CHAPTER 2

Review of Maximum Power Point Tracking Techniques for Photovoltaic Systems

2.1 Introduction

The disadvantages of PV systems are the low efficiency of the energy conversion, the maximum power point (MPP) depended on the weather and irradiation conditions and the non-linear characteristics of PV current-voltage (I-V) and power-voltage (P-V) as shown in Figure 2.1. In order to obtain the maximum energy from PV array, the PV system need to operate at the MPP continuously, to get this, the suitable MPP tracking technique is necessary to take the PV system achieving the MPP operation. Nowadays, the diversity of the maximum power point tracking (MPPT) techniques has been developed and implemented [34]-[38]. They can be classified as two main types of algorithms: indirect and direct MPPT [34]. The indirect MPPT algorithms use a set of database of the desired PV array and/or the temperatures, PV array parameters, or the instantaneous irradiation for estimating the MPP voltage or current reference such as: the voltage controlled technique, the PV equation based technique, or look-up table technique. The direct MPPT algorithms use the instantaneous measurement of the PV voltage or current to define the MPPT direction without the variable operating conditions or any database requirement which are the most popular MPPT algorithms, because it is independent control, low-cost and easy to implementing [34]-[35]. Those algorithms are the perturb and observe (P&O), incrementing conductance (INC), hill climbing (HC) and ripple correction control (RCC). Although, the best tracking factor (TF) is not the one from the direct MPPT techniques but they are very adjacent [61]. In this chapter, the most popular of the conventional MPPT techniques will be discussed with a brief review and then investigated about the advantages and drawbacks which critically affect to the system performance.

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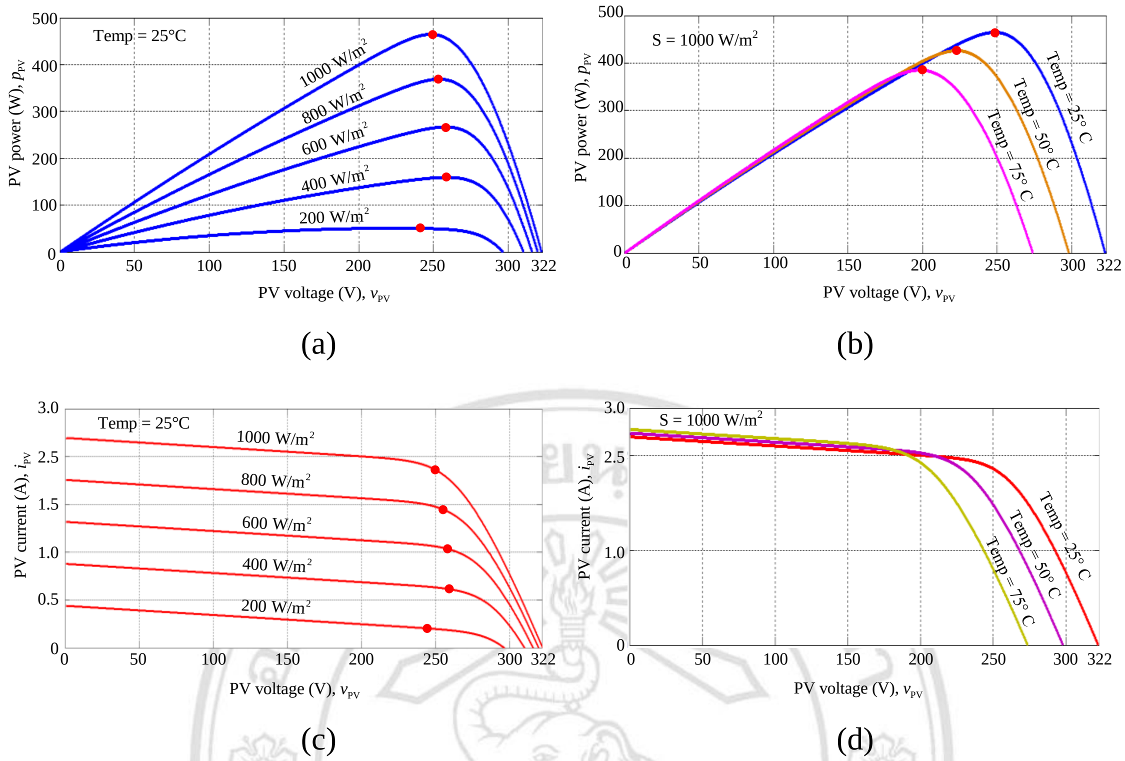

Figure 2.1 The characteristic of PV panel with relationship curves (a) I-V curves when the irradiance is changed, (b) I-V curve when the cell temperature is changed, (c) P-V curve when the irradiance is changed, and (d) P-V curve if the cell temperature is changed.

2.2 Perturbation and observation (P&O)

The P&O MPPT technique is the most commonly used in commercial PV systems because it is simple and easily implementation [61]. The MPP indicator in every condition of PV operation used in this method is the derivative of PV power with respect to PV voltage $dp_{\mathrm{PV}} / dv_{\mathrm{PV}} = 0$, which is on the top of P-V characteristic curve. The classical P&O MPPT algorithm mostly tracks the MPP by the perturbation of reference variable which can be one from these three perturbations; 1) reference voltage perturbation, 2) reference current perturbation or 3) duty ratio perturbation. In case of using the reference voltage perturbation, the classical P&O forces to increasing or decreasing the voltage reference with the constant perturbation step and regulation sampling time as the following conditions. If the power derivative, $dp_{\mathrm{PV}} / dv_{\mathrm{PV}} > 0$, the operating point is in the left hand side of MPP, the PV voltage has to be increased to

