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* **Corresponding author**.

nvumaeee@gmail.com

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Implementation of Modified Incremental Conductance MPPT A lgorithm in Grid Connected PV System Under Dynamic Climatic Conditions

N V Uma Maheswari[1]*, L Jessi Sahaya Shanthi[2]

1 Assistant Professor, Department of Electrical and Electronics Engineering, Government College of Engineering, Bodinayakkanur, 625582, Tamil Nadu, India
2 Associate Professor, Department of Electrical and Electronics Engineering, Thiagarajar College of Engineering, Madurai, Tamil Nadu, India

Abstract

Background: The main goal of the grid-connected Photo Voltaic (PV) system is to extract maximum power from the array with reduced loss by using an appropriate MPPT method. **Methods:** A boost converter topology with linear INCMPPT algorithm is used to provide maximum power of 100 kW from the solar PV array to the grid. The integral regulator in the modified algorithm minimizes the error and guarantees exact control of the duty cycle of the DC-DC converter to produce constant DC voltage 500V with a minimum error of ±2V. This proposed methodology perfectly matches with the optimal design of the DC-AC converter (inverter) for grid integration. A three-level IGBT-based voltage source inverter and filters are designed to supply pure AC voltage to the existing 100 kW grid. Detailed simulation work is completed using MATLAB/ Simulink software to prove the effectiveness of the proposed algorithm under various temperature (25-50°C) and irradiance (200-1000W/m^2) levels. **Findings:** The proposed MPPT algorithm is simple and effective in reducing the error required for the duty cycle correction from 0.45 to 0.518 and eliminating the oscillations at MPP. By using this methodology, the output voltage of the boost converter is adjusted to match the reference value. The simulation results reveal the better performance of the grid-connected PV system with the modified incremental conductance MPPT method. This modified INC MPPT algorithm exactly controls the duty cycle of the boost converter to provide better settling time and low ripples in the grid parameters. **Novelty:** This article provides a simple and effective improved incremental conductance (INC) MPPT algorithm to minimize the tracking error (1.5%). No additional tuning and selection of parameters, computational burden and memory are required for the implementation of the proposed control algorithm.

Keywords: Gridconnected photovoltaic (PV) system; Maximum power point tracking (MPPT); Voltage Source Inverter (VSI); Boost converter; Incremental conductance (INC)

1 Introduction

For low power applications, stand-alone PV systems are used which require a battery to store solar energy. Grid-connected PV system does not require battery storage and it is used in high power applications. In this system, PV array, DC-DC converter with MPPT and DC-AC converter are required to integrate PV with the grid. The maximum power point tracking (MPPT) is a technique used to harness maximum power from the solar PV system under severe climatic conditions [1–8]. Several MPPT algorithms like perturb and observe (P&O), fractional short-circuit current (FSCC), artificial neural networks (ANN), incremental conductance (INC), fractional open-circuit voltage (FOCV), fuzzy logic (FL), and particle swarm optimization (PSO) are identified from literature [1–14]. Fuzzy logic [14] and ANN [10,15] are widely used in motor control applications as well as in MPPT algorithms. These algorithms are ranging simple to more complex. Tracking speed, hardware requirement and cost are different for each algorithm. All the algorithms are developed to track MPP under varying irradiance and temperature. In recent years, ANN-based MPPT is widely used industrial applications because it does not require complex mathematical equations. The P&O and the INC MPPT methods are used mostly because of their easy implementation and tracking speed. But P&O MPPT produces oscillations at MPP [12,13].The main objective of the grid-connected PV system is to extract the maximum possible solar energy and exporting to the existing grid under rapidly changing climatic conditions so that power loss, maintenance and operational cost of the grid are minimized. The main task is to control and maintain the power factor of the inverter and the quality of the power. The power flow between PV array and grid is also controlled in this scheme. A novel INC MPPT with an integrator is used in this work to reduce the oscillations and tracking error. ANN is used for obtaining the global MPPT in a standalone PV system under varying climatic conditions [1]. A variable step incremental conductance algorithm with a fuzzy logic controller is used in the grid connected PV system. An increase in the step size minimizes the accuracy and a decrease in step size improves the tracking accuracy. The performance of the MPPT method is analyzed during snow conditions with computational intelligence [2,3]. The effect of membership functions on the performance of the PV system is detailed [4]. A comparison between hybrid, intelligent and classical MPPT methods is presented [5]. Local maxima occurrences, oscillations at MPP and less efficiency are the limitations of classical MPPT methods. A buck converter is used for charge controller used in the stand-alone PV system [6]. The converter in the PV system reduces the voltage level for storage in the battery. Algorithms like self-tuned P&O [11] ANFIS-PSO [12] and momentum based P&O [13] are discussed for the specified applications in the literature. In the momentum based P&O method, the selection of scaling factor decides the performance of MPPT. Oscillation at MPP occurs when the momentum factor is greater than 0.5. However, the global maximum is not guaranteed for the entire simulation and P& O algorithms are comparatively slower than the INC algorithm [12]. For the implementation of ANN and ANFIS based MPPT methods, the previous and present data set is needed for the training and testing phases of the network and the collection of such data is a tedious process [1,10,12,15]. Training data are obtained either from simulation or from experimentation. Human expertise is required for the rule formation in the fuzzy system and the selection of membership function greatly affects the performance of the MPPT method [4,14]. The proposed MPPT does not require any such large dataset and human expertise and it is simple and efficient to implement in the Simulink environment. Unlike P&O MPPT, oscillations at MPP are eliminated in the proposed MPPT [11,13]. The integral regulator is used to minimize the error required to control the duty cycle variation in accordance with the irradiance so that the overall efficiency is improved. Continuous control of power flow is achieved with this modified algorithm.

