A Modified P&O-MPPT based on Pythagorean Theorem and CV-MPPT for PV Systems

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***Abstract*- Maximum power point tracking MPPT techniques are a crucial part in photovoltaic PV system design to maximise the output power of a PV array which depends on weather conditions. Although several techniques have been developed, Perturb and Observe P&O is widely used for MPPT due to its low cost and simple implementation. However, the main drawbacks of this method are a low converging time, high oscillation around the maximum power point, and drift problem associated with changing irradiance rapidly. In this paper, a modified P&O-MPPT based on Pythagorean theorem and constant voltage CV-MPPT is presented. To assess this modification, conventional and modified P&O methods are simulated by a MATLAB-SIMULINK. Simulation results demonstrate that the modified P&O-MPTT has a highly effective to solve the problem of conventional P&O-MPPT.**

Keywords— photovoltaic (PV); Maximum power point tracking (MPPT); Perturb and Observe (P&O); Power-Voltage curve; variable step size (VSS); constant voltage (CV)

I. Introduction

In last years, the demand for energy has been increased dramatically due to the population growth. In other hand, the phenomenon of global warming has been intensified owing to the CO2 emissions from fossil fuels. To solve those complex issues, many researchers are interested to use renewable energy resources. Therefore, developed renewable energy resources have become a worthy research topic in last decade. A solar photovoltaic (PV), hydropower, wind turbine, biomass and geothermal are the major renewable energy resources. However, the solar PV energy is considered one of the most widespread renewable resources because of its sustainable, clean and safety energy [1].

According to the International Energy Agency (IEA), the global energy production from photovoltaic resources will reach 16% of global electricity by 2050. In other words, the efficiency of PV system is low because the power of a PV array depends on irradiance and temperature of environmental conditions. Hence, the mismatching weather conditions are added a loss of energy about up to 25% [2]. Consequently, the MPPT techniques have been employed in PV system by connect PV module with a power converter, as shown in Fig. 1, to achieve maximum power production continuously. Many key points play significant roles to design the best MPPT technique for the PV system such as cost, efficiency, lost energy, and type of implementation [3, 4]. Regarding to those points, many types of MPPT techniques have been developed such as Perturbation and Observation (P&O) [5], Incremental Conductance (IC) [6], Open Circuit Voltage (OC) [7], Constant Voltage (CV) [8], Fuzzy Logic (FL) [9], particle swam optimisation (PSO) [10], and Neural Networks (NNs) [11]. However, the P&O-MPPT is a popular method for PV-MPPT owing to its low cost and simple implementation [12]. On the other hand, it poses many challenges such as high oscillation around the maximum power point MPP, lower converging time, and drift problem associated with changing irradiance rapidly [13]. Therefore, several modifications have been proposed in literature.

Among them, the authors in [14] have suggested Variable Step Size (VSS) based on power-voltage curve to adapt the P&O-MPPT tracker. Whilst this proposal reduces the oscillation around MPP point and increases the speed of MPPT tracker when the weather conditions change rapidly, the drift problem is not discussed. Similarity, the authors in [15] have adapted MPPT tracking based on power-duty cycle curve which seems a much more robot. However, the drift problem is not eliminated completely when the solar irradiance changes suddenly. Therefore, the authors in [16] have added a new step for the P&O-MPPT algorithm based on the historical change in PV power (ΔP) to detect this deviation early, but this modification seems a non-optimal solution because this threshold is change regarding to weather conditions. Similarity, the authors in [17] have added the historical change in PV current (ΔI) as step decision between the decision of positive historical change in power (ΔP) and positive historical change in voltage (ΔV). Although this modification avoids the system from drift problem, the proposal is not valeted for another side of the P&O algorithm when ΔP and ΔV are negative historical changes. To solve the drift problem completely, the authors in [18] have designed P&O-MPPT algorithm consist of three stages to track all properties for the diversion problem. However, the implementation is become complex.

