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Modelling and Evaluation of MPPT Techniques based on a Ćuk Converter

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***Abstract* — Solar PV plays a vital role in meeting the current power requirements. India has been a forerunner in the utilization of solar energy and currently SPV is the second most used renewable energy source, first being wind energy. For availing most of the power generated by PV panels, we make use of MPPT techniques. The two main environmental factors that affect the output of a PV system are the temperature level and Irradiance level. In this work, the temperature as well as irradiance level for varying atmospheric condition are given from historically available data for Southern India. A PV system for varying atmospheric conditions are modelled using Matlab Simulink and Five MPPT techniques are evaluated based on a Ćuk converter.**

***Keywords*— Solar PV, Ćuk Converter, Photovoltaics, Maximum Power Point Tracking**.

I. INTRODUCTION

India is currently the Fifth largest producer and consumer of electricity in the world. Also it has been a front runner in the usage of renewable energy, in fact India was the first country to include a separate ministry under the government for renewable energy sources. Solar energy is abundant in nature and is free to use Solar PV is the simplest and cheapest mode for transforming incoming solar radiation to electrical energy. Many papers have been published on the mode of conversion. In order to utilize the most of the generated power, we make use of Maximum Power Point Techniques. There are several MPPT techniques that are simple, complex and hybrid in nature. Most of the techniques senses the voltage/current or power, however there are methods which senses temperature and/or irradiance level to track down the MPP. The implementation of the technique can be done on any of the DC-DC converters.

The max power is extracted while operating at the intersection of the I-V, P-V curve [1] namely I_{mp} and V_{mp} as shown in figure 1.

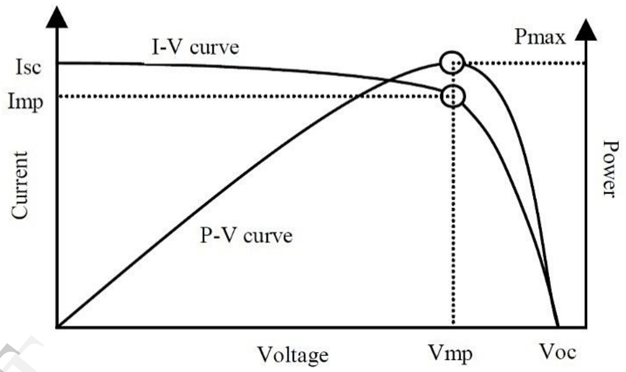


Fig. 1 Current-voltage and power-voltage characteristics of a solar cell

The operation of MPPT are based on the maximum power transfer theorem, the maximum power is transferred when the source impedance matches the load impedance. For standalone systems, it is achieved by varying the duty ratio of DC – DC converters, the change in duty ratio matches the change in impedance level due to varying environmental conditions. Several MPPT methods have been reported on this field. [2,3]These methods can be basically classified as: i) methods based on loadline adjustment of *I-V* curve and ii) method based on artificialintelligence (fuzzy logic or ANFIS based MPPTmethods).The MPPT techniques such as Perturb and Observe, Incremental conductance are based on *I-V* curve and hence are not suitable for highly varying atmospheric conditions. The artificial intelligence based methods are robust in nature and are found to be useful in such conditions. Usually the mode of MPPT is chosen with certain aspects in mind while designing a certain application. The factors to be considered are simplicity, cost, time for tracking the maximum power point and also the importance of application it fulfills.

In this work, five MPP techniques namely, Perturb & Observe (PO), Incremental Conductance Method (ICM), Fractional Short Circuit Current (FSSC), Fractional Open Circuit Voltage (FOCV) and a Fuzzy based System are evaluated on a Ćuk converter. The temperature and insolation values are provided in accordance to the historical data available. The Ćuk converter is designed such that the output voltage is limited to 1% and also the duty ratio is set to 58%. The modelling of PV systems, MPPT techniques, Ćuk converter and comparative analysis of five MPPT techniques is discussed in the following sections...

II. MODELLING OF PV MODULE

The Photovoltaic cell is basically a p-n junction fabricated in a thin wafer of semiconductor in which solar energy is directly converted to electricity by means of photoelectric effect. A PV cell exhibits nonlinear P-V and I-V characteristics that vary with cell temperature (T) and Solar Irradiance. [4] Usually a solar cell can be modelled by a current source with a diode in anti-parallel as shown in figure. The series resistance (Rs) represents the hindrance that occurs during the flow of charge from n–p and the parallel resistance (Rp) represents the leakage current. For an ideal solar cell, Series resistance is zero and Parallel resistance is infinity. The one diode equivalent circuit is shown in figure 2.

