Research Journal of Applied Sciences, Engineering and Technology 9(4): 296-308, 2015
DOI:10.19026/rjaset.9.1408
ISSN: 2040-7459; e-ISSN: 2040-7467

Submitted: August 31, 2014 Accepted: November 13, 2014 Published: February 05, 2015

Research Article

Design of Soft Switching Interleaved Boost Converter for Photovoltaic Application

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Abstract: The objective of our study is to reduce the size of passive components and reduction of ripple in output voltage and input current by using interleaved soft switching dc-dc converter (interleaving action). The PV system converts solar energy into electrical energy but its output varies with variation of solar radiation and temperature. To provide impedance matching between PV and load a dc-dc converter with MPPT technique is used in PV (Photo Voltaic) Systems. This study incorporates design of the interleaved soft switching dc-dc converter for PV System by using P&O (Perturb and Observe) fuzzy logic controller. The P&O Fuzzy MPPT provides an accurate and fast converging under varying illumination and load conditions compared to conventional MPPT methods. The performance of the system is first analyzed by simulation using Matlab/Simulink software. The results of simulation were compared and analyzed.

Keywords: Fuzzy Logic Controller (FLC), Maximum Power Point Tracking (MPPT), perturb and observe, photovoltaic system

INTRODUCTION

Energy becomes the basic need of human life. The rapid increase in the energy requirement and the fast depletion of fossil fuels forces mankind towards the usage of nonconventional energy sources such as wind, solar, geothermal, etc. Among all non conventional energy sources solar energy is attractive because of its reusable; non exhaustible and non polluting nature (Chaitanya *et al*., 2011; Wang *et al*., 2010; Chin *et al*., 2011). The electrical energy obtains from solar energy by using photovoltaic panel. It has the added advantages like incurring no fuel cost, static, noise free operation and less maintenance requirements. The life cycle of the PV panel will be around 20 years (Pradeepa and Sankar, 2013; Elanchezhian, 2012).

Solar panels from the highest standard manufacturing companies could convert 23% of the solar energy into electricity and it reduces to 9-17% at low solar irradiation conditions. The output of PV panel depends upon weather conditions, radiation level, ambient temperature, type of solar cell and array design quality (Chaitanya *et al*., 2011; Lin *et al*., 2011). The power transfer from PV array to AC load is carried out through power conditioning systems. Since the efficiency of the solar panel is poor, the power conditioning system should have high efficiency. The power conditioning system has two conversion stages. The first stage of power conversion in PV Panel is DC-DC converter with maximum power point tracking and the second stage is dc-ac inverter which is supplying power to the load (Marimuthu *et al*., 2012; Jung *et al*., 2011).

The MPPT improves the power output of the PV system by tracks the maximum power point of the PV array under all atmospheric conditions Implementation of the MPPT techniques increases the output power from PV array by 45.2% for a clear sunshine day (Bahgat *et al*., 2005).

This study is mainly concentrated to improve the efficiency of power electronic converters in the power conditioning systems by reducing the power losses. This can be achieved by using interleaved soft switching dc-dc converter topologies (Kim *et al*., 2010).

Proposed system: The proposed PV power generation system for DC loads as shown in Fig. 1 with the following subsystems:

- PV Panel
- Interleaved soft switching converter
- P&O fuzzy MPPT Technique
- DC Load

PV panel: This section briefs the equivalent circuit, PV panel Specifications and the characteristics of the solar cell.

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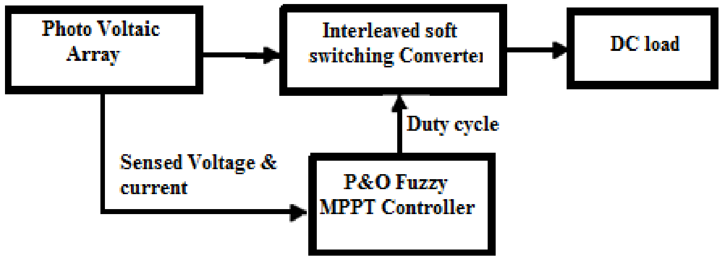

Fig. 1: MPPT controlled PV system block diagram

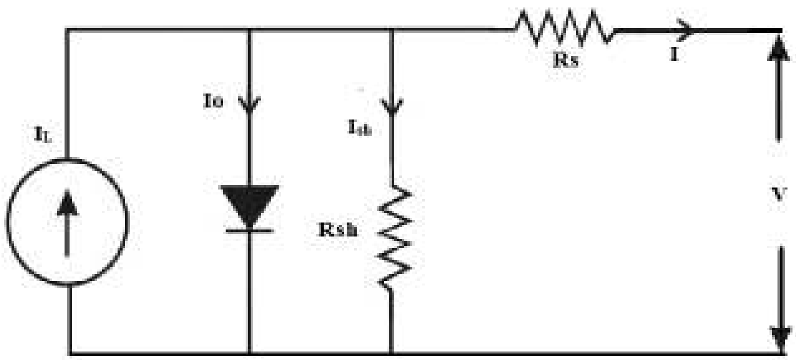

Fig. 2: Equivalent circuit of PV solar cell

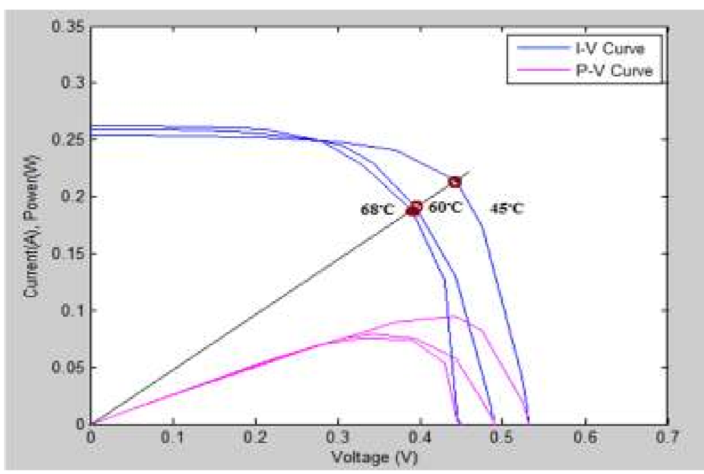

Fig. 3: Output I-V curve under varying temperature

- **PV equivalent circuit:** Basically a solar cell is a p-n semiconductor junction. A DC current is generated when cell exposed to light, Fig. 2 shows the standard equivalent circuit of the PV cell (Pradeepa and Sankar, 2013). The relation between the voltage and current is enumerated by the Eq. (1):

$$I = I_L - I_0 \left(e^{q(V+IR_s)/kT} - 1\right) - (V+IR_s)/R_{sh} \quad (1)$$

I = The cell current (A)
q = The charge of electron = 1.6×10-19(coulomb)
Io = The diode saturation current (A)
I_L = The light generated current (A)
T = The cell temperature (K)
K = The Boltzmann constant (J/K)
V = The cell output voltage (V)
Rsh, Rs = Cell series and shunt resistance (ohms)

PV cell characteristics using solar simulator: The Voltage-Current (V-I) and Power-Voltage (P-V) characteristics of PV cell are non linear and it varies with variation of solar insolation and temperature. The PV Voltage-Current (V-I) and Power-Voltage (P-V) characteristics under varying illumination level and temperature are shown in Fig. 3 and 4.

