Maximum Power Point Tracking Testing Using Photovoltaic Array Emulator Based on Lambert Algorithm

Mr. Nisarg Patel
PG Student, Electrical Engineering Department
C G Patel Institute of Technology
Bardoli, India
nisargpatel161193@gmail.com

Prof. Ankur Rana
Assistant Professor, Electrical Engineering Department
C G Patel Institute of Technology
Bardoli, India
ankur.rana@utu.ac.in

Prof. Hiren Sidhpuria
Assistant Professor, Electrical Engineering Department
C G Patel Institute of Technology
Bardoli, India
hiren.sidhpuria@utu.ac.in

Abstract— **Solar energy is the furthermost imperative resource of energy now a day. It is difficult to test different PV system equipment for particular weather condition because of weather condition is constantly change on earth with real PV panel or array. Also, it is also complicated to maintain weather condition for testing purpose. So, any equipment is required to test PV system equipment against above-mentioned difficulties. A PV emulator is a DC-DC converter, which can duplicate the preferred output behavior unrelatedly of the weather conditions to analyze and tests diverse PV systems equipment for the different environmental condition. In this paper lambert W algorithm-based PV array emulator is presented. It is tested against linear and non-linear load and compares its results with conventional PV array emulator which behavior are similar to the real PV array. And it also gives PV emulator to connect with maximum power point tracking (MPPT) to test MPPT on PV emulator at different techniques. Also, it is tested with MPPT and compare with the Lambert W algorithm.**

Keywords—Photovoltaic, Lambert W and PV array emulator, MPPT, Perturb and Observed

I. INTRODUCTION

One of the major concerns in power is the everyday growing power demand but the absence of enough resources to meet the power demand by means of conventional energy sources. Demand has improved for renewable sources of energy to be utilized along with conventional systems to see the desired energy [1]. Renewable sources like wind energy, solar energy, etc. are the prime energy sources which are being utilized. Among all of this solar energy is the fastest growing renewable resources. A photovoltaic system converts light into electrical direct current (DC) via taking advantage of the photoelectric effect. DC power is converted to AC power using an inverter which can be used to power local load [2].

The constant use of fossil fuels has triggered the fossil fuel deposit to be reduced and has extremely affected the environment and also affect global warming.

Solar energy is available at the greater quantity that has made it possible to produce it and utilize it properly. Solar energy can be a generating unit or can be a grid-connected generating unit liable on the availability of a grid nearby. Similarly, it can be used this power in rural areas where the accessibility of grids is very low [3]. Another benefit of using solar energy is that it can easily transport and easily carried whenever wherever necessary.

The needed of PV emulator is to have a measured environment to test PV equipment is problematic since consistent repeatable condition are unbearable to reproduce. The electrical characteristic of PV panel will change based on a change of factors including the amount of irradiance received, temperature of the panel and the physical used to make the PV panel [6]. It will simulate the current and voltage characteristic of a photovoltaic panel under various state. Cost of actual PV array is very high. For testing of PV system, the huge space requires for solar panel and the other device like inverter, converter.

Thus, the investigation on PV emulator has explain the various tactics in simulator design need to replicate and present. So, this method can be evaluated based on accuracy, level of complication, cost, varying eco-friendly weather condition and efficiency.

The basic function of PV emulator is to duplicate a real panel by correctly emulating IV and PV characteristic [4]. The real task behind the emulator design is to exert the replica of actual PV curves at all ecological condition.

In this paper lambert W algorithm-based PV emulator is discussed to reduce settling time, improve dynamic and steady state response and reduce the ripple in output voltage and output current by comparing conventional PV emulator. Also, comparing with MPPT using lambert W algorithm.

II. EQUIVALENT CIRCUIT OF PV MODEL

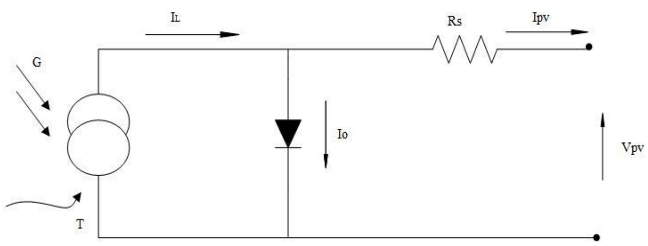


Fig.- 1 Equivalent circuit of single diode of PV cell

Solar cell which is connected in series resistance Rs to take the internal electrical losses. Shunt resistance R_p

generally varies very great and hence ignore but it is not included. Solar cell will produce DC voltage when it is protected to daylight. Fig-1 shows the equivalent circuit of single diode of PV cell, it can be viewed as a non-linear load current source [7].

$$I_{PV} = I_L - I_O\left(e^{\frac{q(V_{PV}+IR_S)}{nKT}}\right) - 1 \quad (1)$$

The diode saturation current Io.

The photo current I_L.

Series resistance Rs, which gives additional accurate shape among the maximum power point and the open circuit voltage (V_{oc}).

Shunt resistance R_p in parallel with diode.

