A Comparative Analysis between Perturb & Observe and Incremental Conductance techniques for MPPT in PV System

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***Abstract*— The paper offers a brief overview of the Perturb and Observe (P&O) MPPT and Incremental Conductance (INC) MPPT methods for maximizing the power output of a PV system connected to a rated resistive load. A PV panel can provide maximum power at a fixed operating point only, which is defined at a fixed voltage and current, called as maximum power point (MPP). So, a simulation is carried out to observe I-V & P-V characteristics of PV panel under varying irradiation and temperature conditions to test the genuineness of the MPPT techniques. Additionally, it compares these MPPT techniques based on control strategies, complexity, price, type of circuitry, number of control variables, and performance by utilizing data from simulations performed using the MATLAB Simulink R2022a software.**

***Keywords*— DC-DC Boost Converter, INC Technique, Maximum Power Point Tracking (MPPT), P&O Technique, PV Panel**

I. INTRODUCTION

Today's primary energy sources are fossil fuels like coal and gas. Severe energy shortages will be encountered during the next few decades as fossil fuel energy becomes scarcer due to rising energy prices and energy instability. The world's environment is being impacted by the rising use of fossil fuels. The high demand of energy can be fulfilled by solar energy easily [1],[2]. Installing solar energy not only reduces the dependency of oil, coal but can also provide jobs locally. The demand for solar energy has expanded because it is free, environmentally beneficial, and has low operating and maintenance costs. Because of the rise in demand, solar power generation must become more effective, making it crucial to maximize its output power. Thus, maximum power point tracking techniques are required [5]. The paper has tried to review two important MPPT techniques which are P&O and INC MPPT techniques [21]-[29].

Even if we have numerous articles based on literature reviews of the algorithms, picking a specific MPPT technique is challenging due to the numerous application domains. There are numerous new MPPT methods, including distributed MPPT, estimated perturb and perturb, Adaptive P&O[9], the Gauss-Newton method, (PSO)-Particle swarm optimization[16] and adaptive fuzzy based MPPT[26], Artificial Neural Networks(ANN) based[10] MPPT, Lookup Table method, Fractional Short-Circuit current and voltage MPPT, forced oscillation methods, Ripple Correlation Control (RCC) method, DC-link capacitor droop control method, Sliding Mode based[12] and hybrid MPPT methods, and more [3],[4]. In this research, we have attempted to contribute to the performance analysis of the P&O and INC MPPT technique in variable irradiance and temperature circumstances independently, holding one constant at a time and varying the other.

Following is the organisation of the paper. After discussing mathematical model of the PV-Cell in section II, section III reviews MPPT approaches. The converter's design and system specifications are shown in Section IV. The results simulated for each technique are displayed in Section V, followed by a comparison analysis in Section VI. Finally, section VII discusses conclusions.

II. MATHEMATICAL MODEL OF PV-CELL

A PV Cell converts Energy from Solar radiations into Electrical Energy. Terminal characteristics of the PV Cell are kept into focus rather than its operating physics.[5] The Equivalent circuit diagram of a Photovoltaic Cell is shown in Fig. 1

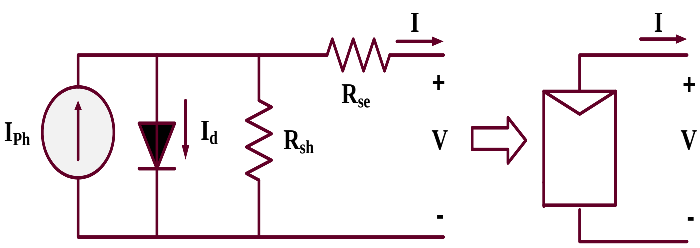

Fig. 1 Equivalent Circuit diagram of a PV-Cell and its Symbol

The following is the Implicit equation of the terminal current & voltage (I, V) of the PV Cell

$$I = I_{ph} - I_0\left(e^{\frac{V+IR_{se}}{\eta V_t}} - 1\right) - \left(\frac{V+IR_{se}}{R_{sh}}\right) \quad (1)$$

