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Module parameter extraction and simulation with LTSpice software model in sub-Saharan outdoor conditions

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In this work, a hybrid algorithm of Levenberg-Marquardt and empiric analytic method is proposed to solve the recurring convergence problem that occurs during the module parameters extraction with the iterative method. The proposed method aims to avoid divergence and a long computation time due to the improper initial value. Elsewhere, LTSpice photovoltaic cell model is developed to simulate the extracted parameters in sub-Saharan outdoor conditions. The LTSpice model with it virtual component is expected to facilitate the understanding photovoltaic module behavior under these conditions. Measurements performed with VSP50P-12V polycrystalline module and compared to simulation results show the accuracy of the hybrid method and the ease of LTSpice model. The hybrid algorithm with RMSE value of 0.9% while correlation one is greater than 97% for simulated irradiation is more accurate than the Levenberg-Marquardt algorithm.

Key words: Cell model, LTSpice model, Levenberg-Marquardt algorithm, empiric analytic.

INTRODUCTION

The electric performance of photovoltaic module is described by mathematic equations that model current-voltage (I-V) curves. Seven mathematical models divided into three groups are usually used (Table 1). The widely used model is the single diode model. These equations are non-linear and need the appropriate methods to extract their parameters. In the literature, several authors have presented reviews of the methods used to extract module parameters (Rabeh Abbassi et al, 2018) (Ashwini Kumari, 2018;Tamrakar and Gupta, 2015). Table 2 shows a non-exhaustive list of various methods used in literature to determine model parameters. Even if these different methods are powerful, most of them, mainly iterative methods as Levenberg-Marquardt (LM) algorithm require

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Table 1. Photovoltaic cell equivalent model classification.

Group	Model	Parameters
One diode model	3 Parameters model	I_{ph}, I_0, n
	4 Parameters model	I_{ph}, I_0, n, R_s
	5 Parameters model	I_{ph}, I_0, n, R_s, R_{sh}
Two diode model	6 Parameters model	I_{ph}, I_{01}, n_1, I_{02}, n_2, R_s
	7 Parameters model	I_{ph}, I_{01}, n_1, I_{02}, n_2, R_s, R_{sh}
Model with recombination in intrinsic layer	One diode model with recombination	I_{ph}, I_0, n, R_s, R_{sh}, $\mu\tau$
	Two diode model with recombination	I_{ph}, I_{01}, n_1, I_{02}, n_2, R_s, R_{sh}, $\mu\tau$

initial values. Generally, the user gives these initial values intuitively. Then, if the values entered are far from the real initial values, the algorithm's calculation time will be long or at worst there will occurred a convergence problem. It would be desirable to have a method to obtain these initial values, because the algorithm accuracy, it convergence and the calculation time can be affected by the inappropriate initial values.

In this paper, we propose to calculate the initial values from the electrical specifications of the module given by the manufacturer using the empiric analytic method developed by Ali Senturk et al. (). Then, this method is incorporated in extraction algorithm of LM to form a hybrid algorithm. The present approach should contribute to improving the accuracy of the LM algorithm as well as saving valuable calculation time. Furthermore, the LTSpice solar cell model is proposed to evaluate the extracted parameters in sub-Saharan outdoor condition. The LTSpice software is a high performance professional variant of Simulation Program with Integrated Circuit Emphasis (Spice) running on graphical interface base. It is an open source software that can contribute to evaluate the influence of the photovoltaic module model parameters and the climatic factors variation on the module performance.