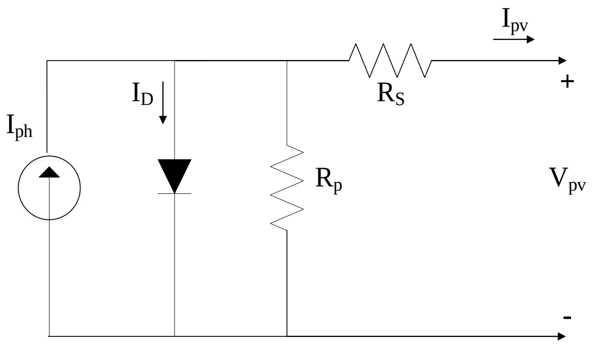


Fig. 2 One Diode Equivalent Circuit of PV Cell

The output current of a PV module is given by

$$I = N_p I_{ph} - N_p I_o \left(exp\left[\frac{q(V/Ns + IRs/Np)}{AkT}\right] - 1 \right) - \frac{V + IR_s}{R_p} \quad (1)$$

where, *I* is the current, *V* is the voltage of the PV module, *Iph*is the photo-current, *I0* is the reverse saturation current, *Np* isthe number of cells connected in parallel, *Ns* is the number ofcells connected in series, *q* is the charge of an electron ($1.6*10^{-19}$C), *k* is Boltzmann's constant (1.38*10-23J/K), *A* is *p-n* junction ideality factor, (1 <*a* < 2, *a* = 1 being the ideal value), and *T* is the PV module temperature.

For a solar cell, the only generated current is by means of a photo current which is directly dependent ontemperature as well as irradiance level given by

$$I_{ph} = [I_{sc} + k_1(T - T_{ref})]G \quad (2)$$

Where Isc is the short circuit current of the PV cell, K1 is the short-circuit current/temperature coefficient T is the present atmospheric temperature and Tref is the temperature at nominal condition (250°C and 1000W/m^2), G is the present irradiance level.

The output of a single solar cell will be very low, so usually cells are connected in series to attain higher voltages and in parallel for higher current levels. The PV module considered for simulation was Tata TP 250 Series with specifications at Nominal Operating Cell Temperature (NOCT – 20°C& 800 W/m^2) was considered rather than Standard Test Condition (STC – 25°C & 1000W/m^2).

The electrical parameters of the TP 250 series PV module is as shown in Table 1.

Electrical Parameters	Value
Maximum Power (P_{max})	180
Voltage at P_{max} (V_{mp})	26.7
Current at P_{max} (I_{mp})	6.74
Open Circuit Voltage (V_{oc})	32.8
Short Circuit Current (I_{sc})	7.35
Number of Series Cells (N_s)	60
Number of Parallel Cells (Np)	1

Table 1. PV Module Parameters

The simulated PV module is shown in figure 3.

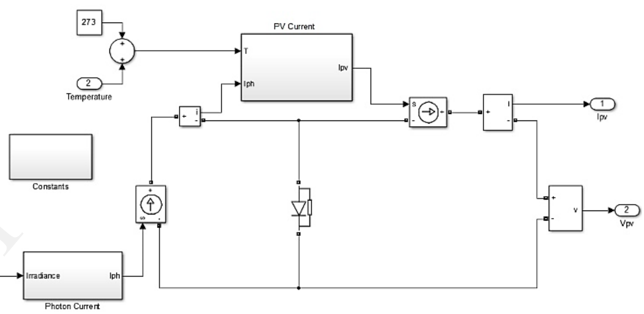


Fig. 2 PV module model

III. INTRDUCTION TO MPPT TECHNIQUES

For extracting the maximum power from a PV module, we make use of MPPT techniques. The basic principle of any MPPT is the maximum power transfer theorem, whenever the source impedance matches the source impedance, the maximum power transfer occurs. As PV module is highly nonlinear and hence its impedance varies. So in order to matchup with that varying impedance we make use of Maximum Power Point algorithms.

