optimization methods.

Amar Tilmatine received an MS degree in electrical engineering and the Magister (Dr. Eng.) degree from the University of Science and Technology, Oran, Algeria, in 1988 and 1991, respectively. He obtained a PhD degree, in 2004, from the Electrical Engineering Institute of Sidi Bel Abbes University, Algeria, where he teaches electric field theory and high-voltage engineering, and was Chairman of the Scientific Committee of this institute for 3 years. He is currently Professor, senior IEEE member and Vice-chairman of the IEEE Algerian subsection. He is also Director of the AP-ELEC Laboratory.

He visited the Electrostatics Research Unit of the University Institute of Technology, Angoulême, France, at various times between 2001 and 2012, as invited scientist for work on a joint research project involving new electrostatic separation technologies. His other fields of interest are high-voltage insulation and gas discharges.

Amine Boudghene Stambouli is a graduate of the University of Science and Technology, Oran, Algeria, in 1983. He received his MS and PhD degrees in modern electronics and optoelectronics from the University of Nottingham, UK, in 1985 and 1989, respectively, He is currently Professor of optoelectronics and material sciences for environment and energy applications in the Department of Electronics at the University of Sciences and Technology, Oran. His studies started in the field of high field electroluminescence and optoelectronics and changed to environmental friendly production of energy. His research interests include photovoltaics, fuel cells, hybrid systems, and environment impacts.

Prof. Amine Boudghene Stambouli is a United

Nations consultant (Index 382958), member of many scientific and industrial organizations and director of several doctoral courses. He served as head of the electronics department, vice rector of the university for almost two years and, later, president of the scientific council of the electrical and electronics engineering faculty. Prof. Amine Boudghene Stambouli has chaired several international conferences in the field of electrical engineering, and has been published in 1 book and 3 polycopies. He has also had a number of papers published in international journals and proceedings of international and national conferences, and is reviewer and editorial board member of several international journals. He actively collaborates with research groups world-wide, including Algeria, Italy, Japan, France, USA, Germany, Turkey, England, Saudi Arabia, Jordan, Morocco, Tunisia and Syria. He was co-responsible, with Professor Enrico Travera, for the research team "Photovoltaics and Fuel Cells" between the University of Roma Tor Vergata and the University of Sciences and Technology of Oran, and awarded best publication of 2009 by CDER and the Ministry of Higher Education and Scientific Research of Algeria. He is co-responsible (Algerian side) for the Sahara Solar Breeder (SSB) project, with Pr. Koinuma (Japan side), and founder of the Sahara Solar Breeder Foundation.