In this paper, a modified P&O-MPPT based on Pythagorean theorem and CV-MPPT is presented. This proposal quickly tracks the maximum power point and reduces the oscillation around the MPP under steady-state conditions. In addition, it avoids the drift problem when the solar irradiance increases rapidly. Finally, the modified algorithm is considered in a simple implementation. The rest of this paper is organized as follows: Section II covers a basic modelling of solar PV system. Section III explains the P&O–MPPT. In section IV, the proposed method is presented. The simulation results are discussed in section V. Finally, section VI reports the conclusion.

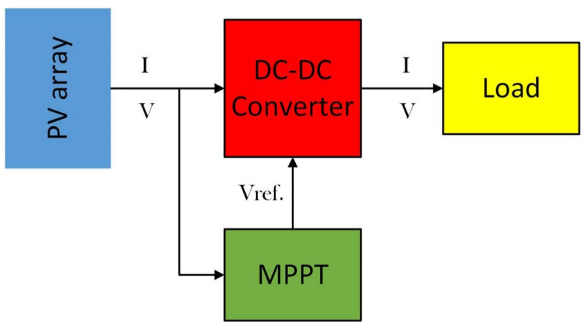


Fig. 1 a scheme diagram of PV system based MPPT.

II. PV System

In PV system, a solar cell is considered an essential part. In ideal PV cell, parallel and series resistances are not present but in practical case they are included due to leakage current and ohmic resistances as shown in Fig. 2. When PV cell is supplied irradiance the output current from the solar PV cell can be found using Kirchhoff's law, as shown in equation (1):

$$I_{PV} = I_L - I_d - I_{sh} \tag{1}$$

where I_L is the light generated current and given as in equation (2):

$$I_L = G\{I_{SC}[1 + a(T - T_{STC})]\} \tag{2}$$

where G is the irradiance, I_{SC} is the PV short circuit current, a is the temperature coefficient, T is the temperature operation of PV cell, T_{STC} is the temperature operation for the PV cell under Standard Test Conditions (STC), and I_d is the diode current as given in equation (3):

$$I_d = I_0 \left\{ \exp\left(\frac{qV_d}{nkT}\right) - 1 \right\} \tag{3}$$

where I_0 is the reverse saturation current of the diode, and V_d is the Voltage across diode, k is Boltzmann's constant (1.38×10^{-23} J/K), q is the electric charge (1.69×10^{-19} C), and n is the diode idealist factor. A general equation that describes the I-V characteristic curve of the PV cell is given in equation (4):

$$I_{PV} = I_L - I_0 \left[\exp\left(\frac{q(V_{PV} + I\,R_S)}{nkT}\right) - 1 \right] - \left[\frac{V_{PV} + I\,R_S}{R_{sh}}\right] \tag{4}$$

where I_{PV} is the PV output current, V_{pv} is the PV output voltage of PV cell, R_{sh} is parallel resistance, R_s is the series resistance. Solar cells are connected in parallel and series to obtain desired current and voltage respectively for the solar PV panel, and then the solar PV panels are connected in series and/or parallel to give different configurations of PV array.

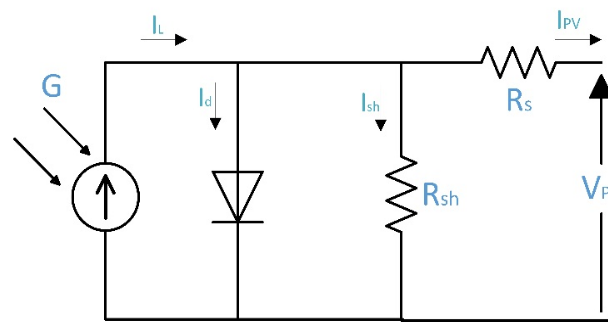


Fig. 2. Circuit diagram of a PV solar cell.

