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Utilization of MOSFET transistor as an electronic load to trace I-V and P-V curve of a solar panel

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Abstract. To understand the electrical behavior of a photovoltaic panel, it is necessary to know the characteristic $I_{pv} = f(V_{pv})$. The best way to obtain this I-V curve is to use a variable resistor.

This paper proposes a new and simple technique based on a MOSFET transistor as a variable load, which whose gate voltage is controlled by an RC filter from the Arduino. A comparison under standard temperature and illumination conditions between the manufacturer's datasheet with the simulation by MATLAB/Simulink on the one hand, and on the other hand between the manufacturer's datasheet with the experimental data for the evaluation of this technique that has been performed.

Nomenclature

a_0	Temperature correction coefficient for current (°C^{-1}).
b_0	Temperature correction coefficient for voltage (°C^{-1}).
G	Solar irradiance on module plane (W/m^2).
I_{ph}	Photo-generated current (A).
Ipv	Solar cell terminal current (A).
I_{SC}	Short circuit current (A).
I_0	Reverse saturation current (A).
I_{0i}	Reverse saturation current of diode in conventional model (A).
n_1	First diode ideality factor
N_S	Cells number connected in series.
N_{sh}	Cells number connected in shunt.
PV	Photovoltaic.
R_S	Series resistance (W).
R_{sh}	Shunt resistance (W).
STC	Standard Test Conditions ($G_0 = 1000$ W/m^2,$T_0 = 25$ °C and $AM = 1.5$).
T	Cell or Module operating temperature (°C).
T_a	Ambient temperature (°C).
ΔT	Temperature difference : $=T - T_0$ (°C).
V_{OC}	Solar cell open-circuit voltage (V).
V_{pv}	Solar cell output voltage (V).

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1 Introduction

There is a lot of research on the measurement of the *I-V* characteristic of PV modules under different operating conditions with a variety of methods [1]. The most and easy one is by using a variable resistor in series with the PV generator as a load.

Another way to plot the *I-V* curve of a PV generator, is the capacitive load. Some authors [2-4] have used capacitors as an automatic variable load to change the voltage V_{pv} and the current I_{pv} during the capacitor charging operation, which allowed them to obtain the *I-V* characteristic of the PV generator.

Kuai and al. [5] proposed a device based on an electronically variable load using the APL501J MOSFET transistor, which covers the full range of the *I-V* characteristic of PV panels in a very short time.

This paper proposes the design of a bench for tracing the *I-V and P-V* characteristics of PV panels based on a MOSFET(IRF740) transistor controlled by Arduino via a DC signal, which is injected into a simple *RC* filter to vary the V_{GS} control voltage in a progressive way (figure 1). The system is analyzed and experimentally tested under standard temperature and lighting conditions using an SX330J solar panel.

This paper is divided into 5 sections: The first one gives the introduction of methods used to obtain the *I-V* characteristic of a PV panel. Then in section 2, we expose a brief description of the MOSFET by presenting the electrical behavior $I_D=f(V_{DS}, V_{GS})$. Then, section 3 gives details on the measurement bench, and section 4 summarizes and discusses the results obtained. We will conclude this article with a conclusion and the perspectives of this work.

2 Theoretical background of MOSFET as an electronic load

The MOSFET is a device that function as an electronically controlled load that change the operating point of a PV generator over the full range of the *I-V* characteristic [6]. When a control voltage is applied to its grid, it generates a fast and variable PV output current from 0 to I_{sc} *(A)*, and a variable output voltage from V_{oc} to 0 (V).

The speed of the scan is made as fast as possible to reduce the effect of variation in illuminance and temperature fluctuations caused by cloud movement or other weather changes [7]. In this way, all points drawn on the *I-V* curve are captured under the same weather conditions in a very short time. The fast scanning also protects the MOSFET from superheating [8]. Figure 1 shows the variations of the I_D current as a function of the V_{DS} voltage and the value of the control voltage V_{GS}.
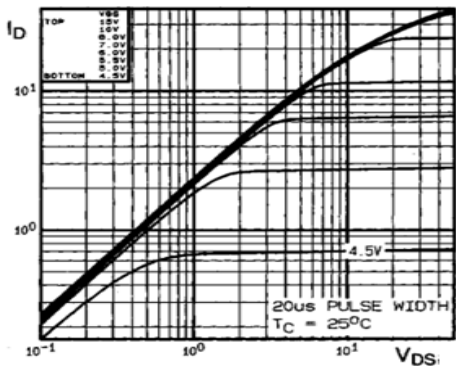

Fig. 1. Characteristics of (IRF740) MOSFET, at 25°C [9]

