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Design of Buck Converter Based on Maximum Power Point Tracking for Photovoltaic Applications

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ABSTRACT

The MPPT converter ensures that the PV system operates at the maximum power point, which is the point where the solar panels can generate the most power. This is done by adjusting the voltage of the output. The converter uses a DC-DC conversion process and can be implemented using a buck converter circuit. This project uses a buck converter to adapt the voltage to its appropriate value to reach a maximal power extraction. This power converter can be designed in several ways. This involves employing a typical power converter design to create the power converter in the MPPT converter. Furthermore, the inductance and capacitance derivation for the MPPT converter is insufficient, making determining the inductance and capacitance unfeasible. Hence, this study focuses on designing the buck converter for MPPT application and tracking the maximum power using the Perturb and Observe (P&O) method. This system will be implemented by using MATLAB/Simulink. To design the MPPT buck converter, several parameters need to be considered and derived. This project finds that the MPPT buck converter that has been designed can track the maximum power from 900 W/m^2 to 1100 W/m^2 of irradiance. The design of the MPPT buck converter using the P&O method is fairly accurate, and the accuracy of tracking the maximum power is around 98%.

1. Introduction

The MPPT converter is a device that optimizes the power output from a photovoltaic module by using a combination of an MPPT technique, a power converter controller, and the power converter. Different types of MPPT methods have been developed by researchers [1].

Several methods can be used to track the maximum power point of a photovoltaic module, such as the Hill-Climbing Method, the Perturb and Observe Method, the Incremental Conductance Method, and the Particle Swarm Optimization Method. The purpose of these methods is to determine the point at which the module produces the most power. The output of the MPPT method is typically a duty cycle or voltage reference, which is then linked to the Pulse Width Modulation

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technique. The controller for the power converter receives this voltage reference and generates the PWM duty cycle, which improves the MPPT converter's transient response. The most commonly used controller for the power converter is the Proportional-Integral controller, but other non-conventional controllers may also be used [2-6].

A buck converter is a type of power supply that reduces the voltage level from the input source. It acts as a step-down converter because it generates a lower DC voltage output than the input voltage. The buck converter is widely used in photovoltaic applications due to its high efficiency, low number of components, and ease of control [1].

The findings of the research indicate that the buck converter is unable to function at the peak power output of the photovoltaic module without the inclusion of an input capacitor. There are mathematical equations available to calculate the appropriate input capacitor for an MPPT buck converter [7-9]. The design of the power converter component in the MPPT converter has been approached from multiple perspectives, one of which includes utilizing traditional power converter design techniques [7,10-12]. There have been various approaches taken in designing the power converter component of the MPPT converter. This includes utilizing traditional power converter design methods. However, the MPPT converter has a non-linear source, which is the PV module, and not a linear voltage source, making this design process not applicable. Additionally, certain aspects of the MPPT converter's design are not displayed in this approach [12-15]. Another approach to designing the MPPT converter is to skip the calculations of inductance and capacitance and instead use small signal analysis [12,16,17]. Furthermore, the information provided for calculating the inductance and capacitance for the MPPT converter is not enough, therefore it is not possible to determine these values.

The analysis of the MPPT converter shows that there is no explicit calculation for the inductance and capacitance needed for the power converter when using the PV module as the non-linear input source. This calculation is crucial for minimizing the amount of inductance and capacitance used in the MPPT converter to prevent it from operating in discontinuous current mode, ensure the output voltage ripple stays within the desired range, and maintain operation close to the maximum power point. Using a large amount of inductance and capacitance can negatively impact the MPPT converter's ability to respond quickly to changes [12,18].

The successful operation of the buck converter in a photovoltaic (PV) system requires defining the range of output resistance. The inductor and capacitor play crucial roles in ensuring a continuous current mode and reducing output voltage ripple, but if their values are too small, the design objectives cannot be met. Conversely, if they are too large, it will negatively impact the performance of the PV system. Although there is a commonly used method for determining these component parameters, it is based on conventional systems where the output voltage is not impacted by the output resistance. However, the output voltage of a PV system is greatly influenced by factors such as load, irradiance, and temperature, which highlights the need for accurate estimations for the buck converter in PV applications [1].

This paper aims to derive the calculations for the inductance and capacitance of the MPPT buck converter in order to improve the MPPT algorithm, specifically using the Perturb and Observe method. The study also examines the impact of the buck converter components on the MPPT's transient response during changes in irradiance and tests the effectiveness of the buck converter in different conditions of the PV system. The MPPT buck converter is based on ideal conditions and is designed to operate in continuous current mode. The goal of the derivation is to create straightforward equations for determining the necessary input capacitance. The Perturb and Observe method is employed as the MPPT algorithm.