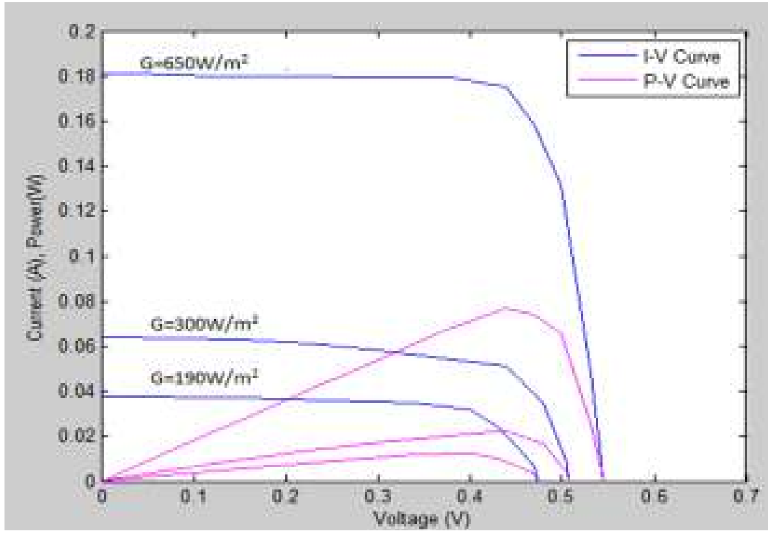

Fig. 4: Output I-V curve under varying illumination

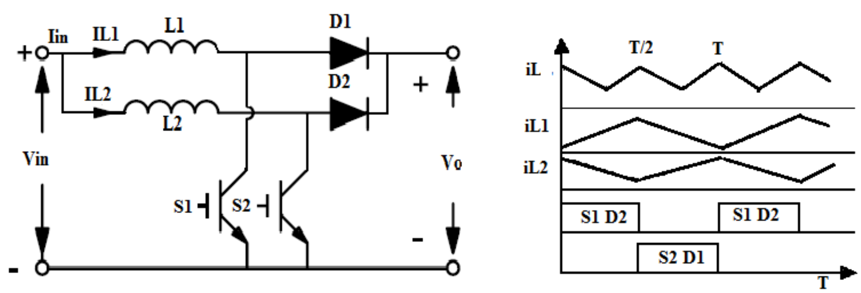

Fig. 5: Circuit diagram and wave forms of interleaved converters

Table 1: PV panel specifications

Monocrystalline	
Peak power (Pmax)	10W
Maximum Current (Imp)	0.59A
Maximum Voltage (Vmp)	17V
Open circuit Voltage (Voc)	21V
Short circuit current (Isc)	0.62A
Tolerance	5%

The PV array produced maximum power as well as maximum efficiency at a particular point in the P-V curve which is known as maximum power point as shown in the Fig. 3. The readings were obtained using solar simulator as shown in Table 1.

INTERLEAVED RESONANT CONVERTERS

This sections deals with the pros and cons of dc-dc converters, interleaved converters and the advantages of interleaved soft switching converters.

DC-DC converters: The output of PV array is given to DC-DC boost converters with MPPT control to provide uniform power to the load. It is widely used in photovoltaic power applications because of its simple topology, continuous input current and fast transient response. The converters have to be operated at extreme duty cycle for providing high output voltage (Kamtip and Bhumkittipich, 2011; Yazadani *et al*., 2011; Safari and Mekhilef, 2011; Jaen *et al*., 2008). The coupled inductors can provide high output voltage and less switching voltage stress without extreme duty cycle. But the efficiency of the converter is reduces due to leakage energy loss in the coupled inductor (Park *et al*., 2011).

Interleaved soft switching converters: The performance of the boost converter is to be improving by using interleaving technique. Interleaving is the process of connecting two or more switching converters in parallel. The ripple content reduces by increase in the number of phases. As compare to conventional converters the two phases interleaved boost converter is reduce the ripple content by a factor of 9%. For different phases, angle difference between the PWM controls signal should be maintained 360/n where n is the number of phases. For a two phase converter it would be 180 degrees. In interleaved boost converters, the amount of ripple in input current is reduced by summing of two inductor current iL1 and iL2 as shown in Fig. 5. Hence, it is also reduced the current rating of the switching devices up to 50% compared to conventional converter (Pinherio *et al*., 1999) as well as size of the inductor can be reduced by a factor of four.

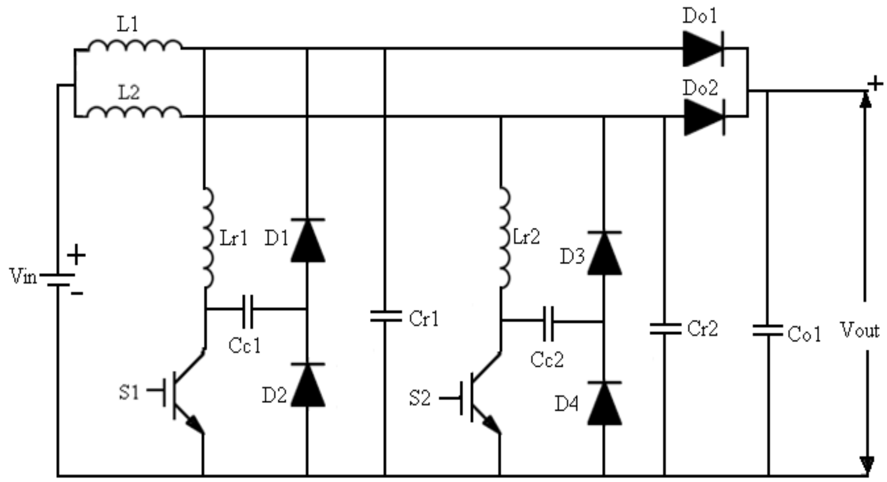

Fig. 6: Interleaved soft switching (resonant) converter

The increase in the number of switching devices like MOSFETs and diodes increases the switching losses.

In order to minimize the switching losses, Soft Switching techniques like ZCS (Zero current switching), ZVS (Zero voltage switching) and resonant switching techniques as in Fig. 6 which turn on the devices at zero current and turn of the devices at zero voltage were preferred (Marimuthu *et al*., 2012; Safari and Mekhilef, 2011; Kim *et al*., 2010).

In all phases the number, type and ratings of the components should be the same. This lead the efficiency will be around 98.5%.

Design of interleaved resonant converter: Boosting ratio is:

$$\frac{V_O}{V_i} = \frac{1}{1-D} \quad (2)$$

The duty ratio is:

$$D_{(min)} = 1-(V_{imax}/v_{omax}) \quad (3)$$

$$D_{(max)} = 1-(V_{imin}/v_{omax}) \quad (4)$$

Inductor Value can be calculated by using Eq. (5):

$$L = \frac{v_S D}{\Delta I_L F} \quad (5)$$

Capacitor value can be calculated by using Eq. (6):

$$C = \frac{v_o D_f}{R \Delta V_o} \quad (6)$$

where,

ΔI_L = The inductor current ripple
D = The duty ratio
V_S = The source voltage
Vo = The output Voltage (V)
R = The resistance
f = The switching frequency
ΔVo = The change in the output Voltage (V) (Park *et al*., 2011; Kappali and Uday Kumar, 2012)

Maximum power point tracking techniques: In this section an introduction about different type of MPPT techniques was given. Then the simplest type conventional P&O MPPT technique and soft computing Fuzzy MPPT technique were discussed and their advantages and drawbacks were analyzed. Then the P&O fuzzy MPPT technique was developed to overcome the drawbacks of P&O and Fuzzy MPPT techniques.