The three operating regimes of the MOSFET that describe the relationship between I_D as a function of V_{GS} and V_{DS} are [5]:

Blocking mode if : $V_{GS} < V_{th}$, So $I_D = 0A$ (1)

Ohmic mode if:

$V_{GS} - V_{th} > 0$ & $V_{GS} - V_{th} > V_{DS}$ So :

$$I_D = K[2(V_{GS} - V_{th})V_{DS} - V_{DS}^2]$$ (2)

Saturation mode if:

$V_{GS} - V_{th} > 0$ & $V_{GS} - V_{th} < V_{DS}$ So :

$$I_D = K(V_{GS} - V_{th})^2$$ (3)

Where K is the constant of the device and V_{th} is the transistor control threshold voltage.

By changing the value of V_{GS} in an appropriate range, the measurement points can scan between I_{SC} and $V_{OC.}$.

According to Figure 2:

$$I_D = I_{pv} \text{ which } I_{pv} = I_{ph} - I_{d1} - I_{sh}$$ (4)

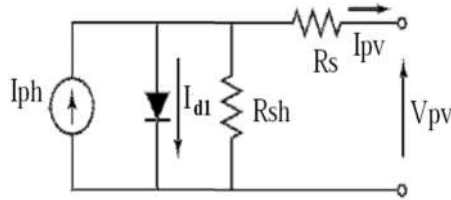I_{pv} The electrical current of the PV panel according to the 1-diode model (Figure 2),

Fig. 2. Equivalent circuit of a PV cell with 1 diode

The photo-current I_{ph} depends linearly on solar radiation, but also influenced by temperature, depending on the following relationship [10]:

$$I_{ph} = \left(I_{ph,ref} + \alpha_0.\Delta T\right)\frac{G}{G_{ref}}$$ (5)

In the STC (Standard Test Conditions) ($G_{ref} = 1000$ W/m², $T_{ref} = 298$ K), the expression of $I_{ph,ref}$ is given by:

$$I_{ph,ref} = \left(1 + \frac{R_s}{R_{sh}}\right)I_{sc,ref}$$ (6)

Therefore:

$$I_{ph} = \left(\left(1 + \frac{R_s}{R_{sh}}\right)I_{sc,ref} + \alpha_0\Delta T\right)\frac{G}{G_{ref}}$$ (7)

By application of the mesh law, the I_{sh} current in the shunt resistor is expressed by:

$$I_{sh} = \frac{V_{pv} + R_s I_{pv}}{R_{sh}}$$ (8)

The diode current I_{di} is given by

$$I_{d1} = I_{01}\left[exp\left(\frac{V_{pv} + R_s I_{pv}}{n_1 V_{th}}\right) - 1\right]$$ (9)

With

$$I_{01} = \frac{I_{sc,ref} + a_0\Delta T}{exp\left(\frac{V_{oc,ref} + \beta_0 \Delta T}{V_{th}}\right) - 1}$$ (10)

And: $V_{th} = \frac{k\,T}{q}$ is the thermal voltage of the module.

I_{01} are the saturation current of the one diode.

n_1 are the ideality factors.

So, the current supplied by the solar cell in 1 diode model is given by the following relation [11]:

$$I_{pv} = I_{ph} - I_{01}\left[exp\left(\frac{V_{pv} + R_sI_{pv}}{n_1V_{th}}\right) - 1\right] - \frac{V_{pv} + R_sI_{pv}}{R_{sh}} \qquad (11)$$

Materials and methods

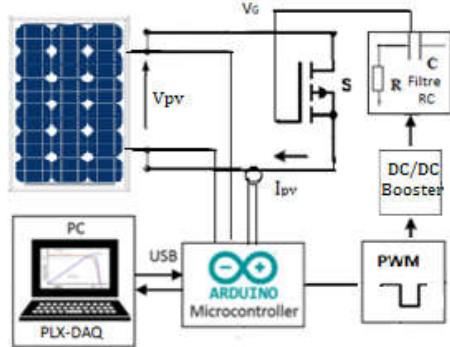A basic circuit with a MOSFET as electronic charge is shown in Figure 3

Fig. 3. Block diagram of circuit setup.

Arduino generates a continuous signal through pin3, then this signal is injected to an *RC* filter, to vary the control voltage of the V_{GS} MOSFET in a progressive way, which also requires the R_{DS} resistor to change progressively (figure 1).

The proposed test bench for real-time characterization of the PV panel is realized using an Arduino UNO board as a data acquisition control, and transfer unit (I_{PV} and V_{PV}) to a computer via the PLX-DAQ tool [12].

