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REGULAR ARTICLE

Modeling and Simulation of Photovoltaic Panel Using Simulink and Proteus Simulation

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This study uses MATLAB/Simulink and Proteus so as to emulate solar photovoltaic (*PV*) for a model Jarrett 60 W – 17.2 V. Our objectives are to identify the nonlinear characteristics of the current-versus-voltage (*I-V*) and power-versus-voltage (*P-V*), then compare the results with the manufacturer's data sheet, therefore using all data obtained from Matlab/Simulink on Proteus Simulation. The Proteus used a SPICE model for a PV cell that depends on mathematical equations and is explained using an equivalent circuit that includes a current source I_{ph}, a diode *D*, and two resistors R_s and R_{sh}. The Proteus is utilized to simulate a *PV* module/Array under varying conditions, such as irradiation, temperature, series and shunt resistances effects, and shading effects. To reach the greatest power output, it is required to understand the location of the maximum power point (*MPP*). Using Arduino, an algorithm is applied to determine the voltage V_{mp} and current I_{mp} of *PV* cells. The paper is highly useful for describing the basis and characteristics of a *PV* module and Array in straightforward terms. This research can also be applied as an instructional methodology for teaching *PV* panels at different levels of study, which demonstrates how to use the prototyping and modeling/simulation software at a reduced cost (Proteus and Matlab/Simulink) to be able to approximately achieve the formation objective for students. This is especially helpful for schools that have difficulty with a lack of materials or don't have the resources to buy them.

Keywords: Matlab/Simulink**,** Proteus simulation, Spice model, PV module, PV array, modeling, MPP, Arduino.

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1. INTRODUCTION

There will be a greater need for energy as the world's population increases [1]. Natural energy sources including the sun, wind, biomass, geothermal, and ocean are examples of renewable energy sources [2]. The most important source of renewable energy is solar energy; in general, solar systems are divided into two systems. Solar power is turned into heat in the first system using a thermal element and into electricity in the second system using a PV element. [3].

Today, street lighting, battery chargers, and connected grid power systems all use solar energy as their primary energy source. Solar radiation, cell temperature, position in relation to the sun and shadows, and cloudiness are the primary elements that influence the PV cell's output voltage V_{PV} and current I_{PV} values [4, 5, 6]. A *PV* array is built up of *PV* modules, which are fixed and connected collections of *PV* cells. The *PV* panel is the greatest amount important component of any *PV* system. The different energy requirements that may be satisfied by connecting *PV* as illustrate in Fig. 1 [7].

In this study, we emulate a model for 60 W – 17.2 V mono-crystalline by using Matlab/Simulink and Proteus approaches. The irradiance *G* (W/m^2) and temperature *T* (°C) serve as inputs for this system, and the resulting outputs are voltage V_{PV}, current I_{PV}, and power P_{PV}. Extract all parameters obtained from a *PV* using MATLAB/Simulink and use them in the Proteus software

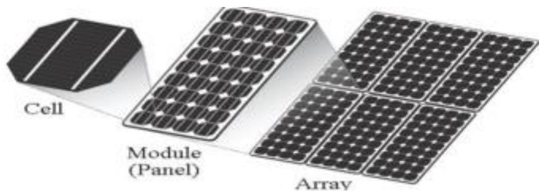

Fig. 1 – Solar PV cell, module and Array

2. MATHEMATICAL MODEL

2.1 PV cell

The ideal circuit for a *PV* solar is shown in Fig. 2. Which is based on a single-diode that contains a photocurrent I_{ph} , a diode *D*, a parallel resistor R_{sh}, and a series resistor R_s [3, 4, 5, 6].

The *PV* output current may be obtained from Kirchhoff's law. The equation is given below [5, 6].

$$I_{PV} = I_{Ph} - I_D - I_{Sh} \tag{1}$$

The photocurrent I_{ph} produced by the *PV* cell, which is influenced by temperature and irradiance

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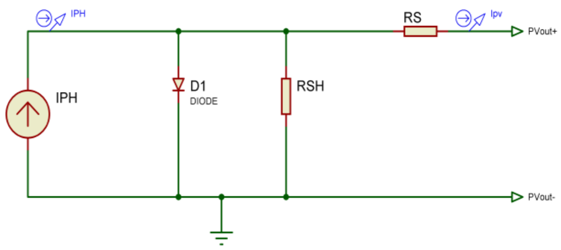


Fig. 2 – illustrates circuit of PV solar cell.

$$I_{ph} = (I_{SC} + K_i(T - T_{ref}))\frac{G}{1000} \quad (2)$$

The Diode current I_D is:

$$I_D = I_0(e^{\frac{(V_{PV}+R_S I_{PV})}{aV_T}} - 1) \quad (3)$$

Where the leakage current I_0 is:

$$I_0 = I_{SC}(\frac{T}{T_{ref}})^3 e^{\frac{qE_g}{nK}(\frac{1}{T_{ref}}-\frac{1}{T})} \quad (4)$$

The shunt I_{sh} current is:

$$I_{Sh} = \frac{V_{PV}+I_{PV}R_S}{R_{Sh}} \quad (5)$$

2.2 PV Module/Array

PV cells may be placed either in series, in parallel, or both. The amount of cells affects the *PV* module's voltage V_{PV}, current I_{PV}, and power P_{PV}. The output voltage and power grow as more cells are linked in series, and the output current and power increase as more cells are connected together simultaneously.

