MJSAT

Malaysian Journal of Science and Advanced Technology

journal homepage: https://mjsat.com.my/

Enhancing Solar Panel Efficiency via MPPT with CUK Converter

Nur Atiqah Adilah Binti Kamarozaman[1], Jabbar Al-Fattah Bin Yahaya *[1]

[1] *Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia, Parit Raja, 86400, Malaysia.*

KEYWORDS

PV System
DC-DC Converter
MPPT Algorithm
PWM

ARTICLE HISTORY

Received 16 February 2026
Received in revised form 8 March 2026
Accepted 19 March 2026
Available online 27 March 2026

ABSTRACT

This project focuses on improving the efficiency of photovoltaic (PV) systems through the development of a CUK converter integrated with the Maximum Power Point Tracking (MPPT) algorithm. This is because the increasing global emphasis on renewable energy has caused the reliability and efficiency of solar energy systems to become increasingly important. Although conventional boost converters used in PV systems have shown good performance, they still fail to achieve optimal power extraction under varying irradiance conditions. This failure has also been the main cause of interrupted input current and even increases the voltage stress on the switch. Therefore, the use of a CUK converter has been introduced in this project to address the limitations that have been encountered by providing a smoother output and reducing the ripple effect. In the implementation of this project, the main objective is to increase the input current generation and energy efficiency by 2-5% across different irradiance conditions while minimizing the voltage stress on the converter components. Therefore, a systematic flow chart has been developed to ensure the smooth implementation of this project by identifying critical areas that require more attention. The implementation of this project also outlines a comprehensive methodology that includes a detailed literature review to identify gaps between knowledge followed by design and simulation for CUK converters using advanced software tools such as MATLAB Simulink and Proteus 8 Professional.

1. INTRODUCTION

In reaching this era of globalization and modernization, the development of renewable energy has become the main focus around the world where it is used to reduce dependence on fossil energy sources. This can be proven through the use of a photovoltaic (PV) system which is a technology that uses sunlight [1] as the main medium to produce electricity. This rapid development has also attracted attention from various countries including Malaysia to launch several initiatives and policies that encourage the use of this renewable energy more often. Among the largest solar farm use in Malaysia are located in Kuala Langat, Selangor where it is able to accommodate capacity of 50MW [2]. The existence of this solar farm has also encouraged the implementation of the Feed-in Tariff (FiT) program in Malaysia where it offers many benefits to the Malaysian government and even gives incentives to solar farm owners with a fixed payment rate for each unit of electricity generated and channeled into grid.

However, this PV system also affected by the use of the Maximum Power Point Tracking (MPPT) algorithm [3], [4] where it plays an important role in ensuring that the PV system operates with high efficiency and can maximize energy production despite weather changes. Usually, the use of this algorithm is applied in the DC-DC converter part of the PV system, especially when it involves charging the battery so that it can control the output voltage and current to maximize the charging of the battery from the solar panel. This also aims for the battery to be charged in the most efficient way even can increase the energy storage capacity.

Other than that, the use of different types of DC-DC converters [5], [6] is also one of the factors that affect the performance of the PV system in terms of energy harvesting efficiency, voltage regulation and also power transfer capability. This is because each type of DC-DC converter used in the PV system has its own operating principle and method to transfer or convert power according to load requirements.

*Corresponding author:
E-mail address: Jabbar Al-Fattah Bin Yahaya < jabbar@uthm.edu.my >.
https://doi.org/10.56532/mjsat.v6i1.719
2785-8901/

For example, a boost converter has an operating principle capable of increasing the input voltage to a higher output voltage. Through this principle, it has made this type of converter more suitable for systems that require a higher output voltage from PV panels to meet the needs of loads or other components. The voltage transformation capability of each type of DC-DC converter used is also one of the reasons for the difference in results obtained in PV systems. This is because each type of DC-DC converter design has its own functionality and characteristics causing it to have a limit to produce the output voltage. For example, a boost converter only works to increase the voltage level efficiently but it cannot decrease the voltage [6]. This will be the main cause of the problem if the load requires less voltage during high irradiance conditions.

