International Journal of Enhanced Research in Science Technology & Engineering, ISSN: 2319-7463
Vol. 3 Issue 10, October-2014, pp: (163-171), Impact Factor: 1.252, Available online at: www.erpublications.com

Modelling an Emulator of Photovoltaic Panels

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Abstract: Photovoltaic emulators (PVE) are power electronic systems able to reproduce the output "Current-Voltage" characteristics of photovoltaic panels in various operating conditions. They are indispensable for the design and evaluation of the operational components of a photovoltaic energy system, such as battery chargers and Maximum Power Point Tracking (MPPT). Those emulators prevent the experimental testing process on a site and ensuring considerable savings in time and cost. In this paper we have model and simulate in Matlab environment a type of solar panel emulator. The simulation results show that the output characteristics of the emulator have good agreement with those of a real PV panel under different conditions of temperature, irradiation and load.

Keywords: Photovoltaic (PV); Photovoltaic emulator (PVE); Buck converter; MPPT; Regulator PID.

Introduction

Over the past decade, the market for photovoltaic (*PV*) has experienced remarkable growth due to various factors, such as the reduction of production costs and support policies. Therefore, a large number of scientific studies are developing in the direction to generalize, improve and optimize the use of *PV* systems. However, several factors produce serious problems in the design and testing of industrial *PV* systems. These factors include [1]:

- The large variety of choices of solar panels.
- The huge space required; for example to obtain a power of 1 kW must be 5-8 m^2 of solar panels.
- Dependence on weather conditions such as changes in temperature and irradiance.
- The high cost of testing process on the site.

However, in laboratories the installations with photovoltaic panels are avoided in order to solve the problems mentioned above. In this sense, extensive research has fairly been conducted in emulators for *PV* systems [2-9]. A photovoltaic emulator (*PVE*) is a power electronic system able to reproduce the characteristics of current-voltage (*I-V*) output of a *PV* module. The advantages of the emulator are: less weight, less bulky, independence of weather conditions and flexibility. The device can be built with low-cost components in a compact arrangement offering portability and ease of use. An emulator is essential for the operational assessment of system components for solar energy, such as *PV* panels, battery chargers, inverters, maximum power point tracking (*MPPT*) techniques.

To develop a *PV* emulator, you can implement one of the following three types of solutions [10]: The first one is based on the equivalent circuit of the *PV* generator (*PVG*). It consists of a power device restoring the equivalent diagram of *PVG* from components such power sources, resistors and diodes [4, 5]. Such a device has a very bad performance due to the dissipated power in the diode which requires an efficient cooling system. The second solution is based on the amplification of an elementary cell. This solution is based on analogue components, such as a photodiode or actual PV cell exposed to a light source under appropriate conditions of irradiation and temperature [11-14]. This method is often used for low power levels (less than 100 Watts),because at high-powers, there are some difficulties in power consumption: heat dissipation, and the bulky size of the testing setup [11].This approach does not emulate the behaviour of a PV system for the entire defects such as increased resistance due to connectivity and partial shade [15].

The last solution is based on the realization of a programmable power supply. This is the most practical solution, given the resources offered by modern power electronics. It consists in achieve a power source with characteristic of programmable output similar to that of a PV generator. These programmable power supplies can be based on a converter controllable power, such as a DC-DC buck-boost converter [8], a DC-DC buck converter [10], a full-bridge structure and high frequency transformers [9].

Description of the PV emulator

In our work, we will focus on the last solution to develop our PV emulator. The proposed solution is schematically shown in Fig. 1. This solution consists of a DC input source, Vin, a programmable power supply based on a buck converter DC/DC for shaping the output I–V curves of the PV panel, the control stage for sensing the output voltage vpv and current ipv, calculation and sending duty cycle command Vcom, and The output load RL is modeled as a variable resistor to represent the output voltage according to the Vcom. In this sense, we have developed and simulated in Matlab/Simulink the model of the elements constituting the PV system under study. The proposed model can simulate different types of *PV* modules for various solar irradiance G, temperature T and load conditions.

