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Comparative Study of the Performance of Three Modeling Approaches for a Photovoltaic Panel Emulator based on the Single-diode Model and Using a Buck-boost DC/DC Converter

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Abstract--- *The photovoltaic emulator provides an efficient solution to maintain the same current-voltage output of photovoltaic module. It includes three major parts: the Photovoltaic model, a controlling strategy, and converter for power stage. The precise determination of the current-voltage characteristic curve is an challenge for the researchers until today. This paper provides three approaches for the modelling of photovoltaic arrays and presents the synthesis results by the simulation of the current-voltage characteristic performances obtained by the modeling approaches. Then an evaluation of the photovoltaic emulator's behavior under different conditions. An identification method is developed using Newton Raphson's, and linear interpolation methods. The mathematical model is built using MATLAB/SIMULINK and a sized buck-boost converter for the power stage. Following this comparative study, we came to a high agreement between the experimental and simulated current-voltage characteristics for the emulator under study.*

Keywords--- *Buck-Boost Converter, Photovoltaic system, Mathematical Modelling, Matlab.*

I. INTRODUCTION

The theoretical modelling of solar cells is crucial for the optimization of the efficiency and the diagnostics of the photovoltaic (PV) generator. It has been today amply demonstrated [1], [2]. The PV module is normally defined by an equivalent circuit [3][4] with parameters experimentally calculated by using the current-voltage characteristic. However, the obtained results requires a validation through experiments where the setup is complex and the temperature of manipulation is not flexible [5].

Therefore, a PV emulator, which is an electronic system able to reproduce the characteristics of current-voltage output of a PV module, provides a useful test facility solution for PV applications; designing and testing PV power systems, PV generation analysis, development of control systems, and power electronic interfaces, among others, with less weight, less bulky, independence of weather conditions and flexibility, etc.. The device can be built with low-cost components in a compact arrangement with the portability and ease of use [6].

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In order to carry out an operational evaluation of the characteristics of the performance of a PV cell system, a specific mathematical model is a main tool for researchers. Solar cell modeling primarily involves the formulation of the non-linear current vs. voltage (I–V) curve. Several models have been developed to represent the behavior of the system under different operating conditions. They vary from models with simple assumptions to advanced models with many physical variables[7], [4].

In practice, there are two major equivalent circuit models to describe the behavior of a solar cell system: the single and double diode models [8], [9]. The solar cell models comprise a group of parameters, namely, photo-generated current based on the single-diode model is presented. This PV emulator system is employed using the MATLAB/SIMULINK application.

In this context, the work we have carried out has allowed us to present a comparative study of three different approaches and to be able to choose the most appropriate for our PV emulator.

The rest of this paper is arranged as follows: Section 2 provides a description of the system that we proposed, the two line approach, the five line approach and the Newthon-Raphson method are explained; Simulation results and discussions are given in Section 3 and finally, conclusion is presented is Section 4.

II. METHODOLOGY

A. System Description

The proposed system is schematically shown in Fig.1. This solution consists in achieving a programmable power supply based on a buck boost converter DC/DC piloted by a control unit.

A Solar PV model is built in MATLAB/SIMULINK with datasheet values taken from Solarex MSX-64 Solar PV panel[10]. Further, this model serves as a reference to obtain any operating point on the Solar PV characteristic, irradiation, temperature corresponding to the expected I-V characteristics of Solar PV

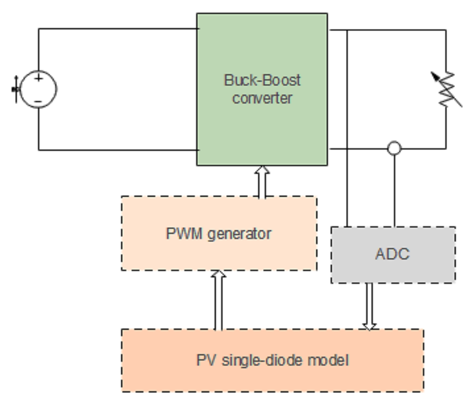

Figure 1: Overview of the Proposed System

B. Mathematical model of PV panels

As the smallest elements of a PV module, the PV cells directly convert solar irradiation to electricity due to the photovoltaic effect [11]. In fact, a solar cell can be represented in different variations. The most common is the so-called "single diode" [12], because of its simplicity and easy implementation shown in Figure 2