2 Methodology

2.1 Mathematical Modeling of PV Array

The series connection in the PV array is responsible for increasing the voltage and the parallel connection is used for increasing the current rating of the system. Power generated by the PV system depends on solar irradiance and cell temperature [1–13]. The sunlight is directly converted into electrical energy by the photovoltaic cell. The typical equivalent circuit model of a PV cell is shown in Figure 1. The PV current (I_L) is the sum of diode current (I_D), shunt resistor current (I_{sh}), and output current (I).

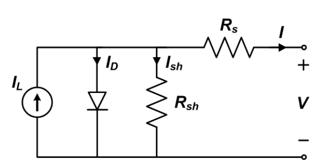

Fig 1. PV cell - Equivalent circuit

The output current of the PV cell is expressed as

$$I = I_L - I_D - I_{sh} \tag{1}$$

$$I = I_L - I_s\left(e^{\frac{q(V+IR_s)}{mkT}} - 1\right) - \frac{(V+IR_s)}{R_{sh}} \tag{2}$$

Where

I - Output current (A),
I_L - Light generated PV current (A),
I_s - Saturation current (A),
I_D - Diode current (A),
I_{sh} - Shunt current (A),
q - Electron charge (1.6×10^{-19} C),
R_s - Series resistance (Ω),
R_{sh} - Shunt resistance (Ω),
m - Diode quality factor,
k - Boltzmann constant (1.38×10^{-23} J/K) and
T - Temperature (K).

The maximum current and power are expressed as

$$I_{mp} = I_L - I_s\left(e^{\frac{q\left(V_{mp}+I_{mp}R_s\right)}{mkT}} - 1\right) - \frac{\left(V_{mp}+I_{mp}R_s\right)}{R_{sh}} \tag{3}$$

$$P_{mp} = V_{mp}\left(I_L - I_s\left(e^{\frac{q\left(V_{mp}+I_{mp}R_s\right)}{mkT}} - 1\right) - \frac{\left(V_{mp}+I_{mp}R_s\right)}{R_{sh}}\right\} \tag{4}$$

At constant temperature, when the irradiance level is increased to 500 W/m^2, 800 W/m^2, and 1000 W/m^2, the PV voltage and current increase, and hence PV power also increase with irradiance as given in Figure 2. At constant irradiance, an increase in cell temperatures like 25^{0}C, 35^{0}C, and 50^{0}C reduce the PV power. The MPPT algorithm maintains the PV operating point close to the MPP. To track the maximum power point under the variable conditions of solar irradiations, accurate control of the duty cycle of the boost converter is required.

