Modelling, Simulation of PV Array and MPPT Control in A Solar Microgrid

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Abstract - *In this paper, modelling, simulation, and analysis of Photovoltaic (PV) array is done with the help of saturation current, reverse saturation current, photo current, shunt resistor current and output current. The power vs voltage (P-V) and current vs voltage (I-V) curve characteristics is also discussed. The power output from photovoltaic (PV) array has very low efficiency, so Maximum power point (MPPT) technique is used to get a better power performance. Boost converter is used to regulate the dc voltage across the PV system. Different maximum power point (MPPT) techniques which includes open loop as well as closed loop techniques, have been discussed. Two types of MPPT algorithms are also discussed which are perturb and observe (P&O) and Incremental conductance technique. A brief comparison of both algorithms is done, and it is found that Incremental conductance technique is comparatively a better algorithm owing to its speed and accuracy. The effect of irradiation and temperature change is seen on Maximum power point (MPPT) power.*

Key Words: PV array, MPPT, Perturb and observe, Incremental conductance, Boost converter, PV control.

1. INTRODUCTION

In the present scenario there is an immense need of renewable source of power generation, and for that solar microgrid is one of the best suitable option. The PV microgrid has basically four components namely PV array, PV control, Inverter, and Inverter control. So, this paper deals with the modelling and realization of PV array and PV array control techniques. SIMULINK modelling of PV array and various MPPT techniques along with the boost converter in a 100KW PV microgrid system is discussed.

The gross installed capacity of solar power has risen to 3.883 GW, according to the Ministry of New and Renewable Energy's 2015 survey. According to the International Energy Agency (IEA), solar photovoltaic systems can provide 16 percent of the world's electricity by 2050 [19].

There has lately been increased anxiety over the loss of fossil fuel stocks. The application of distributed energy resources deployment (DER) has exploded around the world. Solar energy is the most accessible, cleanest, and readily available source of DERs. Integrating a photovoltaic generation unit poses a number of concerns, mostly due to the scholastic design of the unit, issues with power electronics converters, controls, and grid synchronization issues. Solar power also has the disadvantage of varying performance with changes in environmental conditions such as solar irradiation and temperature. As a result, modelling and simulation studies are needed to investigate its power, dynamic properties, transient efficiency, and interaction with the network and load [20].

In this paper, the modelling of PV array is done from the scratch with the help of set of equations which are equations of photocurrent, saturation current, reverse saturation current, shunt resistor current, and output current, in SIMULINK. Mathematical modelling of equation is done, and a subsystem is made of that, and similarly using all the five sets of equations in table (1), and modelling them into SIMULINK, PV array of 200 W is developed. This PV array can now be connected in series and parallel to get the desired value of power. The final PV array model which consists of several subsystems each representing a unique equation out of the set of equation in table 1, has two inputs and two outputs. Irradiance and temperature are its two inputs and dc voltage, and current are its outputs. With the help of PV array outputs, dc voltage and current, the graph of P-V and I-V curve is obtained. From the graph MPP power, voltage and current is also obtained. A detailed analysis of the structure of PV cells, equivalent circuits of solar cells, and characteristics of PV array is also done. The control techniques and mechanism of PV array is discussed. The power obtained from the PV array has very low efficiency, so, to fully utilize the power of PV array, MPPT along with the boost converter is used. Using MPPT technique, the power quality of PV array is enhanced. Since the dc voltage coming from PV array is very low, boost converter boosts the dc voltage and regulates it in the system to match the load characteristics.

Different MPPT techniques and algorithms are used. Firstly, both open loop and close loop techniques are used. Close loop technique uses PI controller to generate the required duty ratio and gives a more improved MPPT tracking performance, since it is a close loop control mechanism. The dc voltage and dc current from PV array is fed to the MPPT algorithm. Here, two different algorithms are used Perturb and observe (P&O) and Incremental conductance technique. The MPPT algorithm produces required duty ratio for PWM generation. The PWM generator then gives the required gate pulse which is fed to the gate terminals of IGBTs of the boost converter to get the desired MPPT value. A comparative study of the two MPPT algorithms is discussed which are P&O and Incremental conductance technique. They both have their own benefits and drawbacks. While P&O checks the difference of power, incremental conductance checks both voltage and current. Incremental conductance technique is a faster and more precise technique than P&O but is more complex than P&O technique. The effect of irradiation and temperature on the performance of PV array is also discussed. On increasing the irradiation, power increases and on decreasing the irradiation, power decreases. The increase in temperature over certain limit can also cause the power to decrease.

This paper is organized as follows, in section 2, the structure of PV cells, mathematical modelling of equations involved in modelling of PV cells, equivalent circuit of solar cells and the characteristics of PV array is discussed. In section 3, control techniques and mechanism of PV array is discussed. Various MPPT algorithms and their comparative analysis is done along with the designing of boost converter. In section 4, SIMULINK modelling of PV array with MPPT and boost converter is done. Section 5, discusses the results of the SIMULINK models. The graph of PV and IV is shown and variation of power from MPPT on changing the temperature and irradiance is discussed.

2. PV ARRAY

The solar PV module is made up of multiple solar cells that are connected in series and parallel in a panel to produce electricity from sunlight.

In this section, working of solar cells and its equivalent model is discussed in detail.

2.1 Solar Cell Structure

To generate electricity from sunlight, a solar PV module is made up of several solar cells linked in series and parallel in a panel.

Here are the basic steps which are involved in the working of solar cells.

i. Light-generated carriers, such as electrons and holes, are produced when incident photons from solar rays are absorbed by semiconductor materials, such as silicon (Si). As a consequence, if the incident photon has a higher energy than the band gap energy, electron–hole pairs are formed.

ii. The p-n junction attracts electron hole pairs, i.e., light-generated carriers, in order to create a current. The p-n junction already has an electric field. As a result, it removes the electrons from the n-type zone and the holes from the p-type field, preventing them from recombining.

iii. The charge carriers are collected at the contacts, resulting in a high voltage being produced through the solar cell. The load and parasitic resistances both lose some strength.

