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A Modified Perturb-and-Observe Control for Improved Maximum Power Point Tracking Performance on Grid-Connected Photovoltaic System

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Abstract. This paper deals with the control of maximum power production in a grid-connected photovoltaic system. The on-grid system ensures the continuity of electricity supply to consumers. It also offers less investment and operation cost due to the removal of battery requirements normally indispensable to guarantee supply continuity. To maintain the maximum output power production of photovoltaic panels regardless of changes in irradiation, proper control of the boost converter is necessary. The known perturb-and-observe method is explored and modified to improve performance. The modification is proposed by adding the measurement of the current variable to reduce the oscillation around the maximum power point once it is achieved. The connection to an existing single-phase alternating-current power grid is accomplished by implementing sinusoidal pulse-width modulation on the inverter. Phase-angle synchronization between the inverter output and the existing power grid is accomplished by using the phase-lock loop technique. Simulation of the proposed method showed that an improvement of the photovoltaic function up to 98% has been achieved.

Keywords: Boost converter; Grid-tie; Inverter; Maximum Power Point Tracking (MPPT); Photovoltaic

1. Introduction

During the development of a photovoltaic system, one of the important challenges to overcome is the reduction of output power due to uneven solar radiation under various shading conditions (Thakurta, 2020; Başoğlu, 2019). In addition, the system reliability and efficiency also depend on weather changes and load operation (Brazovskaia and Gutman, 2021; Guenther, 2018).

The general energy efficiency in a commercially available Photovoltaic (PV) cell is around 20%-25%, with the highest efficiency achieved so far being around 47.1% developed by The National Renewable Energy Laboratory (NREL) (Irving, 2020). This efficiency number decreases even more when we consider its use on various electrical equipment, accounting for the influence of efficiency in the voltage regulator, battery, cables, and inverter.

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The electrical power generated by photovoltaic cells must be adjusted before being connected to the power grid (Andreas *et al.*, 2018). After some adaptation and control steps, the generated electricity in a PV system can be either used directly by consumers or connected to a public electricity network. There have been numerous scientific publications discussing methods of connecting PV systems to the grid, for example, by using a DC boost converter in a nano grid system (Andreas *et al.*, 2018), the use of single-phase inverter (Huy *et al.*, 2021; Ahmad, Tsai, and Chen, 2020; Thakurta, 2020; Zarkov *et al.*, 2019), as well as by the addition of battery before being connected to the grid (Alhuwaishel and Enjeti, 2020).

A Maximum Power Point Tracking (MPPT) system, in general, is required to maximize power production considering the variability of incoming solar radiation. It can be obtained by dynamic or static methods (Wadghule and Aranke, 2016). The dynamic method may not be appropriate for energy conversion at small to medium scales, considering the relatively high cost and energy consumption. To resolve the issue, the alternative static methods can be used. In certain parts of the world, the static panel may become more efficient and less costly than the moving panel.

Several studies have discussed the control of the MPPT system. The use of fuzzy control showed a good tracking ability under changing external conditions (Dhaouadi *et al.*, 2021; Shah *et al.*, 2020). The use of a boost converter in an MPPT system using fuzzy control, which is tuned by an artificial neural network, has demonstrated its superiority in achieving the maximum power point and respond quickly to the change in environmental conditions (Mishra, 2018). Comparison of P&O, PSO (Particles Swarms Optimization), and improved PSM (Pattern Search Method) techniques are presented in (Tobón, 2017), and the simulation results show the advantages and shortcomings of each method for applications depending upon necessity and system availability.

Perturb and Observe (P&O) control is a classic method that has been widely applied to MPPT systems due to its ability to quickly track the maximum power whenever the environmental conditions change. The voltage change is measured each time in order to calculate the power change. However, the oscillation around the maximum power point once it is reached becomes the main shortcoming (Ahmed and Salam, 2018). The conventional P&O also still suffers from low efficiency at low radiation.

In this paper, a modification to the P&O control is proposed. This modification is still considered necessary to provide an alternative solution to the oscillation problem in the P&O method, which is well known for its tracking speed despite its simple characteristic. In particular, this paper examines the connection to a single-phase grid system, commonly found in residential areas and represents a practical case for small-scale PV-grid connection. The study is carried out through system modeling and analyses.

