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Design and Conception of Platform that Allows to Connect Different Solar Panels and Loads through a DC-DC Buck Converter

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A step-down converter-based solar system was designed to reduce and stabilize voltage through adjustable PWM control. To power different loads, we applied a constant voltage to charge the battery throughout the charging time and with good efficiency, even if the solar panel was subjected to shadows or other disturbances. We created a platform to connect photovoltaic (PV) modules to the loads via a DC-DC buck converter with a voltage of up to 38 V and a maximum current of 5 A with a power of 75 W, as well as the voltage at the output up to 36 V. Our results are that we can use three solar panels and attach them to the platform, then place the battery as a load, fix the value of PWM on the converter, and make various measurements on a normal day and a disturbance day. We created an embedded system based on the Arduino ATmega328p microcontroller and sensors to measure different parameters such as voltage, current, power, temperature and monitor the voltage value on the load. Also, an algorithm was implemented in the processor to measure different instantaneous parameters, including the panel values (V_{pv}, I_{pv}, P_{pv}), as well as the buck parameters (V_o, I_o, P_o) using current sensors and tension. This work makes it possible to monitor various instantaneous electrical quantities at the panel and load levels and to acquire real-time data for various parameters, also connect the platform to a computer via a serial port to send data and save it using a microcontroller, and then read the data into a PLX-DAQ spreadsheet.

Keywords: PV panel, Buck converter, Step-down, Arduino Uno, Data acquisition, PLX-DAQ.

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1. INTRODUCTION

With the increasing capacity of solar power plants to supply electricity to the main grid, there is a need to develop grid-level energy storage solutions. These solutions would provide the necessary flexibility for electricity networks to reduce the impact of the disparity that occurs in the intensity of wind, sun and other obstacles [1, 2].

The importance of the MPPT (Maximum Power Point Tracking) regulator plays a major role in stabilizing the output voltage of the step down through the use of the most famous techniques such as HC (hill-climbing), P & O (perturb & observe), INC (Incremental condition) and others, which leads to controlling the duty cycle in order to feed or charge the battery at a constant voltage, by the implementation of a step-down converter, which ensures the stability of the tension at the output of this inverter, and in a constant state with good results and an efficiency curve [3-5].

The photovoltaic (PV) conversion chain will be optimized through a static converter (SC) controlled by potentiometer adjustment [6]. It can be represented by the synoptic diagram in Fig. 1. The Arduino UNO board's microprocessor receives the measurements of tension current and power parameters from two sensors. The data obtained during the acquisition process is saved and plotted in real time in the PLX-DAQ Excel spreadsheet [7]. We started to describe the solar chain as shown in Fig. 2. The test equipment can work with simply controlled settings, when we used 3 panel types: two Welion panels (P-5 W) installed in parallel, a TOTAL ENERGIE (TE400) 40 W panel, or a Canadian Solar Inc. panel (CS4-55 W) and different sensors, one module for reducing the tension of DC-DC buck converter type, which feeds the battery load, when we can adjust with a potentiometer to fix the voltage in the output of this step-down.

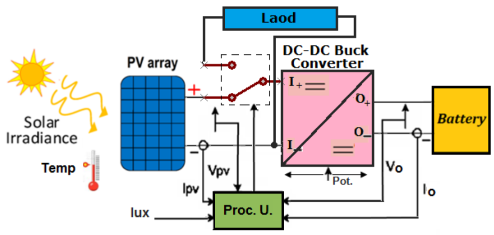

Fig. 1 – Block diagram of a solar chain with a DC-DC buck converter, battery load and processing unit

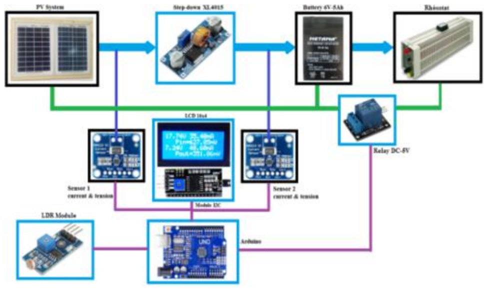

Fig. 2 – Synoptic diagram of the measuring bench for PV modules in the solar chain

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We also relied heavily on various sensors, which we will mention as follows:

- Two current and tension sensors (INA219) for measuring the current and tension at the input and output of the converter;
- PWM DC-DC buck converter or step-down module that allows to fix the value of the output voltage using PWM. Capable of driving a 5 A current in the load with high efficiency, tension up to 38 V in the input and up to 36 V in the output [8, 9];
- LCD 16 × 4 display with I2C module interface;
- Relay DC-5V, to cut off the battery supply when the battery is charged or in the absence of lighting;
- METAMA battery type (FM-6V-5AH);
- Rheostat (load).

