Optimal Power Control Using Modified Perturb and Observe Algorithm for Photovoltaic System Under Partial Shading

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Afrilia Surya Andini*
State Polytechnic of Malang,
Department of Electrical Engineering
Jl. Soekarno Hatta No. 9, Malang, Indonesia
2041150035@student.polinema.ac.id

Gery Prasetya
State Polytechnic of Malang,
Department of Electrical Engineering
Jl. Soekarno Hatta No. 9, Malang, Indonesia
geryprasetya964@gmail.com

Ratna Ika Putri
State Polytechnic of Malang,
Department of Electrical Engineering
Jl. Soekarno Hatta No. 9, Malang, Indonesia
ratna.ika@polinema.ac.id

Achsanul Khabib
State Polytechnic of Malang,
Department of Electrical Engineering
Jl. Soekarno Hatta No. 9, Malang, Indonesia
achsanul.khabib@polinema.ac.id

Ika Noer Syamsiana
State Polytechnic of Malang,
Department of Electrical Engineering
Jl. Soekarno Hatta No. 9, Malang, Indonesia
ikanoersyamsiana@polinema.ac.id

*Corresponding author

Abstract *– Implementation of photovoltaic systems encounters problems, particularly concerning Partial Shading Conditions (PSC), solar irradiance, and temperature, which influence the generated output power. The PSC can diminish the power efficiency of the photovoltaic system. Consequently, a controller is required to optimize the photovoltaic system's power output by considering the power supply characteristics. This paper discusses optimal power control in photovoltaic system under PSC. The proposed method employs a Modified Perturb and Observe (MP&O) algorithm based on the observation of current and voltage output from the photovoltaic system. The MP&O algorithm is integrated into a microcontroller and will provide PWM signals to operate the synchronous buck converter. Testing was performed under PSC. The experimental results indicated that the synchronous buck converter achieved a performance efficiency of 85%. The efficacy of the MP&O algorithm was evaluated without the MPPT method and conventional P&O algorithm. The MP&O algorithm outperformed compared to without MPPT method and conventional P&O algorithm. The MP&O algorithm yielded more consistent output power and necessitated a quicker tracking duration. The proposed method achieves an average output power efficiency of 84%; in contrast, without the MPPT method, it only reached 57%, and with the conventional P&O algorithm, it attains an efficiency of just 70%.*

Keywords: *Photovoltaic, Optimal Control, Perturb & Observe, Partial Shading*

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1. INTRODUCTION

The use of renewable energy as a source of electrical energy continues to increase every year due to the increasing awareness of the use of environmentally friendly energy and the reduction of fossil energy. Using renewable energy is one way to address climate change by reducing carbon emissions [1]. One of the most commonly used renewable energy sources in Indonesia nowadays is solar energy, which is converted into electrical energy through photovoltaic systems. Photovoltaic systems are one of the ideal power plants to be developed in Indonesia because Indonesia is located on the equator, which can receive sunlight throughout the year. However, photovoltaic systems have the main problem of low efficiency in converting electrical energy, with the generated electrical power affected by environmental conditions and uneven lighting, also known as Partial Shading Condition (PSC) [2-4]. The PSC occurs due to shadows from particular objects such as buildings, trees, or dust that partially cover the photovoltaic, thus reducing the power generated from the photovoltaic [5]. Moreover, PSC makes the photovoltaic module unbalanced, resulting in many peaks in the P-V curve, making it challenging to reach Maximum Power Point (MPP). This condition causes a decrease in photovoltaic efficiency of up to 70%, as a result of which the entire performance of the photovoltaic system will be affected [6]. Thus, photovoltaic systems require control to improve system efficiency in the face of PSC [7].

