A Comprehensive Review and Evaluation of Classical MPPT Techniques for a Photovoltaic System

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Abstract. Extracting available maximum power is an important component of solar photovoltaic system which can be achieved by an efficient maximum power point tracking algorithm. Up to date review of related works summarized available MPPT algorithms as classical and modern optimization techniques. Among classical algorithms the incremental conductance (InCond) and perturb & observe (P&O) based tracking algorithms with duty ratio control are widely used due to relatively accurate MPP tracking capability and less implementation complexity under uniform radiation. However; steady-state oscillation, wrong perturbation direction for rapid climate change and failure to track the global peak under partial shade/mismatching operating conditions of the photovoltaic system are some of the limitations of these algorithms. Thus, in this work, a succinct review, formulations and evaluations of widely used classical techniques along with a proposed classical improved perturb and observe (IPO) to improve drawbacks of steady state oscillation has been done. The performance evaluation results of widely used classical perturbation based algorithms (InCond, P&O, IPO) using MATLAB/Simulink revealed improved performances of the improved perturbation based algorithm over the widely used classical (InCond, P&O) algorithms in reducing steady-state oscillations of step-change in irradiance without any partial shading condition of the photovoltaic (PV) of the PV system.

Keywords: Photovoltaic system · InCond · P&O · IPO · Steady-state oscillations

1 Introduction

Rapid growth of energy demand is a common phonon all over the world mainly due to population growth, industrialization and rapid growth of urbanization. Rapid exploitation of conventional energy sources such as coal, petroleum and natural gas is depleting the reserve all over the world and also resulted in global warming challenge to the planet earth. To solve or reduce these global challenges, efficient extraction and utilization of alternative and environmental friendly energy sources is the current research area where experts have been participating [1–3]. Among alternative sources of energy, solar energy

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utilization as a source of electricity is increasing at an alarming rate in the last two/three decades mainly due to clean source of energy, wide distribution of solar energy in many parts of the world, the conversion process has no moving parts, it can be generated at the point of use by which transmission cost/losses will be reduced, and abundant availability of the resource to manufacture photovoltaic cells. However, apart from poor conversion efficiency, solar photovoltaic system has also non-linear feature where its performance is highly affected by climatic conditions solar radiation and operating temperature, and requires high initial investment. These challenges call researchers in the area to look for efficient extraction algorithms of the available maximum power from the photovoltaic system [3–8].

Among different classical MPPT techniques proposed so far, fractional open/short circuit voltage/current methods can locate the maximum power point, however; the periodic short/open circuiting of the photovoltaic system for measurement purposes requires additional switch and this may result in complexity and losses. Perturbation based algorithms such as incremental conductance, perturb and observe, and hill-climbing algorithms share common shortcomings of oscillations during steady state condition, unable to locate the maximum power whenever there is partial shade and wrong tracking directions during fast change is atmospheric conditions [9–11]. Among widely used classical techniques, incremental conductance based maximum power extractions has been proposed to solve the limitation of perturb and observe based algorithm. Incremental conductance based method is based on the idea that slope of power versus voltage curve is zero at maximum power point and proposed to improve the tracking accuracy and dynamic performances for rapidly change in operating conditions. Theoretically, oscillation during steady state operation will be zero because. However; noise and digital resolution errors may create oscillations [10–12]. Thus, this paper provided a concise summary, the corresponding formulations of some of classical MPPT techniques for photovoltaic system and performance evaluations of widely used MPPT techniques along with the proposed voltage controlled classical improved P&O algorithm to improve steady-state oscillation problems of classical techniques.

The contents of this research are organized: the photovoltaic models and characteristics is presented in section two of the research, a concise review of related works and principle of maximum power extraction is presented in the third section of this research, a concise summary and formulations of common classical perturbation based algorithms is presented in the fourth section of the paper, implementations and results discussion for evaluation of some of widely used classical MPPT techniques and the improved perturbation based technique is presented in the fifth section of the research and the basic findings as concluding remarks are presented the sixth section of the research.