To overcome these limitations, alternative converter topologies such as the CUK converter have been introduced. The CUK converter offers the capability to both step-up and step-down voltage while maintaining a continuous input and output current, which significantly reduces current ripple and improves overall system stability [7],[8],[9],[10]. In addition, the use of energy transfer capacitors in the CUK topology allows for smoother power delivery and lower electromagnetic interference compared to conventional converters. Therefore, the CUK converter is considered a suitable choice for photovoltaic applications, especially under varying irradiance conditions where stable and efficient power conversion is required. Based on these advantages, this project aims to explore, evaluate and implement the CUK converter integrated with MPPT techniques to enhance the performance and efficiency of the photovoltaic system.

2. METHODOLOGY

2.1 Project Flowchart

A flowchart is a visual representation that shows steps, activities and decision points in a project implementation. It uses standard symbols such as circle, rectangles, diamonds and arrows to outline the workflow or process from start to finish by providing a clear explanation of how the project will progress. However, each standard symbol used also has its own function where circle represents the start or end, rectangle represents a process or activity, diamond represents a decision point and arrow represents the flow of activities. This is to ensure that the implementation of the project is always well-organized, transparent and manageable so that the project goals are more easily achieved. Furthermore, the use of this flowchart is also very helpful in identifying critical or risky areas that may need more attention. In the implementation of this project, this flow chart is used to plan, analyze and deliver the steps required to achieve the project objectives which can be seen in Figure 1.

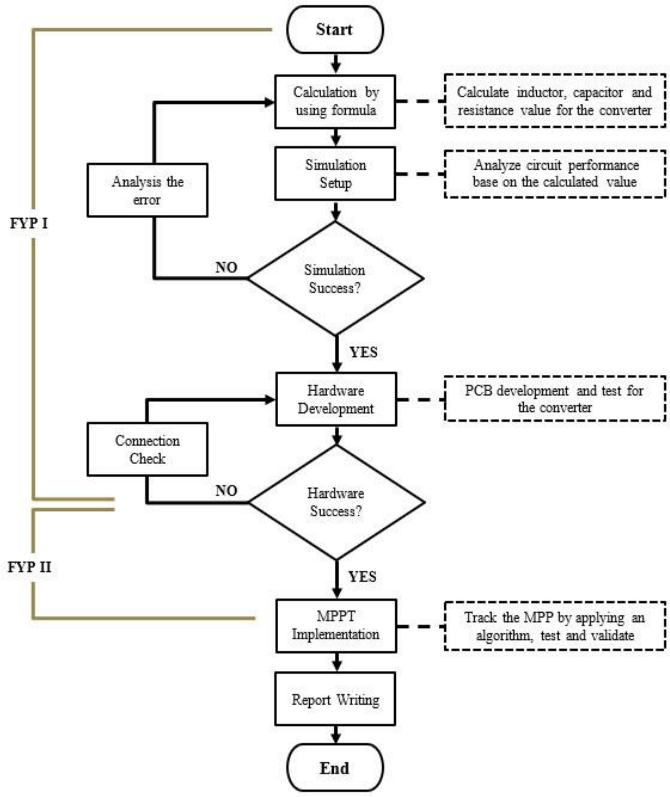

Fig. 1. Flowchart of the project implementation

2.2 Manual Calculation

In the implementation of this project, this manual calculation is used to determine the duty cycle (D), inductor and capacitor values for the CUK converter based on the formula equation below [7],[9].

For Voltage Conversion Ratio :

$$M = \frac{V_o}{V_{in}} = -\left(\frac{D}{1-D}\right) \quad (1)$$

For Inductor Selection :

$$L = \frac{V_{in} \cdot D}{f \cdot \Delta I_L} \quad (2)$$

For Capacitor Selection :

$$C_1 = \frac{I_{in} \cdot (1-D)}{f \cdot \Delta V_{C1}} \quad (3)$$

$$C_2 = \frac{V_{in} \cdot D}{8f^2 \cdot \Delta V_{C2} \cdot L_2} \quad (4)$$

This is to ensure that the converter can operate more optimally and efficiently by taking into account the main design inputs such as input and output voltage, switching frequency and the level of ripple allowed in both current and voltage. Through this method, it can be concluded that the values obtained for D = 0.58, L_1= 0.7 mH, L_2= 0.9 mH, C_1 = 15.65 uF and C_2 = 0.81 uF. However, the selection of inductor and capacitor component values for the implementation of this project is subject to L_1= L_2= 4 mH, C_1 = 140 uF and C_2 = 200 uF due to the calculation values not being available in the market and choosing the closest standard commercial values which may differ slightly from the calculated values.