2. Methodology

Figure 1 shows the process flow of research methodology in order to indicate the overall methodology of the project. It shows that at an early stage, a literature study has been taken to understand the types of DC-DC converters, MPPT techniques, and PV models. The next stage is designing. Designing process will cover three parts, the first part is the Design of the PV model, where the input parameter is determined based on the power-voltage (PV) and current-voltage (IV) curve. The second is to design the conventional buck converter where the derivation of the inductor, capacitor, resistor, and duty cycle is based on the input and output desired. Finally, is the design of the MPPT buck converter. In this part, the derivation is done based on the PV and IV curves to determine the minimum output resistance at a minimum and maximum irradiance, the maximum output resistance, the inductor, and the capacitor from new parameters. The development of the MPPT algorithm then was designed by using the P&O method. In this project, Matlab Simulink is used to model the MPPT buck converter for PV application and analyze the system performance. Lastly, the system performance will be analyzed and compared between the PV and IV curves with the simulation results obtained.

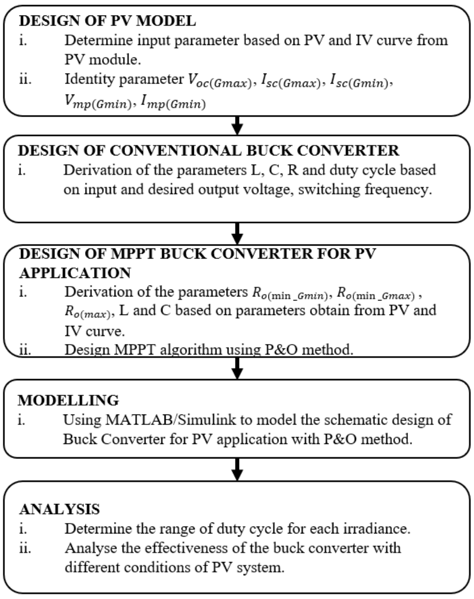


Fig. 1. The overall flow of methodology

2.1 PV Model

The 532 W PV module based on the system in UiTM CPP which is the Sharp NT-U175I module is simulated using the single diode model as shown in Figure 2.

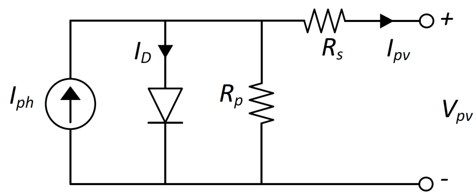


Fig. 2. Single diode mode schematic

To design a 532V PV model, the sizing of PV strings required is calculated by using Eq. (1)

$$\frac{V_{pv}}{V_{oc}} = Number\ of\ Module\ Connected\ in\ Series \tag{1}$$

where the V_{pv} is desired PV voltage and V_{oc} is the Open Circuit Voltage.

The parameters for the Sharp NT-U175I PV panel provided from the manufacturer's catalog are listed in Table 1. In addition, the I-V and P-V curves for this PV system are plotted in Figure 3. The maximum power point at 25°C with three different irradiances in Table 2 is obtained based on Figure 3. These parameters are used in designing buck converters.

Table 1
The parameters of solar NT-U175I by Sharp

Parameter	Value
Open Circuit Voltage, V_{oc}	44.4V
Short Circuit Current, I_{sc}	5.4 A
Voltage at Maximum Power Point, V_{mp}	35.4V
Current at Maximum Power Point, I_{mp}	4.95A
Maximum Power, P_{max}	175.5W
Number of Cells in Series, N_s	72
Diode Ideality Factor, A_f	0.96711
Series Resistance, R_s	0.74999
Parallel Resistance, R_p	195.1116
Temperature coefficient of I_{sc}, α	0.021%/°C
Temperature coefficient of V_{oc}, β	-0.34%/°C

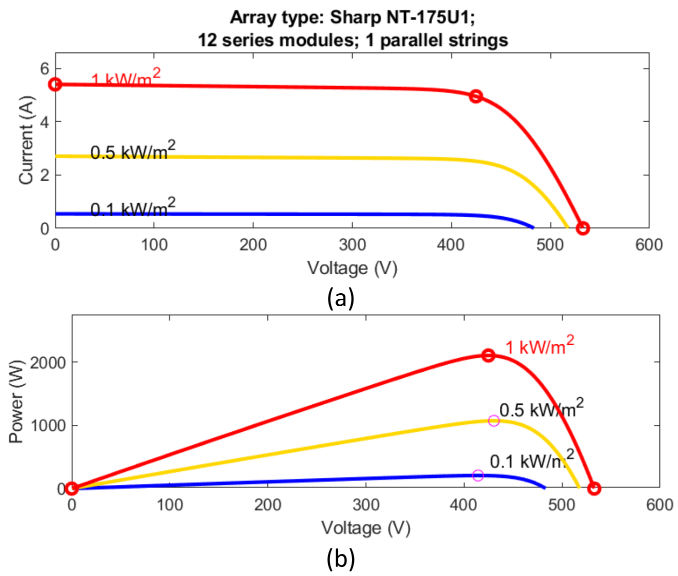


Fig. 3. The characteristics curve produced by the PV model (a) The current-voltage (I-V) curve (b) The power-voltage (P-V) curve