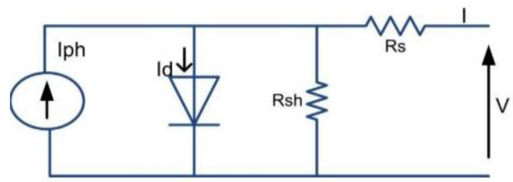

Figure 2: Electrical equivalent circuit of a solar cell

According to Fig. 1, the output current of the model is described as follows:

$$I - I_0\left[exp\left(\frac{V + R_s I_{ph}}{AV_t}\right) - 1\right] - \frac{V_{pv} + R_s I_{ph}}{R_p} - I_{ph} = 0 \qquad (1)$$

$$V = a\frac{NsKT}{q}ln\left(\frac{I_{sc} + I_0 - I}{I_0}\right) - R_s I_{ph} \qquad (2)$$

$$I_{sc} = I_{sc,n} \times \left(\frac{G}{G_n}\right) + \left(K_i \times \left(T - T_n\right)\right) \qquad (3)$$

$$I_0 = I_{sc} \times exp\left(\frac{-V_{oc}}{a \times N_s \times V_t}\right) \qquad (4)$$

$$V_{oc} = V_{oc,n} + N_s \times V_t \times log\left(\frac{G}{G_n}\right) + K_v \times \left(T - T_n\right) \qquad (5)$$

The mathematical model presented is an explicit type because of its universality by developing compatibility with different types of PV panel, thus adaptable to changing weather conditions (G and T).

C. DC-DC Buck-boost Converter

The authors, in their previous work, have used DC-DC Buck converter to control emulators due to the preference of step down operation[7].

A DC-DC Buck-Boost converter can minimize the input voltage.[13] We can use a 12V voltage source to emulate a panel with an open circuit voltage that goes to 30V, and less costly compared to most of the other converters.

The output of DC-DC Buck-Boost converter is inverted which introduces complexity in the sensing and feedback circuit. Therefore, the designed converter is represented in figure 3 and the configuration of sensors must possess the ability to replicate the characteristics of Solar PV panel selected. The values of L and C are designed with the help of the following equations:

$$\frac{Vo}{Vs} = D\sqrt{\frac{Lc}{L(1-D)^2}} \qquad (6)$$

$$L_{cmin} = \frac{R_{Lmax}(1-D_{min})^2}{2fs} \qquad (7)$$

$$C_{min} = \frac{Dmax}{f_s.R_{Lmin}}\frac{V_{omax}}{\Delta Vo} \qquad (8)$$

Further, equation (6) helps to know the range of duty cycle and also safety factor are taken into consideration in the design process. The DC-DC Buck-Boost converter is operated at switching frequency of 40 kHz with Vin =12V, voltage and current ripple are set to 1% and <1.5% respectively. The computed values of L and C are 1.49mH and 1,23mF respectively.

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To limit the current and the voltage ripple at the load, a low-pass LC filter has been added [14].

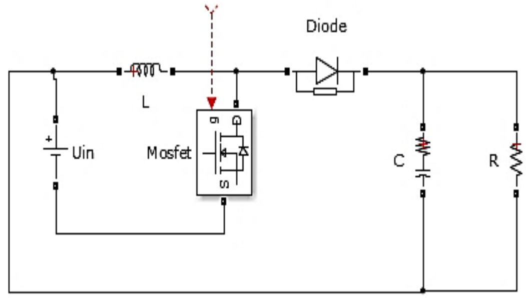

Figure 3: Buck-boost converter equivalent circuit

D. Performance Of The Solar Emulator And Modeling Approaches

D.1 Five Line Approach

To model our PV panel, we, first propose a system of polynomial equations allowing the calculation of six points of the I-V characteristic (Fig. 4). These six points will then serve to calculate, by linear interpolation, the other points of the characteristic I-V.

