Original Article

Optimized PV Step-up Power Conversion System with Energy Storage and Control Unit

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Abstract - This paper presents an optimized PV step-up power conversion system with energy storage and control unit by proposing an optimized step-up DC/DC conversion system that uses Arduino Uno as a control unit to implement all the necessary algorithms to apply a closed-loop circuit where the actual input current is used as a feedback. Then, it is compared with the desired input current in order to update the duty cycle value to achieve the desired output voltage, which leads to maximising the efficiency and improving the performance of the power conversion system. Moreover, this paper describes some I-V and P-V characteristics of the PV panel which were under consideration for the design phase as it affects enhancing the performance. Moreover, it illustrates the detailed design and topology for the step-up power conversion system with energy storage and the control unit by focusing mainly on two parts, which are the power conversion system and the control unit. A comparison was made to highlight the improvement in the performance after deploying a closed-loop system. In addition, the algorithm presents some actions performed by the control unit for different situations. Some ideas were illustrated as potential enhancements in the future to increase power conversion systems efficiency.

Keywords - Closed-loop System, Energy storage, Photovoltaic, Power optimization, Solar panel.

1. Introduction

Lately, the global demand for clean energy has increased since extracting energy from fossil fuel resources negatively affects the environment by causing global warming, climate change and greenhouse gases in the atmosphere. In addition, these fossil resources have some impacts on the economy, for instance, expensive production costs, and they require high maintenance. As a result, societies and governments were highly encouraged to seek alternative solutions [1].

In recent years, renewable sources have been considered pollution-free sources, especially solar energy, because it has less impact on the economy and environment by having abundant resources little maintenance and zero greenhouse gas emissions [2]. Therefore, developed countries moved toward generating power and electricity from solar panels as a primary power source. As a result, as they started using the generated power for different fields, they faced issues such as low photovoltaic panel efficiency, where it cannot exceed 12% for monocrystalline silicon under practical conditions since weather leads to a significant decrease in the efficiency significantly. Moreover, the power conversion up or down resulted in a lot of dissipated power [3].

This article addresses the above issues by maximizing the power conversion system efficiency by firstly shedding light on the chosen PV by measuring the quality and performance of I-V and P-V, which are taken under consideration for designing the optimized PV step-up power conversion system with energy storage and the control unit.

In addition, it highlights the implemented topology of the main two parameters in the design which are the power conversion system and the control unit. The implementation of unoptimized (open-loop system) and optimized (closed-loop system) in real and practical conditions. Finally, the article concludes by presenting some innovations that can be applied to the system in the future to overcome other issues and increase performance.

2. Practical I-V and P-V Characteristics of the PV Panel

Solar panels are semiconductor devices that are used to convert solar radiation into electrical power by exploiting the photovoltaic effect, which focuses on generating photovoltage when electrons transition from low-energy states to high-energy states by absorbing photons from the sun [4]. The PV panels that were used in the experiment is a polycrystalline silicon, and it has an efficiency between the range (5-7%), which is quite enough in the experiments to present the optimized design [5]. Table 1 shows the specifications of the PV under practical conditions where the maximum power the

PV can generate is 4.508 W, which is quite excellent for a single PV panel.

Table 1. Solar panel specification under practical conditions

Parameters	Symbols	Values
Open-Circuit Voltage	V_{oc}	21.9 V
Short-Circuit Current	I_{sc}	0.25 A
Voltage at the Maximum Power Point	V_{max}	20.4 V
Current at the Maximum Power Point	I_{max}	0.22 A
Resistance at the Maximum Power Point	R_{max}	92 Ω
Maximum Power	P_{max}	4.5 W

The Fill Factor (FF) of solar panels measures the closeness of the I-V curve of the panel to the ideal shape, which is a rectangular shape, as shown in Figure 1. Perfect PV panels are considered good quality as FF gets as close as possible to the unity. However, it is impossible to achieve that due to the exponential behaviour of the solar cells, which prevents this. As per the practical test, the measured FF for chosen PV panel is (0.798), which is considered since good PV panels have FF between (0.7) and (0.85), which means this is a good choice of PV panel for this experiment [6].

