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A prediction Model Based on Nelder-Mead Algorithm for the Energy Production of PV Module

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***Abstract*— The use of a reliable model of a photovoltaic (PV) module is the main step for energy prediction and an important tool for monitoring and supervision. To this end, PV modeling primarily involves the formulation of the non-linear current versus voltage (I-V) curve. This paper presents the application of the Nelder-Mead simplex search method for identifying the parameters of solar cell and photovoltaic module models. The proposed technique allows the extraction of the unknown model parameters, namely, the generated photocurrent, saturation current, series resistance, shunt resistance, and ideality factor that govern the current-voltage relationship of a solar cell. The extracted parameters have been tested against several static IV characteristics of the PV module collected at different operating condition. Comparative study among different parameter estimation techniques is presented to demonstrate the effectiveness of the proposed approach. The dynamic MPP model has also been derived and simulated using the extracted parameters against MPP real dynamic measurements of a grid connected system located in the Centre de Developpement des Energies Renouvelables (CDER) in Algiers**.

***Index Terms*— N-M algorithm, Optimization, Parameters extraction, Photovoltaic module, dynamic MPP model.**

I. INTRODUCTION

Renewable energy is expected to be an important source of energy in the future because it replaces the depletion of the fossil fuel reserves and mitigates the pollution caused by the conventional energy sources. In particular, photovoltaic power systems could be a suitable solution to meet local energy demand. The possibility of predicting a photovoltaic array's performance in various irradiance and temperature conditions is very important for sizing the PV arrays as well as for the design of the Maximum Power Point Tracking and control strategies [1].

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For this end, several research papers have focused on the modeling and parameters extraction of the PV modules as it is the key element in the energy production chain, not only to increase their performance, but also to simulate their behavior and optimize their different characteristics [2-7].

In the literature, there are two main equivalent circuit models used to describe the non-linear I–V relationship, the model with five parameters commonly called the single diode model and the one with seven parameters commonly called double diode model. Therefore, to provide an accurate modeling and reliable performance evaluation of a given solar system, a valid estimation of these models parameters is always required. The methods employed to solve the problem of PV parameter identification can be divided in two groups; deterministic and heuristic approaches [8]. Metaheuristic algorithms are suitable choices for solving this problem due to their global search power as well as derivative-free advantage. In [9], it is stated that the heuristic algorithms give better results than classical methods in term of accuracy with a high probability to converge toward the global optimum.

This paper presents the application of the Nelder-Mead simplex search method for identifying the parameters of solar cell and photovoltaic module models. The proposed technique is a simple and direct search method that does not require calculation of any derivatives. For these reasons, it is used to identify the unknown models parameters, namely, the generated photocurrent, saturation current, series resistance, shunt resistance, and ideality factor that govern the current-voltage relationship of a solar cell. Real measurements data are used to test and verify the consistency of accurately estimating the unknown parameters of the single and double diode models respectively.

Moreover, the characteristic equation with the extracted parameters has been tested against several static IV characteristics of a PV module collected at different operating condition.

Finally, the extracted parameters are used in a behavioral model of the maximum power point of a PV generator and compared against reel measured data from an operating PV grid connected system located at Centre de Developpement des Energies Renouvelables situated in Algiers (Algeria). The results prove that the N-M is very suitable tool for estimating electrical parameters needed for modeling the PV array for long term prediction.

The rest of this paper is organized as follows: brief description of the single and double diode models are provided in section II. In section III, election of the cost function and optimization principle is given. Brief description of N-M optimization algorithm is given in section IV. Simulation results and related discussions are provided in section V. Finally, the drawn conclusions from this work are provided in section VI.

II. PHOTOVOLTAIC MODULE MODELING

Although various models have been developed in the literature to describe the behavior of solar cells, a special attention has been made, in this paper, to single and double diode models.

A. *Single diode model*

The single diode model is the most commonly used for modeling purposes [10]. As shown in Fig. 1, this model is simple, easy to solve, and suitable for electrical engineering applications.

The behavior of photovoltaic module is generally described by its current-voltage characteristic, in which their shapes are dependent on the value of the five parameters, solar irradiance and module temperature.