2.2 Equivalent Circuit Model

The I-V curve can be used to demonstrate the output of a solar cell by comparing its current and voltage. The I-V curve is a superposition of the solar cell diode's I-V curve in the dark with the current provided by illumination. The IV curve of a solar cell as seen in Figure 1.

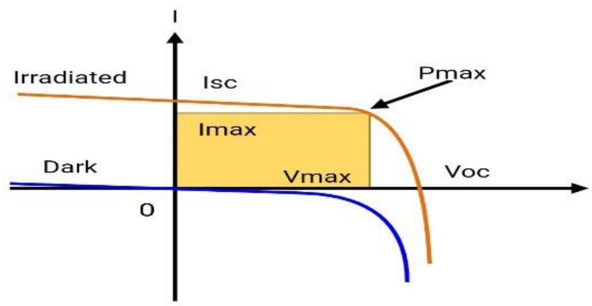

Fig.1. Common I-V curve in a solar cell.

In the dark, the I-V curve of a solar cell has an exponential characteristic, like that of diode under no illumination.

$$I_D = I_{dark} = I_O \exp\,(q_v/K_B T) \qquad (1)$$

Under forward bias conditions, the solar cell can emit current while blocking current under reverse bias conditions.

The I-V curve changes as the solar cell generates electricity, as the solar cell conducts additional current relative to the light excited charge.

The above explained behavior of solar cell can be described as an electrical circuit as shown in Fig 2 and Fig 3.

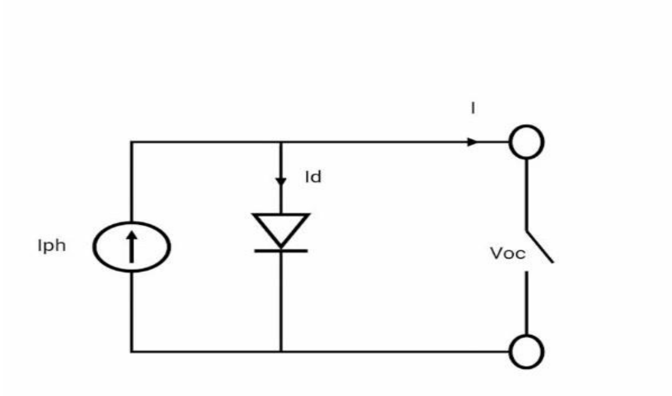

Fig.2. Equivalent circuit model of an ideal solar cell under open circuit voltage.

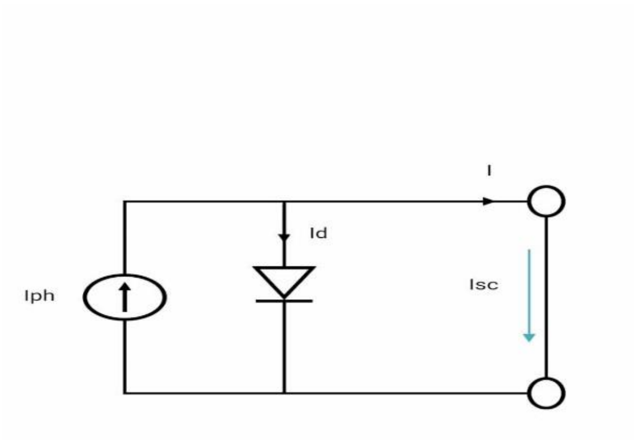

Fig.3. Equivalent circuit model of an ideal solar cell under short circuit condition.

A current source (Iph) represents the photocurrent, and a triangular shaped symbol represents the diode of a solar cell in the dark (Id). The open circuit voltage is generated when the circuit is open, that is, when there is no load attached to the cell and it is just generating voltage but no current (Voc). When the solar cell's external circuit is attached in a short circuit with no external resistance, the cell emits current but no voltage, which is known as short circuit current. Both Voc and Isc are critical in determining the I-V characteristics curve. The multiplication of the voltage and current at any point on the I-V curve is the solar cell's power. The maximum power point monitoring (MPPT) can also be determined using the I-V curve [5]. The solar module must run at full capacity since this is the power that is supplied to the rest of the PV system and, ultimately, to the load. The voltage and current at which MPP is reached is another critical parameter that determines the solar module's characteristics. The IV and PV curves of a solar cell are seen in Figure 4 [4].

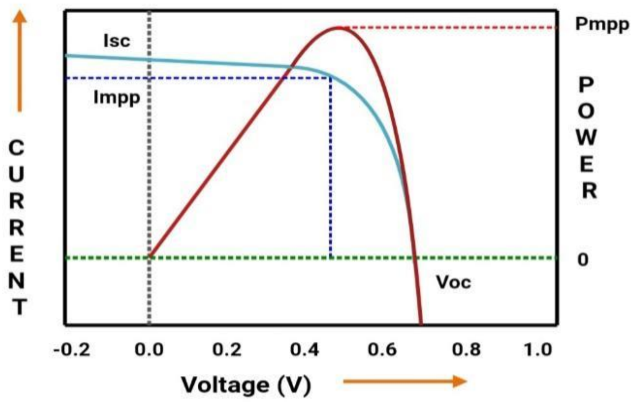

Fig.4. I-V and P-V curve of a solar cell.

2.3 Photovoltaic System Modelling

A more accurate electrical circuit of a solar cell is shown in Fig 5, with parasitic resistances, and this is the circuit which we would consider while modelling [1]. The equation for electrical circuit by applying Kirchhoff's law is: -

$$I = I_L - I_D - I' \quad (2)$$

$$I = I_L - I_O \exp\left[\frac{q(V+IR_S)}{nKt}\right] - V + IR_S/R_{sh} \quad (3)$$

Where I_L, I_O, I_D, I, R_S, R_{sh}, V, q, n, K, t is line current, saturation current, diode current, series resistance, shunt resistance, output voltage, charge, identity factor of diode, Boltzman's constant, working temperature respectively [3].