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approach the MPP , and otherwise, when the operating point is in the right hand side of MPP, the power derivative, $dp_{PV} / dv_{PV} < 0$, the PV voltage has to be decreased to approach the MPP as shown in Figure 2.2 [37]. This process is continuously repeated until the MPP is reached, then the PV system operating point is oscillated around the MPP. Its optimized operation depends on the sampling interval and the step size of perturbation. The sampling interval must be cover periodic or measuring speed of the PV voltage and current to calculate the system PV power and then to be compared with previous PV power value in order to define the direction (increasing or decreasing PV voltage reference) of tracking the MPP. For the step size of the perturbed voltage reference (Δ), it can be minimized to reduce the amplitude value of oscillations around the MPP in steady state condition leading to reduce power losses, but in the dynamic atmospheric conditions such as in cloudy days, the speed of the algorithm response is slowed down providing lower the MPPT efficiency. Otherwise, if the step change perturbation PV voltage is large, the MPP can be reached very fast, however, the amplitude value of the oscillation around the MPP will be higher providing to increase the power losses [37]. This drawback can be solved by adapting the step size of the perturbation in order to optimize the perturbation time to reach the MPP. The process of this classical P&O MPPT technique is shown in Figure 2.3.

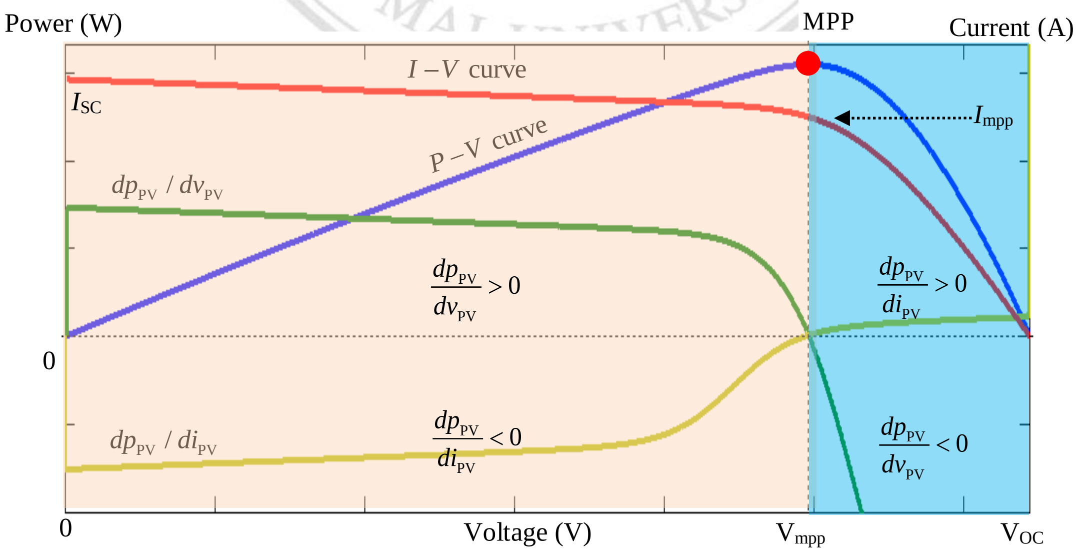

Figure 2.2 MPP tracking direction on P-V characteristic curve

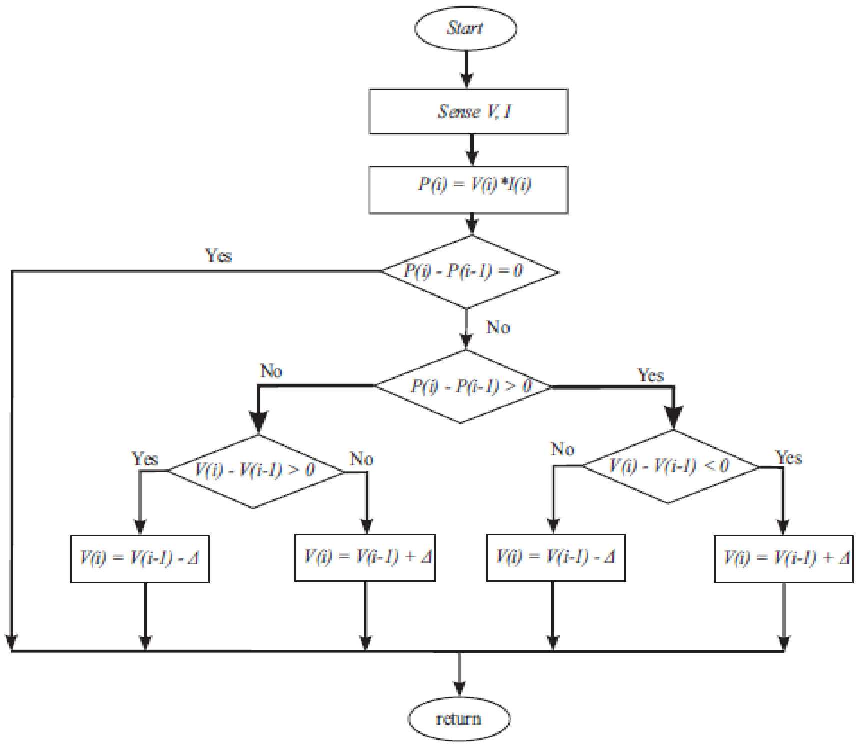

Figure 2.3 Flowchart of the classical P&O MPPT algorithm with reference voltage perturbation [37].

