Comparative Analysis of MPPT Controllers for Boost Converter in Solar PV Systems: PO, Incremental Conductance, and ANN

M Pavan Kumar
Department of Electrical and Electronics Engineering
SR University
Warangal, India
pavan121985@gmail.com

Rajababu Durgam
Department of Eelectrical and Electronics Engineering
SR University
Warangal, India
durgamrajababu@gmail.com

Ram Krishan
Department of Electrical Engineering
National Institute of Technology
Warangal, India
rkrishan@nitw.ac.in

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***Abstract*—In order to maximise the performance of solar PV systems combined with a boost converter, this Paper provides a comparative examination of several Maximum Power Point Tracking (MPPT) approaches, namely Incremental Conductance , Perturb and Observe , and Artificial Neural Network. Extensive MATLAB simulations were conducted to evaluate the output voltage, settling time, and duty cycle of each method under varying input conditions. The results demonstrate that while all methods successfully achieve the desired output voltage of 390V, the ANN method outperforms the others by providing precise tracking with minimal oscillation and a faster settling time of 0.03 seconds. In contrast, the IC and P&O methods, despite achieving similar output voltages, exhibit oscillations and longer settling times. These results demonstrate how well using a boost converter in combination with ANN-based MPPT may improve the stability and efficiency of solar energy systems. The report offers insightful information about the development and application of renewable energy technology.**

***Index Terms*—Boost Converters,Fuzzy Logic,Incremental Conductance,MATLAB/Simulink,MPPT,Solar PV systems**

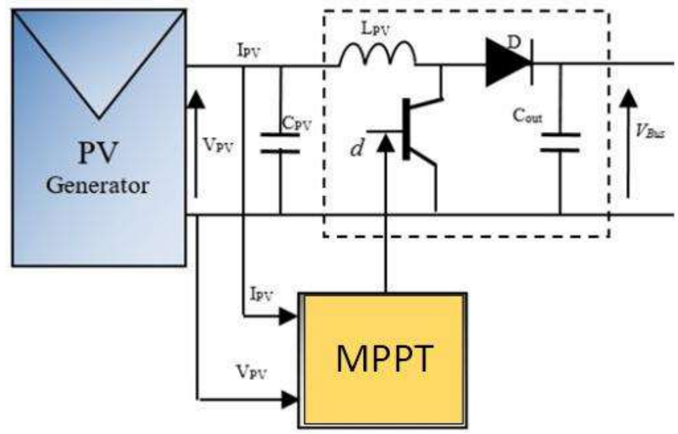

Fig. 1. Solar PV With Boost Converter

I. Introduction

One of the most important forms of renewable energy is solar energy.This solar energy has seen rapidly increasing in terms of the technology and various application. The key area of focus is the sources that which is the photovoltaic (PV) systems to maximize the energy extraction. Among the various approaches, DC-DC various converters and different types of MPPT controllers play a crucial role in maintaining system efficiency. This paper compares three MPPT methods—(P&O), Incremental Conductance (INC),and their impact on the performance of boost converters in solar PV systems Figure 1 Because it is sustainable and technology is advancing, solar energy has become an important part of the global energy shift.One of the most important challenges that which are in Solar PV systems is optimizing Voltage and Current in terms of power extraction from the solar panels, which is influenced by fluctuating the environmental conditions such as irradiance and temperature. This is where Maximum Power Point Tracking which has an important role, ensuring that the panels of the solar that which operate at their optimal point to deliver maximum power output and the MPPT techniques, when solar Photo voltaic is integrated with various DC- DC Converters, as they regulate the voltage levels and ensure stable power transfer. Among the most of the commonly used converters are the boost, buck-boost converters. The boost converter is preferred because of its simple nature of use and excellent voltage stepping up efficiency, that which makes it perfect for solar applications where the output voltage of the panel needs to be raised to meet load or grid requirements [1] .However, because they can convert voltage both up and down, buck-boost converters are adaptable and work well in systems with large voltage swings [2]. Recent studies have that which have be shown the potential of interleaved boost converters (IBC) to further improve efficiency by reducing current ripple, increase the voltage and distributing the thermal load across multiple power electronics switches. This reduces the stress on individual components, enhancing the system's reliability [3] . The introduction of artificial intelligence techniques in MPPT algorithms has also been gained the attention, for providing faster and more exact tracking compared to the other

