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Fuzzy Logic Based MPPT for Solar PV Applications

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Abstract: To extract Maximum Power from PV system, many MPPT techniques have been employed by the researchers. This paper presents a fuzzy logic based MPPT algorithm for a 100 kW PV System. The Duty Cycle of the DC-DC Boost converter is controlled by the proposed Fuzzy MPPT control Technique and hence Maximum power is obtained from PV system. Simulations were carried out and the proposed MPPT technique is tested under different environmental conditions. The proposed method is effectively tracking the maximum power for all environmental conditions. The output voltage of the DC-DC Converter is varying one with respect to Maximum Power Point (MPP). One more DC-DC Buck-boost converter with PI control is used in order to make the DC Bus voltage constant. A PWM Inverter with L-filter is used to generate three phase supply required to operate three phase loads and single phase loads. The results are presented for different irradiation and temperature conditions.

Keywords: Solar PV system, MPPT, DC-DC Converter, Fuzzy logic controller (FLC) based MPPT, PWM Inverter.

I. INTRODUCTION

Energy crisis today in this world has been unresolved one. The rate of increase in the demand is more than the rate of increase in the supply. To overcome this problem, use of renewable energy resources is the alternate for fossil fuel power systems. This is clean, pollution free and abundantly available in nature.

Government of India has launched the Jawaharlal Nehru National Solar Mission (JNNSM), which targets 20 GW of grid connected solar capacity by year 2022. Increasing importance for solar energy in India requires more research in the areas such as new materials, novel MPPT techniques, and Converters design etc. In the above research areas MPPT techniques is one of the important areas to extract maximum power from the PV system under varying environmental conditions. Nowadays many researchers are using soft computing techniques for this purpose. This paper deals about the design of the fuzzy based MPPT Technique.

Solar cells have non-linear relationship between solar irradiation, cell temperature and total resistance that makes non-linear output efficiency also. This can be analyzed based on the I-V curve of solar cell. To obtain maximum power from solar PV system MPPT is used. The purpose of the MPPT system is to sample the output of the PV system and apply the proper load resistance to obtain maximum power for any given environmental conditions. The Maximum Power Point Tracking (MPPT) is used to maximize the output power and it transfers to load. Stand-alone PV systems are designed to operate independent of the electric utility grid, and are generally designed to supply certain DC or AC electrical loads. Stand-alone systems may be powered by a PV array only or may use utility power as a backup power source. Since there is no battery to store the electrical energy, which is used immediately. DC voltage is supplied to DC load; it is considered application of water pumping and telecommunications. The DC voltage is converted to AC by using inverter, it can also power to AC loads. This system only works when it is sunny days. Stand-alone PV System with Battery backup can supply power 100 % of the time at night, on cloudy days and when the utility power is down. The solar PV maximum output power is depends on the atmospheric conditions such as Solar cell Temperature (T), Solar irradiation (G) and load.

The output power from Solar PV is fluctuating due to variation in cell temperature and solar irradiance. So controller is needed to make the system more reliable. Hence, in this paper a fuzzy logic based MPPT technique is proposed. The proposed MPPT controller is designed for 100 kW solar PV system. The fuzzy based MPPT technique is used to generate voltage reference from PV system by modulating the duty cycle applied to boost converter switch. The proposed MPPT algorithm gives a good maximum power of solar PV system. In order to track MPP and to make the output voltage constant, two stage of conversion is required. Hence, MPPT controllers with DC-DC converters are designed to obtain an efficient output for all operating conditions.

II. MATHEMATICAL MODEL OF PHOTOVOLTAIC MODULE

The equivalent circuit generally used for solar PV cell is shown in Fig. 1. It is essentially consists of a current source shunted by a diode. The resistances R_s and R_{sh} can be considered to be parasitic circuit elements. For an ideal cell, R_{sh} is infinite and would not provide an alternate path for current to flow, while R_s would be zero. The Equation

1 shows the Shockley diode equation which describes the I-V Characteristic of diode, [1,2]

$$I_D = I_{sat}\left[\exp\left(\frac{V_D}{nV_T}\right) - 1\right] \quad (1)$$

Where I_D is the diode current, I_{sat} is the reverse bias saturation current, V_D is the voltage across the diode, n is the ideality factor (typically between 1 and 2) of the diode.

