Mathematical Modeling of Simplified Photovoltaic Module for Evaluation of Maximum Power Point Tracking

Bipin Singh
Electrical Engineering Department
IET
Lucknow (U.P.)
singhbipin08@gmail.com

Arunima Verma
Electrical Engineering Department
IET
Lucknow (U.P.)
arunimadey@gmail.com

Vinod Kumar Giri
Electrical Engineering Department
MMMUT
Gorakhpur (U.P.)
girivkmmm@gmail.com

***Abstract*—** The mathematical modeling of solar photovoltaic system is accurate model is essential due to highly demand of electric energy and problem due to conventional thermal power plant recently, more attention is given to solar photovoltaic based generation. PV model have complexity due to a lay of transcendental nonlinear expression. In this paper proposed a simplified solar PV model is constructed by using simple computational block and a current controlled source. The proposed technique is neglects the nonlinearity equation. Hence, simple computational blocks are used. The performance of simplified model of solar photovoltaic is proposed for MPPT system has been critically analysed. Based on above design methodologies, a PV module of maximum voltage 32.9V, maximum current 8.2A and maximum power 200W is simulated. Solar PV panel output depends on the temperature and insolation. In addition, a power electronic circuit is needed to connect the solar PV output for boost the voltage. A boost DC to DC converter circuit is modeled for simulation and implementing algorithms P&O and IncCond. The work deals with solar PV panel to operate at MPP and improves efficiency of photovoltaic system applications.

Keywords*— *Solar Energy, Equivalent circuit, MPPT algorithm, DC to DC converter

I. Introduction

Renewable source is most important due to higher demand of electricity and reduction of coal, fossil fuel etc. for power generation [1]. The solar PV technologies is more increasing in generation of electric power, providing noise less, pollution free and secure power source. In last decade, various research has been carried out the power generation of renewable source [2]. Renewable source provides electric power generation is globally but due to unpredictable nature. The solar PV modeling is more essential for extraction of energy from sun. A wide range of atmospheric appearance photovoltaic (PV) modules operates, but Standard Test Condition (STC) electrical parameter provided by datasheets of manufacturing [3-4]. A studies control technique of photovoltaic simulation to succeed MPPT techniques.

Photovoltaic (PV) system designers need easy-to-implement and a reliable model to estimate photovoltaic (PV) energy generation under different insolation and temperature conditions [5]. Photovoltaic (PV) equivalent circuit can be categorized into three types.

- Fig. 1 shows the ideal single diode model (ISDM) is simplest and first model [2]. ISDM does not assurance a perfect characteristic at the maximum power point (MPP) due to its simplicity [6].

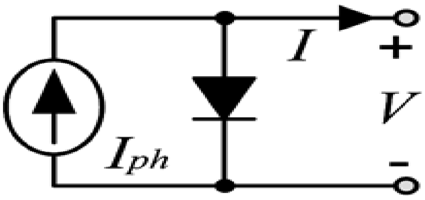

Fig. 1. Equivalent circuit of ISDM

- Fig. 2 shows the single-diode model (SDM) is mostly used for studies of photovoltaic. For simulation model it has five parameters essentially to spring the photovoltaic system. By iteration, method solving nonlinear equation is obtained the five parameters [7]; otherwise it obtained characteristic conflict provided by the manufacturer datasheet by tuning the some parameters [2].

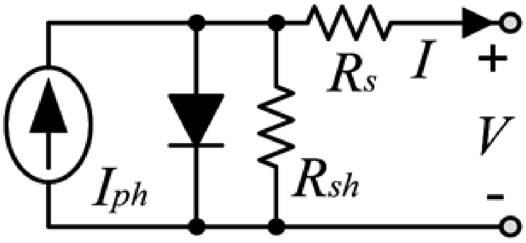

Fig. 2. Equivalent circuits of SDM

- SDM requires a numerical solver because output current is the function of both voltage and current i.e. I = f(V, I) and output voltage is the function of both current and voltage i.e. V = f(I,V) for implementation of simulation [4].

Fig. 3 shows the simplified single diode model (SSDM) by eliminating shunt resistance of single diode model (SDM) to reduce the complexity [8-9].

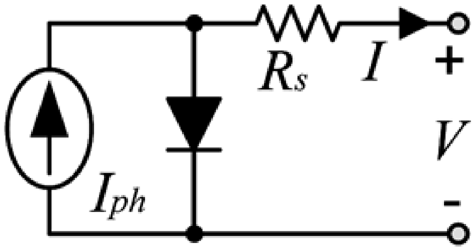

Fig. 3. Equivalent circuit of SSDM

In this paper, a proposed technique for photovoltaic (PV) modeling is adds the advantages of ISDM and SDM models which include easy of modeling, accuracy and simplicity. This technique relies to developed two newly mathematical expressions, developed to calculate photovoltaic (PV) parameters, for the ISDM. The implemented two most common algorithms (P&O and IncCond) to evaluate the performance of SSDM for maximum power point tracking. SSDM mathematical model has been simulated to analyze the characteristics of the SSDM. A step-up DC to DC power converter is used. The main criteria of step-up power converter selection has been appropriateness for applications of grid interfaced system. The parameters of photovoltaic (PV) module consider for comparison are input voltage, maximum power and efficiency.