Diode quality factor (n)

Temperature °C

Electronic charge q=1.6*10^-19 C

Boltzmann constant k=1.38*10^-23 J/K

The non-linear transcendental equation (1) is hard to solve and so, some mathematical technique needs to be used to solve it. The approach recommended by Walker et.al, [7] is used for solving (1). Since, some data for that module are required, which can be attained from the datasheet of the PV module. To solve (1) the earlier known values of open circuit voltage (V_{oc}) and short circuit current (I_{sc}) at two dissimilar temperatures T_1 and T_2 are used.

$$I_L = I_{L(T1)}\left(1 + K_O(T - T_1)\right) \quad (2)$$

$$I_{L(T1)} = G * I_{SC(T1;nom)}/G_{(nom)} \quad (3)$$

$$K_0 = \left(I_{SC(T2} - I_{SC(T1)}\right) = \left(T_2 - T_1\right) \quad (4)$$

$$I_O = I_{O(T1)} * \left(\frac{T}{T_1}\right)\frac{3}{n} * e^{\left(\left(-\frac{qVg}{nK}\right)*\left(\frac{1}{T}-\frac{1}{T1}\right)\right)} \quad (5)$$

$$I_{O(T1)} = I_{SC(T1)}/\left(e^{qVOC(T1)/nKT1} - 1\right) \quad (6)$$

$$R_S = -dV = dI_{VOC} - 1/X_V \quad (7)$$

$$X_V = I_{O(T1)} * \frac{q}{nKT_1} * e^{qVOC(T1)/nKT1} \quad (8)$$

III. OPERATING PRINCIPLE

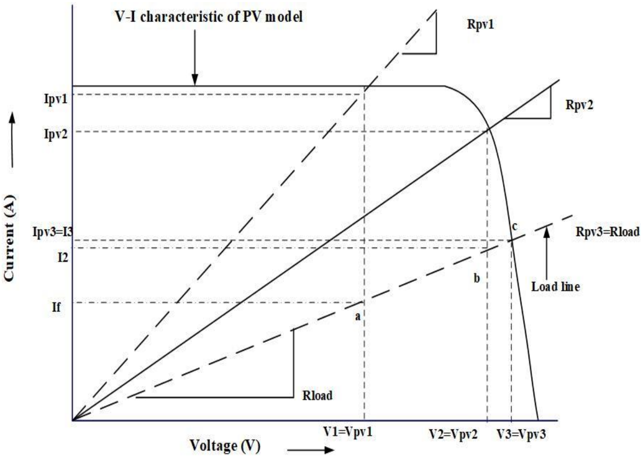


Fig.- 2 PV array operating principle

Figure 2 shows a V-I characteristic of a module to be emulated and load line equivalent to fixed resistive load (R_{load}) on the same V-I Plot. For the specified load; if the converter operated at the intersection point of V-I characteristic of a module and the load line R_{load}; the converter is able to work as an emulator [8]. It shows that as the load line R_{load} meets the V-I characteristic of module at point 'c' and the converter can performance as an emulator if its steady-state output voltage and current are V_{pv3} and I_{pv3} respectively where V_{pv3} I_{pv3}=R_{pv3}=R_{load} [9].

Let the 'a' is the operating point at which the voltage and current are V_I and I_I respectively. The PV model generates the voltage V_I=V_{pvl} and current I_{pvl} this point load resistance is R_{pvl} which is lesser than R_{load} so the converter force to act as emulator; that time point 'a' moved to point 'b'. At point 'b' the voltage increases from V_{pvl} to V_2=V_{pv2} and current decrease from I_{pvl} to I_{pv2} so the resistance at point 'b' is R_{pv2} which is also less the R_{load} therefore once again converter force to act as emulator and reach at point 'c'. The voltage V_3=V_{pv3} and the current I_3=I_{pv3} at point 'c'. The load resistance is R_{pv3} at point 'c' which equal to R_{load} [8].

IV. SYSTEM CONFIGURATION

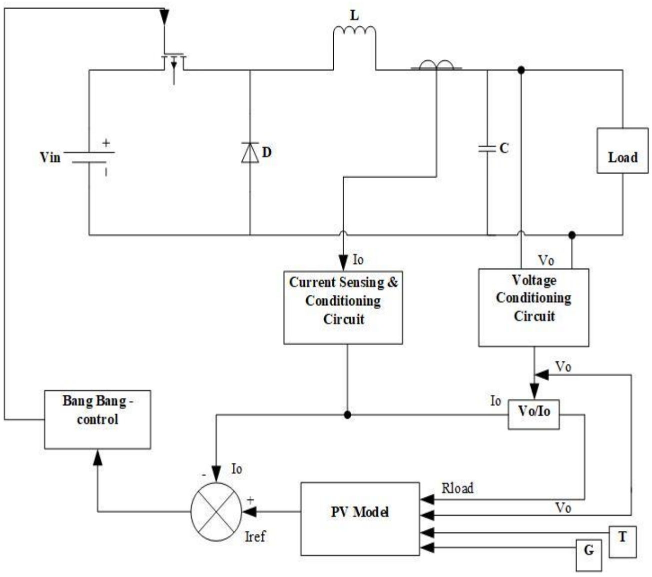


Fig.- 3 System configuration of PV emulator

Fig. 3 shows the system configuration for a PV emulator which contains a buck type converter, sensors, conditioning circuits. V_{in} represents a DC source. Bang-bang (Hysteresis) control is used to deliver controlled output current. The reference current for the bang-bang controller is derived using the PV model [7].

As we have seen in Fig 3 Vo and Io which is output voltage and output current of converter are identified, filter and fed to the controller which control the converter act like a PV emulator. A PV module runs at different values of V_{pv} and I_{pv} dependent on values of G, T and the load connected across it R_{load}. So, to control buck converter to operate at the voltage and current to the values at which a PV module run under given conditions, the controller is fed with G, T, Vo and Io. Using equation (1)-(8) along with the parameters of G, T, Vo and Io, the controller computes the value of R_{pv} and R_{load}. R_{pv} which is well-defined as the ratio of V_{pv} and

I_{pv}. Depending upon the different in the value of R_{load} and R_{pv}, the controller takes the corrective action to force the operating point where, difference in R_{load} and R_{pv} is zero or is insignificant.