Increasing photovoltaic efficiency can be done through optimal power regulation, which is done by adjusting the duty cycle of the connected power converter. Several power converters are used in photovoltaic systems, including a DC-DC converter. DC-DC converters play an important role in renewable energy [8]. Nevertheless, power converters try using fewer parts, namely capacitors and inductors. The voltage spikes result from the elimination, causing the converter's design to be more complicated [9]. Several power converters that can be used, including buck converters. A buck converter, or step-down converter, is one type of DC-DC converter that can convert voltage from a high level to a lower level. Buck converters are ideal when implemented on DC current-based systems [10, 11]. Buck converters installed in photovoltaic systems provide stability and quick response during transient circumstances, even though they are susceptible to instability during voltage drops. This makes the efficiency of the buck converter not optimal [12]. The synchronous buck converter is a buck converter that uses two MOSFETs; replacing the diode with a MOSFET can reduce conduction losses and improve voltage stability at the output [13]. On the secondary side, using MOSFET to replace a diode can increase converter efficiency and reduce voltage spikes, and MOSFET can last a long time [14]. To get high efficiency, it is necessary to regulate the duty cycle of the synchronous buck converter. Several methods have been developed for managing the duty cycle of this power converter, called the Maximum Power Point Tracking (MPPT) method. In its implementation, this MPPT method is embedded in an embedded system to regulate the converter's performance [15, 16]. One of the most widely used conventional MPPT methods is the Perturb and Observe (P&O) algorithm, which can be implemented cheaply [17, 18]. However, this algorithm continues to be trapped at the Local Maximum Power Point (LMPP), which happens under PSC so that it cannot reach the Global Maximum Power Point (GMPP) [19]. Compared to the Particle Swarm Optimization (PSO) algorithm, the P&O algorithm is faster in determining the optimum power but solves the steady state [20]. The P&O algorithm experiences drift problems during rapid changes in resistive loads because it is hampered in overcoming power loss problems, so that the P&O algorithm can produce oscillations [21-23]. To improve the performance of the P&O algorithm, the conventional method is modified by providing constraints on specific parameters to enhance the method's performance in PSC. This modification makes the system adapt faster to rapidly changing environmental conditions and reduces the tracking time needed to reach MPP. A modification of the P&O algorithm has been developed for photovoltaic systems, where the step size is not constant. Still, it can change accordingly based on changes in the slope of photovoltaic characteristics. Based on simulation results, it performs better with the same tracking time as P&O and more minor oscillations. However, this algorithm has not considered the PSC [24].

This paper will explain the application of Modified Perturb and Observe (MP&O) to photovoltaic systems using synchronous buck converters under PSC. A synchronous buck converter is designed and tested experimentally. The MP&O algorithm is embedded in the microcontroller, and the performance will be compared without the MPPT method and with the conventional P&O algorithm on the same PSC. The use of a microcontroller in this equipment will produce a reliable and economically valuable system.

2. METHODOLOGY

Fig. 1 shows the block diagram of the photovoltaic system, consisting of a photovoltaic, switch, synchronous buck converter, current sensor, voltage sensor, loads, and embedded system. The output of the photovoltaic module will be connected to the synchronous buck converter. The voltage sensor and current sensor will detect the photovoltaic current and voltage output. An embedded system in the form of a microcontroller functions as a controller. The MP&O algorithm is embedded in the microcontroller, creating a duty cycle to drive the synchronous buck converter. The microcontroller will read the photovoltaic module output voltage and current and calculate its output power based on it. Based on the output power generated by the photovoltaic module, the MP&O algorithm will determine the converter's duty cycle so that the system can work at the maximum power point. For the system's safety, the microcontroller will set the input switch that connects the photovoltaic module with the converter and the load switch that connects the converter and the load. Suppose the output voltage of the photovoltaic module is low and cannot supply the load. In the case, the microcontroller will activate the input switch to disconnect the photovoltaic module from the synchronous buck converter.

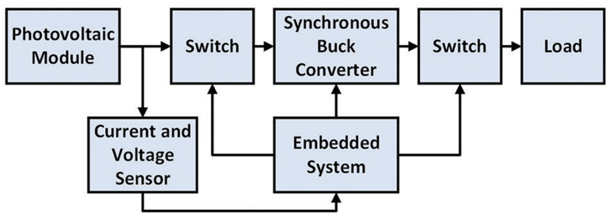

Fig. 1. System Block Diagram

This paper uses a 200 Wp polycrystalline photovoltaic module that is commercially available for use. Photovoltaic converts solar irradiation into electrical energy through electrons, attracting semiconductor materials such as monocrystalline and polycrystalline. Photovoltaic modules are composed of main components such as current sources, diodes, and resistors connected in parallel and series, as shown in Fig. 2 [21]. The equivalent circuit diagram of the photovoltaic module supports the design of converters and also MPPT methods. This ensures that the designed system can operate efficiently according to environmental conditions. The current source (I_{ph}) indicates the current produced by solar energy. The diode (d) is represented with the leakage current in the photovoltaic module, which enables the diode current (I_d) to flow when forward biased. The parallel or shunt resistance (R_p) symbolizes the leakage current in the module, with the current through it represented as I_p. The series resistor (R_s) represents the interval resistive losses within the module and its connections. The output current (I_{pv}) from the module is the current delivered to the load. V_{pv} describes the voltage at the terminals of the photovoltaic module.