MATERIALS AND METHODS

The equivalent mathematical model of one diode (five parameters) for the solar cell is given by Equation 1:

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

where I_{ph}, I_0, n, R_s and R_{sh} are a photo-generated current, dark saturation current, ideality factor, series resistance, and shunt resistance, respectively. These parameters are to be determined. The initial values required by LM algorithm to perform calculation are calculated with the empiric analytic method exposed after LM algorithm presentation. The LM algorithm combines the methods of the gradient descend and the Gauss-Newton's. This led the algorithm to be robust and fast. A vector $(V_i, I_i)_{i=1:m}$ (m is the number of points measured for the current-voltage curve) is considered. For each measured voltage value V_i, a theoretical current $I_{th}(p)$ is calculated from the equivalent model with a function L_p (V) of 5 parameters p (I_{ph}, I_0, n, R_s and R_{sh}). A residue vector is obtained from the theoretical current and the measured current as shown in the Equation 2. The values of the parameters p which minimize the norm f(p) (Equation 3) of the residue r(p) are the parameters which model the module. For each iteration *i*, the norm of the vector residue r(p) is calculated. The parameter λ (Figure 1) varies in the same direction as the error to adjust the influence of the hessian (H) on the convergence of the solution. This adjustment may result in an increase or decrease in the parameter λ. Knowing the vector pi of the parameters at iteration *i*, the parameters at iteration P_{i+1} are obtained using Equation 6. The optimal parameters are obtained after several iterations.

The method process is assumed as shown in Figure 1, where $r(p)$, $f(p)$, $\nabla f(p)$, H and P_{i+1} are given by Equations 2 to 6.

$$r(p) = \begin{pmatrix} I_{th1}(p) - I_1 \\ I_{th2}(p) - I_2 \\ \vdots \\ I_{thm}(p) - I_m \end{pmatrix} \quad (2)$$

$$f(p) = \frac{1}{2}\sum_{j=1}^{m}\left[r_j(p)\right]^2 \quad (3)$$

$$\nabla f(p) = J^T \times r(p) \quad (4)$$

$$H = J^T \times J(p) \quad (5)$$

$$p_{i+1} = p_i - [H_i + \lambda diag(H_i)]^{-1} \times \nabla f(p_i) \quad (6)$$

The initial parameters $p_{initial}(I_{phin}, I_{oin}, n_{in}, R_{sin}, R_{shin})$ are calculated based on an empiric analytical method proposed by Senturk et al. (2017). This method performed in six calculation steps uses the electric data at reference conditions from module datasheet given by the manufacturer. Even if Senturk's method saves calculation time, it allows lot of assumption. The number of equations is reduced by taking the diode ideality factor as a constant value. Consequently, the method accuracy can be affected because the ideality factor characterizes the recombination mechanism that takes place in the solar cells. Elsewhere, Singh et al. (2013) reported an increasing maximum output power with the diode ideality factor. Assuming this factor as a constant value, may affect the maximum output power also. Then, we prososed to use the parameters calculated by Senturk's method as the initial

Table 2. The non-exhaustive list of various extraction methods.

Extraction method	Reference
Analytical Parameter Extraction Methods	
Lambert W-function	Gao (2016), Batzelis and Papathanassiou (2016), Peng (2014), Chunfu (2011)
Numerical/Analytical approach	Bonkoungou (2015), Mares et al. (2015), Laudani (2014)
I-V curve fitting using multiple nonlinear regression analysis	Ayala-Mató (2017), Ryan (2018),
Reduced form of equation	Antonino (2014)
Partern search algorithm	Park and Choi (2015), AlRashidi et al.(2012)
Fast Least-Squares Approximation	Ma et al. (2014)
Piecewise Linear Approximation	Ahmad (2017), Al-Hamadi (2014)
Adaptive differential evolution algorithm	Jiang et al. (2013)
Iterative Parameter Extraction Methods	
Trust-region doleg	Mohapatra (2013)
Explored geometric estimation based slope method	Jesús (2018)
The Taylor's series expansion	Lun et al. (2013)
Derivate a Nonlinear I-V curve fitting base on manufacturer datasheet	Villalva et al. (2009)
Newton – Raphson + Lambert W-function	Emad (2018), Hejri et al. (2014), Faisal (2012)
Levenberg–Marquardt Algorithm	Alain (2014)
Evolutionary Parameter Extraction Methods	
Genetic algorithm GA	Zagrouba (2010)
Particle Swarm Optimization (PSO)	Babu et al. (2018)
Simulated annealing	AlRashidi (2013)
Artificial bee colony (ABC)	Chen (2016), Chopde (2014)
Mimetric algorithm Cuckoo Search	Ma et al. (2013)
Bacterial Forging Optimization	Bidyadhar (2018)
Hybrid Generic algorithm + Nelder - Mead	Maherchandani et al.(2012)
Hybrid Generic algorithm + Particle Swarm Optimization	Panneerselvam (2013)
Chaotic Particle Swarm Optimization algorithm (CPSO)	Huang (2011)
Cuckoo Search + Nelder Mead	Raka (2014)
Artificial Fish Swarm	Han et al. (2014)
Chaotic asexual reproduction Optimization (CACO)	Yuan et al. (2014)
Harmony Search	Rezazadeh (2012)
Fuzzy control	Bendib et al. (2013)
Neuronal network	Karamirad et al.(2013)
Shuffled frog leaping algorithm (SFLA)	Hasanien (2015)
Wind-driven optimisation (WDO) algorithm	Derick (2017)