2 Photovoltaic Modules and Characteristics

Usually, photovoltaic modules are represented using equivalent circuit diagram of a current source connected parallel to a diode. Further improvement in accuracy of simulation of the simple model is done by adding a series resistor to consider connection losses and a shunt resistance considering leakage current. Summary of related works in the equivalent circuit models identified the available circuit models as, ideal diode, Rs, Rp and two diode Rp models having unknown parameters of three, four, and five respectively with improved accuracy of simulation. However, estimating unknown parameters is another challenge. Out of these models, Rp model with five unknown parameters is widely used due to relative accuracy and simplicity [13–15]. Environmental factors like operating temperature, speed of wind, surrounding humidity and radiation affect the performance of the photovoltaic module. Solar radiation has direct impact on the performance of the photovoltaic module, however; operating temperature has logarithmic and negative impact the performance of the photovoltaic module [13–17]. The corresponding equivalent circuit models and current-voltage (I-V)/power-voltage (P-V) characteristic plots and the corresponding effects irradiance and operating temperature on the performance of the module for a typical photovoltaic module (KC200GT) is presented in Fig. 1.

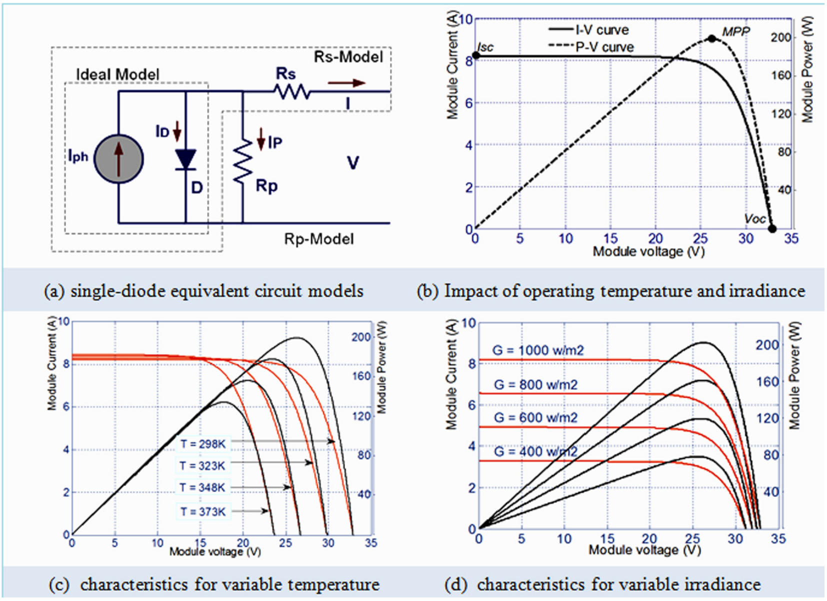


Fig. 1. Equivalent circuit of PV modules, characteristics & impact of environmental factors

Mathematically, the current/voltage relations for the corresponding equivalent circuit models of single diode are presented in Eqs. (1)–(3) [13–17].

(i) Rs-Model:

$$I = I_{ph} - I_0\left[\exp\left(\frac{V + IRs}{vT}\right) - 1\right] \tag{1}$$

(ii) Rp-model:

$$I = I_{ph} - I_0\left[\exp\left(\frac{V + IR_S}{vT}\right) - 1\right] - \frac{V + IR_S}{R_P} \tag{2}$$

(iii) Ideal (simple-diode):

$$I = I_{ph} - I_o\left[\exp\left(\frac{V}{vT}\right) - 1\right] \tag{3}$$

where the dark saturation current is, I_o and modified ideality factor is vT.