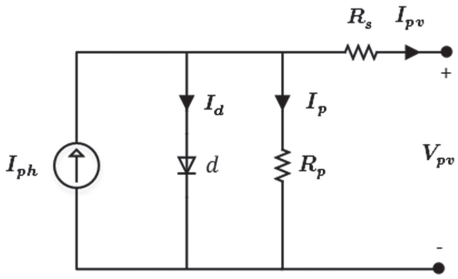

Fig. 2. PV Equivalent Circuit Diagram

Fig. 3 shows the I-V and P-V characteristic curves with an irradiance difference of 200 W/m2 up to 1000 W/m2 and a constant temperature of 25°C. The I-V curve indicates that the output current of the photovoltaic module is affected by solar irradiation; increased irradiation results in higher current production, and conversely, decreased irradiation results in lower current output. Similarly, the P-V curve indicates the power output is enhanced under higher irradiation conditions. Nonetheless, if the irradiation is ineffective, it cannot reach the peak value. The characteristic curve shows the MPP location; this curve is also used to design the MPPT method. This analysis aims to demonstrate the efficacy of the photovoltaic module utilized. Modelling and simulation with MATLAB/Simulink related to the module specification data used to comprehend the relationship between current, voltage, output, and features. The red curves denote maximum conditions, whilst the blue curves indicate lower irradiance.

PSC occurs because the photovoltaic module is partially covered by shadows from buildings, trees, and dust. Thus, the maximum power generated under PSC becomes non-uniform. In the photovoltaic characteristic curve shown in Fig. 3, the MPP has different variations and depends on environmental conditions. However, the MPPT method is designed to track the MPP dynamically, even under PSC, providing reassurance of its effectiveness [19].

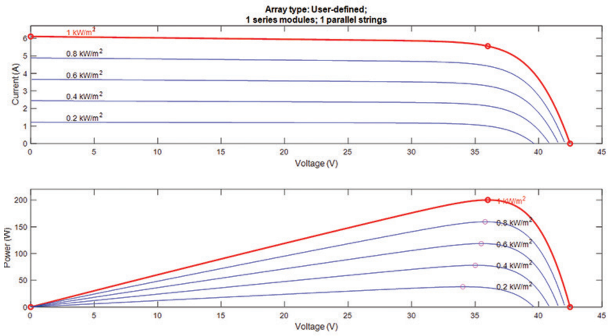

Fig. 3. I-V and P-V Characteristic Curve Photovoltaic Module with Different Irradiation

2.1. SYNCHRONOUS BUCK CONVERTER

When the photovoltaic module is covered with shadow, the power produced by the module is significantly reduced. Thus, a converter with higher efficiency is needed to minimize power loss. The synchronous buck converter is a modification of the buck converter to reduce the voltage from a higher level to a lower level; in this synchronous buck converter, the function of the diode is replaced by Metal Oxide Semiconductor Field Effect Transistor (MOSFET). This replacement aims to increase the efficiency of the power loss resulting from thermal performance [13].

The synchronous buck converter consists of principal components, namely inductors, capacitors, and MOSFET, as a switch that aims to reduce the voltage from a higher level to a lower level. In its operation, the synchronous buck converter operates using two switches, so-called MOSFET, whose circuit can be seen in Fig. 4. On the circuit diagram to show how the components are interconnected to facilitate the implementation of the converter and assist in simulating the converter before it is implemented. To achieve high efficiency, it is divided into two modes; in an active mode, where MOSFET 1 is on and MOSFET 2 is off, the current from the input source will pass through the inductor to supply energy to the load, which makes the inductor current increase. In discharge mode where MOSFET 1 off and MOSFET 2 on, the energy stored by the inductor in active mode will flow to the load, which decreases the inductor current, but the load still gets the energy supply [25, 26].