2. PARAMETERS OF A SOLAR PV SYSTEM

We consider various components of a solar system.

2.1 Modeling of the PV Generator

A PV cell is a photodiode; it can be represented by a circuit in Fig. 3, and it is a simple model. Taking into account the connection resistances and leakage currents, based on the ideal model, we can represent a GPV by the diagram, also called the four-parameter model [4, 10].

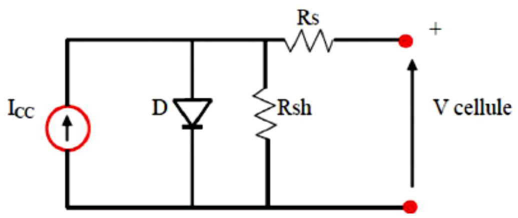


Fig. 3 – Equivalent circuit of the four-parameter model

The expression of the total current can be given as

$$I = I_{ph} - I_d - I_{sh} . \quad (1)$$

The photocurrent I_{ph} is the light generated current, also known as the short-circuit current I_{sc}, K_o is the temperature sensitivity, G is the solar irradiance and is calculated as [3, 5]

$$I_{sc} = \frac{G}{1000}\left[I_{scr} + K_o\left(T_c - T_{ref}\right)\right] . \quad (2)$$

The expression of the diode current is given as:

$$I_d = I_0\left(e^{\frac{q(V+R_s I)}{KT_c}} - 1 \right), \quad (3)$$

where I_0 is the saturation current, q is the electron charge ($q = 1.6 \cdot 10^{-19}$ C), K is the Boltzmann constant ($K = 1.38 \cdot 10^{-23}$ j/k), T_c is the cell temperature (K), and $V_T = kT_c/q$ is the thermal voltage (V). The expression of the total current can be written as [3, 4, 8, 10]:

$$I = I_S - I_0 . e^{\frac{V+R_s I}{V_T}} - \frac{V + R_s I}{R_{sh}} . \quad (4)$$

Table 1 – Electrical parameters of each PV module for the three panels used

Variable	Values of different PV modules		
	Welion (P-5W) 2 panels	TOTAL ENERGIE (TE400)	Canadian Solar Inc. (CS4-55)
P_{MP} (W)	5 W	40 W	55 W
V_{OC} (V)	11.1 V	21.8 V	21.6 V
I_{SC} (A)	0.62 A	2.5 A	3.48 A
V_{MP} (V)	9 V	17.3 V	17.2 V
I_{MP} (A)	0.56 A	2.3 A	3.2 A

2.2 The Influence of Irradiation on the Panel

This panel can be subjected to perturbations from the shading, wind and deflection of the sun.

We keep the temperature $T = 25$ °C constant and apply irradiation perturbations by varying the sunlight (G) from 200 up to 1000 W/m² [4, 5], the results obtained are illustrated in Fig. 4.

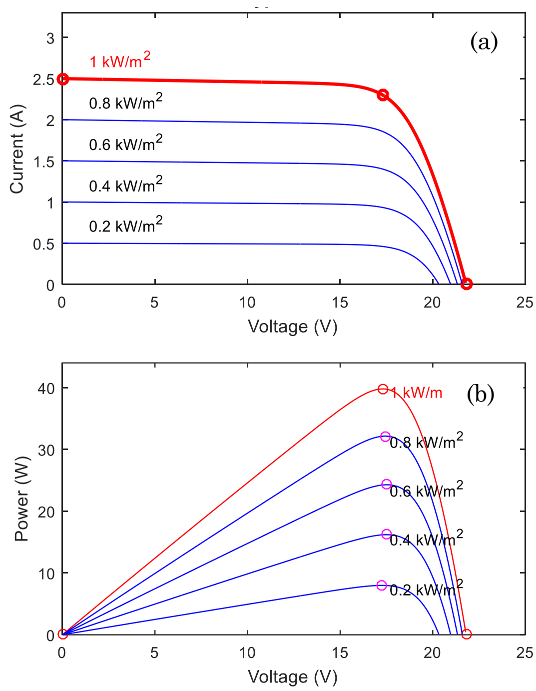


Fig. 4 – Influence of solar radiation on (a) *I-V* and (b) *P-V* characteristics of PV panel under MATLAB for Total (TE400)