PV Array is collections of *PV* Modules, that are electrically linked in parallel and series circuits to produce the necessary values $I_{PVarray}$ and $V_{pVarray}$. As shown in Fig. 3, the corresponding electrical circuit, in which the cells are arranged in N_P *(parallel)* and N_S *(series)*.

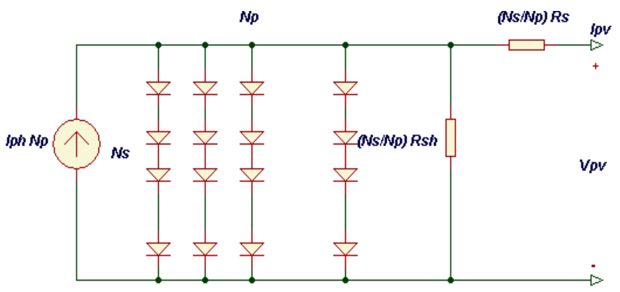


Fig. 3 – Illustrate the corresponding circuit.

$$I_{PV} = N_P I_{ph} - N_P I_0(e^{\left(\frac{q\left(V_{PV}+I_{PV}\frac{N_S}{N_P}R_S\right)}{akTN_S}\right)} - 1) - (\frac{V_{PV}+I_{PV}\frac{N_S}{N_P}R_S}{\frac{N_S}{N_P}R_{Sh}}) \quad (6)$$

The equation (6) is represented mathematically of a *PV* array.

The shading effect and fill factor ratio are two intriguing extra elements in this work. The ratio between the products of voltage (V_{mp}) and current (I_{mp}) to those of voltage (V_{oc}) and current (I_{sc}) is known as the fill factor. It can be calculated using the equation shown below [8]. The shading is caused by a variety of factors, including clouds, trees, high structures in front of the panels, and other obstructions that stop the sun's rays from reaching the panel's surface uniformly [9].

$$FF = \frac{V_{mp}I_{mp}}{V_{OC}I_{SC}} \quad (7)$$

3. SIMULATION AND DISCUSSION

3.1 Extract the Parameters of a 60 W – 17.2 V Using MATLAB/Simulink

This study uses a PV 60 W/17.2 V, as shown in Table 1. Manufacturers provide only some parameters. So, several parameters that are essential for our work are missing from manufacturer specifications, such as diode saturation current I_0, luminous flux I_{ph}, series R_s and shunt R_{sh} resistors, and ideality factor a.

The Matlab/Simulink tools get the parameters listed in the manufacturer specifications (Table 1), as shown in Fig. 4. After that, the tools complete the rest of the missing parameters, as shown in Table 2.

Table 1 – Missing Parameters of a 60 W – 17.2 V at STC

Parameters	**60 W – 17.2 V**
Light-generated current, I_{ph} (A)	4.2628
Diode saturation current, I_0 (A)	2.6836E-10
Diode Ideality factor, a	1.0018
Shunt Resistance, R_{sh} (Ω)	31.0659
Series Resistance, R_s (Ω)	0.4648

There are three sections, as shown in Fig. 4: Section 1 module data (Table 1), Section 2 model parameters (Table 3), and Section 3 presents a plot of the characteristics of current I_{PV} and power V_{PV} in terms of voltage V_{PV}, as shown in Fig. 5.

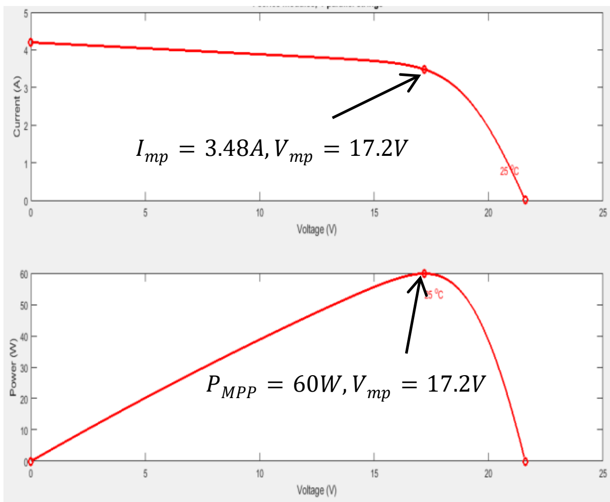


Fig. 5 – *I-V* and *P-V* curves of a 60 W – 17.2 V *PV* at *STC*

Fig. 5 shows the curves of current and power as a function of voltage for a 60 W – 17.2 V *PV* module. The *MPP* is the location where the most power is extracted from the *PV*, as is apparent in the power curve. This quality is influenced by both temperature and irradiation.