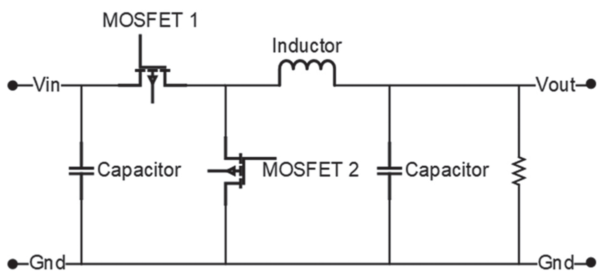

Fig. 4. Synchronous Buck Converter Circuit Diagram

The output voltage produced by the synchronous buck converter (V_{out}) determined based on the duty cycle (D) given to the MOSFET. The V_{out} can be determined using the following equation.

$$V_{out}=D\cdot V_{in} \quad (1)$$

The converter input voltage (V_{in}) is the output voltage of photovoltaic module with a maximum voltage 36 V, and duty cycle dynamically adjusted to keep the V_{out} constant at 15 V, even with fluctuations in the V_{in}. The selection of inductor (L) with inductor current ripple (ΔI_L) is limited to 35% if the reduced inductance value causes an increase in the peak current within the inductor, causing it to operate over its specified limitations. This results in a reduction in the inductor's performance inside the system. Consequently, it is necessary to evaluate the actual dimensions of the inductor utilizing the following equation.

$$L=\frac{V_{out}\cdot(V_{in}-V_{out})}{\Delta I_L\cdot f_s\cdot V_{in}} \quad (2)$$

Where is the switching frequency (f_s) of 39 kHz was chosen because it is stable, smooth, and efficient for power regulation. Based on the equation (2), the specified inductance value is 60 µH. Due to the high inductance value, it will reduce the ripple current even though it increases the component size.

Input capacitors are crucial to stabilizing the input voltage for peak current demands during duty cycle switching and mitigating voltage fluctuations caused by fast current variations. The output voltage ripple (ΔV_o) value is set to 5% to reduce the capacitor size. The following equation determines the capacitance value.

$$C=\frac{\Delta_{I_L}}{8\cdot f_s\cdot \Delta V_{out}} \quad (3)$$

Based on equation (3), using the Electrolytic Capacitor (ELCO) type, the specified capacitance value is 470 µF. The ELCO type is selected because it has a high capacitance ratio, suitable for filtering and energy storage. This capacitor effectively minimizes output voltage ripple and supports transient current demands on switching. Furthermore, the selection of N-channel MOSFET IRFP4110 as the switching component is because it can handle continuous currents up to 120 A with adequate cooling and peak current up to 670 A for a short duration. Fig. 5 shows the built synchronous buck converter.

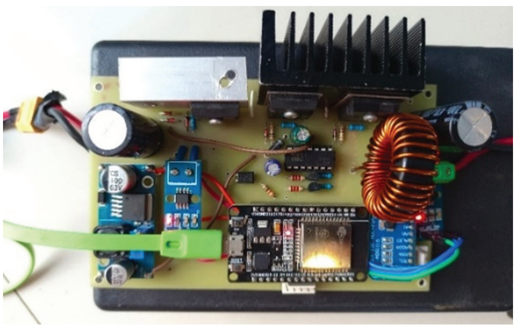

Fig. 5. Synchronous Buck Converter

2.2. MODIFIED PERTURB AND OBSERVE

The MPPT method is used to improve the energy efficiency of photovoltaic systems [17]. Increasing the efficiency of photovoltaic systems in PSC can be done through duty cycle converter settings using MPPT algorithms. One of the widely implemented MPPT algorithms is P&O. P&O has a high tracking speed and lower computational complexity compared to metaheuristic algorithms such as Particle Swarm Optimization (PSO) and Firefly Algorithm (FA) [23]. The P&O algorithm has advantages in simplicity and ease of implementation. However, the P&O algorithm has limitations, such as the step size selection and possible oscillations around the MPP when the step size is not appropriate. Therefore, although the P&O algorithm is simple, it does not provide the same tracking accuracy and stability as other algorithms [27]. Fig. 6 shows the flowchart for the P&O algorithm. The duty cycle change in this algorithm depends on the step size with a value of 0.05.