3. BUCK CONVERTER

A buck converter, also known as a series chopper, is a switching power supply that converts a DC voltage at the input into another DC voltage at the output with a lower value. The buck chopper's or step-down mathematical model is created by applying Kirchhoff's laws to the basic chopper schematic (see Fig. 5) and the operation of this converter can be divided into two switching sequences based on the state of the switch Q and diode D [7]. The scheme of the buck converter is given in Fig. 5 [2, 4].

During a period of time T, two switching modes can be expressed: the first mode Q: ON and D: OFF and the second mode Q: OFF and D: ON shown in Fig. 5 [2, 12].

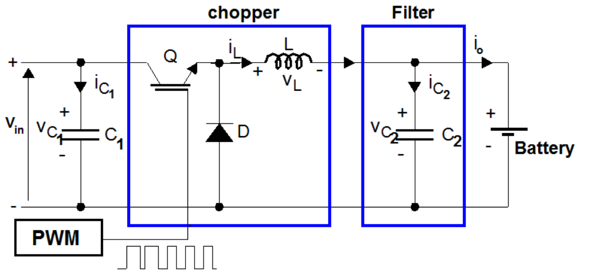


Fig. 5 – DC-DC buck converter, we can split its operation into two sequences depending on the state of the switch Q and D

The output voltage is calculated by the average value

$$V_o = V_{C_2} = \frac{t_{on}}{T} V_{in} = \alpha V_{in} \,, \qquad (5)$$

where T is the repeating period ($T = 1/f$), f is the chopping frequency, t_{on} is the switch-on time, and α is the conduction duty cycle, $\alpha = t_{on}/T$ [12].

The dynamic chopper equations are presented for the following state variables: inductance current i_L, capacitor output voltage v_{C2} or v_0, and input voltage v_{in}.

When $x = [x_1 \;\; x_2 \;\; x_3] = [v_o \;\; i_L \;\; v_{in}]$, we can put

$$\lambda_1 = \frac{1}{C_2}\,;\; \lambda_2 = \frac{1}{L}\,;\; \lambda_3 = \frac{1}{C_1}\,. \qquad (6)$$

$$\begin{cases} \dfrac{dv_o}{dt} = -\dfrac{1}{C_2} v_o + \dfrac{1}{C_2} i_L \\ \dfrac{di_L}{dt} = -\dfrac{1}{L} v_o + \dfrac{d}{L} v_{in} \\ \dfrac{dv_{in}}{dt} = -\dfrac{d}{C_1} i_L + \dfrac{1}{C_1} i_{in} \end{cases} \Rightarrow \begin{cases} \dot{v}_o = -\dfrac{1}{C_2} v_o + \dfrac{1}{C_2} i_L \\ \dot{i}_L = -\dfrac{1}{L} v_o + \dfrac{d}{L} v_{in} \\ \dot{v}_{in} = -\dfrac{d}{C_1} i_L + \dfrac{1}{C_1} i_{in} \end{cases} \qquad (7)$$

The equation of state can be written in the following form:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{bmatrix} = \begin{bmatrix} -\lambda_1 & \lambda_1 & 0 \\ -\lambda_2 & 0 & \lambda_2 .d \\ 0 & -\lambda_3 .d & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \lambda_3 \end{bmatrix} i_{in} \,. \qquad (8)$$

A well-designed buck converter has a high efficiency (up to 95 %) and offers the possibility of regulating the output voltage.

We propose the step-down shown in Fig. 6, capable of driving loads up to 5 A with high efficiency and a fixed frequency of 180 kHz. We can adjust the potentiometer to fix the voltage at the output of the converter depending on the relationship (5) [9, 13].