2.3 Software

2.3.1 MATLAB Simulink

In the implementation of this project, this software used as a tool to design CUK converter circuits with component behavior in detail [11]. This aims to analyze the performance of the converter in terms of efficiency, voltage regulation and power quality virtually based on the value of inductors and capacitors, switches and diodes that have been selected. However, the setting of inductor and capacitor values for this converter needs to be done by manual calculation first using the formulas in (1), (2), (3) and (4). With the use of this software, it can help users to identify and resolve design issues early in the development process and even save costs associated with prototype failures. Therefore, the use of this software is very important in the implementation of this project to avoid the issues as mentioned. The simulation setup for the implementation of this project can be found in Figure 2.

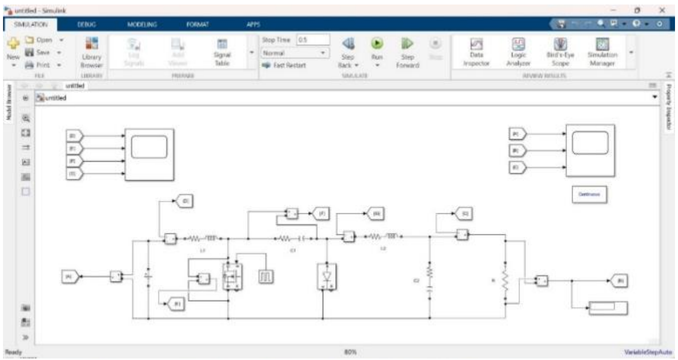

Fig. 2. Simulation Setup for this project implementation

By refer to the Figure 2, it depicts a Simulink model of a CUK converter used as a simulation to analyze the behavior of selected components when converting DC input voltage to DC output voltage. This circuit connection is also built based on the topology theory for DC-DC converters which explains how the converter operates under normal conditions. However, to simulate a more realistic circuit behavior, the existing circuit needs to be modified by adding small resistors in series with both the inductor and capacitor as shown in the Figure 2. This is intended to model the losses that are naturally present in real components and help in stabilize the simulation by dampening noise or high-frequency oscillations that can occur during the conversion event. Furthermore, the MOSFET is operated using a PWM signal where it controls the switching time and thus effectively controls the output voltage. Measurement block also included in the model to capture and display important electrical parameters such as input and output for voltage and current. These measurements are important for analyzing and evaluating the performance of the converter. Overall, this simulation setup provides a comprehensive and realistic environment to study the dynamic behavior and efficiency of the CUK converter under various operating conditions.

2.3.2 Protues 8 Professional

In the implementation of this project, this software used as a tool to design a CUK converter circuit on a PCB layout [12]. This is because this software has a function where it supports auto routing for efficient track routing and manual adjustment for critical signals. This functionality greatly assists users in finding and arranging the shortest or most efficient routing path for each component connection involved. Furthermore, it also indirectly benefits users in reducing the possibility of human error in routing, reducing trace length and improving signal integrity. Therefore, the use of software is very important in the implementation of this project to obtain an efficient PCB design. The PCB design for the implementation of this project can be found in Figure 3.

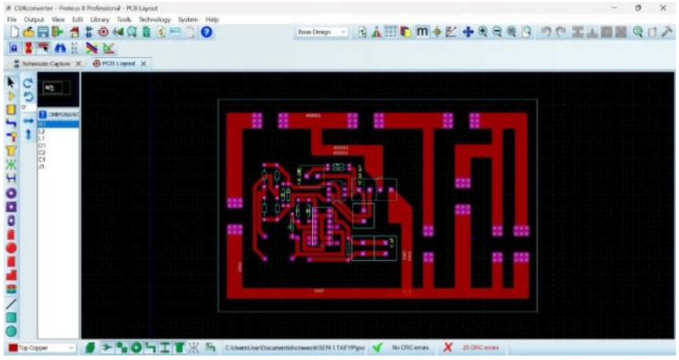

Fig. 3. PCB Design for this project implementation

By refer to the Figure 3, it illustrates the PCB layout through Proteus 8 Professional software for the proposed CUK converter. In this layout, the red line represents copper to handle the current flow. This copper line also deliberately designed with increased thickness on the PCB layout to minimize resistance and support smooth flow of high input and output currents which means it can improve the efficiency and reliability of the overall power circuit. Furthermore, core components such as inductors (L_1 and L_2), Capacitors (C_1 and C_2) Diodes and MOSFET switches are also arranged according to the desired PCB size to avoid congestion and it can also help reduce electromagnetic interference and conduction loss. This PCB circuit design is also built based on the topology theory for DC-DC converters which explains how the converter operates under normal conditions. However, it has been modified according to the implementation needs of the project which requires a gate driver circuit to control the switching device as can be seen in Figure 3.