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traditional methods like Perturb and Observe or Incremental Conductance (INC) [2].Recent studies have that which have be shown the potential of interleaved boost converters (IBC) to further improve efficiency by reducing current ripple, increase the voltage and distributing the thermal load across multiple power electronics switches. This reduces the stress on individual components, enhancing the system's reliability [3] . The introduction of ANN Techniques, such as Artificial Neural Networks (ANN), in MPPT algorithms has also been gained the attention, for providing faster and more exact tracking compared to the other traditional methods like Perturb and Observe (P&O) or Incremental Conductance (INC) [2]. Furthermore, the integration with the high-gain boost converters with novel application and topologies is being investigated to achieve higher voltage gains stability analysis without the need for transformers, simplifying the system and reducing losses [4] . This paper aims to provide a comprehensive comparison of various MPPT Techniques for the DC-DC converters—boost converter—utilized in solar PV systems . It analysis their performance in terms of efficiency, voltage gain, and stability, while also considering advancements in control strategies such as ANN,Incremental Conduction and P&O algorithms. Through MATLAB/Simulink simulations, this study seeks to highlight the trade-offs and benefits of each MPPT for the boost converter

II. SOLAR CELL MATHEMATICAL MODELLING

It is commonly known that in order to study the electrical behaviour of solar cells, a p–n junction with nonlinear properties is usually used as the model figure 2.

A. Modeling Single Diode PV cell

As illustrated in figure 2, the simple model of a solar cell consists of a current source coupled in parallel with a diode.

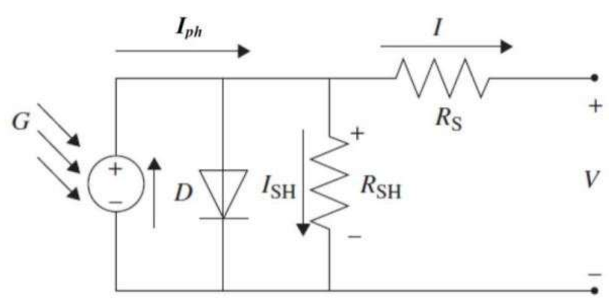

Fig. 2. Single Diode PV Cell Modeling

In the typical solar cell, the series resistance $R_s = 0$ and the shunt resistance $R_{SH} \to \infty$, fails to accurately establish the relationship between voltage and cell current.

To get more accurate findings, a series resistance R_s is taken into consideration in the single-diode modelling approach. The single-diode model's output current is shown as:

$$I = I_{ph} - I_0 \left(e^{\frac{q(V+IR_s)}{nkT}} - 1 \right) - \frac{V + IR_s}{R_{sh}} \tag{1}$$

$$I = I_{sc} - I_0 \left[\exp\left(\frac{V + IR_s}{nV_T} \right) - 1 \right] \tag{2}$$

Where:

- I_{sc}:nominal conditions for Short circuit current
- I_0: Diode reverse saturation current
- V: Voltage across the solar cell
- R_s: Series resistance of the solar cell
- n: Ideality factor of the diode
- V_T: Thermal voltage ($V_T = \frac{kT}{q}$, where k is the Boltzmann constant, T is the temperature, and q is the charge of an electron)

The short circuit current I_{sc} can be described as:

$$I_{sc} = K_1(G - G_r) + I_{sc,r} \tag{3}$$

Where:

- K_1: short circuit current for the Temperature coefficient of the cell
- G: Solar irradiance on the cell
- G_r: Reference solar irradiance
- $I_{sc,r}$: Short circuit current at reference conditions

The diode reverse saturation current can be expressed as:

$$I_0 = I_{sc} \exp\left(\frac{V_{oc}}{nV_T} \right) \tag{4}$$

Where V_{oc} solar cell open-circuit voltage.