As shown in Fig. 3, there are unique points on the P-V curve of the PV array. This is known as the maximum power point MPP which depends on weather conditions such as solar irradiance and temperature operation [19]. The voltage operation of PV array also depends upon the impedance of the load-connected. When PV array is connected to the load it drops to the new operating point. To track the MPP continuously, the MPPT is employed with a conversion system. Though there are various types of the conversion system for the PV system, a DC-DC boost converter is widely used due to easy adapted MPPT controller. Basically, the MPPT is an electronic system.

The principle work of this system is to feed an appropriate reference voltage V_{ref} to the conversion system regarding to the output of PV array such the current and voltage or/and the input of PV array such solar irradiance level and temperature operation. This voltage is converted to signal by a gate driver circuit to adjust the conversion system operation. The optimal V_{ref} depends on the location of the operational point in the P-V curve. If the operating point is to the right of MPP, then V_{ref} will be decreasing until it reaches to the MPP, otherwise it will be decreasing. In the last years, many types of MPPT techniques have been presented; and each one has advantage and disadvantage. Typically, there are major key points are played a significant role to adapt the best technique for example cost, efficiency, lost energy, and type of implementation. Therefore, several types have been developed in literature reviews such as P&O, IC, CV, OC, FL, PSO, and NN-MPPT techniques.

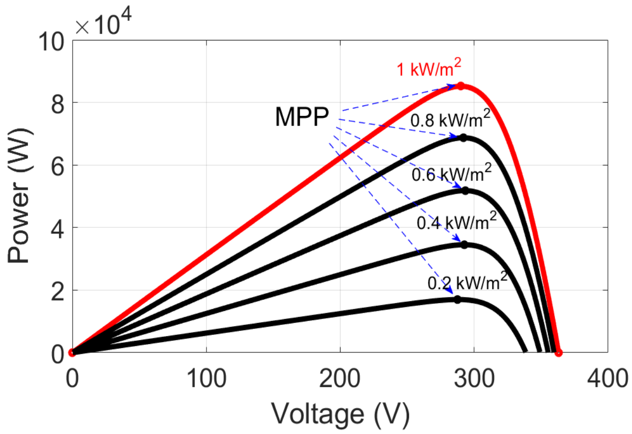


Fig. 3. P–V curve of a PV array for various values of irradiance.

III. P&O ALGORITHM

The P&O algorithm is widely used for PV-MPPT techniques due to its low cost and simple implementation. As shown in Fig. 4, the principle work of this method depends on calculate the PV power by using the sensed values of the voltage and current PV array and then compared with the previous power to address the direction of P&O algorithm and then updating the reference voltage according to equation (5):

$$Vref_{\cdot k+1} = Vref_{\cdot k} \pm \Delta V \qquad (5)$$

where $V_{ref.k+1}$ *and* $V_{ref.k}$ are the next and previous perturbation of the reference voltage respectively and the ΔV is the incremental step size of the reference voltage.

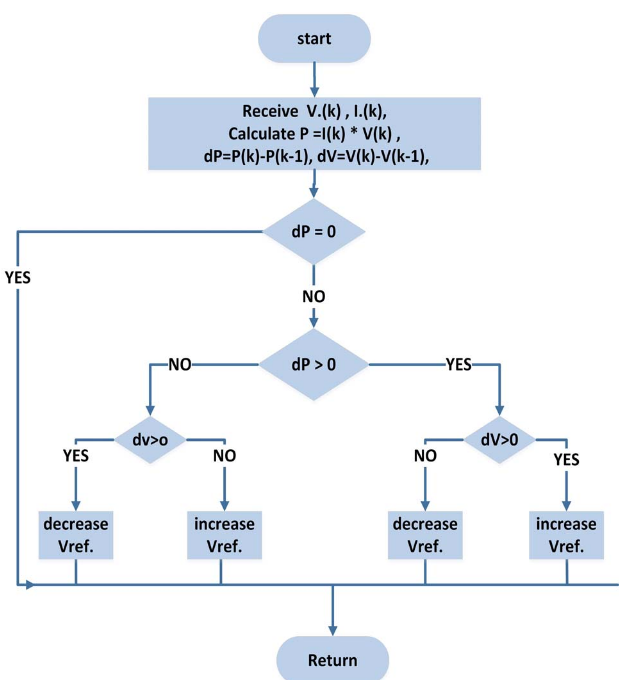


Fig. 4. Flowchart of a conventional P&O algorithm.