After that, the PV was tested in order to measure the I-V and P-V curves, as shown in Figures 2 and 3; by using a light source, its intensity could be adjusted easily in order to take current, voltage and power measurements by using a multimeter under different conditions. Then, these measurements are converted to two curves, and these two curves are 80% exactly the curves under ideal situations, which again means the PV quality is great enough to proceed to the next stage, which is designing the power conversion system.
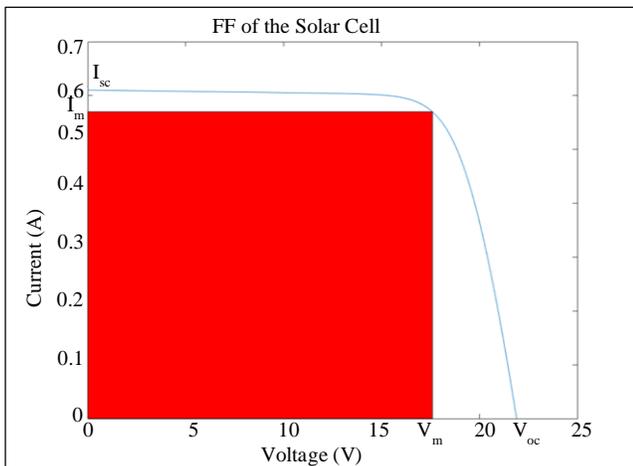
Fig. 1 Fill Factor of the chosen solar panel
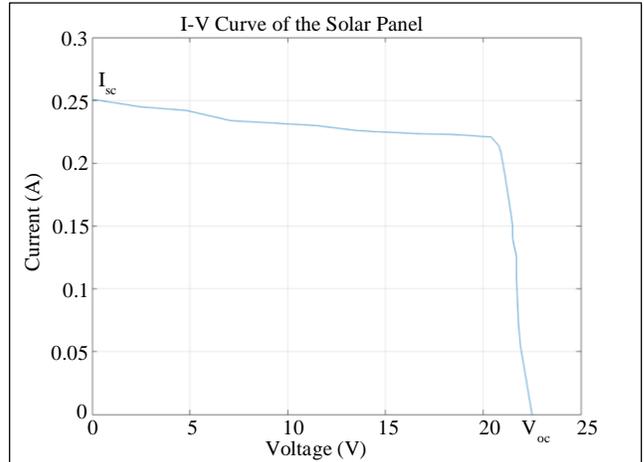
Fig. 2 Practical I-V curve of the PV panel
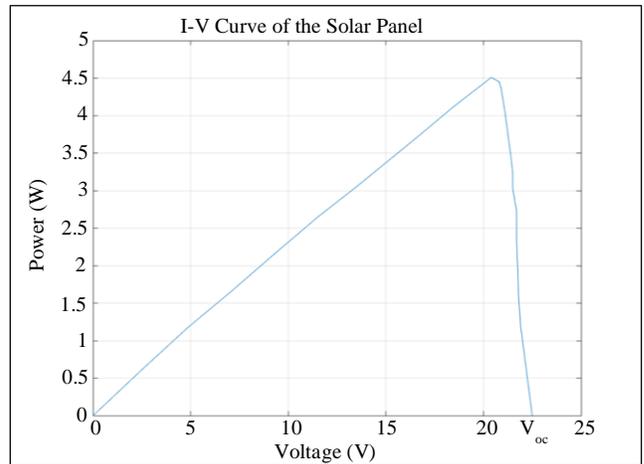
Fig. 3 Practical P-V curve of the PV panel

3. Topology and Design of PV Step-up Power Conversion System with Energy Storage and Control Unit

Solar panels are still developing in terms of increasing efficiency since, under practical conditions, the efficiency cannot exceed 12%. As a result, a step-up DC/DC converter is highly needed to maximize efficiency. Figure 4 depicts the block diagram of the system, which consists of two main parts, which are the PV panel and Arduino Uno, which is used as a microcontroller to control the duty cycle of the converter. An interfaced circuit was designed to integrate the low-voltage part (Arduino Uno) with the high-voltage part (converter) by providing electrical isolation.

A power supply unit was used as a battery in this experiment which means only the discharging process was applied. A step-up Cuk converter was chosen to boost the output voltage to maximize efficiency. In addition, it does not suffer from resolution problems since it is always in step-up mode. It has some benefits, for instance, continuous input and output current, which leads to a reduction in the voltage