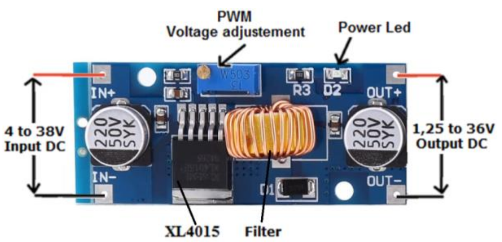


Fig. 6 – DC-DC buck converter of XL4015 module with PWM adjustment allows to connect an input voltage up to 38 V

Table 2 – Parameters of the DC-DC buck converter [9]

Parameters	Variables and Units	Values
Input voltage	V_{in} (V)	4 to 38
Output voltage	V_{out} (V)	1.25 to 36
Output current	I_{out} (A)	max 5
Output power	P_{out} (W)	75
High efficiency	(%)	up to 96
Switching frequency	f (kHz)	180
Dimensions	(cm)	5.4 × 2.3 × 1.5

4. BATTERY LOAD

Batteries have become extensively used in many fields nowadays, as they are found in all cars and emergency generators to store electrical energy (DC), and not only these things but also widespread in homes and small, medium and large projects to store energy produced by solar panels for use at night and in winter [1, 2, 8].

The DC-DC buck converter module has applications where the input voltage is higher than the output voltage. In our project, the input voltage V_{oc} is up to 20 V for three panels applied to the converter input. As for the output of the converter, we set the tension on the value cycle used to charge the battery.

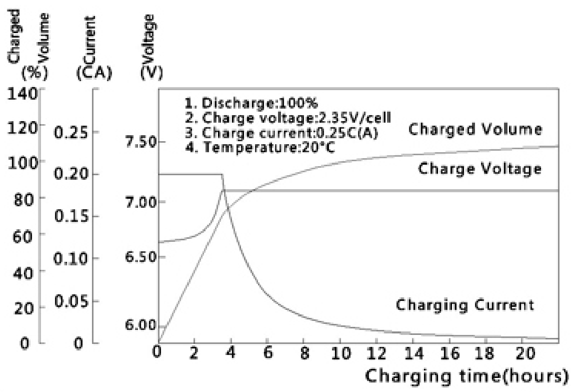


Fig. 7 – Charging characteristics of the battery (6 V, 4.5 Ah) [14, 15]

Table 3 – Characteristics of the charging battery METAMA FM-6V-5Ah (T_n = 20 °C)

	Stand-by use	Cycle use
Voltage regulator	6.75 to 6.90 V	7.20 to 7.50 V
Initial current	1.5 A max	

5. EXPERIMENTAL PROCEDURES

Three types of PV generators are used in the university laboratory (Welion type P-5W, total power model type TE400-40W, Candian solar Inc. model type CS4-55W) to supply the platform (Fig. 8).

Fig. 9 shows how to get the data acquisition or DAQ with a microcontroller, it allows to receive quantitative data according to the period, it can be voltage, current and many variables. Everything can be viewed on a PC directly or saved to be analyzed later [7, 16].

Then the prerequisites are to have the Arduino and Excel software, as well as hardware ATmega328p [7].

Fig. 8 – PV modules installed, three panels were used

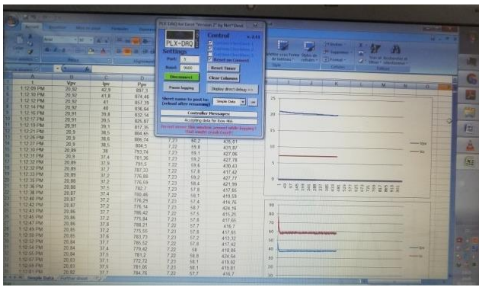


Fig. 9 – The measurement bench and Excel PLX-DAQ table displayed on the monitor in real time, with data saving and plotting curves of different parameters

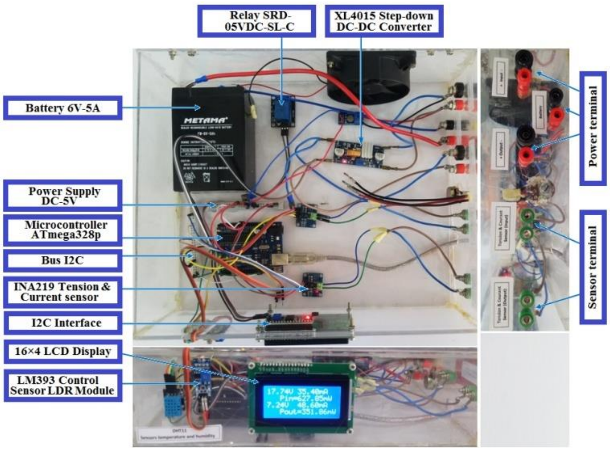


Fig. 10 – Platform designed to measure the data packet (at the output of the panel I_{pv}, V_{pv}, P_{pv} and at the output of the converter I_o, V_o, P_o), we can also measure radiation and temperature