From the drawback of the classical P&O MPPT technique, focusing on the rapidly changing irradiation on the PV panels. An optimized MPPT technique based on the P&O algorithm called the optimized dP-P&O MPPT technique is presented to improve the MPPT performance in case of the rapidly changing conditions. This technique defines the behavior of change in the irradiation to be two cases, rapidly and normally changing. They are detected and separated by calculating the power difference dP between two derivative powers dP_1, dP_2 from three points of time as shown in Figure 2.4 power difference dP can be given as

$$\begin{aligned} dP &= dP_1 - dP_2 = (P_x - P_k) - (P_{(k+1)} - P_x) \\ &= 2P_x - P_{(k+1)} - P_k \end{aligned} \tag{2.1}$$

The consideration gain is defined that if the absolute value of change in power $|dP_2|$ is smaller than the absolute value of final change of power $|dP|$, it means that the slowly changing condition is occurred. The small step size of perturbation is used and operated

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follow the flowchart shown in Figure 2.5 to reduce the oscillation around the MPP. Otherwise, the absolute value of final change of power $|dP|$ smaller than $|dP_2|$, that means the rapidly changing condition is happen, and then, the optimized dP-P&O technique will be operated with faster tracking as the flowchart of process shown in Figure 2.6. This technique is proposed by Dezso et al [38]. It can be used MPPT in the PV system with a quick and accurate tracking even in the conditions of sudden changing atmospheric.

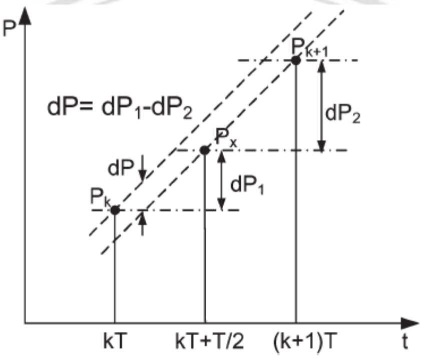

Figure 2.4 Measurement of the power between two MPPT sampling instances.

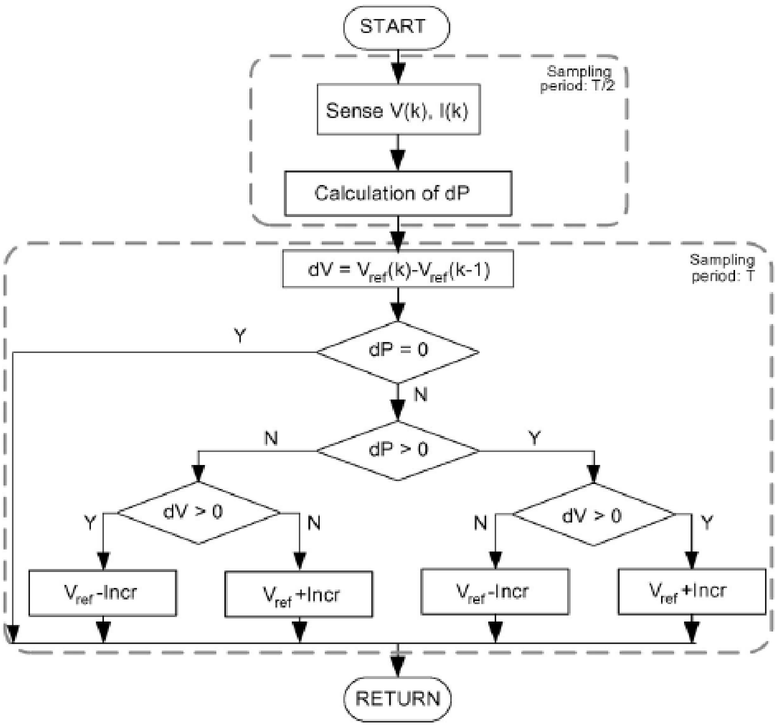

Figure 2.5 Flowchart of the dP-P&O algorithm.

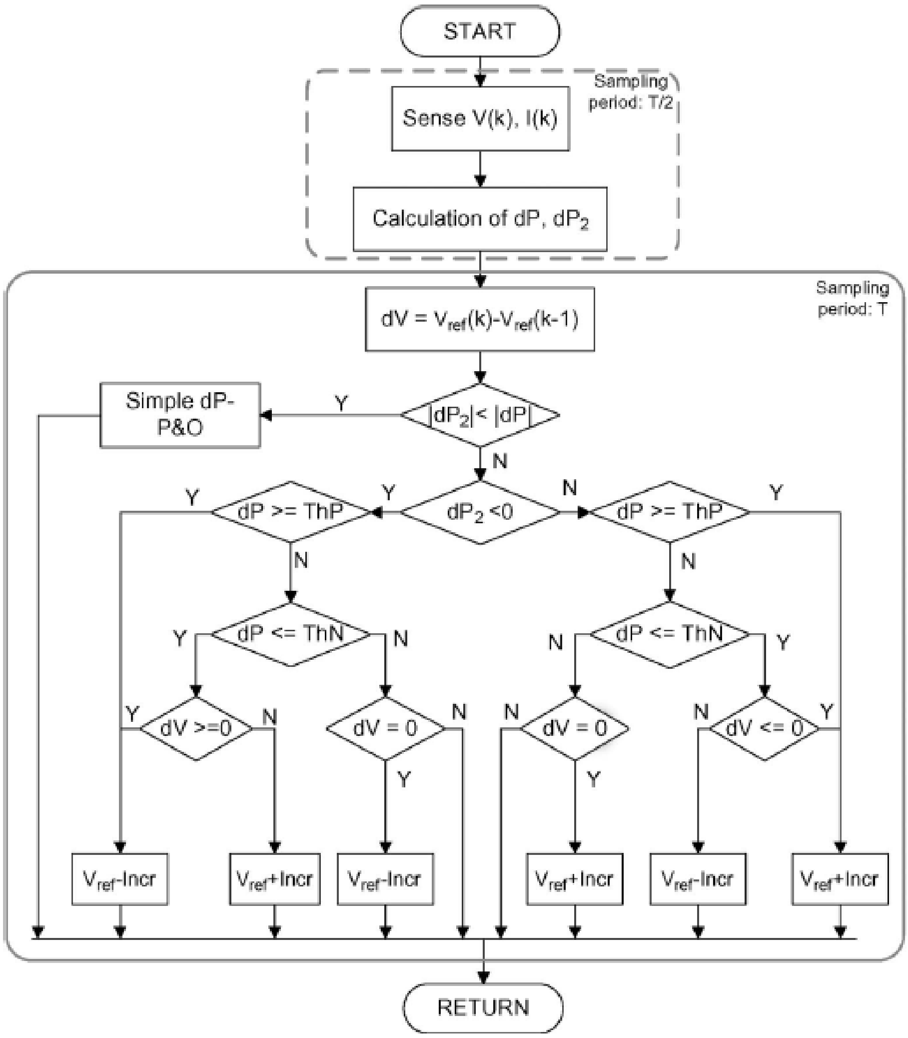

Figure 2.6 Flowchart of the dP-P&O method with optimized tracking.