Table 2
The input parameters

Parameter	Value
PV Module	
Open Circuit Voltage at Maximum Irradiance, $\boldsymbol{V_{oc(Gmax)}}$	44.4 V
Short Circuit Current at Maximum Irradiance, $\boldsymbol{I_{sc(Gmax)}}$	5.4 A
Short Circuit Current at Minimum Irradiance, $\boldsymbol{I_{sc(Gmin)}}$	0.542 A
MPP Voltage at Minimum Irradiance, $\boldsymbol{V_{mp(Gmin)}}$	34.5 V
MPP Current at Minimum Irradiance, $\boldsymbol{I_{mp(Gmin)}}$	0.499 A
Buck Converter	
Minimum Duty Cycle, $\boldsymbol{D_{min}}$	0.05
Maximum Duty Cycle, $\boldsymbol{D_{max}}$	0.80
Switching Frequency, $\boldsymbol{f_s}$	200kHz
Output Voltage Ripple Factor, $\boldsymbol{\gamma_{V_o}}$	1%

2.2 Conventional Buck Converter

The buck converter is highly efficient since it can minimize the power loss in the system. Therefore, the buck converter is recommended in PV applications because of its great efficiency. Figure 4 show the buck converter schematic diagram.

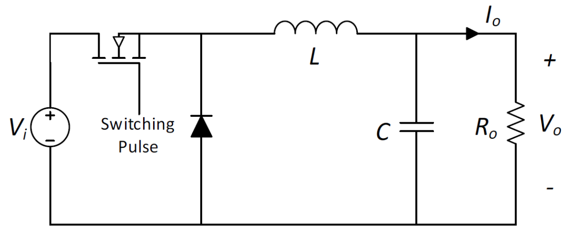


Fig. 4. The buck converter schematic diagram

The main parameters to design a Buck Converter are output resistance, capacitance, inductance, duty cycle, and the targeted Output Voltage. All the parameters stated are derived and calculated to design a buck converter. To control the Output Voltage, V_o, the duty cycle, D is injected through a switching pulse and the equation between output voltage, input voltage, and the duty cycle is as follows

$$D = \frac{V_o}{V_i} \tag{2}$$

The buck converter needs to operate in continuous current mode for the PV application to function properly. If the operations change to the discontinuous current mode, a separate controller is required as the transfer function of the converter differs between the two modes. It is important to ensure that the buck converter remains in continuous current mode to guarantee the proper functioning of the PV application.

$$L = \frac{(1-D)R_o}{2f_s} \tag{3}$$

The proper functioning of a buck converter in a PV application requires the use of the correct inductance value, L, to maintain continuous current mode operation. By using Eq. (3), the minimum value of L necessary for this can be calculated. In order to emulate the behavior of a PV module, the output voltage ripple is set to a low value of 1%. The capacitance, C, also plays a role in determining the output voltage ripple. A smaller ripple requires a larger value of C, but this can negatively impact the performance of the PV system. The typical calculation for C in a buck converter is shown in Eq. (4)

$$C = \frac{(1-D)}{8L\gamma_{V_O} {f_s}^2} \tag{4}$$

The remaining parameters are calculated and listed in Table 3.

Table 3
The conventional buck converter parameters

Parameter	Value
Output Voltage, $\boldsymbol{V_o}$	24 V
Duty Cycle, $\boldsymbol{D}$	0.048
Output Resistance, $\boldsymbol{R_o}$	10 Ω
Inductance, L	23.8 µH
Capacitance, C	12.5 µF

Figure 5 shows the Simulink model of the buck converter used in this project.

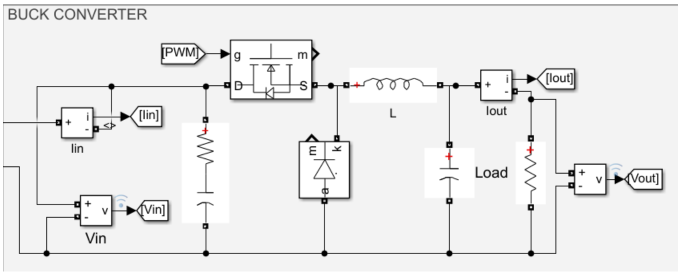


Fig. 5. The block of buck converter in MATLAB/Simulink

2.3 Buck Converter Design for Photovoltaic Application

The buck converter for the PV application for this project was designed based on the flowchart, as shown in Figure 6. Eq. (5) to Eq. (8) is based on [1].