Table 2. Contd.

Firefly algorithm	Louzazni (2016)
Imperialistic competitive algorithm (ICA)	Ahmed (2017)
A hybrid of flower pollination algorithm and Nelder-Mead algorithm	Shuhui (2017)
Whale optimization algorithm	Diego (2017), Omnia and Elazab (2017)
Mine blast algorithm	Fergany (2015)

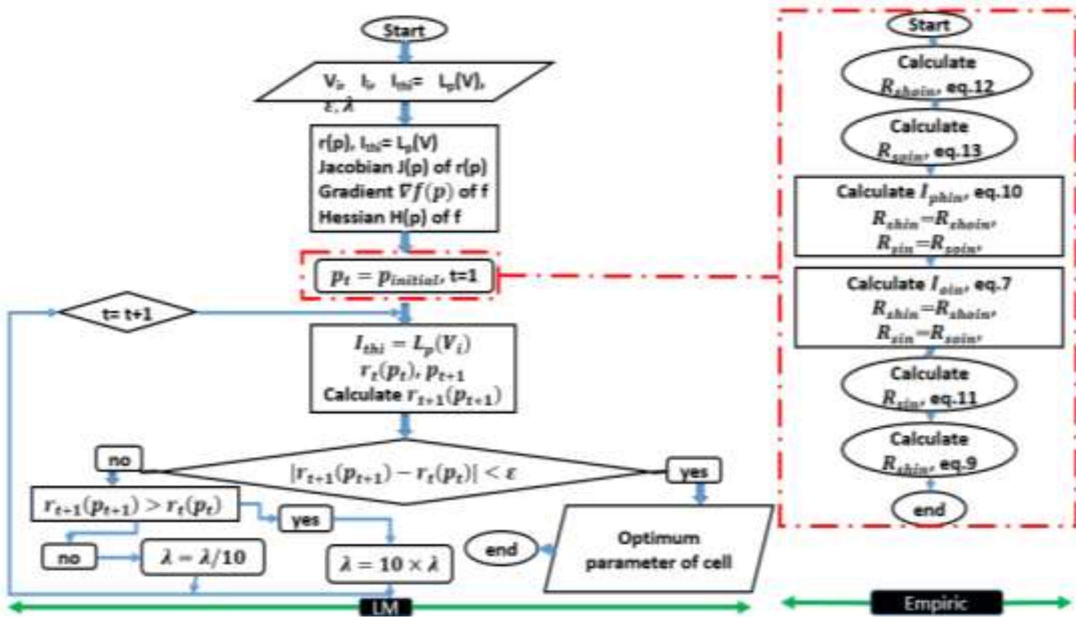

Figure 1. Diagram of the parameter extraction process.

parameters for LM algorithm.