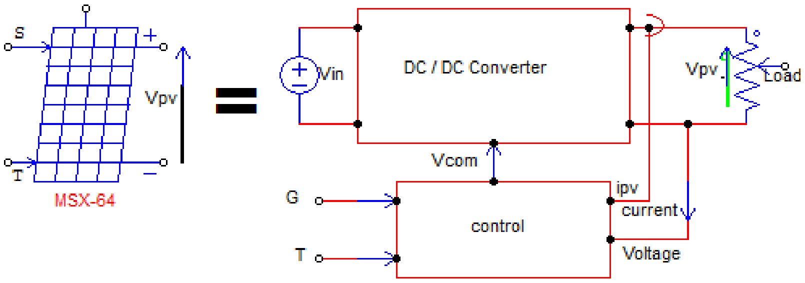

Figure 1. Block diagram of a PV emulator

Mathematical model of PV panels

In this paper, we used a well-known one-diode model. This model offers a good compromise between simplicity and accuracy. Many power electronic designers prefer this model for the simulation of PV devices with power converters [16, 17]. Its characteristic is given in by the following equations:

$$V_{pv} = a\frac{NsKT}{q} ln\left\{\frac{I_{sc}+I_0-I_{pv}}{I_0}\right\} - R_s I_{pv} \quad (1)$$

$$I_{sc} = I_{scn} * \left(\frac{G}{G_n}\right) + \left(K_i * (T - T_n)\right) \quad (2)$$

$$I_0 = I_{sc} * exp\left(\frac{-V_{oc}}{a*N_s*V_t}\right) \quad (3)$$

$$V_{oc} = V_{ocn} + N_s * V_t * Log\left(\frac{G}{G_n}\right) + K_v * (T - T_n) \quad (4)$$

With:

a: Ideality factor of the solar cell.
Ns: Number of cells connected in series (Here 36).
K: Boltzmann's constant (1.38 10-23 J/K).
T: Real junction temperature (K).
q: Electron charge (1.6 10-19 C).
Isc: Short-circuit PVG (A).
I0: Reverse current diode saturation (A).
Ipv, Vpv: Current and voltage PVG (A, V).
Rs: Series resistance (Ω).
Iscn: Short-circuit PVG generated in STC (25 °C, AM 1.5 and 1000 W/m2) (A).
G: Real irradiance (W/m2).
Gn: Nominal irradiance (W/m2).
Tn: Nominal temperature (K).
Voc: Open circuit voltage of PVG (V).
Vt = NsKT/q: Thermal voltage.
Kv: Temperature coefficient of the open circuit voltage.
Ki: Temperature coefficient of the short-circuit.

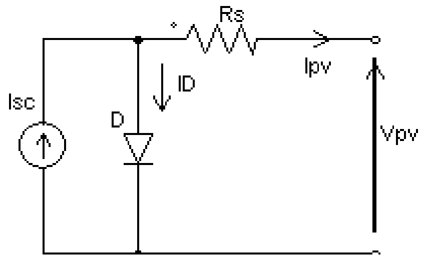

Figure 2. Electrical equivalent circuit of a solar cell

The mathematical model presented is an explicit type. It can satisfy the following two advantages. The first is its universality by developing compatibility with different types of *PV* panel, so it is adaptable to the changes of the weather conditions (G and T).The second is its simplicity which can greatly reduce the computation time, ensuring easy implementation at the level of low-cost processors.

PV emulator based on a buck converter

The architecture of the *PV* emulator is shown in Figure 1. This emulator is composed of two stages: the control stage and the power stage:

A. Control stage

As shown in Fig 1, the control stage allows the evaluation of Vcom signal to the DC-DC converter to reproduce the *I-V* characteristic of *PV* module for different irradiance values *G* and temperature *T*. The I-*V* characteristic is determined through simulations of *PV* model described in section 2. In fact, the *I-V* characteristic it is very important as it can ensure and certify the quality and performance of each *PVG* [16, 18].

B. Power stage: Buck converter DC/DC

The power stage contains a programmable power supply connected to a load. This power supply is made based on a buck converter which is used to vary the output voltage according to the control signal *Vcom*.