Although, the perturb and observe (P&O) MPPT technique is the most commonly used technique due to its easy implementation and it has been improved to reduce the power losses caused by its drawbacks; the operating point oscillates around the MPP and the confusing in first tracking during the rapidly changing of the irradiation, as the aforementioned MPPT techniques based on the P&O principle. However, those MPPT algorithms still need the process of measuring the voltage and current of PV system to calculate the PV power at less two sampling interval and then to be compared each other. In addition, to avoid the drawbacks by using the *dP*-P&O MPPT technique, it must need more time to get the required parameters.

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2.3 Incremental conduction (INC)

K. H. Hussein et al have presented the incremental conductance (INC) in order to overcome the drawbacks of the classical P&O MPPT technique during rapidly changing atmospheric conditions, in case that the P&O technique cannot consider the relationship between the change in the PV power to the change in the atmospheric conditions. Only the change in PV power is analyzed to obtain a result of the perturbation based on the array terminal voltage. The principle of the INC technique is to analyze the MPP with the change in PV power to the change in PV voltage must be zero $dp_{\mathrm{PV}} / dv_{\mathrm{PV}} = 0$ which is on the top of P–V curve, it can be represented in terms of voltage and current as

$$\begin{aligned} \frac{dp_{\mathrm{PV}}}{dv_{\mathrm{PV}}} &= \frac{d(v_{\mathrm{PV}} \cdot i_{\mathrm{PV}})}{dv_{\mathrm{PV}}} = v_{\mathrm{PV}} \frac{di_{\mathrm{PV}}}{dv_{\mathrm{PV}}} + i_{\mathrm{PV}} = 0 \\ \frac{di_{\mathrm{PV}}}{dv_{\mathrm{PV}}} &= -\frac{i_{\mathrm{PV}}}{v_{\mathrm{PV}}} \end{aligned} \qquad (2.2)$$

The MPP is determined by balancing between the instantaneous conductance $-(i_{\mathrm{PV}} / v_{\mathrm{PV}})$ and the incremental conductance $di_{\mathrm{PV}} / dv_{\mathrm{PV}}$. Normally, the signs of the change in PV voltage and PV current are presented in opposite way follow the I-V characteristic curve of PV panel, the size of the change in PV current $|di_{\mathrm{PV}}|$ is small while the operation point is in the left hand side of the MPP providing the $(di_{\mathrm{PV}} / dv_{\mathrm{PV}}) < -(i_{\mathrm{PV}} / v_{\mathrm{PV}})$, the MPP can be tracked by increasing the PV voltage. And then, the $|di_{\mathrm{PV}}|$ is sharply inflated during the operation point is in the right hand side of the MPP making $(di_{\mathrm{PV}} / dv_{\mathrm{PV}}) > -(i_{\mathrm{PV}} / v_{\mathrm{PV}})$, the PV voltage must be decreased to reach the MPP. In case of the change in PV voltage is closed or equal zero $dv_{\mathrm{PV}} \succ 0$. The slop $di_{\mathrm{PV}} / dv_{\mathrm{PV}}$ is quite large or becomes infinite, only di_{PV} is used to track the MPP. From the mentioned operating, its algorithm can be operated as the flowchart shown in Figure 2.7. The performance of this algorithm is better than the P&O technique in a rapidly changing atmospherics and is robust to the rapidly varying solar radiation [34]-[35].

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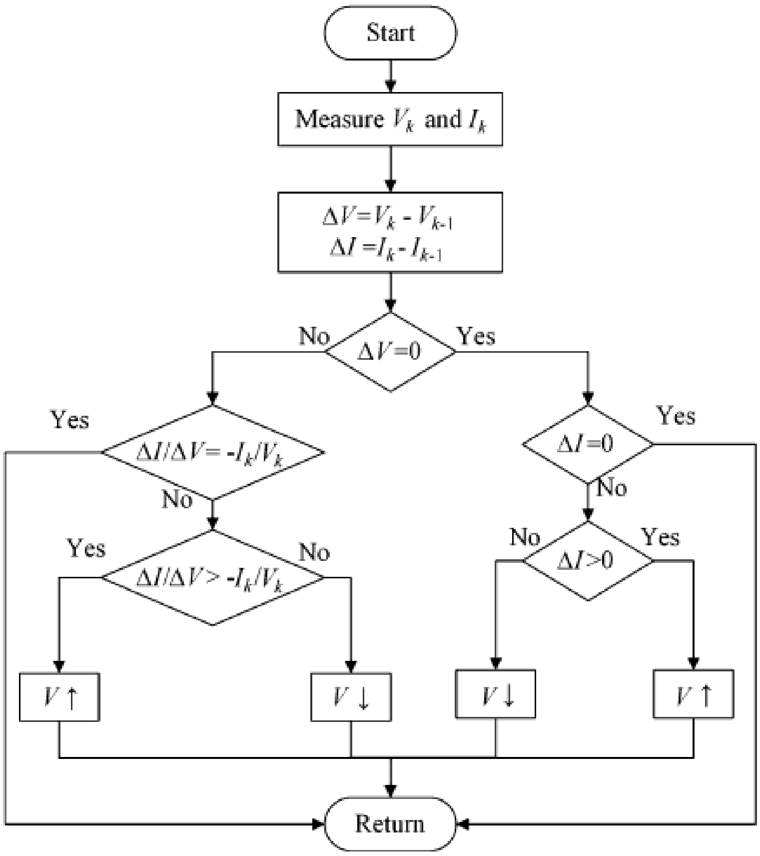

Figure 2.7 Flow chart of INC MPPT algorithm.