3 Maximum Power Extraction of Photovoltaic Systems

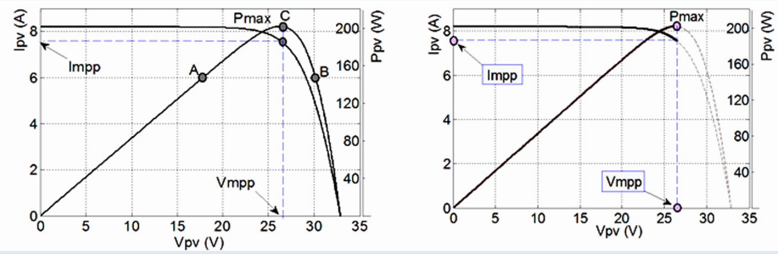
An important component of photovoltaic system is maximum power point tracking where it main task is to operate the converter at the maximum available power of the photovoltaic system. Review of related works in the area verified availability of a number of algorithms with differences in operating principle, simplicity, cost and efficiency in tracking the maximum available power. The review result can summarize the available maximum power tracking algorithms for photovoltaic system in broad as evolutionary and classical technique [6–12].

Among perturbation based classical techniques, incremental conductance [3, 4, 11], perturb and observe, hill-climbing [11, 19], fractional short circuit current/voltage [11], variable step size perturbation based [11, 12, 20, 25], Curve-Fitting (CFT) [11], Look-up Table (LUT) [11], Differentiation Technique (DFT) [11], One-Cycle Control (OCC) [1], Feedback Voltage or Current (FV/FC) [11], feedback of power variation with current/voltage[11, 12, 20], Forced Oscillation (FCO) [11, 12], Ripple Correlation Control (RCC) [11, 12], Current Sweep (CST) [11], Estimated-Perturb-Perturb (EPP) [11], Parasitic Capacitance based (PCT) [11], Linearization-Based MPPT (LBT) [11, 20, 25], Load Current/Load Voltage Maximization (LCM/LVM) [12], DC Link Capacitor Droop Control (DC-LCDC) [11, 20], Gauss-Newton (GNT) [23, 24], Steepest-Descent (SDT) [24, 25] and Sliding-Mode-Based MPPT (SMC) [11, 24] techniques has been discovered. But, wrong tracking direction, oscillations during steady-state operating condition and unable to track the maximum peak whenever, there is partial shade/mismatching conditions arise are some of the common limitations that classical algorithms share for the particular application. These challenges and non-linear features of the photovoltaic module need algorithms to solve the problems [9–12, 18–24]. The operating points and the corresponding control action of a maximum power tracking algorithm for a particular photovoltaic module (KC200GT) are presented in Fig. 2.

Once the maximum power operating points is achieve, it is supposed to operate at that point unless there is a change in input/output parameter that shifts the MPP. Figure 2(b) shows the current/power locus plot to the maximum operating point. When the derivative of power with respecte to voltage is zero, that point is the maximum power point (in the graph, it is point C), PV voltage (V_{pv}) needs to be regulated either increasing or decreasing to/from MPP using some control action. For positive slope ($dP_{pv}/dV_{pv} > 0$), V_{pv} increases and for negative slope ($dP_{pv}/dV_{pv} < 0$), V_{pv} should decrease. Table in Fig. 2(c) shows the corresponding control action of the operating regions indicated. The current-voltage and power-voltage plots are indicated by the broken line trajectory [9, 11].

4 Concise Summary of Classical MPPT Techniques

Among perturbation based classical techniques, incremental conductance, perturb and observe, and hill-climbing algorithms are commonly used due to simplicity. These methods are efficient for uniform distribution of irradiance and they are simple to implement and inexpensive. However, they all share drawbacks of steady state oscillation, missing the right direction of perturbation for sudden change in atmospheric conditions like radiation, and unable to track the maximum power during partial-shade/mismatch operating conditions of the photovoltaic system [6–12, 22–24]. Descriptions to show the basic difference among classical techniques and the corresponding formulations are presented in the following sub-sections.