ripples which means less noise level due to switching and as a result, it improves efficiency. The duty cycle of the step-up Cuk converter is controlled by Arduino Uno, while the current and voltage come from the PV panel as a power source. On the other hand, it supplies the necessary power to the load, as shown in the figure. The two main parts will be explained in detail in the next sub-sections:
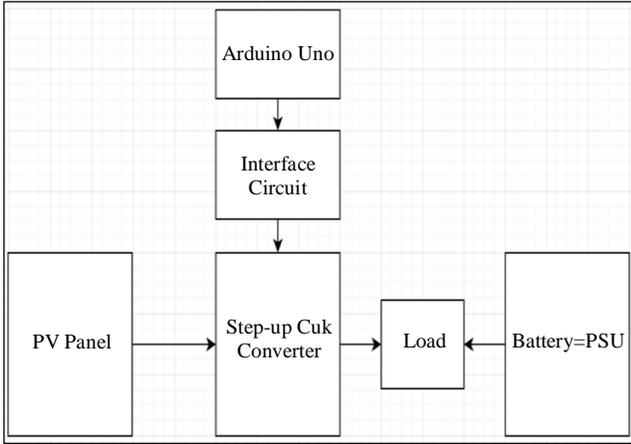
Fig. 4 Block diagram of PV power conversion system with energy storage and control unit

3.1. PV Power Conversion System with Energy Storage Design

A Step-up Cuk converter is a key element that increases the output voltage that comes from the solar panel. This part is going to focus mainly on the step-up Cuk converter block, while the PV Panel block and PSU are only going to be highlighted as power sources because the converter design is the crucial part, and its design and factors need to be discussed carefully to shed lights on the importance of the optimized system. There are six electronic components in the Step-up Cuk converter, which are one transistor (S), one diode (D), two capacitors (C_n and C_o) and two inductors (L_1 and L_2), as presented in Figure 5.

The transistor (S) is a very important component since the duty cycle can be set through it by adjusting Pulse Width Modulation (PWM) which means it is the interface to connect the control unit with the converter. The diode (D) ensures that the current is continuous during the off state of the converter, which happens when the transistor is opened and no current flows through it. As a result, this assists in protecting other electronic components in the circuit from getting destroyed. The output capacitor (C_o) is used to filter the output voltage by removing the ripples and noises, which keeps the output voltage and current relatively constant and as a result, the load will be protected from voltage sparks. The input capacitor (C_n) transfers the energy from the input to the output during on and off states. Both inductors (L_1 and L_2) are used to store and release energy during on and off states [7]. The PV panel (V_s) is used as a power source for the load (R) in the circuit.
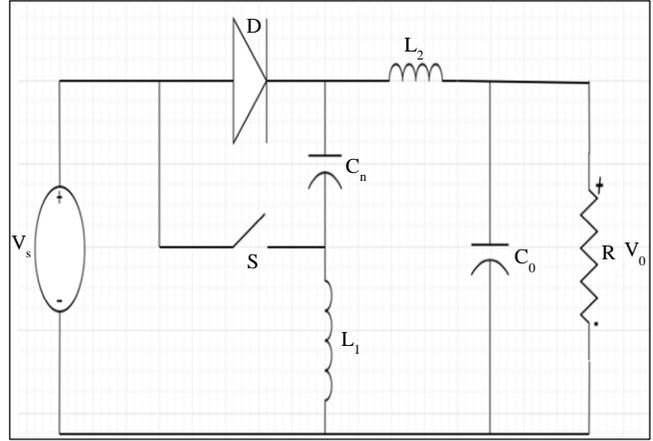
Fig. 5 Circuit of step-up cuk converter

Table 2 highlights the most optimized values of the electronic components implemented in the experiment.

Table 2. Component values in the converter

Parameters	Symbols	Values
Inductor 1	L_1	2.2 mH
Inductor 2	L_2	2.2 mH
Output Capacitor	C_o	10 μF
Input Capacitor	C_n	10 μF

3.2. Control Unit Design

Arduino Uno is considered the fundamental element in the control unit where it is used to control the duty cycle by generating a Pulse Width Modulation (PWM) in the closed-loop system. The duty cycle (K) is a value between 0 and 1, which represents an increase in the output voltage, as shown in the below equation:

$$\frac{Vo}{Vs} = \frac{1}{1-K} \tag{1}$$

Therefore, as the duty cycle gets close to one, the output voltage gets higher. Arduino Uno controls this value in the closed-loop system to maximize efficiency since the measured value under practical conditions is less than the calculated value in Equation 1. This is due to the dissipated current and voltage in the electronic components. Figure 6 depicts the block diagram of the control unit where the Nokia 5110 LCD is used with Arduino Uno to monitor the system by printing the main measured values. As a result, this assists in noticing abnormalities in the system's behaviour while implementing the closed-loop system. Arduino Uno was chosen as a microcontroller because it can be integrated easily with the LCD since it consists of an 8-bit microcontroller as presented. Furthermore, it executes generating a PWM signal by ATmega328, which is a high-performance microcontroller that has (32 KB) of flash memory. Also, the operating voltage is (5 V) [8].
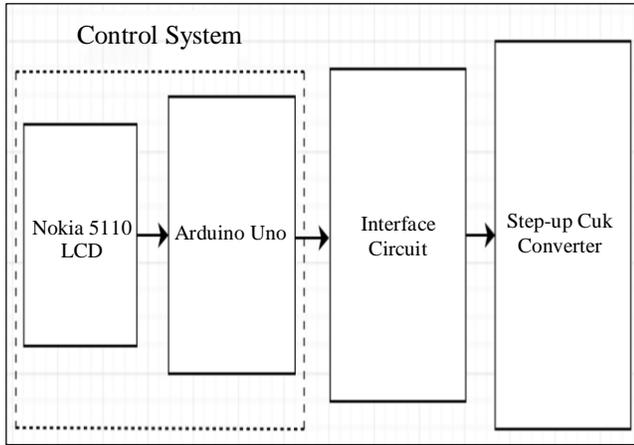
Fig. 6 Block diagram of the control unit and interfaced circuit

Table 3 shows the Nokia 5110 LCD pinout that was used to integrate the LCD with Arduino Uno.

Table 3. Nokia 5110 LCD pinout

Pin	Function
VCC	Positive Voltage
GND	Ground
SCE	SPI Slave Chip-Enable
RST	Reset
D/C	Data/Command Select
MOSI	SPI Master-out/Master-in
SCLK	SPI Clock
LED	LED Backlight

As per the LCD datasheet, a resistor was used to protect the LCD from any high voltage, as presented in Figure 7. Figure 7 shows the connections between all the pins in the LCD with Arduino Uno.
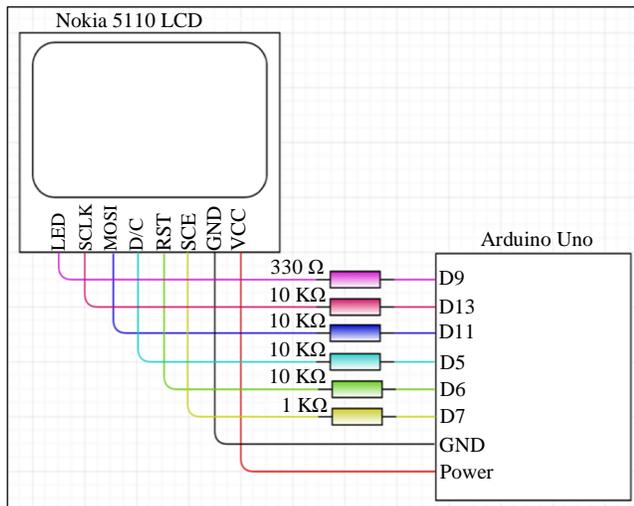
Fig. 7 Nokia 5110 LCD connections

An interfaced circuit is required to integrate the low-voltage system, which is Arduino Uno, with the high-voltage system which is the converter. This integration was formed by providing an electrical isolation between the two systems. The interfaced circuit consists of four components which are an optocoupler, two voltage regulators and a battery pack. As depicted in Figure 8, the optocoupler integrates Arduino Uno with the converter through the transistor (S) to choose the output voltage value by setting the PWM.

As observed in Figure 8, (15V) voltage is required to power up the optocoupler. This was achieved by attenuating the voltage that comes from the battery pack from (12V) to (5 V) by using the LM1085IT voltage regulator. After that, the voltage was amplified from (5V) to (15V) by using the IL0515S voltage regulator.
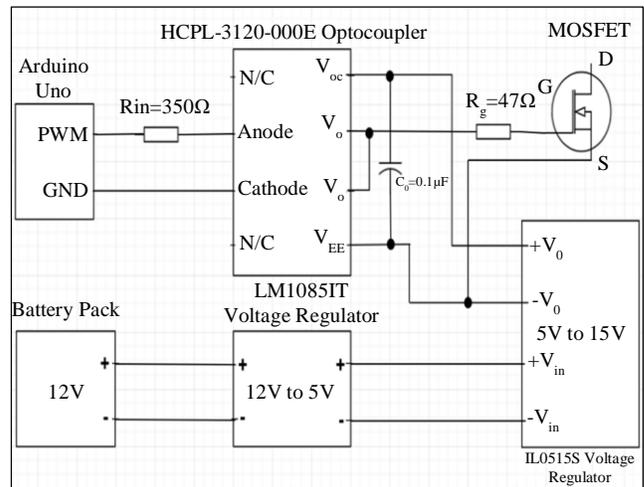
Fig. 8 Block diagram of an interfaced circuit

An input resistor (R_{in}) was added in order to protect the optocoupler from any inrush current. Furthermore, a ground resistor was added to minimise switching losses and prevent overcurrent. Finally, an output capacitor (C_o) was used to remove any voltage ripples coming from the voltage regulator [9, 10].