A MPPT technique of hybrid circuit having both analog and digital signals designed by Mattavelli et al [37] which the main circuit parts consisted of a field-effect transistor, analog switches, a comparator, and an operational amplifier; digital logic gates are used to select the time interval and direction of the search algorithm. [37-39]. A current-based MPPT uses the current as a signal in the modification of the INC algorithm. The automatically adjustable variable step size is used to improve accuracy and MPP tracking speed of the conventional INC technique. The step size is large when the operating point is far from the MPP for fast tracking and smaller during operation point is closer to the MPP to minimize the steady-state oscillation [40]. The step size (*step*) is can be given by

$$step = N \cdot \left| \frac{dP}{dV} \right| \tag{2.3}$$

where N is the coefficient of weight factor used to optimize scale of the step size. The process of calculating and controlling the MPPT is run as the flowchart shown in Figure 2.8.

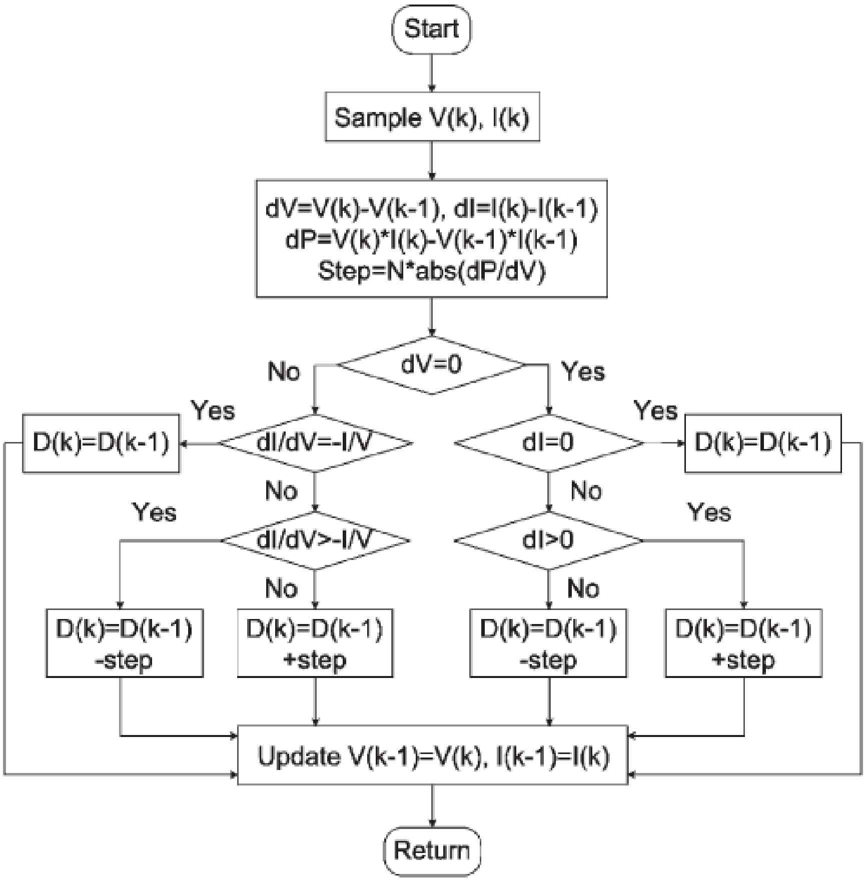

Figure 2.8 Flowchart of the variable step size INC MPPT algorithm.

Qiang et al present a novel improved variable step-size incremental-resistance (INR) MPPT method for PV systems by using the modified derivative of resistance ($dv_{\mathrm{PV}} / di_{\mathrm{PV}}$) instead the derivative of the conductance [41]. The modified algorithm is a variable step-size incremental-resistance algorithm, based on the P–I characteristic curve which the change in PV power to the change in PV current is zero ($dv_{\mathrm{PV}} / di_{\mathrm{PV}} = 0$) at the MPP, positive on the left of the MPP ($dv_{\mathrm{PV}} / di_{\mathrm{PV}} > 0$), and negative on the right of the MPP ($dv_{\mathrm{PV}} / di_{\mathrm{PV}} < 0$). The step size ($step$) can be given by

$$step = P^{n} \cdot \left| \frac{dP}{dI} \right| \tag{2.4}$$

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where n is the exponential index of PV power (P) used to adjust scale of the step size. The response of step size ($step$) based on the P-I curve of PV array is shown in Figure 2.9. The response speed of this modification is improved and the steady-state oscillation is decreased.

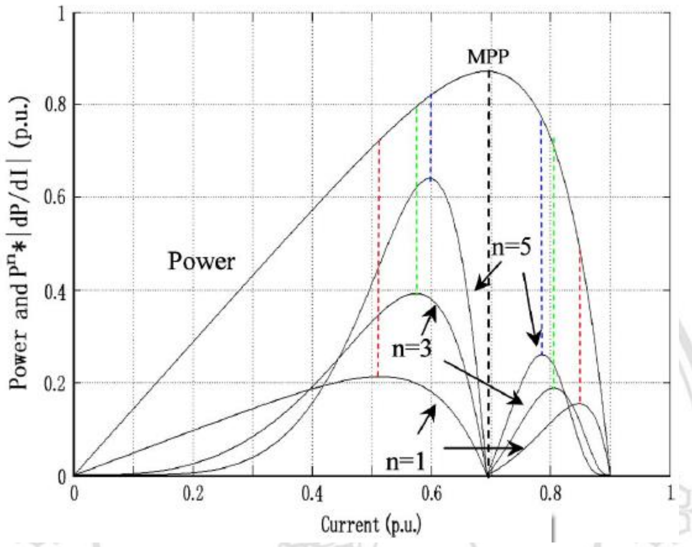

Figure 2.9 Per unit P-I curve and response of the step size, $step = P^n \cdot (dI / dV)$ when n = 1, 3, 5 [41].