2.4 Hardware Configuration

2.4.1 CUK Converter and MPPT Controller Setup

In this project, the Arduino Uno serves as the main controller that executes the MPPT algorithm which is P&O and INC to maximize the efficiency of the solar panel. It collects voltage and current readings from dedicated sensors such as voltage sensor and current sensor that connected to the solar panel and load. By using this data collection, the Arduino will calculate the power output and adjusts the CUK converter operation through a driver circuit where this converter is responsible for regulating the voltage by either stepping it up or down depending on the required output to maintain optimal power transfer. Furthermore, the driver circuit also helps in amplify the Arduino control signals to properly switch the power components in the converter. Altogether, these hardware components work in synchronize to keep the solar panel operating at its most efficient power point. For detailed hardware configuration for the implementation of this project can be found in Figure 4 and Figure 5.

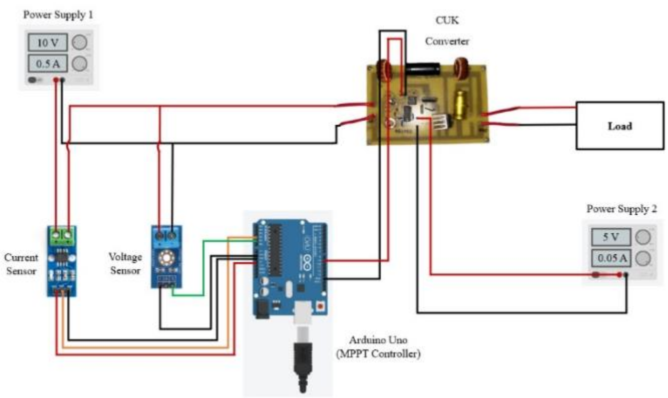

Fig. 4. Connection Circuit for CUK Converter and MPPT Controller Setup

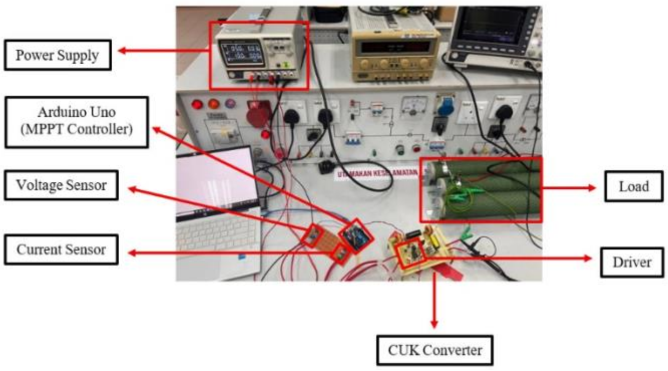

Fig. 5. CUK Converter and MPPT Controller Setup

2.4.1 CUK Converter and MPPT Controller Setup

In this project, two PV solar panels are connected in parallel to increase the current output while maintaining the same voltage. These panels then will be connected to a DC-DC converter which is CUK converter where it will function to adjust the received voltage to the suitable level according to the load requirements. To support the effective operation of this project, spotlights are used to represent irradiance condition which is set at 1000 W/m². This value is selected because it represents a "full sun" condition that commonly used in Standard Test Conditions (STC) for evaluating the performance of solar PV panels. By using 1000 W/m², the setup mimics the maximum irradiance intensity that typically reaches the Earth surface under clear sky conditions at sea level. This ensures that the PV panel receives consistent and optimal lighting for accurate testing and performance analysis. Other than that, an MPPT controller is also used in this project to continuously monitor the voltage and current from the solar panels and determine the point where the panel can produce maximum power. Then, it will send a control signal to the converter to adjust its operation so that the system always produces the highest possible power from the solar panels. Furthermore, this setup also aims to ensure efficient energy conversion and stable power delivery to the load, making it a common and effective configuration in solar energy applications. For detailed hardware configuration for the implementation of this project can be found in Figure 6 and Figure 7.