The following equations are used to perform calculation empiric analytic method at the open-circuit from Equation 1 in the reference condition, that is, I=0, V=V_{ocref}, I_{oin} is deducted,

$$I_{oin} = \frac{I_{phin} - \frac{V_{ocref}}{R_{shin}}}{exp\left(\frac{qV_{ocref}}{nkT_{ref}}\right) - 1} \quad (7)$$

at the short-circuit point in reference condition, that is, I=I_{scref}, V=0, I_{phin} is calculated,

$$I_{phin} = \frac{R_{sin} + R_{shin}}{R_{shin}} I_{scref} + I_{oin}\left[exp\left(\frac{qR_{sin}I_{scref}}{nkT_{ref}}\right) - 1\right] \quad (8)$$

at the maximum-power point in reference, that is, V=V_{mref}, I=I_{mre}f;

$$R_{shin} = \frac{\left(V_{mref} + I_{mref}R_{sref}\right)}{I_{phin} - I_{mref} - I_{oin}\left(exp\left(\frac{q\left(V_{mref} + I_{mref}R_{sin}\right)}{nkT_{ref}}\right) - 1\right)} \quad (9)$$

Base on assumption well describe in Villalva et al., (2009), de Soto et al., (2006), and Dezso (2007), Equations 10 and 11 are expressed as follow:

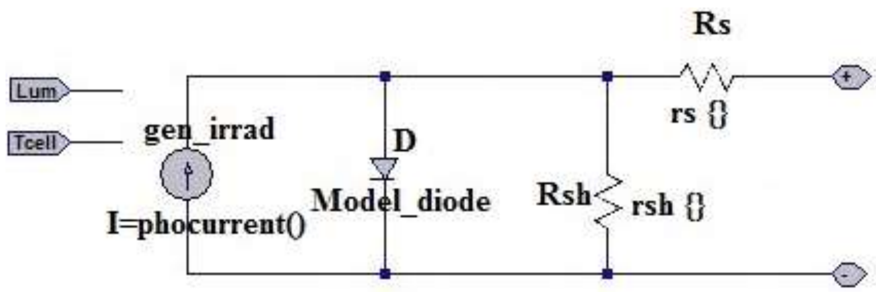

Figure 2. LTSpice equivalent circuit of photovoltaic model.

Figure 3. Illustrative diagrams of the inputs and outputs of the LTSpice model.

$$I_{phin} = \frac{R_{sin} + R_{shin}}{R_{shin}} I_{scref} \tag{10}$$

$$R_{sin} = R_{soin} - \frac{1}{\frac{q}{nkT_{ref}} I_{oin} exp\left(\frac{qV_{ocref}}{nkT_{ref}}\right)} \tag{11}$$

where k is the Boltzmann constant, q is the charge of electron, R_{sin} is the initial series resistance, R_{shin} is the initial shunt resistance, R_{soin} is the reciprocal slope of the initial I-V curve at open-circuit condition, I_{phin} is the initial photo-generated current, I_{oin} is the initial dark saturation current, V_{ocref} is the reference open circuit voltage, V_{mref} is the reference maximum output voltage, I_{mref} is the reference maximum output current, I_{scref} is the reference short circuit current and T_{ref} (25°C).

R_{soin} and R_{shoin} are evaluated as follows:

$$R_{shoin} = \frac{V_{mref}}{I_{scref} - I_{mref}} \tag{12}$$

$$R_{soin} = \frac{V_{ocref} - V_{mref}}{2I_{mref}} \tag{13}$$

The LTSpice photovoltaic cell model shown in Figure 2 is used to evaluate the extracted parameters (I_{phref}, I_{oreel}, n, R_{sref} and R_{shref}) in the sub-Saharan outdoor conditions. The model takes as input, the parameters of the cell in the reference conditions (extracted with hybrid method) and the climatic data (temperature of the module, the irradiation) as shown in Figure 3. The solar cell parameters vary according to climatic variables (irradiation, temperature, wind speed). The influence of the wind speed is implicitly integrated in the model through the relation established by (Kratochvil et al., 2004) between this one and the temperature of the module:

$$T_{cell} = Lum \times exp(a + b \times WS) + T_a \tag{14}$$

Equations 15 to 18 allow to translate module performance in the real operating conditions using LTSpice model presented earlier.