The INC MPPT technique does not oscillate around the MPP and efficiently tracks the MPP during partially cloudy days and rapidly varying environmental conditions, which makes it suitable for the regions where environmental conditions are unstable. However, the response of using the variable step size algorithm is not linear; it can give the fast response MPPT while the PV operating point is in the area closed to the MPP. If the operating point is far from the MPP in a distance, the step change is downsized providing the MPPT response is slow down follow the step size also. Furthermore, this algorithm has a drawback of requiring costly complex microcontrollers to implement the algorithm. Therefore, it is suitable for large applications in the regions of sudden change environmental conditions.

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2.4 Ripple correlation control (RCC)

Ripple correlation control (RCC) technique is a dynamic process for reaching the MPP of the solar cell. The principle of RCC is considered from the fact that the slope $dp_{\mathrm{PV}} / dv_{\mathrm{PV}}$ and $dp_{\mathrm{PV}} / di_{\mathrm{PV}}$ are the indicators for MPPT of the PV cell as presented in P-V and I-V curves shown in Figure 2.2. A ripple is an AC component which acts as the derivative of its signal. Therefore, the derivative of PV power dp_{PV} / dt, PV voltage dv_{PV} / dt or PV current di_{PV} / dt can be replaced as ripple of PV power $\tilde{p}_{\mathrm{PV}}$, PV voltage $\tilde{v}_{\mathrm{PV}}$ and PV current $\tilde{i}_{\mathrm{PV}}$, respectively. Practically, those ripples can be achieved by using the analog or digital high-pass filter. The multiplication between ripple of PV power and PV voltage $\tilde{p}_{\mathrm{PV}} \cdot \tilde{v}_{\mathrm{PV}}$ and PV power and PV current $\tilde{p}_{\mathrm{PV}} \cdot \tilde{i}_{\mathrm{PV}}$ can be used to track the MPP as the use of $dp_{\mathrm{PV}} / dv_{\mathrm{PV}}$ and $dp_{\mathrm{PV}} / di_{\mathrm{PV}}$, respectively. The RCC technique can decide the MPPT direction in a single process of multiplying the ripples of PV power and voltage without the comparison between two calculated PV power for obtaining the change in PV power dp_{PV} / dt by using at less two time periods as the P&O MPPT technique. Normally, the ripple of PV power and PV voltage are out of phase each other when the operating point is on the right hand side of MPP (blue area) providing the ripples product $\tilde{p}_{\mathrm{PV}} \cdot \tilde{v}_{\mathrm{PV}} < 0$, otherwise, when the operating point is in the left hand side the ripple of PV power and PV voltage are in-phase (green area) resulting in $\tilde{p}_{\mathrm{PV}} \cdot \tilde{v}_{\mathrm{PV}} > 0$, as shown in Figure 2.10.

The application of RCC MPPT in PV system was firstly presented by Pallab et al [42] with the practical application based on the RCC analog controller circuit and the dc-dc converter for battery charger. The output of analog controller is the duty cycle command for the boost converter $d(t)$ which is analyzed from average value from the ac component of the PV power.

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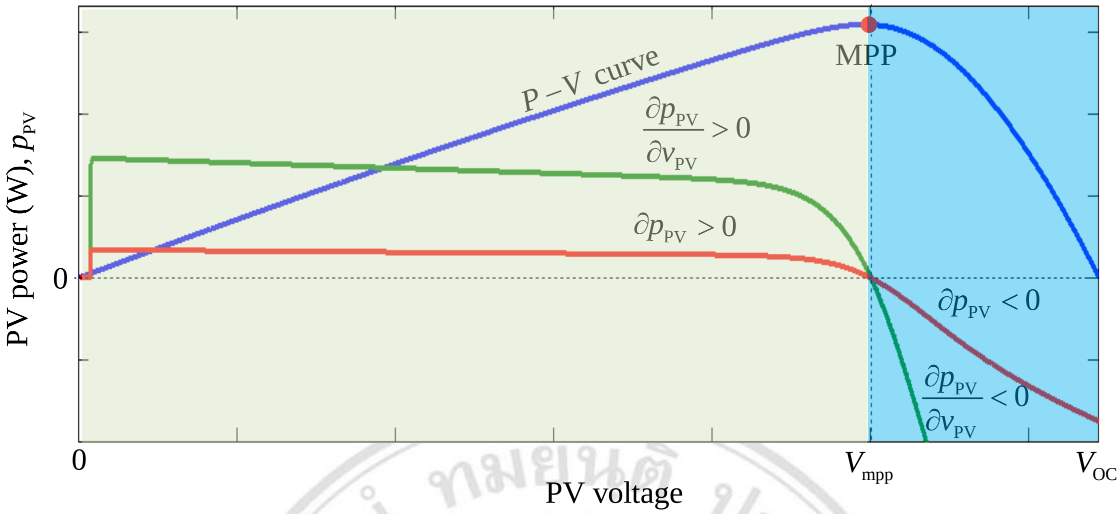

Figure 2.10 The product of PV power and voltage ripple $\tilde{p}_{\text{PV}} \cdot \tilde{v}_{\text{PV}}$ curve and the derivative of $dp_{\text{PV}} / dv_{\text{PV}}$ can be the indicators for tracking the MPP.

$$
\begin{aligned}
\int \tilde{p}_{\text{PV}} \cdot \tilde{v}_{\text{PV}} \text{ dt} &= \int (v_{\text{PV}} \cdot \tilde{i}_{\text{PV}} + i_{\text{PV}} \cdot \tilde{v}_{\text{PV}}) \cdot \tilde{v}_{\text{PV}} \cdot dt = 0\ ;\ \text{at MPP} \\
d(t) &= -k \int \left(v_{\text{PV}} \frac{di_{\text{PV}}}{dt} + i_{\text{PV}} \frac{dv_{\text{PV}}}{dt} \right) \cdot \frac{dv_{\text{PV}}}{dt} dt
\end{aligned}
\tag{2.5}
$$

Its result is shown that the response of tracking can be reached the MPP quickly without the PV parameter requirement. But this method has two main limitations; 1) to avoid the disturbance from the filter circuit which may eliminate the required ripple. It can degrade the system performance. 2) Inaccurate response caused by phase shifts generated from the inherent capacitance in P-N function of solar cell.