A. Perturb and Observe Method

The PO method is the simplest, cheapest to implement MPPT.[5] In PO method, the voltage and current of the PV module is sensed by means of sensors and the PV power P_1 is calculated. Now for a change in voltage due to change in duty ratio produces another power P_2. If $P_2 > P_1$, then the perturbation is in the correct direction, if not it is reversed. The process is repeated and slowly the Maximum Power Point is attained, afterwards it just oscillates around that point. The main drawback of the PO method is that it doesn't stop at the MPP, but go on perturbing on either side and hence creates a number of maxima. Also the algorithm fails when the irradiance level drops suddenly due to some moving cloud or shadow falling on the module etc. The flowchart of PO is shown in figure 3.

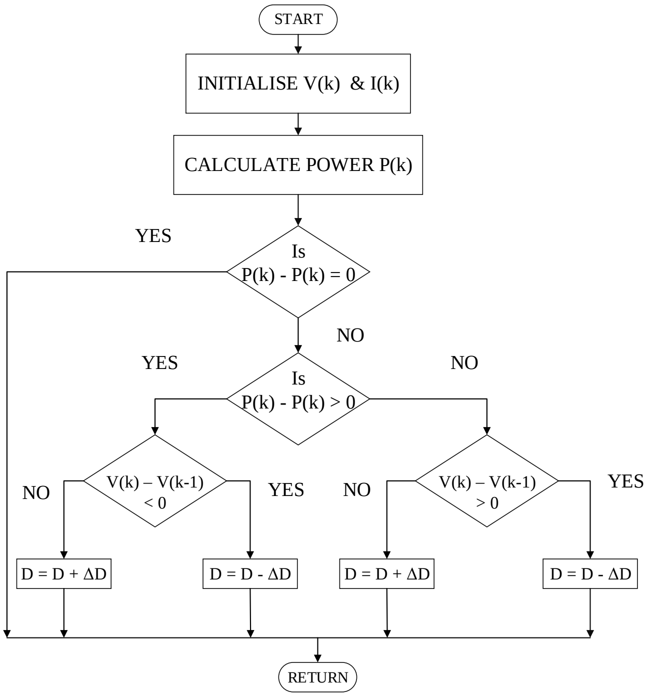


Fig.3 Perturb and Observe Algorithm

B. *Incremental Conductance Method*

The Incremental conductance method also senses voltage and current of the panel, it is based on the fact that slope of the P-V characteristics is zero at maximum power point (dP/dV=0) and increases on the left (positive) of MPP and decreases on the right (negative) of MPP and hence the MPP can be found in accordance to the PV voltage conductance [6].With Incremental conductance the left side represents the instantaneous conductance becomes equal to the PV conductance the MPP is attained. The main advantage of the INC method is that it can rapidly track change in irrac and can respond with a fair bit of accuracy. The disadva is that it is slightly complex in nature and also the cost is a concern. The slope is given by

$$\frac{dP}{dV} = \frac{d(V * I)}{dV} = I + V\left(\frac{dI}{dV}\right) = 0 \quad (3)$$

At MPP

$$\frac{\Delta I}{\Delta V} = -\frac{I}{V} \quad (4)$$

On the left of MPP

$$\frac{\Delta I}{\Delta V} > -\frac{I}{V}$$

On the right of MPP

$$\frac{\Delta I}{\Delta V} < -\frac{I}{V}$$

The flowchart is as shown in figure 4.