The values of current intensity I_{pv} and voltage V_{pv} of the PV panel are measured using Arduino compatible current and voltage sensors, the temperature of the PV panel is measured using a thermocouple, while the irradiance is evaluated by using the FI 109SM Solar Meter [13], the panel used in this characterization is of polycrystalline type SX 330J, the electrical characteristics of which are summarized in Tables 1.

Table 1. Electrical characteristics of the PV panel SX 330J at STC (1000 W/m² and 25°C) [14]

	Symbol	Value
Maximum power	P_{max}	30 W
Voltage at P_{max}	V_{mp}	16.8 V
Current at P_{max}	I_{mp}	1.78 A
Warranted minimum P_{max}	---	27 W
Short-circuit current	I_{sc}	1.94 A
Open-circuit voltage	V_{oc}	21.0 V

Arduino *UNO*, is an open source microcontroller, used to manufacture *PWM* control. Pulse Width Modulation (*PWM*) is a technique used to control an analog circuit via the digital output, using two functions, either analogWrite or digitalWrite. A *PWM* (Pulse Width

Modulation) signal is an electrical voltage with a maximum amplitude of 5V, a variable duty cycle and a constant frequency [15].

In this circuit (Figure 3), the signal delivered to control the MOSFET(IRF740) is amplified by a DC/DC booster, shown in Figure 4.
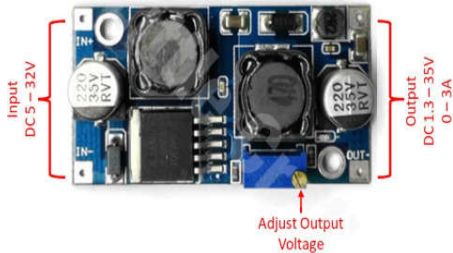

Fig. 4. XL6009E1 Typical Application Circuit (DC/DC Boost Converter) [16]

The signal at the output of DC/DC Boost Converter, is injected into a *RC* filter, which $R=110 \pm 5.5$ Ω [17], and capacitor $C = 4.7 \pm 0.94$ mF [17], connected in series to change the control of the MOSFET, and finally plotted the *I-V and P-V* characteristic of the solar panel.

According to Figure 5, the expression of the $V_{GS}(t)$ command voltage of MOSFET is given by:

$$V_{GS}(t) = V_{PWM}.\left(1 - e^{-\frac{t}{RC}}\right) \qquad (12)$$
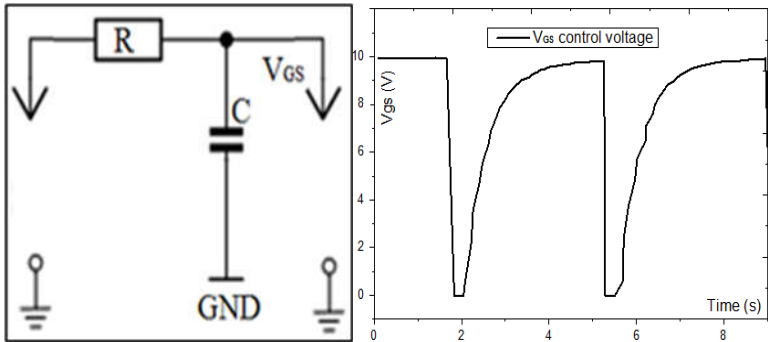

Fig. 5. Filter Flow Chart and V_{DS} control voltage variation with time

So according to the figure we can notice that the control voltage varies progressively, up to the value 10V, which leads to the variation of the resistor R_{DS} of the MOSFET also in a progressive way.

3 Results and discussion

4.1 Variation of the I_{pv} and V_{pv} curve with time

The precision of the *I-V* curve in comparison to the datasheet depends strongly on the control voltage V_{GS} which also depends on the resistance and capacitor in the control circuit, the following figures show the variation of the plotting time as a function of the values of the *R* and *C* components of the control circuit
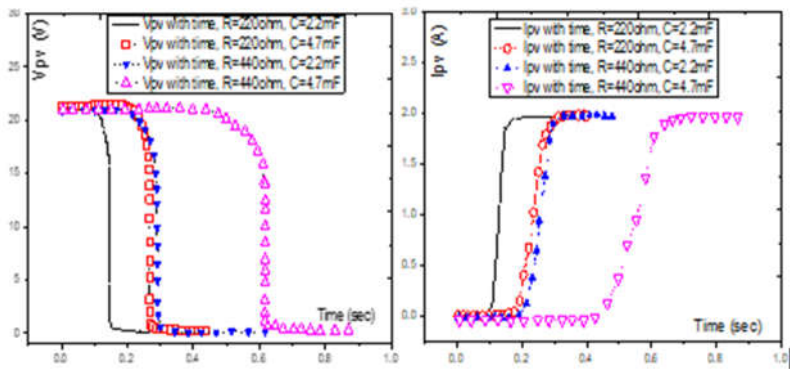
Fig. 6.*Ipv* and *Vpv* with time at 25 °C and G=1000W/m²