The proposed system consists of a power converter DC/DC step-down chopper serial or controlled using the principle of pulse width modulation (*PWM*) Fig 3.

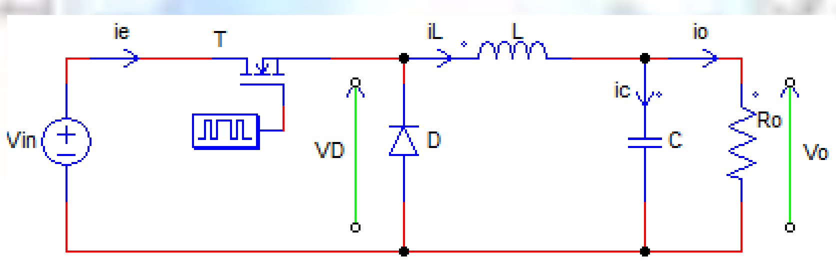

Figure 3. Equivalent circuit of buck chopper

The buck converter is a power converter DC-DC. In continuous mode, the average values of output voltages *Vo* and the input *Vin* are proportional *Vo* = □ *Vin*, where □ is the duty cycle in the range [0, 1].

In order to limit the output current and the voltage ripples, a low-pass *LC* filter has been added. The minimum inductance and capacitance values can be determined as in equations. (5) and (6), using the following constraints:

- The current through the inductor should be in a reasonable interval for all load conditions, because the converter operates in continuous mode.
- The maximum ripple of the output voltage must not exceed a small percentage, usually 5% of the output voltage *Vo*.

$$L \geq \frac{V_{in}}{\Delta I_o f_c} \alpha(1-\alpha) \quad (5)$$

$$C \geq \frac{(1-\alpha)}{8Lf^2{}_c} \left(\frac{V_o}{\Delta V_o}\right) \quad (6)$$

Here, ΔIs = 0.05 Is the limit current between the continuous and discontinuous conduction mode, and ΔVo = 0.05 Vo is the maximum allowed voltage variation.

Vomax = 23.4 V is the maximum output voltage of the converter.

Iomax = 5 A the maximum output current of the converter.
Vin = 24 V is the input voltage of the converter.
fc = 15 kHz is the PWM switching frequency.

From (5) and (6), the value of the inductor L is L ≥ 1.6 mH.

The ripple voltage Vo (t) io maximum for α = 0.5, hence C ≥ 2.7 µF.

Models of solar emulator under matlab/Simulink

In this section we suggest modelling and simulating two models *PVE* in *Matlab*/Simulink: The first is an emulator without correction (*PVEWC*) and the second is a corrected emulator (*PVEC*). For *PVEWC* the measured output current of the converter is used directly for the development of the PV input signal control figure 4. The *PVEC* uses the measured of the current and voltage with a *PID* controller for determining the control signal. Both models will be compared for the solar variation irradiance, temperature, and load conditions.

A. Emulator photovoltaic without correction (PVEWC) Model

The schematic diagram of the *PV* emulator without correction is schematized in the following figure:

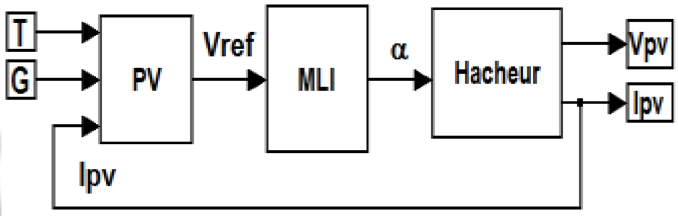

Figure 4. Block diagram of a PVEWC

The PVEWC consists of three blocks: the *PV* block, the *PWM* control and the Buck converter block. *PV* block represents the simplified mathematical model of the photovoltaic panel studied (section II), it determines the reference voltage *Vref* according to the current load *Ipv*, irradiance (*G*) and temperature (*T*) [*Vref* = *f*(*Ipv*, *G*, *T*)]. The control unit generates a *PWM* signal duty ratio α for switching the DC/DC converter. Finally the Buck converter block series represents the power stage between the photovoltaic module and the load.