This paper represent the PV emulator exhibit the similar characteristic of PV panel. And also, it is compared with lambert function using equation.

V. MODELING OF PV EMULATOR WITH LAMBERT W ALGORITHM

This paper deals with the modelling of a PV system in MATLAB / SIMULINK based on the mathematical equations.

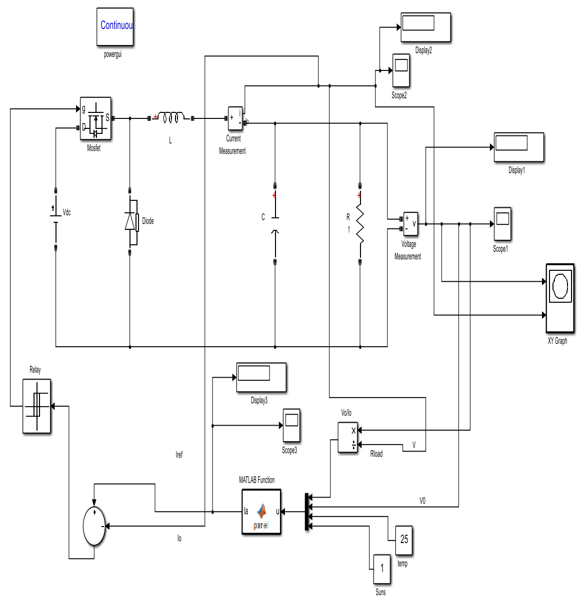


Fig.- 4 Simulation model of PV emulator with resistive load

Buck Converter

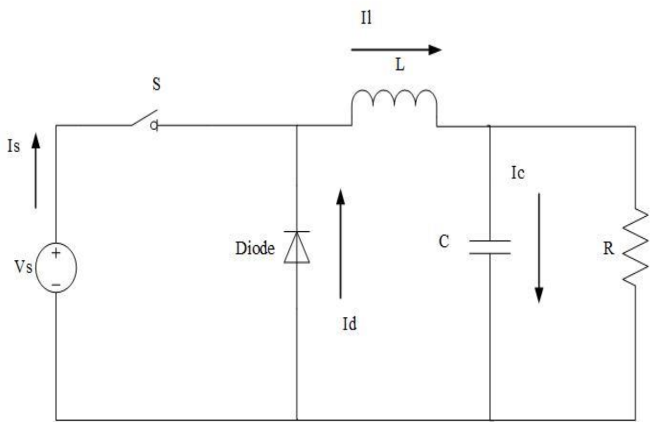


Fig.- 5 Buck Converter

A Buck Converter is a voltage step down and current step-up converter, also it is a DC-DC converter. Buck converter is the most basic SMPS topology. It is widely used throughout the industry to convert a higher input voltage into a lower output voltage [8].

Suppose this circuit we always operate the transistor as an ideal switch. If we keep ON and OFF the switch the average voltage across the load will be less than the voltage of battery but this is only because of voltage across the load is zero when the switch is open. We can try to prevent the voltage from dropping to zero by adding a capacitor across the load.

Now when we close switch we are trying to change the voltage of a capacitor instantaneously which is impossible. So large current will flow to the charge the capacitor and this cause the damage. We can try to reduce the current by adding a resistor. But we don't want resistor because resistor dissipates energy as heat. Instead of using a resistor we can limit the current by using the inductor.

An ideal inductor doesn't dissipate energy as heat. But since the current through an inductor can't change instantaneously the inductor will force the current to keep flowing through switch even after we open it which is dangerous. We can prevent the current from flowing through the open switch by adding a diode. The diode will give current a different path to flow through so it's called buck converter.

$$(V_s - V_o)DT = -Vo(1 - D)T$$

The act of PV emulator is shown in fig 3.
with different types of linear and non-linear loads.

TABLE 1-PV SPECIFICATION

Open circuit voltage	V_{oc}	21V
Short circuit current	I_{sc}	3.8A
Voltage at MPP	V_m	17.1V
Current at MPP	I_m	3.5A
Maximum power	P_m	60W

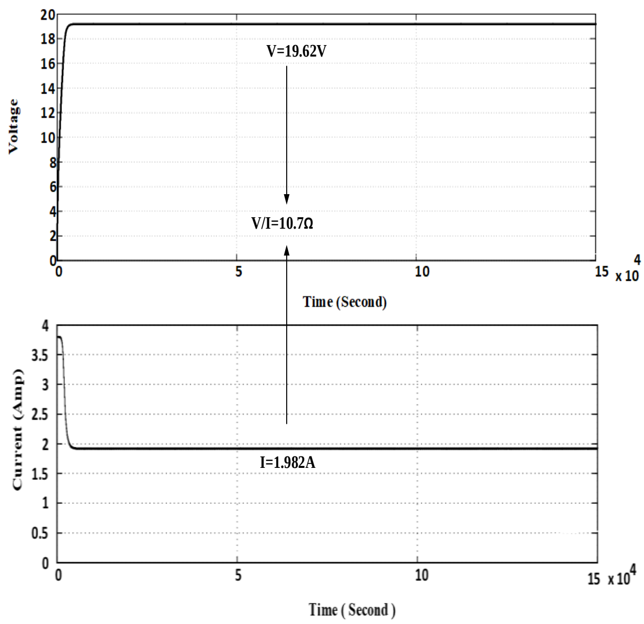


Fig.- 6 PV emulator response with resistive load a) output voltage and b) output current.