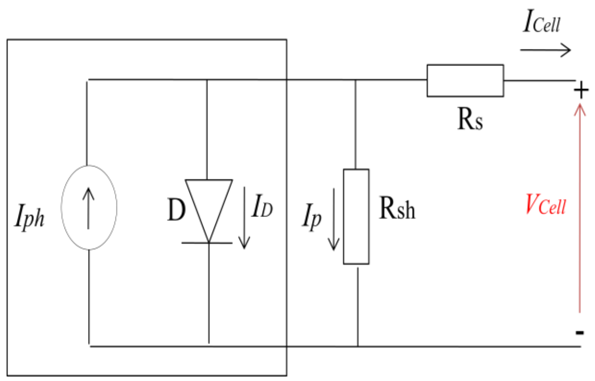

Fig. 1. The equivalent circuit model of the single diode model

The output current versus output voltage characteristics is given by the following expression [11]:

$$I = I_{ph} - I_0 \left[\exp\left(\frac{q(V+R_S I)}{nkT}\right) - 1\right] - \frac{V+R_S I}{R_{sh}} \quad (1)$$

Where I_{ph} is the photocurrent in (A), I_0 the diode saturation current (A), n the diode ideality factor, k the constant of Boltzmann ($1.38\text{x}10^{-23}$ JK^{-1}), q the electric charge ($1.602\ \text{x}10^{-19}$ C), T the cell temperature (K), V_t (V) the thermal voltage (V_t =kT/q), R_s the series resistance (Ω) and R_{sh} is the shunt resistance (Ω).

The five parameters of the characteristic equation namely $I_{ph}, I_0,\ R_s,\ R_{sh}$ and n are usually given by module manufacturers in standard test conditions (STC). However, experience has proved that real values obtained in real working conditions are different from the nominal ones. Therefore, the need of matching the PV module model given by (1) with experimental data, for prediction purpose, passes inevitably by finding out the correct values of the five parameters.

B. *Double diode model*

In this model, an extra diode is added in parallel to the circuit of single-diode model as shown in Fig. 2. The inclusion of an additional diode increases the number of computed parameters.

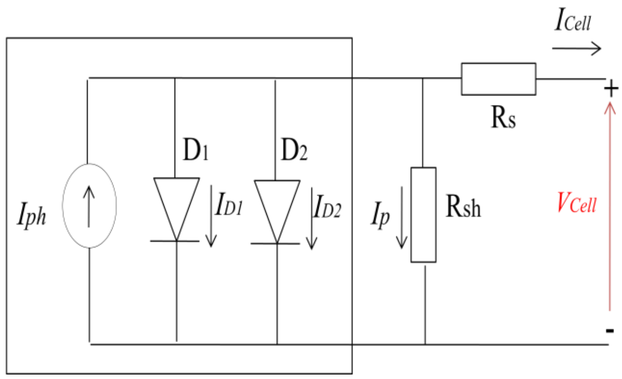

Fig. 2. The equivalent circuit model of double diode model

The output current versus output voltage characteristics is described by the following expression [12]:

$$I = I_{ph} - I_{01} \left[\exp\left(\frac{q(V+R_S I)}{n_1 kT}\right) - 1\right] - I_{02} \left[\exp\left(\frac{q(V+R_S I)}{n_2 kT}\right) - 1\right] - \frac{V+R_S I}{R_{sh}} \quad (2)$$

Where I_{ph} is the photocurrent in (A), I_{01} and I_{02} are the saturation currents of diode 1 and 2 respectively (A), n_1 and n_2 are the diodes ideality factor, In the double diode model, the number of the unknown parameters increases to seven, namely R_s, R_{sh}, I_{ph}, I_{01}, I_{02}, n_1 and n_2. To reflect the solar cell performance as well as that of the actual system, the identification of the parameters is of prime interest.

III. OPTIMIZATION PRINCIPLE

Parameters extraction process can be transformed to an optimization problem which can be solved by the N-M algorithm. In this paper, the root mean square error (RMSE) is chosen as a criterion to quantify the difference between the model results based on equations (1) or (2) and the measurement data. The RMSE is evaluated for each pair of the experimental (I, V) values as the difference between the real measured current and the calculated current based on the N-M algorithm as follow:

$$RMSE = \sqrt{\frac{1}{N}\left(\sum_{i=1}^{N}(f(V,I,x))^2\right)} \qquad (3)$$

In the case of single diode model

$$f(V,I,x) = I - \left(I_{ph} - I_0\left[\exp\left(\frac{q(V+R_SI)}{nkT}\right) - 1\right] - \frac{V+R_SI}{R_{sh}}\right) \qquad (4)$$