The writing of this paper is organized as follows. The second section explains the methods involved in the research. It covers the description of the photovoltaic and the related characteristic curves for various values of solar irradiation and temperature. It is followed with a description of the principle of tracking method of the maximum power points, the Direct Current (DC-DC) power converter on which the tracking method is to apply, and the description of the proposed modified P&O technique and the grid connection method. The results are shown in the third section with the detailed discussions. The fourth section concludes this study.

2. Methods

The methods used in this research involve the determination of the photovoltaic P-V curves, the tracking method principle of the maximum power points, the modeling of the

DC-DC converter, the elaboration of the proposed modified P&O method, and the grid-connection method.

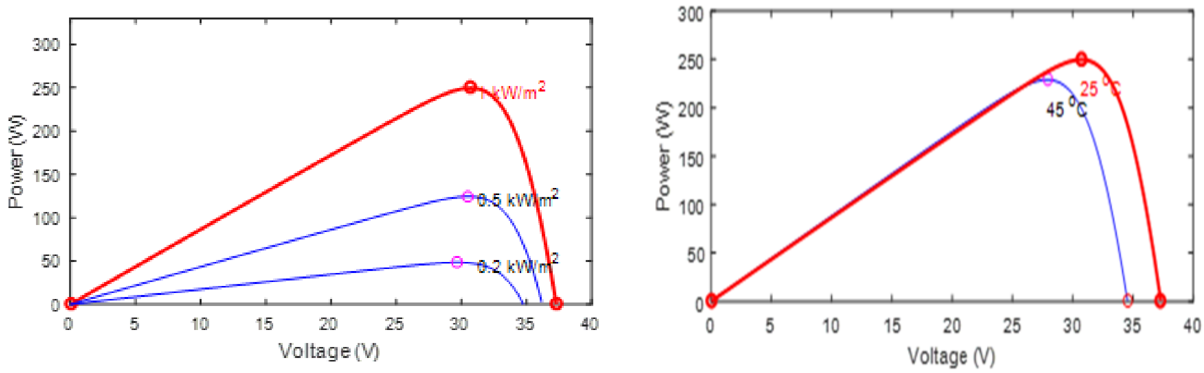
2.1. The Photovoltaic P-V Curves under Consideration

The type of PV module considered in this paper is 1soltech 1STH-250-WH, which has a maximum power of about 250 W and consists of 60 cells in each module. This module has a 37.3 V open circuit voltage and a short circuit current of 8.66 A. At the condition of maximum power point, the voltage and current would reach 30.7 V and 8.15 A, respectively.

The mathematical model of the photovoltaic cell is shown in Equation 1. I_o is the output current of the photovoltaic cell, Irs is the saturation current of the cell, q is electron drift, or moving velocity, n_p, and n_s are the number of cells connected in parallel and series, respectively.

$$I_o = n_p I_{ph} - n_p I_{rs}\left[\exp\left(\frac{qV_o}{kTAn_s}\right) - 1\right] \tag{1}$$

The PV module is also affected by irradiation and temperature changes. The P-V curves for various irradiation are shown in Figure 1a, and for various temperature conditions are shown in Figure 1b. As seen, irradiation has a big influence on the generated power. The greater the irradiation received by the photovoltaic, the greater the generated power. The changes in temperature and power also have an impact on the generated voltage.



(a) (b)

Figure 1 The P-V curves of photovoltaic cell: (a) for various irradiation conditions; and (b) for various temperature conditions

2.2. The Tracking Method Principle of Maximum Power Points

Since changes in the environment affect the generated photovoltaic power, the MPPT algorithm control is required to keep continuously track the Maximum Power Point (MPP) of the solar system. There are some selection parameters for the controller described in (Podder, 2019), e.g. stability, efficiency, prior training, cost, design complexity, sensed parameters, etc. In this study, current is selected as an essential sensed parameter in the MPPT control algorithm. The control will be implemented on a DC-DC converter, used to adapt the generated voltage to the desired specification based on the load requirements.

2.3. Direct Current (DC-DC) Converter

Boost-type converter is one of the DC-DC power converters that can be used to change and adapt the PV output voltage to a higher voltage as required by the load. A schematic simulation model of a boost converter is given in Figure 2. It consists of one IGBT switch, one passive diode switch, an inductor, and two capacitors.