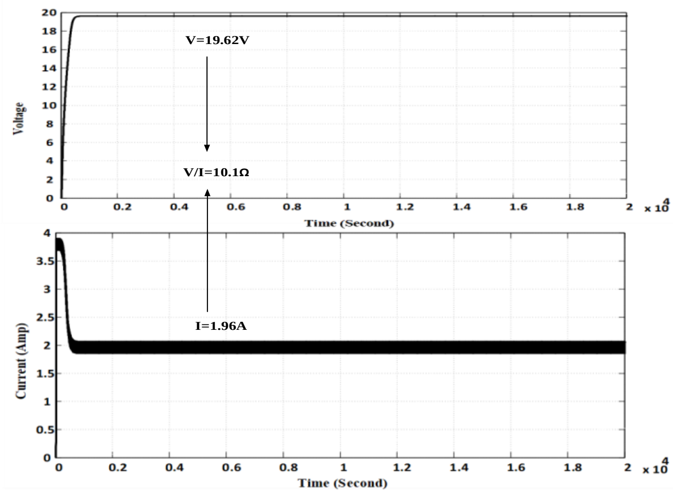


Fig.- 7 PV with lambert W function feeding with resistive load a) output voltage and b) output current

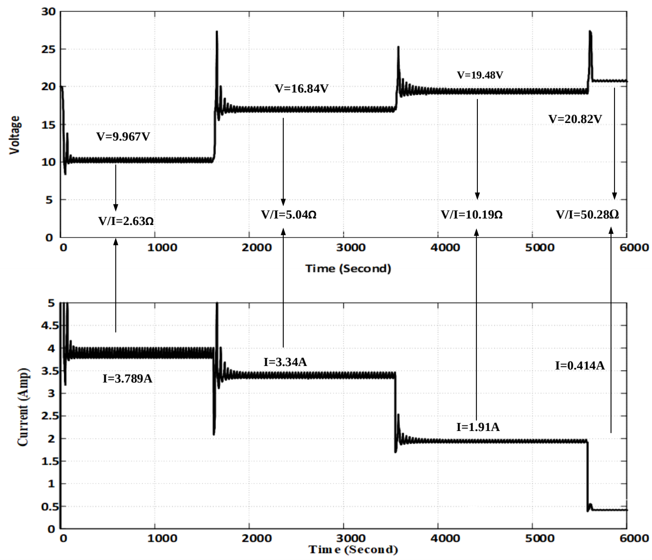


Fig.- 8 PV emulator with parallel resistance

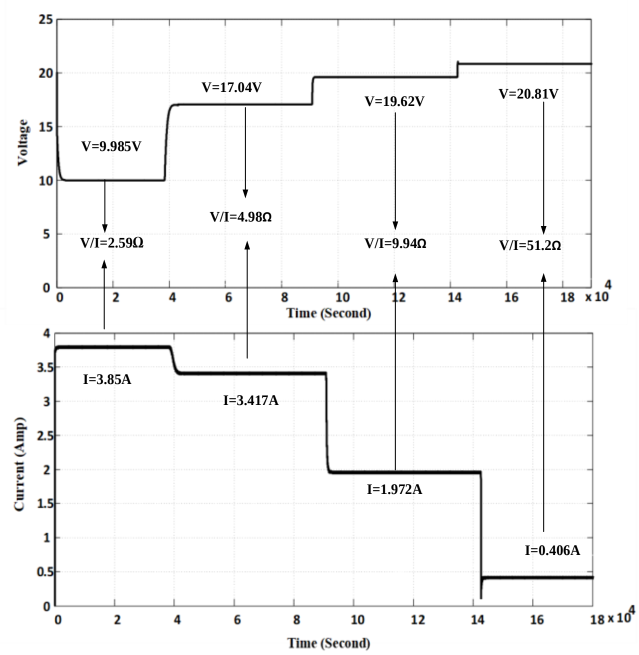


Fig.- 9 PV emulator with parallel resistance using lambert W function

Fig. 7 shows concert of the PV emulator (Fig. 3), when the resistance is varied. The R_{load} at time t=0s is 2.63Ω. The step is modified in the resistances are applied at t=0.2s (2.63Ω to 5Ω), t=0.4s (5Ω to 10Ω), and t=0.6s (10Ω to 50Ω). The variation between current and voltage in dc-dc converter has shown in fig 7 to its resistance.

It observed that in Fig. 7 PV emulator connect with parallel resistance the dynamic response of the PV is good. However, ripple is high (0.492s) in I_o and not significance when PV emulator is used in place of PV model for testing. In Fig 7 it is observe that by using lambert function the dynamic response is better than PV and not only that but also ripple is very low (0.372s) in Io.