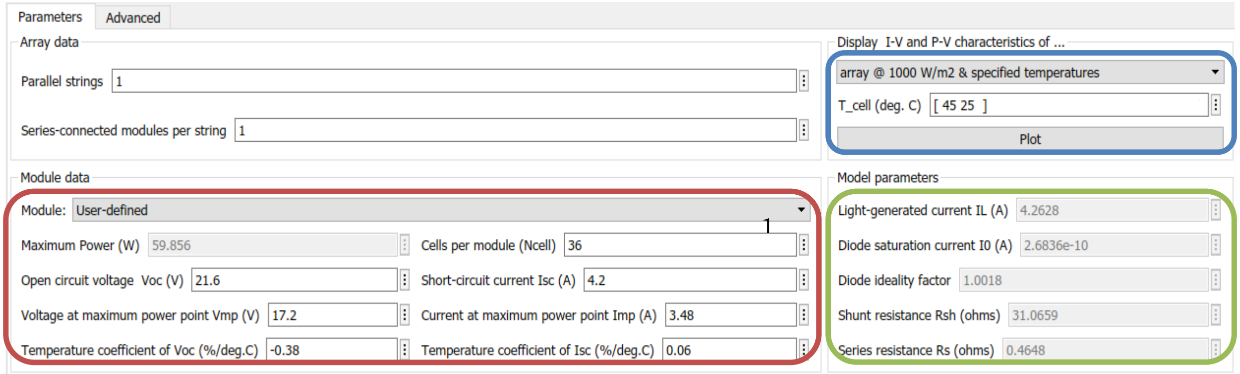
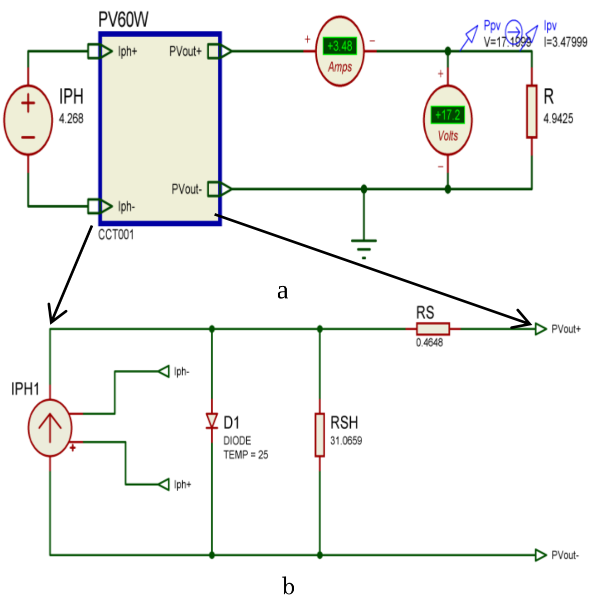


Fig. 4 – Block Parameters *PV* module of Jarett 60 W – 17.2 V under Matlab/Simulink tools

3.2 Software Proteus Based Model of PV Cell

Fig. 2 depicts the comparable circuit for the *PV* panel, it includes of a current generator I_{ph} associated with a diode *D* in parallel that simulates the *P-N* junction, and two resistors R_{sh}, R_s. The Spice code and Proteus model are displayed in Fig. 6. Table 2 shows the all parameters of a 60 W – 17.2 V at STC.




```
*SCRIPT SPICE
.MODEL PV D (
   IS=2.6836e-10
   +N=36
   +Eg= 1.12
   +TEMP=25
   + G=1000   )
```

c

Fig. 6 – Present sub-circuit model under Proteus (a), corresponding circuit based on a single-diode model (b), SPICE code (c)

According to Fig. 6 (a), which shows the sub-circuit block of *PV*, it helps us to simulate our circuit, and it has load resistance *R*:

$$R = \frac{V}{I} = \frac{V_{mp}}{I_{mp}} = \frac{17.2}{3.48} = 4.9425\Omega \qquad (8)$$

Table 2 – Manufacturers datasheet of all Parameters

Parameters	**60 W – 17.2 V**
Current, I_{sc} (A)	4.2
Voltage, V_{oc} (V)	21.6
Current, I_{mp} (A)	3.48
Voltage, V_{mp} (V)	17.2
KV (mV/°C)	– 380
KI (mA/°C)	6
N_{cell}	36
Light-generated current, I_{ph}	4.2628
Diode saturation current, I_0	2.6836E-10
Diode Ideality factor, *a*	1.0018
Shunt Resistance, R_{sh}	31.0659
Series Resistance, R_s	0.4648

According to equation 8, the resistance *R* represents the value at P_{MPP}, where:

$$P_{MPP} = V_{mp} * I_{mp} = 60\ W \qquad (9)$$

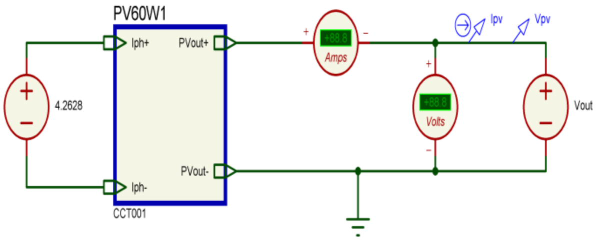
The voltage output (Vout) corresponds to the "Sweep variable" value of the "DC SWEEP ANALYSIS" graph that was used to simulate our model.

Fig. 7a show the sub-circuit block, by adding a V_{out} as voltage output (V_{out}) in parallel with the *PV* panel model and varying V_{out} from 0 to $V_{OC} = 21.6\ V$, we got two graphs that represent a change in Current I_{PV} and Power P_{PV} in terms of Voltage V_{PV}, as shown in Fig. 7b and Fig. 7c.

As depicted in Fig. 7, the curves $P_{PV}(W)$ and $I_{PV}(A)$ obtained from the model are consistent with the manufacturer's datasheet for a 60 W – 17.2 V. Based on equations (1)-(5), The physical conduction of the *PV* is dependent upon the two resistors R_{sh}, R_s, solar irradiation, and temperature. Therefore, the effect of these parameters on the output of the *PV* is investigated in this work.

3.3 Influence of Solar Irradiation Variation

In Fig. 8, it can be observed how the current I_{PV} and power P_{PV} curves are affected by changes in irradiation from 1000 W/m² to 200 W/m² in steps of 200 W/m².