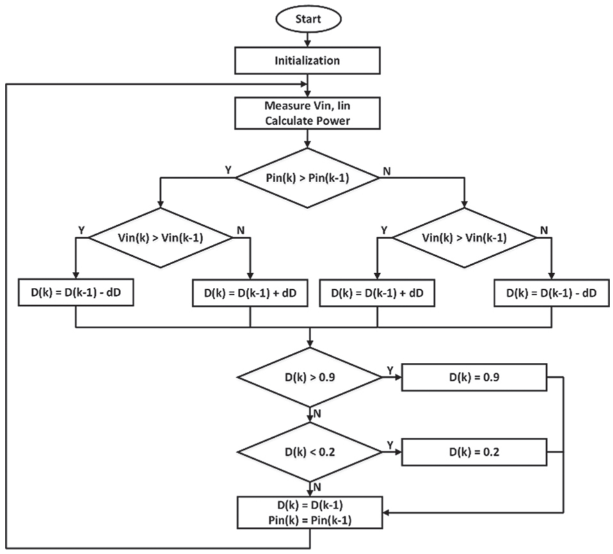

Fig. 6. Conventional P&O Algorithm Flowchart

In this paper, a Modified P&O (MP&O) algorithm is carried out to increase the efficiency of the photovoltaic system. The MP&O algorithm is expected to reduce the oscillation in a steady state and accelerate the achievement of MPP in PSC. Since the MPPT method can prevent power loss by stabilizing power fluctuations during extreme weather conditions, it is important to improve photovoltaic systems. The performance of the modified P&O algorithm will be compared with the conventional P&O algorithm.

Efficiency (*Eff*) evaluates a method's effectiveness of by comparing the output power produced by the proposed method to the output power real generated by the photovoltaic module, represented as a percentage. The proposed methods tested are divided into three parts: without the MPPT method, with the P&O algorithm, and with the MP&O algorithm. A near 100% efficiency result signifies the method's success in power utilization, whilst a low efficiency value denotes its ineffectiveness in power optimization. Efficiency can be determined using following equation.

$$Eff = \frac{Output\ Power\ Proposed\ Method}{Ouput\ Power\ Real\ Photovoltaic} \quad (4)$$

Fig. 7 shows the flowchart of the MP&O algorithm, which generates the duty cycle that will be sent to the synchronous buck converter. The algorithm works based on the measuring of the output current and voltage at the photovoltaic module, which is used to calculate the photovoltaic output power (P). The change in output power will determine the duty cycle sent to the converter, where the following equation determines the change in power (dP)

$$dP=P(k)-P(k-1) \quad (5)$$

Where $P(k)$ is current power and $P(k-1)$ is previous power. There are several possibilities for the MP&O algorithm.

- If power reaches the MPP then $dP<\beta$, the duty cycle value is fixed $D(k)=D(k-1)$.
- If power $P(k)>P(k-1)$ and duty cycle $D(k)>D(k-1)$ or $P(k)<P(k-1)$ and $D(k)<D(k-1)$, the duty cycle must be increased $D(k)=D(k-1)+dD$.
- If power $P(k)>P(k-1)$ and duty cycle $D(k)<D(k-1)$ or $P(k)<P(k-1)$ and $D(k)>D(k-1)$, the duty cycle must be decreased $D(k)=D(k-1)-dD$.

dD is a step size that will change depending on the iteration. At each iteration the dD value will be updated by $dD(k)=dD(k-1)-C$. Where C is a constant value. This paper C has two values, namely $C1=0.02$ and $C2=0.03$. The more iterations, the smaller the dD value because it is close to the optimum value to reduce oscillations in the steady state.