II. MODELING BLOCKS OF SYSTEM COMPONENTS

Fig. 4 shows the main component of modeling system and performance evaluation for maximum power point tracking algorithm [10].

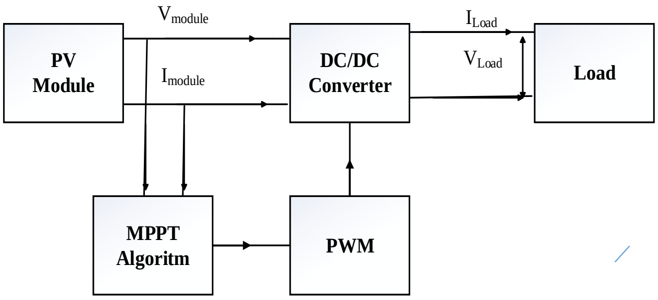

Fig. 4. Model of system components

A. *Calculations of the Parameters of Photovoltaic (PV) Model from Data Sheet*

The generalize Eqn. of current voltage of a photovoltaic model is [11]:

$$i = I_{ph} - I_0 \left(e^{\frac{v+iRs}{Ns\ V_t}} - 1\right) - \frac{v+iRs}{Rsh} \quad (1)$$

Thermal voltage: $V_t = \frac{AkT_{STC}}{q}$

Where;

Photo generated current in standard temperature condition: I_{ph}

Dark saturation current in standard temperature condition: I_o

Series resistance: Rs

Shunt resistance: R_{sh}

Diode ideality factor: A

Boltzmann constant: k

Charge of electron: q

Total number of cells in series: N_s

Temperature at STC: T_{STC}

A. *Proposed PV Modeling Technique*

The photovoltaic (PV) module characteristic Eqn. I-V is given by connecting series Ns cells as:

$$i = I_{ph} - I_0 \left(e^{\frac{v+iRs}{Ns\ V_t}} - 1\right) - \frac{v+iRs}{R_{sh}N_s} \quad (2)$$

Reducing the number of unknowns, some parameters was assumed. Unfortunately, overall model accuracy affected. By eliminating complexity of circuit, inflict by (2) the proposed technique will give the ideal single diode model presented in (3)

$$i = I_{ph} - I_0 \left(e^{\frac{qV}{k\,A\,T\,N_s}} - 1\right) \quad (3)$$

Ideal single diode model has three I_{ph} , I_0 and A unknown parameters.

I_{ph} is calculated from datasheets of manufacturer, are as follows:

$$I_{ph} = G\,(I_{sc} + \alpha \vartriangle T) \quad (4)$$

Where;

Irradiance (kW/m): G,

Temperature difference between module and standard condition temperature: $\vartriangle T$

Temperature coefficient of current: α

By first setting expression is derived as follows:

$$V_{OC}(G,T) - V_{OC}(G,T_{STC}) = -|\beta| \vartriangle T \quad (5)$$

Where;

At a certain temperature voltage at open circuit: $V_{OC}(G,T)$

At the Standard temperature condition open circuit voltage: $V_{OC}(G,T_{STC})$

For specific irradiance level.

Absolute value of the coefficient of voltage temperature: β

In (3) putting $i = 0$, the voltages open circuit (V_{OC}) is calculated as follows:

$$V_{OC} = \frac{N_s kTA}{q} \ln\left(\frac{I_{ph}}{I_0} + 1\right) \quad (6)$$

So

$$V_{OC}(G,T) = \frac{N_s kTA}{q} \ln\left(\frac{G\,(I_{sc} + \alpha\vartriangle T)}{I_0} + 1\right) \quad (7)$$

And

$$V_{OC}(G,T_{STC}) = \frac{N_s kT_{STC}A}{q} \ln\left(\frac{G\,(I_{sc} + \alpha\vartriangle T)}{I_0} + 1\right) \quad (8)$$

Eq. (7) and (8) substituting in (5)

$$\frac{N_s kTA}{q} \ln\left(\frac{G\,(I_{sc} + \alpha\vartriangle T)}{I_0} + 1\right) - \frac{N_s kT_{STC}A}{q} \ln\left(\frac{G\,(I_{sc} + \alpha\vartriangle T)}{I_0} + 1\right) = -|\beta| \vartriangle T \quad (9)$$