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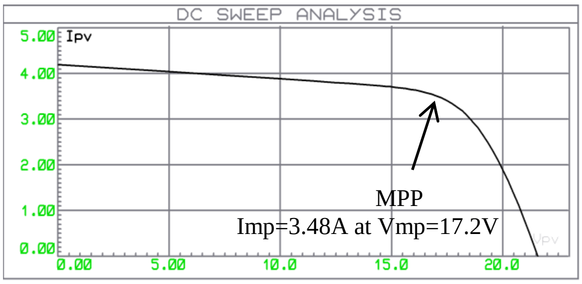

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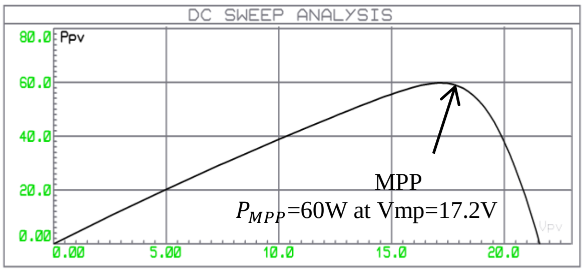


c

Fig. 7 – Present sub-circuit model under Proteus (a), I_{PV} versus V_{PV} characteristic of *PV* (b), P_{PV} versus V_{PV} characteristic of *PV* (c)

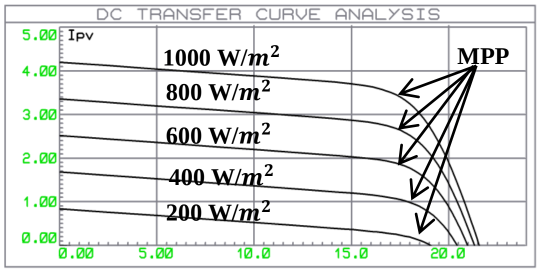
The voltage output (V_{out}) and the input irradiation (G) correspond to the "sweep variables" values of the "DC TRANSFER CURVE ANALYSIS" graph that was used to simulate our model. By varying the irradiance G (W/m^2) from 200 to 1000 and the output V_{out}(V) from 0 to $Voc = 21.6\,V$, We get as Fig. 8 displays I_{PV} and P_{PV} curves for a range of solar irradiation values. The *PV* panel's current is significantly impacted by solar irradiation. However, the power increases by W when the irradiance is raised from 800 W/m^2 to 1000 W/m^2 the outcome, variations in irradiance have a considerable effect on the *PV* panel current.

It is clear when comparing the two curves that when irradiation increases, higher power (*MPP*) and a larger current I_{sc} occur, while the voltage V_{oc} practically remains constant.

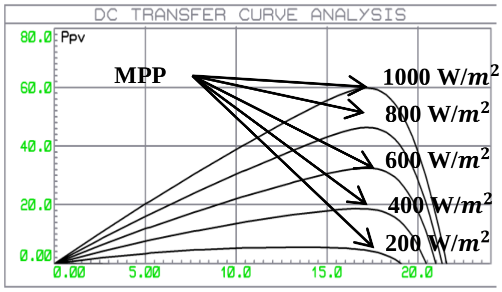
3.4 Influence of Temperature

The result obtained by the *PV* module in Proteus shows how the curve is affected by changes in temperature from 25 °C until 45 °C in steps of 10 °C, as illustrated in Fig. 9.

According to Fig. 9, by varying the temperature from 25 °C to 45 °C and maintaining constant solar irradiation, the voltage V_{oc} decreases and the current I_{sc} increases. The voltage V_{mp} and power P_{MPP} decrease when the temperature value increases by 10°C. As a result, temperature variations have a considerable impact on the PV voltage.



a

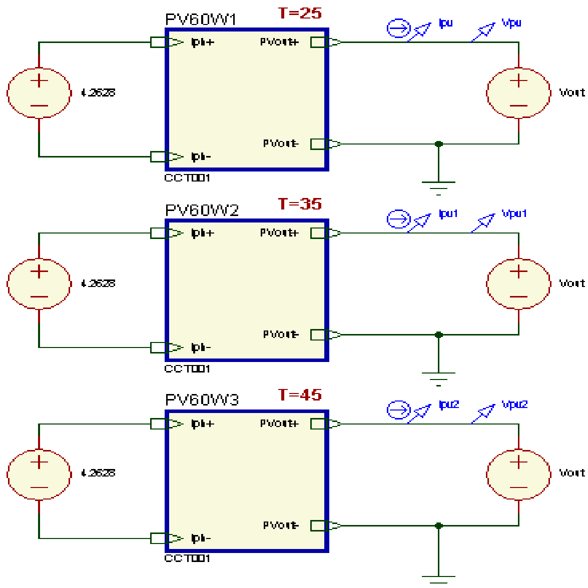


b

Fig. 8 – I_{PV} and P_{PV} curves characteristics for different values of irradiance (a), (b)

Due to this, the power is ultimately lowered when compared to the effect in Fig. 9, which significantly decreased the output open-circuit voltage V_{oc} in contrast to the short-circuit I_{sc} perturbation. This can be seen in the *P-V* curve of Fig. 8b.

In conclusion, the system performs better with more irradiation (Fig. 8) and a lower temperature (Fig. 9). This means that the work point determined by the intersection of the *P-V* curve and the load curve applied will be located at a point of higher power if the *P-V* occupies a wider area.