$$I_0 = I_0(T_r) \left(\frac{T}{T_r} \right)^3 \exp\left[\frac{qE_g}{nk} \left(\frac{1}{T_r} - \frac{1}{T} \right) \right] \tag{5}$$

Where : Eg- band gap energy of semiconductor.

$$I_0(T_r) = \frac{I_{sc}}{\exp\left(\frac{qV_{oc}}{nkT_r} \right) - 1} \tag{6}$$

The solar cell series resistance can be obtained by

$$R_s = -\frac{dV}{dI|_{V_{oc}}} - \frac{1}{X_V} \tag{7}$$

$$X_V = I_0(T_r) \frac{q}{nkT_r} \exp\left(\frac{qV_{oc}(T_r)}{nkT_r} \right) \tag{8}$$

Here, X_V is a term that relates the recombination processes inside the solar cell to the cell's open-circuit voltage and temperature. Breaking down this term:

- $I_0(T_r)$: The reverse saturation current (leakage current) of the diode at reference temperature T_r. This is the small current that flows when the cell is reverse-biased, and it depends on temperature.
- q: The electron charge, a fundamental constant (1.6×10^{-19} C).
- n: The diode's ideality factor, which for actual solar cells usually varies from 1 to 2, shows how nearly the cell follows to the stable diode equation.
- k: Boltzmann's constant, a fundamental physical constant relating temperature and energy (1.38×10^{-23} J/K).

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- T_r: The reference temperature, usually in kelvins (K).
- $V_{oc}(T_r)$: The open-circuit voltage of the solar cell at the reference temperature T_r.
- $\exp\left(\frac{qV_{oc}(T_r)}{nkT_r}\right)$: This exponential term represents the relationship between the cell's voltage and the saturation current, where the higher the voltage, the lower the reverse saturation current.

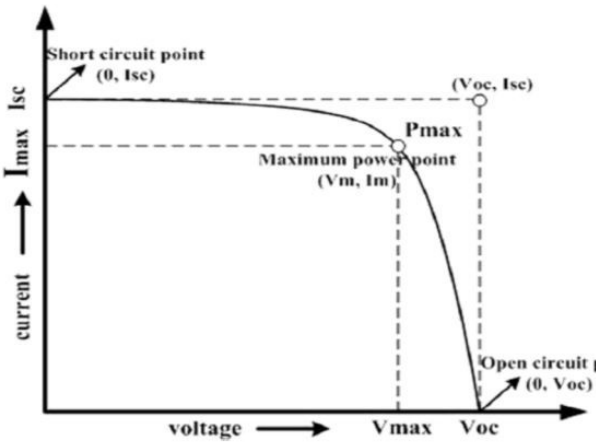

Fig. 3. I-V characteristics curve of a PV cell

The Solar Panel Detials for the the Simple boost Converter for the connecting with the MPPT are shown in the table 1.and I-V Characteristics cure of a PV Cell shown in the figure 3

TABLE I
SOLAR PV DETAILS

Parameter	Value
Maximum Power (Pmax)	200 W
Maximum Power Voltage (Vmpp)	47 V
Maximum Power Current	4.26 A
Open Circuit Voltage (Voc)	57 V
Short Circuit Current (Isc)	4.6 A
Max System Voltage	200 V
Temperature Coefficient of open circuit Voltage	$-0.36099V/C$
Temperature Coefficient of Isc	$0.102A/C$
Number per Module per string	4

III. MPPT TECHNIQUES FOR THE BOOST CONVERTER USING SOLAR PV

DC-DC converters, especially boost, buck-boost, and interleaved boost converters, are widely used in PV systems to regulate the output voltage and ensure maximum power extraction.MPPT algorithms modify the system's operating point to align with the Maximum Power Point (MPP) in response to variations in temperature and sunshine.