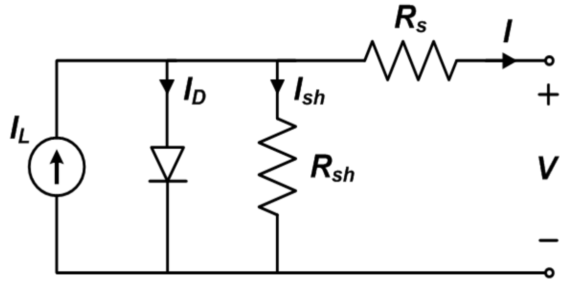

Fig.1 Equivalent circuit of a solar cell

Thermal voltage V_T can be defined as,

$$V_T = \frac{KT}{q} \quad (2)$$

where, K is Boltzmann constant (1.38065*10^{-23}J/K), T is temperature in degrees Kelvin and q is charge of electron (1.6021764*10^{-19} C).

The equation for this equivalent circuit is formulated by using Kirchoff's current law is expressed as,

$$I = I_L - I_D - I_{sh} \quad (3)$$

To model the I-V characteristic of PV array, equation (3) can be derived from the Fig. 1,

$$I = I_{pv} - I_0\left[\exp\left(\frac{V+R_sI}{V_ta}\right) - 1\right] - \frac{V+R_sI}{R_{sh}} \quad (4)$$

I_{PV} is the light generated current, I_0 is the reverse saturation current, V is the PV array terminal voltage, R_s is the equivalent series resistance of the solar cell and R_{sh} is shunt resistance. The parallel resistance R_{sh} is the great influence when PV module acts as current source. The light generated current of the photovoltaic cell depends on the solar irradiance and cell temperature according to the following equation,

$$I_{pv} = (I_{pv,n} + K_I\Delta_T)\frac{G}{G_n} \quad (5)$$

where, $I_{pv,n}$ is the light generated current at nominal condition (usually 25° C and 1000W/m^2), Δ_T =T-T$_n$ (T and T_n the actual and nominal temperature [K]), G[W/m^2] is the irradiance and G_n is the nominal irradiance.

The diode saturation current I_0 and its depends on the temperature is given by,

$$I_0 = \frac{I_{sc,n} + K_I\Delta_T}{\exp\left(\frac{V_{oc,n} + K_V\Delta_T}{aV_t}\right) - 1} \quad (6)$$

where, a is the ideality constant. K_v and K_I is the voltage and current coefficients. I_{sc},n and V_{oc},n are the nominal short circuit current and open circuit voltage.

I-V and P-V characteristics for the TITANS6_60 PV module at 25 ^{o}C and 1000 W/m^2 are shown in Fig. 2 and Fig. 3 respectively. Table I shows the parameters of the TITANS6_60 PV module.

TABLE I
Parameters of the TITANS6_60 PV module at 25° C and 1000W/m^2

Parameter	Value
Peak Power, P_{MPP} (W)	215.015
Peak Power Voltage, V_{MPP} (V)	28.9
Peak Power Current, I_{MPP} (I)	7.44
Open Circuit Voltage, V_{OC}(V)	37
Short Circuit Current, I_{SC} (A)	8.21
Temperature Coefficient of current(mA/°C),K_i	3.183e^{-3}
Temperature Coefficient of voltage(mV/ °C),K_v	-0.123
Number of series cells, Ns	60

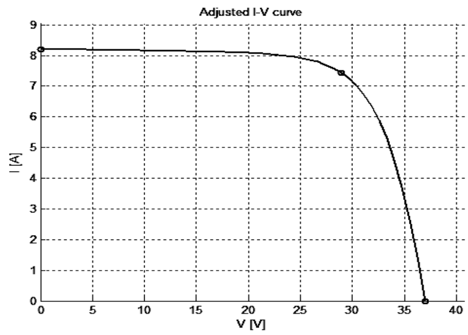

Fig. 2 I-V Characteristics of Solar PV system

The solar PV module contains 24 modules connected in series and 20 strings connected in parallel. When the modules are wired in parallel, their current rating is increased while the voltage remains constant. When the modules are wired together in series, their voltage is increased while the current remains constant. Hence, in this paper a fuzzy logic based MPPT technique is proposed. The fuzzy logic based MPPT can track the maximum power point faster and also it can minimize the voltage fluctuation after MPP has been recognized.