(a) characteristics with points (b) MPP locus plots

Operating pt	ΔVpv	ΔPpv	$\Delta Ppv/\Delta Vpv$	Control action
A	>0	>0	>0	$Vpv\uparrow$ (Increase)
	<0	<0	>0	$Vpv\uparrow$ (Increase)
B	>0	<0	<0	$Vpv\downarrow$ (decrease)
	<0	>0	<0	$Vpv\downarrow$ (decrease)
C	>0	0	0	No change
	<0	0	0	

(c) control actions required for the corresponding operating region

Fig. 2. Current/power versus voltage and power locus plots for a MPPT control actions

4.1 Perturb and Observe Algorithm

It is one of classical MPPT techniques characterized by perturbation of operating point and observe. The PV operating point is perturbed periodically by changing the voltage at PV source terminals, and after each perturbation, the control algorithm compares the values of the power fed by the PV source before and after the perturbation. For positive change in PV power, the direction of perturbation will be in the same direction otherwise direction of perturbation will be reversed [11, 18, 19, 25]. The mathematical representation of P&O algorithm is given in Eq. (4).

$$x_{k+1} = x_k \pm \Delta x = x_k + (x_k - x_{k-1})sign\,(p_k - p_{k-1}) \tag{4}$$

where x represents the variable of perturb, Δx is the perturbation size*;* and p is the available power from the photovoltaic system. In general, the algorithm can be described in Fig. 3.

4.2 Incremental Conductance Algorithm

Incremental conductance algorithm is among commonly used classical techniques where the principle of operation is based on the slope of power versus voltage curve. In principle, it is supposed to improve the drawbacks of steady-state oscillation and wrong direction of perturbation during fast climate changes. However, practically sampling, quantization error and noise results in oscillation with reduced amplitude [3, 4, 11, 26]. The direction of perturbation is based on comparison result of conductance and incremental conductance until the operating points reach at the MPP ($dP_{pv}/dV_{pv} = 0$). The principle can be described mathematically using Eq. (5).

$$\begin{aligned}\frac{dP_{pv}}{dV_{pv}} &= \frac{d(V_{pv}I_{pv})}{dV_{pv}} = I_{pv} + V_{pv}\frac{dI_{pv}}{dV_{pv}}\\ &= \frac{1}{V_{pv}}\cdot\frac{dP_{pv}}{dV_{pv}} = \frac{I_{pv}}{V_{pv}} + \frac{dI_{pv}}{dV_{pv}}\end{aligned} \tag{5}$$

Expressions in Eq. (6) show signs of conductance and incremental conductance relative to MPP [11, 25, 26].

$$\begin{cases}\dfrac{dP_{pv}}{dV_{pv}} = 0, & \dfrac{I_{pv}}{V_{pv}} = -\dfrac{dI_{pv}}{dV_{pv}} \quad G = \Delta G,\ at\ MPP\\ \dfrac{dP_{pv}}{dV_{pv}} > 0, & \dfrac{I_{pv}}{V_{pv}} > -\dfrac{dI_{pv}}{dV_{pv}} \quad G > \Delta G,\ left\ of\ MPP\\ \dfrac{dP_{pv}}{dV_{pv}} < 0, & \dfrac{I_{pv}}{V_{pv}} < -\dfrac{dI_{pv}}{dV_{pv}} \quad G < \Delta G,\ right\ of\ MPP\end{cases} \tag{6}$$

The procedures for implementation of InCond MPPT technique can be described using the flow chart in Fig. 4. $I(k)$, $V(k)$ and V_{ref} in the algorithm shows the photovoltaic current, the photovoltaic voltage and reference voltage to the voltage controller of the boost converter respectively.

4.3 Variable Step-Size Perturbation

MPPT techniques (P&O, hill-climbing and InCond) discussed in sections above use fixed step-size perturbation. Variable step-size perturbation based MPPT techniques can solve