6. RESULTS AND DISCUSSION

We achieved the results by exploiting three types of solar panels as mentioned earlier (Fig. 8), where we charged the battery using the measurement bench and first used software and hardware to program the microcontroller and then an PLX-DAQ excel spreadsheet to save data. As for the electrical components, they are on the platform and are shown in Fig. 10 [16]. The graphics represent a simulation of instantaneous values that were taken in a data table. Fig. 11 represents various instantaneous values of solar panel tensions V_{pv} and the constant value ($V_o = V_{batt}$) at the battery level under stable normal conditions.

The first battery charging occurs in a direct way, i.e., solar panel – converter – battery, where the step-down DC-DC lowers the tension, whose value is up to

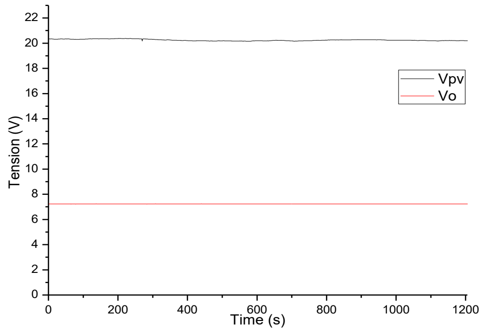
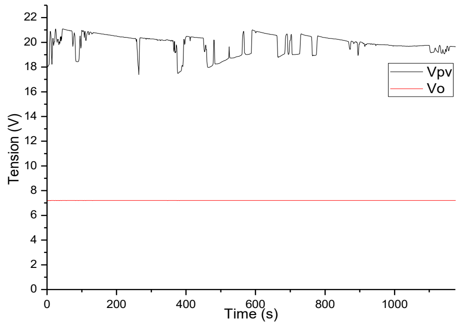


Fig. 11 – V_{pv}-V_o curves measured under radiation (750 W/m²) with total energy panel, at the battery terminal we fixed V_{batt} = 7.20 V, hour 10:58 – 11:33, and date 15/05/2022

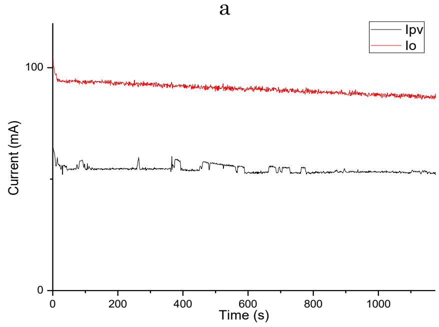
21 V at the converter input, to a fixed value that we appoint it by adjusting the potentiometer value V_o = 7.20 V at the output, and this is the maximum voltage to charge the battery, as shown in figures below. The values on the time axis represent instantaneous values of about 1 s.

The measurement enables us to have several uses such as battery monitoring, information storage, data reading and the relationships of each of the instantaneous input and output values for current, voltage, and power. We also compared the three panels on the characteristics of each under good weather conditions (Fig. 11), as well as when the weather is disturbed by a change in solar radiation (Fig. 12). The experiments gave good results despite our lack of total energy extraction, and the efficiency of this system is shown in maintaining a constant output tension in the region of the operating curve.

The results of the experiments show graphs of the system's response at different stages of atmospheric changes to battery charging, ensuring battery protection from overcharging and deep discharging, as well as through the algorithm applied in Arduino, in addition to improving the efficiency of the PV generator.



a



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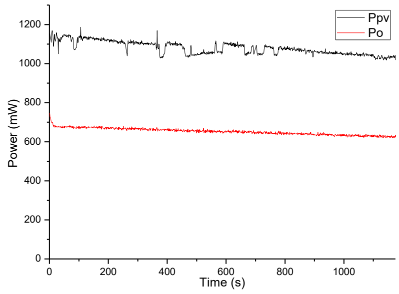
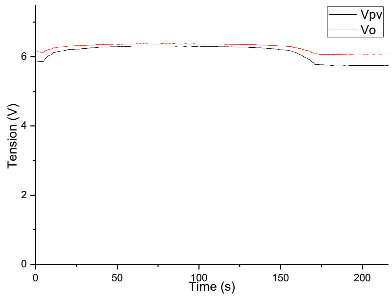


c

Fig. 12 – (a), (b) and (c) respectively show the I_{pv}-I_o, V_{pv}-V_o, and P_{pv}-P_o curves measured under radiation (770 W/m²) with perturbation shading and wide. We used a Canadian panel to see the reaction of the output voltage V_o if perturbation affects it. On the battery terminal, we fixed V_{batt} = 7.20 V, hour 13:17 – 13:51, and date 28/05/2022