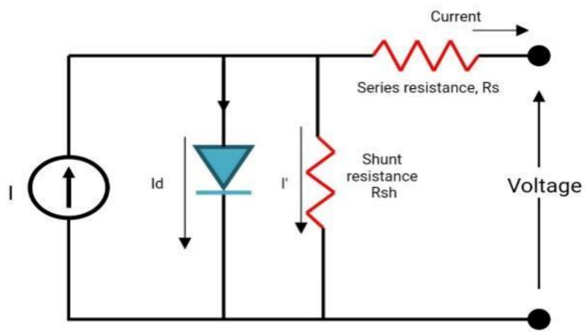

Fig.5. Equivalent circuit of a non-ideal solar cell.

To model the PV array in SIMULINK basically five equations are used, with the help of which solar module is designed, which are equations of photo current (Iph), saturation current (Io), reverse saturation current (Irs), shunt resistor current (Ish), and with the help of all these four equations, output current(I) of the PV array is obtained [4]. Given below in the table 1 are all the five set of equations required for PV modelling [3].

Table -1: The set of equations used in PV array modelling.

Current Parameters	Current Equations
Photo current	$I_{ph} = [I_{sc} + K_I(T - 298)]G/100$
Saturation current	$I_O = [I_{rs}\left(\frac{T}{T_n}\right)^3 \exp\,[qE_{go}\left(\frac{1}{T_n} - \frac{1}{T}\right)]/nK$
Reverse saturation current	
Shunt resistor current	$I_{sh} = [(V + IR_S)/R_{sh}$
Output current	$I = I_{ph} - I_O[\exp\left(\frac{q(V+IR_S)}{nK\,N_S T}\right) - 1] - I_{sh}$

Table -2: The values of constants used in table 1.

Symbols	Description	Values
K_i	Short circuit current of cell at 25⁰C and 1000W/m²	0.0032
T_n	Nominal temperature (K)	298
q	Electron charge (C)	$1.6*10^{*-19}$
n	The identity factor of diode	1.3
K	Boltzman's constant (J/K)	$1.38*10^{-23}$
E_{go}	Band gap energy of semiconductor (eV)	1.1
R_S	Series resistance (Ω)	.221
R_{sh}	Shunt resistance (Ω)	415.405

3. CONTROL OF PV SYSTEM

In photovoltaic cells, the efficiency of converting solar energy into electrical energy is very poor. It's important to have as much electricity back as possible. To do this, the PV system must run at maximum power point (MPP), which necessitates the use of an MPPT (Maximum power point tracker) in conjunction with the boost converter [8]. The MPPT receives the DC voltage and current from the solar module as input, and the MPPT's output is the duty ratio, which is then fed to the PWM generator, and the PWM generator's output pulse is fed to the gate terminals of the DC-DC boost converter's IGBTs. The block diagram of MPPT operation of a PV system is shown in Figure 6. Figure 7 depicts a block diagram of a PV array, MPPT, and boost converter [1].

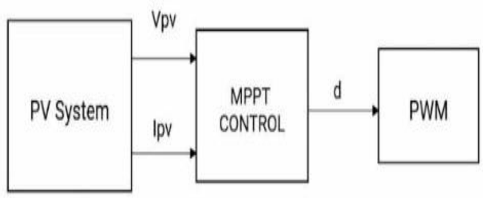

Fig.6. Block diagram of MPPT control of PV system.

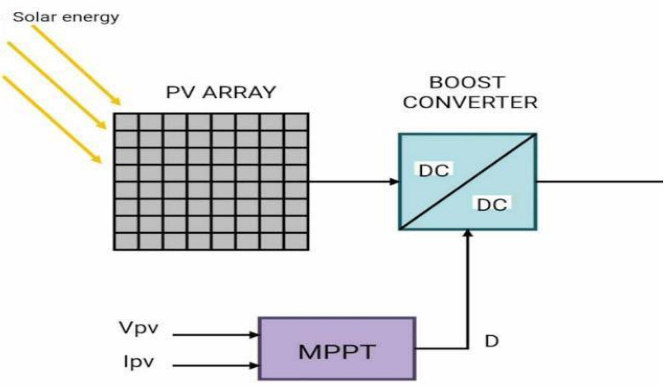

Fig.7. Block diagram of PV array and MPPT along with boost converter.

International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395-0056
Volume: 08 Issue: 05 | May 2021 www.irjet.net p-ISSN: 2395-0072

3.1 Design Of MPPT

The electrical energy converted by a conventional PV is only about 30 to 40 percent of the incident sunlight. On the other hand, the productivity of the PV array can be boosted by the medium provided by MPPT. Task of tracking the point of maximum power is summarized for the case of impedance matching. The converter's duty cycle when altered accordingly will result in matching of the load impedance with source and in this case Thevenin's impedance [1].

Here, MPPT is designed in three different ways, but the purpose of all methods will be achieving maximum power point.

In the first method, the voltage and the current from PV array is fed to the MPPT, a duty ratio is obtained as the output for the required PWM generation. This duty is compared with the carrier signal and is given to the gate terminal of MOSFET/IGBTs. Fig 8 shows the circuit diagram of MPPT and boost converter design by method one.

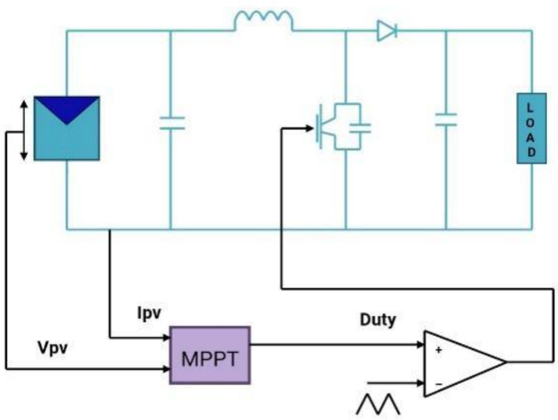

Fig.8. MPPT and boost converter design method one.

In the second method, the voltage and current is sensed from the PV array and fed to the MPPT. The MPPT generates reference voltage instead of a duty ratio in the first method, the reference voltage is compared with the actual voltage from the PV array and the error is fed to the PI controller. The PI controller generates the required duty ratio and is compared with the carrier signal and is then given to the terminals of MOSFETs/ IGBTs.