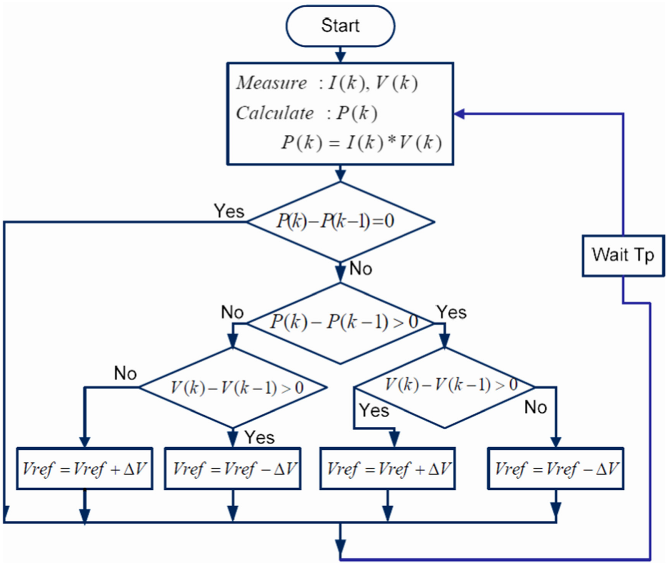


Fig. 3. Flowchart to implement P&O MPT technique

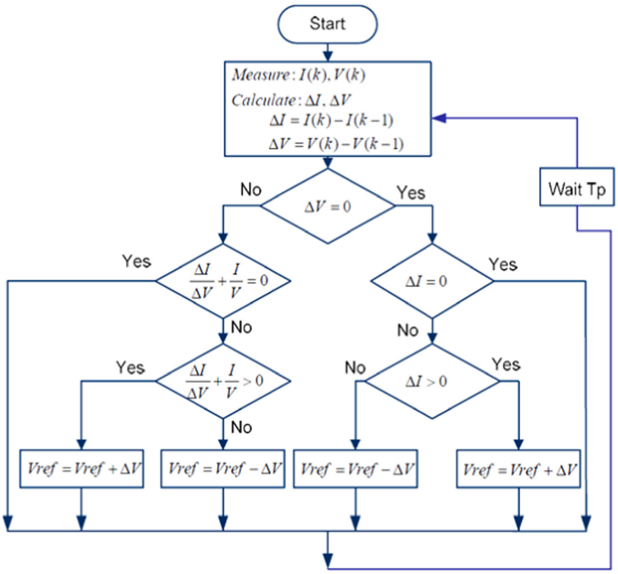


Fig. 4. Incremental conductance algorithm

limitations of oscillation during steady-state operation and missing the right direction of perturbation for rapid change in climatic conditions [12, 20, 27]. The expression in Eq. (7) shows the principle of perturbation with different size.

$$\begin{cases} d(k) = d(k-1) \pm N\left|\dfrac{\Delta P}{\Delta V}\right| \\ d(k) = d(k-1) \pm N\left|\dfrac{P(k) - P(k-1)}{V(k) - V(k-1)}\right| \end{cases} \tag{7}$$

where coefficient N is factor toe scale to be determined during step size selection and the duty cycle is given by *d(k)*. Variable scaling factor can be determined by choosing large step size, Δd, initially. The derivative of power with voltage can be determined under constant step condition with Δd_{max} that can be selected as the maximum limit for the variable size operation [20]. Around MPP, derivative of power with voltage is the lowest value and for convergence of MPPT, variable step size rule should fulfill the relation in Eq. (8).

$$\begin{cases} N\left|\dfrac{\Delta P}{\Delta V}\right|_{fixed\ step=\Delta D\ \max} < \Delta d_{\max} \\ N < \Delta d_{\max}/\left|\dfrac{\Delta P}{\Delta V}\right|_{fixed\ step=\Delta d\ \max} \end{cases} \tag{8}$$

where $\left|\frac{\Delta P}{\Delta V}\right|_{fixed\ step=\Delta d\ \max}$ is the $\left|\frac{\Delta P}{\Delta V}\right|$ at fixed step size operation of $\Delta d_{\max}$.

If N is determined by satisfying the relation in Eq. (8), a fast dynamic response can be achieved. If the relation is not satisfied, the MPP tracking will continue working with fixed step size [20]. The principle of variable perturbation size can be explained using P-V characteristic curve in Fig. 5. The initial operating point (P) is assumed to be P_1 with the assumption of perturbation size to be one. Imposing perturbation with size proportional to the photovoltaic power change, we can have the sequence P_l–P_7 [12, 20].