In the case of double diode model

$$f(V,I,x) = I - \left(I_{ph} - I_{01}\left[\exp\left(\frac{q(V+R_SI)}{n_1kT}\right) - 1\right] - I_{02}\left[\exp\left(\frac{q(V+R_SI)}{n_2kT}\right) - 1\right] - \frac{V+R_SI}{R_{sh}}\right) \qquad (5)$$

x denotes the optimal parameters' vector of the calculated current based on N-M algorithm. Where $x = [I_{ph}, I_0, R_{sh}, R_s, n]/x = [I_{ph}, I_{01}, I_{02}, R_{sh}, R_s, n_1, n_2]$ and N is the number of data points.

IV. NELDER-MEAD ALGORITHM

Due to the implicit form of the characteristic equations given by (1) or (2), the Newton-Raphson iterative method based on the N-M simplex search algorithm is used, in this paper, in order to match the predicted current and the measured one (i.e., the N-M algorithm minimizes the residuals between the theoretical models and the measured data)

The N-M algorithm is one of the best known algorithms for multidimensional unconstrained optimization without derivatives [13]. The N-M algorithm was proposed as a method for minimizing a real-valued function $f(x)$ for $x \in \Re^n$ where four scalar parameters must be specified to define a complete method: coefficients of refection (ρ), expansion (χ), contraction (γ), and shrinkage (σ). These parameters are fixed so that $\rho = 1$, $\chi = 2$, $\gamma = 1/2$ and $\sigma = 1/2$. The Statement of the N-M algorithm for one iteration is detailed in [14 and references therein].

The basic steps of the N-M algorithm are given by the flowchart of Fig.3.

In the following section, several modeling comparisons are conducted using the models given by (1) and (2) for several scenes of the PV database.

V. SIMULATION RESULTS

The Nelder-Mead algorithm has been coded in Matlab environment to extract the PV module parameters using real I-V data. In order to check the effectiveness of the parameters extraction obtained by the application of this algorithm, the collected measurement data from **ISOFOTON 106/12** module has been used, where its electrical characteristic are summarized in Table I. Table II summarizes the upper and the lower band of the PV module parameters. In table III, the extracted parameters using N-M algorithm are depicted for the single diode model, while table IV depicts the extracted parameters of the double diode model. A comparison between the measured (I-V), (P-V) characteristics and the estimated ones using the extracted parameters of PV models given by (1) and (2) are presented in Fig.4, Fig.5, Fig.6 and Fig.7 respectively. The validation test using different meteorological conditions is presented in Fig.8. Finally during the extraction process, convergence rate of N-M algorithm is illustrated in Fig.9.

TABLE I ELECTRICAL CHARACTERISTIC OF ISOFOTON 106/12 PV MODULE

	ISOFOTON 106/12
$P_{mp}(W)$	106
$V_{OC}(V)$	21.6
$I_{SC}(A)$	6.54
$V_{mp}(V)$	17.4
$I_{mp}(A)$	6.10
$\alpha I_{SC}(\%/°C)$	0.060
$\beta V_{OC}(\%/°C)$	-0.36

ρ : Reflection coefficient, **χ** : Expansion coefficient, **γ** : Contraction coefficient, and **σ** : Shrink coefficient.

Pi : Simplex point

fi : cost function value in Pi

Ph: Simplex point for which the cost function has the highest value

Ps: Simplex point for which the cost function has the second highest value

Pl: Simplex point for which the cost function has the lowest value

Pm: Average simplex point (without considering Ph)