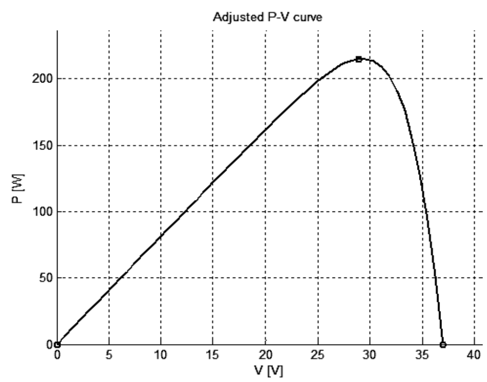

Fig. 3 P-V Characteristics of Solar PV System

III. DC-DC BOOST CONVERTER

A boost converter (step-up converter) is a DC to DC power converter with an output voltage is greater than its input voltage. It is a class of switched-mode power supply (SMPS) containing at least two semiconductor switches (a diode and a transistor) and at least one energy storage element, a capacitor, inductor, or the two in combination.

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Filters made of capacitors (sometimes in combination with inductors) are normally added to the output of the converter to reduce output voltage ripple. The boost converter is used to regulate a chosen level of the solar photovoltaic module output voltage and to keep the system at the maximum possible power from solar panels at all times [3-6].

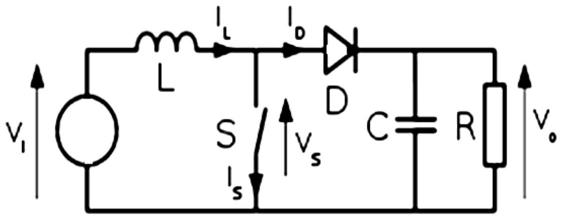

Fig. 4 Boost Converter

Design Calculation

The Boost converter parameter values are calculated by the following formulae.

1. Duty cycle, $k = 1 - V_s/V_o$
2. Ripple current, $\Delta_{IL} = \frac{VS*k}{Lf}$
3. Inductance, $L = \frac{Vs*K(1-K)}{\Delta IL*f}$
4. Ripple voltage, $\Delta_{Vc} = \frac{Io*k}{C*f}$
5. Capacitance, $C = \frac{Io*k}{\Delta Vc*f}$

TABLE II
Operating Values of Boost Converter

Parameter	**Value**	**Symbol**
Input voltage	200-900 V	V_s
Output voltage	1100 V	V_0
Switching frequency	20 kHz	F_s
Inductance	0.00698 H	L
Capacitance	2 µF	C
Load resistance	10 **Ω**	R

IV. FUZZY BASED MPPT

One of the most simple and popular techniques of MPPT is the P&O technique [3, 4]. The main concept of this method is to push the system to operate at the direction which the output power obtained from the PV system increases. Following equation describes the change of power which defines the strategy of the MPPT technique.

$$\Delta P = P_K - P_{K-1} \qquad (7)$$

If the change of power is defined by (6) is positive, the system will keep the direction of the incremental current (increase or decrease the PV current) as the same direction, and if the change of power (ΔP) is negative, the system will change the direction of incremental current command to the opposite direction. This method works well in the steady state condition (the radiation and temperature conditions change slowly).

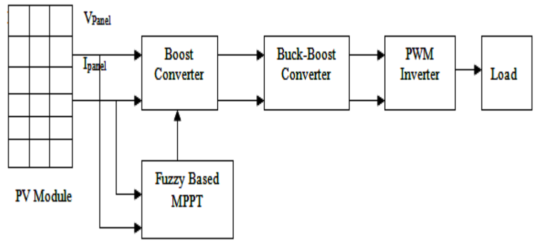

Fig. 5 Typical diagram of Fuzzy based MPPT in PV system

The input variables of MPPT are the PV module output voltage and current. In this paper implemented the fuzzy logic based P&O MPPT algorithm. A fuzzy logic based MPPT control is implemented to generate the optimal voltage reference from the PV system by modulating the duty cycle applied to the boost converter. The output voltage and current of the PV panel are measured and fed to the fuzzy based control unit for MPP tracking. Based on the change of power with respect to change of voltage dp/dv and Δdp/dv, fuzzy determines the voltage reference and compared with the modulating signal and generate pulse, which is applied to the gate pulse of IGBT. The Buck-boost Converter is used to maintain the constant output voltage. The output voltage is controlled by using PI Controller. The DC source is converted into three phase AC by using PWM Inverter [11]. The passive filter is used to reduce the harmonics in output voltage.