I_0 can be obtained by rearranging (9)

$$I_0 = \frac{e^{\frac{|\beta|\vartriangle Tq}{N_s kTA}} G\,(I_{sc} + \alpha\vartriangle T)}{(G\,I_{sc}/I_{ro} + 1)^{\frac{T_{STC}}{T}} - e^{\frac{|\beta|\vartriangle Tq}{N_s kTA}}} \quad (10)$$

Where

Saturation current at Standard Test Condition: I_{r0}

I_{r0} can be calculated as follows (3);

$$I_{r0} = \frac{I_{sc}}{[e^{\left(\frac{qV_{oc}}{N_s k T_{STC} A}\right)} - 1]} \quad (11)$$

Under Standard Test Condition (STC), (3) is expressed at Maximum Power Point V_m and I_m as follows;

$$I_m = I_{sc} - I_{ro}[e^{\left(\frac{qV_m}{N_s k T_{STC} A}\right)} - 1] \quad (12)$$

The unknown parameter "A" can be obtained by putting (11) into (12) and for maximum power point solving the equation of V_m and I_m. Eqn. obtained (12) can be modified as;

$$\frac{I_m}{I_{sc}} = e^{\left(\frac{qV_m}{N_s k T_{STC} A}\right)} - \left(\frac{I_{sc} - I_m}{I_{sc}}\right) e^{\left(\frac{qV_{oc}}{N_s k T_{STC} A}\right)} \quad (13)$$

The photovoltaic parameters from datasheet and the expression of (10) and (13) will be substituted in (3) to obtain the photovoltaic model of simulation.

B. Block Model for Proposed Technique

The block model of proposed technique for photovoltaic (PV) model is presented in Fig. 5.

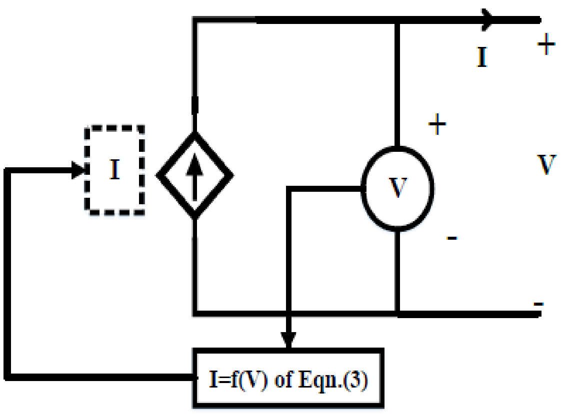

Fig. 5. Proposed model of Simplified single diode PV cell

So, proposed technique is using to constructing a simulation model is easy and simple because output current is a function of only voltage shown in Fig. 5. The proposed technique neglects the nonlinear equation solver. Hence, mathematical simple blocks are required. The proposed modeling simulation results are presented in Fig. 6.

The simulation results has been verified and shows the efficacy of the proposed modeling technique.

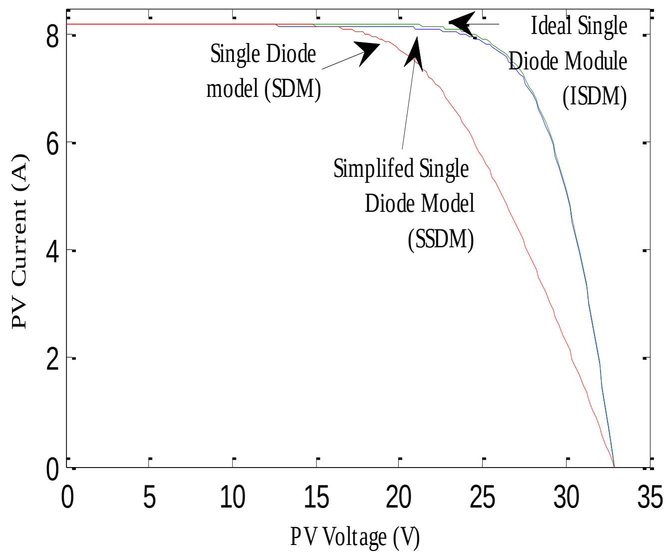

Fig. 6. Comparison of curves above the three modeling technique

C. MPPT Techniques

For efficiency improvement and development methods have been considered by numerous researchers and number of MPPT techniques has been proposed [7]. Solar photovoltaic system is operating at its MPP (P_{max}) the common principle of operation of these methods is that all of them enhance the system efficiency. In mentioned methods, P&O and IncCond algorithm is greatest application for MPP. Above both algorithm, operating principle is briefly described in this section.

D. Perturb & Observe (P&O) Algorithm

P&O algorithm is "Hill-Climbing" MPPT techniques. P&O algorithm tracks the MPP of the solar PV module with respect to the sign of $\frac{dP}{dV}$. Fig. 7 shows the variation of $\frac{dP}{dV}$ on voltage and power characteristic of solar photovoltaic module.