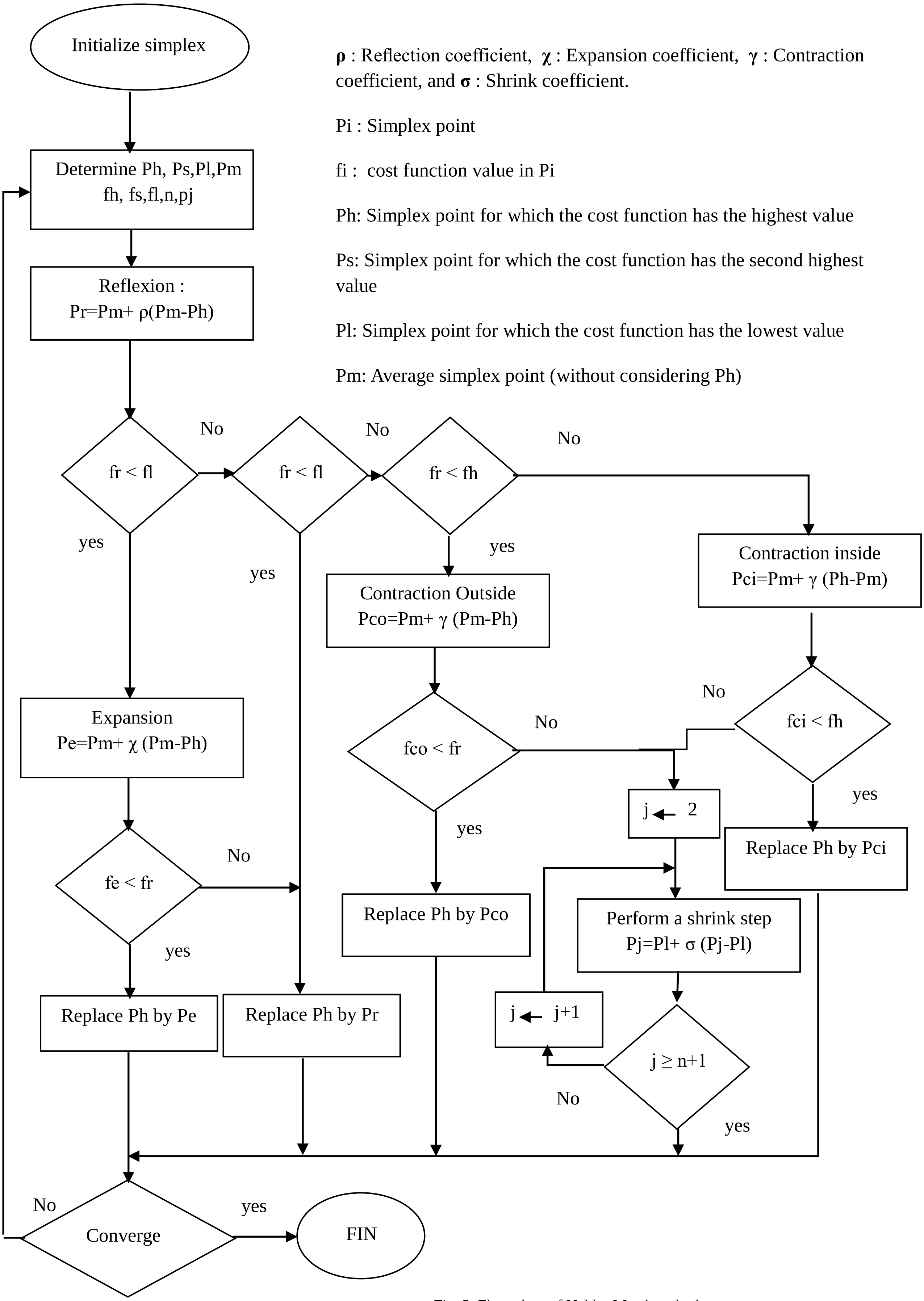

Fig. 3. Flow-chart of Nelder-Mead method

TABLE II UPPER AND LOWER VALUES OF THE ISOFOTON 106/12 PV MODULE

	ISOFOTON 106/12
$R_S(\Omega)$	[0 – 1]
R_p (Ω)	[0 - 400]
I_{ph} (A)	[0 - 10]
$I_{01/02}$ (A)	[10^{-7} – 10^{-4}]
$n_{1/2}$	[0 - 75]

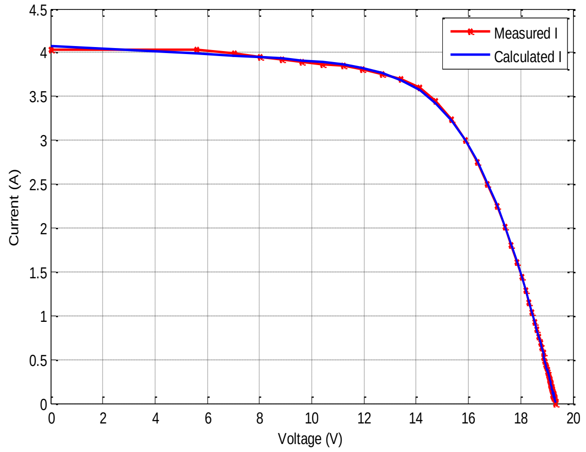

Fig. 4. Measured and calculated IV curve of ISOFOTON106/12 PV module (single diode model)