A. Perturb and Observe (P&O)

The P&O method is one of the simple,easy and one of the most commonly used MPPT techniques. It operates by varying the PV panel's operational voltage and current and tracking the resulting change in power output. In the scenario that the power increases, the perturbation will continue in the same direction; otherwise, it will reverse. The Principle of the algorithm is to check the unsettled voltages and notice the power change (P). If , the voltage is increased, and If , the voltage is decreased.And it is Simple to implement and Requires fewer computations compared to other algorithms [5] various conditions potentially leading to operating away from MPPT which is shown in the flow chart figure 4

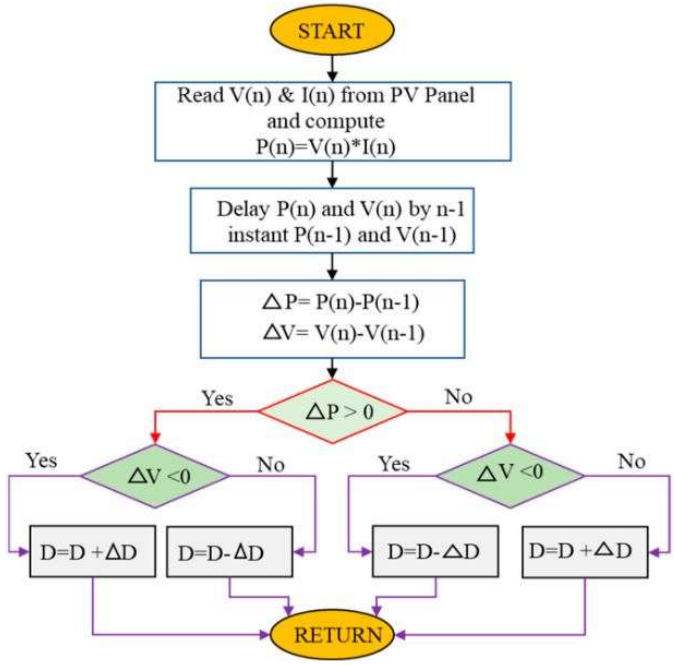

Fig. 4. Peturb and Observe Technique

The key equation for the Perturb and Observe (P&O) method is derived from the power change in response to a voltage change. MPPT tracking condition is :

$$\frac{\partial Power(P)}{\partial voltage(V)} = 0 \tag{9}$$

Where:

- P -power of the PV module.
- V -voltage of the PV module.

In the P&O algorithm, this condition is approximated by calculating the change in power ΔP due to a change in voltage ΔV:

$$\Delta P = P(k) - P(k-1) \tag{10}$$

$$\Delta V = V(k) - V(k-1) \tag{11}$$

Where:

- $P(k)$ and $P(k-1)$ are the power values at the current and previous time steps.
- $V(k)$ and $V(k-1)$ are the corresponding voltage values.

The P&O decision rule is as follows:

- If $\Delta P > 0$, then continue perturbing in the same direction.
- If $\Delta P < 0$, reverse the direction of the voltage perturbation.

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The duty cycle D of the converter is adjusted according to the direction of the voltage perturbation:

$$D(k+1) = \begin{cases} D(k) + \Delta D, & \text{if } \Delta P > 0 \\ D(k) - \Delta D, & \text{if } \Delta P < 0 \end{cases} \tag{12}$$

Where:

- $D(k+1)$ is the updated duty cycle.
- $D(k)$ is the current duty cycle.
- ΔD is the step size of the perturbation.

The P&O method modifies the duty cycle to maintain the system functioning at or close to the maximum power point, as shown by this set of equations. [6].

B. Incremental Conductance (INC) Based MPPT

The algorithm of Maximum power point tracking for the incremental conductance ($\frac{dI}{dV}$) is very popular method It finds the MPPT by comparing the INC to the immediate conductance ($\frac{I}{V}$). The concept that results from the finding that the slope of the photovoltaic power curve is zero at the maximum power point (MPP) [7] Left side is positive, right side is negative. The condition for tracking the Maximum Power Point (MPP) using the Incremental Conductance (INC) method is:

$$\frac{\partial P}{\partial V} = I + V\frac{\partial I}{\partial V} \tag{13}$$

At the MPP, this simplifies to:

$$\frac{\partial I}{\partial V} = -\frac{I}{V} \tag{14}$$

Where:

- I Photo Voltaic Current module.
- V Photo Voltaic Voltage module.