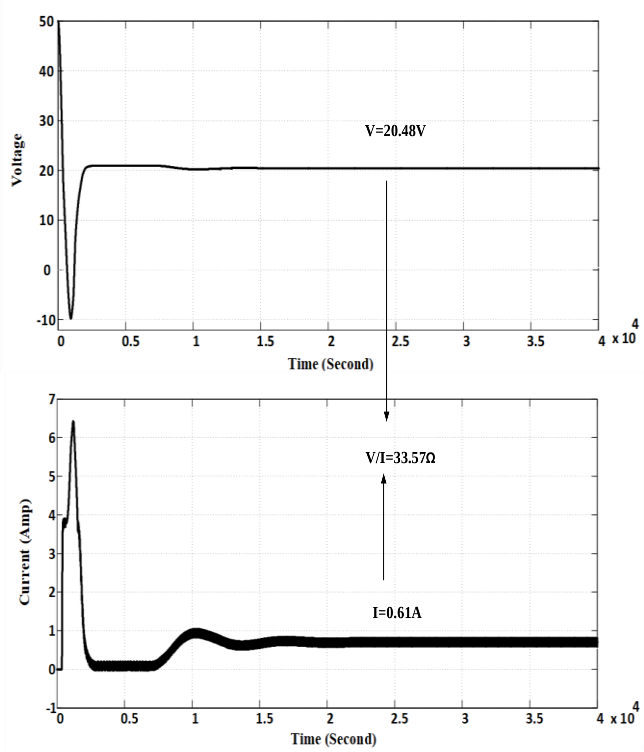


Fig.- 10 PV emulator with Boost converter as non-linear load

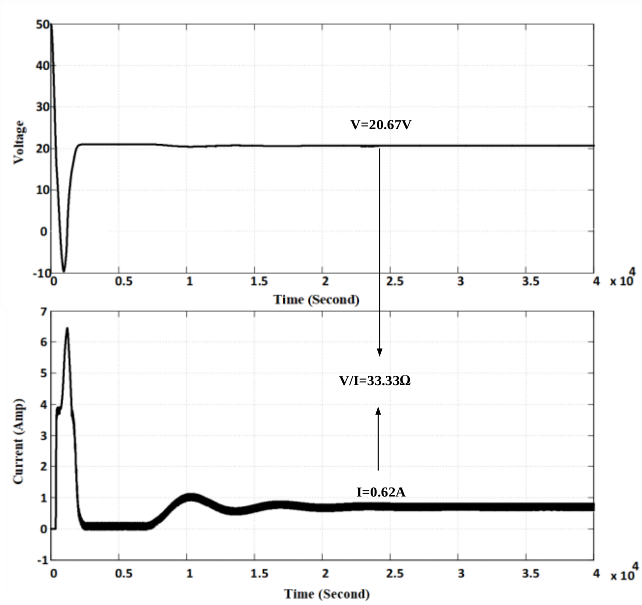


Fig.- 11 PV emulator with Boost converter as non-linear load using lambert W function

PV emulator is also tested with non-linear load that consist dc-dc boost converter feeding with resistive load. Fig. 9 shows the performance of the PV emulator. Here a fixed resistance of 120Ω is considered which is the output port of boost converter which work as a load. This set-up consists of two dc to dc converters. As from previous case, first converter that acts as a PV emulator is a buck converter while the other one that acts as a load converter is a boost converter. The load converter is worked at a constant duty cycle D = 0.5 and 6.6 kHz switching frequency. For boost converter active resistance can be obtain from equation.

$$R_{in} = R_{Out} \text{X} (1 - D)^2$$

The output port of PV emulator is approximately 30Ω. The steady state of the output current and output voltage of PV emulator are 0.61A and 20.48V respectively. The time to reach the steady state is 1.5s. as shown in Fig. 9 while, comparing to lambert function the time to reach at steady state is same as PV shown in Fig. 10 and also the output current and output voltage is 0.62A and 20.67V.

VI. Maximum Power Point Tracking

It is an electronic system that operates the photovoltaic modules in a manner to extract the maximum power from the system. MPPT is a fully electronic system that varies the electrical operating point of the modules so that the modules are able to deliver maximum available power. The first thing we should know that great power loss occurs in operating power (OP) which is not close to a power point. MPPT is a system to operating PV voltage or current in order to get maximum power. It depends on three variables which are irradiation of sun, cell of temperature and load impedance.

Role of MPPT:

MPPT plays a vast role in PV systems because it maximizes the power output from a PV system for a given set of environmental changes and load variations, and therefore maximize the array efficiency and minimize the total system cost.

The MPP varies liable on the irradiation and cell temperature, consequently; appropriate algorithms must be developed to track the MPP and maintain the operation of the system as close as possible to this point.

There are different techniques used for tracking the maximum power point.

1. Perturb and Observed
2. Incremental conductance
3. Fuzzy logic control
4. Neural network
5. Artificial intelligence

Perturb and Observed:

Perturb and observe states that when the operating voltage of the PV is perturbed by a small increment, if the resulting changes in power ΔP are positive then we are going in the direction of MPP and we keep on perturbing in the same direction. If ΔP is negative we are going away from the direction of MPP and the sign of perturbation supplied has to be changed.

Figure shows the plot of module output power versus module of voltage for a solar panel at given irradiation. The point marked as MPP is the maximum power point the theoretical maximum output obtainable from the PV. Panel let's consider A and B are the two-operating points. Point A is on the left-hand side of the MPP.

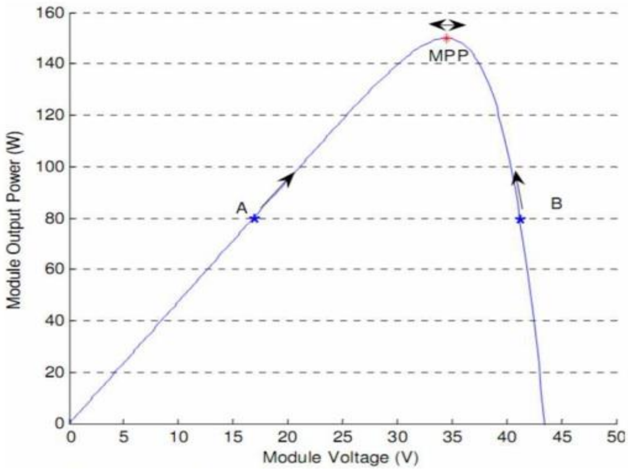


Fig.- 12 P&O characteristic

So, we can move towards the MPP by providing a positive perturbation to the voltage. On the other hand, side point B is on the right-hand side of the MPP. When we give a positive perturbation the value of ΔP becomes negative so it changes the direction of perturbation to achieve MPP.