where, I = PV Cell current (A)
V = Voltage at Terminals of PV Cell(V)
I_{ph} = Photocurrent / Light Dependent Current (A)
I_0 = Reverse Saturation current (mA)
V_t = Thermal Equivalent Voltage (mV)
η = Diode Non – Ideality Factor (unitless number between 1-2)
R_{se} = Practical Series resistance (Ω)
R_{sh} = Practical Parallel resistance (Ω)

$$\text{Now, } V_t = \frac{kT}{Q} \quad (2)$$

where,
k (Constant of Boltzmann) = 1.38 x 10^{-23} $Kgm^2s^{-2}K^{-1}$,
T =Temp. in Kelvin and Q = 1.602 x 10^{-19} Coulombs
Reverse Saturation Diode current (I_0) is given by:

$$I_0 = KT^m e^{-\frac{V_{GO}}{\eta V_t}} \quad (3)$$

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where, K= A constant that depends upon the dimensions and material of the p-n junction to be formed, m= 1.5 for Silicon

V_{GO} = Equivalent Band gap Energy or Forbidden Band gap Energy (in eV) = 1.16 eV (Solar Grade) to 1.21eV (Electronic Grade) for Silicon

III. Review of MPPT-Techniques

In this paper, a brief review about the two renowned and simple kind of the MPPT techniques to get the maximum power output from a PV system is discussed. The block diagram of MPPT operation in a PV system is illustrated in Fig. 2

A. MPPT Operation

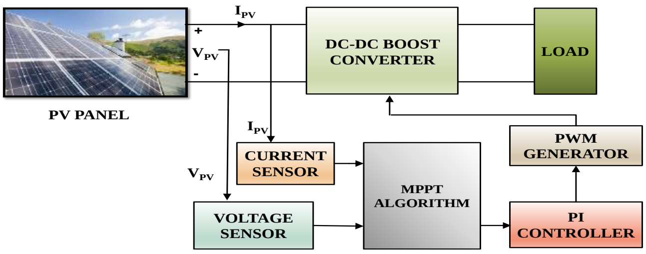

Fig. 2. Block Diagram of MPPT operation

The MPPT operation is explained below:

To improve the output voltage and current ratings of the entire PV panel, parallel and series connections are made between several PV modules in a PV panel. The load receives power from it. The Boost Converter is utilised to further raise the PV panel's voltage level before supplying it to a rated load that needs to be supplied with a certain rated amount of power and voltage. Depending on the operating frequency range, the switch may be an IGBT or a MOSFET. The Analog to Digital converters (ADC) that gather current and voltage samples from the PV panel's output and digitally feed them to the MPPT controller algorithm block are known as Current and Voltage Sensors. The operational point and solar irradiation both affect the PV system's output power (combination of V and I). The amount and direction of solar radiation landing on the PV panel determine the PV panel's maximum power point, or MPP, at a specific operating point. An algorithm and an electronic circuit are necessary for the MPPT method. By matching the load and source impedances, the MPPT system between the source (PV Panel) and load verifies that the maximum power is drawn from the PV Panel. In a closed loop system, the output of an MPPT controller is a reference voltage that is sent to a Proportional Integral (PI) controller, which, after adjusting the circuit, outputs a duty cycle [15],[19],[20]. Due to the closed loop system that is ensured, stability is increased. The controller is tuned with the system and will give signal to the PWM generator as necessary. The DC-DC converter's IGBT and MOSFET switches are fed Gate Pulses produced by the PWM generator. The MPPT algorithms directly or indirectly regulate the duty cycle of the switch in the DC-DC converter to ensure that the load impedance and the converter's source impedance are matched, allowing the maximum power to be flown from the PV panel towards the load [5].