Compared to the first method, this method will give a more improved MPPT tracking performance since it is a close loop control mechanism. Fig 9 shows the circuit diagram of MPPT and boost converter design by method two.

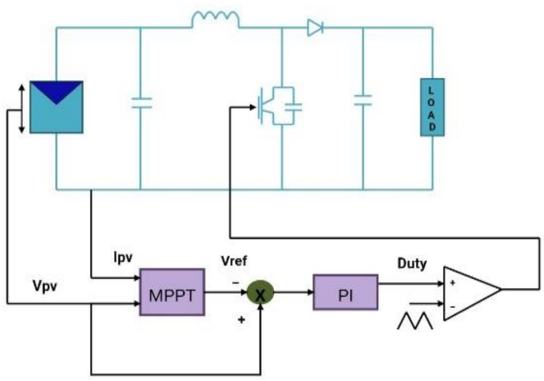

Fig.9. MPPT and boost converter design method two.

In the third method, voltage and current from the PV array is fed to the MPPT and MPPT gives a duty ratio as its output, that duty is then fed to the PWM generator and then the pulse of PWM is then given as a gate pulse to the DC-DC boost converter. But out of all the three methods, method two is the best approach since it uses close control mechanism. Fig 10 shows the circuit diagram of MPPT and boost converter design by third method.

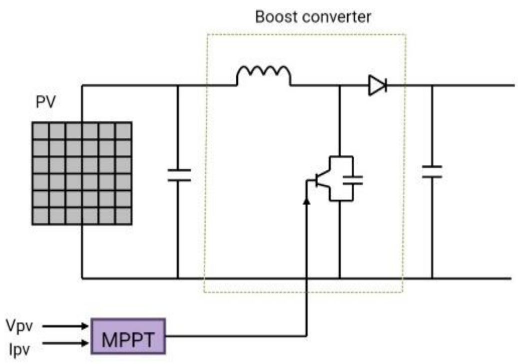

Fig.10. MPPT and boost converter design method three.

In order to choose algorithm for the selection of tracking techniques, one must keep in mind the various factors such as computation, complexity level, cost and effectiveness. Here, two methods have been discussed. One is Perturb and Observe (P&O) technique and the other is Incremental conductance technique. Both techniques have their own benefits and drawbacks, which is discussed in further sections.

3.2 Perturb and Observe Technique (P&O)

In this section the realization of the Perturb and Observe is discussed which can increase the efficiency of the solar energy using MPPT.

After measuring the current I(K) and voltage V(K), the power is determined using the formula P(K) = V(K)*I. (K). The new output power P(K) is equivalent to the previous output power [P(K-1)], where K-1 denotes the previous time and K denotes the current time.

The machine has a slight amount of Perturbation (ΔD), which results in a power shift in the PV module. As the power is increased by adding Perturbation, the Perturbation continues in the direction of (D+ΔD). When the power is increased to its maximum level, it reduces the next second. In the meanwhile, the Perturbation (D-ΔD) [5] began.

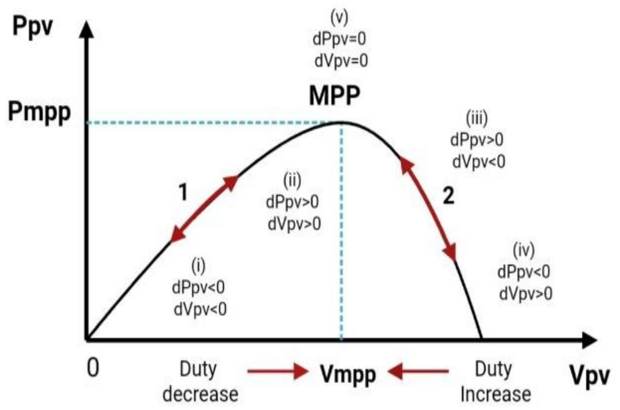

Fig.11. A PV graph showing the working of (P&O) technique.

In Fig 11, consider point 1, if the point is moved upwards from position 1 then the power and voltage increase but it has to reach the peak that is the maximum power point. So, to achieve that, duty is decreased. Similarly, when the point is moved below the original position, power is decreasing as well as voltage is decreasing so, in this case to achieve the peak voltage is increased. In the second half of the graph in Fig 11, at position 2, when point is moved above its original position, power is increased but voltage is decreased but it has to reach at the maximum power point so for that voltage is increased. Similarly, when point is moved downwards from its original position power is decreased and voltage is increased so to reach maximum power point duty is increased [5].

Here in the Fig 12, is the flow chart of P&O technique of MPPT algorithm.

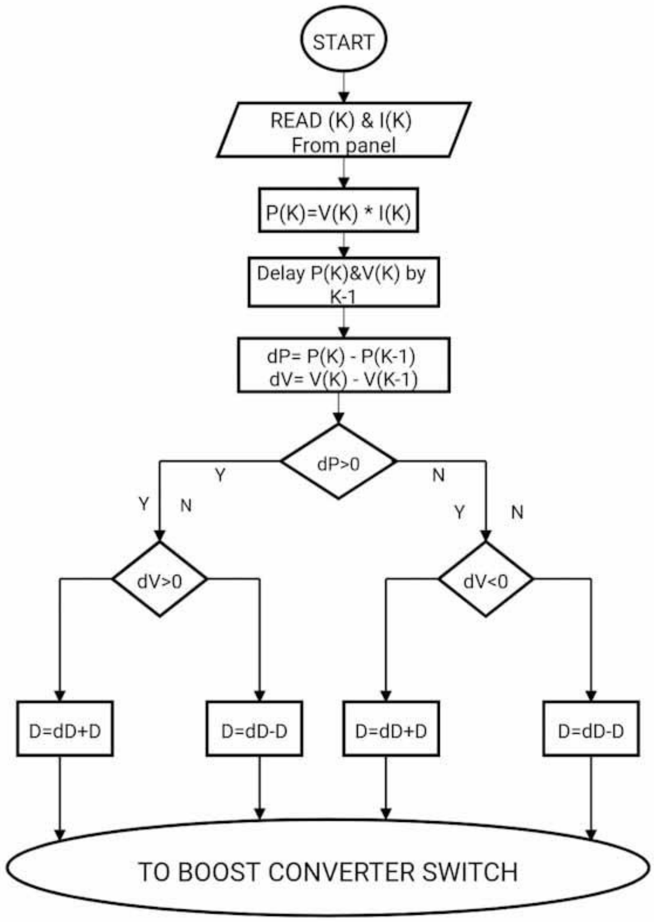

Fig.12. Flow chart of P&O algorithm of MPPT.