4. Implementing and Testing the PV Step-up Power Conversion System with Energy Storage and Control Unit

After discussing the design and methodology in the previous section, this section highlights the implementation and test results for the Step-up Cuk converter, as it is one of the crucial parts of the whole system. The tests were done in two different methods which are an open and closed system. The open-loop test represents the system without taking the actual output current as feedback to be compared with the desired input current to achieve the desired output voltage. On the other hand, the closed-loop test is a test where the system takes some measurements by using current and voltage

sensors in order to use these measurements to get the feedback and then use it to adjust input again to achieve the desired voltage. The two systems will be compared with each other in detail in the below sub-sections.

4.1. Open-Loop System

The open-loop system contains Arduino Uno, a Step-up Cuk converter and a PV panel as a power source, as presented in Figure 9. In the system, Arduino Uno was used to generate the PWM signals to set the value of the duty cycle to provide an output current and voltage to operate the load. These two outputs were not used as feedback to enhance the performance of the system, which means the actual output voltage is less than the desired output voltage.
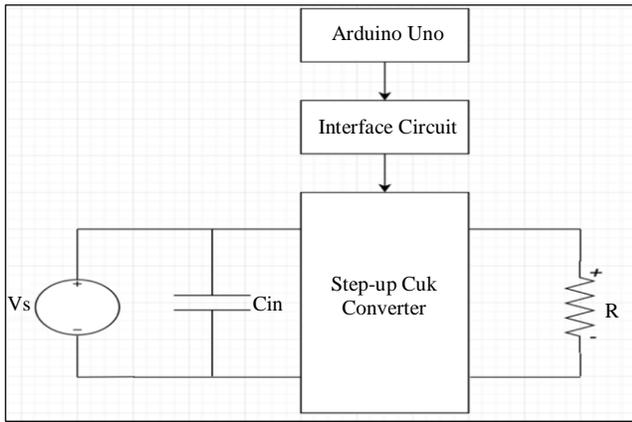
Fig. 9 Open-loop system diagram

During the implementation of the open-loop system, the output voltage (V_o) and current (I_o) were tested by using a multimeter through a (100Ω) load. The input voltage (V_{in}) was controlled in the PV panel by changing the light intensity in a lamb as a light source. The intensity value was set to get three different input voltages (V_{in}) in the experiment, which are (5V), (7.5V) and (10V). In addition, the duty cycle (K) was modified between (20%) and (50%) in Arduino Uno.

Therefore, the input current was calculated by Equation 2 since all other values were measured by the multimeter or set by the light intensity:

$$\frac{Is}{Io} = \frac{Vo}{Vs} = \frac{1}{1-K} \tag{2}$$

As depicted in Table 4, when the duty cycle (K) increased, the actual output voltage (V_o) increased. Furthermore, the theoretical input current (I_{in}) and output voltage (V_o) were calculated by using Equation 2 to compare them with the practical input current (I_{in}) and output voltage (V_o). Therefore, the results show as the duty cycle (K) or input voltage (Vin) increased, the error, which represents the difference between theoretical and practical output voltages (V_o) increased due to the conduction losses. The same tests were conducted with higher loads, which are (150Ω), (300Ω) and (450Ω). As a result, the performance was improved as expected since more output voltage dropped in the load which resulted in less error.

4.2. Closed-Loop System

The closed-loop system consists of an Arduino Uno, a Step-up Cuk converter, a PV panel, and two voltage sensors to measure the input and output voltage to do some calculations by using Equation 3 to use the actual input current as feedback to develop the system efficiency. The input current leads to adjust the duty cycle to get the desired output voltage. Figure 10 shows the block diagram of the closed-loop system where voltage sensor 1 measures the from the PV panel in order to get the desired actual current by using ohms law while voltage sensor 2 measures the output voltage dropped in the load in order to get the actual voltage.