The decision rules for adjusting the duty cycle D are as follows:

$$\frac{\partial I}{\partial V} = \begin{cases} > -\frac{I}{V}, & \text{Increase voltage} \\ < -\frac{I}{V}, & \text{Decrease voltage} \\ = -\frac{I}{V}, & \text{MPP reached} \end{cases} \tag{15}$$

The duty cycle D of the converter is adjusted accordingly to keep the system at the MPP. The following table summarizes the control actions for the Incremental Conductance (INC) method:

TABLE II
MPPT CONTROL ACTIONS BASED ON INCREMENTAL CONDUCTANCE METHOD.

Condition	Action on Voltage	Action on Duty Cycle
$\frac{\partial I}{\partial V} > -\frac{I}{V}$	Increase voltage	Decrease D
$\frac{\partial I}{\partial V} < -\frac{I}{V}$	Decrease voltage	Increase D
$\frac{\partial I}{\partial V} = -\frac{I}{V}$	MPPT reached	No change

This table- II shows how the system adjusts the voltage and duty cycle based on the conditions evaluated by the Incremental Conductance algorithm.

The algorithm continuously monitors the slope of the PV curve and adjusts the duty cycle of the boost converter to drive the operating point towards the MPP. This method is more accurate than Perturb and Observe (P&O) in rapidly changing irradiance conditions and reduces power oscillations around the MPP, especially in stable environments.

However, the challenges include increased complexity compared to the P&O method.

C. Artificial Neural Network MPPT

the Intelligent MPPT is one of the ANN is one form of artificial intelligence approach. There are several benefits that artificial intelligence offers over traditional techniques. The old method's limitations include its delayed response time to abrupt changes in solar temperature and irradiance and its irregular incapacity to follow the maximum power point. The overview of ANN in MPPT is shown in Figure 5. The inputs are Voltage and Current. The duty ratio of the DC-DC converter is the goal of the neural network. [8].A neural network will provide a certain duty ratio value for each change in the sun's temperature and irradiance level in order to calculate the maximum power point. In order to account for this value and cost, complexity is necessary. During training,

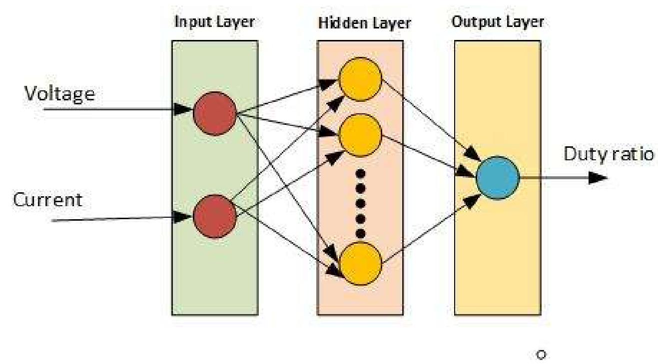

Fig. 5. ANN Technique

the Levenberg-Marquardt algorithm is applied to acquire the network. An ANN is trained for a range of temperature and solar irradiation combinations, and the duty ratio is calculated. During training, the weights of the layers in a neural network must be changed to get the required values. In order to follow the goal values with the least amount of error, weights are adjusted during the training process.An overview of the the determination of MPPT equation using ANN is as follows:

$$D = f_o\left(f\left(\sum_{i=1}^{n} w_{ij}X_i + b_j\right)\right) \tag{16}$$

Where:

- D is the duty cycle.
- $X = [G, T, V, I]$ are the input parameters.
- w_{ij} are the trained weights.
- f and f_o are the activation functions.
- b_j This is the bias term, a constant added to the weighted sum to adjust the output independently of the input values

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This setup would allow the ANN to continuously adjust the duty cycle for MPPT.