Referring to Figure 2, when the Insulated-Gate Bipolar Transistor (IGBT) switch is closed during the time range t_{on}, current flows into the inductor, causing energy to be stored in the inductor. When the IGBT switch is open during the time range toff, the inductor current flows towards the load through the diode, causing the stored energy in the inductor to decrease. During the t_{off} period, the load is supplied by the source voltage plus the inductor voltage, which releases its energy. This condition causes the output voltage to be greater than the input, according to Equation 2.

$$\frac{V_o}{V_{in}} = \frac{1}{1-D} \tag{2}$$

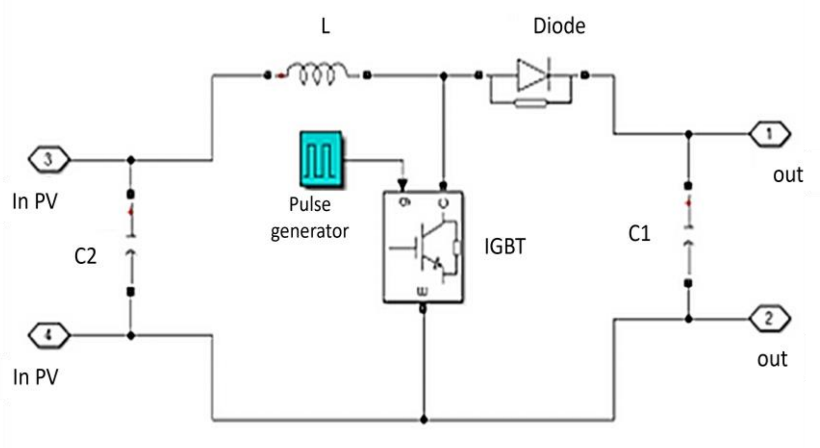


Figure 2 A simulation model of a boost converter

The capacitor used in the boost converter is designed to have a value greater than the minimum value given in Equation 3.

$$C_{\min} = \frac{V_o * D}{2 * \Delta V_o * f} \tag{3}$$

Similarly, the inductance value in the boost converter is designed to have a value larger than the minimum value given in Equation 4.

$$L_{\min} = \frac{D(1-D)^2}{2 * f} * R \tag{4}$$

By using Equation 3 and Equation 4, the capacitor and inductor parameter values for the boost converter are given in Table 1 by considering the following specification: duty cycle D = 0.44, V_o = 440 V, ripple voltage of 13.2, resistor of 30 ohms and switching frequency of 1000 Hz, and the calculated results of C_{min} and L_{min} respectively 488 F and 2069.76 µH.

Table 1 Inductor and capacitor parameters value

Inductor/Capacitor Parameter	Value	Unit
Capacitor (C)	2000	µF
Inductor (L)	4000	µH

2.4. The Proposed Modified Perturb-and-Observe (P&O) Method

The modified P&O method used in this study is described in Figure 3. As indicated, the output is used to set the duty cycle of the converter. The power changes are shown whenever the duty-cycle changes. The first step is the measurement of voltage V(k) and current I(k). The power P(k) is then calculated before being set as the power of recent condition P(k=k+1). If the difference between power P(k) and P(k-1) were greater or smaller than 0, then the output voltage is to be increased or decreased by changing the value of duty-cycle ΔD.

The modification proposed to overcome this issue of oscillation is accomplished by adding a step of ΔI=I(k)-I(k-1)>0, as indicated using the red diamond box on the flowchart in Figure 3. The addition of ΔI is useful for calculating the current value before giving an increase or a decrease in the duty cycle.