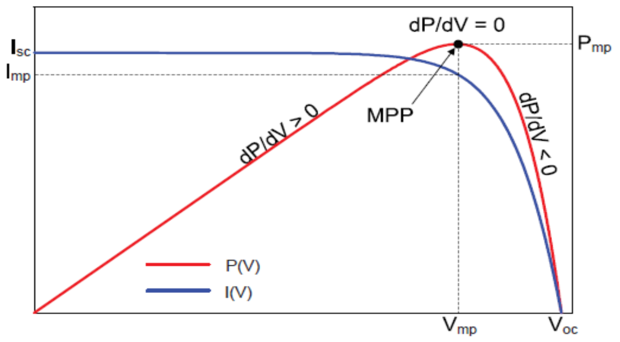

Fig. 7. Variation of $\frac{dP}{dV}$ characteristic of solar photovoltaic module

The flowchart of the P&O for MPPT techniques is presented in Fig. 8.

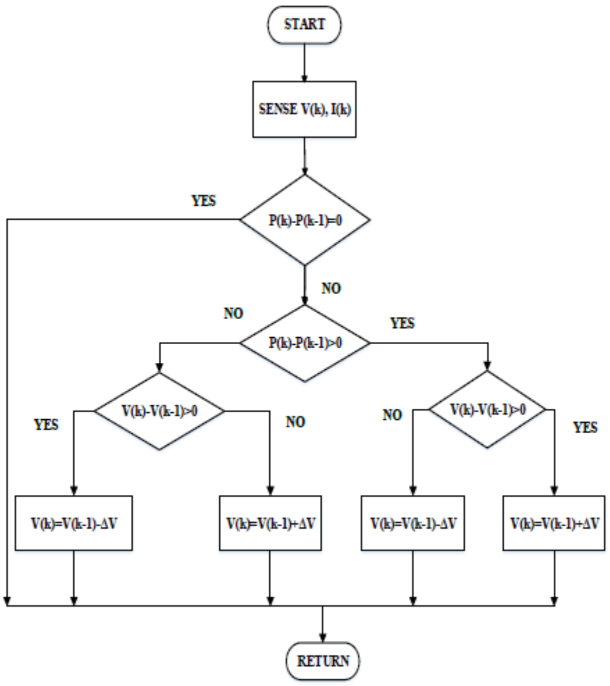

Fig. 8. Flowchart of the P&O for MPPT techniques

E. Incremental Conductance (IncCond) Algorithm

An improvement in the Perturb & Observe algorithm introduced as another "Hill-Climbing" is IncCond algorithm. The MPP tracking by IncCond algorithm is comparing the current-voltage characteristics of the module and its incremental conductance $\frac{dI}{dV}$ using by the following (14) and (15),

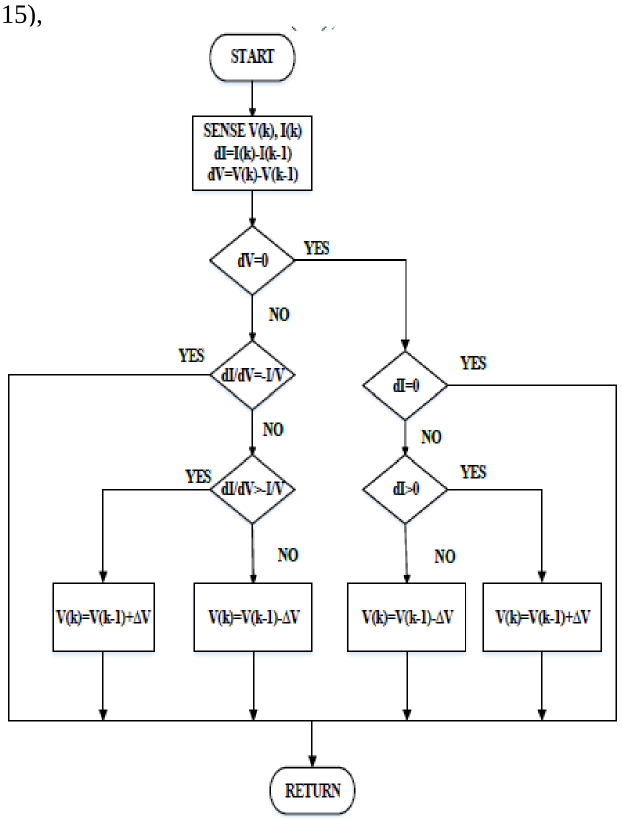

Fig. 9. Flowchart of the IncCond for MPPT algorithm

$$\frac{dP}{dV} = \frac{d(IV)}{dV}$$

$$= I + V\frac{dI}{dV} \qquad (14)$$

$$\left|\frac{dP}{dV}\right|_{I=Im,\ V=Vm} = 0; \left|\frac{dP}{dV}\right|_{I=Im,\ V=Vm} = -\frac{Im}{Vm} \qquad (15)$$

Where; V_m - MPP voltage of the array

I_m - MPP current of the array

The Incremental Conductance uses the photovoltaic array's incremental conductance $\frac{dI}{dV}$ to compute the sign of $\frac{dP}{dV}$. It does this using an expression derived from the condition, at the MPP, $\frac{dP}{dV} = 0$. Beginning with this condition, it is possible to show that, at the MPP $\frac{dI}{dV} = -\frac{I}{V}$ [7]. Fig. 9 shows the flowchart of the IncCond for MPPT techniques.