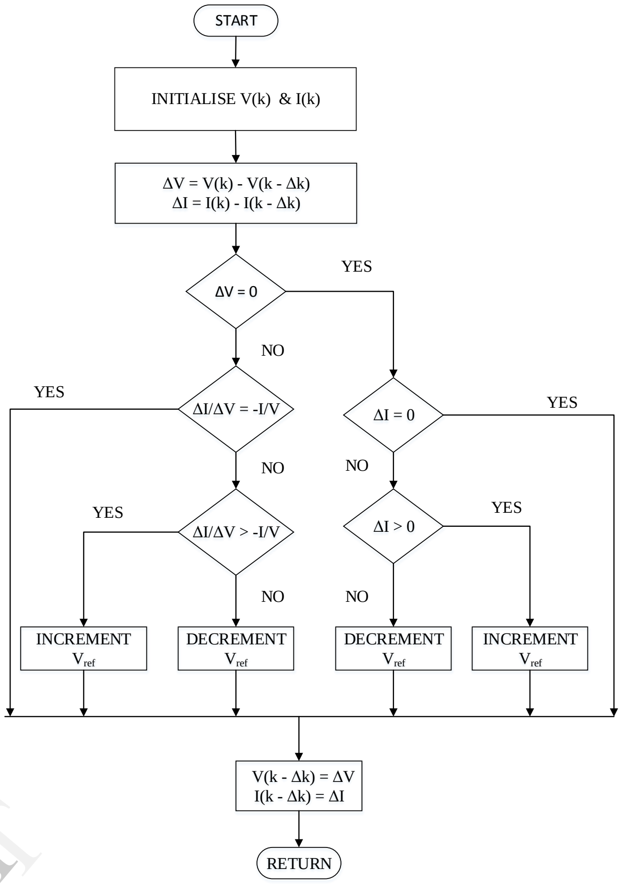


Fig. 4 Incremental Conductance Algorithm

C. *Fractional Open Circuit Voltage Method*

The maximum power point voltage has a linear dependency between open circuit voltages under different atmospheric conditions given by

$$V_{MPP} = k_V * V_{OC} \quad (7)$$

The constant K_V depends on the type and configuration of PV module. Although the method is simple and robust, it is not a true MPPT method as there is no actual tracking of the available power [7].Once the constant of proportionality, k_V, is known, the MPP voltage V_{MPP}can bedetermined periodically by measuring V_{OC}. To measure $V_{OC}$the power converter has tobe shut down momentarily so in each measurement a loss of power occurs. Anotherproblem of this method is that it is incapable of tracking the MPP under irradiationslopes, because the determination of $V_{MPP}$is not continuous. One more disadvantage isthat the MPP reached is not the real one because the relationship is only anapproximation. The value of K_V has been founc (5) between 0.71 and 0.78.

D. *Fractional Short Circuit Current Method*

The maximum power point can also be determined from the short circuit current because I_{MPP} is linearly related to varying environmental conditions given by

$$I_{MPP} = K_I * I_{SC} \quad (6 \ (8)$$

Here too, the constant depends on the type of panel and system [7]. Measuring the short circuit current while the system is operating is a problem. It usuallyrequires adding an additional switch to the power converter to periodically short the PVarray and measure I_{SC}. In $I_{SC}$is measured by shorting the PV array with anadditional field-effect transistor added between the PV array and the DC link capacitor. The K_I value was found to be in between 0.78 and 0.92.

E. Fuzzy Based System

The advent of VLSI has made fuzzy based MPPT the most popular over the years. It can be stated as accurate when compared to other techniques because of its good and fast response to varying temperature and irradiance levels. Also the Fuzzy based system doesn't require an exact model of the PV module for the designing the controller. There are three stages – Fuzzification, Inference (Rule base Lookup table) and Defuzzification. During the Fuzzification process, the input variables are transformed into a linguistic variable based on crisp sets of membership function. The number of membership functions used depends on the accuracy of the controller, but it usually varies between 5 and 7. The seven fuzzy levels used are namely - NB (Negative Big), NM (Negative Medium), NS (Negative Small), NZ (Negative Zero), ZE (Zero), PZ (Positive Zero), PS (Positive Small), PM (Positive Medium) and PB (Positive Big) [8]. In most of the works, the fuzzy based MPPT has two inputs and one output. The two inputs being Error and change in error given by

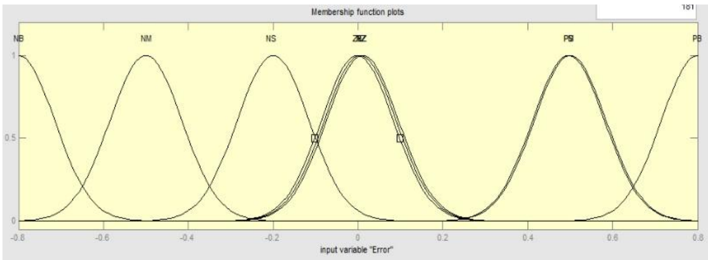
$$E(k) = \frac{\Delta I}{\Delta V} + \frac{I}{V} \quad (9)$$

$$\Delta E(k) = E(k) - E(k-1) \quad (10)$$

Where, I is output current from PV array; V is voltage from array,$\Delta I = I(k) - I(k-1)$and$\Delta V = V(k) - V(k-1)$.