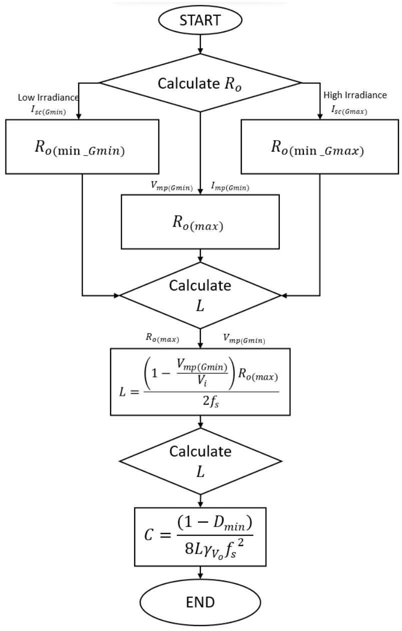


Fig. 6. The flowchart of the MPPT buck converter

The minimum output resistance, $R_{o(min)}$ varies with changes in the irradiance level, G. As G decreases, $R_{o(min)}$ increases and is referred to as the minimum output resistance during low irradiance, $R_{o(\min\_Gmin)}$. Conversely, as G increases, $R_{o(min)}$ decreases and is referred to as the minimum output resistance during high irradiance, $R_{o(\min\_Gmax)}$. This relationship can be described by Eq. (5)

$$\frac{D_{min} V_i}{I_{sc(Gmax)}} \leq R_{o(min)} \leq \frac{D_{min} V_i}{I_{sc(Gmin)}} \tag{5}$$

The PV module's voltage and current are at their maximum open-circuit values when connected to infinite resistance. However, the buck converter's inductance, L must also be infinite to operate in continuous current mode. To ensure that the PV's buck converter functions in continuous current mode, the maximum output resistance is defined as per Eq. (6)

$$R_{o(max)} \leq \frac{V_{mp(Gmin)}}{I_{mp(Gmin)}} \tag{6}$$

The proposed maximum output resistance, $R_{o(max)}$, for the buck converter in the PV application is determined based on the maximum power point (MPP) during the lowest level of irradiation. This calculation takes into account the voltage and current at the MPP at the minimum irradiance, $V_{mp(Gmin)}$ and $I_{mp(Gmin)}$, respectively. Using this information, the formula (7) is used to calculate the required value of L for the buck converter to operate in continuous current mode.

$$L = \frac{\left(1 - \frac{V_{mp(Gmin)}}{V_i}\right) R_{o(max)}}{2 f_s} \tag{7}$$

The buck converter's output voltage ripple, also known as V_o ripple is affected by the value of the capacitor, C. By increasing the capacitance, the V_o ripple can be reduced. However, the actual PV module does not have any voltage ripple, so the suggested C value should be relatively small to prevent excessive V_o ripple. The ripple factor of the output voltage, V_o, is used to quantify the ripple. As the duty cycle, D, decreases, the voltage ripple increases. Therefore, the C required by the buck converter during operation with the minimum duty cycle, D_{min} is calculated as per (8) to prevent overproduction of ripple.

$$C = \frac{(1-D_{min})}{8L\gamma_{V_o} {f_s}^2} \tag{8}$$

All the parameters are calculated based on Table 2 and listed in Table 4.

Table 4
The values of Reynolds number and velocity

Parameter	Value
Minimum Output Resistance at Minimum Irradiance, $\mathbf{R_{o(min\ \_Gmin)}}$	49.15Ω
Minimum Output Resistance at Maximum Irradiance, $\mathbf{R_{o(min\ \_Gmax)}}$	4.93Ω
Maximum Output Resistance at Maximum Irradiance, $\mathbf{R_{o(max)}}$	69.24Ω
Inductance, L	161.89µH
Capacitance, C	1.834µF

2.4 Perturb and Observe Algorithm

The design of the buck converter for photovoltaic (PV) systems is distinctive from that of the conventional buck converter due to the effect of the output resistance on the output voltage of the PV system. Unlike the conventional buck converter where the output voltage is not impacted by the output resistance, the output voltage of the PV system is influenced by it. In this project, a simple maximum power point tracking (MPPT) approach was adopted because the conducted analysis did not consider partial shading. The Perturb and Observe (P&O) Technique was selected as the MPPT method due to its simplicity and the fact that it does not require a power converter controller. Figure 7 illustrates the flowchart of the P&O algorithm, where the duty cycle is immediately calculated using this method. The perturbation of the duty cycle occurs every 2 milliseconds with a fixed step size of 0.01% based on variations in PV power and voltage. The parameters used for the perturbation were obtained from Table 2.

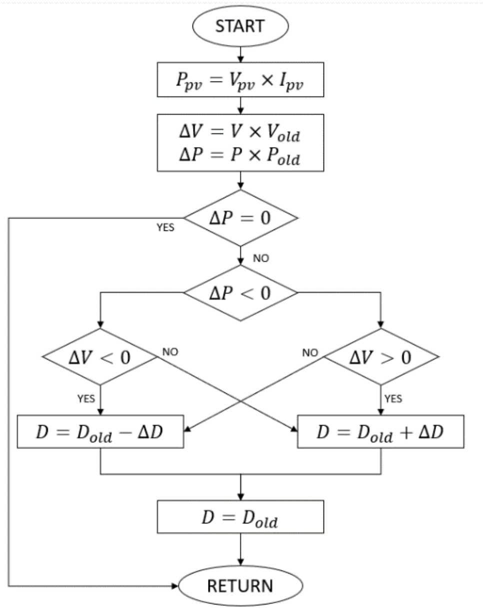


Fig. 7. The flowchart of P&O MPPT algorithm

2.5 Performance Evaluation

When assessing the effectiveness of an MPPT, examining its accuracy and error is a common approach to evaluate its performance. These metrics offer valuable information about the MPPT's capability to precisely follow the PV array's maximum power point and efficiently convert that power into usable energy.