3.3 Incremental Conductance Technique

This is also a very good technique of MPPT algorithm. In this method, voltage and current is measured first and then difference in both voltage and current is checked parallelly. At First difference in voltage is checked and then the rate of change of voltage with respect to current is measured. Difference in current is also checked and accordingly reference voltage is adjusted.

Incremental conductance algorithm is a better algorithm than Perturb and Observe algorithm. Since in this method difference in both voltage and current is measured while in P&O algorithm only difference in power is seen so, incremental conductance is more precise and accurate, and it is faster than P&O algorithm since in this parallel operation is done and voltage and current is checked parallelly and step size change is less in it. In incremental conductance technique, MPPT is achieved faster than P&O method [8].

Here in this Fig 13, is the flow chart of incremental conductance algorithm.

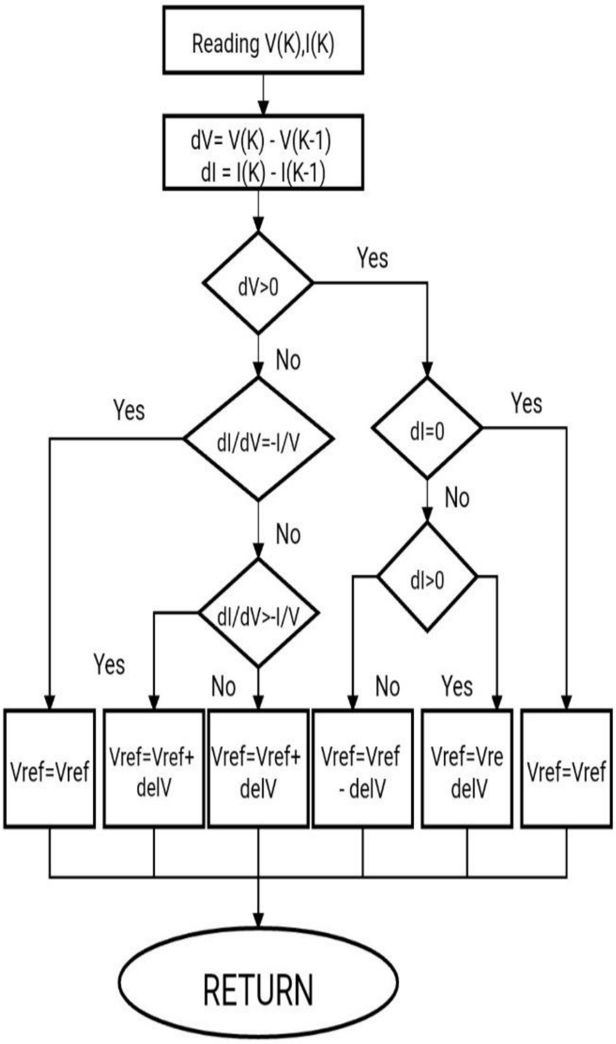

Fig.13. Flow chart of Incremental conductance technique.

3.4 DC-DC Boost Converter

Boost topology, which controls the output voltage for a given input voltage, allows for maximum PV device use. The converters are regulated by the control signal (duty ratio) produced by the MPPT algorithm. Convertor topologies are divided into three categories: buck, boost, and buck-boost. Each of them has a specialization in conversion. Buck converters also have a lower peak voltage. Boost converters boost the output voltage. Buck-Boost converters are capable of both step-up and step-down voltage conversion. The boost converter is used to model in this article. The explanation for this is that PV systems have less voltage at low irradiation, and can be scaled up using a boost converter to achieve load characteristics [7]. The following equation gives the voltage output expression.

$$V_O = 1/(1-D)V_{dc} \qquad (4)$$

Where D is the duty ratio and Vdc is the DC input voltage. Here is the table for specification of Boost converter design for a 100KW PV system.

Table -3: Specification of Boost converter.

Parameters	Values
V output	250-350V
V input	600V
Rated power	100KW
Switching frequency(f_{sw})	5KHz
Current ripple(ΔI)	5%
Voltage ripple(ΔV)	1%

The formula for inductance and capacitance of the boost converter is given by:

$$L = V_{ip}(V_{op} - V_{ip})/f_{sw}\Delta I V_{op} \qquad (5)$$
$$C = I_{op}(V_{op} - V_{IP})/f_{sw}\Delta V V_{op} \qquad (6)$$

Where ΔI, ΔV, I_{op}, V_{op}, V_{ip} are ripple current, ripple voltage, output current, output voltage and input voltage respectively.

Here in Fig 15, electrical circuit of boost converter is shown [2].

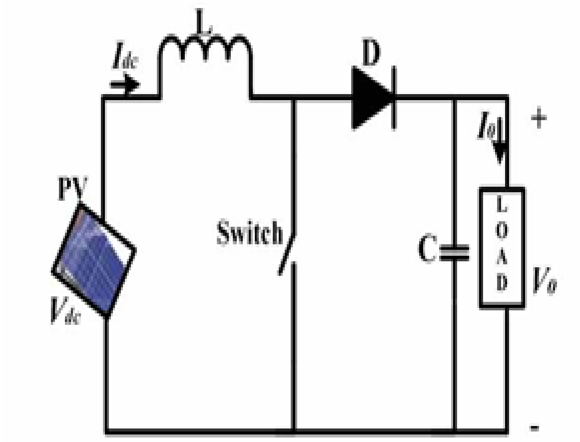

Fig.14. Electrical circuit for DC-DC boost converter.

4. Simulink model

SIMULINK modelling of PV array is done with the help of equations in table (1). The inputs of the PV array will be irradiance and temperature while the outputs will be DC voltage and current. At the output end, scopes and measuring devices are connected to measure the current and voltage outputs. SIMULINK model of PV array is shown in Fig 15.