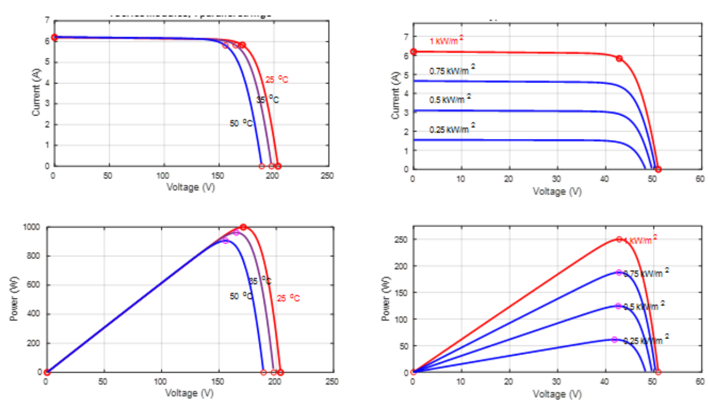

Fig 2. I-V and P-V Characteristics at different temperatures and irradiances

3 Incremental Conductance MPPT Algorithm

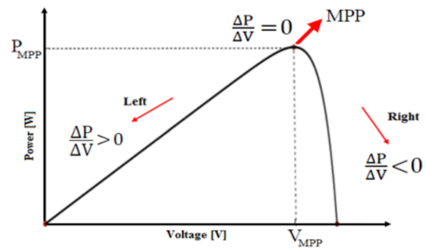

Fig 3. P-V characteristics of PV array

The typical P-V Characteristics curve of a PV array is shown in Figure 3. The PV power is maximum at the point MPP. In this paper, the modified INC MPPT algorithm is used for the grid-connected system. In the conventional INC MPPT control, dP/dV should be zero for getting MPPT. This dP/dV ratio is positive for the left side of the MPP and is negative for the right side of MMP. The MPP is identified based on the comparison of array conductance (I/V) with incremental conductance (ΔI/ΔV). When these are equal (ΔI/ΔV=I/V), the output voltage is the MPP voltage [2]. This algorithm uses voltage and current measurements of the PV array. The flowchart of this algorithm is depicted in Figure 4. Equations related to this algorithm are given as follows

$$\frac{\triangle P}{\triangle V}=\frac{\triangle (VI)}{\triangle V}=\frac{I\triangle V}{\triangle V}+\frac{V\triangle I}{\triangle V} \tag{5}$$

$$\frac{\triangle P}{\triangle V}=I+\frac{V\triangle I}{\triangle V} \tag{6}$$

$$\left(\frac{I}{V}\right)\frac{\triangle P}{\triangle V}=\left(\frac{I}{V}\right)+\frac{\triangle I}{\triangle V} \tag{7}$$

$$\frac{\triangle P}{\triangle V}=0 \text{ at MPP} \tag{8}$$

$$\frac{\triangle P}{\triangle V}>0,\ \text{Left of MPP} \tag{9}$$

$$\frac{\triangle P}{\triangle V}<0,\ \text{Right of MPP} \tag{10}$$

$$\frac{\triangle I}{\triangle V}=-\frac{I}{V},\ at\ \text{MPP} \tag{11}$$

$$\frac{\triangle I}{\triangle V}>-\frac{I}{V},\ Left\ of\ \text{MPP} \tag{12}$$

$$\frac{\triangle I}{\triangle V}<-\frac{I}{V},\ \text{Right of MPP} \tag{13}$$

Where ΔP is the output power deviation, ΔV is the output voltage deviation of PV module and ΔI is the change in PV current.

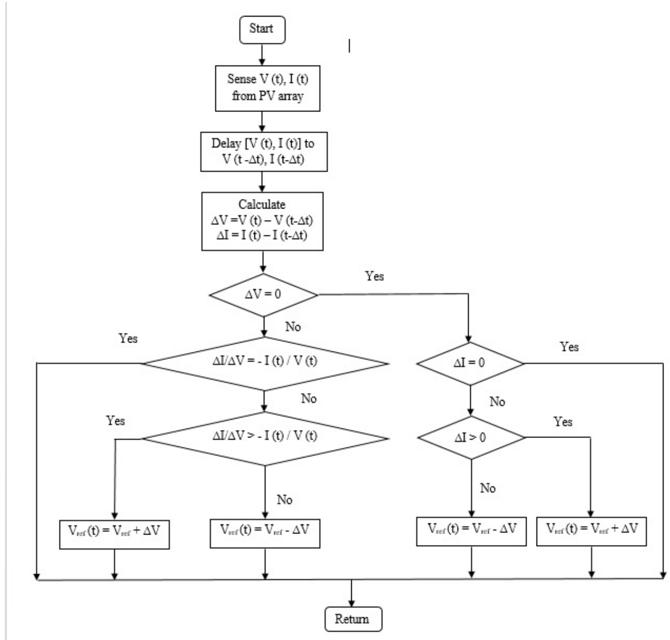

Fig 4. Incremental conductance MPPT Flowchart

3.1 Proposed MPPT Algorithm

In the proposed algorithm as given in Figure 5, the integral regulator used in the modified MPPT method minimizes the error $\left(\frac{I}{V}\right)+\frac{\triangle I}{\triangle V}$ and the regulator output is used for the duty cycle correction. Here integral gain of 10 is selected for simulation. DC-DC PWM generator is used for the generation of pulse required for the boost converter switch.