TABLE III THE EXTRACTED PARAMETERS (SINGLE DIODE MODEL)

	ISOFOTON 106/12
$R_S(\Omega)$	0.43
R_p (Ω)	66.62
I_{ph} (A)	4.09
I_0 (A)	4.64e-6
n	51.17
RMSE	**0.013**

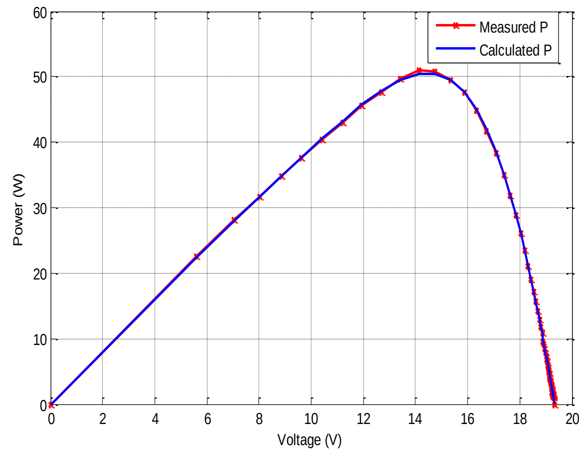

Fig. 5. Measured and calculated PV curve of ISOFOTON106/12 PV module (single diode model)

TABLE IV. THE EXTRACTED PARAMETERS (DOUBLE DIODE MODEL)

	ISOFOTON 106/12
$R_S(\Omega)$	0.359
R_p (Ω)	70.306
I_{ph} (A)	4.060
I_{01} (A)	2.971e-06
I_{02} (A)	2.080e-06
n_1	52.111
n_2	69.104
RMSE	**0.018**

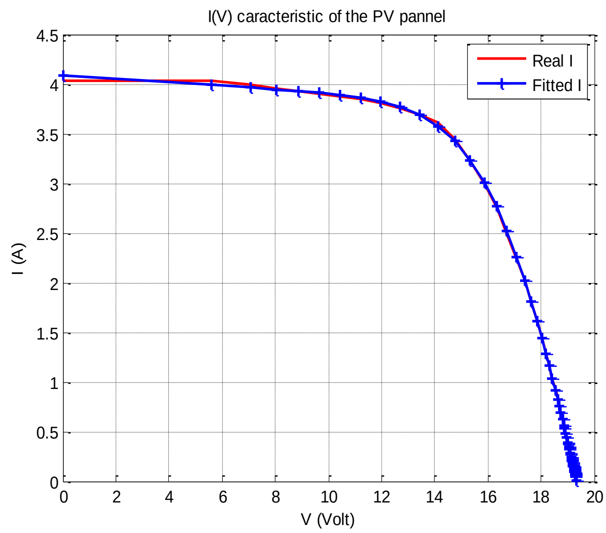

Fig. 6. Measured and calculated IV curve of ISOFOTON106/12 PV module (double diode model)

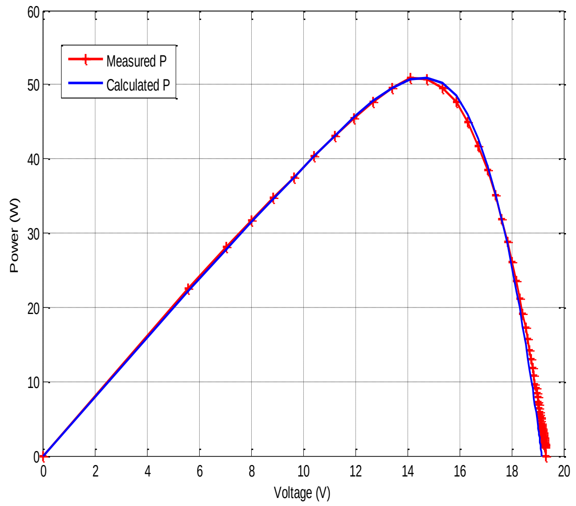

Fig. 7. Measured and calculated PV curve of ISOFOTON106/12 PV module (double diode model)