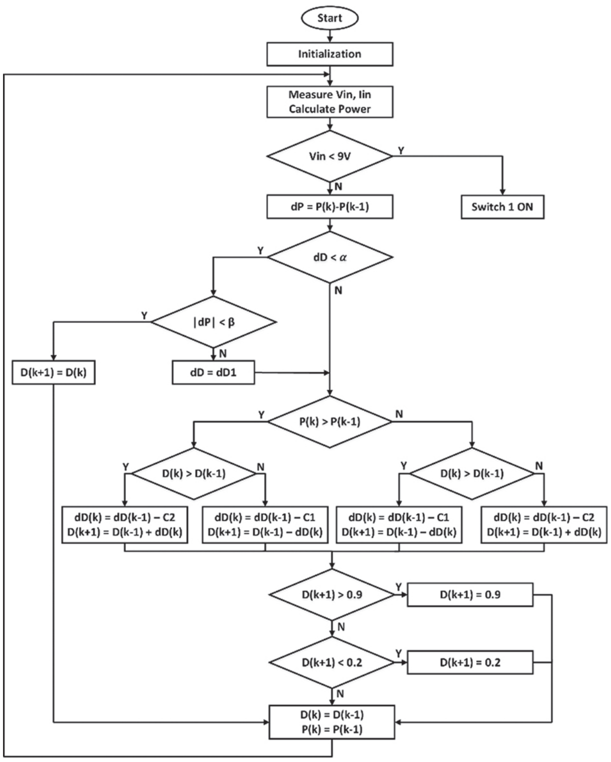

Fig. 7. Modified P&O Flowchart

3. RESULTS AND DISCUSSION

The designed and built photovoltaic system was tested experimental testing to assess the performance of both the overall system and the integrated modified P&O algorithm within the embedded system. The tests were carried out in several stages: photovoltaic module, synchronous buck converter, and whole system. Photovoltaic testing is done by shading the photovoltaic without a synchronous buck converter circuit. The converter testing aims to evaluate the performance of the synchronous buck converter. This test is carried out by changing the duty cycle and input voltage, so that the efficiency of the circuit can be evaluated. The overall system test evaluates the performance of photovoltaic systems equipped with optimal power control using the modified P&O algorithm. Overall system testing is done by providing three PSCs. The three conditions are 0% shading, 30% shading, and 50% shading.

When the synchronous buck converter circuit and resistive load are connected directly, the characteristic curve of the photovoltaic output power test results under PSC is displayed in Fig. 8. This photovoltaic test involves varying the resistive load and testing the photovoltaic module in both shading and without shading environments. Testing of photovoltaic modules is done to find the MPP produced by photovoltaic module under various shading scenarios in the field, such as building shading. The resistive load is also adjusted to assess the photovoltaic reaction to changes in the load connected to the system. Because shading affects the output power produced by photovoltaic module, the test findings demonstrate that the output power of a photovoltaic module can drop when shading is present. The photovoltaic module may provide up to 36.5 W of power. The graphs from the testing show that the MPP changes in response to the load resistance value and irradiation level. Therefore, in order to maximize the output power under PSC, the MPPT approach is required.

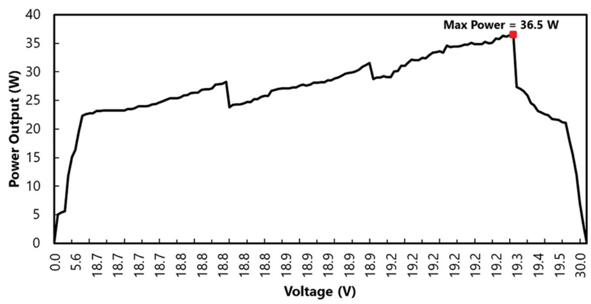

Fig. 8. Photovoltaic Characteristic Curve with Shading Based on Test

Fig. 9 shows the experiment setup for testing the synchronous buck converter in the laboratory. The test is conducted by changing the duty cycle and input voltage. The synchronous buck converter output voltage and duty cycle are displayed on the oscilloscope equipment, as shown in Fig. 10. The graph on the oscilloscope shows the shape of the voltage at a particular duty cycle.

Fig. 9. Converter Testing Process

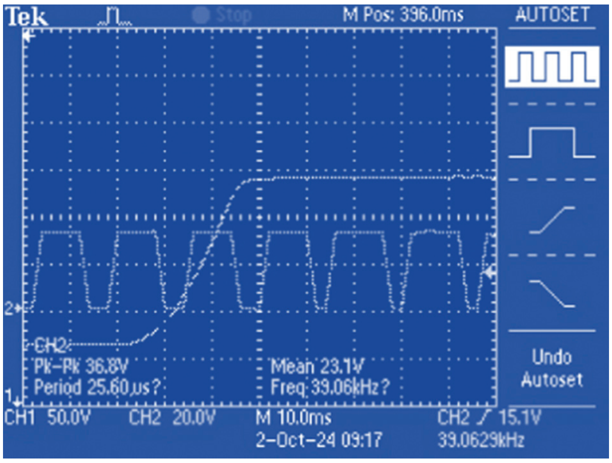

Fig. 10. Oscilloscope Graph of Synchronous Buck Converter Response

Based on the test results of the synchronous buck converter in Fig. 11 shows the performance generated from this converter. Given a voltage of 40 V DC, the greater the duty cycle value, the higher the output voltage produced. This is because the switch has a longer active time, while the smaller the duty cycle value will reduce the active time.