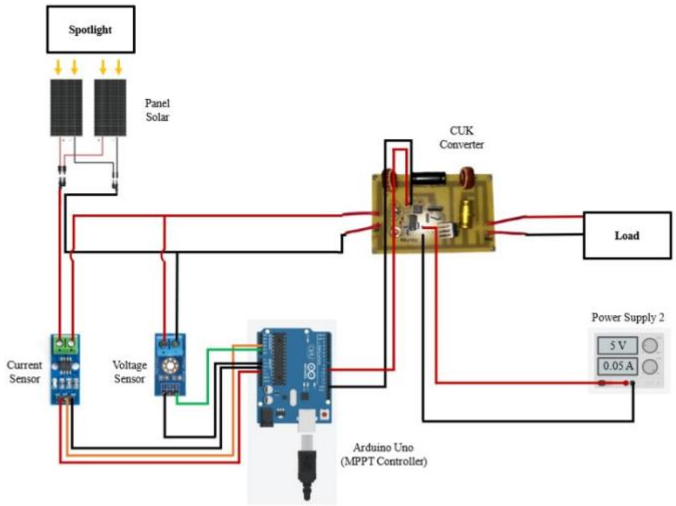

Fig. 6. Connection Circuit for Solar Panel Setup

Fig. 7. Solar Panel Setup

3. RESULT AND DISCUSSION

3.1 Verification of PWM Signal Generation via CUK Converter with Load

Based on the test observations, students found that the PWM signal generated by Arduino Uno successfully controlled output voltage of the Cuk converter at D values equal to 30%, 40% and 50% when the frequency is equal to 800 Hz. Although the initial frequency setting for this project was 85 kHz, students found that operating at a frequency below 1 kHz produced more stable waveform output compared to higher frequency values. This can be proven through Figure 8, Figure 9 and Figure 10 which show the maximum output voltage waveform for each set value of D.

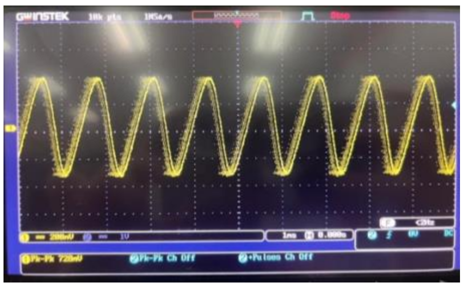

Fig. 8. PWM signal via CUK Converter with Load when D = 30%

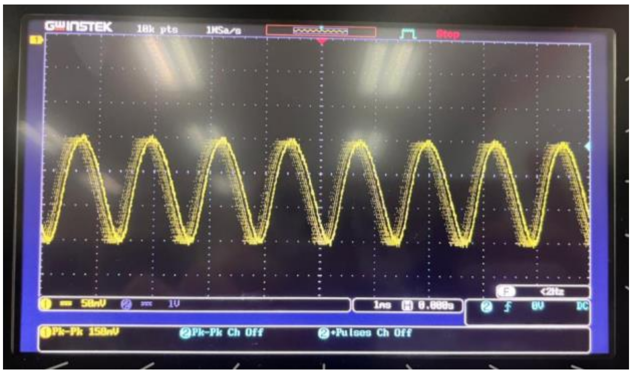

Fig. 9. PWM signal via CUK Converter with Load when D = 40%

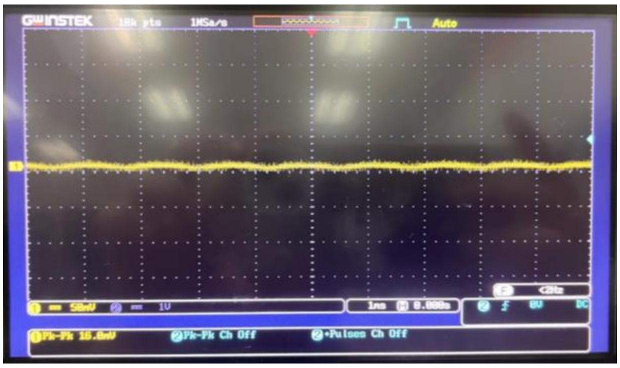

Fig. 10. PWM signal via CUK Converter with Load when D = 50%

However, the results obtained from this converter show an AC-like waveform where a clear sinusoidal shape with a significant peak-to-peak voltage can be observed on the oscilloscope. This behavior deviates from the theoretical operation of a DC-DC converter which is expected to produce a pure DC output voltage. The main reason for this AC waveform is because the CUK converter operates very fast without adequate filtering and causes the high frequency components of the switching signal to not be fully smoothed out and then produce a waveform that appears sinusoidal.