B. MPPT Techniques

a) Perturb and Observe (P&O) MPPT Technique:

This technique is used to maximize the power output of a PV panel. It is one of the renowned and simplest methods of MPPT. At first the PV current and voltage samples are taken from the output. The MPPT tracking method starts with calculating the power and a small change in PV voltage is introduced called as perturbed voltage value(ΔV), as a result the equivalent change in the PV output power is observed. Practically, the ΔV is indirectly controlled by small change in the duty ratio(ΔD) of the converter operating switch. The Converter's duty ratio is decreased to increase voltage and vice versa[6],[8]. The P-V characteristics, which is the variation of the PV output power with change in output voltage of PV panel is shown in Fig. 3.Now, four cases arise depending upon what is the value of PV voltage, PV power, the perturbed value(ΔV) and corresponding observed value(ΔP).

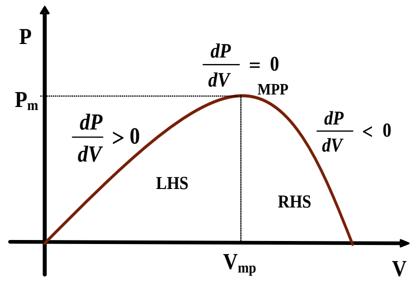

Fig. 3. P-V characteristics of a PV system

Case 1: dV>0 & dP>0, LHS of MPP and voltage is increasing, V must further increase to reach MPP

Case 2: dV<0 & dP>0, RHS of MPP and voltage is decreasing, V must further decrease to reach MPP

Case 3: dV<0 & dP<0, LHS of MPP and voltage is decreasing, V must increase to reach MPP

Case 4: dV>0 & dP<0, RHS of MPP and voltage increasing, V must decrease to reach MPP

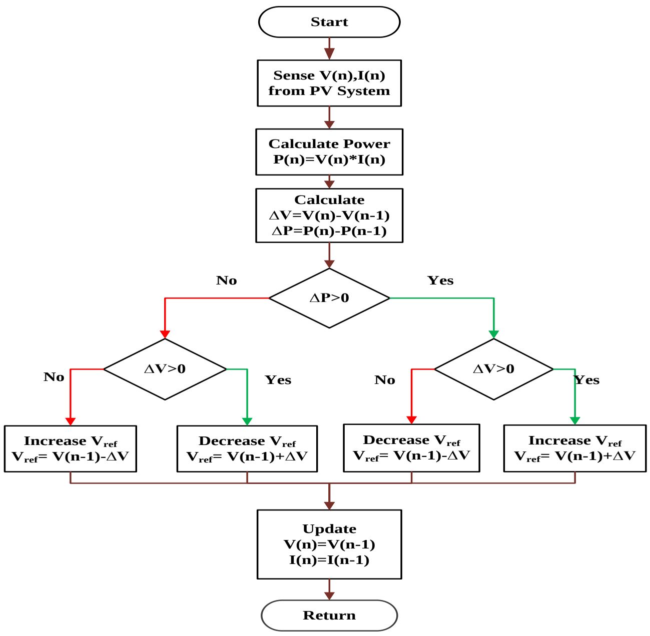

Fig. 4. Flowchart to implement P&O MPPT algorithm

To sum up, if the power gets increased when the PV voltage is perturbed in one direction (V>0 or V<0), then the perturbation should be maintained in that direction; otherwise, the perturbation must be in the other direction. At MPP, the PV array's output power is maximum also the voltage is at its maximum value, Vmp, and is essentially constant. Hence, on the P-V curve, At points LHS of MPP: $\frac{dP}{dV} > 0$

At points RHS of MPP: $\frac{dP}{dV} < 0$

At MPP: $\frac{dP}{dV} = 0$ (4)

P&O MPPT algorithm's drawback is that it performs poorly in steady state due to oscillation in PV output power at the MPP point caused by continual reversal of the perturbed value at the MPP point. To reduce the oscillation, we can reduce the step size of the perturbed voltage but in that case MPP tracking process will slow down. Adaptive P&O techniques can also be used where the step size of perturbed voltage decrease as we move closer to the MPP point [11]. P&O technique is also called as Two-point power comparison method as we compare the values of power at an old value and a new value after voltage perturbation. This technique works fine if the solar irradiance is maintained constant and problem occurs when the PV panels are partially shaded. Fig. 4 illustrates the flowchart to implement P&O MPPT algorithm.