The PVEWC is represented in Matlab/Simulink model by using the following scheme:

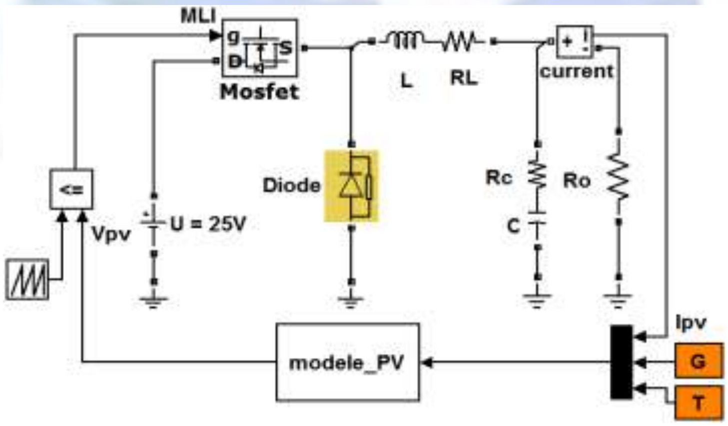

Figure 5. PVPWC model in Matlab/Simulink

B. Emulator photovoltaic corrected (PVEC) Model

The diagram of the *PVEC* is given by the following figure:

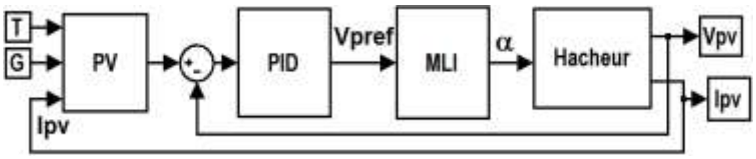

Figure 6. PVEC block diagram

In this model, we have two loops: the voltage and current (*Vpv*, *Ipv*) loops. In the inner loop *Vpv* we added a *PID* controller. The outer loop Ipv used to calculate the reference voltage *Vref*, while the inner loop *Vpv* minimizes the gap between *Vpv* and *Vref*. The *PVEAC* is represented in Matlab/Simulink model using the following scheme:

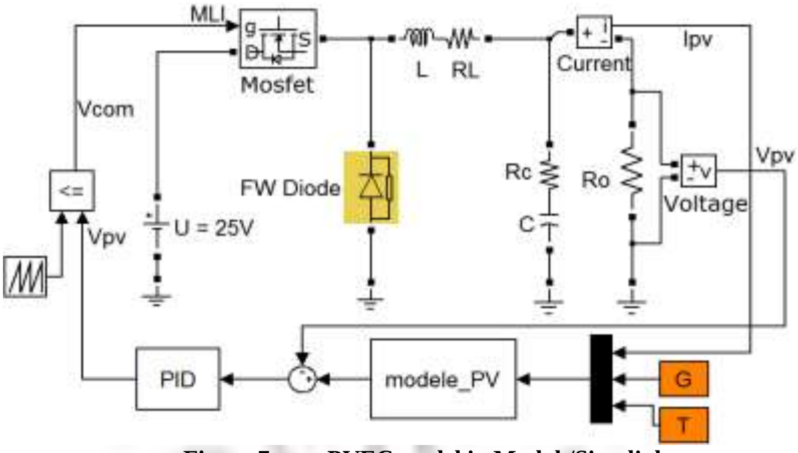

Figure 7. PVEC model in Matlab/Simulink

The structure of the *PID* block (Fig. 8) is represented by the following transfer function:

$$PID = K_p\left[1 + \frac{K_i}{p} + K_d\frac{N_d p}{p+N_d}\right] \quad (8)$$

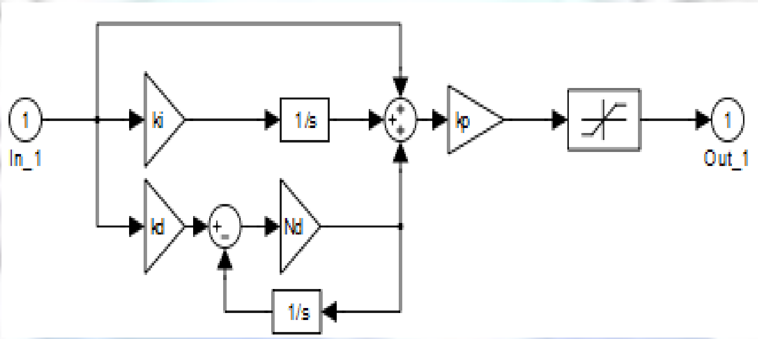

Figure 8. .PID controller

The converter and its control are represented in [19] by the transfer function *H*(*p*) (9) linearized around the operating point (□ = 0.5,*Vo* = 12 V).

$$H(p) = \frac{\Delta V_o}{\Delta\alpha} = G_o\frac{1+Rcp}{1+pB+p^2A} \quad (9)$$

With a static gain $Go = \frac{V_o}{\propto}$

And: $$A = \frac{L_c(R_o+R_C)}{R_o+R_L} \quad (10)$$

$$\text{B} = RC + \frac{R_o R_L C}{R_o+R_L} + \frac{L}{R_o+R_L} \quad (11)$$

ΔVo and *Δ*□ corresponding to small variations of the duty cycle □ and *Vo*.
The inner loop voltage *PVEC* (Fig. 6) can be represented by the following block diagram:

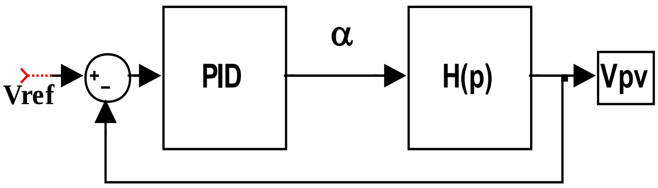

Figure 9. The structure of the inner loop voltage PVEC

For the determination of the parameters of *Ki*, *Kd* and *Kp* of the *PID* controller parameters, we proceed by zero offsetting and poles open loop system (Figure 9). The closed loop system is reduced to a system of first order. For a response time of 5% given regulator elements are:

$$K_i = \frac{N}{NB-1} \; ; \; K_d = \frac{AK_iN-1}{N} \; ; K_p = \frac{3}{K_iG_o t_r} \; ; N_d = \frac{1}{RC} \qquad (12)$$

Simulation results of the system of emulator

A. Characteristics and parameters

In order to test and validate the operating principle of the emulator of photovoltaic panels with *PID* control, simulation results of *PVEC* models are compared to those of *PVEWC*. Also we present, as a general result, the current-voltage characteristics of output (*I-V*) of our photovoltaic emulator compared with the characteristics specified by the manufacturer (datasheet) Figure 14. Details of the simulations are shown in figures [10-13]. The parameters of the *PV* panel emulated (MSX-64), buck converter (Fig. 5) and *PID* controller are shown in Tables I, II and III.

TABLE I. PARAMETERS PANEL MSX-64AT 25 °C, AM 1.5, 1000 W/M2

Parameter	Value
Current at maximum power (I_{mp})	3.66 A
Voltage at point of maximum power (V_{mp})	17.5 V
Maximum power (P_{max})	64 W
Cell number (N_s)	36
Nominal open-circuit voltage (V_{ocn})	21.3 V
Nominal short-circuit current (I_{scn})	4.0144 A
K_v Temperature coefficient of V_{oc}	–(80±10)mV/°C
K_i Temperature coefficient of I_{sc}	(0.065±0.015)%/°C

TABLE II. SIMULATION PARAMETERS

Buck converter	Ignition switch and blocking transistor controlled	MOSFET Transistor
	Capacitor C	100 µF
	Inductor L	2 mH
	Résistor R_C	0 Ω
	Résistor R_L	0.01 Ω
PWM switching frequency	f_c	15 kHz
Load	Variable resistor R_0	0 à 100 Ω

For the *PID* controller (Fig. 8), we used the parameters summarized in Table III below:

TABLE III. PID PARAMETERS

N_d	10^6
K_I	$7.3401\ 10^{-3}$
K_P	$3.4\ 10^{-3}$
K_d	$1.5\ 10^{-3}$

B. PVEWC simulation

The dynamic response of the emulator was tested for various solar irradiance and temperature. Here, the load resistance was set to a constant (10Ω) during each state of the simulation. The irradiation and temperature levels in each case are shown as can be seen from Figure 10.