Basically, if the voltage and power of the PV array increase due to increasing reference voltage. The operating point moves in the same direction; otherwise it moves in the opposite direction. The process is continued until it reaches to the MPP and then oscillated around it. The total properties of P&O direction are explained in Table 1. In general, there are three major issues facing the P&O-MPPT operation: long converged time, high oscillation around the MPP and drift problem associated with changing irradiance rapidly. These issues are explained as following. Clearly, a large ΔV leads to a fast steady-state and large fluctuation after reach the MPP. Conversely, a small ΔV results in slow steady state and smooth fluctuations. Due to this conception, the size of ΔV is a crucial point to adjust the system operation.

Table 1. The probabilities of direction for P&O algorithm.

ΔP	ΔV	Direction of Perturbation
+	+	+
+	-	-
-	+	-
-	-	+

Another drawback is loss of the right direction of MPPT tracker when weather conditions increase rapidly. This phenomenon can be happened, as shown in Fig. 5, when point **A** (low point) which is represented the MPP at the low solar irradiance level is oscillated between **B** and **B`** and then moves to point **C** or **D** (high point) due to rapid increasing irradiance. As a result, the right direction of algorithm moves far away from the new MPP according to the principle properties direction of conventional P&O algorithm, as shown in Table 1. In other hand, this phenomenon is happened in case of the increasing irradiance only [9, 20]. Hence, the efficiency of the P&O-MPPT will be dropped owing to the above issues. To address those drawbacks, several modifications have been presented such as variable step size and adaptive P&O algorithm.

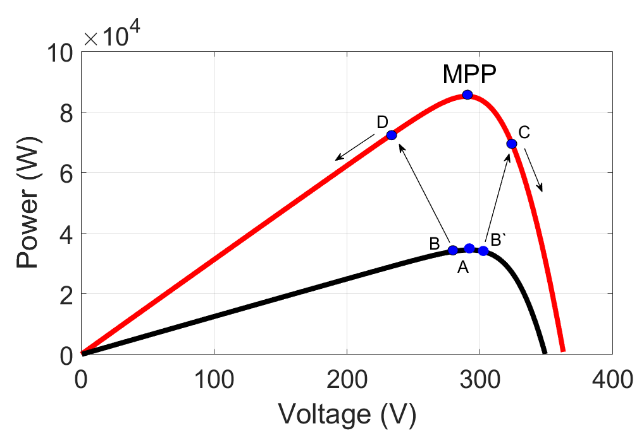


Fig. 5. P-V curve for rapid irradiance change from A (low point) to D or C (high point) illustrating the drift problem.

IV. PROPOSED METHOD

The proposed modification is divided into 2 parts. The first part is developed a novel and simple variable step size VSS which can improve tracking faster and reduce the oscillation around the MPP. This VSS is calculated regarding to Pythagorean theorem which proves that the square of the side opposite the right angle is equal to the sum of squares other two sides, as shown in equation (6):

$$a^2 + b^2 = c^2 \tag{6}$$

where c is the length of the hypotenuse and a and b are the lengths of the triangle's other two sides. This triangle seems equal to the movement of ΔP and ΔV in P-V curve, as shown in Fig. 6. This theorem is adopted to represent the VSS for P&O algorithm, as shown in equation (7):