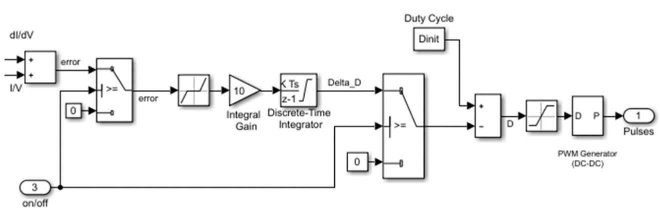

Fig 5. Integral regulator in INC MPPT

4 Design of Boost Converter

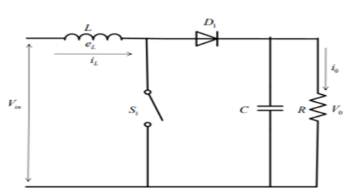

Fig 6. Boost converter

The boost converter (Figure 6) consists of a diode, capacitor, inductor, and a switch. The ripple reduction filters are used in both supply and load sides[13]. The average output voltage V_0 is

$$\frac{V_i}{1-D} \tag{14}$$

Duty cycle D of the boost converter is expressed in terms of efficiency η.

$$\mathrm{D} = 1 - \left(\frac{\mathrm{V_i}}{\mathrm{V_0}}\right)\eta \tag{15}$$

The inductor value is calculated using the following expression

$$\mathrm{L} \geq \frac{V_{s(\min)}D}{f_s \Delta i_L} \tag{16}$$

where fs - Switching Frequency

D -Duty Cycle

$\triangle i_L$- Ripple current (20–40% of i_L).

Capacitors present in the input and the output sides are calculated using equations (17) and (18).

$$C_i \geq \frac{I_{0m}D^2}{0.02\,(1-D)\,V_i f_s} \tag{17}$$

$$C_{out} \geq \frac{I_{0m}D}{f_s \Delta V_C} \tag{18}$$

5 Simulation Results and Discussion

The simulation model of the proposed system is developed using MATLAB/Simulink. This proposed algorithm is used to track the MPP under dynamic climatic conditions and is given in Figure 7. Irradiance has a direct impact on PV output at constant temperature. To analyze the system with the modified IC-MPPT, MATLAB simulation is carried out at different irradiance levels (250-1000) W/m^2 and different temperatures (25-50)^{0}C. The signal builder block in the Simulink is used to set the irradiance and temperature profile. All the simulation results are discussed here to prove the effectiveness of the proposed MPPT.