The process of keeping the operating point of the PV panel at maximum power for the corresponding radiation is known as MPPT. It transfers maximum power from the PV panel to load. The conventional MPPT techniques are of two type's namely interruptive type and non interruptive type.

Conventional MPPT techniques:

Interruptive type (off line): Two methods namely Constant voltage control method for the measurement of open circuit voltage (Voc) and Constant current control method for the measurement of short circuit current (Isc) comes under Interruptive type. This method requires the delinking of the panel from the power electronic converters for the measurement of Voc and Isc which leads to the loss of output power (Salas *et al*., 2006).

Non-interruptive type (on line): In this type the voltage and current are measured by using sensors and the power is calculated. This makes the controller a little bit complicated. The duty cycle of the dc-dc converter is adjusted till the power becomes maximum. In this method there is no need for delinking of the panel from the converters. Perturb and observe (P&O) method, modified P&O method and incremental conductance method are examples of non-interruptive type.

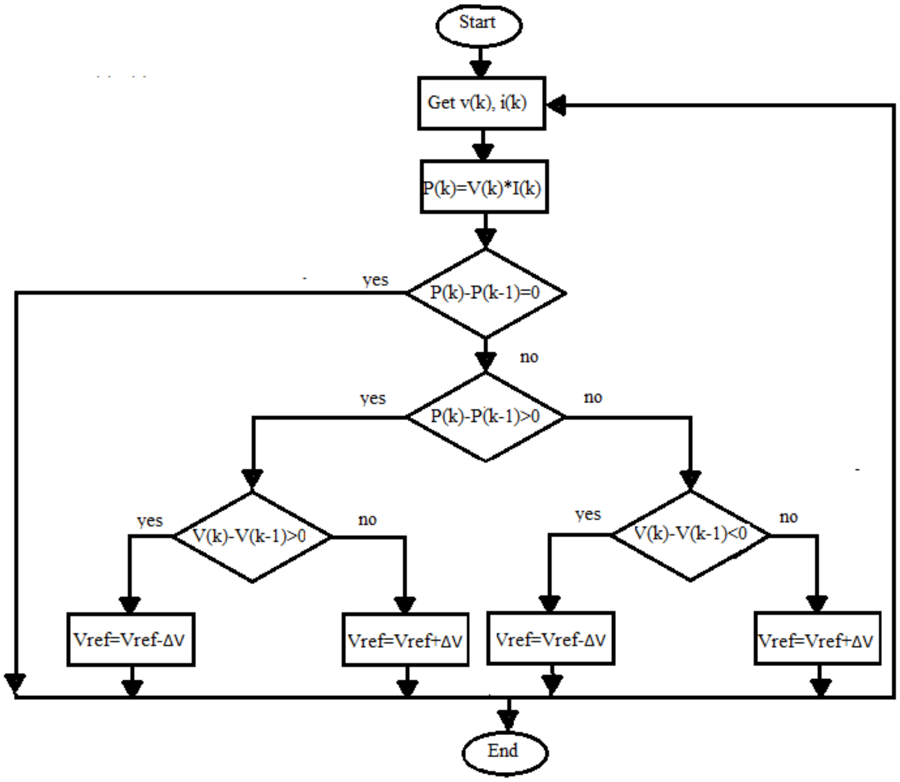

Fig. 7: Flow chart for P&O MPPT technique

Soft computing techniques: The soft computing techniques are flexible, fully digital and effective in handling non linear problems. Since PV characteristics are nonlinear in nature, soft computing techniques will be suitable for MPPT implementation. Fuzzy logic control, Adaptive fuzzy logic control, neural network control, particle swarm intelligence, Ant colony optimization, Genetic algorithm and differential algorithm are examples of soft computing techniques. Among these methods Fuzzy logic controller can be implemented using simple, less expensive microcontrollers (Samer and Basim, 2012).

P&O MPPT technique: It is the simplest type of algorithm. It needs not required previous knowledge of the PV system characteristics. In this algorithm current and the array terminal voltage are sensed and processed as shown in the Fig. 7.

The power output is calculated. The present PV output power is compared with the power of previous perturbation cycle. The PV voltage or current is perturbed periodically after comparing. If the PV operating voltage varies and change of power is greater than zero (dP/dv>0), the algorithm moves the operating point in the same direction and if the change of power is less than zero (dP/dv<0), the algorithm moves the operating point in the opposite direction and the change of power is equal to zero (dP/dv = 0) that represents the condition of maximum power point. The operation of this algorithm can be summarized as in Table 2.

Table 2: Operation of algorithm

Condition	Operating point position	Duty cycle change
$\Delta v_k>0$, $\Delta p_k>0$	Left of MPP	Increased
$\Delta v_k<0$, $\Delta p_k>0$	Left of MPP	Decreased
$\Delta v_k>0$, $\Delta p_k<0$	Left of MPP	Decreased
$\Delta v_k<0$, $\Delta p_k<0$	Left of MPP	Increased

The advantages of P&O algorithm is previous knowledge of the PV array characteristics is not required and its simple procedure. But the oscillation of the operating point around MPP under steady state conditions as in Fig. 8 and inability to respond for the rapid changing atmospheric conditions are the drawbacks of this system (Faranda and Leva, 2008; Dolara *et al*., 2009; Hohm and Ropp, 2003; Onat, 2010).

Fuzzy Logic Systems (FLC): FLC provides an automatic control algorithm by using linguistic variables which may take any value between 0 and 1 (Khan and Hossain, 2010). This algorithm does not require an accurate mathematical model hence the uncertainties such as non linear operating characteristics and unexpected changes in the operating point can be dealt easily. FLC is more suitable for handling non-linear problems.

The FLC system has three processing stages namely rules inferences, fuzzification and defuzzification. It has a rule table to store the fuzzy rules and calculations of FLC are performed in

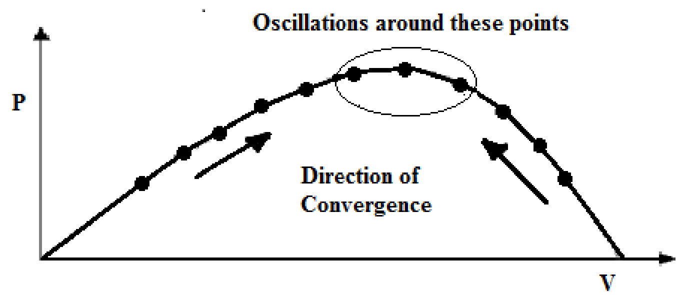

Fig. 8: MPPT convergence

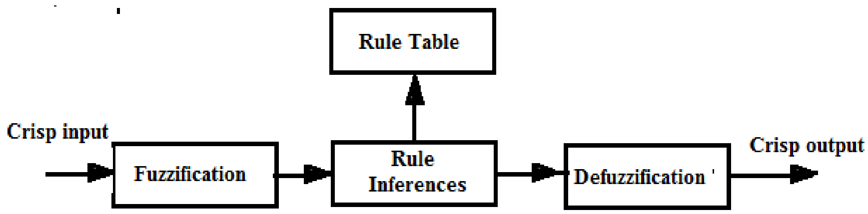

Fig. 9: Block diagram of FLC

Table 3: FLC rules

E\CE	NB	NS	ZE	PB	PS
NB	ZE	ZE	PB	PB	PB
NS	ZE	ZE	PS	PS	PS
ZE	PS	ZE	ZE	ZE	NS
PB	NS	NS	NS	ZE	ZE
PS	NB	NB	NB	ZE	ZE

Rules inference. The system consists of two linguistic input variables namely change in Error (CE), Error (E) and one output variable Duty Cycle (D) as in Fig. 8 (Alabedin *et al*., 2011; Algazer *et al*., 2012; Salam *et al*., 2013).