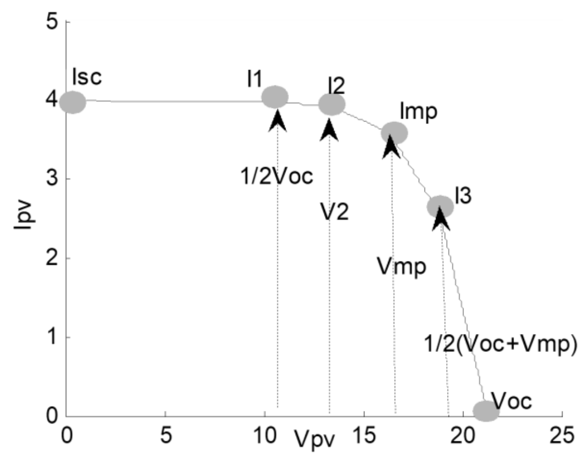

Figure 4: Equivalent Circuit of a Solar Cell with Rs and Rp

We need to select N + 1 points from the curve to generate N number of fitting lines. To begin with, the two end points from the curve are the open-circuit voltage (Voc, 0 A) and short-circuit current (0 V, Isc). The third point (Vmp, Imp), is selected as the maximum power point (MPP) of the curve. To improve the accuracy of the adjustment curve method, we have selected three other points: ((Voc + Vmp)/2,I3), (V2, I2), (Voc/2, I1).

Consequently, we will get six points and five lines.

$$\begin{cases} V_{oc} = c_0 + c_1\ x_2 + c_2\ x_3 \\ V_{mp} = c_0 + c_1\ x_3 + c_2\ x_2 + c_3\ x_1\ x_3 \\ I_{sc} = c_1\ x_1 + c_2\ x_2 \\ I_1 = c_1\ x_1 + c_2\ x_2 + c_3\ x_1\ x_2 \\ I_2 = c_0 + c_1\ x_1 + c_2\ x_2 + c_3\ x_1\ x_2 \\ I_{mp} = c_0 + c_1\ x_1 + c_2\ x_2 + c_3\ x_1\ x_2 \\ I_3 = c_1\ x_1 + c_2\ x_1^2 + c_3\ x_1\ x_2 + c_4\ x_1^2\ x_2 \end{cases} \quad (9)$$

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In these equations x_1, x_2 and x_3 present the functions of temperature T and radiation G, according to the following equations:

$$x_1 = G/G_n$$
$$x_2 = T - Tn$$
$$x_3 = log_{10}(G/Gn)$$

Where G_n= 1000 W/m^2 and T_n = T = 25 °C
c_0, c_1, c_2, c_3 and c_4 are the interpolation coefficients ensuring a good smoothing.

D.2 Two Line Approach

In this approach, we propose a system of polynomial equations allowing the calculation of three points of the characteristic I-V (Fig. 5). These three points will then serve to calculate, by linear interpolation, the other points of the characteristic I-V. The two end points from the curve are the open-circuit voltage (Voc, 0 A) and short-circuit current (0 V, Isc). The third point (Vmp, Imp), is selected as the maximum power point (MPP) of the curve.