The MPPT's accuracy, whether static or dynamic, indicates how effectively it operates the PV array at the maximum power point (MPP). This measurement is usually expressed as a percentage of Imax, Vmax, or Pmax, and it offers valuable information about the MPPT's capability to track and sustain the optimal operating point for the PV array. Static accuracy pertains to the MPPT's capacity to track the MPP during stable conditions, while dynamic accuracy relates to its ability to track the MPP when confronted with varying factors like irradiance and temperature.

$$\alpha_{MPPT.X} = \frac{X}{Xmax}\ ; \quad \text{where X can be V, I, or P} \tag{9}$$

The error, encompassing both static and dynamic components, quantifies the variance between the real values of voltage, current, or power and the maximum power point (MPP) values. This variance can be represented as an absolute or relative difference and offers an understanding of how closely the MPPT is aligning the PV array with the MPP. The static error denotes the disparity between actual and MPP values during stable circumstances, while the dynamic error refers to the disparity encountered during changing conditions like fluctuations in irradiance and temperature.

$$\varepsilon_{MPPT.X} = X - X_{max}\ ; \quad \text{where X can be V, I, or P} \tag{10}$$

$$\eta_{MPPT.X} = \frac{\int_0^{Tm} X(t)dt}{\int_0^{Tm} Xmax(t)dt} - 1\ ; \quad \text{where X can be V, I, or P} \tag{11}$$

2.6 Simulink Implementation

In this project, Simulink® is used to model a PV system and then simulate the dynamic behavior of that system. The PV model, buck converter model, and the P&O algorithm are combined in this Simulink as shown in Figure 8.

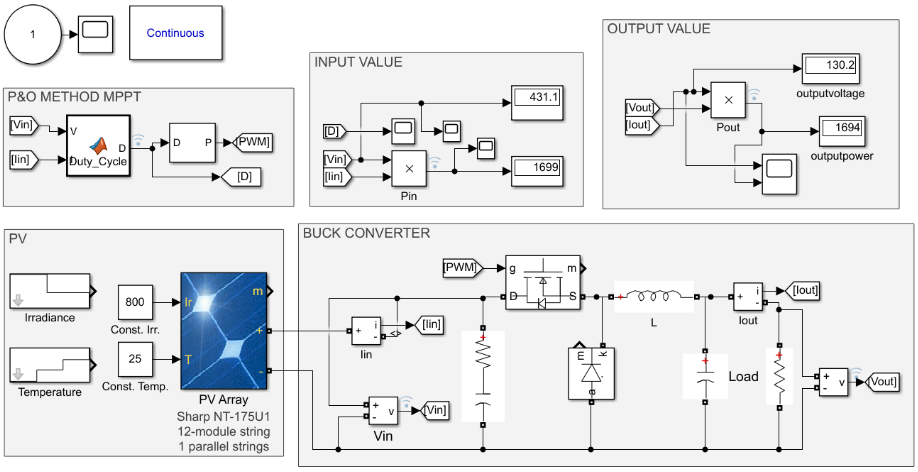


Fig. 8. The block of MPPT buck converter

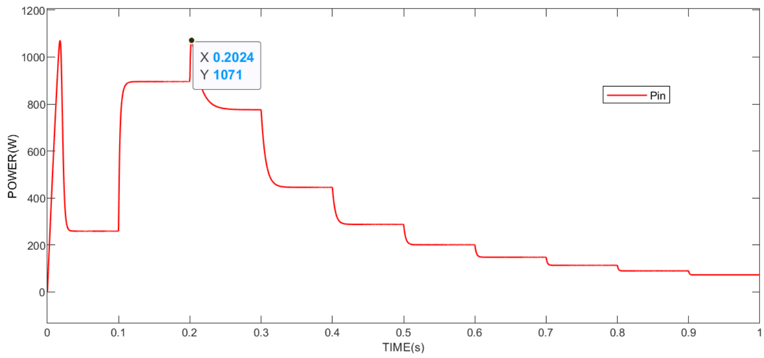
3. Results and Discussion

To ensure that the design that has been made is accurate and efficient, several tests have been conducted on the system. A total of three analyses were performed via duty cycle range for different irradiance, maximum power tracking for different irradiance, and maximum power tracking for different temperatures.