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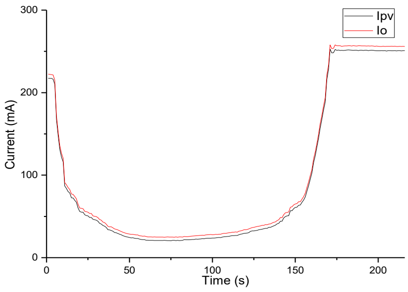

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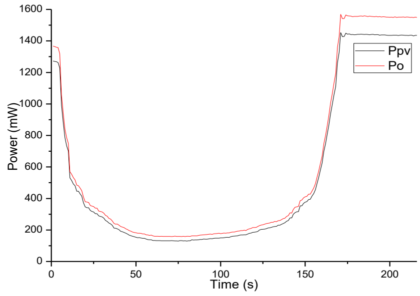

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Fig. 13 – (a), (b) and (c) respectively show the I_{pv}-I_o, V_{pv}-V_o, and P_{pv}-P_o curves. We use a reverse conversion chain, a variable battery supply rheostat, $Vo = V_{batt}$ = 6.3 V, hour 14:17 – 14:23

Then for battery discharging in the sense of energy consumption, it takes place indirectly, when we use the reverse method through the battery – converter – rheostat load, and the process is completely reversed, and this time to get tension at the input of the converter, we can say that the step-down is reversible in tension, as shown in Fig. 13.

7. CONCLUSIONS

This work presents a simulation study of a pilot application, we are currently working on, to achieve an autonomous solar system that allows reading solar panel data as well as output load data through a DC-DC converter, which has the advantage of stabilizing tension at the output, this provides use of maximum power point tracking (MPPT) technique. We can add reading and recording of various electrical values at the solar panel and battery level, values affecting the panel such as solar radiation and temperature to the data table and save them as information and read the data later. And this research may serve as a basis for future publications and articles.

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Дизайн і концепція платформи, яка дозволяє з'єднувати різні сонячні панелі та навантаження через понижуючий перетворювач DC-DC

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Сонячна система на основі понижуючого перетворювача була розроблена для зменшення та стабілізації напруги за допомогою регульованого PWM контролю. Для живлення різних навантажень ми застосували постійну напругу для заряджання батареї протягом усього часу заряджання та з хорошою ефективністю, навіть якщо сонячна панель була в тіні або піддавалася іншим перешкодам. Ми створили платформу для з'єднання фотоелектричних (PV) модулів з навантаженнями через понижуючий перетворювач DC-DC з напругою до 38 В і максимальним струмом 5 А з потужністю 75 Вт, а також вихідною напругою до 36 В. Наші результати полягають у тому, що ми можемо використовувати три сонячні батареї та прикріпити їх до платформи, потім розмістити батарею як навантаження, зафіксувати значення PWM на перетворювачі та проводити різні вимірювання у звичайний день і день з перешкодами. Ми створили вбудовану систему на основі мікроконтролера Arduino ATmega328p і датчиків для вимірювання різних параметрів, таких як напруга, струм, потужність, температура, і моніторингу значення напруги на навантаженні. Крім того, в процесорі реалізовано алгоритм для вимірювання різних миттєвих параметрів, включаючи значення панелі (V_{pv}, I_{pv}, P_{pv}), а також параметри зниження (*Vo*, *Io*, *Po*) за допомогою датчиків струму та напруги. Робота дозволяє контролювати різні миттєві електричні величини на панелі та рівнях навантаження та отримувати дані в реальному часі для різних параметрів, а також під'єднати платформу до комп'ютера через послідовний порт для надсилання даних і збереження їх за допомогою мікроконтролера, і потім для зчитування даних в електронну таблицю PLX-DAQ.

Ключові слова: PV панель, Понижуючий перетворювач, Arduino Uno, Збір даних, PLX-DAQ.