VII. SIMULATION AND RESULT OF MPPT

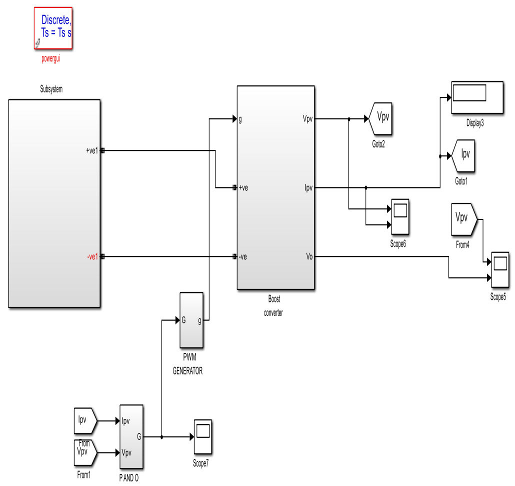
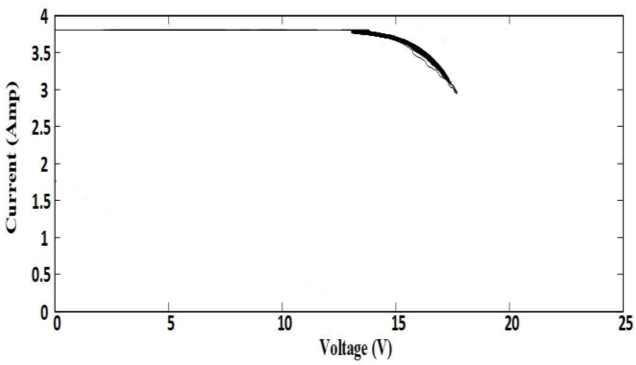


Fig.- 13 Simulation model of PV emulator with P&O MPPT



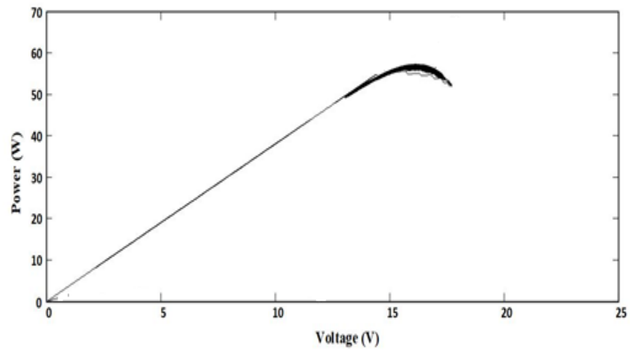


Fig.- 14 IV and PV curve of P&O MPPT

Results of PV Emulator With P&O MPPT:

There are different cases of MPPT has been shown below:

1. Case: running system with MPPT

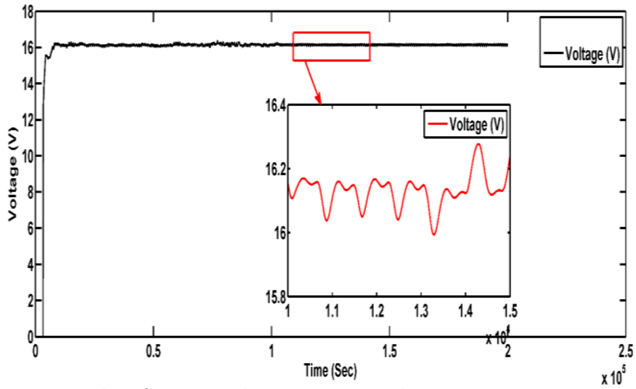


Fig.- 15 Plot of Output Voltage Vs Time With MPPT

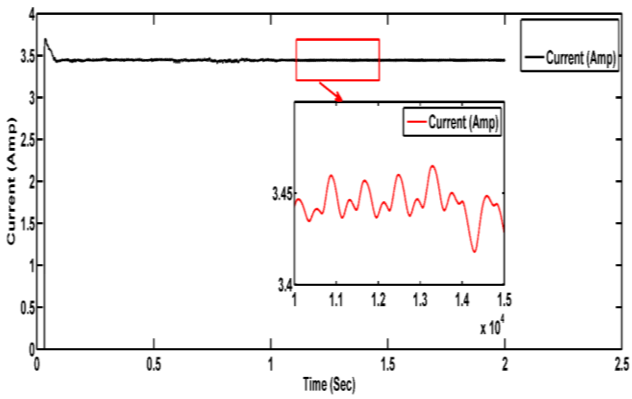


Fig.- 16 Plot of Output Current Vs Time With MPPT

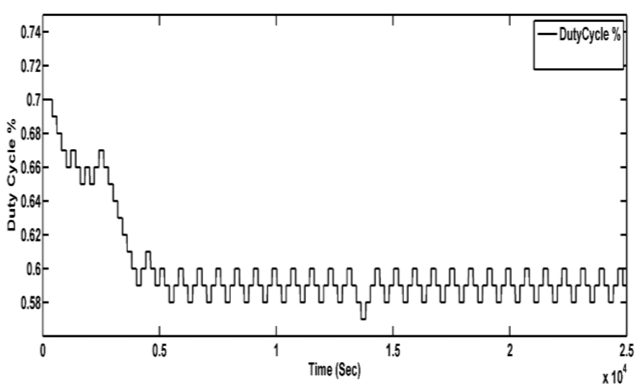


Fig.- 17 Plot Of P&O Vs Time With MPPT

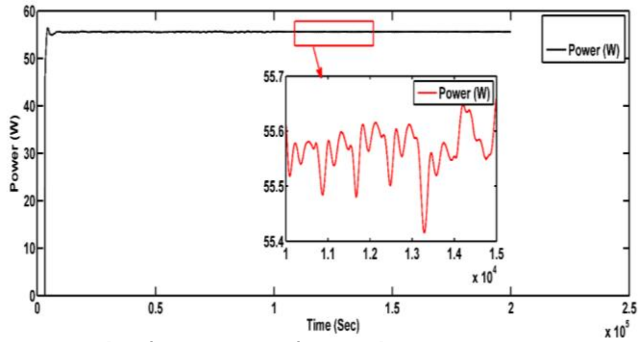


Fig.- 18 Plot of Power Output of PV Panel Vs Time

2. Case: running the system with lambert using MPPT

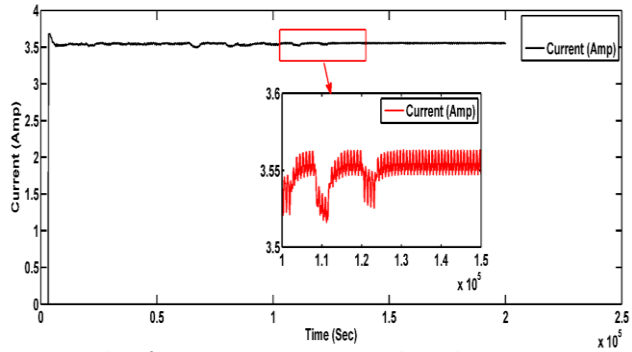


Fig.- 19 Plot of Output Current Vs Time with Lambert Using MPPT

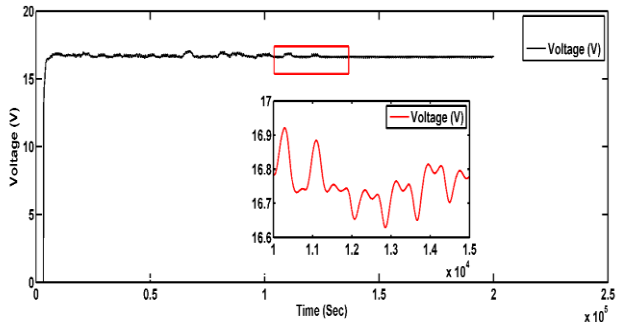


Fig.- 20 Plot of Output Voltage Vs Time with Lambert Using MPPT

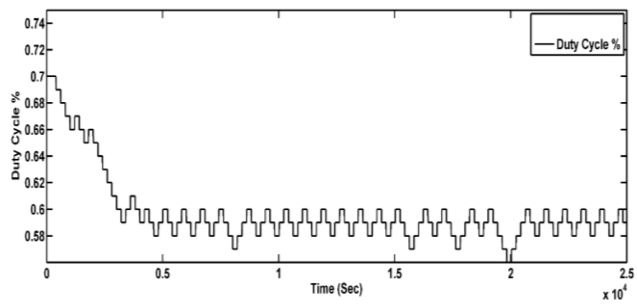


Fig.- 21 Plot of P&O Vs Time with Lambert Using MPPT

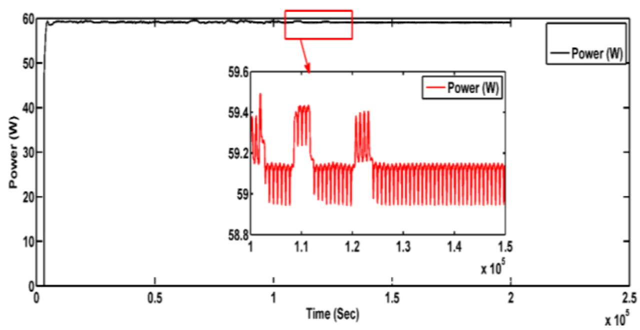


Fig.- 22 Plot of Power Output Vs Time with Lambert Using MPPT

VIII. HARDWARE IMPLEMENTATION

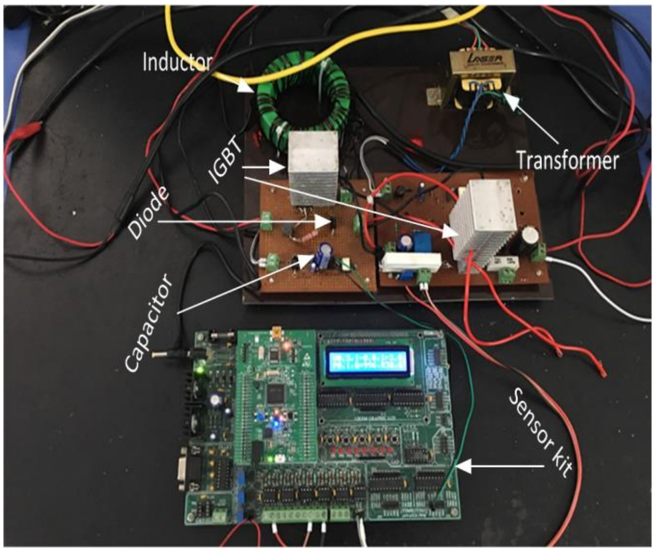


Fig.- 23 Hardware setup

A diode is used for higher frequency because low frequency can't be used due to having high switching frequency or it will be burn on a second. So, switching frequency is 40Khz.