In this manipulation the signal delivered by Arduino with duty cycle α=100%, we can observe that for high R and C values the time required to plot the I-V characteristic increases, for R=220Ωand C=2.2mF the time of the trace is 0.18sec, while R=440Ω and C=4.7mF tracing time is 0.69sec, but on the other hand when R and C increases the number of points displayed by the Macro-Excel PLX-DAQ increases.

4.2 I-V and *P-V* characteristics of the PV module

Using the electronic circuit described in Section 3 (Figure 3), the *I-V and P-V* curves were traced for the SX 330J polysilicon solar panel, a comparison between the datasheet of the manufacturers with the simulation by MATLAB/Simulink on the one hand was made, and on the other hand between the datasheet of the manufacturers with the experimental data.

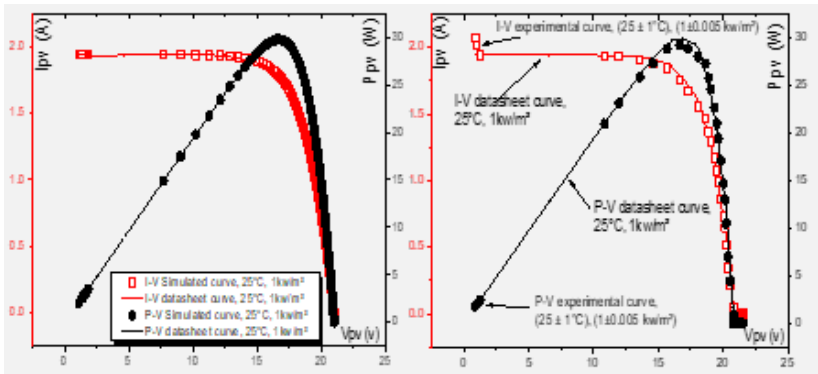#### *4.2.1 I-V and P-V characteristics of the SX330J module at 25 °C and G=1000W/m²*

Fig. 7. *I-V and P-V* characteristics of the SX 330J module at 25 °C and G=1000W/m²

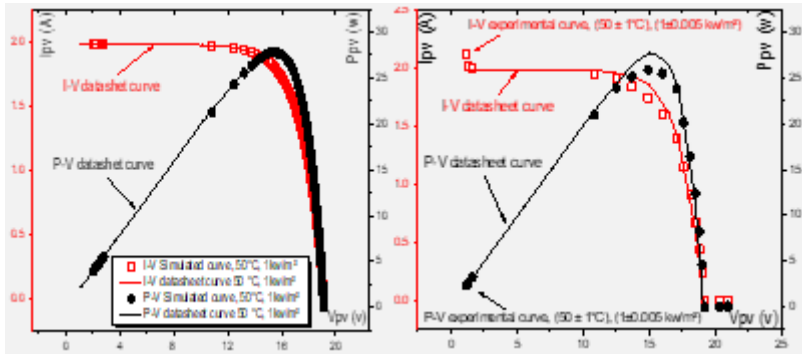### *4.2.2 I-V and P-V characteristics of the SX330J module at 50 °C and G=1000 W/m²*

Fig. 8. *I-V & P-V* characteristics of the SX 330J module at 50 °C and G=1000 W/m²

The small deviation observed between the experimental results and the datasheet of the SX 330J polycrystalline panel is caused by several factors, such as the fluctuations of the illuminance G, of the resistor R with temperature variations but also, the effect of the ohmic contacts between the cells of the PV panel and the rest of the mounting circuit.

5 Conclusion and perspectives

In this paper, we have proposed and realized a simple low-cost instrumentation solution to provide the I-V and P-V characteristics of the PV panel based on a MOSFET(IRF740) transistor controlled by Arduino via a DC signal. The whole system is composed of simple components, less complicated, less expensive and above all widely used in laboratories. The acquisition is realized through low-cost current and voltage sensors in communication with an Arduino type electronic board. The data is then reported in the Excel spreadsheet in real time using the Macro-Excel PLX-DAQ Spreadsheet interface. Experimental tests on a PV module type SX330J were performed under real operating conditions. The experimental results agree with the theoretical analysis carried out for the development of this methodology. The proposed circuit is suitable for future use to analyze the influence of real operating conditions, such as temperature, illumination, dust Shading effect and real-time observation of the PV module performance.

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