When the value of D is increased to 40% and 50%, the output results appear to be progressively smoother as can be seen in Figure 9 and Figure 10. This also indirectly proves that more energy is being transferred in each D and cause the filter able to smooth the output. However, the selection of the output capacitor and inductor values also plays a very important role for the switching frequency and load resistance given. This is because without the appropriate values, the converter may not be able to filter high frequency ripples effectively and cause the output to look like an AC signal. Therefore, in this case, this AC waveform is not a true alternating signal but the result of high ripple due to inadequate filtering in the converter output stage.

3.2 Verification of I-V Characteristic on Solar Panel

Based on observations from the tests, student found that the current-voltage (I-V) characteristic curve of PV solar panel follows a predictable pattern where the current decreases when the voltage increases. This can be proven through Figure 11 and Figure 12 where the behavior of this curve is in line with the principle of the PV effect. The highest current can be seen when the voltage is zero (short circuit condition). However, when the voltage increases, the current gradually decreases and reaches zero when the voltage reaches the open circuit voltage (V_{OC}) where it indicates no current flow. The MPP is identified at a voltage of approximately 12.6 V and a current of 0.32 A as shown in Table 1 where the product of voltage and current produces the most efficient power output.

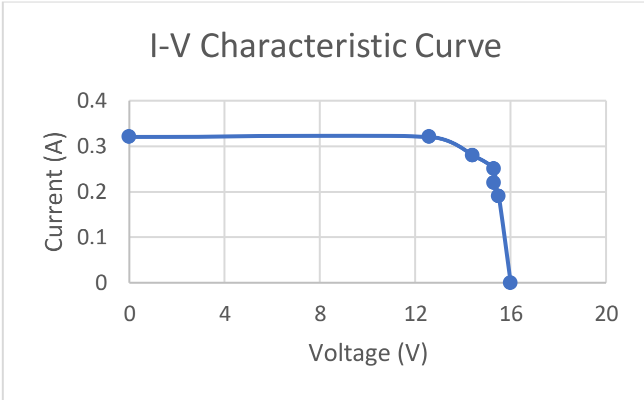

Fig. 11. I-V Characteristic Curve on Solar Panel

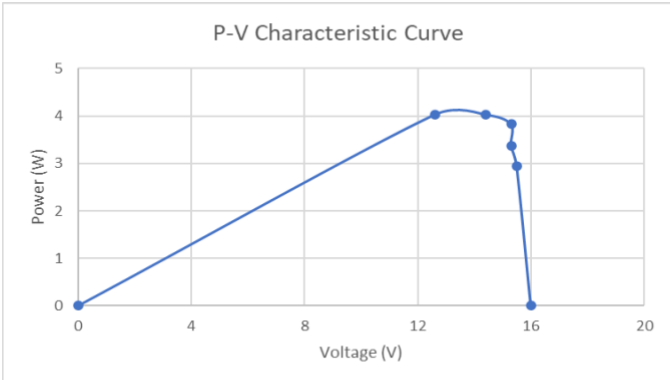

Fig. 12. P-V Characteristic Curve on Solar Panel

Table 1. Data collection for I-V Characteristic Curve on Solar Panel

Voltage (V)	Current (A)	Power (W)
0	0.32	0
12.6	0.32	4.03
14.4	0.28	4.03
15.3	0.25	3.83
15.3	0.22	3.37
15.5	0.19	2.95
16	0	0

3.3 Verification of Voltage, Current and Power via CUK Converter without MPPT

From the test observations, students found that the waveform displayed by the PV system voltage output remained relatively stable and followed a repetitive oscillation pattern. This can be proven through Figure 13 where this behavior shows that the system is running without an MPPT algorithm. In this case, the PV panel is simply outputting voltage based on its natural characteristics which are influenced by the available irradiance and the connected load.

There is no feedback or control mechanism used to adjust the system to operate optimally. Therefore, the output voltage tends to settle at a fixed level which may not correspond to the panel's MPP. This waveform also reflects the uncontrolled nature of the system because energy extraction depends only on external conditions rather than internal optimization.