$$\Delta V_{ref.k} = M.\sqrt{\Delta P_k{}^2 + \Delta V_k{}^2} \tag{7}$$

where ΔP_k is the historical change in PV power and the ΔV_k is the historical change in PV voltage and M is a constant step size which is adjusted according to the parameters of PV system. The general tracking equation is now written as equation (8):

$$V_{ref\ k+1} = V_{ref\ k} \pm M.\sqrt{\Delta P_k{}^2 + \Delta V_k{}^2} \tag{8}$$

where $V_{ref.k}$ is previous perturbation and $V_{ref.k+1}$ is next perturbation of voltage reference. This VSS is automatically tuned according to the operating point to enable a fast-tracking ability. If the operational point is far from the MPP, the historical change in PV power and voltage are large, and they automatically become small when the operational point closes to the MPP, as shown in Fig. 6. Consequently, the proposed system increases the speed of MPPT tracker when the weather conditions change rapidly and reduces the oscillation around the MPP at steady-state conditions.

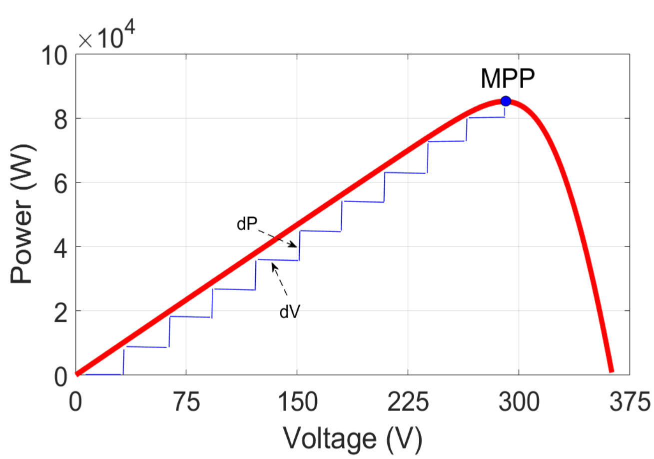


Fig. 6. P-V curve of PV module illustrating the variable step size VSS.

The second part of this modification is adopted a new step decision for conventional P&O algorithm to address the drift problem early. The drift problem happens when the solar irradiance on PV array increases rapidly about more than 10 $W/m^2/s$ [20]. Therefore, the input of solar irradiance is divided into two types; slow change and fast change as shown in equations (9) and (10):

$$\Delta G < 10\ W/m^2 \qquad slow\ change \tag{9}$$

$$\Delta G > 10\ W/m^2 \qquad fast\ change \tag{10}$$

Where ΔG is the historical changes in the solar irradiance. The standard test condition of solar irradiance G_{STC} is 1000 W/m2, as shown in equation (11):

$$G_{STC} = 1000\ W/m^2 \tag{11}$$

Substituting equations (9) and (10) into equation (11) the following is obtained:

$$\frac{\Delta G}{G} < 0.01 \qquad slow\ change \tag{12}$$

$$\frac{\Delta G}{G} > 0.01 \qquad fast\ change \tag{13}$$

As proved in [21], the normalised change in power is equal to the normalised change in solar irradiance, as shown in equation (14):

$$\frac{\Delta P}{P} = \frac{\Delta G}{G} \tag{14}$$

Substituting equations (12) and (13) into equation (14), then:

$$\frac{\Delta P}{P} < 0.01 \qquad slow\ change \tag{15}$$

$$\frac{\Delta P}{P} > 0.01 \qquad fast\ change \tag{16}$$

where ΔP is the historical change in PV power and P is the previous iteration for PV power. If the value of P changes due to the changing irradiance, the value of ΔP also changes in the same direction. Consequently, the value of $\Delta P/P$ is an almost constant during different environmental conditions.