V. FUZZY LOGIC CONTROLLER DESIGN

P&O method for MPPT tracking will not respond quickly to rapid changes in temperature or irradiance. Therefore the fuzzy control algorithm is capable of improving the tracking performance. A FLC allows for rapid prototyping because the system designer doesn't need to know everything about the system before starting and it can achieve steady state in a shorter time interval. FLC can deal with non-linearity and it does not require the exact mathematical model of the system and more robustness than conventional logic controller [7-10].

FLC can be classified into four steps:

1. Fuzzification
2. Membership function
3. Inference
4. Defuzzification

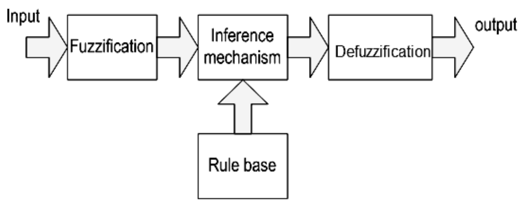

Fig. 6 Block Diagram of a Fuzzy Logic Controller

A. Fuzzification

The process of converting a crisp input value into a fuzzy value is called “fuzzification”.The membership function values are assigned to the linguistic variables using seven fuzzy subset called as negative big (NB), negative medium (NM), negative small (NS), Zero (ZE), positive small (PS), Positive medium (PM), Positive Big (PB).

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B. Membership Function

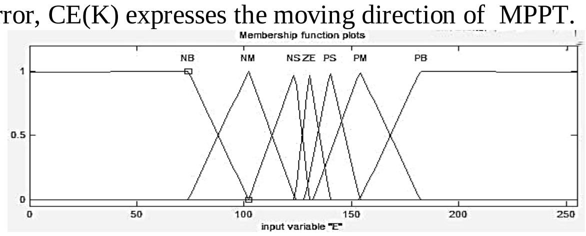
The membership function is a curvature that describes each point of membership value in the input space. The number of membership functions are used depends on the required accuracy of the controller.

The fuzzy logic based MPPT technique the error (E) and change in error (CE) are taken as input variables which are as below for K^{th} sample time.

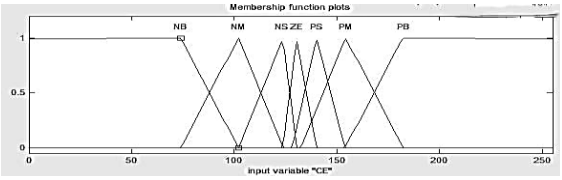
$$E(K) = \frac{dp}{dv} = \frac{P_K - P_{K-1}}{V_K - V_{K-1}} \quad (8)$$

$$CE(K) = E(K) - E(K-1) \quad (9)$$

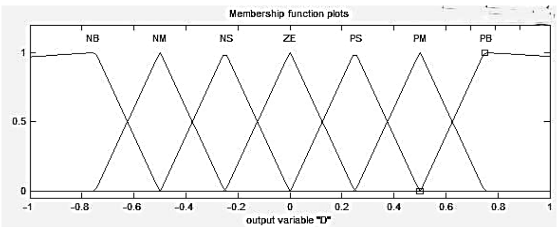
where, Error E(K) is the load operation point at the instant K is located on right or left of MPPT. The Change of Error, CE(K) expresses the moving direction of MPPT.



Input variable "Error"
(a)



Input variable "Change in Error"
(b)



Output voltage "Voltage reference"
(c)

Fig. 7 Membership function of (a) Error E (b) Change in Error CE (c) Voltage reference Vref

C. Inference (Rule Base)

Fuzzy rule base is a collection of if-then rules that contains all the information for the controlled parameters. A fuzzy inference method, Mamdani's method is used with Max-Min operation fuzzy combination. Fuzzy inference is based on fuzzy rule base system. Rules are framed in inference engine block.

The commonly used method is MAX-MIN. The output membership function of each rule is given by MIN (Minimum) operator and MAX (Maximum) operator.

The behaviour of the control surface which relates the input and output variables of the system is governed by a set of rules.

TABLE III

CONTROL RULE TABLE

Change in Error \ Error (E / CE)	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PM
ZE	ZB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

D. Defuzzification

Defuzzification is the process of conversion of fuzzy value into crisp value. The output of fuzzy controller is a fuzzy subset. As the actual system requires a non fuzzy value of control, so the defuzzication is required. There are several methods are available for defuzzification. The most prevalent one is centroid method, which utilizes the following formula:

$$\int \frac{x*\mu(x)dx}{\mu(x)dx} \quad (10)$$

where, μ is the membership degree of output x.