The system then uses Equation 3 to calculate the actual input current based on the measured input voltage and the desired output voltage. This actual input current is fed back to the control algorithm, which adjusts the duty cycle of the Step-up Cuk converter to regulate the output voltage and achieve the desired system efficiency.

Table 4. Error estimation after implementation of the open-loop system

K	V_{in} (V)	V_o (V) Theoretical	V_o (V) Practical	Error	I_o (mA) Practical	I_{in} (mA) Theoretical	I_{in} (mA) Practical
20%		6.25	5.50	0.75	54	78	65
40%	5	8.33	7.37	0.96	70	139	117
49.8%		9.96	8.75	1.21	85	198	172
20%		9.38	8.49	0.89	83	117	104
40%	7.5	12.50	11.27	1.23	109	208	182
49.8%		14.94	13.26	1.68	129	298	261
20%		12.50	11.61	0.89	114	156	141
40%	10	16.67	15.33	1.34	153	278	250
49.8%		19.92	18.02	1.90	178	397	355
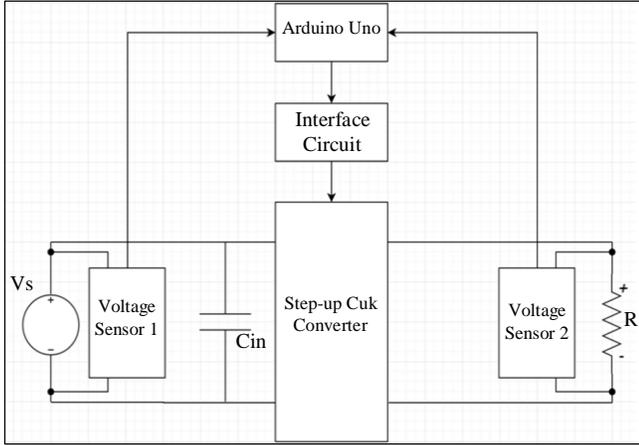
Fig. 10 Closed-loop system diagram
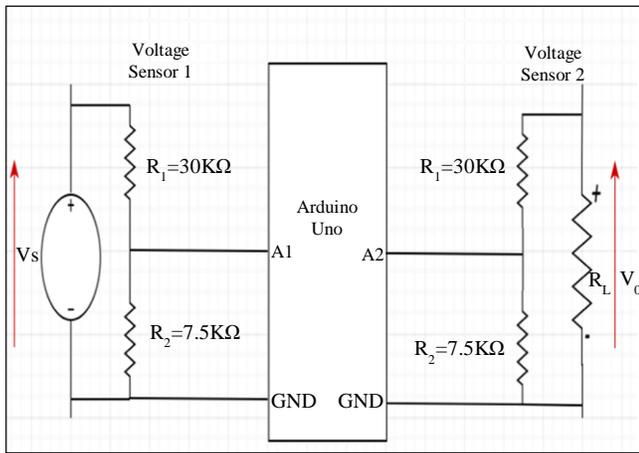
Fig. 11 Voltage sensors in the converter

The voltage sensors are basically potentiometers that measure the dropped voltage across (R_2). Then, the measured voltage will be divided by the ratio of the two resistors, as shown in Figure 10. Arduino Uno is connected to the two sensors, which means the algorithms and codes will implement all the necessary calculations to measure all the input and output current and voltage. Figure 11 presents a block diagram for the two sensors where they started by measuring the voltage across the potentiometer while the operator already defines the duty cycle. After that, Ohm's law was used to calculate both output currents. Then, Equation 3 was used to get the desired input current (I_{in1}) and the actual current (I_{in2}).

In the next stage, Arduino Uno uses another code and algorithm to calculate the error that represents the difference between the desired and actual currents. After that, Arduino Uno uses the calculated error to update the duty cycle ($K_{updated}$), which leads to a reduction in the difference between the actual output voltage and the desired output voltage, as presented in Figure 12. This process repeats itself until the error between the actual input current and the desired input

current is zero. As a result, this means the actual output voltage is going to be close to the desired output voltage. Therefore, Arduino Uno is a critical element in the closed-loop system since it implements all the required operations for instance, measuring and calculating all the parameters to generate the PWM to update the duty cycle to get the desired output voltage.

Another test was implemented under the same conditions as in the open-loop system in order to compare both results with each other and notice the enhancements and improvements in efficiency and performance easily. Therefore, the same components were used which are the PV panel, light source, Arduino Uno and a load. The input voltage was set to be in these three values, which are (5V), (7.5V) and (10V).