F. Boost DC to DC Power Converter

In this paper boost DC to DC power converter is used for suitability for interfaced inverter tied grid. Fig. 10 shows the electrical circuit diagram of boost DC to DC power converter. From Fig. 10, it is clear that boost power converter circuit composed of a switch, inductor, diode and capacitor.

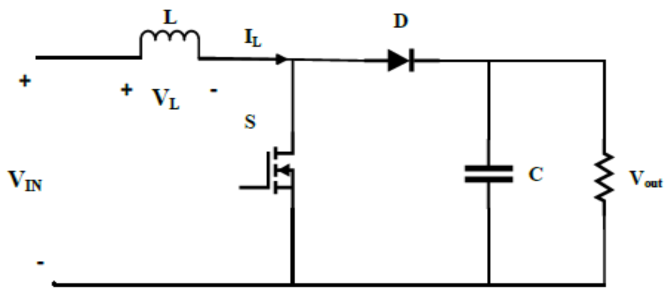

Fig. 10. Electrical circuit of boost DC to DC power converter

This power converter boost DC to DC is operates in the two different modes [11]:

In the 1st mode of operations, switch 'S' is turned on by gating positive pulse in gate i.e. t = T_{ON} and current rising to flow through inductor through switch and inductor is charged i.e. inductor is stored energy.

In the 2nd mode of operations, switch 'S' is turned off by gating negative pules in gate i.e. t = T_{OFF} and current is flows from the inductor, diode, capacitor and load. In this duration current of inductor, falls until the next cycle of operation is begin. The stored energy in inductor is transferred to the load.

Output voltage can be described in terms of input voltage by the following Eq. (16),

$$V_O = \frac{V_{in}}{(1-\alpha)} \qquad (16)$$

Where, α = Duty cycle

III. MODELING OF MPPT ALGORITHM

The modeling of proposed MPPT algorithm is P&O and IncCond algorithm. For maximum power point tracking, these two algorithm are constructed by using explained flowcharts as in Fig. 8 and Fig. 9 respectively. P&O algorithm simulation is shown in Fig. 10, and IncCond algorithm simulation is shown in Fig. 11.