IV. Simple Design of Boost Converter

A boost converter is a type of DC-DC converter that steps up the input voltage to a higher output voltage while maintaining power continuity. The basic operation principle of a boost converter relies on storing energy in an inductor during the ON state of a switch (typically a transistor) and releasing it to the output during the OFF state [9] shown in the figure 6. The list of the components are given in the table-IV for Boost converter.

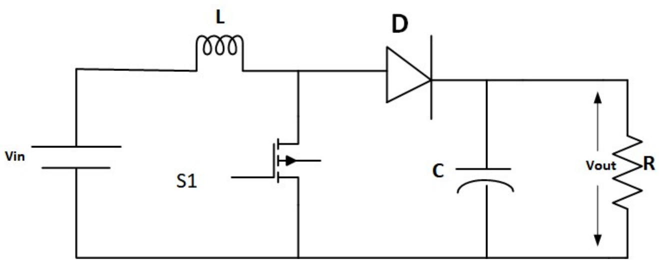

Fig. 6. Boost Converter

TABLE III
Summary of Component Values

Component	Value
Inductance	3.5 mH
Capacitance 1	1000 µF
Capacitance 2	200 µF
Resistance	300 ohms

A. Duty cycle and Inductor Value

The switching ON and OFF of switch depends on the ratio switching period by the duty cycle (D) .The inductor (L) in a boost converter which plays a key role to find out the inductance value by using the equation which is given below, which considers the input voltage, duty cycle, allowable inductor ripple current (ΔI_L), and switching frequency (f_{sw}):

$$D = \frac{V_{in}}{V_{out}} \tag{17}$$

$$L = \frac{V_{in} \cdot D}{\Delta I_L \cdot f_{sw}} \tag{18}$$

where: V_{out} = output voltage V_{in} = input voltage, D = duty cycle, ΔI_L = ripple current through the inductor, typically chosen as a percentage of the output current, f_{sw} = switching frequency.

B. Capacitor Value

The output capacitor (C) is crucial in reducing the O/P voltage ripple. The required capacitance for the boost converter can be calculated with the equation:

$$C = \frac{I_{out} \cdot D}{\Delta V_{out} \cdot f_{sw}} \tag{19}$$

where: - I_{out} = output current, - ΔV_{out} = allowable output voltage ripple.

C. Resistive Load

For a resistive load, the output voltage and current are related by Ohm's law. The load resistance (R) can be calculated as:

$$R = \frac{V_{out}}{I_{out}} \tag{20}$$

V. Simulation and Results

MATLAB/Simulink simulations were conducted to evaluate the performance of boost converter and with different MPPT algorithms. The voltage gain, and control complexity of each combination were analyzed that which is shown in the Table -III, and figure 7 MPPT Methods Comparison

TABLE IV
Comparison of MPPT Methods

Method	I/P Voltage	O/P Voltage	Settling Time (s)
Incremental method	222	390	0.8
P&O Method	210	390	0.8
ANN Method	210	390	0.6

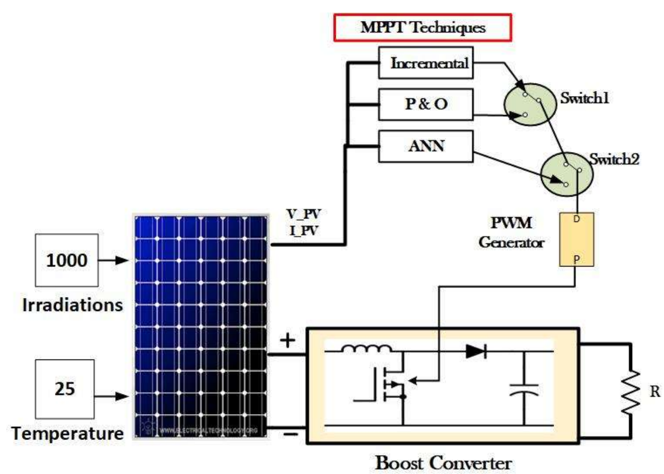

Fig. 7. Matlab Circuit Design Model

The simulation results for the Incremental Conductance (IC), Perturb and Observe (P&O), and Artificial Neural Network (ANN) methods that which are going to demonstrate varying performance in terms of O/P voltage, power, settling