Table 5 shows the results after implementing the closed-loop- system. The results present that the actual output voltage (V_o) is much closer to the desired output voltage, where the error, which represents the difference between the actual and desired values, gets reduced significantly by almost (80%). Furthermore, the table presents the updated duty cycle value in the first column to get the desired value where it increased as per the code in Figure 13. In addition, the closed-loop system has better performance at low duty cycle and input voltage (V_{in}) due to less conduction losses.
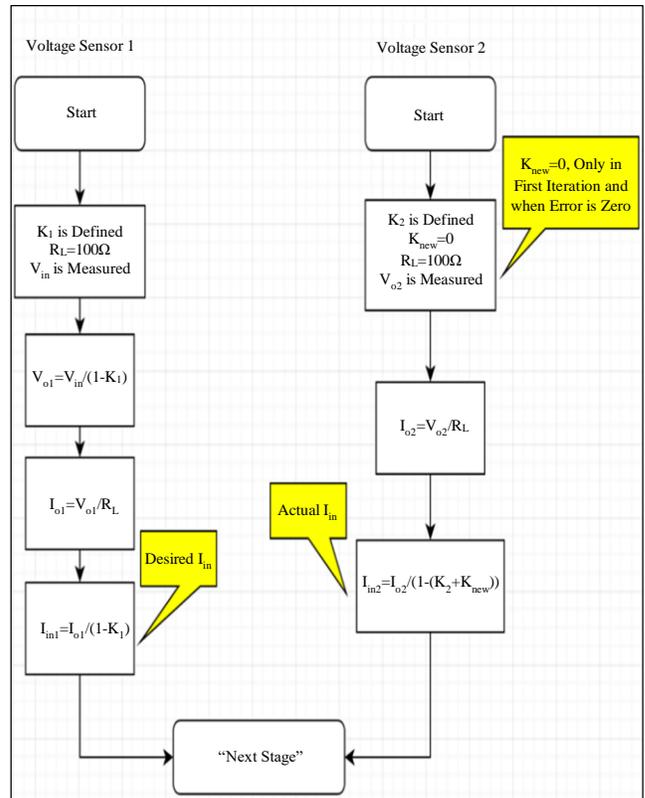
Fig. 12 Flowchart of a calculation process for the desired and actual
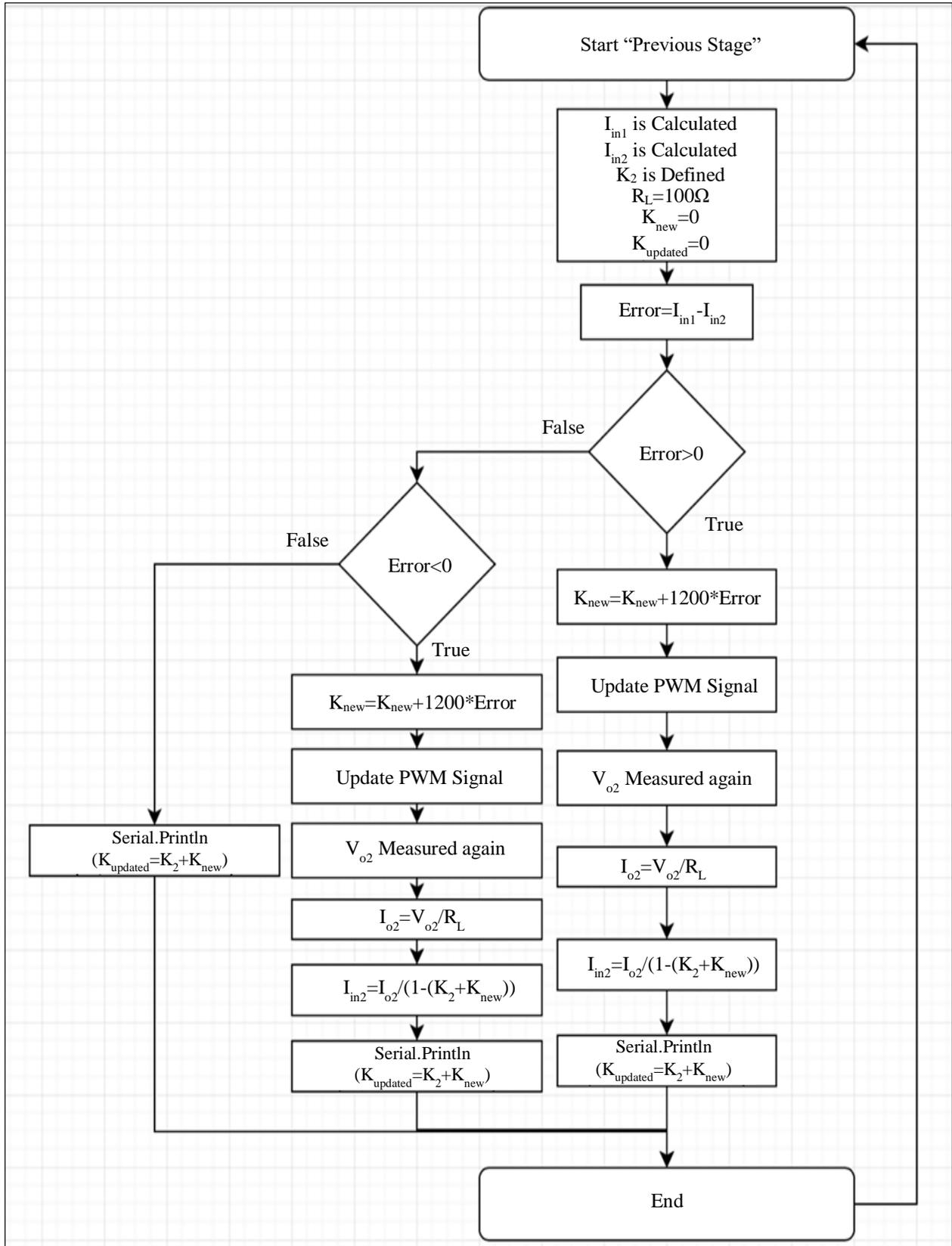
Fig. 13 Flowchart of the closed-loop system