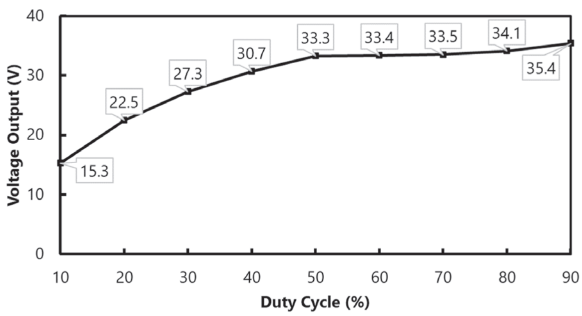

Fig. 11. Voltage Output of Synchronous Buck Converter with 40 V Input Voltage

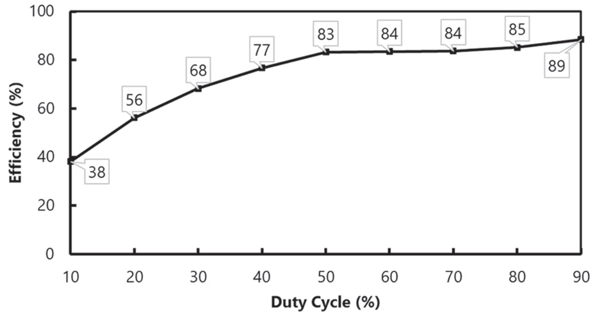

Fig. 12. Efficiency of Synchronous Buck Converter with Duty Cycle Variations

Overall, system testing is conducted to test the performance of the MP&O algorithm embedded in the microcontroller. The MP&O algorithm is based on the measurement of current and voltage generated by the photovoltaic by the current and voltage sensors. The microcontroller will read the output of the current and voltage sensors and calculate the power generated based on the measurement results. The output of the MP&O algorithm is the duty cycle. The microcontroller will send a Pulse Width Modulation (PWM) signal with the duty cycle to drive the switching components in the synchronous buck converter. Through this duty cycle setting, the photovoltaic system will produce optimal power. The performance of MP&O is compared with the performance of the without MPPT method and with the conventional P&O algorithm.

Fig. 13 shows the output power of the photovoltaic system without the MPPT algorithm, conducted under PSC divided into three scenarios: 0%, 30%, and 50% shading. The average output power without shading is 23.8 W. Shading reduces power; specifically, under 30% shading, the average power is 20.7 W, while 50% shading further drops it to 20 W.

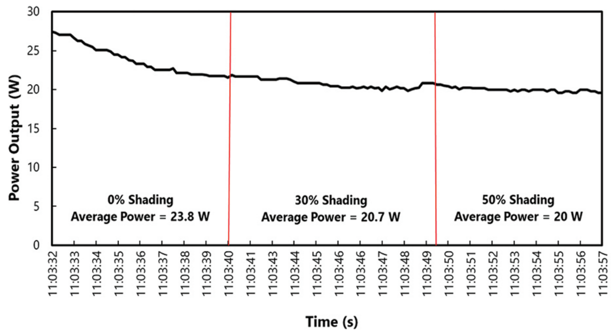

Fig. 13. Power Output Without the MPPT Method

Fig. 14 shows the output power of the photovoltaic system by applying the conventional P&O algorithm under PSC. PSC changes are given in several conditions: the initial condition with 0% shading, then given shading of 30%, and then 50% shading. The average output power with 0% shading condition is 28 W, with 30% shading is 25 W. In the 50% shading condition, the photovoltaic system with the P&O algorithm will produce an average output power of 23.4 W.