A constant value (C = 0.01) is added in start program to address the drift problem early, as shown in Fig. 7 which explains the flowchart of proposed algorithm. If the $\Delta P/P$ is less thanC; the proposed algorithm will recognise that the solar irradiance on PV array changes slowly and the P&O algorithm should process this operating point, otherwise the CV-MPPT algorithm processes it. The CV-MPPT assumes that the irradiance level and temperature operation variations on the PV array are insignificant, and the constant reference voltage is an approximation of the real MPP voltage [8]. The

MPP voltage is calculated nearly 78% of the open voltage (V_{oc}) under varying weather condition [7]. Therefore, V_{set} is applied as 0.76 V_{oc} to enable the proposed algorithm to address the side of operating point after the solar irradiance changes rapidly. If PV voltage goes upper than V_{set}. The operation point is on the right MPP, result in decreasing voltage reference. If PV voltage goes downer than $Vset$, result in increasing voltage reference; and when operation point is close to MPP, the C value becomes very tiny. Consequently, the control unit switches to the conventional P&O algorithm to address the exactly optimal MPP.

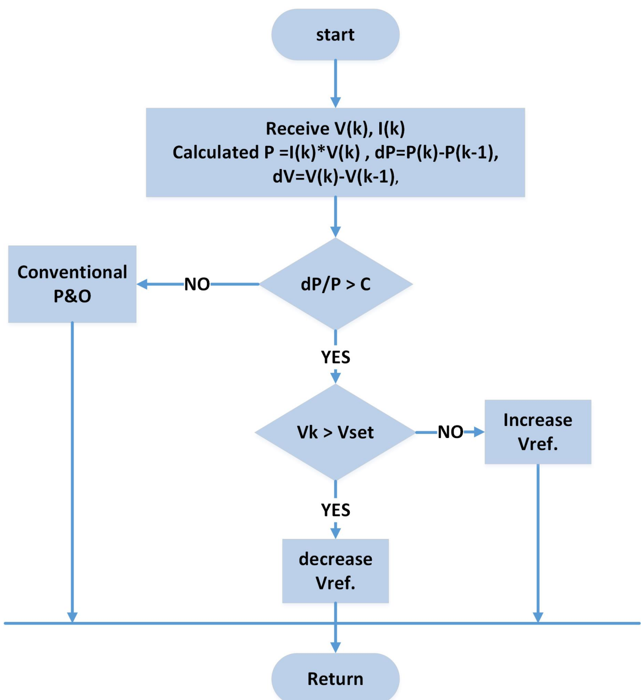


Fig.7. the flowchart of a modified P&O-MPPT method.

V. Simulation Results

To test the performance of the modified P&O-MPPT method, a MATLAB-SIMULINK model for a stand-alone PV system is developed. The stand-alone PV system consists of a PV array, DC–DC boost converter with MPPT controller and load. The parameters of the PV array which used in this simulation have 315 V open-circuit voltage and 395 A short-circuit current. The simulations are configured under exactly the same parameters for conventional and modified P&O-MPPTs. The updating period time of V_{ref} is every 1ms. The fixed step size of traditional PO-MPPT is 0.5 V. As shown in Fig. 8, the input of solar irradiance, which used in this simulation, decreases rapidly from 1000 to 400 W/m^2 at 0.5 to 1 second, and then increases rapidly from 400 to 1000 W/m^2 at 1.5 to 2 second. The temperature operation is kept at a constant value of 25°C.

As shown in Fig. 9, the tracking power of conventional P&O-MPPT method is almost good when the irradiance decreases. However, it loses the right direction when the irradiance increases rapidly. While, the modified P&O-MPPT method avoids the drift problem under different changes (increasing and decreasing in the input of solar irradiance). As a result, the modified P&O method tacks a shorter time than the conventional P&O method to address the drift problem.