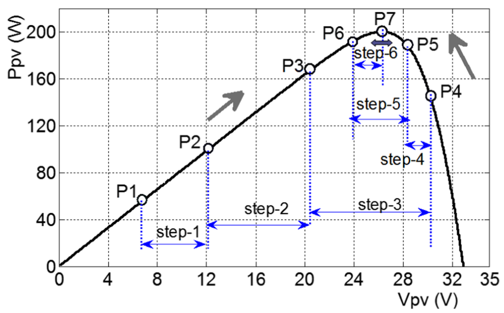
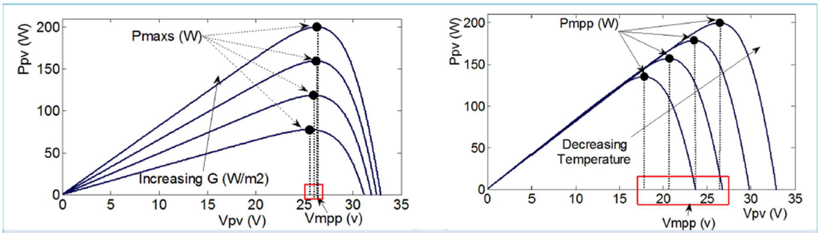


Fig. 5. P-V characteristic showing variable step-size perturbations

4.4 Reference Voltage Constant

Maximum power extraction based on the principle of constant reference voltage is based on the assumption that the corresponding voltage for the maximum power point is constant whenever there is change is radiation as shown in Fig. 6(a) and assumed that there is no change in operating temperature. Figure 6(b) shows the impact of operating temperature on the reference voltage [11, 19].



(a) Variable irradiance (b) Variable operating temperature

Fig. 6. Power versus voltage plots for variable radiation and operating temperature

4.5 Perturbation Based Improved MPPT Algorithm

Different techniques have been proposed to solve drawbacks of classical techniques. The research in [27] proposed a maximum power tracking algorithm to solve the failure to perturb the right direction whenever there is a rapid change in irradiance by taking measurements at half of sampling time in between sampling instants without any perturbation as shown in Fig. 7 (a). Power change between P_x and P_k is caused by MPPT perturbation and change in operating conditions. The basic concept behind can be described by Eq. (9) having the idea of constant radiation within one sampling instant.

$$\begin{cases} \Delta P = \Delta P_1 - \Delta P_2 = (P_x - P_k) - (P_{k+1} - P_x) \\ \quad = 2P_x - P_{k+1} - P_k \end{cases} \tag{9}$$

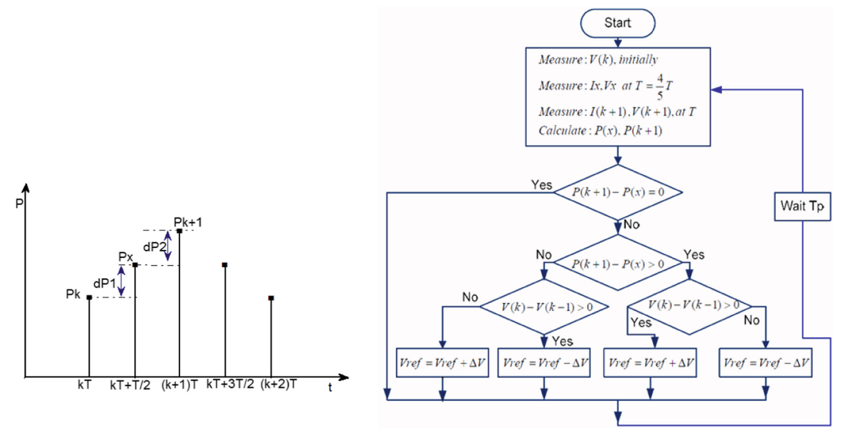
After calculating the change in power (ΔP), the process follows the principle of perturbation based technique approach. This method has drawbacks of increased complexity and also the probability missing right direction of perturbation when there is a rapid change in irradiance after a period of half sample time. To solve the drawbacks of perturbation based classical techniques, an improved perturbation based algorithm is formulated based on the idea described in [27]. Unlike the technique described above, additional measurement will be done close to P_{k+1} point ($\geq$80% of one sample time). The basic procedures for implementation of the proposed algorithm can be explained using the flowchart in Fig. 7 (b). The parameters Ix and Vx are the measured PV current and voltages respectively.