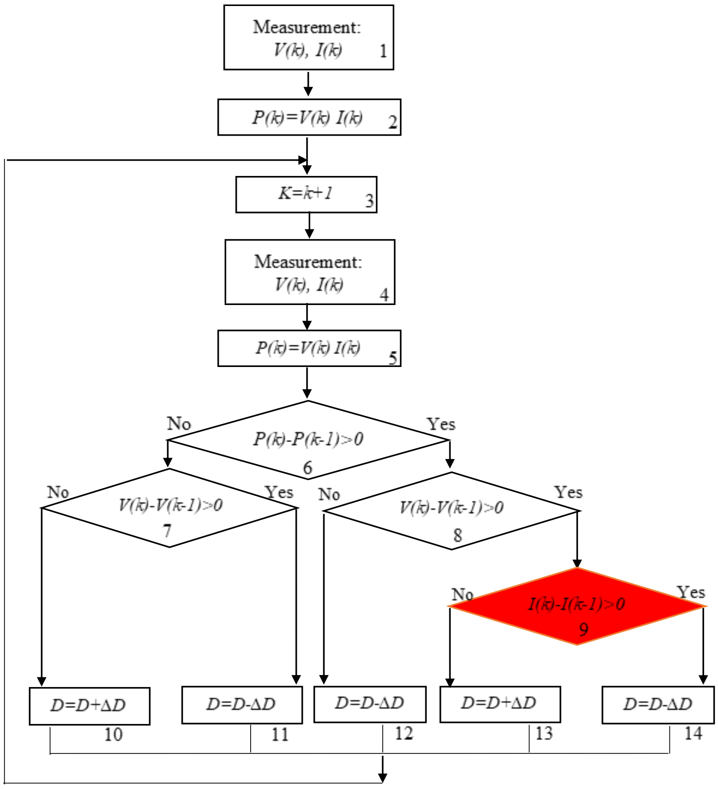
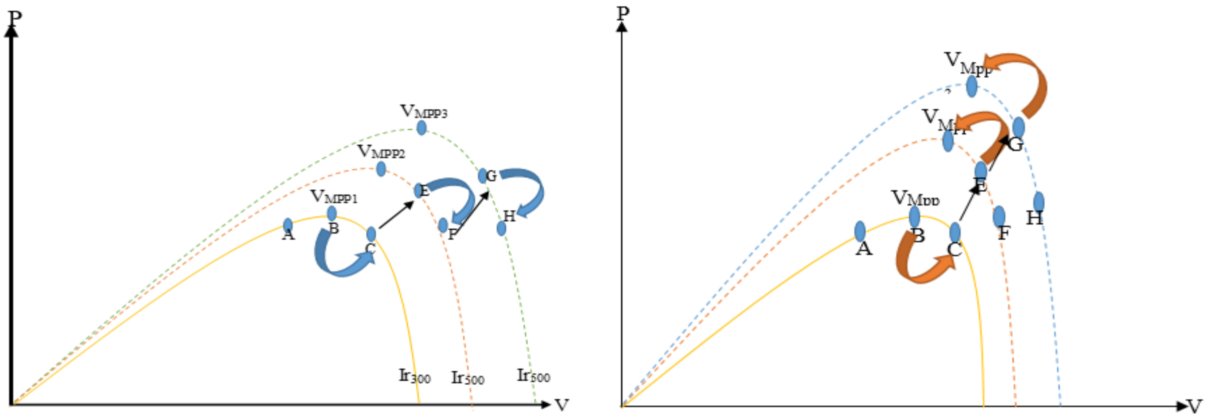


Figure 3 Modified perturb-and-observe algorithm flowchart (the proposed modification part is shown in the red diamond box)



(a) (b)

Figure 4 The working principle: (a) Conventional P&O analysis, (b) Modified P&O analysis

Figure 4 describes the possible problems experienced by the controller when the irradiation changes during the search for the maximum power condition. As can be observed in Figure 4a, in the use of the conventional P&O method, the operation moves from point A to point B. At point B, it is calculated that there are irradiation changes from 300 to 500, making the operation jump to point E. At point E, it is found that dP = (P_E-P_B)> 0. There is an increase in the cycle. Using the conventional P&O controller, it will move towards point F and away from maximum power point, V_{mpp2}, and so on if irradiation changes increase.

Analysis of the modified P&O controller by involving the current sensing technique is illustrated in Figure 4b. As indicated, point B should jump to C, however, it moves away towards point E due to the irradiation changes. At point E, the measurements involve $dP=(P_E-P_B)>0$, $dV=(V_E-V_B)>0$, and $dI=(I_E-I_B)$. On the modified P&O, the result is to reduce the duty cycle to the V_{mpp2} point, whereas, in the previous conventional P&O, it goes to point F. In this way, a positive value of dP can be detected using the dI parameter whenever there is a disturbance or irradiation increase.

2.5. Grid Connection Method

The use of a grid-connected inverter is considered in this paper to create a power supply system that is synchronous with the electricity grid without the use of the battery. This paper considers the Sinusoidal Pulse Width Modulation (SPWM) method to invert the DC voltage into AC voltage (Ahmad, Tsai, and Chen, 2020; Hannan, Aslam, and Ghayur 2018). Controlling the voltage and current entering the inverter is done using the Proportional-Integral (PI) technique.