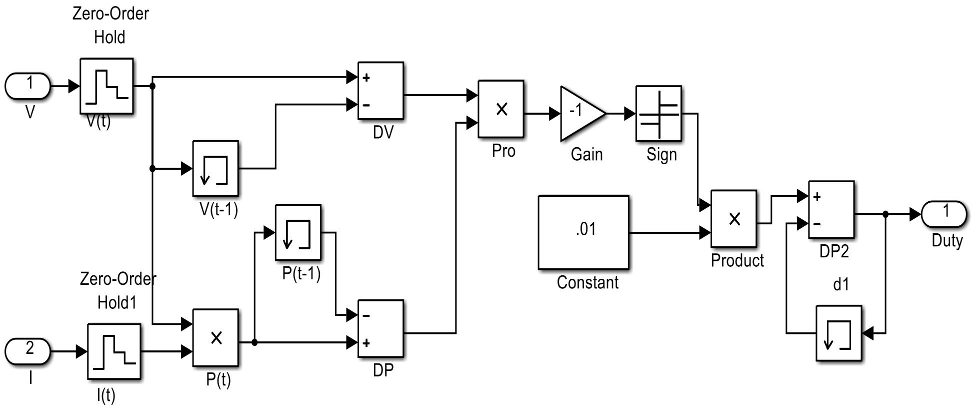

Fig. 11. Model of Perturb & Observe for MPPT algorithm

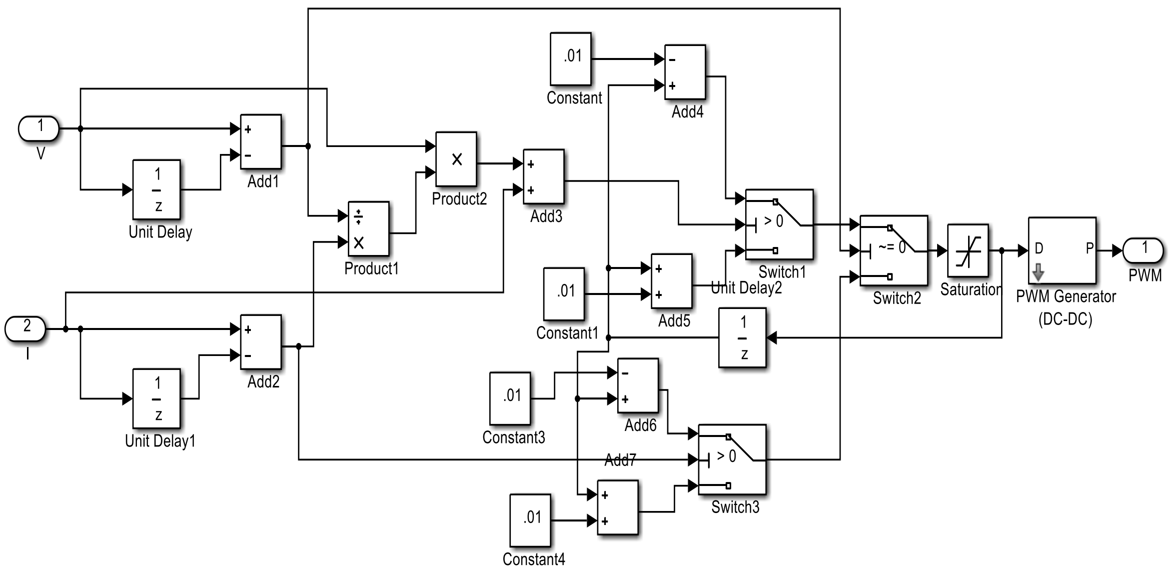

Fig. 12 Model of Incremental Conductance maximum power point tracking algorithm

IV. SIMULATION RESULTS AND DISCUSSION

This research paper has carried out the simulation with both Perturb & Observe and Incremental Conductance for MPPT algorithms. The Matlab/simulation model is run for 0.1 second under standard temperature condition (Ambient Temperature = 25^0 C and G = 1000 W/m^2,). Emphasize the value and improving effects of maximum power point tracking application and simulation results are compared with algorithms carried out from simulation model.

A model of boost DC to DC power converter using Perturb & Observe for MPPT techniques and complete model is presented in Fig. 13.

Model of boost DC to DC power converter using Incremental Conductance for maximum power point tracking algorithm is shown in Fig. 14.

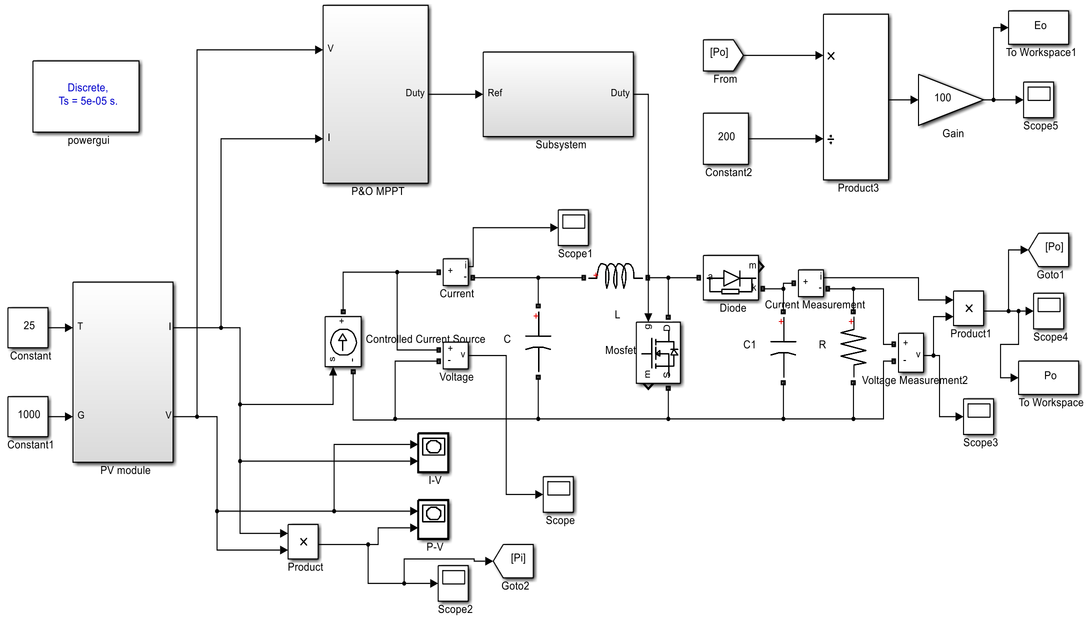

Fig. 13. Model of boost DC to DC converter using Perturb & Observe for MPPT algorithm