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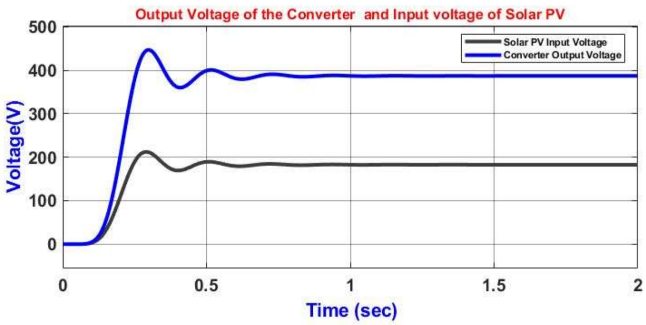

Fig. 8. Incremental MPPT Technique

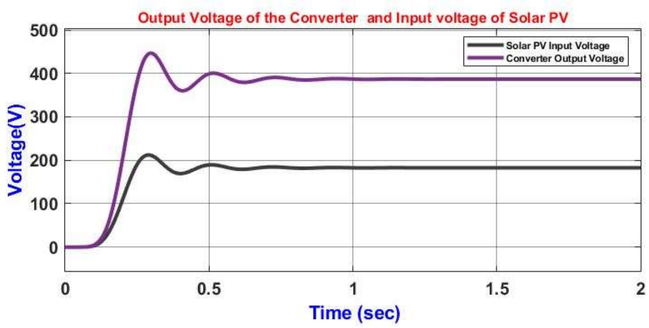

Fig. 9. P& O MMPT Technique

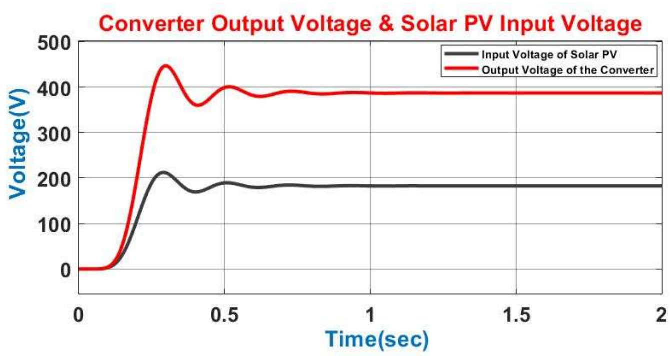

Fig. 10. ANN MPPT Technique

time (Stability), and duty ratio. All three methods were tested with an input voltage of around 210-222V and boosted the output voltage to 390V, with a duty cycle of 0.5 that whcih are shown in the figure 8-10 for the three methods of incremental , P &O , ANN Technique . The IC method exhibited stable output with the small oscillations around the maximum power point (MPP) and a settling time of 0.6 to 0.8 seconds. The P&O method also achieved similar output voltage and settling time but suffered from inherent oscillations due to continuous perturbation around the MPPT. The variation around the MPPT can lessen the power output marginally, although being easier to carry out. The ANN approach, on the other hand, fared better than both, tracking the MPPT precisely and quickly with no discernible oscillations. Because of its capacity for learning and adaptation, it can continue to operate steadily and with little error. While the IC and P&O approaches might be appropriate for less demanding applications where cost or simplicity is a priority, overall, the ANN method provides the best performance for systems requiring high accuracy and stability.

VI. Conclusion

In Conclusion, the simulation of MPPT techniques revealed unique benefits and drawbacks of the Artificial Neural Network (ANN), Perturb and Observe (P&O), and Incremental Conductance (IC) techniques. With its accurate output voltage and quick, oscillation-free settling time, the ANN approach proved to be highly effective and is the best choice for applications requiring a high degree of accuracy and stability. On the other hand, although the output voltages produced by the IC and P&O approaches were comparable, they showed variations near the maximum power point, which might have an effect on efficiency. As a result, the MPPT technique selection should balance performance, complexity, and cost factors while also taking into account the unique requirements of the system.

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