b) Incremental Conductance (INC) MPPT Technique:

This technique is a similar type of MPPT tracking approach that samples the PV panel's output voltage and current first. Additionally, it is easy to understand.From Fig.3, it is a fact about the slope of the PV curve from (1)

Now, we can write

$\frac{dP}{dV} = \frac{d(VI)}{dV} = V\frac{dI}{dV} + I$

If $\frac{dP}{dV} = 0$ at MPP, $V\frac{dI}{dV} + \mathrm{I} = 0$

or $V\frac{\Delta I}{\Delta V} + \mathrm{I} = 0$

or $\frac{\Delta I}{\Delta V} = -\frac{I}{V}$, where $\frac{I}{V}$ is known to be the instantaneous conductance and the corresponding $\frac{\Delta I}{\Delta V}$ is called as the incremental conductance (IC) at a point on the P-V curve of the PV system. So, (4) can be rewritten as,

At points LHS of MPP: $\frac{\Delta I}{\Delta V} > -\frac{I}{V}$

At points RHS of MPP: $\frac{\Delta I}{\Delta V} < -\frac{I}{V}$

At MPP: $\frac{\Delta I}{\Delta V} = -\frac{I}{V}$ (5)

Here, PV panel voltage is perturbed to monitor the IC. If the IC equals the negative of instantaneous conductance, the PV system operates at MPP. We are at the LHS of MPP if, at a given operating point, the incremental conductance is greater than the instantaneous conductance's negative value. In this scenario, increasing the PV voltage to reach MPP would logically entail lowering the duty ratio of the DC-DC converter switch. Like this, if the incremental conductance is lower than the instantaneous conductance's negative value, we are at the RHS of MPP, and the PV voltage must be decreased to approach MPP. This process is continued until we reach the MPP where incremental conductance, and the instantaneous conductance are equal. If change in voltage ΔV=0, then we can't find instantaneous conductance $\frac{\Delta I}{\Delta V}$ as the ratio will tend to give infinite value. In such a case, change in current ΔI must be checked. If both ΔV and ΔI are zero, we are at MPP. If ΔI>0, then we can either increase or decrease the voltage so that ΔV≠0 and value we can reach the MPP depending upon whether we are at the RHS or LHS of the MPP. The speed of tracking or convergence depends upon the increment step size. But a larger step increment can cause power oscillation at the MPP rather than operating at the MPP. It has almost equal efficiency as P&O algorithm has but it can perform better in rapidly changing weather conditions. If variable increment in the voltage value is done, then oscillations can be received but complexity and cost of circuit will increase. Fig. 5 shows the flowchart to implement INC algorithm.

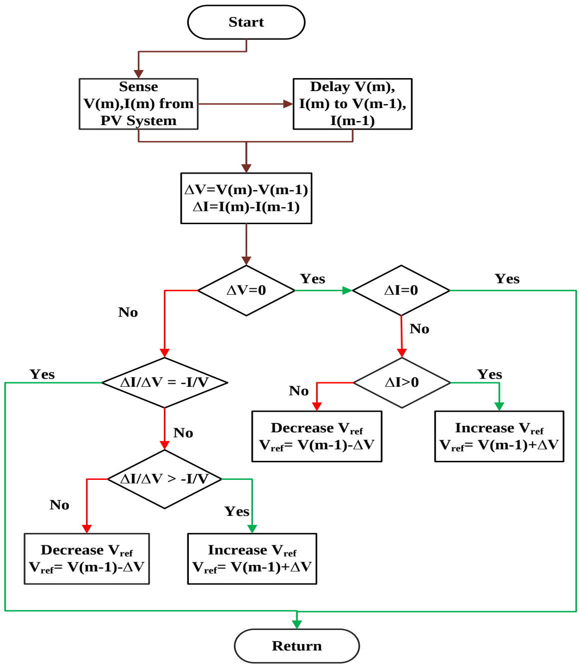

Fig. 5. Flowchart to implement INC MPPT algorithm

IV. System Specifications And Converter Design

A. System Specifications

a) Solar Panel Ratings

The output voltage of the PV panel in the range of 18-20V acting as the voltage at input of Boost converter is considered. MPPT techniques' performance is tested taking a resistive load in the converter's output. The Solar Panel ratings are mentioned in Table I