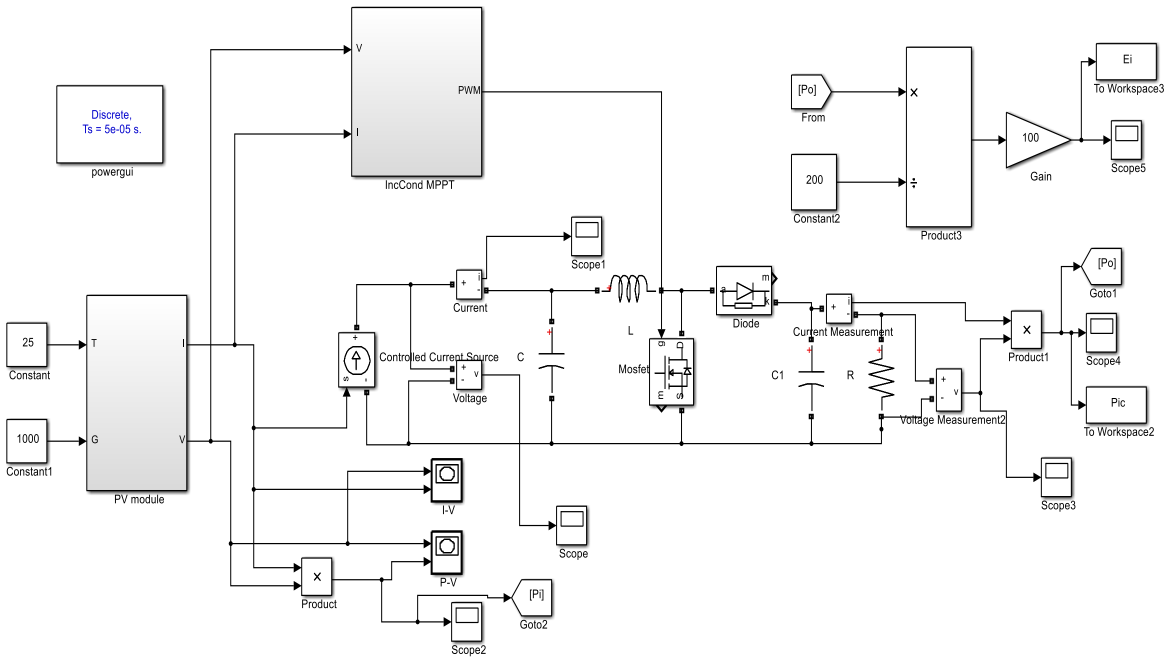

Fig 14. Model of boost DC to DC power converter using Incremental Conductance maximum power point tracking algorithm

From results, it is clear that the both algorithms have same power delivered to the load but Incremental Conductance algorithm output power has been slightly higher than the Perturb & Observe algorithm.

The evaluation of efficiency and comparison is performed by given Eq. (17),

$$\eta = \frac{Pout}{Preal} \qquad (17)$$

Where,

P_{real} = Under test condition available maximum power

The simulation results of output power without and with MPPT algorithm and their efficiencies of the MPPT algorithms for both Perturb & Observe and Incremental Conductance are presented in Fig. 15 & Fig. 16 respectively.

The operating point of SSDM with Incremental Conductance method represents the right side of the maximum power point while the Perturb & Observe method operates the SSDM at the left side of the maximum power point are presented in simulation results in Fig. 15. Fig. 15 is also shows the operating point without application of MPPT technique of open circuit.