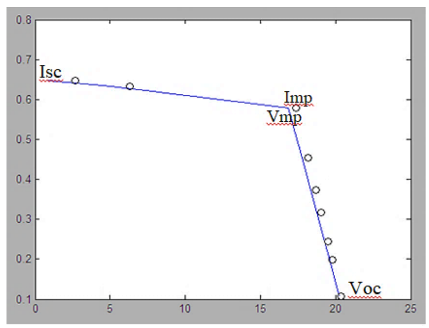

Figure 5: Model of the two line approach

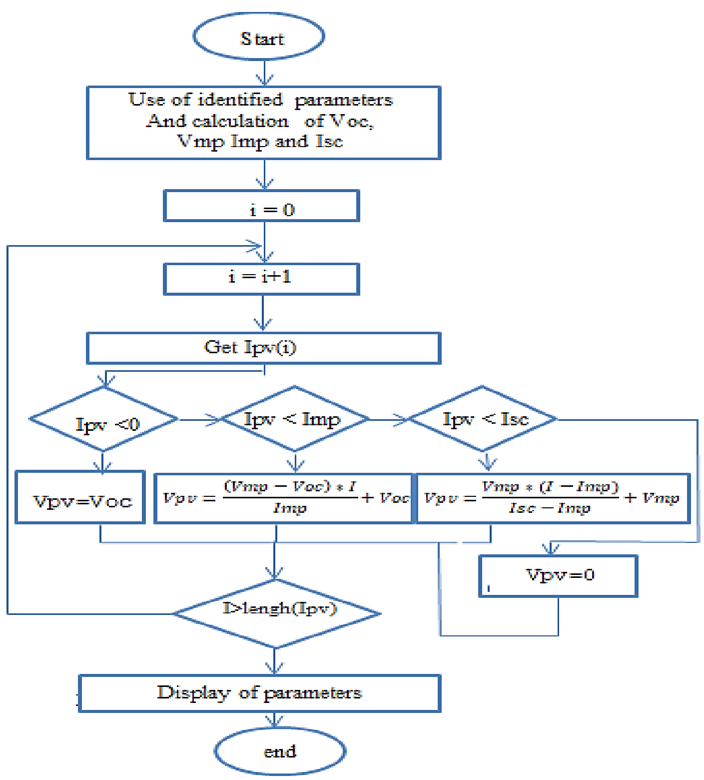

Figure 6: Two lines approach flowchart

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D.3 Newton Raphson Method

The Newton-Raphson method, or Newton Method, is a powerful technique for solving equations numerically. Like so much of the differential calculus, it is based on the simple idea of linear approximation. The Newton Method requires knowledge of the panel parameters [15], [16], [17].

The algorithm corresponding to this method, presented by the flowchart in Figure 7, is based on the Taylor development, stipulated for each iteration, the equation (1) is linearized at a current point, and the point next is taken equal to the zero of the linearized function. Thus, the current I of equation (1) can be calculated iteratively according to the relation (9).

The stop criterion of the iterations is expressed by the relation (10) giving ε = f (I, V) which represents the value of the equation (1) for the current I_{k+1} which is expressed by:

$$I_{k+1} = \frac{I_{ph} - I_0\left[\exp\left(\frac{V+R_S I_k}{AV_t}\right)-1\right] - \frac{V+R_S I_k}{R_p} - I_k}{-I_0 \frac{R_S}{AV_t}\exp\left(\frac{V+R_S I_k}{AV_t}\right) - \frac{R_S}{R_p} - 1} \quad (9)$$

$$\varepsilon = I_{ph} - I_0\left[\exp\left(\frac{V+R_S I_{k+1}}{AV_t}\right) - 1\right] - \frac{V+R_S I_{k+1}}{R_p} - I_{k+1} \quad (10)$$

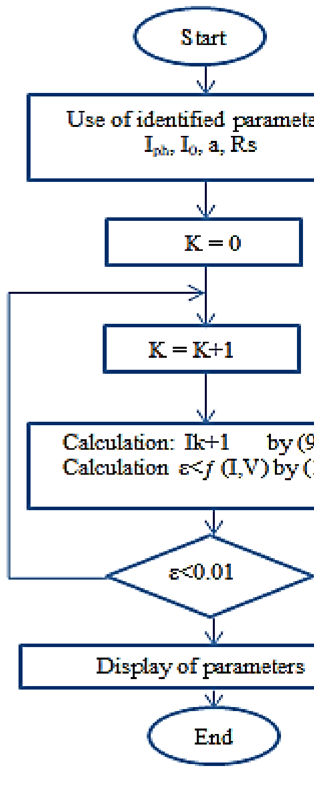

Figure 7: Newton Raphson method flowchart

E. Models Of Solar Emulator In Matlab / Simulink

E.1 Five Lines Approach

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The schematic diagram of the PV emulator based on five line approaches is established in the following figure:

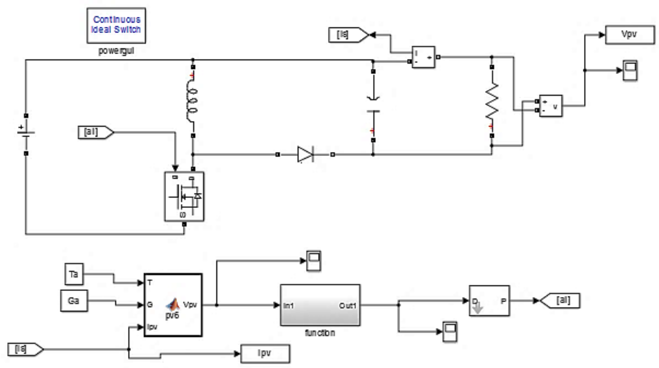

Figure 8: The developed PV emulator based on five lines approach model in Matlab / Simulink

It consists of four blocks: the PV block, the function block, the PWM control and the Buck-boost converter block. PV block represents the mathematical model of the photovoltaic panel studied, it determines the reference voltage Vref according to the current load Ipv, irradiance (G) and temperature (T). The control unit generates a PWM signal duty ratio α for switching the DC / DC converter. Finally the Buck-boost converter block represents the power stage between the photovoltaic module and the load.

E.2 Two Lines Approach

The schematic diagram of the PV emulator based on the two line approach is established in the following figure:

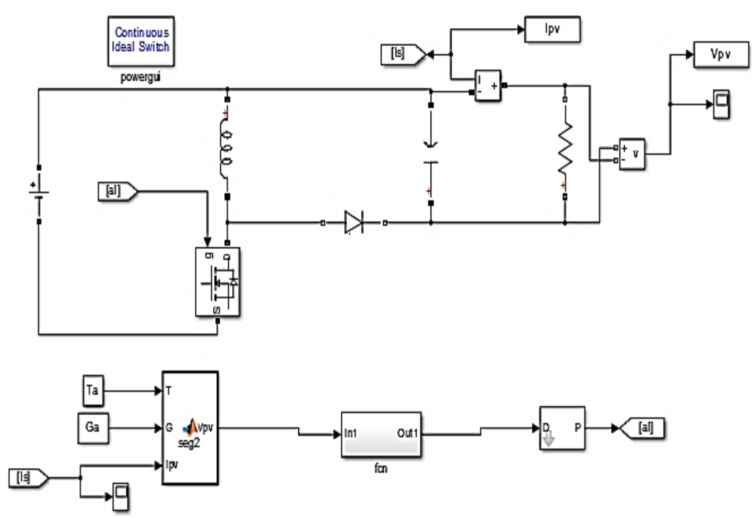

Figure 9: The developed PV emulator based on two lines approach model in Matlab / Simulink

E.3 Newthon-Raphson Method

The schematic diagram of the PV emulator based on the newthon-raphson method is established in the following figure:

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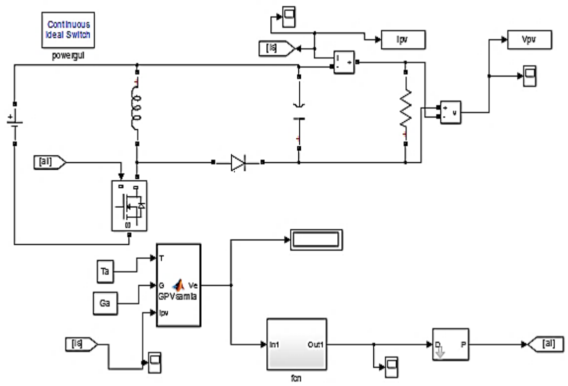

Figure 10: The developed PV emulator based on newthon-raphson method model in Matlab / Simulink

III. Results and Discussion

In this section we expose the various parameters of simulation. Then, we will expose the simulation results and the obtained measurements. The modeling of I-V characteristics is validated through the datasheet of PV module Solarex MSX-64.

I-V characteristics for the PV module Kyocera MSX-64 obtained from datasheet are listed in the following table:

The results are validated through the datasheet of PV panel Solarex MSX-64. Tables 1 summarize the electrical characteristics of the panel under study.