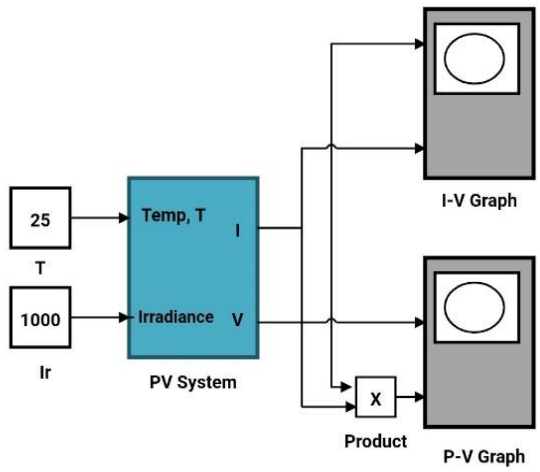

Fig.15. SIMULINK model of PV model.

Fig.16, shows the subsystem of PV array, which is modelled with the help of saturation current (I_O), reverse saturation current (Irs), shunt resistance current (Ish), photon current (Iph) and output current (I). Given below are the equations of these currents.

$$I = I_{ph} - I_O \left[\exp\left(\frac{q(V+IR_S)}{nKN_S T}\right) - 1\right] - I_{sh} \qquad (7)$$

$$I_O = I_{rs} (\frac{T}{T_n})^3 \exp\left[\frac{qE_{go}\left(\frac{1}{T_n}-\frac{1}{T}\right)}{nK}\right] \qquad (8)$$

$$I_{ph} = [I_{sc} + K_I(T-298)]G/100 \qquad (9)$$

$$I_{rs} = I_{sc}/[\exp\left(\frac{qV_{OC}}{nN_S KT}\right) - 1 \qquad (10)$$

$$I_{sh} = [(V + IR_S)/R_{sh} \qquad (11)$$

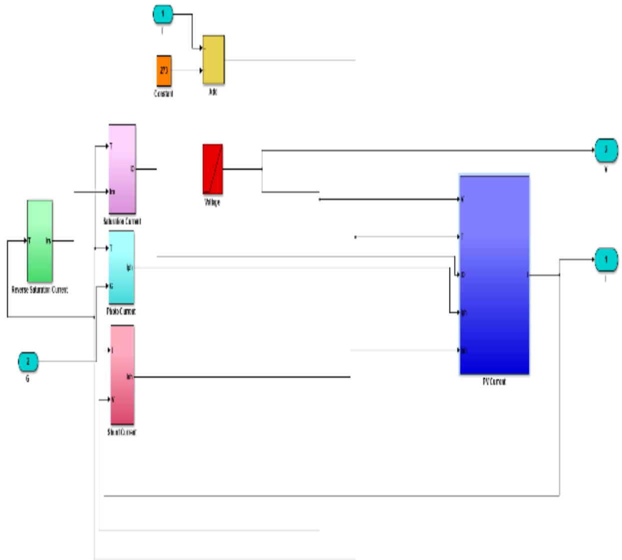

Fig.16. SIMULINK model of PV array subsystem.

Values and specification of some parameters related to the PV model in Fig 15 is given in table 4.

Table 4. Rated values of PV array

Parameters	Values
Power (Pmp)	200W
Voltage at maximum power (Vmp)	26.4V
Current at maximum power (Imp)	7.54A
Open circuit voltage (Voc)	32.9V
Short circuit current (Isc)	8.21A
Total number of cells in series	54
Total number of cells in parallel	1

In Fig 17, SIMULINK diagram of PV array with MPPT is shown to get maximum power. Fig 18, shows the Simulink model of PV array along with MPPT and boost converter. In this, Perturb and observe (P&O) algorithm is used to get maximum power point.

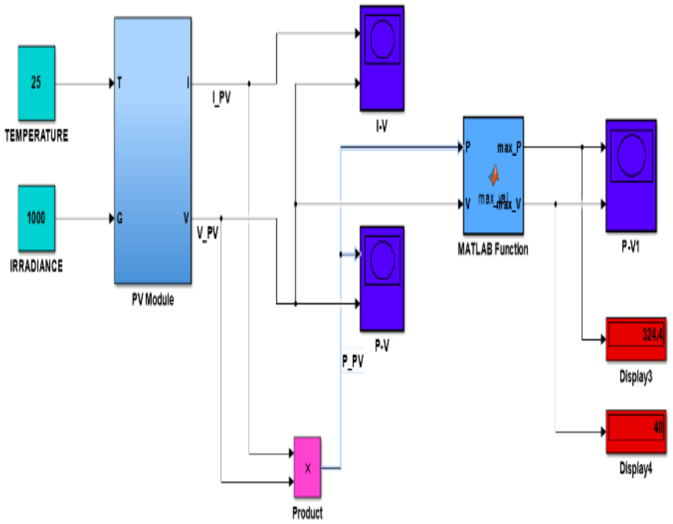

Fig.17. SIMULINK model of PV array with MPPT.

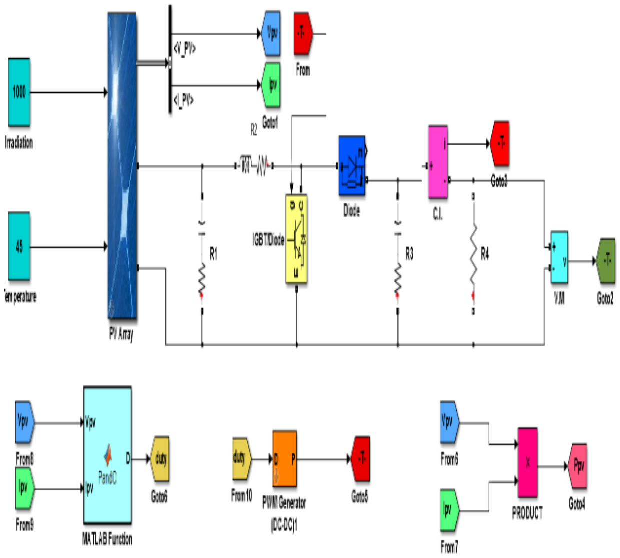

Fig.18. SIMULINK model of PV array and boost converter along with MPPT.