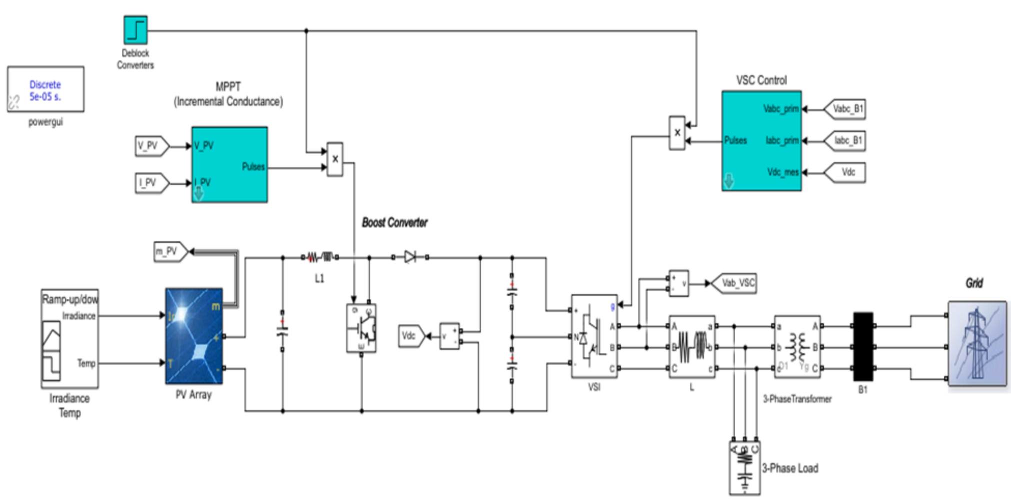

Fig 7. Simulation diagram of grid connected PV system

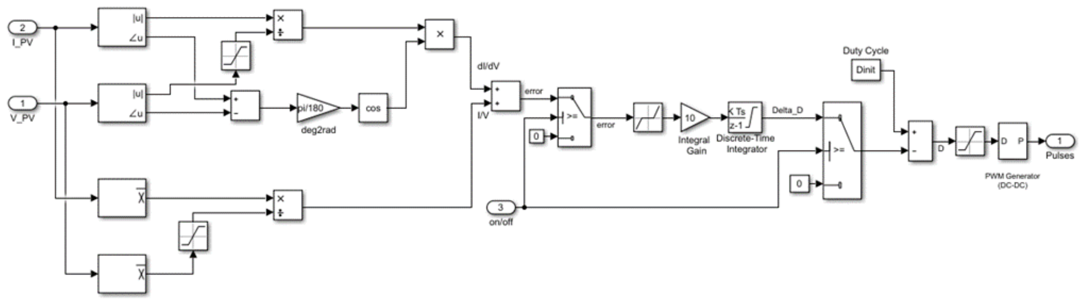

Fig 8. Proposed MPPT

Table 1. Simulation Parameters

Parameter	Value
PV array Open circuit voltage (Voc)	64.2 V
Maximum voltage (Vm)	54.7 V
Short circuit current (Isc)	5.96 A
Maximum power (Pm)	305.2 W
Diode saturation current (Is)	1.1753e−08
Shunt Resistance (Rsh)	993.51 Ω
Maximum Power Current (Im)	5.58 A
Series Resistance (Rs)	0.0379 Ω
Boost Converter Inductance	5.5 mH
Input Capacitance	110 μF
Output Capacitance	15 mF
Switching frequency	5kHz