Table 1: Typical Electrical Characteristics of MSX-64: 25 °C, AM 1.5, 1000 W/M2

Parameter	Value
Voltage at point of maximum power (V_{mp})	17.5 V
Current at maximum power (I_{mp})	3.66 A
Cell number (Ns)	36
Nominal open-circuit voltage (V_{ocn})	21.3 V
Nominal short-circuit (I_{SCN})	4.0144 A
Kv temperature coefficient of the voltage circuit open	0.074107
Ki temperature coefficient of the short circuit	0.004832

The algorithms are coded and executed in the Matlab environment to identify the cell parameters using the single diode model. Tables 2,3,4, summarize the results of efficiency, for each model and the efficiency of the model on our emulator.

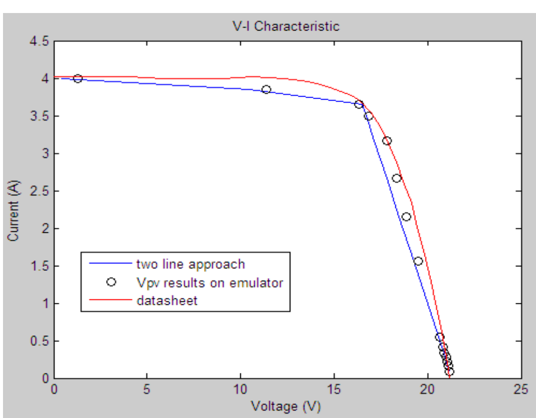

Figure 11: Comparison between experimental and theoretical results on two line approach

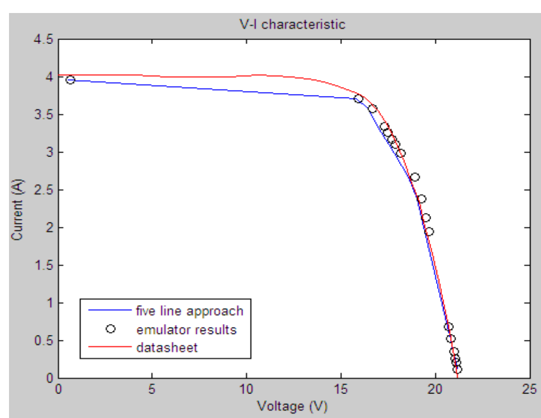

Figure 12: Comparison between experimental and theoretical results on five line approach.

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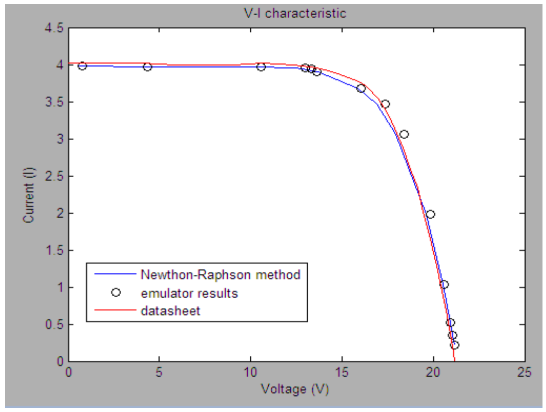

Figure 13: Comparison between experimental and theoretical results on Newthon-Raphson method

In order to confirm the quality of each approach, the statistical analysis based on mean absolute error (MAE) is made. Tables 2,3,4, show the relative error (eq (10)) for each measurement along with the MAPE (eq (11)

The MAPE (Mean Absolute Percent Error) measures the size of the error in percentage terms. It is calculated as the average of the unsigned percentage error [18].

$$e = \frac{I_{measured} - I_{calculed}}{I_{measured}} \quad (10)$$

$$MAPE = \left(\frac{1}{N}\sum_{i=1}^{N}|e_i|\right) \times 100 \quad (11)$$

Table 2: Mean absolute error (MAE) based on the extracted parameters (Newthon-Raphson method).

Measurement	V(t) calculated	V(t) measured	Relative error
1	0,53	0,75	0,415094
2	4,32	4,36	0,009259
3	10,1655	10,59	0,041759
4	12,4328	13,0057	0,04608
5	12,7925	13,358	0,044206
6	13,6997	13,595	0,007643
7	15,8881	16,0301	0,008938
8	16,92	17,3419	0,024935
9	17,9431	18,3834	0,024539
10	19,5896	19,837	0,012629
11	20,5161	20,9573	0,021505
12	20,9218	21,0632	0,006759
13	21,0505	21,1463	0,004551
MAPE			4,77068

Table 3: Mean absolute error (MAE) based on the extracted parameters (five lines approach).