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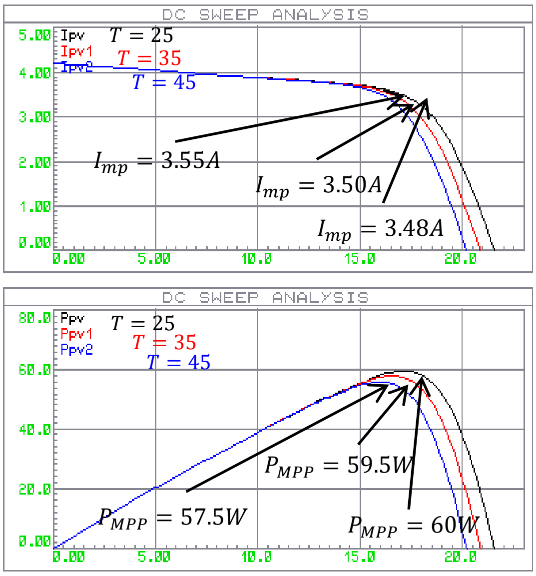


b

Fig. 9 – shows the sub-circuits (a), I_{pV} and P_{pV} curves characteristics at different temperature settings using Proteus software (b)

3.5 Impact of Shunt and Series Resistances

Due to the very low value of the series resistor, it might occasionally be disregarded. However, it is advised to create a different version of this resistor and demonstrate how it affects the output of the *PV*, in order to create the proper model. In Fig. 10, the *MPP* deviates when the series resistor is modified. Regarding *Rs*, it has no impact on voltage V_{oc} but effects current I_{oc}, which has a decreasing impact on fill factor and leads to a deviation from the ideal curve, reducing the maximum amount of power P_{MPP} that can be provided.

Three different series resistance values – 200 mΩ, 400 mΩ, and 600 mΩ – were simulated. Additionally, as illustrate in Fig. 10, the power P_{pV} decreases as series resistance increases.

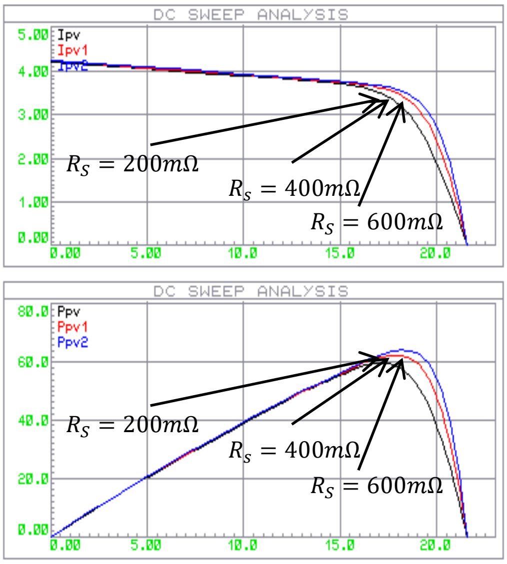


Fig. 10 – Shows I_{pV} and P_{pV} curves for different values of R_s

While changing R_{sh} has no impact on voltage V_{oc}, it does cause a decrease in current I_{sc} and fill factor, as shown in Fig. 11.

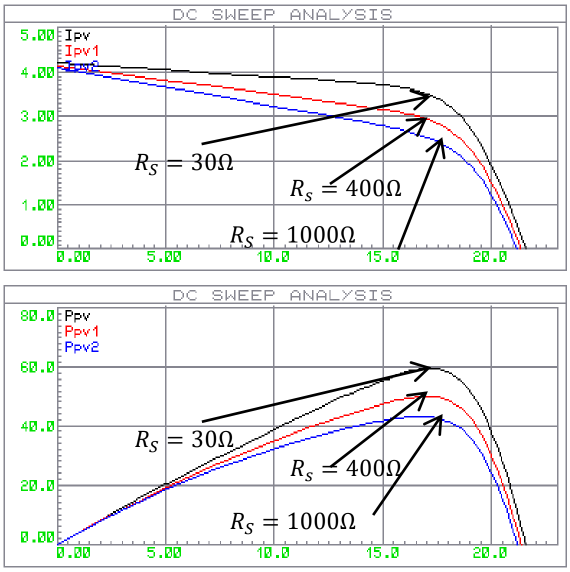


Fig. 11 – Shows I_{pV} and P_{pV} curves for different values of R_{sh}.

3.6 Impact of Shading

The power production of *PV* systems is also significantly impacted by partial shading. When one portion of a *PV* panel (dark cells) receives less insolation than another portion (illuminated cells).

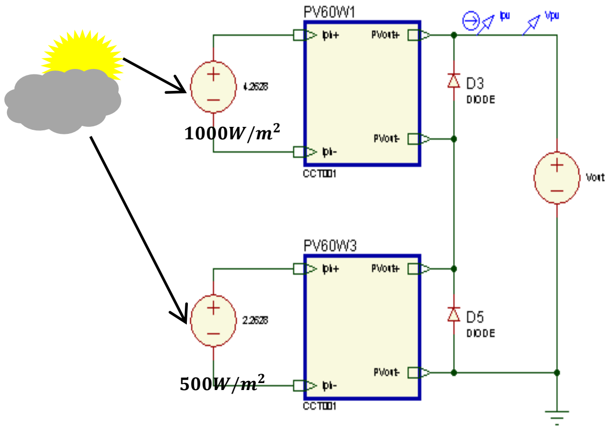
As shown in Fig. 12a, a bypass-diode is connected to each connector of the panel, which should be noted has two connectors, in order to replicate the effect of shade. As a result, the first module is exposed at 1000 W/m^2 and the second module at 500 W/m^2.