C. PVEC simulation

For the same variations of *G* and *T* cited above (Fig. 10), the values of output voltage *Vpv*, and of reference voltage *Vref*, are recorded and summarized in the figure 11.

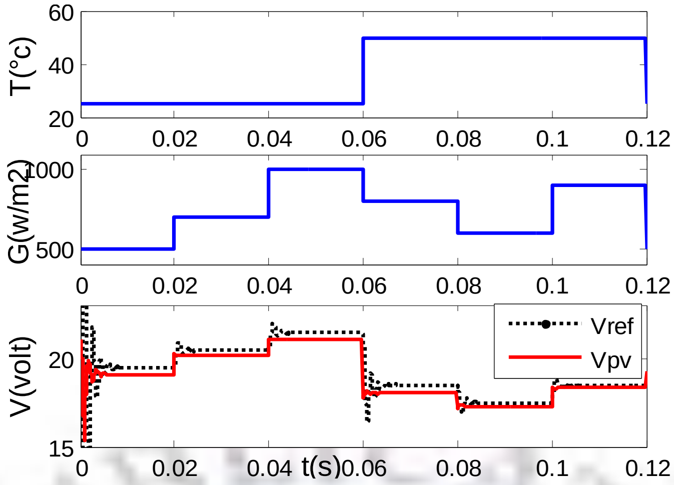

Figure 10. Output characteristics of the PVEWC with irradiation and temperature variations

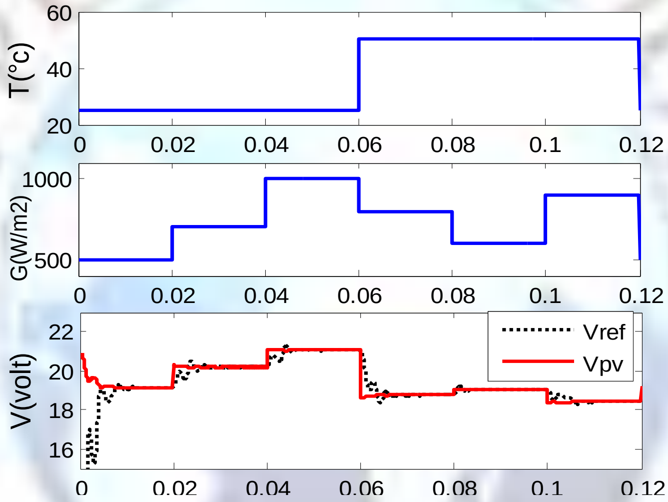

Figure 11. Output characteristics of the PVEC with irradiation and temperature variations.

D. PVEWC simulation according load changes Ro

The load resistance was decreased gradually and the dynamic response of the emulator was evaluated. As shown in Figure 5. Here, the solar irradiation and temperature values were set to 1000 W/m^2 and 25 °C respectively.

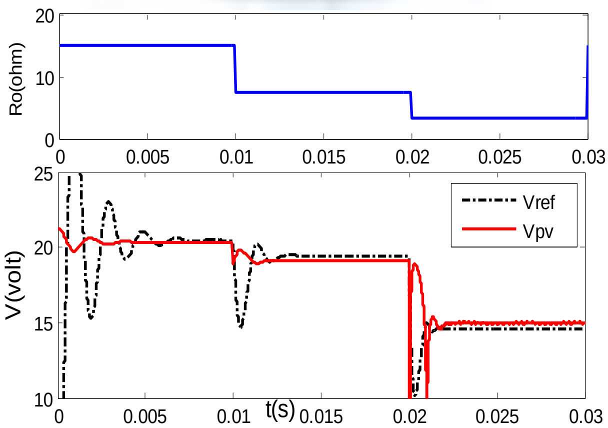

Figure 12. Output characteristics of the EPVWC with load variations.