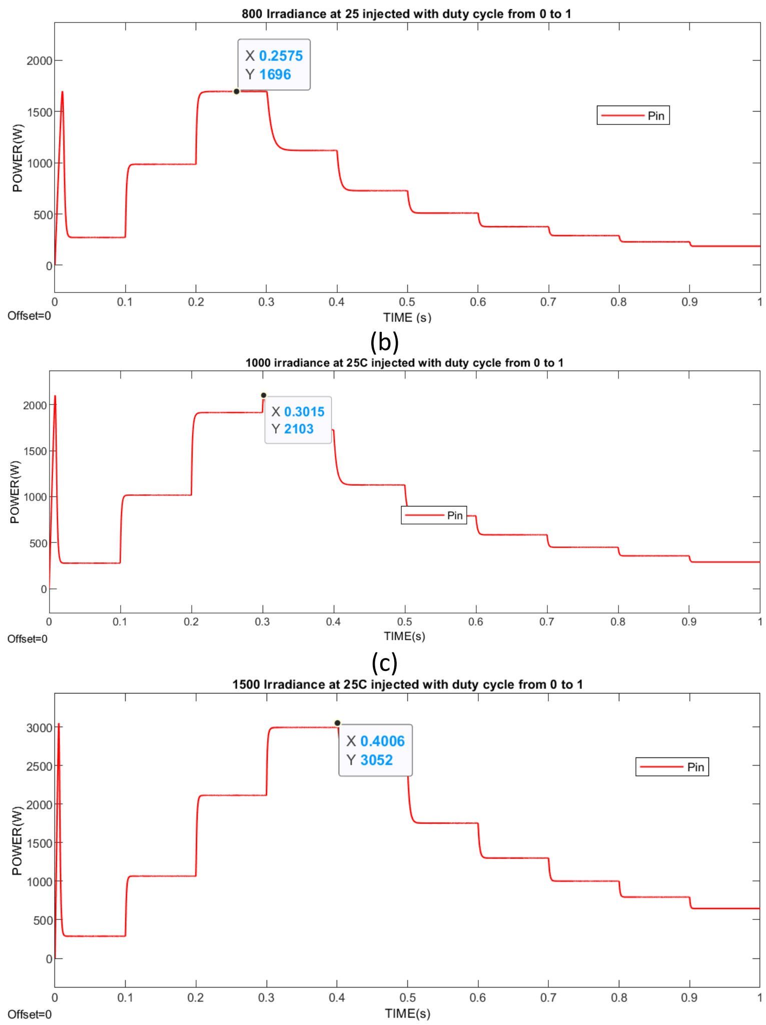
3.1 Analysis of Duty Cycle with Different Irradiance

In this analysis, the duty cycle is set from 0 to 1 with a step size of 0.1 to identify the range of duty cycles needed to achieve the maximum power point at the selected irradiance. The irradiance is injected into the system from 500 W/m^2 to 1500 W/m^2 at 25˚C.

Figure 9 shows the change in the duty cycle to the input power of the buck converter. Each value of the duty cycle shows a different value on the input power of the buck converter. Figure 9(a), Figure 9(b), Figure 9(c), and Figure 9(d) show the range of the duty cycle of the buck converter at 500 W/m^2, 800 W/m^2, 1000 W/m^2 and 1200 W/m^2 respectively.



(a)



(d)

Fig. 9. MPP of Irradiance at 25°C with Duty Cycle from 0 to 1: (a) 500 W/m^2, (b) 800 W/m^2, (c) 1000 W/m^2, (d) 1500 W/m^2

Table 5 tabulated the value of the maximum power point and the duty cycle range to achieve this maximum power. The result obtained shows that the range for the duty cycle is 0.3 to 0.4 for irradiance values of 800 W/m^2, 1000 W/m^2, and 1500 W/m^2. Besides, at an irradiance value of 500 W/m^2, the range for the duty cycle is at a value of 0.19 to 0.21.

Table 5
The duty cycle range for different irradiance

Irradiance (W/m^2)	Range of duty cycle
500	0.19 to 0.21
800	0.20 to 0.30
1000	0.30 to 0.34
1500	0.30 to 0.40

3.2 Different Irradiance at a Temperature of 25°C

The MPPT buck converter design is able to track the MPP between 900 W/m^{2}to 1100 W/m^2. The MPP obtained is compared to the MPP in Figure 10. This simulation was done using a variant of constant irradiance input to the solar array via MATLAB model.