VI. MATLAB MODEL OF THE SOLAR PV SYSTEM

The solar PV system consists of PV module, DC-DC Converters, MPPT control, Fuzzy Logic Control and a load. The single solar PV module consists of series and parallel solar cells, which is used to increasing the voltage and current. The output of solar PV module current is given to the input of a current controlled source. The single solar cell does not provide the maximum power, so the numbers of solar cells are connected in series and parallel and improve the output power. The output power system is connected to boost converter and to track the maximum power using Fuzzy logic controller.

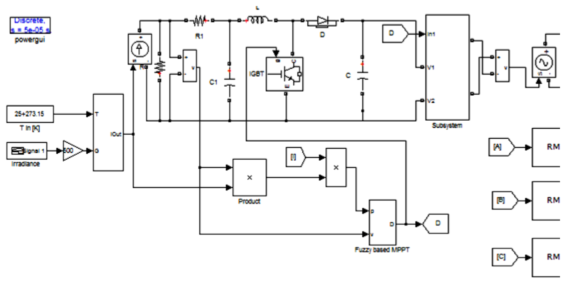


Fig. 8 Simulation of Solar PV System

The voltage supplied by the PV module does not have constant values, but it fluctuates according to the atmospheric conditions such as solar irradiance and temperature. The output voltage and current of the PV panel are measured and fed to the fuzzy based MPPT control unit for maximum power tracking. Based on the change of power with respect to the change of voltage $\frac{dp}{dv}$ and $\Delta\frac{dp}{dv}$, fuzzy system determines the voltage reference of the PWM (Pulse Width Modulation) signal, which is given to the gate pulse of Boost converter switch. The output of

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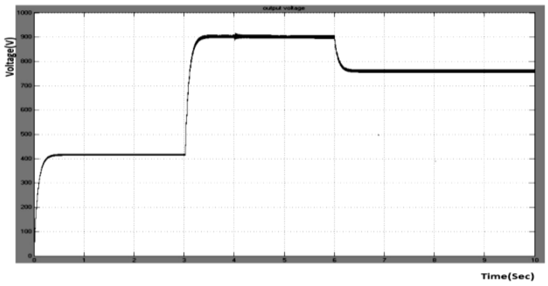
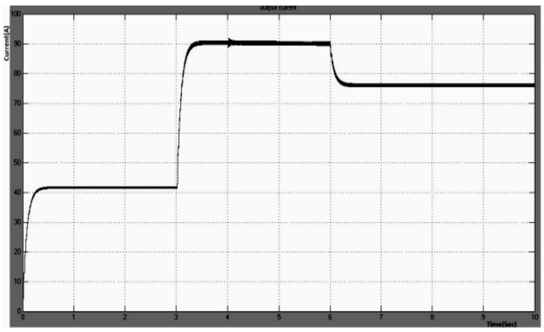
DC-DC Boost converter is varying corresponding to the Maximum Power Point (MPP). In order to make the output voltage constant, two stage of DC-DC conversion is required to maintain a constant output voltage. The maximum power can be extracted by varying the duty cycle of DC-DC converter. Buck-boost Converter output voltage is controlled by using PI controller. The DC voltage is converted to AC by using inverter, the low harmonic distortion of the voltage and current at the output of inverter is reduced by using L-filter. The output voltage is supplied to AC load.

VII. SIMULATION RESULTS

The solar PV system is modelled and simulated in MATLAB/Simulink. The PV module has the variable temperature and the irradiance. For analysis purpose, irradiance levels of 300 W/m^2, 720 W/m^2, and 600 W/m^2 are considered. The PV module output voltage, current, and output power are shown in Fig. 9.

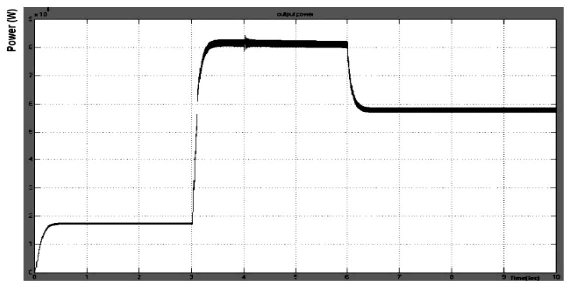


(a) Output Voltage



(b) Output current

When the solar irradiance varies and equivalent change in power output can be seen in Fig. 9 it is verified that the power varies with respect to the solar irradiance. The fuzzy can track the maximum power at all irradiance and cell temperature.