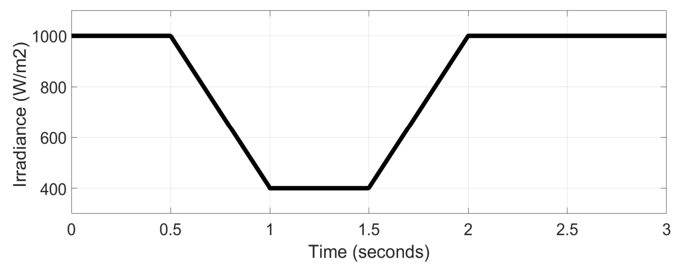
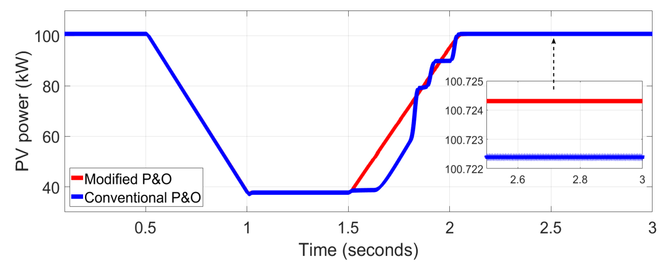
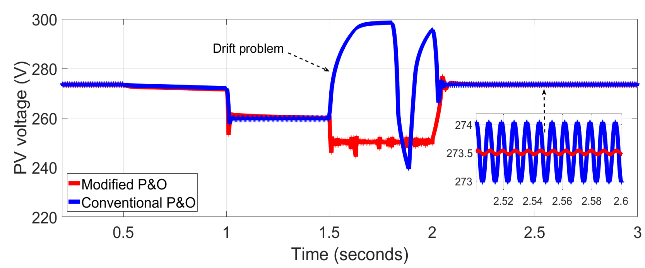


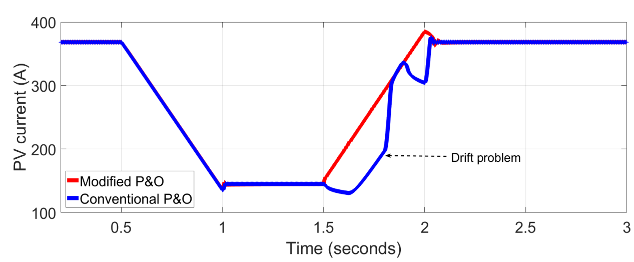
Fig. 8. The input of solar irradiance.



(a)



(b)



(c)

Fig. 9. PV array output for modified P&O VS conventional P&O under rapidly changes in solar irradiance; (a) power , (b) voltage , and (c) current.

In addition, the PV voltage of proposed method has a smooth oscillation around the MPP at steady-state conditions compared with the conventional P&O-MPPT due to the VSS, as shown in the zooming of Fig. 9 (b). Consequently, the lost power is a higher in conventional P&O-MPPT compared with modified P&O-MPPT. Thus, the output power of conventional P&O-MPPT and proposed method at steady-state conditions are 100.722 kW and 100.724 kW respectively, as shown in the zooming of Fig. 9 (a). According to the simulation results, the modified P&O-MPPT method quickly tracks the MPP during weather condition changes, reduce the oscillation around MPP under steady-state condition and avoids the drift problem when the weather conditions increase rapidly. In addition, the output PV power is a higher than the conventional P&O-MPPT.

VI. Conclusion

A modified P&O-MPPT technique based on Pythagorean Theorem and CV-MPPT method is presented to solve the problems of conventional P&O algorithm. To sum up, the issues of conventional P&O algorithm are discussed, and a novel and simple variable step size VSS is developed. In addition, the simple step decision is added in the start program of P&O algorithm to address the drift problem early. Conventional and modified P&O methods are simulated by a MATLAB-SIMULINK. The simulation results demonstrate that the proposed technique quickly tracks the maximum power point MPP during fast changing irradiance, reduces the oscillation under steady-state conditions and avoids the drift problem. In addition, it achieved a higher output power compared with the conventional P&O-MPPT.

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