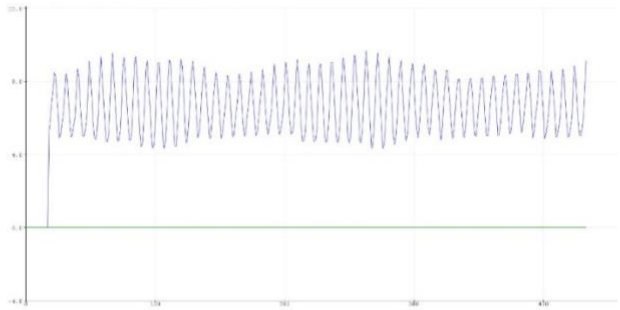

Fig. 13. Voltage waveform without MPPT algorithm

Furthermore, through the theory of PV systems, students learn that solar panels have a unique I-V characteristic curve, and there is a point on this curve representing the MPP, which is the product of voltage and current at its peak. The main purpose of this MPP is to ensure that the system delivers as much power as possible. However, without an MPPT controller, the system does not have the ability to adapt to changes in solar radiation or temperature. As a result, the constant voltage output shown in Figure 13 proves that the system does not respond to environmental variations and is likely to operate inefficiently. This observation also indirectly emphasizes the importance of MPPT in solar energy systems, especially in dynamic conditions where environmental factors change throughout the day.

3.4 Verification of Voltage, Current and Power via CUK Converter with MPPT

Based on the test observations, students found that the output voltage of the PV system in Figure 14 showed significant variations over time with changes in both amplitude and waveform pattern. This dynamic behavior indicates that the MPPT algorithm is actively controlling the PV system, where it continuously adjusts the operating voltage of the panels in real time and seeks the voltage level at which the power output can be maximized. This voltage variation is not random but part of a controlled process to track the maximum power point. Furthermore, the resulting waveform also reflects the system's ability to respond to fluctuations in irradiance intensity, temperature, or load demand to optimize energy extraction even under changing conditions.

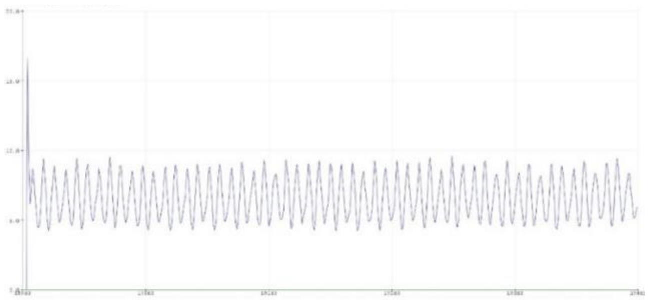

Fig. 14. Voltage waveform with MPPT algorithm

From a theoretical perspective, MPPT algorithms such as P&O or INC work by introducing small changes in the operating voltage and observing the effect on the power output. If the changes made show an increase in power, the algorithm will continue in that direction. Therefore, the voltage appears to oscillate slightly around the MPP as can be seen in Figure 14 which shows that the voltage output is no longer flat as the system is constantly searching for the best operating point to extract maximum energy. This observation also confirms that the MPPT controller is managing the PV system effectively and adjusting it to operate at high efficiency.

4. CONCLUSION

In conclusion, the integration of the CUK converter with the MPPT algorithm has been proven to significantly improve the efficiency of the solar panel system. The experimental results revealed that the system provides better voltage regulation and smoother power output compared to systems that do not incorporate MPPT. The data obtained in this project also shows a significant reduction in ripple effects and increase in power extraction especially when the system adjusts to changes in radiation levels. The I-V characteristic curve also confirms the theoretical prediction that the MPP is observed at 12.6V and 0.32A that confirming the effectiveness of the system.

Furthermore, the performance analysis also shows that the application of the MPPT algorithm together with the CUK converter facilitates real-time adjustments to optimize the energy collection of the solar panels. In contrast, the system without MPPT exhibits stable power output but less efficient. This indirectly further strengthens the critical role of MPPT in solar PV systems as it allows dynamic adjustment to varying environmental conditions and can even maximize power output and increase energy efficiency. The project successfully achieved its goal of increasing system efficiency by 2-5% across different irradiation scenarios, meeting the set objectives and demonstrating the potential of the CUK converter for future solar applications

ACKNOWLEDGEMENT

The authors would like to express their sincere appreciation to the Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia, for their continuous support. The valuable guidance and assistance provided played a significant role in the successful completion of this project.