T. Esram *et al* [28] proposed the practical of using the principle of RCC MPPT for PV system with the analog controller applied circuits of the high-pass filter, the multiplying, the integral, voltage and current sensors and the boost converter circuits. The analog controller as shown in Figure 2.11 is designed to generate the duty cycle command as given by

$$
d(t) = k \cdot \int \left(\frac{dp_{\text{PV}}}{dt} \cdot \frac{dv_{\text{PV}}}{dt} \right) \cdot dt\ , \tag{2.6}
$$

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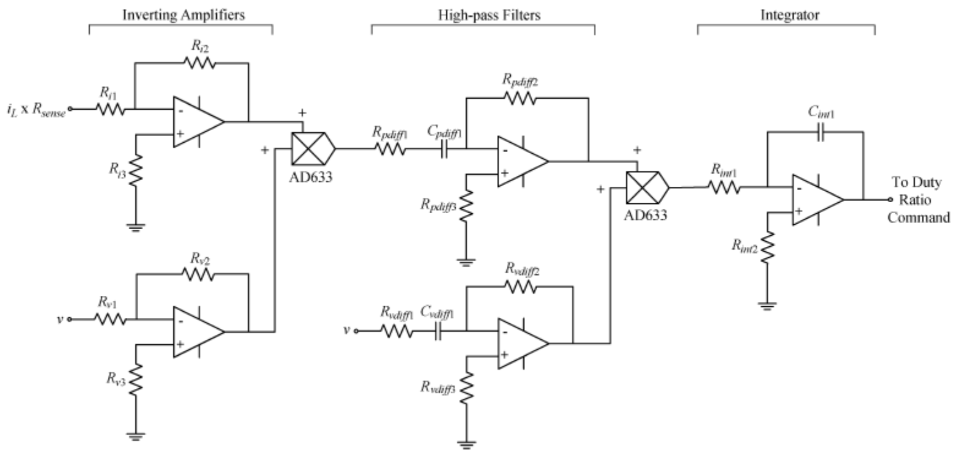

Figure 2.11 Schematic of RCC analog controller used in experimental studies [28]

based on the principle of the multiplied ripples $\tilde{p}_{\mathrm{PV}} \cdot \tilde{v}_{\mathrm{PV}}$ to interpret and obtain the direction of MPP tracking. The technique converges asymptotically at maximum speed to the maximum power point without any PV array parameters requirement. And also, the circuit can be easily implemented.

J W. Kimball *et al* [30] proposed the optimized MPPT technique with real-time digital domain which is improved from the previous analog RCC technique, it is called the discrete-time RCC (DRCC) algorithm. The lower cost of the proposed digital implementation compared to the analog domain is an essential consideration. With the way of digital, this technique can reduce a sampling problem by achieving the proper variables which are sampled at the correct times which involve to the switching frequency of the power converters. This technique can reach the steady-state with small oscillation by using only the ripple information that is agreeable with any switching power converter. The waveforms occurred in switching power is used to be the ripple frequency of this technique leading to have stability in the control system. The DRCC can be applied in the PV system for MPPT. The performance of MPP tracking accuracy is more than 98% for direct insolation, based on more than 1 kHz update rate is tracking maximum power.

A mode of RCC MPPT applied for the grid-connected PV system, the inverter must extract the maximum power from the PV array to inject into the utility grid. In case of grid current and grid voltage are in-phase, the instantaneous grid power is always

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oscillated with twice grid frequency. This effect leads to occur the ripple or AC component included in the instantaneous PV voltage and current $\tilde{v}_{\mathrm{PV}}$, $\tilde{i}_{\mathrm{PV}}$ with the same frequency as instantaneous grid power. D. Casadei *et al* [29] proposed the application of RCC MPPT for the single-phase single-stage grid-connected PV system. The power extracted from the PV array and to be injected to the grid is controlled by a power conditioning system (PCS), which should be kept the power transferring close to the MPP continuously to maintain the maximum efficiency of MPPT and system. The sinusoidal current i_{g} injected to the grid is the first priority of this control to keep unity power factor. The shape and amplitude of grid current is controlled by the perturbation of the output voltage of a single-stage voltage source inverter (VSI) following the obtained grid current reference i_{g}^{*}. And the grid current reference i_{g}^{*} is generated by the dc voltage controller which automatically tracks the MPP based on the RCC MPPT technique. The simple power schematic used in this system is presented in Figure 2.12.

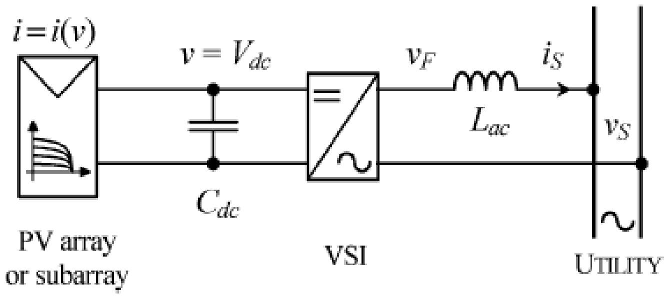

Figure 2.12 The simple power schematic used in this system [29].