E. PVEC simulation according to variation of load Ro

For the same variations of load cited above (Fig. 12), we compare the output voltages *Vpv* and *Vref* in the following figure:

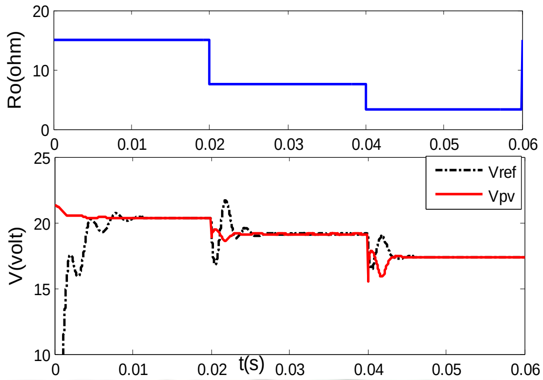

Figure 13. Output characteristics of the EPVC with load variations.

F. Comparison of the I-V characteristic of PVEC and that given by the manufacturer

For $G = 1000$ W/m^2 and different temperatures T (0, 25, 50 and 75 °C). As shown in figure 14, we compare the simulated values of current and voltage (*Ipv*, *Vpv*) of EPVC in permanent regime at those provided by the manufacturer.

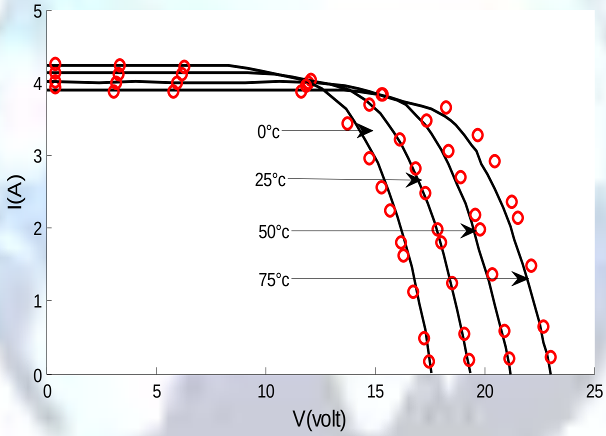

Figure 14. Characteristics of current-voltage (I-V) PVEC, G = 1000 W/m2, compared to those of the manufacturer

Analysis and Discussion

Simulations have been carried out with two different scenarios to analyze the performance of the simulation for both emulator studied: EPVWC and EPVC. In the first scenario given in Figures 10 and 11, the dynamic response of the emulator was tested for various solar irradiance and temperature .Here, the load resistance was set to a constant (10Ω) during each state of the simulation. For PVEWC we notice that there's a difference between Vref and Vpv (about 0.5 V) .while, for the EPVC after an insignificant time(less than 0.01 s) Vpv and Vref are similar. Note that the maximum ripple and the waveform on the output voltage are higher in the model EPVWC.

In the second scenario given in Figures 12 and 13, the load resistance was increased gradually and the dynamic response of the emulator was evaluated. Here, the solar irradiation and temperature values were set to 1000 W/m^2 and 25°C, respectively. We notice the same conclusions as the first scenario. Also, in order to evaluate the static response of the emulator, we have simulated the characteristics current-voltage (I-V) of EPVC, and we compared it to those provided by the manufacturer as can be seen from Figure 14. This shows that the performances of PVEC model are significantly better than those of PVEWC model. And more it is able to reproducing the output characteristics I-V of the PV modules.

CONCLUSION

In this paper we have model and simulate in Matlab environment the different parts of a PV emulator .Namely the simplified analytical model of PV panel, the buck converter and the controller PID. Our emulator can produce the electrical behaviour of the photovoltaic panel for various solar irradiance, temperature and load conditions. The performance of the proposed PV emulator has been tested under dynamic and static conditions, and satisfactory results have been obtained. The PVEC is relatively easy to use and can be very useful for researchers and design engineers in order to test, study and optimize the different components of *PV* systems quickly and accurately.

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