REFERENCES

[1] K. Mohammad, M. F. Rashid, H. Rahat, F. Khan and K. Rahman, "Detailed Analysis of DC-DC Converters Fed with Solar-PV System with MPPT," 2022 International Conference for Advancement in Technology (ICONAT), Goa, India, 2022, pp. 1-6. doi: https://doi.org/10.0.4.85/ICONAT53423.2022.9725881

[2] "Malaysia Pioneers Large-Scale Solar Project", 2022 World-Energy Cooperation. url: https://www.world-energy.org/article/24055.html

[3] P. Rao, V. Siraswar and B. B. Pimple, "Efficient implementation of MPPT and comparison of converter for variable load Solar PV system," 2017 Second International Conference on Electrical, Computer and Communication Technologies (ICECCT), Coimbatore, India, 2017, pp. 1-6. doi: https://doi.org/10.1109/ICECCT.2017.8117967

[4] S. P. Singh, A. K. Gautam, S. P. Tripathi and B. Kumar, "Performance comparison of MPPT techniques using CUK converter for photovoltaic energy conversion system," 2017 3rd International Conference on Computational Intelligence & Communication Technology (CICT), Ghaziabad, India, 2017, pp. 1-6. doi : https://doi.org/10.1109/CIACT.2017.7977369

[5] K. Mohammad, M. F. Rashid, H. Rahat, F. Khan and K. Rahman, "Detailed Analysis of DC-DC Converters Fed with Solar-PV System with MPPT," 2022 International Conference for Advancement in Technology (ICONAT), Goa, India, 2022, pp. 1-6. doi: https://doi.org/10.0.4.85/ICONAT53423.2022.9725881

[6] V. Magar, S. G. Kanade and A. P. Kinge, "Transformerless Buck-Boost DC-DC Converter," 2018 IEEE Global Conference on Wireless Computing and Networking (GCWCN), Lonavala, India, 2018, pp. 200-203. doi: https://doi.org/10.1109/GCWCN.2018.8668646

[7] B.-R. Lin, C.-L. Huang and J.-F. Wan, "Analysis of a Zero Voltage Switching CUK Converter," IECON 2007 - 33rd Annual Conference of the IEEE Industrial Electronics Society, Taipei, Taiwan, 2007, pp. 1972-1977. doi: https://doi.org/10.1109/IECON.2007.4459884

[8] K. D. Joseph, A. E. Daniel and A. Unnikrishnan, "Reduced ripple interleaved CUK converter with phase shifted PWM," 2015 10th Asian Control Conference (ASCC), Kota Kinabalu, Malaysia, 2015, pp. 1-6. doi: https://doi.org/10.1109/ASCC.2015.7244782

[9] B.-R. Lin, Y.-S. Huang, J.-J. Chen and J.-J. Shieh, "Zero voltage switching double ended CUK converter," 2009 4th IEEE Conference on Industrial Electronics and Applications, Xi'an, China, 2009, pp. 2038-2043. doi: https://doi.org/10.1109/ICIEA.2009.5138560

[10] M. S. Syam and T. S. Kailas, "Grid connected PV system using CUK converter," 2013 Annual International Conference on Emerging Research Areas and 2013 International Conference on Microelectronics, Communications and Renewable Energy, Kanjirapally, India, 2013, pp. 1-6. doi: https://doi.org/10.1109/AICERA-ICMiCR.2013.6576036

[11] M. S. Syam and T. S. Kailas, "Grid connected PV system using CUK converter," 2013 Annual International Conference on Emerging Research Areas and 2013 International Conference on Microelectronics, Communications and Renewable Energy, Kanjirapally, India, 2013, pp. 1-6. doi: https://doi.org/10.1109/AICERA-ICMiCR.2013.6576036

[12] Simplilearn, "An Introduction to Using Matlab Simulink", 2023 Simplilearn Solution. url: https://www.simplilearn.com/tutorials/matlab-tutorial/what-is-matlab-simulink

[13] Staff Writer, "The Ultimate Guide to Using Proteus 8 Professional for Electronics Design", 2023 Ask Media Group, LLC. url: https://www.ask.com/news/ultimate-guide-using-proteus-professional-electronics-design