The equalization of the phase angle between the grid and the inverter is carried out using a Phase-Locked Loop (PLL) technique (Banerjee, 2006). It is a frequency system control that utilizes phase sensitivity detection between the input and output of a controlled oscillation circuit. The block diagram of a PLL is shown in Figure 5.

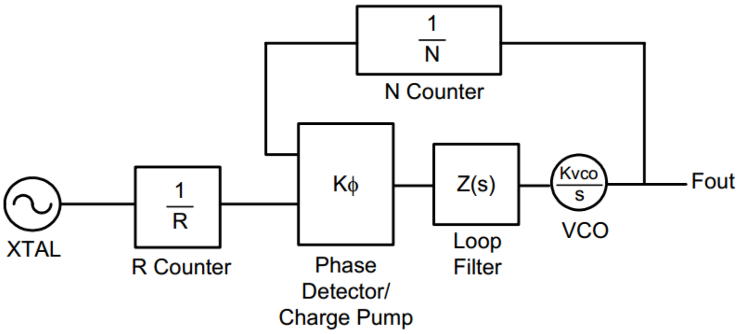


Figure 5 The basic PLL (Banerjee, 2006)

As shown, the function of PLL begins with a stable crystal reference frequency (xtal). The R counter, also known as the comparison frequency, is one of the input values used for the phase detector. The phase detector output is the average current value, proportional to the error phase that is obtained from the frequency comparison and output frequency. When the phase is the same, the frequency will also be equal. The output frequency F_{out} can be found using Equation 5.

$$F_{out} = \frac{N}{R} * XTAL \tag{5}$$

The power flow in the grid-connected system can be found using Equation 6, where X_L represents the power transmission line inductive reactance, P_{max} is the desired maximum transmitted power, δ is the phase angle between the inverter voltage and the grid voltage, V_{inv} is the inverter voltage, V_{grid} is the grid voltage.

$$P_{\max} = \frac{V_{inv} * V_{grid}}{X_L} * \sin\delta \tag{6}$$

3. Results and Discussion

The study has been undertaken by first considering the whole system without connection to the grid, and secondly, by taking grid-connection into consideration. Without a connection to the grid, the simulation scenarios were as follows: 1) the use of the conventional P&O method in the PV system, 2) a comparison of conventional and modified P&O MPPT controller at irradiation of 1000 W/m^2, and 3) the use of modified P&O method as irradiation changes. With the grid-connection consideration, the simulation scenarios were: 1) simulation of the use of modified P&O method at a fixed irradiation value, and 2) comparison of inverter voltage V_{inv} and grid voltage V_{grid}.

3.1 Prepreg fabrication

The curves of voltage and current obtained using the implementation of the conventional P&O control on the photovoltaic MPPT are shown in Figure 6, whereas the respective power response being compared to the use of the modified P&O control is shown in Figure 7. The simulation was conducted by assuming a temperature of 25oC and an irradiation of 1000 W/m^2.

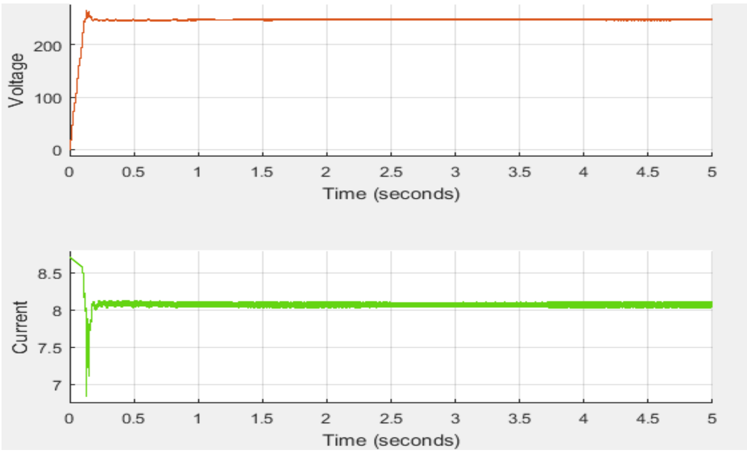


Figure 6 The voltage and current curves resulted using the conventional P&O control on the photovoltaic MPPT

As shown in Figure 6, the MPPT system was able to achieve a steady-state condition in less than 0.2 seconds. The average voltage (Vpv) and current (Ipv) generated by the PV system were 244.5 V and 8.07 A, respectively, which are close to the maximum voltage (Vmp) and maximum current (Imp) of the PV system under consideration.