The photocurrent I_{ph} :

$$I_{phréel} = I_{phref} \times \left(1 + coef\_I_{sc} \times \left(T_{cell} - T_{ref}\right)\right) \frac{Lum}{Lum_{ref}} \tag{15}$$

The saturation curent I_0:

$$I_{0reel} = I_{0ref} \times \left(\frac{T_{cell}}{T_{ref}}\right)^3 \times exp\left(\frac{1}{k}\left(\frac{Eg_{ref}}{T_{cell}} - \frac{E_g}{T_{cell}}\right)\right) \tag{16}$$

where $\frac{E_g}{E_{gref}} = 1 - constante\left(T_{cell} - T_{ref}\right)$

The series resistance R_s:

$$R_{Sreel} = R_{sref} \times \frac{T_{cell}}{T_{ref}}\left(1 - 0{,}217 \times ln\left(\frac{Lum}{Lum_{ref}}\right)\right) \tag{17}$$

The shunt resistance R_{sh}:

$$R_{shréel} = \frac{Lum}{Lum_{ref}} R_{shref} \tag{18}$$

RESULTS AND DISCUSSION

Sofiane Kichou et al. (2016), compared the accuracy of five methods of extracting parameters. These methods are: Levenberg-Marquardt (LM), Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Differential Evolution (DE) and Artificial Bee Colony (ABC). Two models (the five-parameter model (5PM) and the Sandia Array Performance Model (SAPM)) were used to model three PV modules of different technologies: crystalline silicon (c-Si), amorphous silicon (a-Si:H) and micromorph silicon

Table 3. Solar module electrical specifications.

Module specification	PV modules	
	pc-Si (VSP50P-12V)	pc-Si (SQ175)
Short current Isc (A)	3.09	5.43
open circuit voltage Voc (V)	22.2	44.6
maximum power current Imp (A)	2.85	4.95
maximum power voltage Vmp (V)	18	35.4
Maximum power Pmp (W)	50	175
Isc temperature coefficient (%/°C)	0.037	0.026
Voc temperature coefficient (%/°C)	-0.34	-0.29
Pmp temperature coefficient (%/°C)	-0.48	-0.43
Area (m^2)	0.6318	1.22
Number of cells	36	72
Efficiency (%)	12.23	13.3

Table 4. Comparison of the extracted parameters between Hybrid algorithm and LM or empiric analytic method.

Study	Iph	Io	n	Rs	Rsh	Number of data points	Number of iteration	RMSE (%)
Proposed method	5.43	1.74E-09	1.1	0.7	224.34	75	9	0.9
Senturk	5.5	9.70E-09	1.2	0.47	118.47	-	1	1.7
Tossa et al	5.45	1.20E-09	1.09	0.7	196.2	-	237	<2

(a-Si:H/mc-Si:H). The study was conducted under different conditions ranging from clear to cloudy skies. At the end of the study, they concluded that the least fair method is the LM method. It was reported that the RMSE obtained in the comparison of the daily evolution of main electrical parameters of the PV systems is below 8% in all cases except the case of using LM. The extraction of PV cell parameters requires to initialize the parameters values. An improper initial values can affect the accuracy of the algorithm as reported by Sofiane kichou et al. (2016).

In order to evaluate the contribution of the present method, the results of the study are compared with the results of the methods developed by Senturk et al. (2017)empirical method and Alain and Tossa et al. (2014) LM for the polycrystalline module SQ175. Tables 3 and 4 show the used modules datasheet and the extracted parameters of module SQ175, respectively. The proposed method presents the best value of RSME (0.9%). Considering the number of iteration points, the present hybrid method improves the calculation time of the LM algorithm.