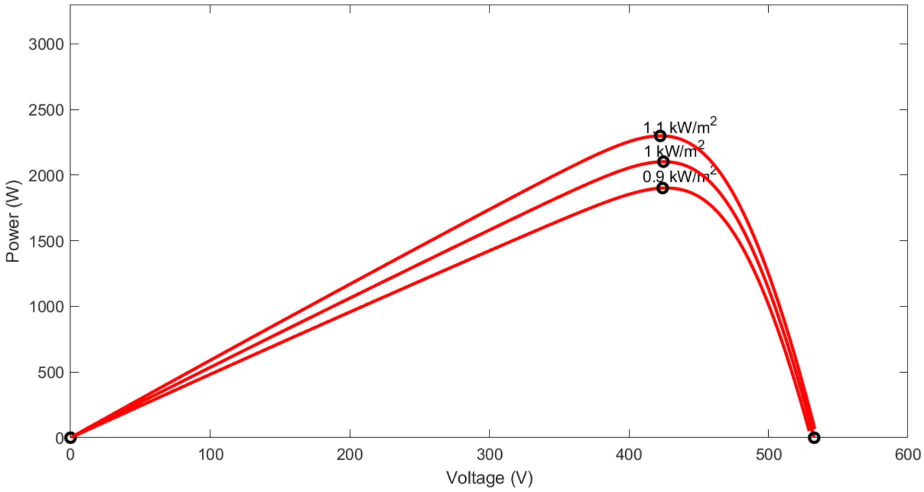
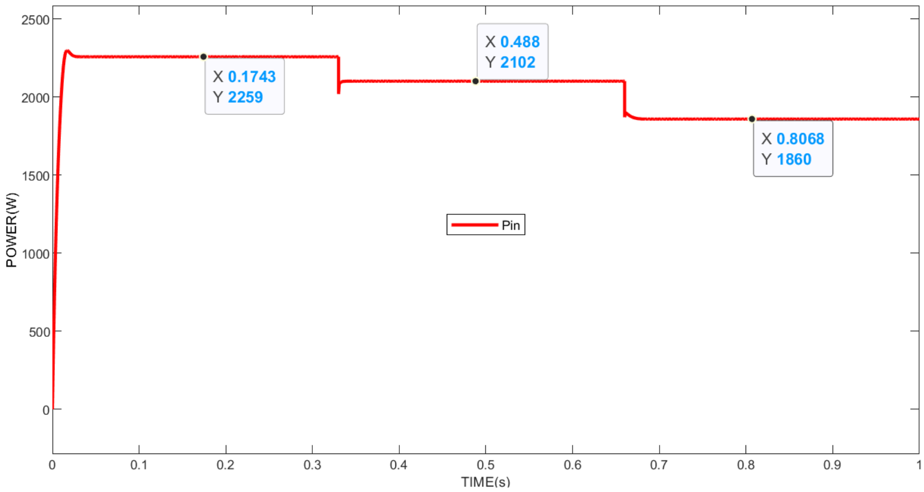


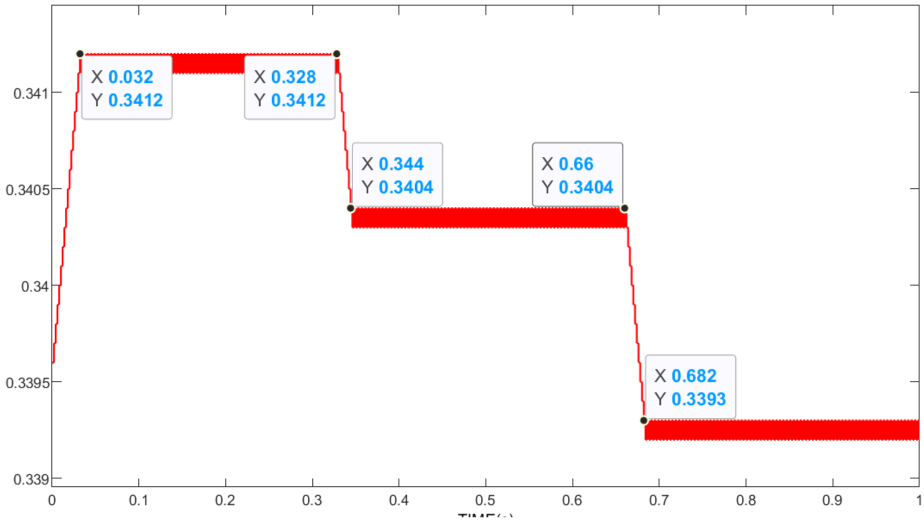
Fig. 10. PV-curve of different irradiance at 25°C

Figure 11(a) shows the behavior of the PV system's maximum power tracking with three different irradiance values at 25°C temperature. At 900 W/m^2 the maximum power point tracking is 1864 V within 32 ms with the duty cycle increasing its value to 0.3412 from 0.03395. While at 1000 W/m^2 The maximum power value of the irradiance is 2102 W within 16 ms, and the duty cycle decreased from 0.3412 to 0.3404. The maximum power at 1100 W/m^2 is 2256 W within 2 ms, and the duty cycle decrease from 0.3404 to 0.3393 as shown in Figure 11(b). In terms of the converter's accuracy, it is 98% accurate by comparing the actual input power with the input power tracked by the designed MPPT buck converter.

Concerning Table 6, it is found that the percentage error between the actual maximum power value and the maximum power track value by P&O is small, which is below 3%.



(a)



(b)

Fig. 11. 1100 W/m^2, 1000 W/m^2, 900 W/m^2 Irradiance at 25°C: (a) Maximum Power Point Tracking at Different Irradiance, (b) Duty Cycle Perturbation at Different Irradiance

Table 6
The comparison of input power at different

Temperature (°C)	Power (W)		Error (%)	Accuracy (%)
	Actual	P&O method		
900	1902	1860	2.21	97.79
1000	2103	2102	0.05	99.95
1100	2300	2256	1.91	98.09

3.3 Constant Irradiance at Different Temperatures

This simulation was carried out by using a MATLAB model that provided a variety of temperature using a timer block, 4 constant values of temperature, 20°C, 25°C, 30°C, and 35°C, are used to determine the efficiency of the MPPT buck converter including to test the range of temperature that the buck converter will be able to track the maximum power point.