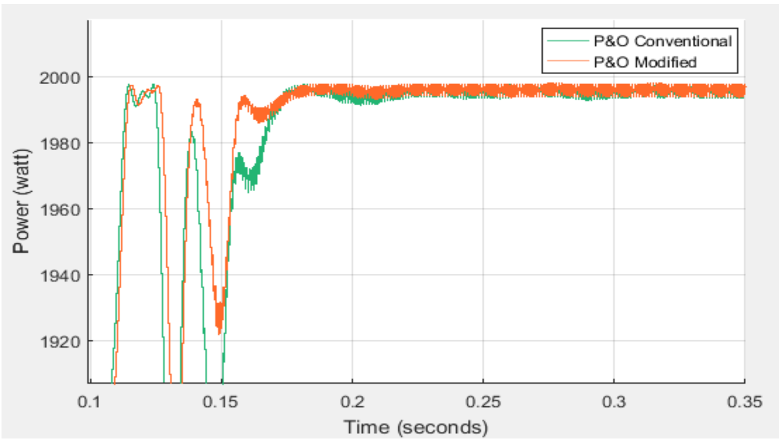


Figure 7 Comparison between the conventional and modified P&O methods in reaching the maximum power point

The power response comparison results depicted in Figure 7 indicate that both methods were able to reach a steady-state condition in less than 0.2 seconds. By utilizing the same resistance for both methods, the conventional P&O MPPT achieved a power of approximately 1997 W, which was significantly higher than the 125.9 W obtained without implementing the MPPT system. The modified P&O method reached only a slightly higher power than the conventional one. However, the modified P&O controller is significantly capable of reducing the oscillation of the generated power to reach the steady state of a maximum of up to 90 W. It can also be observed that using the modified method, it became stable at 0.18 s, while using the conventional method, it became stable at 0.26 s.

The results of a study on the influence of irradiation change are shown in Figure 8. The simulation was done by considering the irradiation values of 300 up to 1000 W/m^2. As seen, the change in irradiation occurred at the time of 1.515 seconds. It is indicated that the modified P&O controller performed better than the conventional P&O method because it can reduce the occurrence of power loss of approximately 25 W.

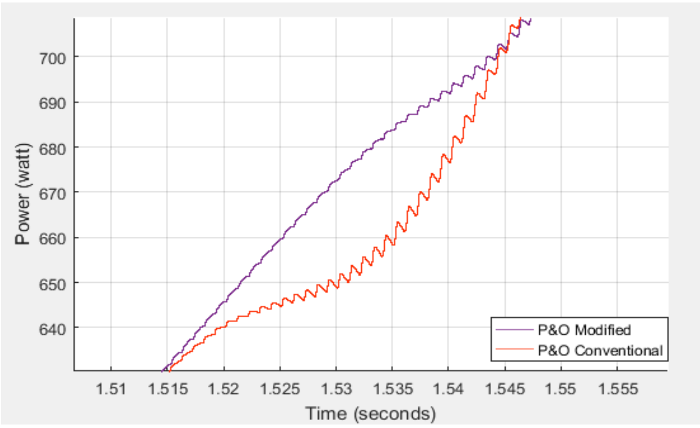


Figure 8 Power curve at irradiation changes

3.2. Results of Study on the PV-MPPT System Connected to Grid

The two following simulation scenarios were implemented by considering a grid-connected system with a grid voltage of 220 V and a frequency of 50 Hz. The first simulation was accomplished using a temperature of 25^o C and a fixed irradiation of 1000 W/m^2. The generated power by the grid-connected PV-MPPT system using the modified P&O controller can be seen in Figure 9. In the same figure, the power received by the grid can also be observed.