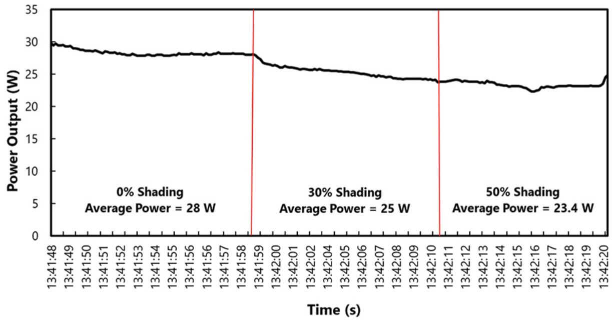

Fig. 14. Power Output Using Conventional P&O

Fig. 15 shows the output power of the photovoltaic system using modified P&O algorithm under PSC, namely with 0% shading, 30% shading and 50% shading. The average output power without shading condition is 32.6 W; with 30% shading, it is 31 W, and at 50% shading, the photovoltaic system with MP&O will produce an average output power of 28 W.

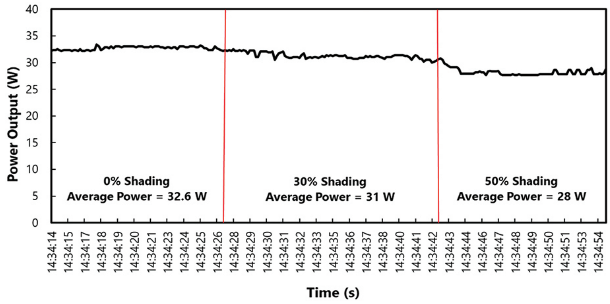

Fig. 15. Power Output Using Modified P&O

The performance of the photovoltaic system with modified P&O is compared with the without MPPT method and P&O algorithm under PSC. The output power of the photovoltaic system (P_{out}) without any MPPT method is lower than that of the conventional P&O algorithm and modified P&O algorithm. In addition, without the MPPT method, the system lacks the ability to maintain the drop required to optimize the photovoltaic performance. The modified P&O algorithm is more stable with lower oscillations than without the MPPT method and with the conventional P&O algorithm. Efficiency is defined as the ratio of the output power extracted by the modified P&O method, which is the suggested way, to the without MPPT method and with conventional P&O algorithm as a comparison method with maximum output power of the photovoltaic module. Under some circumstances, the efficiency formula used to evaluate the proposed method may be the most effective way to harvest power from photovoltaic modules. The algorithm's efficiency is calculated by the equation (4). Table 1 shows the efficiency comparison between without the MPPT method, with conventional P&O algorithm, and with modified P&O under PSC. Modified P&O algorithm has a higher efficiency; the average efficiency is 84%, while without the MPPT method is 57%, and using conventional P&O algorithm is 70%.

Table 1. Efficiency of Proposed Method

Shading	Without MPPT		Conventional P&O		Modified P&O	
	Pout (W)	Eff (%)	Pout (W)	Eff (%)	Pout (W)	Eff (%)
0%	23.8	65	28	77	32.6	89
30%	20.7	56	25	69	31	85
50%	20	55	23.4	64	28	77

4. CONCLUSION

This paper describes applying the modified P&O algorithm on a photovoltaic system with PSC to enable optimal power production. The modified P&O algorithm is integrated into a microcontroller that will adjust the duty cycle of the PWM signal transmitted to the synchronous buck converter. Optimal power management in the photovoltaic system is attained by adjusting the duty cycle transmitted to the synchronous buck converter. The effectiveness testing findings indicate that the synchronous buck converter achieves an efficiency of 85%. The efficacy of the modified P&O algorithm is juxtaposed with that of the conventional P&O algorithm. The proposed method was evaluated under three shading conditions: 0% shading, 30% shading, and 50% shading. The proposed method yields more stable photovoltaic output power than conventional P&O algorithm under partial shading conditions and can significantly improve the power conversion efficiency. The efficiency of the photovoltaic system utilizing modified P&O algorithm is 84%, whereas the photovoltaic employing conventional P&O algorithm achieves an efficiency of 70% and without MPPT method, the efficiency is 57%. Further research will advance the photovoltaic system utilizing the suggested technology linked to alternating current loads and integrated with additional electrical energy sources or a hybrid renewable energy system.

5. ACKNOWLEDGMENT

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