Measurement	V(t) calculated	V(t) measured	Relative error
1	0,5201	0,652	0,253605
2	15,8017	15,9427	0,008923
3	16,4393	16,6853	0,014964
4	16,9524	17,2932	0,020103
5	17,1614	17,5007	0,019771
6	17,3601	17,6981	0,01947
7	17,5496	17,886	0,019169
8	17,8176	18,1515	0,01874
9	18,5982	18,9177	0,017179
10	19,0192	19,2781	0,013613
11	19,2496	19,481	0,012021
12	20,96	20,9791	0,000911
13	21,1938	21,1755	0,000863
MAPE			2,995232

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Table 4: Mean absolute error (MAE) based on the extracted parameters (Two lines approach).

Measurement	V(t) calculated	V(t) measured	Relative error
1	0,4205	1,3211	2,141736
2	10,4776	11,3524	0,083492
3	16,5319	16,3198	0,01283
4	16,7314	16,8737	0,008505
5	17,1631	17,8107	0,037732
6	17,8182	18,3324	0,028858
7	18,484	18,8746	0,021132
8	19,2608	19,5219	0,013556
9	20,5796	20,6583	0,003824
10	20,7555	20,8135	0,002794
11	20,8623	20,9083	0,002205
12	21,0787	21,0991	0,000968
13	21,1821	21,1544	0,001308
MAPE			16,84957

Fig. 11 shows the measured results on the prototype using the two line approach. The results are very close to the two operating lines. Tables 11,12,13 shows error results on the three approaches. The result approved that the five line approach has the most efficiency on the emulator based on buck-boost converter. Due to the memory limitation of the low cost micro-controllers, multiple straight lines for modeling an I–V curve of the PV panel is fast and straight-forward.

To improve the accuracy of modeling further, however, the Newton-Raphson method that requires the exponential expressions can be used and a more powerful micro-controller needed to be used.

IV. Conclusion

This paper presents the modelling, design and simulation of a PV emulator based on a buck-boost DC/DC converter and a multiple approach for emulating Solar PV characteristics. The PV emulator has been tested using resistive loads. A comparative study is performed conclude on the performance of the modelling methods of photovoltaic panels for the emulators based on a buck-boost controller. After modelling, simulating the different approaches, for a PV emulator, under Matlab / Simulink, the five line approach perform better according to the theoretical curve. In the case of the efficiency of the model, the Newthon-Raphson is more efficient and it can be used with powerful micro-controller.

Nomenclatures

A. Acronyms

DC Controllable direct current

AC Alternating current

I Current

V Voltage

PV Photovoltaic

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B. Symbols / Parameters

I_{ph} : Photocurrent.

I_0: Reverse saturation current for an ideal pn-junction diode.

a: Ideality factor of the solar cell.

V_t = NsKT / q: thermal voltage.

Ns: Number of cells connected in series.

K: Boltzmann's constant (1.38 10-23 J / K).

T: Real junction temperature (K).

q: Elementary charge.

R_s: Series resistance (Ω).

R_p: Shunt resistance (Ω).

I_{mpp}: Current at the Maximum Power Point (A)

V_{mpp}: Voltage at the Maximum Power Point (A)

V_{oc}: Open-circuit voltage of the panel (V)

I_{sc}: Short circuit current of the cell (A)

$I_{mpp,n:}$ Nominal current at the Maximum Power Point (A)

$V_{mpp,n}$: Nominal voltage at the Maximum Power Point (V)

$I_{sc,n}$: : Nominal short-circuit current (A)

$V_{oc,n}$: Nominal open-circuit voltage (V)

$V_{t,n}$: Nominal thermal voltage.

G: Real Irradiance level (W/m²).

G_n: STC irradiance levels (W/m²).

T_n: Nominal temperature (K).

K_i: Temperature coefficient of the short-circuit

Kv: Temperature coefficient of the open-cirvuit voltage

$I_{ph,n}$: Nominal photocurrent.

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