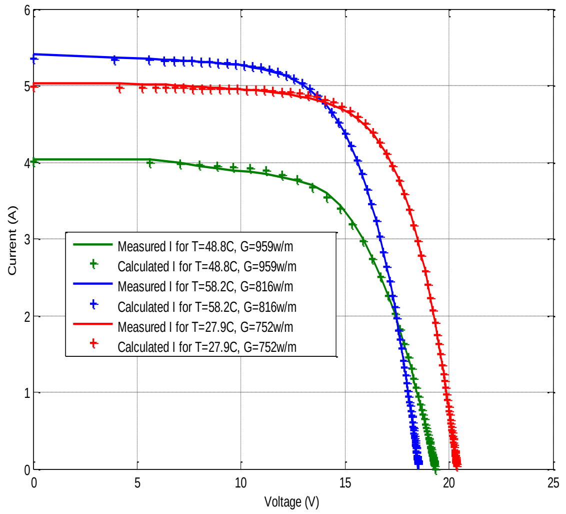

Fig. 8. Measured and calculated IV curve of ISOFOTON106/12 PV module for different meteorological condition

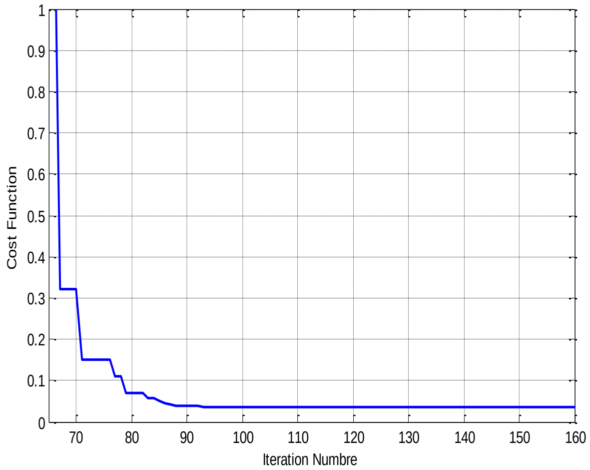

Fig. 9. Convergence speed of N-M algorithm during the extraction process

From the obtained figures (4, 5 and 8) in the case of single diode model, one can see that the theoretical (I-V) characteristics are very close to the experimental measured (I-V) characteristics. The same remark is observed when the double diode model is considered (Fig. 6 and Fig. 7). The results prove the effectiveness of the proposed technique to extract, with good precision, the parameters of the equivalent circuit models.

A comparative study in the case of single diode model with three others optimization algorithms found in the literature [14, 15, 10] has been carried out to check the performance of the proposed algorithm. The algorithms are: Deferential Evolution (DE), Particle Swarm Optimization (PSO) and Bee Colony. From the obtained results, given in table V, and based on the RMSE value, as a test criterion, which is equal to 0.013, we conclude the good quality of the identified parameters using the N-M algorithm with respects to those obtained by DE, PSO and ABC.

TABLE V COMPARATIVE STUDY OF THE OPTIMIZATION ALGORITHMS

	N-M	**DE**	**PSO**	**ABC**
R_S(Ω)	0.43	0.12	0.13	0.12
R_p (Ω)	66.62	120	95.50	103
I_{ph} (A)	4.09	6.71	6.73	6.73
I_0 (A)	4.64e-6	1.62e-5	1e-5	1.38e-5
n	51.17	62.53	60.24	61.76
RMSE	**0.013**	**0.018**	**0.018**	**0.015**

Another study to verify the accurateness of the extracted parameters using N-M algorithm is considered where an experiment was carried out on a dynamic maximum power point evolution in a real operating grid connected photovoltaic system. The PV system is situated in the roof top of the administrative building of the "Centre De Développement des Energies Renouvelables (CDER)" in Algiers, Algeria, as shown in Fig.10. It consists of three sub-arrays of 30 PV modules each. The output of each sub-array is connected to a 2.5 kW single-phase grid connected PV inverter type Fronius IG30.

Fig. 10. The PV system diagram

For this purpose, the adapted model based on MPP daily evolution has been plotted against real MPP profiles obtained for two typical Algerian sky: a clear sky condition and cloudy sky condition. The real PV system is formed by two parallel strings; each string is composed of fifteen serially connected ISOFOTON 106/12 PV modules. The data were recorded with a sampling period of 1 minute.