(C) Output Power

Fig. 9 Output Waveforms of 100 kW Solar PV System

TABLE II
Parameters of Buck-Boost Converter

Parameter	**Symbol**	**Value**
Input Voltage	Vs	350 V-1200 V
Output Voltage	V_0	850 V
Switching frequency	F_s	20 kHz
Inductance	L	8 mH
Capacitance	C	85 µF
Proportional gain	K_p	2
Integral gain	K_i	50

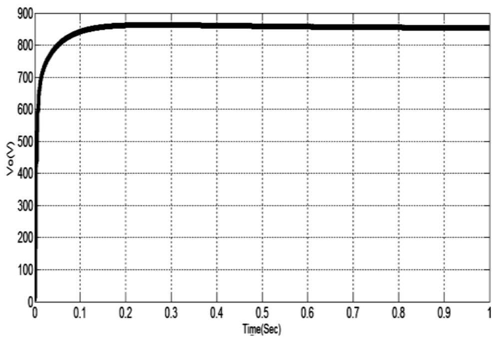


Fig. 10 Output voltage of Buck-Boost converter

The output voltage 850 V is maintained as constant as shown in Fig.10, under different solar irradiance and temperature. Three Phase PWM Inverter output voltage is 586V as shown in Fig. 11. The three phase RMS voltage is 415 V as shown in Fig.12.

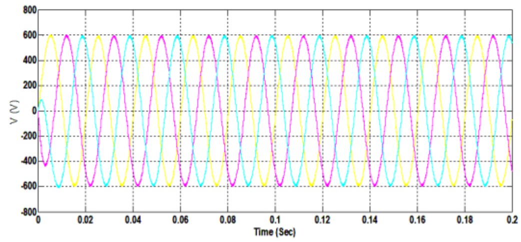


Fig. 11 Output voltage of three phase PWM Inverter

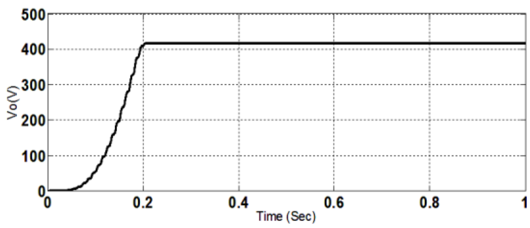


Fig. 12 RMS Voltage of Inverter

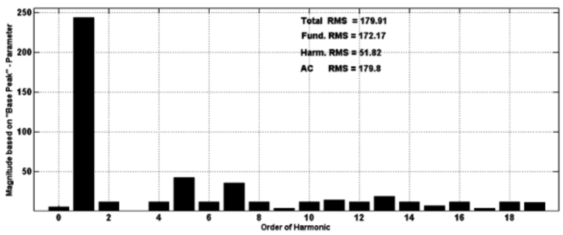


Fig. 13 THD Spectrum of Output Current without Filter

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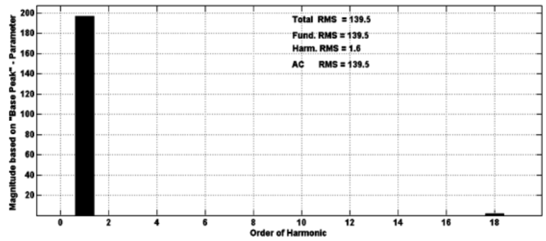

Fig. 14 THD Spectrum of Output Current with Filter

The output current of three phase inverter without filter has 51.82 % THD, which is shown in Fig. 13. By using L-filter, the current harmonic is reduced to 1.6 % THD as shown in Fig. 14, which is less than the IEEE-519-1992 standard.

VIII. CONCLUSION

In this paper solar PV module, fuzzy logic based MPPT, DC-DC Converters has been implemented and simulated in MATLAB/Simulink. To extract the maximum power from the solar PV module, Fuzzy Logic Controller is used. For different operating conditions the algorithm has been verified and it's found that the error percentage lies between 0.29 % to 1.19 %. The simulation shows that the system follows the irradiance and the temperature changes, the output power varies rapidly and the regulation is robust against disturbances. This solar PV module not only boosts up the voltage and also produces a signal free from transient noise. Hence the performance of the closed loop system can be improved by using FLC. The PV power can be utilized either for remote generation plants or it can be utilized for grid integration. The consumer appliances and industrial applications can also utilize PV power with the help of duly designed inverter. In order to produce a pure sine wave output with low harmonics an L-filter is used. The inverter output voltage can be utilized for grid integration.

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