5. RESULT

From the modelling of PV array shown in Fig 15, graph of PV and IV are obtained. In PV graph, the maximum power obtained is 200W and is obtained at 26.5V. In IV graph, at MPP, the current is 7.5A. In Fig 19, Fig 20, graphs of PV and IV curve, obtained at 1000W/m^2 irradiance and 25^{0}C temperature is shown.

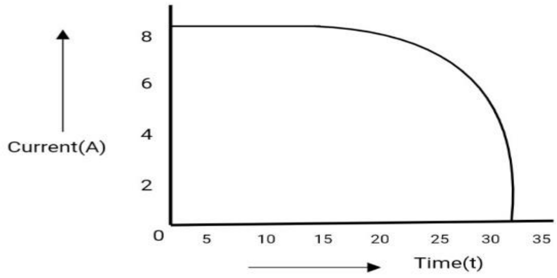

Fig.19. Graph of IV curve showing MPP current.

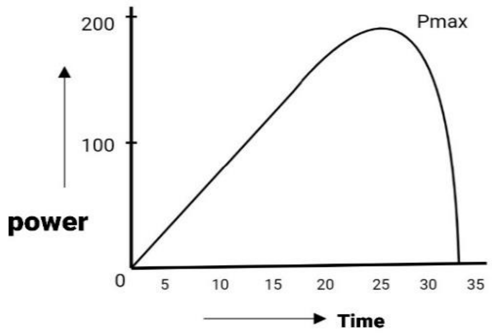

Fig.20. Graph of PV showing MPP point.

Now, from the modelling of MPPT in the PV system along with boost converter in Fig 18, graph of power is obtained with improved characteristics.

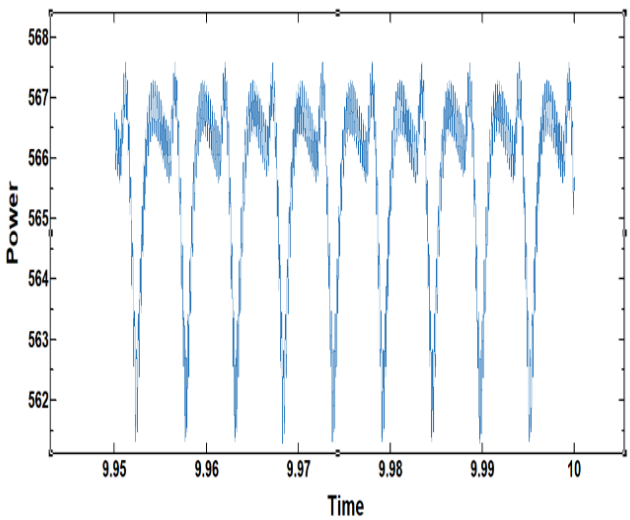

Fig.21. Graph of power at 400W/m^2 irradiance at 25^{o}C with MPPT.

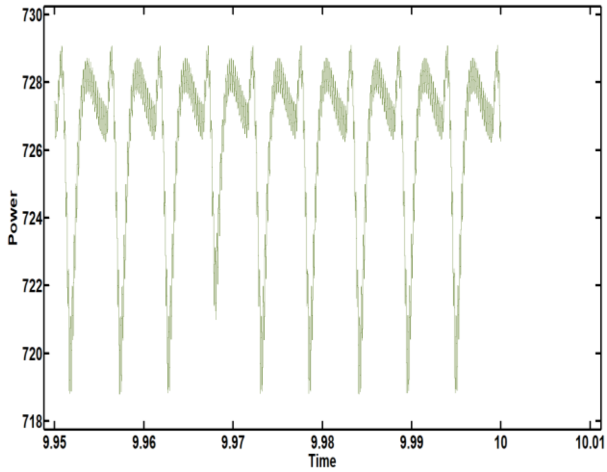

Fig.22. Graph of power at 500W/m² irradiance at 25°c with MPPT.

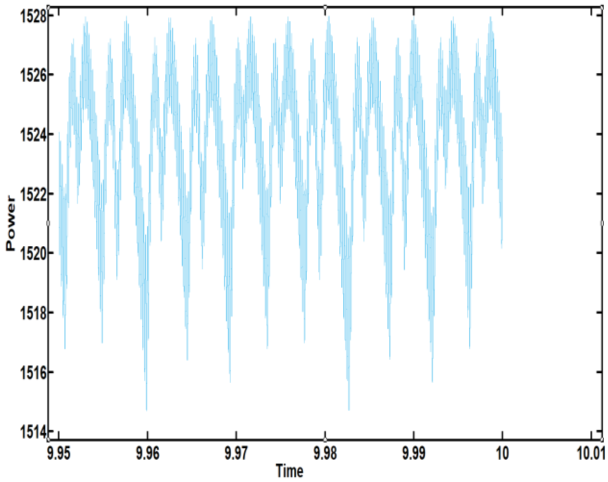

Fig.23. Graph of power at 1000W/m² irradiance at 25°C with MPPT.

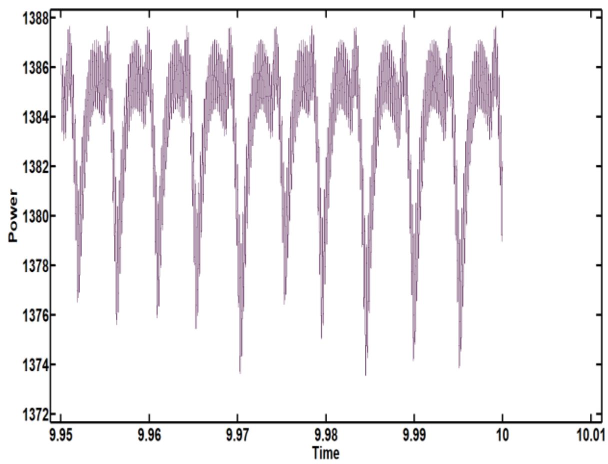

Fig.24. Graph of power at 1000W/m² irradiance and 45°C with MPPT.