Fuzzification: The FLC input variables are divided into five subsets namely Negative Small (NS) and Negative Big (NB), Zero (Z), Positive Big (PB), Positive Small (PS). The partition of the fuzzy subsets and shape of the membership functions are shown in Fig. 9. The input error and change in error values are normalized by an input scaling factor such that the input values lie between-1 and 1. To get only one dominant output for a particular input triangular shape of the membership functions were chosen.

The Error (E) and Change in Error (CE) are calculated using the following formulae:

$$P(k) = V(k)*I(k) \tag{7}$$

$$E(k) = P(k) - \frac{P(k-1)}{I(k)-I(k-1)} \tag{8}$$

$$CE(k) = P(k)-P(k-1) \tag{9}$$

where,
V(k) = The current of the PV panel
I(k) = The voltage of the PV panel
P(k) = The power of the PV panel
E(k) = Error value
CE(k) = Change in error value

The current and voltage of the Photovoltaic panel are measured inorder to calculate power. The values of the error (E) and Change in Error (CE) are calculated and used for the Fuzzy Inference System (FIS).The inputs are processed by fuzzy set of rules. The output of the inference system is subjected to defuzzification. The defuzzifier output is the change in the duty cycle. The change in the duty cycle is given to dc-dc converter to track the maximum power point of the PV panel (Fig. 10).

Inference method: The Mamdani fuzzy inference method is used. The MAX-MIN method is commonly used from several composition methods such as MAX-MIN and MAX-SOT are in fuzzy tool box and the same is used in this analysis also. The rule table for the FLC is given by Table 3.

Defuzzification: The fuzzy set is a output of fuzzy inference system. But non fuzzy value is necessary to control the dc-dc converter. For that many defuzzification methods are available such the centroid method, mean of maximum method, first of maxima method and last of maxima method. The centroid method is used in our system. The formula for defuzzification using centroid method is given by Eq. (10):

$$D = \frac{\sum_{j=1}^{n} u(D_j)-(D_j)}{\sum_{j=1}^{n} \mu(D_j)} \tag{10}$$

where,
D = The duty ratio

P&O fuzzy technique: The P&O FLC system using microcontroller is designed for the improved MPPT, based on the following points:

- In P&O method the oscillation of the operating point around MPP under steady state conditions and inability to respond for the rapid changing atmospheric conditions can be improved either by increasing the speed of operation of the algorithm or by using optimization technique (Samer and Basim, 2012; Faranda and Leva, 2008).
- The performance P&O method can be improved by using FLC which provides dynamic modification of the step size and makes system to reach the MPPT faster (Alabedin *et al*., 2011).
- The implementation of fuzzy logic control is easy and requires compact size, low cost components El Khateb *et al*., 2013; Mahammad *et al*., 2013).
- The P&O fuzzy technique will have the simplicity of P&O with the elimination of oscillations at MPP.
- The FLC deals with variable step size to increase or decrease the reference voltage. This reduces the tracking time. The performance of the system during steady state conditions is better than compared with the conventional P&O system.
- The rule table of FLC cannot be changed dynamically. To overcome this difficulty the FLC can be coupled with traditional P&O controller. Hence implementation of P&O technique is preferred (Hohm and Ropp, 2003).
- The zero membership function helps to keep the system without oscillations at MPP during steady state.

Though there are several MPPT techniques, the commonly used technique is P&O and Fuzzy in most of the papers.

From random analysis carried out from IEEE papers for the year 2012, out of 27 seven papers, P&O and modified P&O MPPT used in nine papers, Fuzzy in three papers, incremental conductance in two papers, fuzzy combined with other conventional methods four papers and all other MPPT techniques in nine papers were used.

The above points lead to the selection of P&O fuzzy MPPT selection for this analysis. The fuzzy block diagram and P&O fuzzy block shown in Fig. 10a and b.

SIMULATION RESULT

The simulation study is carried out using MATLAB simulink environment for soft switching interleaved for different MPPT Technique as shown in the Fig. 11 to 13. The output of the converter with various MPPT algorithms is verified. While compare