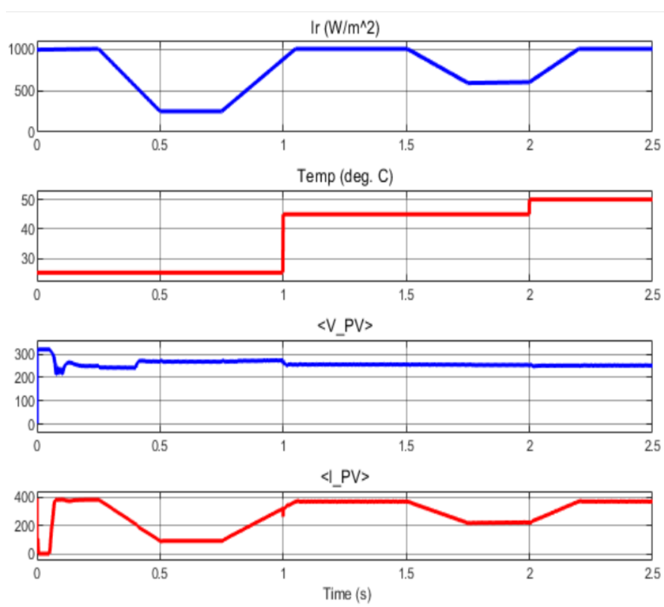

Fig 9. Irradiance,Temperature profile, PV voltage and current

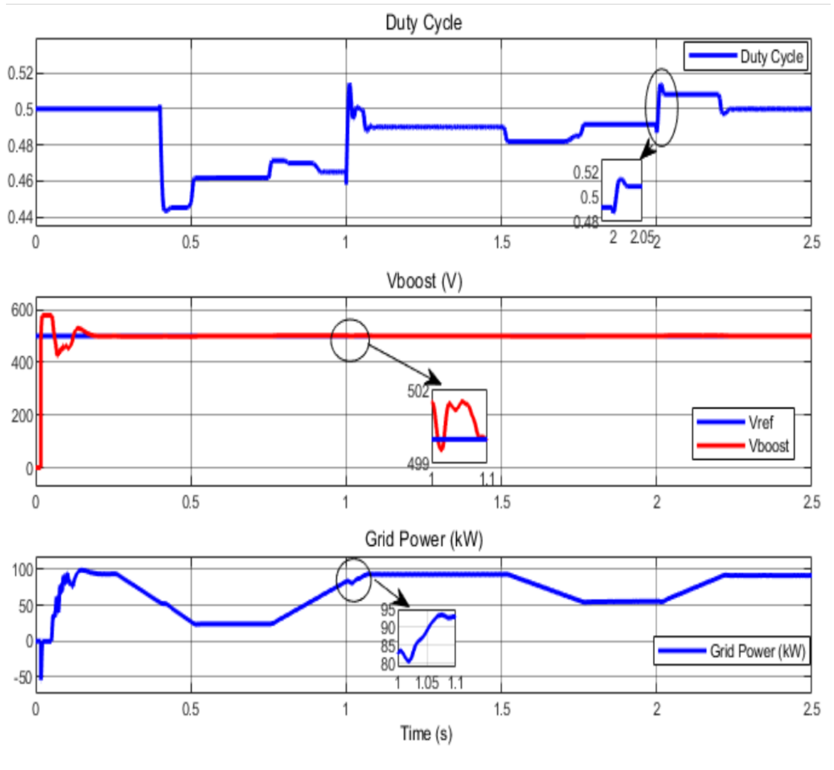

Fig 10. Duty cycle, Boost converter output voltage and Grid power

Figure 8 shows the Simulink model of the proposed MPPT algorithm with integral regulator and simulation parameters are listed in Table 1. Figure 9 shows the irradiance and temperature profile used for the simulation.

Initially the duty cycle (D) is set as 0.5 for the simulation. At time t=0.5 sec, irradiance level is decreased to 250 W/m^2 from the initial level of 1000 W/m^2 at 25^{0}C and the duty cycle is decreased to 0.45. At 1 sec, the duty cycle attains a maximum value of 0.518 because of the sudden change in temperature and irradiance level. The boost converter voltage is maintained at a constant 500V irrespective of the changes in the climatic conditions. Exact control of the duty cycle is ensured during the entire simulation to get constant output voltage in the boost converter. The pure DC voltage of the boost converter is used as input to the voltage source converter (VSC). It is a three-level DC- AC converter in which proper gating signals to the IGBT switches are given to produce 500V AC at the output side. The grid power of 92.5 kW is obtained at 1000 W/ m^2, 45^{0}C level and it is 25 kW at 250 W/ m^2, 25^{0}C. After the ripple reduction using an LC filter, the alternating voltage is integrated with the existing grid for customer use. Grid power of 100 kW and the corresponding duty cycle and boost converter voltage waveforms are shown in Figure 10 with negligible variations. The entire simulation results are summarized in Table 2 and it is proved that PV power (Ppv) is almost equal to the grid power with a 1.5% error. The superiority of the proposed method is shown in Table 3. With minimum modification in the existing method, tracking error and oscillation at MPP are minimized. Computational burden and memory requirement are less when compared with the other MPPT methods in the literature.

Table 2. Summary of results

Time Sec	Irradiance W/m^2	Temperature ^{0}C	V_{PV} V	I_{PV} A	D	Vboost V	P_{PV} kW	Grid powerKw
0.5	250	25	280	100	0.45	499	28	25
1	900	25	250	320	0.51	502	80	79
1.5	1000	45	250	380	0.49	501	95	92.5
2	600	45	240	280	0.49	499.9	67.2	68
2.5	1000	50	240	385	0.5	500	92.4	91.5

Table 3. Comparison of proposed method with other MPPT Algorithms

	Proposed method	Momentum based P&O [13]	Fuzzy [4]	ANN [10]	ANFIS-PSO [12]
Complexity	Low	Low	Medium	High	High
Memory requirement	Medium	Medium	>Medium	High	Very high
Required sensors	One voltage and current	One voltage	One voltage and current	One voltage and current	One voltage and current
Tuning / selection parameters	No	Momentum factor(α)	Membership functions	Weights, inputs, neurons	Weights, inputs, neurons, no of particles and iterations
Computational burden	Low	Low	High	High	Very high
Additional requirement/limitation	No	Oscillations at MPP (α>0.5)	Expertize in rule base	Data set, training and testing of NN	Data set,training and testing of ANFIS

6 Conclusion

A modified INC MPPT with DC-DC converter topology is presented for grid connected PV 100 kW small customer and residential applications. The integral regulator present in the modified INC MPPT algorithm is used to reduce the error for duty cycle correction from 0.45 to 0.518 and the boost converter output is maintained at 500 V with negligible error ($\pm$2V). This proposed methodology is exactly matched with the optimal design of VSC for grid integration. Simulation results reveal the improvement in the system performance with temperature and solar irradiance variations. This modified INC MPPT reaches MPP faster than other conventional methods like P&O that perturbs around MPP. The incremental conductance algorithm with an integral regulator can track the MPP for the PV module under dynamic climatic conditions (200-1000) W/m^{2}and (25-50) $^\circ$C and mitigate the inaccurate response. It is inferred that the oscillations in the power tracking are minimum (less than 1.5%) with this simple proposed algorithm.

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