5 Evaluation of Classical MPPT Techniques

Performance evaluation of widely used classical techniques (P&O and InCond) and the proposed technique has been done for variation of solar radiation keeping other factor at standard test conditions.

5.1 Architecture for Implementation

The basic components of the photovoltaic system include the maximum power point tracking algorithm, the boost converter and the controller along with the pulse width modulating signal generator. The architecture of the over all system for implementation is given in Fig. 8. In this schematic diagram, the letter "D" represents the diode.



(a) Power measurements b/n instants (b) improved perturbation based MPPT technique

Fig. 7. Power measurements instants and flow-chart for Improved P&O

Tables in Fig. 9(a) and (b) give the converter component values and manufacturer data sheet specifications of the commercial PV module selected for implementation respectively.

5.2 Discussions of Results

The performance evaluation of the corresponding algorithm has been done for variable input of radiation while keeping other factors at standard test condition. Figure 10 shows the MPP trajectories tracked (solid and colored lines) for the corresponding MPPT technique and P-V characteristic curves with circled dots indicating theoretical maximum power points.

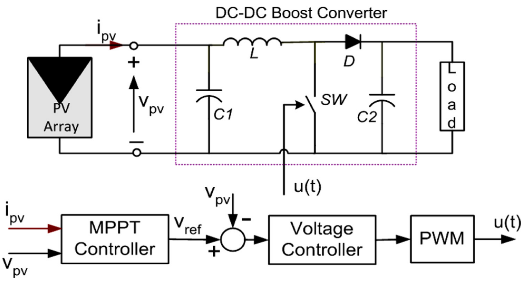


Fig. 8. Implementation diagram

Parameter	Value
Input voltage (V_{in})	V_{in} = 26V
Output voltage (V_{out})	V_{out} = 100V
Switching frequency (f_s)	f_s = 25kHz
Output voltage ripple ($\Delta V_O/V_O$)	1%
Load (R_L)	R_L = 50 Ω
Inductance (L)	L = 75μH
Input Capacitance (C_1)	C_1 =100μF
Output capacitance (C_2)	C_2 =592μF

(a) specifications of the Boost converter

Parameter	Value
Voltage at MPP	Vmpp = 26.3V
Current at M P	Imp = 7.61A
Open Circuit Voltage	Voc = 32.9V
Short Circuit Current	Isc = 8.21A
Temp. Coeff. Isc, α_{Isc}	+3.18 mA/°C
Temp.Coeff. V_{OC}, β_{Voc}	−123 mV/°C
N0 of cells in series (Ns)	54

(b) specifications PV modules at STC

Fig. 9. Specifications for Boost converter and KC200GT PV module

The plots in Fig. 10 (a) are for the step increase in irradiance, solid lines indicate the MPP trajectories and Fig. 10 (b) show the results for step decrease with the same step as in (a) and solid lines are for traced MPP paths for the corresponding MPPT technique. Maximum power points on the I-V plot in Fig. 10 look close to each other. To see clearly the differences, absolute value deviations from theoretically computed and plotted in Fig. 11. Small deviations are observed for the proposed and InCond techniques than P&O. This shows improved performances of the proposed MPPT technique apart from easy implementation reduced complexity compared to InCond technique.