The RCC MPPT algorithm is based on the power derivative $\partial p_{\mathrm{PV}}/\partial v_{\mathrm{PV}}$ which can be achieved by detecting the ripple or ac component of the PV voltage and power $\tilde{v}_{\mathrm{PV}}$, $\tilde{p}_{\mathrm{PV}}$ and substitute them into the power derivative equation as given by

$$\frac{\partial p_{\mathrm{PV}}}{\partial v_{\mathrm{PV}}} \cong \frac{\int_{t-T}^{t} \tilde{p}_{\mathrm{PV}} \cdot \tilde{v}_{\mathrm{PV}} \cdot dt}{\int_{t-T}^{t} \tilde{v}_{\mathrm{PV}}^{2} \cdot dt}. \qquad (2.7)$$

To achieve the ripple of PV power and voltage $\tilde{v}_{\mathrm{PV}}$, $\tilde{p}_{\mathrm{PV}}$, the high-pass filters (HPFs) is selected to eliminate the dc component from the PV power and voltage. And the low-

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pass filters (LPFs) can be used to calculate the integral term of the average value of the multiplied ripples. The block diagram of the power derivative $\partial p_{PV}/\partial v_{PV}$ can be presented in Figure 2.13, and it can be simplified leading to scheme represented in Figure 2.14, where only the sign of ($\partial p_{PV}/\partial v_{PV}$) is required. That sign is acted as the MPPT direction pointer of the PV system and used to increase or decrease the voltage reference v_{PV}^{*} used in the portion of voltage controller with the convergence speed defined by a constant (k) and integral function.

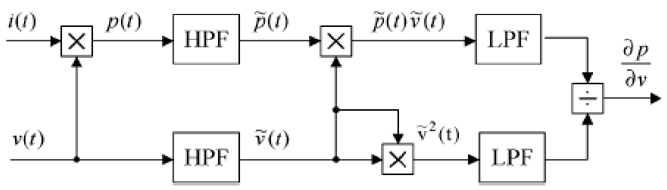

Figure 2.13 Block diagram of the power derivative $\partial p_{PV}/\partial v_{PV}$.

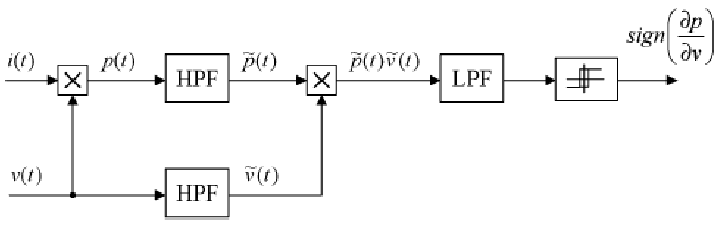

Figure 2.14 The sign of the change in PV power ∂p_{PV} simplified from Figure 2.13.

This MPPT algorithm does not need the information of PV array. The calculated power derivative can produce the right sign for tracking the MPP, together with the suitable voltage regulator can take the PV voltage toward the MPP value. The current regulator can transfer the maximum power to grid with the steady-state sinusoidal current and unity power factor with good performance. However, this method of MPPT still need to design the suitable time constant used in the high-pass and low-pass filters portion. Also the inherent 2^{nd} order harmonics in the PV voltage must be filled out before comparing with the dc voltage reference to keep the high quality of the injected grid current.[18]

A. Costabeber *et al* [43] proposed a dynamic analysis of a sliding mode scheme of the battery charger based on the RCC-MPPT. The information of the design guidelines and

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the MPPT controller tuning are presented in detail to guarantee that the proposed method can efficiently respond to a dynamic changing of irradiation transients. Modeling of convergence time and stability has been developed based on the sliding-mode theory. It includes both the chattering phenomena analysis, and a discussion on the effects of reactive parasitic elements in the PV module, showing their detrimental effect on the controller. The ripples of power and voltage are the main variables used for reaching the MPPT direction based on the RCC, which are detected by the high-pass filter function. The validation of design, the process of establishing and analysis have been done with a good agreement between the theoretical models and simulations and experimental results applied to a single PV module charging a lead-acid battery in both convergence time and chattering.

2.5 Conclusion

From the aforementioned popular direct MPPT technique, the perturb and observe (P&O), incremental conductance (INC) and the ripple correlation control (RCC), the P&O MPPT techniques is the most commonly used technique due to its easy implementation. In the classical version, its drawbacks are the operating point oscillated around the MPP and the confusing in first tracking during the rapidly changing of the irradiation. Although, it can be improved to reduce the power losses caused by its drawbacks by using the dP-P&O MPPT technique or the variable step size of perturbation. However, those algorithms still need the more process of measuring the voltage and current to calculate the desired PV powers and comparing them. It means that they need more time to get the required parameters.

The use of INC MPPT technique can overcome both drawbacks of the use of classical P&O. However, the INC MPPT technique needs more number of processes to calculate the direction and take the PV system to reach the MPP. In case of using the variable step size in this technique, the step size factor is not linear; it can give the fast response MPPT while the PV operating point is close to the MPP. If the operating point is far from the MPP in a distance, the step change is downsized. The MPPT response is slow down follow the step size also. Furthermore, this algorithm has a drawback of requiring costly complex microcontrollers to implement the algorithm.

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In case of the RCC MPPT technique, it has simple circuit implementations for both analog and digital types. It is useful to the users that applies to the general power electronics applications. In the context of PV arrays, the RCC has the following general features relative to previous MPPTs:

1) It uses only one process to give decision of MPPT direction by multiplying the ripples of PV power and voltage.
2) The voltage and current ripples are inherent detected by the measurement of PV system.
3) A high rate of convergence to the MPP tracking makes it suitable for the rapidly changer.
4) The voltage and current ripples already present according to switching converter yield speedily determine the MPP depended on the switching period.
5) Gradient information, no artificial perturbation is required.
6) To achieve convergence at a rate limited by switching period.
7) No need the information of the PV array for MPPT.
8) Low cost implementation and well developed theoretical basis.

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