Due to their reverse bias, the bypass diodes are inert when exposed to uniform irradiation. However, because the bypass diode is directly biased, when there is shading, the current passes via the diode rather than the shaded *PV* module. As a result, no power will be wasted in the shaded cells, and only the lighted cells will produce electricity. Fig. 12b illustrates how bypass diodes affect the properties of *PV* panels, and as seen, the P_{pV} curve may have several peaks. Point *A* is the global peak while point *B* is the local peak, making a total of two peaks. As a result, actual *MPP*, which is the global peak, cannot be tracked by standard *MPPT* algorithms.

3.7 PV Array

A *PV* array with nine *PV* modules has been constructed to maximize the potential of the model. There are three groups of three *PV* panels; each group consists of three panels connected in series. The groups have been connected in parallel, as illustrated in Fig. 13a.

Fig. 13b shows the simulation results of the PV array in the Proteus simulation. Parallel panels enhance current and power whereas those connected in series increase voltage and power.



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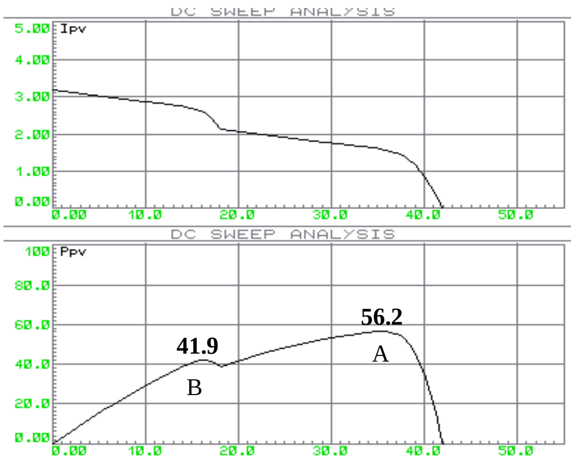

b

Fig. 12 – shows sub-circuit *a*, characteristics of the *PV* panel under irregular irradiation *b*.

3.8 Proteus and ARDUINO-based Simulation

As shown in Fig. 14, the schema represents the Arduino UNO, a PV module, a current sensor (ACS712), a voltage sensor, an LCD display, and load resistance. As described below, we tested our work using an Arduino ATMEGA328P, which is referred to as the brains of a system. Arduino combines a physical and programmable circuit board with software. The voltage sensor senses the voltage, while the current sensor (ACS712) senses the current. The results are passed into the Arduino and displayed on the LCD.

Voltage divider networks were utilized for *PV* voltage sensing. From the ATMEGA 328P data sheet, the specified operating voltage for the (I/O) pins is 5 V, and the maximum DC current per I/O pin is 40 mA; therefore, a ratio of resistors is used to regulate down the voltage so that the maximum voltage fed from the voltage divider is 5 V to avoid damaging the analog (I/O) ports while limiting the current drawn. The resistance values were calculated by using voltage divider equation 10.

$$V_{ARDUINO} = \frac{R_2}{R_2+R_1} V_{PV} \tag{10}$$

The worst case scenario of V_{PV} is $V_{OC} = 21.6\ V$ to give a $V_{ARDUINO} = 5\ V$ as a safety measure. Since the Atmega328P has a 10-bit ADC it allocates the analog read values to 210 (1024) levels (0-1023) and to get the sensed voltage from the ADC output to be used for computation by the ATMEGA328P in the our work we need to calculate V_{PV} by using the formula

$$V_{PV} = \left(\frac{V_{ADCvalue}*5}{1024}\right) * \left(\frac{R_2+R_1}{R_2}\right) \tag{11}$$

For the solar panel resistors of R_1 = 10 K, R_2 = 4 K were used. The ACS 712 was chosen because it had *Vcc* = 5 V, it was bidirectional and had 5, 20 and 30 A versions. The 5 A version was chosen based on the *PV* model current range $I_{SC} = 4.2\ A$. Consequently, in the ideal case, the stated current in amperes is

$$I_{PV} = \frac{\left(I_{ADCvalue}*\frac{5}{1024}\right)-2.5}{0.1} \tag{12}$$

To calculate the voltage V_{PV} and current I_{PV} values, we follow the simplified flowchart of the algorithm illustrated in Fig. 15.

Fig. 16 illustrates the power P_{PV}, current I_{PV}, and voltage V_{PV} of the *PV* according to the resistive variable load. By parallel-connecting a resistance R_{load} (from 0 to 20 Ω) to the *PV* model. We note that the decrease in current I_{PV} and augment in voltage V_{PV}, as well as the increase in R_{load}, are due to Ohm's law. In reality, the power must be kept constant regardless of the value of the resistance load in order to exploit all the power of the *PV*. Hence, the DC-DC converters and MPPT algorithms must be added to keep the power at 60 W.

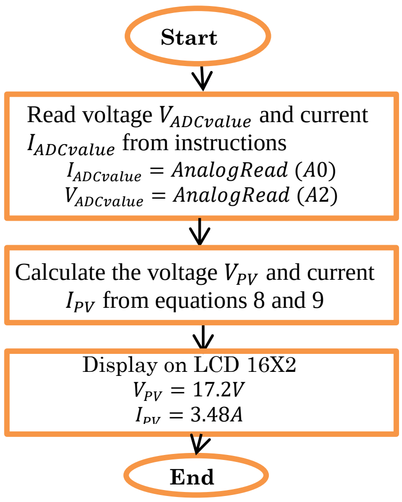

Fig. 15 – Algorithm of the system used to measure the current I_{PV} and Power P_{PV}.