If 25V is given on the positive side it will give -3V voltage drop in shunt side whereas in series 1Ω is connected in parallel with 1Ω it will give 0.5V.

$$1\Omega \| 1\Omega = 0.5V$$

Suppose 1A current is flowing so voltage V= I x R. if we increase the current the voltage also increases so to get equivalent current resistance should be across in voltage. So, by sensing the voltage, it gives to controller the ground so with respect to ground we get voltage.

Example: V=I x R

$$1A \times 0.5\Omega = 0.5V$$
$$2A \times 0.5\Omega = 1.0V$$
$$3A \times 0.5\Omega = 1.5V$$

Now by changing the potential meter, we can vary the gain if we get 25V it should give -3V drop voltage with respect to ground. For that, we are bypassing the inductor (short-circuited) so only remaining sensor by varying rheostat.

Now we are using TLP 350IC. Here +5V supply is given to gate pin 2 and 3. Pin 1 and 2 are N.C.

Also, we have used a transformer of 9-0-9 (winding) to create 18V AC.

Real-time implementation results of PV Emulator

TABLE 2 CALCULATION OF PV EMULATOR

Current	Voltage	Power =P(A*V)
0	21.2	0
0.5	20.8	10.4
1	19.7	19.7
1.5	19.2	27.2
2	18.8	36.5
2.5	18.4	46
3	18	54
3.5	16.5	57
3.8	13.5	51
3.8	10	38
3.8	5	19
3.8	0	0

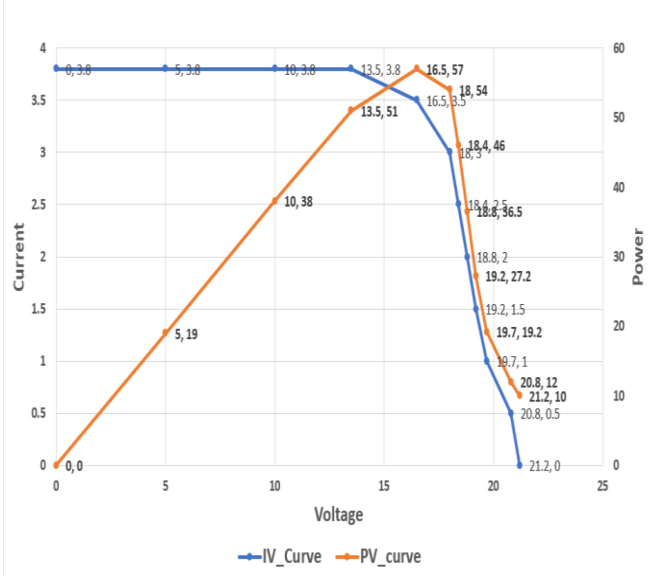


Fig.- 24 Hardware results of IV and PV Curve

IX. CONCLUSION

PV array emulator based on current-controlled buck converter with and without Lambert W function is obtainable and simulated in this thesis. After detecting the simulation results following are the concluding remarks:

1) Settling time occupied by Lambert W function-based emulator is less comparing with the conventional emulator.
2) Steady-state and dynamic response of Lambert W function-based emulator is better than the conventional emulator.
3) Lambert W function-based emulator has less ripple in current than conventional emulator and this ripple can be eliminated by proper filtration techniques.
4) After observing overall behaviour of both the emulator, Lambert W function-based emulator most correctly follow the PV array than the conventional one.
5) The MPPT (P&O) algorithm is tested using PV emulator. Simulation results of both of the emulators are matched with the behaviour of a real PV panel.
6) After observing the results of hardware implementation, it is proved that buck converter-based PV array emulator follows the behaviour of a real PV panel.

X. REFERENCES

[1] Chetan Singh Solanki. Solar photovoltaics - fundamentals, technologies and applications hard cover. Third ed. 14th Apr; 2015.

[2] M. G. Villalva, J. R. Gazoli, and E. R. Filho, "Details of Various Projects Outline Business cases," vol. 24, no. 5, pp. 1198–1208, 2009.

[3] N. Rajasekar, N. Krishna Kumar, and R. Venugopalan, "Bacterial Foraging Algorithm based solar PV parameter estimation," Sol. Energy, vol. 97, pp. 255–265, 2013.

[4] Jiang Tianxiang, Putrus Ghanim, McDonald Steve, Conti Matteo, Li Bowen, Johnston David. Generic photovoltaic system emulator based on Lambert ω function. In: Proceedings of the 46th international universities power engineering conference 5–8th; 2011.

[5] S. N. Deshkar, S. B. Dhale, J. S. Mukherjee, T. S. Babu, and N. Rajasekar, "Solar PV array reconfiguration under partial shading conditions for maximum power extraction using genetic algorithm," *Renew. Sustain. Energy Rev.*, vol. 43, no. 2015, pp. 102–110, 2015.

[6] D. S. L. Dolan, J. Durago, J. Crowfoot, and Taufik, "Simulation of a photovoltaic emulator," North Am. Power Symp. 2010, NAPS 2010, 2010.

[7] G. Walker, "Evaluating MPPT Converter Topologies Using a MATLAB PV Model," J. Electr. Electron. Eng., vol. 21, no. 1, pp. 49–56, 2001.

[8] A. V. Rana and H. H. Patel, "Current Controlled Buck Converter based Photovoltaic Emulator," J. Ind. Intel. Inf., vol. 1, no. 2, pp. 91–96, 2013.

[9] J. P. Ram, H. Manghani, D. S. Pillai, and T. S. Babu, "Analysis on solar PV emulators: A review," vol. 81, no. May 2016, pp. 149–160, 2018.

[10] M. Taciuc and A. Crăciunescu, "Application of the Lambert W-function for a PV module parameters' estimation," vol. 420007, p. 420007, 2017.