Considering the Solar Panel Specifications, the different I-V characteristics, and P-V curves of the Solar panel are as follows:

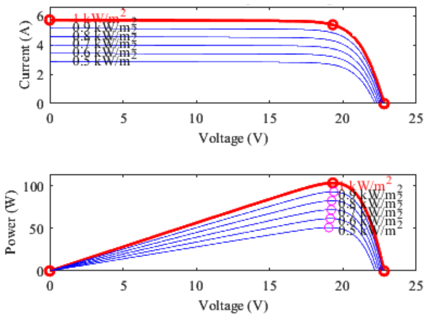

Fig. 6. I-V and P-V curves of the Solar panel at constant temperature of 25°C and variable irradiances from 1000W/m^2 to 500W/m^2

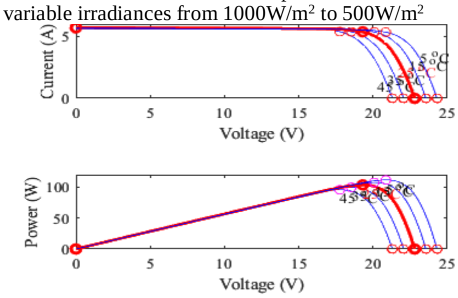

Fig. 7. I-V characteristics and P-V curves of the Solar panel at constant irradiance of 1000W/m^2 and variable temperature from 45°C to 5°C

It is desired that the MPPT techniques maintain the required rated Maximum Power Output of 100W, V_{oc} of 22.8V, I_{sc} of 5.7A, Voltage and Current at MPP i.e., V_{mp}=19.3V and I_{mp}=5.37A, which would ensure that the MPPT techniques are functioning properly, at the rated condition of 1000W/m^2 irradiance and 25°C temperature. However, they should produce matching outputs when irradiance or temperature change in accordance with the original P-V and I-V curves of the solar panel, depicted in Figs. 6 and 7, respectively.

TABLE I. SOLAR PANEL RATINGS FOR IRRADIANCE OF 1000W/M^2 AND AT 25°C TEMPERATURE.

Sl. No.	Rated Power, P_{rated}	100 W
1	Open Circuit Voltage (V_{oc})	22.8 V
2	Short Circuit Current (I_{sc})	5.7 A
3	PV Voltage at MPP (V_{mp})	19.3 V
4	PV Current at MPP (I_{mp})	5.37 A

b) Load Rating

Rated Output Power (P_{rated}) of load= 100W and
Desired Output Voltage = 40V

B. Converter Design

The Boost converter with MOSFET as the switch operating at a switching frequency (f_{sw}) of 25kHz has been used. The Boost converter diagram is shown below:

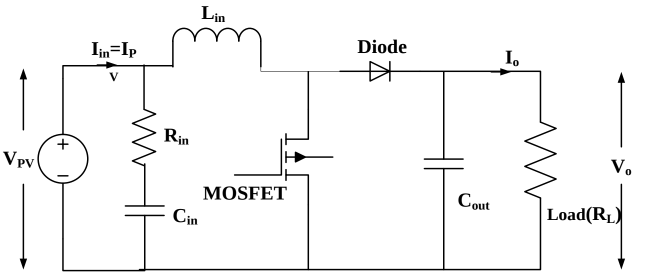

Fig. 8. Boost Converter Diagram

The voltage level is increased by using the Boost converter mentioned above between the PV panel and the load. The converter's input voltage is equal to the PV voltage (V_{PV}) and input current (I_{in}) is equal to the PV panel's output current (I_{PV}). Now that the PV panel voltage at MPP is 19.3V, the boost converter's input voltage range is taken to be between 18V and 20V. (if the input voltage fluctuates). The output voltage is 40V and the output power rating is Prated = 100W. The boost converter's input side inductor (L_{in}), output capacitor (C_{out}), duty cycle (D), output current (I_0), input current (I_{in}), ripple in inductor current (ΔI_L) and capacitor voltage(ΔV_0) are calculated.