Fig.11 and Fig.12 report the time evolution for the extracted current and power using the NM adapted model and measured ones respectively for a clear sky day profile. While, time evolution of the same quantities for a cloudy day profile is shown in Fig.13 and Fig.14 respectively.

From the simulation results and for the two tests (clear sky and semi-cloudy day), we observe a good agreement between the measured and the estimated values of maximum power point current and power, which prove the effectiveness of the identification process and the powerful of the proposed approach.

The effectiveness of the proposed approach is more clearly highlighted in the bar-graph of Fig. 15 and Fig. 16, in which it is, reported the predicted and measured hourly array yield (Y_a) of the clear sky and semi-cloudy day respectively. The hourly array yield (Y_a) is defined as the hourly power output of the PV array divided by the nominal rated power of the installed PV array, it is given by:

$$Y_a = \frac{\sum_{i=1}^{n} \Delta t.P_i / n}{rated\ power} \qquad (6)$$

where n is the number of samples and the rated power is the peak power of the installed PV array.

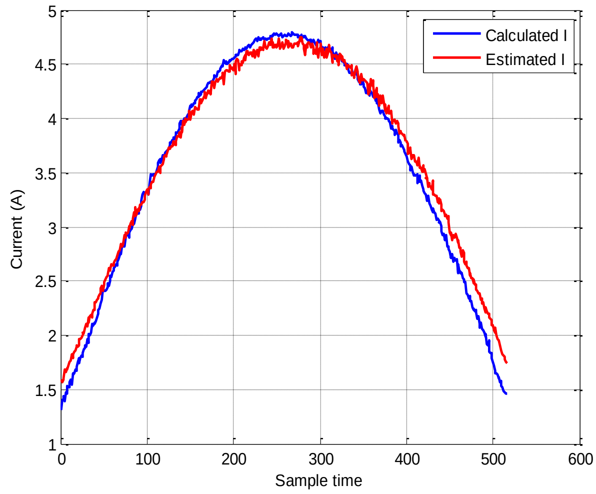

Fig. 11. Comparison between measured and estimated I_{MPP} for a clear sky day.

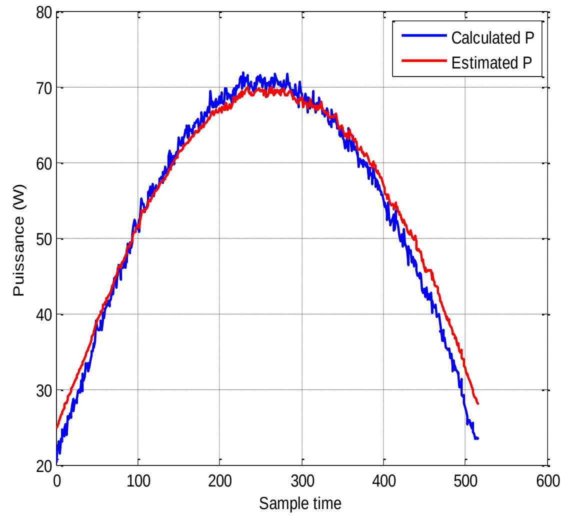

Fig. 12. Comparison between measured and estimated P_{MPP} for a clear sky day.

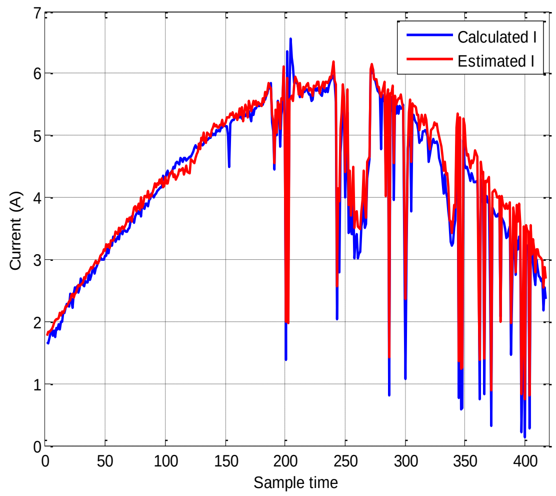

Fig. 13. Comparison between measured and estimated I_{MPP} for a semi-cloudy day.