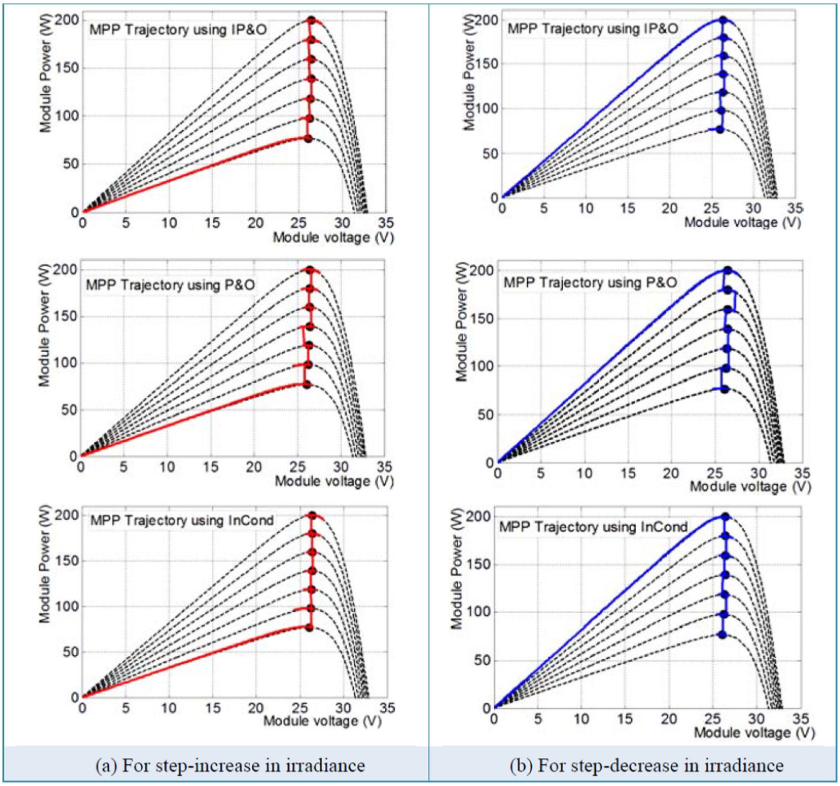


Fig. 10. MPP locus plots for the given test input of radiation

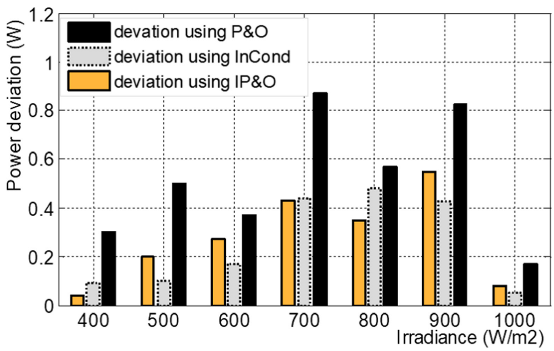


Fig. 11. Deviation of MPPs from theoretical values

6 Conclusions

As part of objective of the research paper, a concise summary of literatures on global energy demand growth, fast depletion of conventional source of energy and the corresponding challenges is presented in the introduction part of the research paper. In the same unit, rapid growth of utilization of photovoltaic power system, promising benefits and challenges of photovoltaic systems due to the non-linear characteristic, strong impact of atmospheric conditions, high initial installation cost requirement and the need for efficient extraction techniques is presented. The broad classification of available MPPT techniques, advantages, drawbacks and formulations for PV-systems application of classical techniques is presented concisely in the paper.

Performance evaluation of the widely used classical techniques of perturbation based (InCond, P&O) and improved perturbation based (IPO) with the criterion of capability in tracking maximum power point trajectory, oscillation reduction during steady state operating condition and maximum power tracking efficiency improvements for test conditions of step increase and decrease radiation is done. The proposed improved P&O MPPT technique showed significant improvements over P&O technique for the prescribed measurement criterion apart from the advantages of simple to implement and less complexity.

In summary, this paper can help to develop clear image of the concepts and operating principles of classical maximum power point techniques and identify the drawbacks of wrong perturbations during fast change in radiation, oscillation during steady-state and unable to track the maximum power point when the photovoltaic system is operating in partial-shade or mismatching conditions.

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