The output of the fuzzy logic converter is usually a change in the duty ratio of the powerconverter, ΔD, or a change in the reference voltage of the DC-link, ΔV. The rule base,also known as rule base lookup table or fuzzy rule algorithm, associates the fuzzyoutput to the fuzzy inputs based on the power converter used.The advantages of these controllers, besides dealing with imprecise inputs, not needingan accurate mathematical model and handling nonlinearity, are fast convergence and minimal oscillations around the MPP. Furthermore, they have been shown to perform well under step changes in the irradiation.

Next comes the inference part, which can be carried out using many of the available methods – Mamdani's method is the most widely used technique. The Final stage is the defuzzification, which is done using the centroid method produces the Output which is the required duty cycle.



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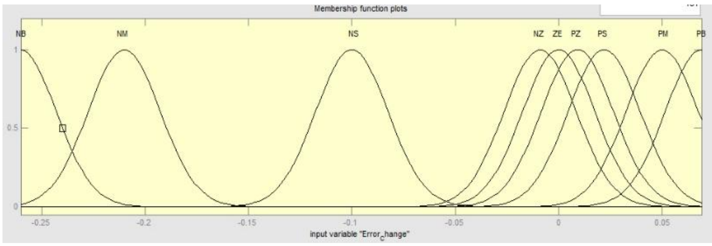

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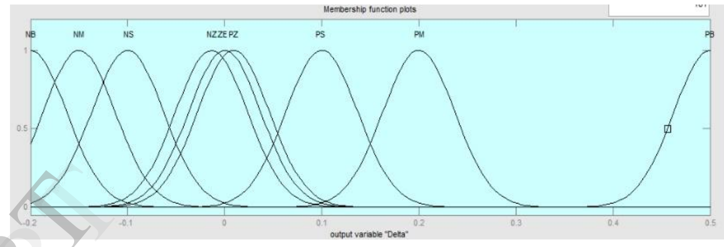


(c)

Fig. 5 Fuzzy Membership Function

(a) Input – Error (b) Input – Error Change (c) Output- Delta D

IV. ĆUK CONVERTER

The main component of an MPPT system is a DC-DC converter which is used for converting unregulated DC voltage to a controlled DC output with desired voltage level. While the same converter uses the converter for another purpose. A DC – DC Converter in a MPPT system regulates the PV maximum power point and provides load matching for maximum power transfer to occur. For this regulation purpose any DC – DC converters can be used and is dependent on the application for which it is used. While the DC – DC converters match the change in source impedance due to varying atmospheric conditions by changing the duty ratio. For this work, I will be using a Ćuk converter which drives a constant load. The converter is as shown in figure 6.

When the switch S1 turns on, inductor L_1 will be charged and capacitorC_1 discharges energy through S_1 simultaneously the current I_{L2} will be negative and the capacitor C_2 and inductor L_2 will damp their energy to the load togetherand the current of capacitor C_2 flows via diode D. Inductor L_2 will release its energy to the load at the same time.

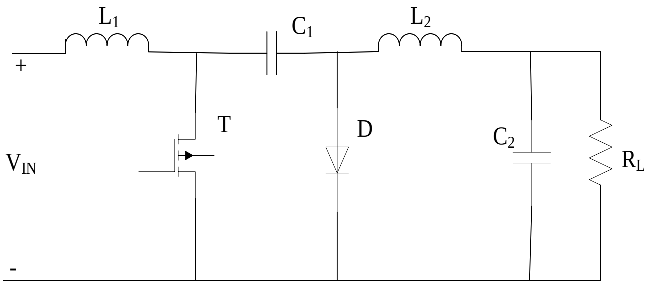


Fig. 6 Ćuk Converter

The output voltage and current are given by

$$\frac{V_O}{V_i} = \frac{D}{1-D} \tag{11}$$

$$\frac{I_O}{I_S} = \frac{1-D}{D} \tag{12}$$

The design equations are given by

$$L_1 = \frac{V_{dc}D}{\Delta I_1 f} \tag{13}$$

$$L_2 = \frac{V_{dc}D}{\Delta I_2 f} \tag{14}$$

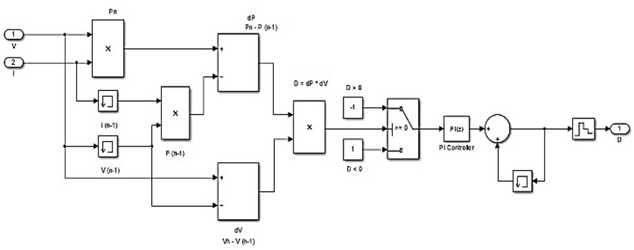
$$C_1 = \frac{I_S(1-D)}{\Delta V_{C1} f} \tag{15}$$