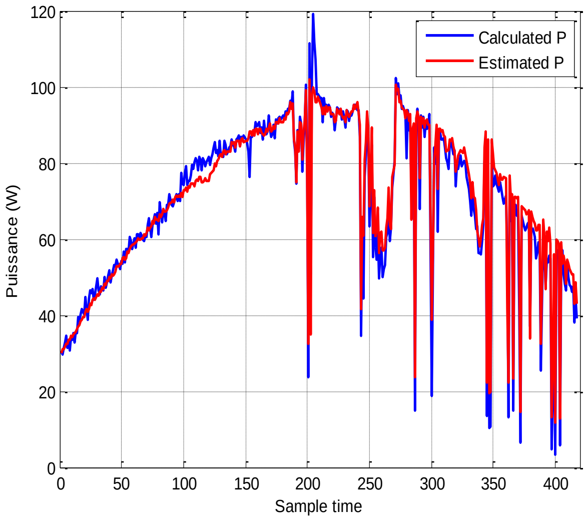

Fig. 14. Comparison between measured and estimated P_{MPP} for a semi-cloudy day.

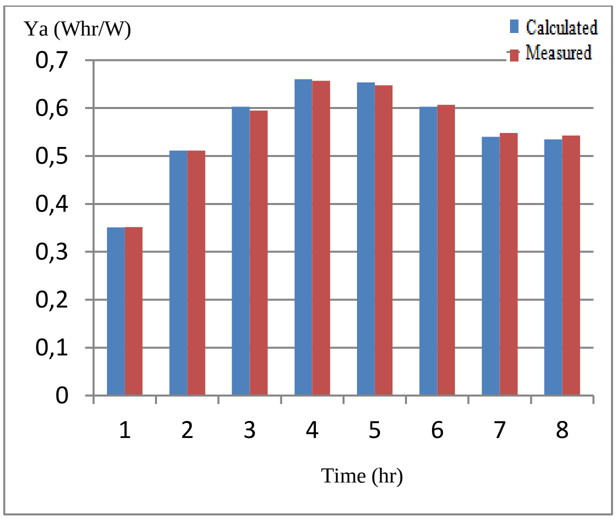

Fig. 15. Hourly array yield for a clear sky day.

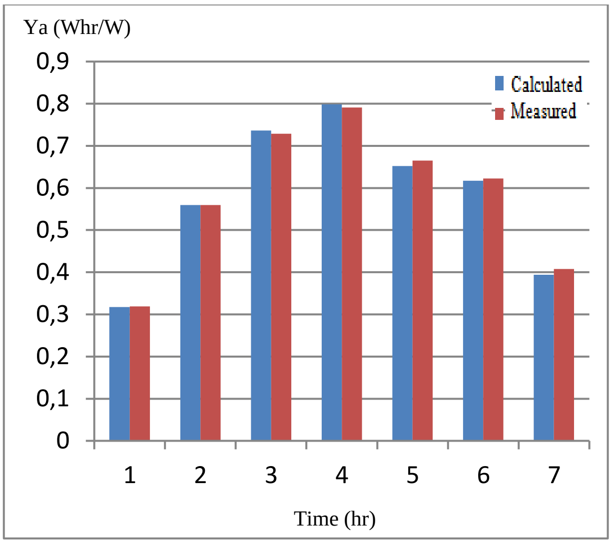

Fig. 16. Hourly array yield for a semi-cloudy day.

VI. CONCLUSION

This paper proposes the application of the Nelder Mead algorithm to extract the electrical parameters of a PV module: I_{ph}, I_0, R_s, R_{sh} and n. The proposed algorithm has been applied to ISOFOTON 106/12 module. The extracted parameters have been integrated in the characteristic equations and then tested against IV curves measurements. The obtained results show clearly the effectiveness of the proposed N-M algorithm to extract PV module parameters. Furthermore a comparison study with other heuristic algorithms such as DE, PSO and ABC has shown the good results of N-M algorithm.

Additional analysis using an experimental test based on the comparison of the adapted model to the MPP evolution against MPP with real weather profiles of typical Algerian sky for two conditions: a clear sky condition and cloudy sky condition. The relative error associated with the simulation results obtained shows that the simulation results are in good agreement with the experimental data at real working condition and justify its use for deeper investigation such as energy prediction of photovoltaic modules.

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