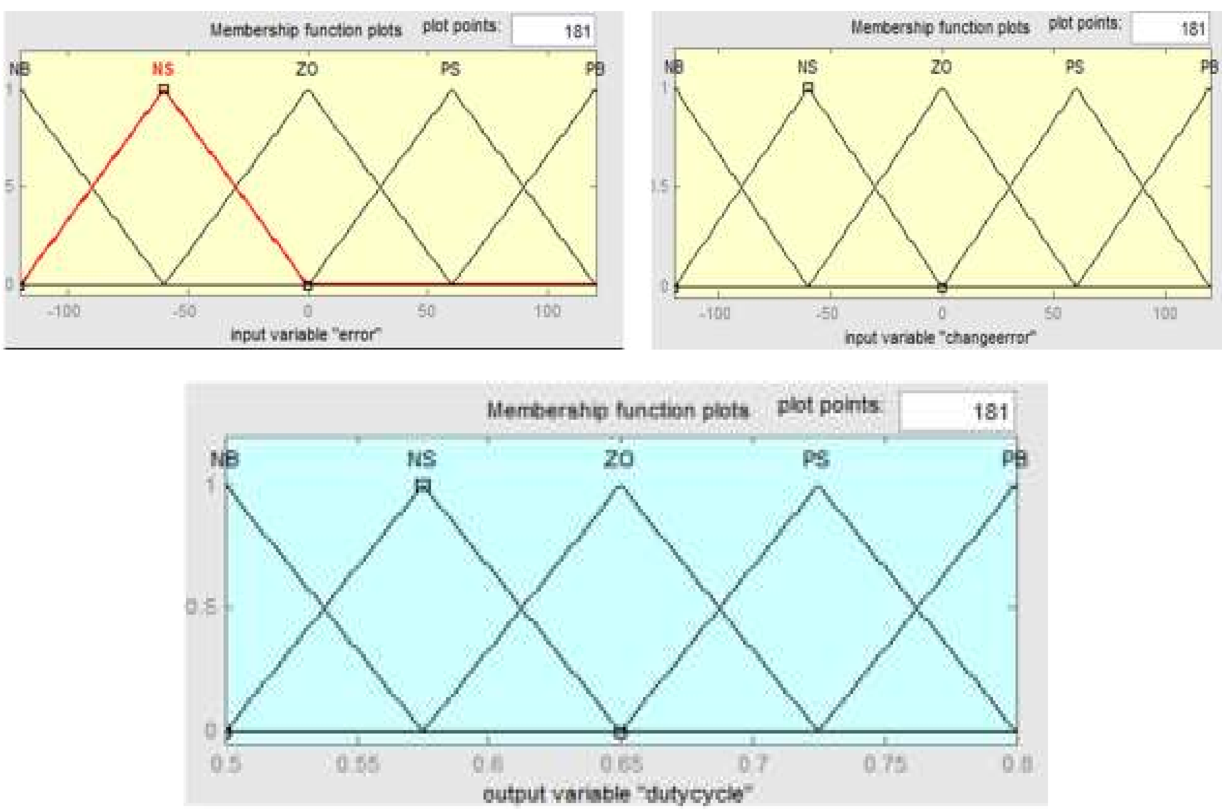

Fig. 10: Fuzzy logic memebership functions for input and output variables

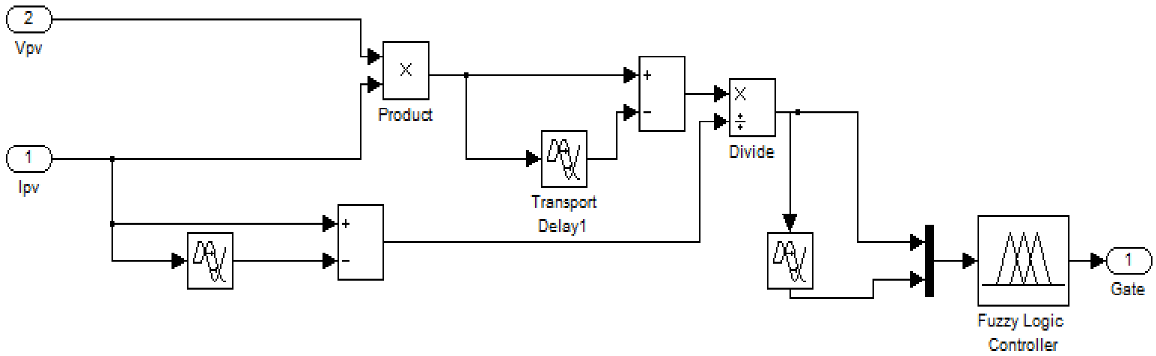

Fig. 10a: Simulated fuzzy block

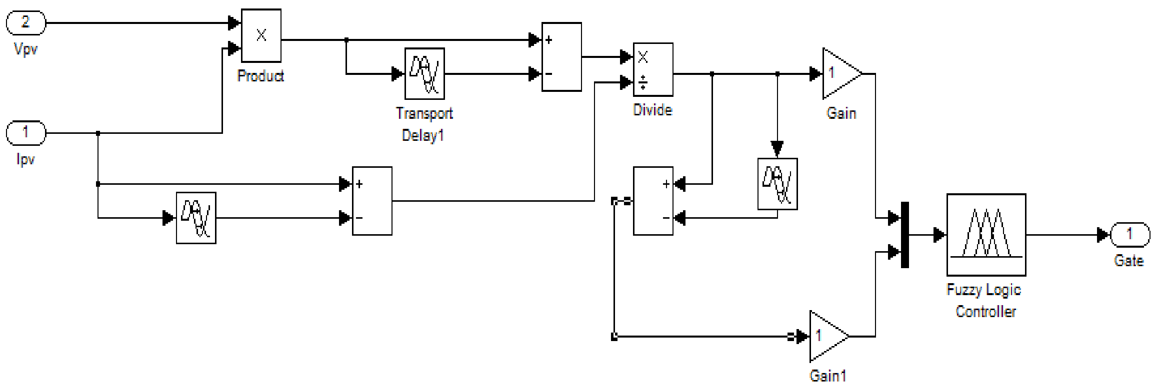

Fig. 10b: Simulated P&O fuzzy block

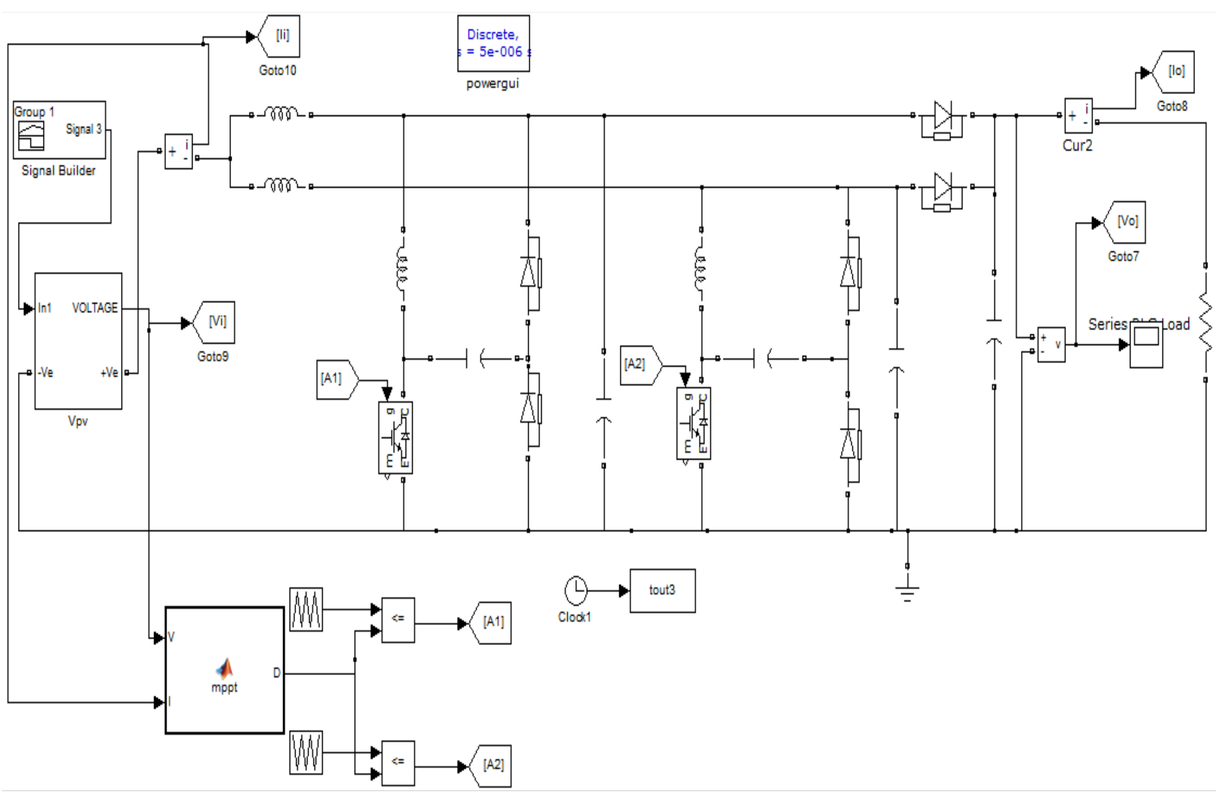

Fig. 11: Simulation of soft switching converter using MPPT

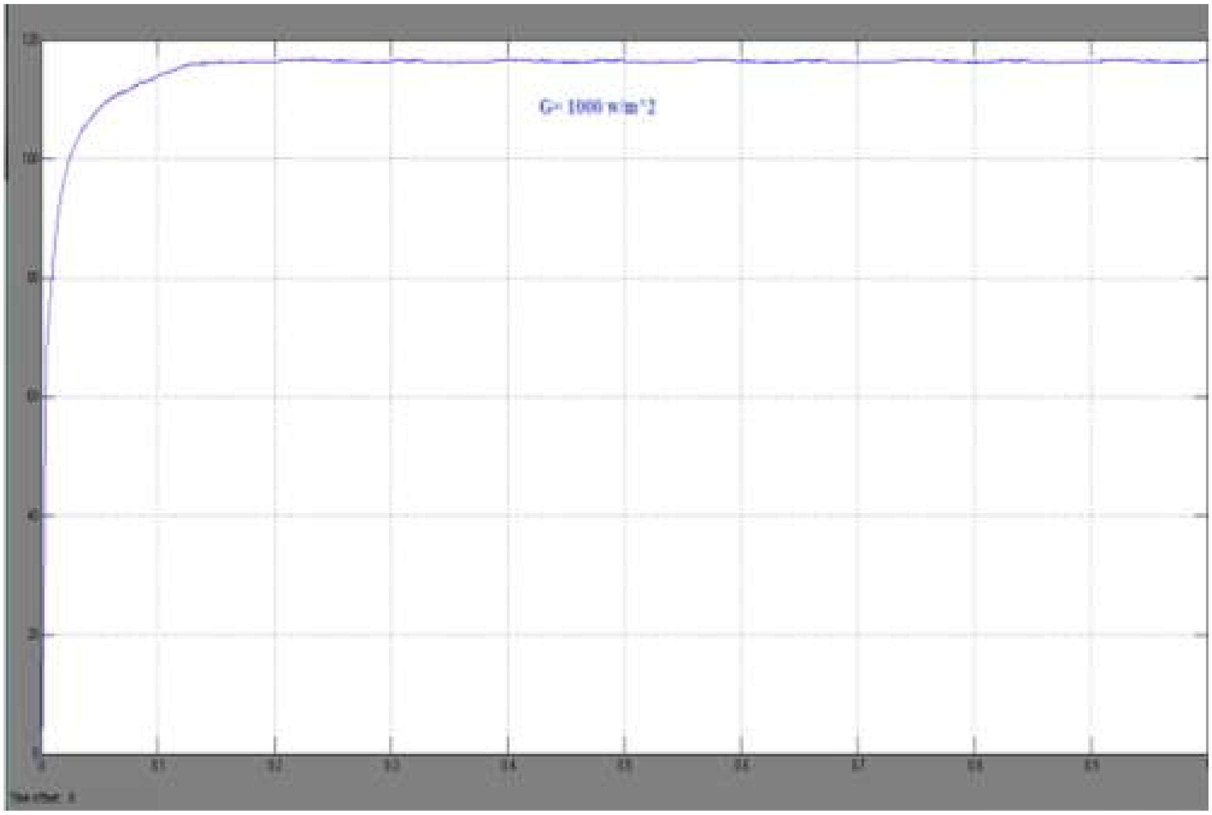

Fig. 11a: Simulations results for P&O MPPT technique for constant illumination