Table 5. Error estimation after implementation of the closed-loop system

K Updated	V_{in} (V)	V_o (V) Desired	V_o (V) Actual	Error	I_o (mA) Actual	I_{in} (mA) Desired	I_{in} (mA) Actual
27.5%		6.25	6.15	0.10	62	78	79
35.5%	5	8.33	8.13	0.20	82	139	140
54.6%		9.96	9.64	0.32	97	198	199
25.5%		9.38	9.15	0.89	93	117	117
43.4%	7.5	12.50	11.96	0.23	121	208	206
54.6%		14.94	14.18	0.76	144	298	294
24.5%		12.50	12.15	0.35	124	156	155
43.7%	10	16.67	16.21	0.46	165	278	273
53.3%		19.92	18.92	1.00	193	397	391

Finally, the actual values cannot be exactly as the desired values which means the error will not reach zero, but it will get close to it. This is because Arduino Uno has only 8 bits, which results in some limitations when numbers are converted from binary to decimal and the other way around, which means Arduino Uno cannot generate all decimal numbers. For example, Arduino Uno cannot generate a duty cycle (50%), but it can generate a value close to it, which is (49.8%). This can be solved by using a microcontroller with a higher bit number, but this kind of microcontroller consumes more power.

5. Future Enhancements

Several ideas can be implemented with the system to enhance its performance and the way of monitoring the operation. For example, the Internet of Things can be used to improve monitoring by utilizing the Internet to control the system with a remote device such as a tablet or computer. This can be enabled by using one of the Internet of Things platforms for instance, Blynk, where it provides multiple libraries to be used with common portable devices such as phones, tablets, or computers. These libraries help to integrate two different systems that utilise different languages [11]. Moreover, another enhancement can be applied, which is using a server instead of Arduino Uno. This can be used for large converters in companies that need to manage the convertor operation carefully by saving logs and implementing very complete algorithms. The servers can be connected to set computers through the company network, which helps the system administrators manage the converter [12].

6. Conclusion

In summary, this paper presented how to develop an optimized PV power conversion system with energy storage and control unit by highlighting the PV characteristics, system design and results of the operations and tests. This power is developed to maximize the power generated from the PV panel and to address dissipated power issues during step-up power conversion. As a result, this ensures high power reliability and availability.

Furthermore, the behaviour of the solar panel was explained by presenting the characteristics of the I-V and P-V curves. In addition, the topology of the system was illustrated by explaining the design of the two main parts which are the PV power conversion system and Arduino Uno as a control unit.

Moreover, a comparison was made between the open-loop and closed-loop systems under the same conditions to show the enhancements and improvements by applying the closed-loop system. This comparison proves that the system was optimized by taking measurements and calculations as feedback to develop the input of the system to achieve the desired outcome.

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