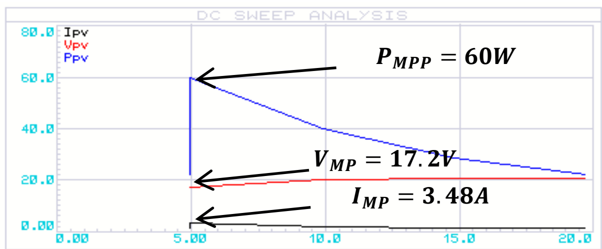

Fig. 16 – Shows current, voltage, and power curves according to resistance R_{load}.

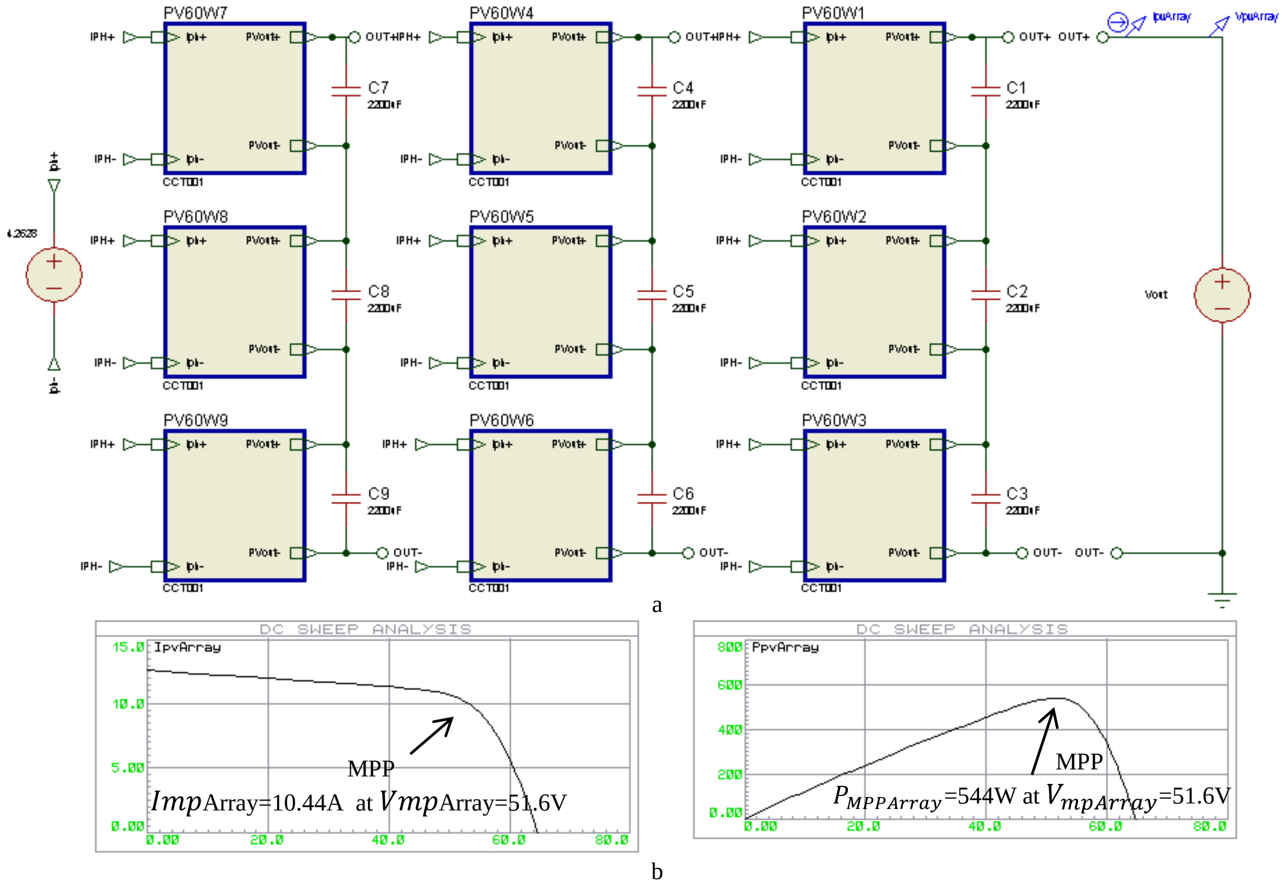

Fig. 13 – PV Array Model *a*, Current I_{pV} and Power P_{pV} Curves *b*.