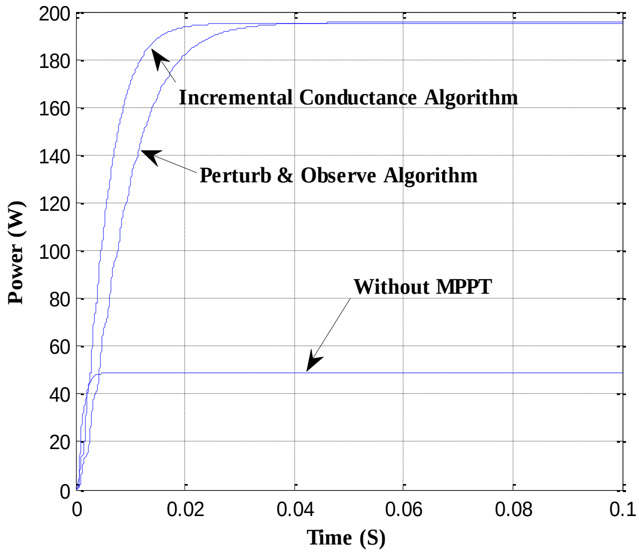

Fig. 15. Output power with and without MPPT Algorithm

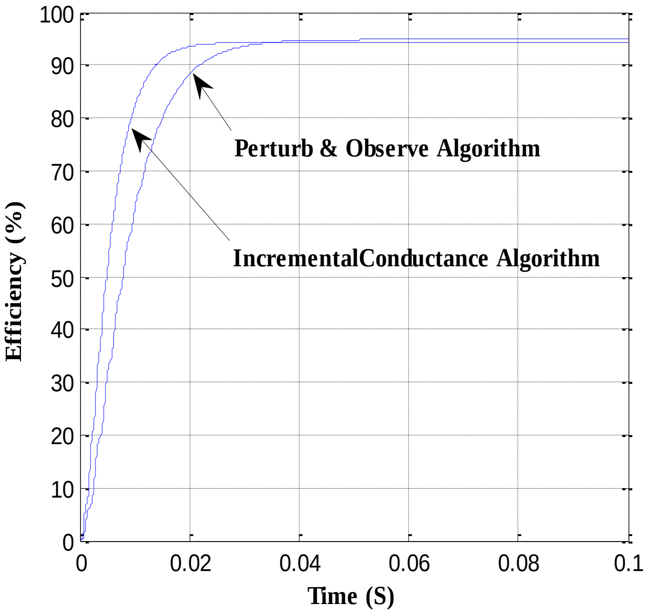

Fig. 16. Efficiency of MPPT Algorithm

Simulation result presented in Fig. 16 shows the efficiency for both of the algorithms is more than 92%. From Fig. 16 is cleared that the Incremental Conductance method efficiency is slightly more than Perturb & Observe method. In addition, Incremental Conductance method has shorter duration (0.02 Sec.) to reach the maximum point.

TABLE I. Simulation Result (Numerical value)

Parameter	P&O Algorithm	IncCond Algorithm	Without MPPT
V_{in} (V)	32.9	32.9	47
P_{max} (W)	198.6	198.9	48.55
Efficiency (Ƞ%)	94.49	95.56	22.10

Table I. shows the numerical data for simulation results of both the algorithm (P&O and IncCond). From simulation results, it is cleared that the both algorithm having some merits and demerits, but in tracking system both algorithm simultaneously to tracks the maximum power point of the SSDM modules. Depending on the application requirement and environmental appearance MPPT techniques can compare and control the outputs of the both algorithm and use the proper in circumstances MPPT techniques. Therefore, most reliable and efficient control can be given to take the merits of each individual MPPT techniques under application requirements and environmental conditions.

V. CONCLUSIONS

In this research paper proposes an intended technique to modeling of photovoltaic modules.The Perturb & Observe method is the simplest maximum power point tracking (MPPT) techniques. The Incremental Conductance algrithm is an improvement to the Perturb & Observe method and it has a quite complex structure. The results of simulation verified under identical insolation conditions both of the methods have nearly same efficiencies greater than 92%. The presented simulation results, shown slightly better performance by Incremental Conductance method in tracking the maximum power point tracking of the simplified single diode model (SSDM). It is shown in simulation results, the Incremental Conductance method output power has reached at maximum power point (MPP) in short time duration (0.02 sec.) as compared with the Perturb & Observe algorithm which takes more time duration (0.03 second). The high tracking and its simple structure efficiency makes the Perturb & Observe method is to be more preferable one and can utilize MPP tracker for SSDM module.

REFERENCES

[1] M. G. Villalva et al., “Comprehensive approach to modeling and simulation of photovoltaic arrays”, *IEEE Trans. Power Electron*., vol. 24, no. 5, pp. 1198–1208, May 2009.

[2] D. Sera et al., “PV panel model based on datasheet values”, *in Proc. IEEE Int. Symp. Ind. Electron.,* 2007, pp. 2392–2396.

[3] J. David et al., “Maximum power point tracking architectures for photovoltaic systems in mismatching conditions: a review”, *IET Power Electron.*, 7(6), 1396–1413, 2014.

[4] W. Xiao et al., “Real-time identification of optimal operating points in photovoltaic power systems”, *IEEE Trans. Ind. Electron.*, vol. 53, no. 4, pp. 1017–1026, Jun. 2006.

[5] R. F. Coelho et al., “Analytical and experimental analysis of DC-DC converters in photovoltaic maximum power point tracking applications”, *Proc. IECON, IEEE Press*., Nov. 2010.

[6] W. D. Soto et al., “Improvement and validation of a model for photovoltaic array performance”, *Solar Energy*, vol. 80, pp. 78–88, 2006.

[7] Shu-Hung et al., “A novel maximum power point tracking technique for solar panels using a SEPIC or cuk converter”, *IEEE Trans. on Power Electron*., vol. 18, May 2003.

[8] Wies et al., “Simulink model for economic analysis and environmental impacts of a PV with diesel-battery system for remote villages,” *IEEE Trans. on Power Sys.*, vol. 20, May 2005.

[9] S. B. Kjaer, “A review of single-phase grid-connected inverters for photovoltaic modules*,” IEEE Trans. on Ind. Appl.,* vol. 41, Oct 2005.

[10] A. K. Abdelsalam,et al., “High-performance adaptive perturb and observe MPPT technique for photovoltaic-based microgrids,” *IEEE Trans. Power on Electron.*, vol. 26 [4], Apr. 2011.

[11] P. Chaitanya et al., “Development of hybrid smart grid system using MATLAB/SIMULINK”, *Journal of Engg. Tech*., vol. 6, no. 2, pp. 548-563 Jul. 2018.