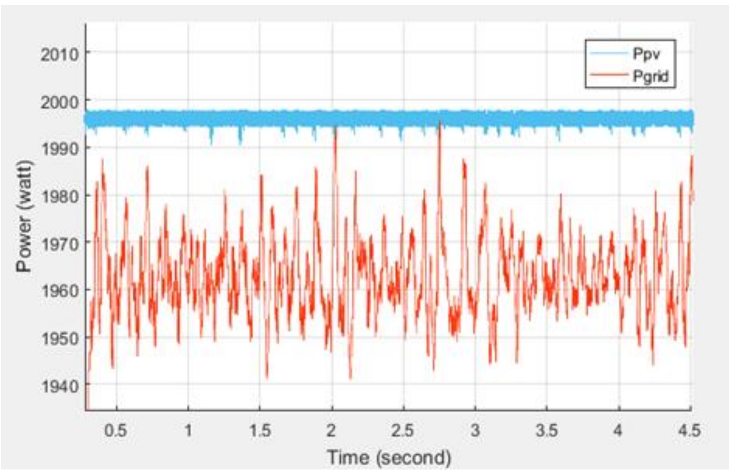
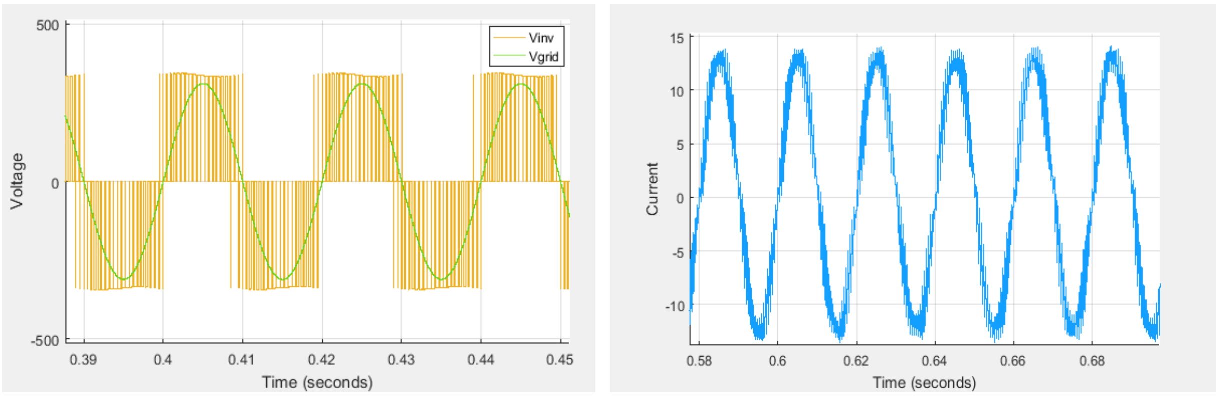


Figure 9 The PV-generated power and the power received by the grid using the modified P&O MPPT method

During the simulation, the PV maximum power was set to 2000 W, and using the modified P&O MPPT controller, a maximum power of 1997.3 W was obtained, confirming an accuracy of about 99.8%. The supplied power to the grid was 1944.3 W, giving an accuracy of 97%. Using the modified P&O controller on the Photovoltaic-Maximum Power Point Tracking (PV-MPPT) grid-connected system, a power difference of only 22 W on average (or 2% losses) between the output of PV and the grid was obtained. It is a favorable result like what was obtained by Ahmed and Salam (2018); however, they proposed more modification measures. The obtained result is still in the tolerated range as the generated power was still around the maximum power point. It can be concluded that in the grid-connected PV-MPPT system, the modified P&O controller worked successfully in finding the maximum power.

Results of the simulation under the irradiation changes, 450 W/m² up to 1000 W/m², are presented in Figure 10. The results comparison between the inverter output voltage and the grid voltage is shown in Figure 10a, whereas the inverter current is shown in Figure 10b.

By using the SPWM method, the inverter voltage (260 V) was designed to be slightly higher than the grid voltage (220 V). It was aimed to prevent an occurrence of current backflow to the MPPT system. The results seen in Figure 10b indicate that the generated current by the grid-connected MPPT system has an average value of 8.9 A. The generated voltage by the inverter in the system changes when there are changes in the generated current due to irradiation changes. In a grid-connected PV-MPPT system, the change in irradiation will result in a change in current, which is not the case with the generated voltage by the inverter. The generated voltage by the inverter is always kept constant.



(a) (b)

Figure 10 The resulting current and voltage in a grid-connected using system the modified P&O MPPT method, (a) inverter and grid voltage; (b) inverter current

4. Conclusions

It can be concluded that without using the MPPT system, the PV could not generate maximum power. The PV with an MPPT system could generate the maximum power. The conventional P&O method and the modified P&O method perform differently in tracking the maximum value of the PV-generated power. Under irradiation changes, the modified P&O method could improve the performance of the conventional P&O controller. The modified P&O MPPT system performs better under irradiation changes. When connected to the grid, the proposed modified P&O control method was still able to track the maximum power value, confirming that the proposed modification of the conventional P&O controller has improved the MPPT system performance in PV power generation.

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