FORMULAS USED:

Input voltage range, V_{in}= (18-20) V

Output voltage rated V_o = 40V

Duty ratio, $D = \frac{t_{on}}{T} = 1 - \frac{V_{in}}{V_o}$,where T is Time period of switching operation (T=1/f_{sw}), f_{sw} being 25kHz

Input current, $I_{in} = \frac{P_{rated}}{V_{in}}$ (6)

Output current, $I_o = I_{in}(1-D)$ (7)

Inductor current, $I_L = I_{in}$ (8)

According to IEEE standards, we have considered:

Inductor (L_{in})Current ripple, ΔI_L= 5% of the Inductor current I_L

Capacitor (C_{out})Voltage ripple, ΔV_o= 1% of the output voltage V_o.

$$L_{in} = \frac{D*V_{in}}{f_{sw}*\Delta I_L} \quad (9)$$

$$C_{out} = \frac{D*I_O}{f_{sw}*\Delta V_O} \quad (10)$$

Load, $R_L = \frac{V_O}{I_O}$ (11)

Using the above formulae [7], the calculated design parameters are listed in the TABLE II

TABLE II. BOOST CONVERTER DESIGN PARAMETERS

Sl. No.	Parameters	Values (in units)
1	$I_{in} = I_L$	5A
2	I_{out}	2.5A
3	ΔI_L	0.25A
4	ΔV_o	0.4V
5	L_{in}	1.6mH
6	C_{out}	125µF
7	R_L	16Ω

V. Simulation Results And Discussions

From the system specifications and the converter design specification given in sections IV-A and IV-B, the simulation results with P&O Technique and INC Technique are tested.

A. P&O Technique:

a) At constant temperatue of 25°C temperature and Variable Irradiance (W/m^2)

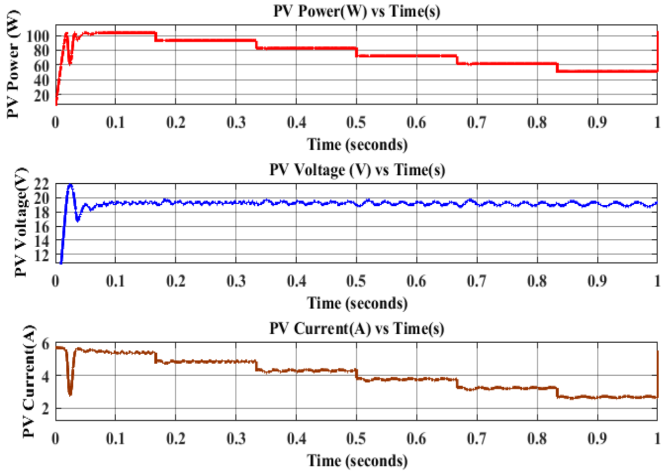

Fig. 9. PV Power(W), Voltage (V)and Current(A) when irradiance is decreased from 1000W/m^2 to 500W/m^2

b) At constant Irradiance of 1000W/m^2 and variable Temperature(°C)