Furthermore, the solar cell parameter obtained with hybrid LM and empiric method is used in an LTSpice solar cell model. A single junction polycrystalline silicon module (VSP50P-12V in Table 3) is proposed to compare the measurement results with those obtained by simulating the extracted parameters. The I-V characteristic measurements were performed in Laboratory of Solar Energy and Energy Saving (LESEE) of international institute of water and environment engineering (2iE) of Burkina Faso using outdoor monitoring test facility named ‘’IV bench’’. The module temperature and sun irradiation were measured at the same time as module I-V characteristic. Three multimeters are used to measure simultaneously module voltage and module current whereas a pyranometer was used to measure the sun irradiation. The module temperature was measured by a PT100 temperature sensor stuck on solar cell with thin aluminium tape at the back of the module. The two measurements of I-V data were separated by a 5 min interval and the time required to complete I-V curve was less than 2 s. Then, the solar irradiation can be considered constant for each I-V measurement. The range of -0.5V to 105% of Voc voltage were applied to module. All I-V data stemming from measurements are stored in CSV Excel format on PC.

The maximum power output of the module was calculated from measurements and LTSpice simulation. The results are as shown in Figure 4a and 4b, respectively for the current-voltage (V-I) and the voltage-maximum power output (V-P) characteristic. The correlation coefficient between the measured and simulated maximum power values was also calculated for different climatic conditions. This coefficient remains higher than 97% under each of these conditions.

The module daily output power is examined with the

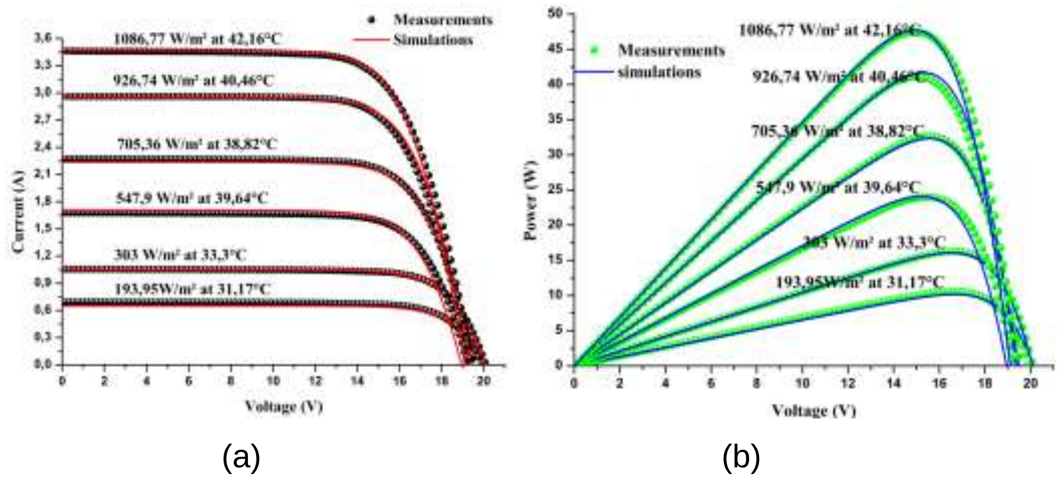

Figure 4. The measured and simulated I-V (a) and P-V (b) curves for different operating conditions.