$$C_2 = \frac{\Delta I_2}{8\Delta V_{C2} f} \tag{16}$$

V. MODELLING AND SIMULATION OF MPPT TECHNIQUES

A. Simulation

The modelling of the MPPT techniques were carried out in MATLAB™/SIMULINK™ and the simulation is carried out for varying temperature and insolation levels.The initial duty value is taken as 0.58 and the model of MPPT techniques are as shown in figure 7.



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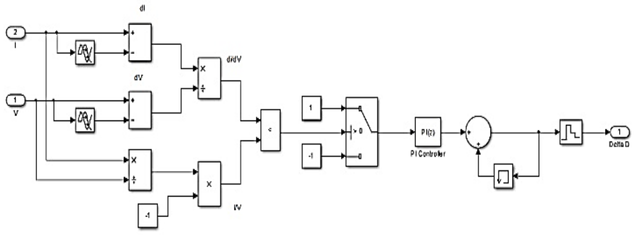

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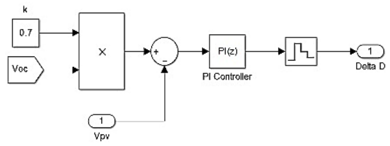

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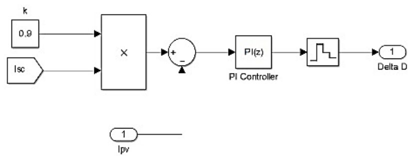

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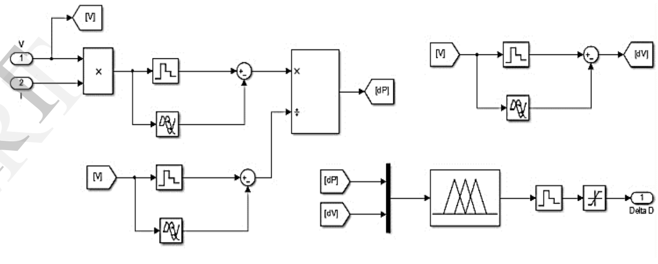

(e)

Fig. 7 Various MPPT Techniques

(a) P&O (b) ICM (c) FOCV (d) FSSC (e) Fuzzy based system

The Irradiance and temperature level are given with respect to the available data from a study conducted for over years [9].

The overall Simulation model is shown in Figure 8.

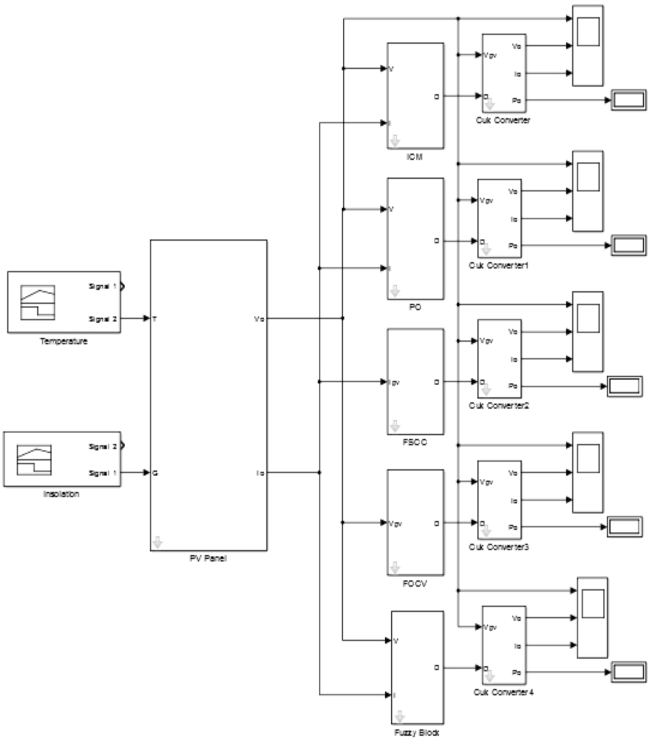

Fig. 8 Overall Simulation Model

The output voltage waveform for each MPPT technique is as shown in figure 9.