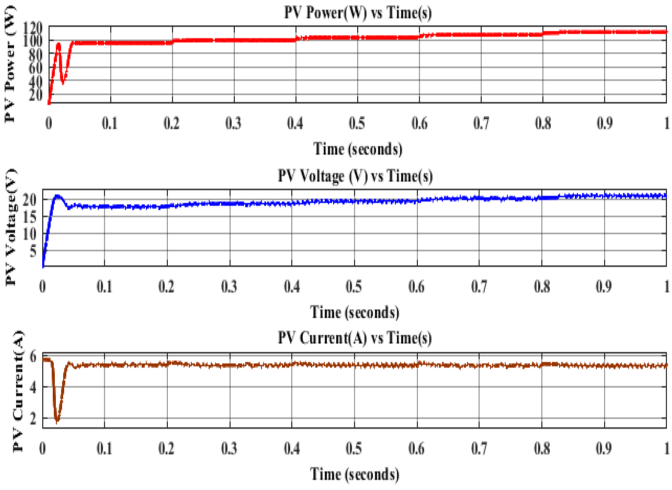

Fig. 10. PV Power(W), Voltage (V)and Current(A) when temperature is decreased from 45°C to 5°C

B. Incremental Conductance (INC) Technique:

a) At constant temperature of 25°C and Variable Irradiance (W/m²)

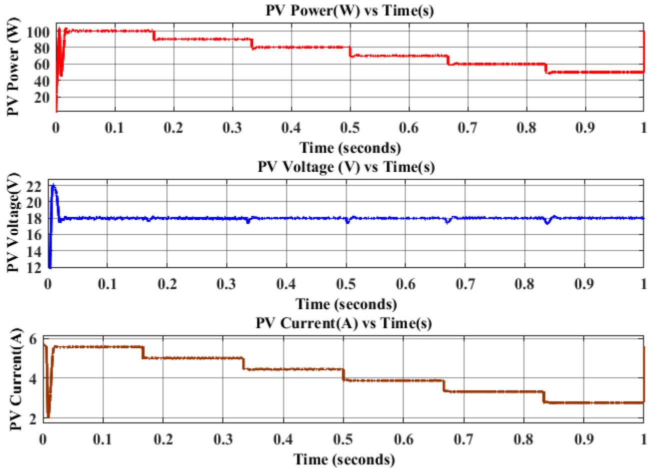

Fig. 11. PV Power(W), Voltage (V)and Current(A) when irradiance is decreased from 1000W/m² to 500W/m²

b) At constant Irradiance of 1000W/m² and variable Temperature(°C)

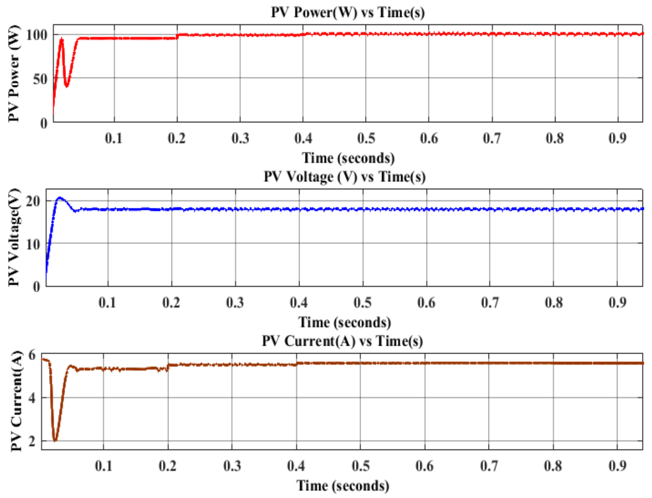

Fig. 12. PV Power(W), Voltage (V)and Current(A) when temperature is decreased from 45°C to 5°C

From Fig.9., with P&O technique, when temperature is fixed at 25°C and Irradiance is decreased from 1000W/m² to 500W/m², the PV maximum power remains constant around 103.6W, with PV voltage fixed at 19.3V and PV current at 5.37A for irradiance of 1000W/m². As the Irradiance is decreased, the PV current decreased but PV voltage is maintained constant around V_{mp}=19.37V (with slight dip at points where irradiance changes suddenly), hence providing corresponding maximum power output at various irradiances. From Fig.10, at constant irradiance of 1000W/m² and decreasing temperature from 45°C to 5°C, the PV current remains almost constant around I_{mp} with increase in the PV voltage due to decrease in temperature, showing corresponding increased maximum power output from the PV panel.