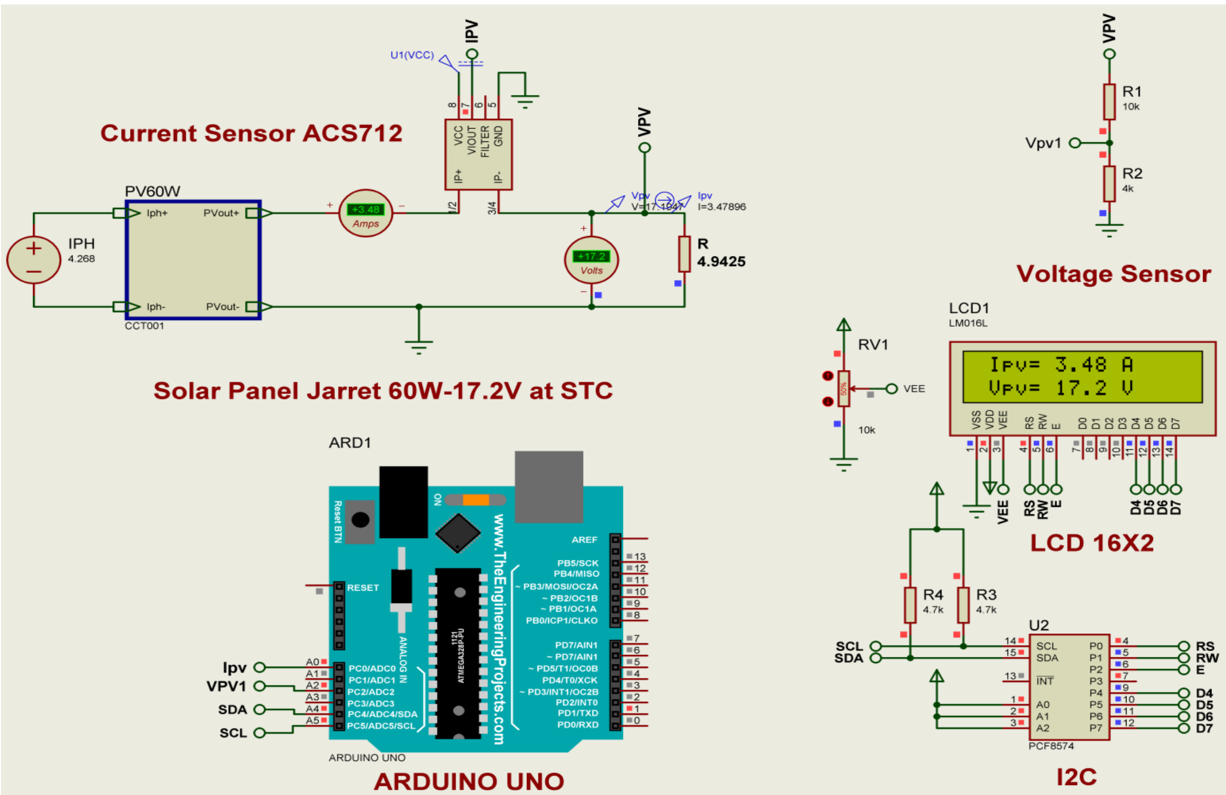

Fig. 14 – Shows the simulation PV model using Proteus and Arduino.

4. CONCLUSION AND PERSPECTIVES

In this paper, Matlab and Proteus Simulation are used to emulate PV cells. The V_{PV} and P_{PV} properties are examined for a range of temperatures and irradiance. The proposed Proteus study model of *PV* cell and module for varying equivalent circuit parameters R_s, R_{sh}, solar insolation, temperature, shading effect, and their dependencies, including the *V-I* and *P-V* properties of *PV* array, is simulated. An algorithm is used to verify the *PV* model using microcontroller.

As perspectives, first, we are currently working on verifying the PV model in an experimental setting using a microcontroller. Second, as we noted earlier in simulation, tracking the *MPP* gets even more complicated when the *MPP* shifts on the *P-V* curve with a change in the irradiance at a constant temperature and with a change in the module temperature at a constant irradiance. In reality, an augment in solar irradiance leads to an increase in module temperature, so to overcome the problem mentioned above, a power conditioner such as a DC-DC converter is usually used as an interface between the PV module and the load, and together with an *MPPT* controller used to control the duty cycle of the converter, it makes the PV module to work at its *MPP*.

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Моделювання та симуляція фотоелектричної панелі за допомогою Simulink та Proteus Simulation

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У цьому дослідженні використовуються MATLAB/Simulink і Proteus для імітації сонячної фотоелектричної (PV) моделі Jarrett 60 W – 17,2 V. Наші цілі полягають у тому, щоб визначити нелінійні характеристики залежності струму від напруги (*I-V*) і потужності від напруги (*P-V*), а потім порівняти результати з даними виробника, використовуючи всі дані, отримані з Matlab/Simulink на Proteus Simulation. Proteus використав модель SPICE для фотоелектричної комірки, яка залежить від математичних рівнянь і пояснюється за допомогою еквівалентної схеми, яка включає джерело струму I_{ph}, діод *D*, два резистори R_s і R_{sh}. Proteus використовується для моделювання фотоелектричного модуля/матриці за різних умов, таких як опромінення, температура, послідовний і шунтовий опори, а також ефекти затінення. Щоб досягти найбільшої вихідної потужності, необхідно розуміти розташування точки максимальної потужності (*MPP*). Використовуючи Arduino, застосовано алгоритм для визначення напруги V_{mp} і струму I_{mp} фотоелектричних елементів. Стаття дуже корисна для опису основи та характеристик фотоелектричного модуля та масиву простими словами. Це дослідження також може бути застосовано як навчальна методологія для викладання фотоелектричних панелей на різних рівнях навчання, яка демонструє, як використовувати прототипування та програмне забезпечення для моделювання/симуляції за зниженою ціною (Proteus і Matlab/Simulink), щоб мати можливість приблизно досягти формування мети для учнів. Це особливо корисно для шкіл, які відчувають труднощі через брак матеріалів або ресурсів для їх придбання.

Ключові слова: Matlab/Simulink, Симуляція Proteus, Модель Spice, Фотоелектричний модуль, Фотоелектрична матриця, Моделювання, MPP, Arduino.