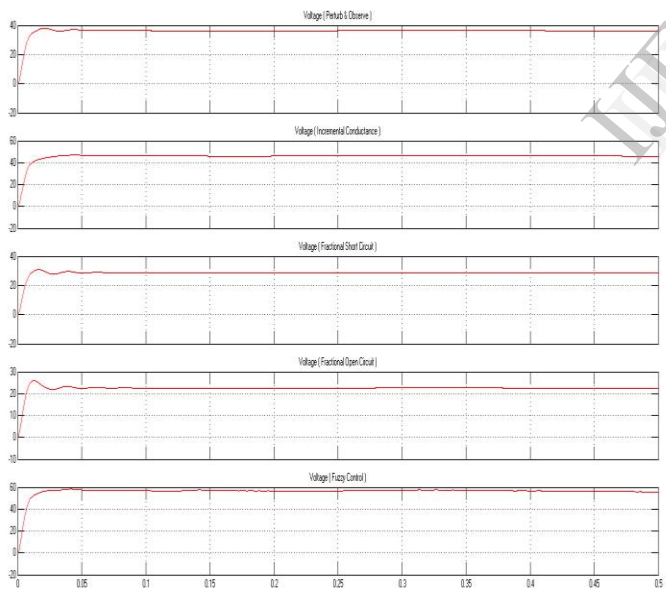

Fig. 9 Output Voltage of MPPT techniques

The power output of combined MPPT technique is shown in figure 10.

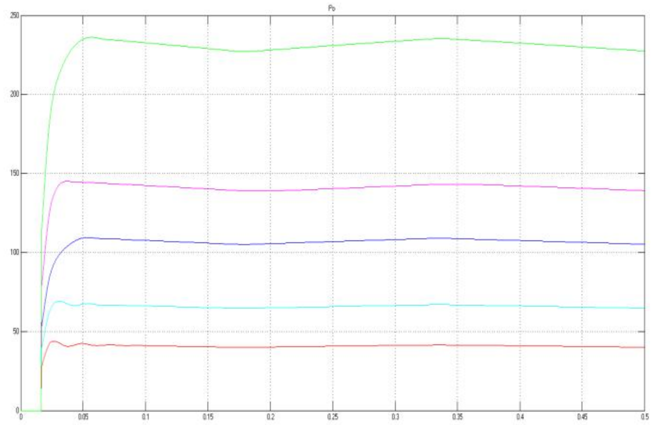

Fig. 10 Power Output of MPPT techniques

B. Results

The response of the five MPPT techniques were evaluated on the Ćuk converter. The PO method was simulated with a perturbation size (ΔD) of 0.01 and for Incremental conductance, the value was set to 0.1. From the simulations, the fuzzy based system extracted the maximum power followed by Incremental Conductance method. The PO method, which is the simplest to implement extracts power effectively but the maximum attainable power is not extracted. The Fractional Open circuit voltage and short circuit current methods hardly extract any power it is same without any MPPT technique. The Fuzzy based system doesn't have any peak overshoot whereas all the others do have some peak overshoot. Also the settling time is high for every method except Fuzzy based system. The table show the comparative analysis of the five MPPT techniques on the Ćuk converter.

MPPT Method	Power Output (W)	Settling Time (ms)	Peak Overshoot	Sensors Used
P & O	110	40	NO	V & I
INC	145	50	YES	V & I
FOCV	70	55	YES	V
FSSC	45	90	YES	I
Fuzzy	240	25	YES	V & I

Table 2.Comparison of MPPT Techniques

VI. CONCLUSION

The Simulation and analysis of five MPPT techniques for SPV systems were carried out in Matlab\Simulink. Various criteria such as power output, settling time, and peak overshoot were analyzed. From the simulation results, it was found that the Fuzzy based MPPT extracts the maximum power and also it has the lowest settling time as compared to others. Although the settling time for simulation is dependent on the Computer configuration, results has proven it worth. The second fastest to extract maximum power was the Incremental Conductance method followed by Perturb and Observe method. The FOCV & FSSC extracts power but when compared to the other three, they hardly extract any power. From the results, it is clear that fuzzy based system extracts the maximum power but the implementation of Fuzzy system is highly complex and not economic for domestic purposes. So the best technique that can extract the maximum power at a comparatively lower price will be the Incremental Conductance method.

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