From Fig.11, considering INC technique, at a constant temperature of 25°C and decreasing the Irradiance from 1000W/m² to 500W/m², it is observed that the PV voltage is maintained constant but at slightly lower value of 18V (except slight dip when irradiance changes suddenly), PV current is decreased with decrease in irradiance causing corresponding decrease in maximum power output from PV panel. From Fig.12, when the temperature is reduced from 45°C to 5°C at constant irradiance of 1000W/m², the PV voltage is maintained around 18V, PV current and PV power increase slightly when the temperature decreases from 45°C to 35°C and remaining constant at around I_{mp}=5.37A and maximum power of 100W respectively.

VI. Comparison of MPPT Techniques

The P&O technique and the INC technique are compared based on features which are discussed below.

A. Based on Control Strategies

The MPP is immediately determined by considering the fluctuations in the operating point of the system without taking into consideration, the features of the PV panel beforehand in both MPPT procedures. It comes in two varieties: sampling methods and modulation methods. The output current and voltage of the PV panel are sampled in the sampling method. The power, dP/dV, and dI/dV components make up the sample and location of the MPP is tracked while compiling historical and present information about the sample. Both the P&O and INC approaches are examples of sampling techniques that use voltage and current sensors, respectively, to sample voltages and currents from the PV output.

B. Based on Number of Control Variables or Sensors

As per the different variables wanted to be sensed, MPPT methods can be divided into one-variable techniques and two-variable methods. In both P&O and INC techniques current and voltages are sensed. Voltage sensors are cheap to implement whereas current sensor implementation is costly

C. Based on Types of Circuitry Used

Digital and analogue circuitry are the two types of circuitries used in MPPT procedures. According to the preferences of the users, the MPPT approaches are categorized based on the type of utilised circuitry (analogue or digital).

D. Based on cost

Without building and implementing an MPPT technique, it is exceedingly difficult to make an estimation of its exact cost. The cost of implementation is high for P&O and INC approaches.

E. Based on Complexity

Both the P&O and INC techniques are complex when it comes to actual implementation.
TABLE III better compares the two techniques.

TABLE III. COMPARISON OF MPPT TECHNIQUES AS PER THE VARIOUS PARAMETERS.

Parameters	P&O MPPT	INC MPPT
Control Strategy	Sampling Method	Sampling Method
Control variable	Voltage, Current	Voltage, Current
Circuitry	Analog, Digital	Digital
Cost	Expensive	Expensive
Complexity level	Complex	Complex
Converter used	DC-DC	DC-DC
Parameter Tuning	No	No
Applications	Stand-alone	Stand- alone

VII. Conclusions

This paper reviews the P&O and INC MPPT techniques based on the parameters like control strategy, control variable, circuitry used, cost, complexity level, converters used, whether parameters can be tuned or not etc. It also has simulation results of the techniques in MATLAB Simulink R2022a software which gives an idea about the performance of the MPPT control techniques. A Boost Converter is used to increase the voltage output. By providing output to a resistive load, it is seen that both the techniques are equally efficient. In both the techniques, the Power oscillates around MPP as the perturbed value ΔV is fixed. Fluctuations can be reduced if ΔV is reduced, but on account of increase in time taken to reach MPP (tracking speed reduces).INC has somewhat better steady state performance than the P&O as the fluctuations in value of PV voltage, PV Current and Power is less. Also, the MPPT techniques face problem in partial shading conditions when PV panels are shaded by trees, bird droppings, wires, poles etc. The MPPT techniques are used in stand-alone applications. Since these MPPT algorithms suffer from power fluctuations near the MPP, adaptive P&O and INC can be applied, allowing for smaller ΔV as we approach the MPP locations. But both the price and the complexity is increased. Particle Swarm Optimization (PSO) based MPPT techniques, Fuzzy Logic (FL) based MPPT techniques, Artificial Neural Networks (ANN) based MPPT techniques, and other Intelligent MPPT techniques are also available. These techniques are very promising and have achieved excellent performances, faster response with less overshoots, and fewer fluctuations in the steady state output for rapid temperature and irradiance variations.

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