From Figure 12(a) and by referring to Table 7 the input power decreases as the temperature increases from 20°C to 35°C, indicating that the temperature changes are tracked by the algorithm with an overall 99.84% of accuracy since the maximum power tracked by the MPPT have an error around 0.5% differences. From Figure 12(b), the duty cycle fluctuates depending on the input's condition. In this case, the changes in temperature indicating the perturbation of the duty cycle is in process. This shows that P&O algorithms track the maximum power by perturbing the duty cycle.

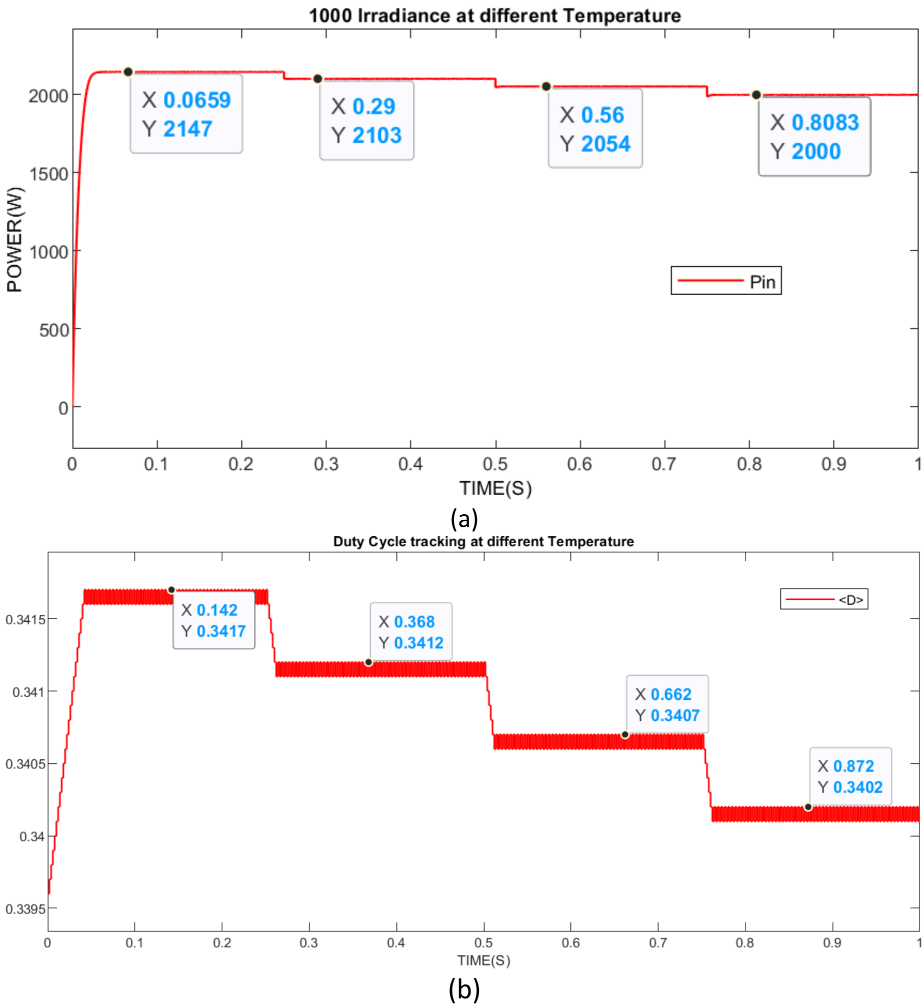


Fig. 12. 1000 W/m^2 Irradiance at 20°C, 25°C, 30°C, 35°C: (a) Maximum Power Point Tracking at Different Temperature, (b) Duty Cycle Perturbation for at Different Temperature.

Table 7
The comparison of input power at different temperatures

Temperature (°C)	Power (kW)		Error (%)	Accuracy (%)
	Actual	P&O method		
20	2149	2147	0.09	99.91
25	2103	2103	0.00	100.00
30	2056	2054	0.10	99.90
35	2009	2000	0.45	99.55

4. Conclusions

In this paper, a buck converts for MPPT was successfully designed based on a solar PV system in UiTM CPP. The study shows that the buck converter components' effects on MPPT transient response during sudden changes in irradiance are that it can only operate in a certain range of irradiance. In this case, the MPPT buck converter design can only track from 900 W/m^2 to 1100 W/m^2. This project has also successfully used the P&O method in obtaining the maximum power value for PV systems by applying a buck converter that has been designed. It can be concluded that the parameter calculation for the buck converter in this project is different from the conventional buck converter.

Recommended for the future, this project can be implemented using other converters and other methods of obtaining maximum power points.

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