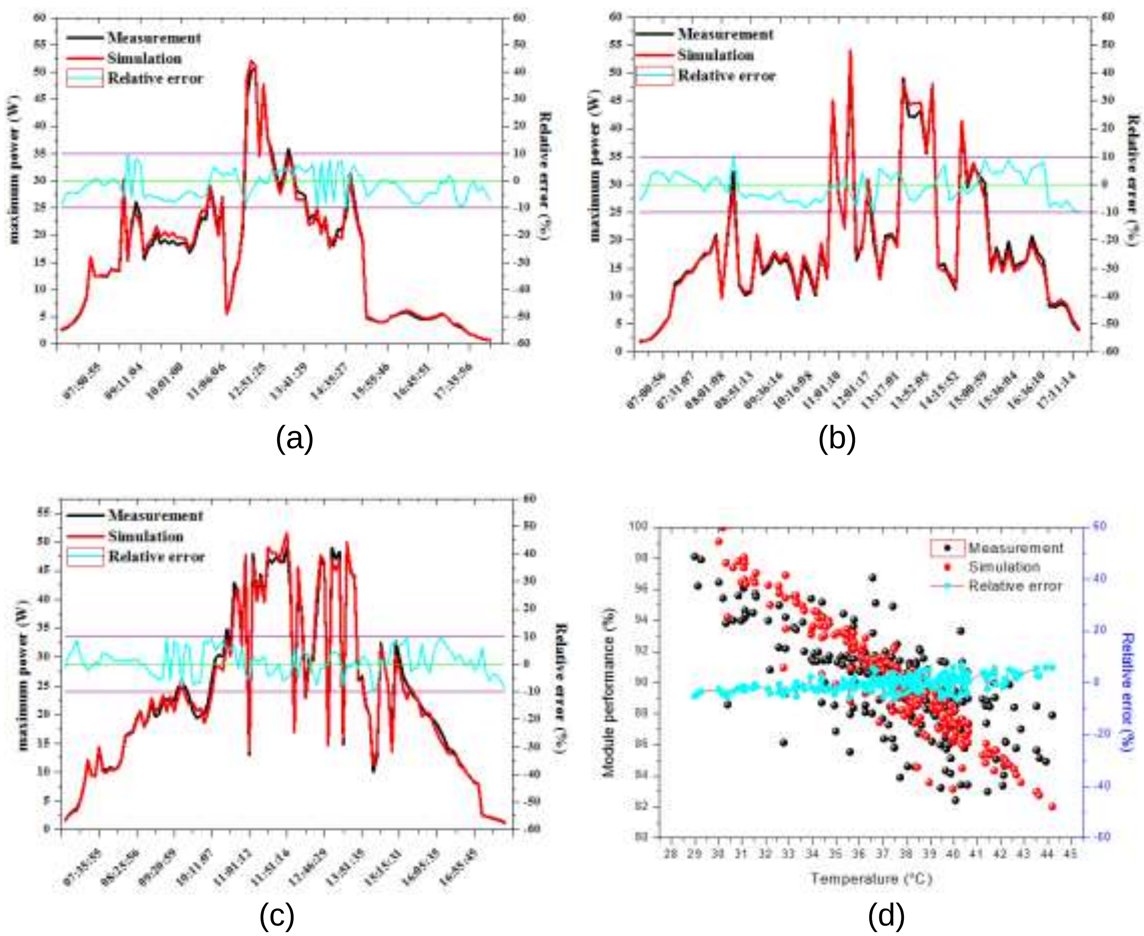

Figure 5. The measured and simulated output peak power values for 05th October 2014 (a), 15th October 2014 (b) and 21st October 2014 (c). (d) is measured and simulated performance ratio for 05th October 2014.

proposed method and compared to the measurement. Figure 5a, 5b and 5c shows the daily result for 05th October 2014, 15th October 2014 and 21st October 2014, respectively. A relative error of less than 10% is obtained for each simulation. The module performance ratio is as shown in Figure 5d. It shows a good performance of the hybrid and LTSpice model to evaluate the module performance.

Conclusion

A hybrid Levenberg-Marquardt and empiric analytic algorithm is proposed to extract module parameters. The proposed method aims to avoid divergence and a long computation time due to the improper initial value. The hybrid algorithm is shown to be more accurate than Levenberg-Marquardt and empiric algorithm taken separately. Elsewhere, LTSpice photovoltaic cell model is developed to simulate the extracted parameters in outdoor conditions. The LTSpice model with virtual components gives advantage of conceptualizing and anticipating the characterization of solar module in outdoor conditions. Measurements performed with VSP50P-12V polycrystalline module are compared to simulation results. The RMSE value of 0.9% and correlation one greater than 97% for simulated irradiation indicate computation efficiency and accuracy of the proposed algorithm. An improvement in the accuracy of the LM algorithm, will contribute to the accuracy of system performance estimated under real operating conditions.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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