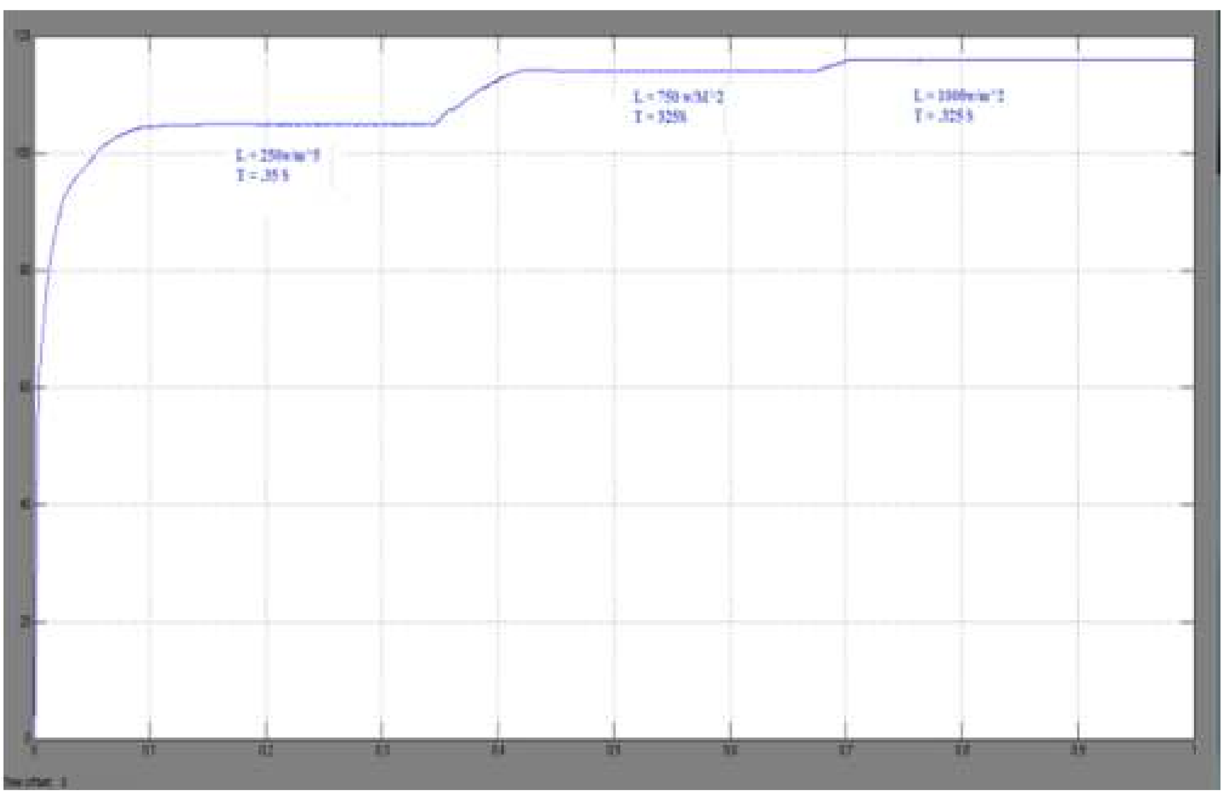

Fig. 11b: Simulations results for P&O MPPT technique for varying illumination

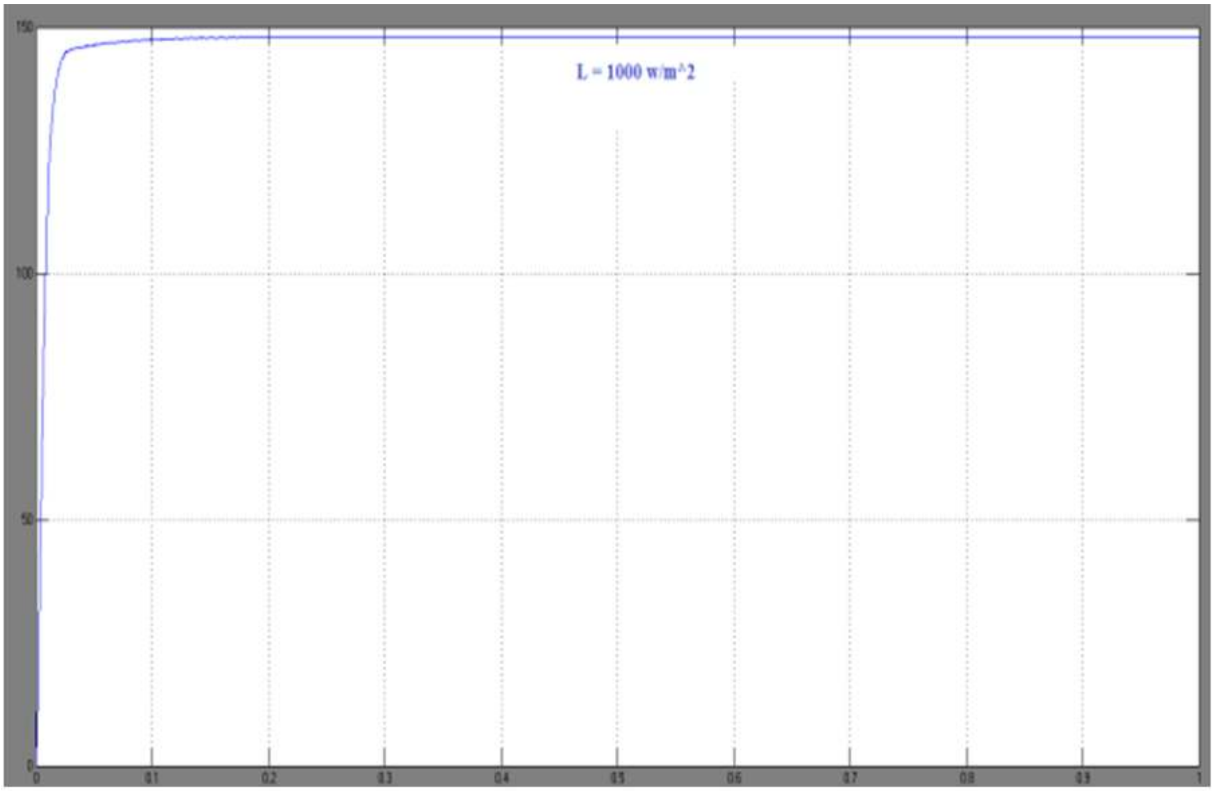

Fig. 12a: Simulations results for fuzzy MPPT technique for constant illumination

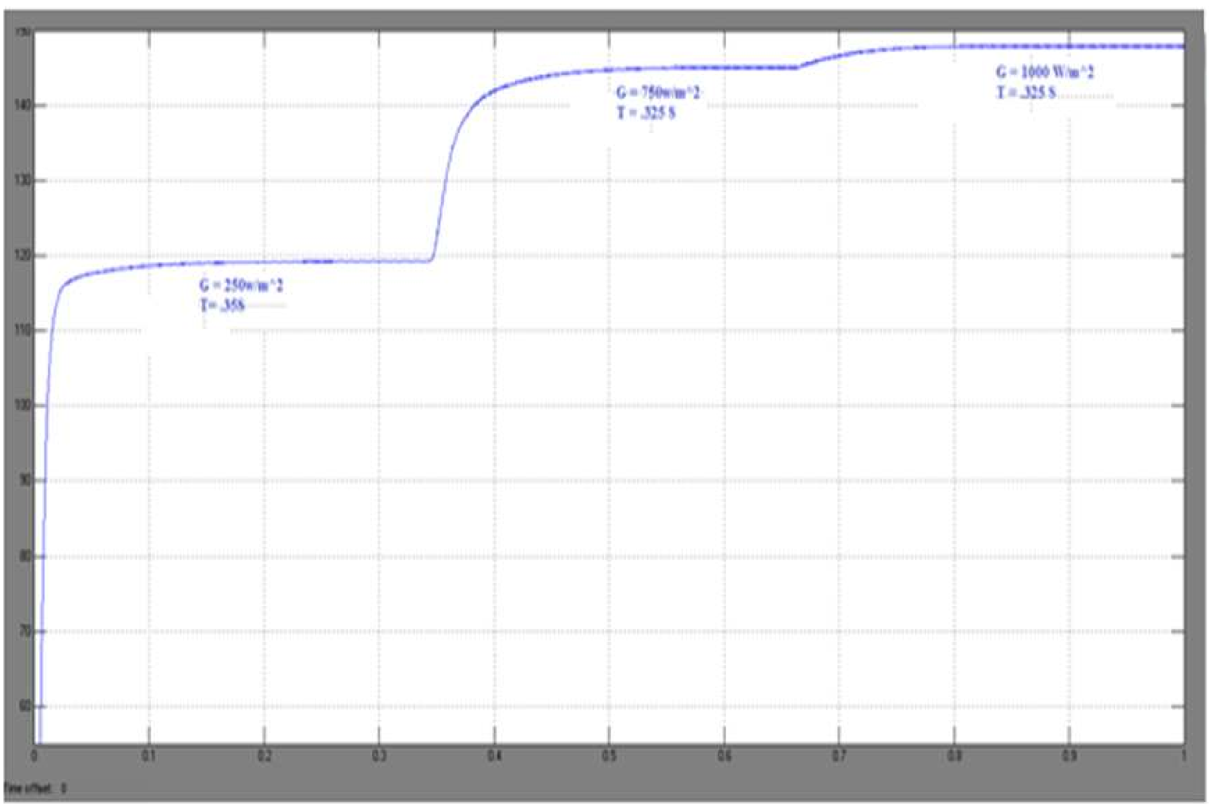

Fig. 12b: Simulations results for fuzzy MPPT technique for varying illumination

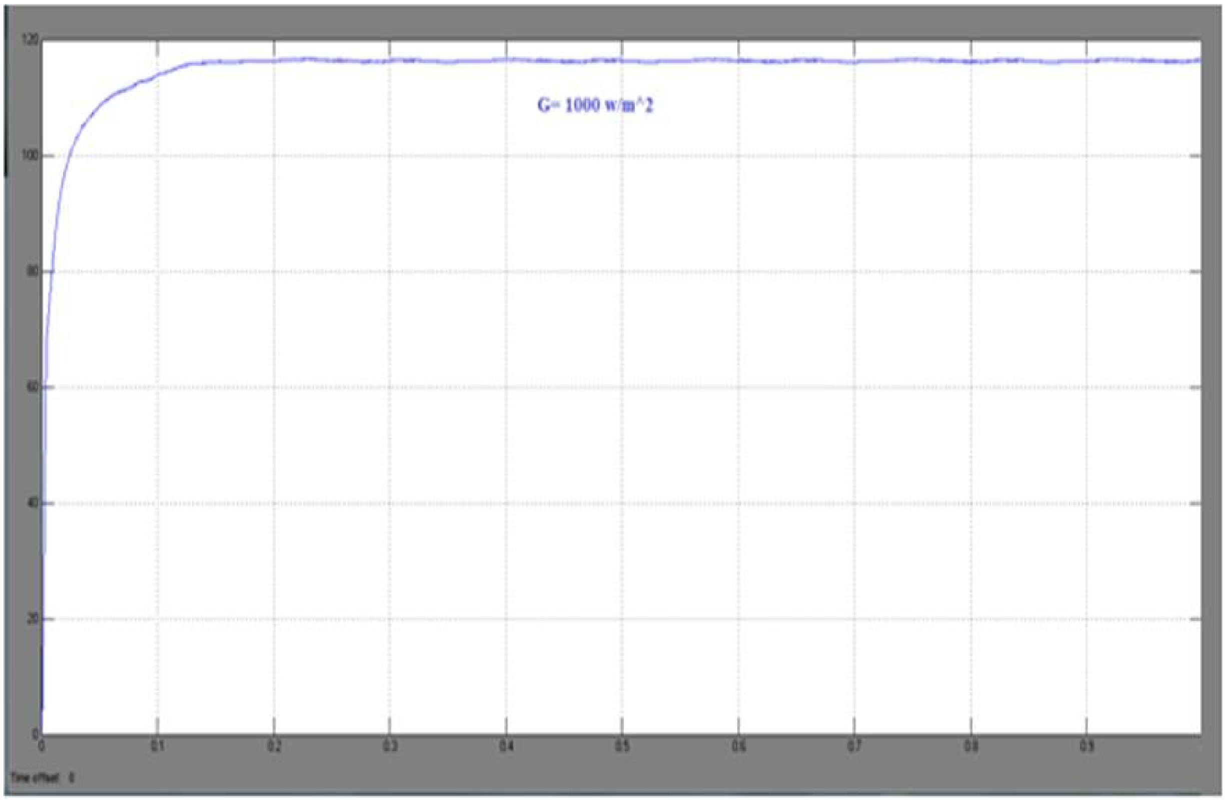

Fig. 13a: Simulations results for P&O fuzzy MPPT technique for constant illumination