Fig 21, shows the output graph of power of MPPT model from Fig 18. In this irradiation is kept at 400W/m² and temperature at 25°C. The MPP power obtained is 568 watts. In Fig 22, the irradiation is 500W/m² and temperature at 25°C, MPP power obtained in this case is 726.2 watts and boost voltage (Vboost) are 83.69V, where PV voltage (Vdc) is 53.88V. In Fig 23, irradiation is 1000W/m² and temperature is 25°C and the MPP power obtained in this case is 1524 watts. Boost voltage (Vboost) is 119.9V, while PV voltage (Vdc) is 55.6V. So, it is observed that on increasing the irradiation MPP power increases and on decreasing the irradiation MPP power decreases. Also boost converter is boosting the dc voltage from PV array.

Fig 24, shows the output graph of power of MPPT model from Fig 18, showing the effect of temperature on power. Keeping the irradiation at 1000W/m² temperature is increased from 25°C to 45°C. The MPP power obtained is 1382 watts. The MPP power is decreased as the temperature is increased.

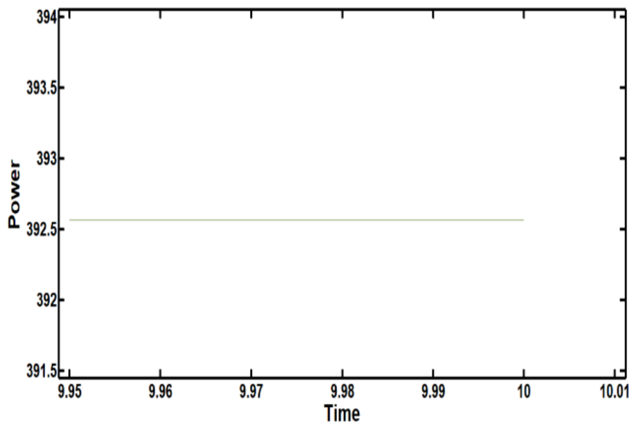

Fig.25. Graph of power at 1000W/m² irradiance at 25°C without MPPT.

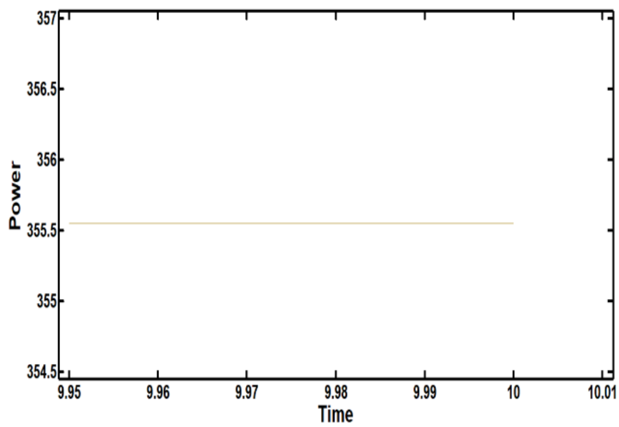

Fig.26. Graph of power at 500W/m² irradiance at 25°c without MPPT.

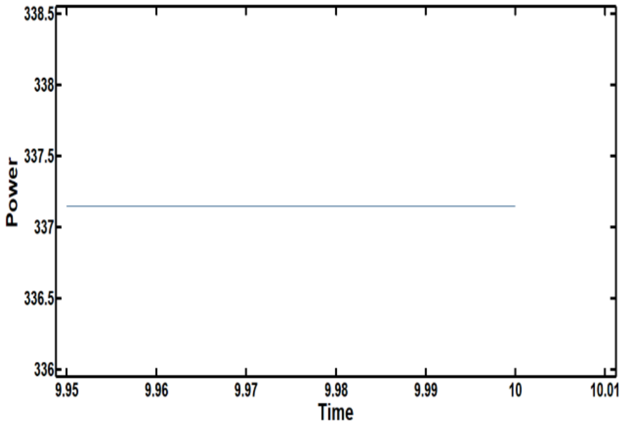

Fig.27. Graph of power at 1000W/m² irradiance at 45⁰C without MPPT.

Fig 25, shows the graph of power of PV system along with boost converter without MPPT. The output power without MPPT is 392.6W at 1000W/m² irradiance and 25ºC temperature. The output power at 500 W/m² irradiance and 25ºC temperature is 355.6W as shown from graph in Fig 26. Fig 27, shows the output power of PV model at 1000W/m² irradiance and 45ºC. The output power without MPPT in this case is 337.2W. Table 5 shows the response of PV system without MPPT. In table 6, response of PV system with MPPT is shown.

Table -5: Response of PV model without MPPT.

Irradiation (W/m²)	Temperature (ºC)	Vboost (V)	Vdc (V)	Power (W)
500	25	58.93	60.33	355.6
1000	25	61.94	63.37	392.6
1000	45	57.38	58.76	337.2

Table -6: Response of PV model with MPPT.

Irradiation (W/m²)	Temperature (ºC)	Vdc (V)	Vboost (V)	Power (W)
500	25	53.88	83.69	726.2
1000	25	55.6	119.9	1524
1000	45	51.04	114.0	1382

6. CONCLUSION

In this paper, modelling of PV array is done with the help of mathematical equations involved. From the Simulink model of PV array graph of P-V and I-V is analyzed. The PV array gives the maximum power of 200W at 26.5V and MPP current of 7.5A. DC-DC boost converter is implemented to regulate the DC voltage in the system since power from PV array is very low so, boost converter is used to boost the dc voltage so that the system meets the required load characteristics. PV system is modelled with both MPPT and without MPPT, and their results are discussed. Different MPPT technique is implemented out of which the close loop control of MPPT gives a more improved MPPT tracking. Perturb and observe (P&O) and Incremental conductance algorithm is used. Incremental conductance algorithm is found out be a better algorithm than P&O algorithm owing to its speed and accuracy. The effect of irradiation and temperature is seen on MPP power. On increasing the irradiation, the MPP power increases while on decreasing, it decreases. Also, the MPP power starts decreasing as temperature is increased up to a certain level.

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