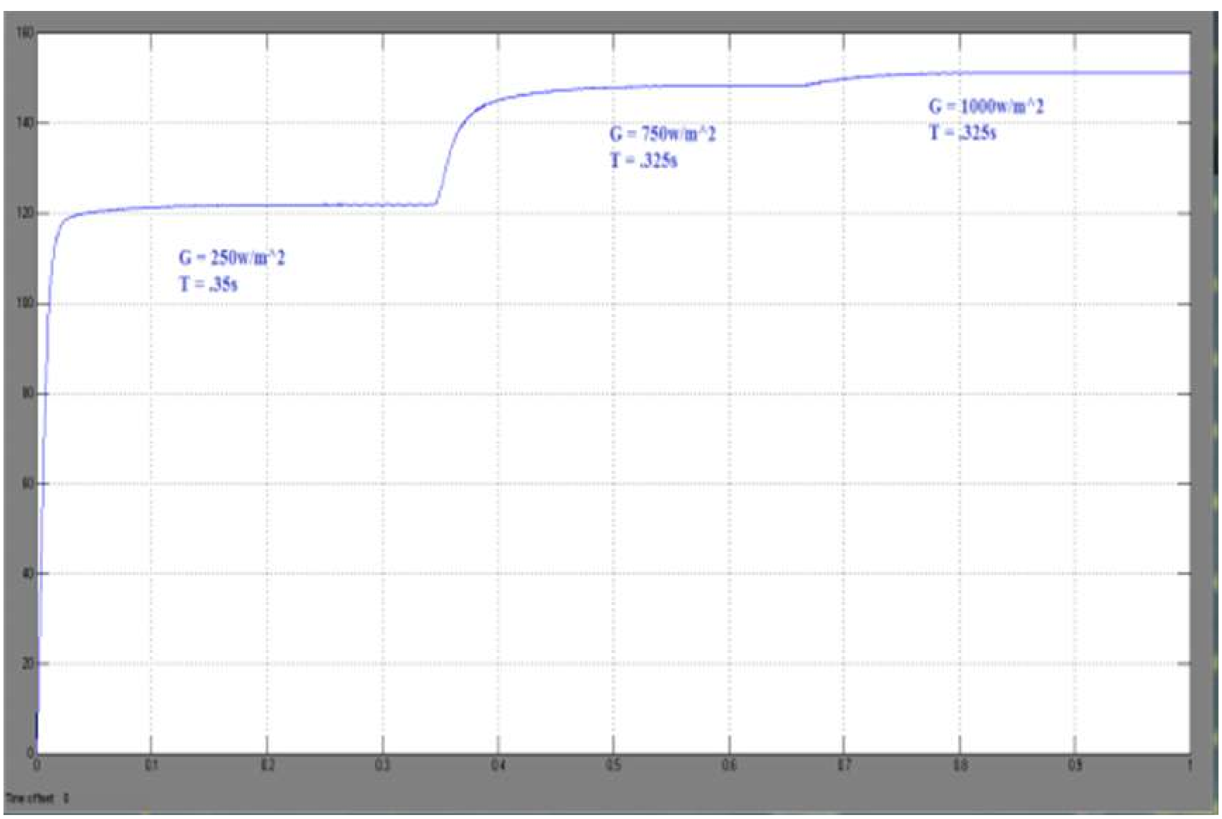

Fig. 13b: Simulations results for P&O fuzzy MPPT technique for varying illumination

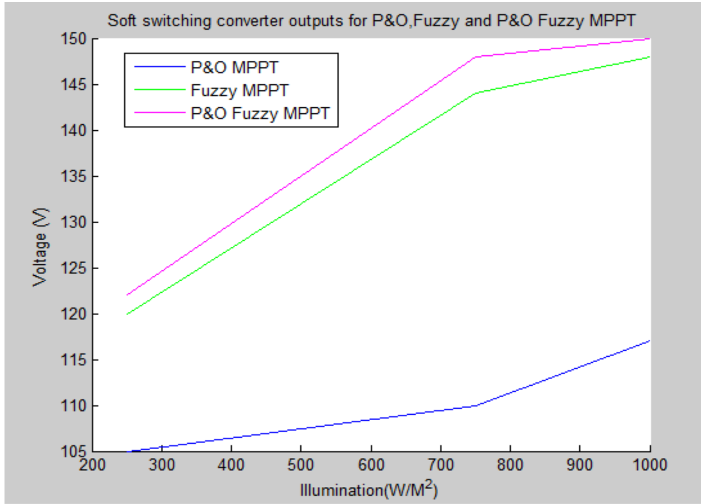

Fig. 14: Soft switching converter outputs for various algorithm

with different MPPT Technique like P&O, Fuzzy and P&O Fuzzy MPPT, the output of the P&O Fuzzy MPPT is improved to the maximum level as shown in Fig. 14.

CONCLUSION

The soft switching interleaved converter has been designed and developed. The function of soft switching interleaved converter is modeled using MATLAB Software. The Simulation of soft switching interleaved converter is carried for different MPPT techniques such as P&O, Fuzzy and P&O Fuzzy MPPT. The effectiveness of the P&O Fuzzy MPPT Technique is verified through the simulation results. The Soft Switching Interleaved Boost converter provides low switching losses and improves overall efficiency of the converter.

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