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Cascaded Multilevel Inverter for Photovoltaic Systems With PI Control

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Abstract— Use of renewable Energy such as solar, wind, water, nuclear energy etc is of huge demand in recent era. Converters used in Photovoltaic Systems have two stages: a boost up chopper and a PWM inverter. But this integration of these two stages have certain problems like decrease in efficiency, problem in interaction between the stages and also problem in MPPT(i.e Maximum Power Point Tracking) etc. So the Total energy which is produced is not utilized fully rather only a part of it can be utilized fruitfully. So in this paper we have proposed a novel use of Cascaded H-Bridge Multilevel Inverter Topology in integrations with PV module controlled by a PI controller. The usefulness of this topology is in the use of fully controlled PI controller and the increase in system performance. All the Gate Pulses to the IGBT switches are provided by the FPGA (Field Programmable Gate Array) kit. The detailed discussion and performance of the whole system alone with the block diagram and basic designing is discussed in this paper. Simulated Results and comparison is also done in this paper. This System provide a results in more efficiency and specially in low or medium power application. Detailed harmonic discussion is also done here in this paper.

Keywords— FPGA,PI controller, Cascaded Multilevel Inverter, PV cell(PV Module),Renewable Energy Source, THD.

1.INTRODUCTION

The ever growing demand for Renewable Energy resources is gaining importance day by day. Wind, Solar, Nuclear, Hydral etc are some examples of such renewable energies. It is expected that by 2050,60% of our energy requirement will be supplied by these Renewable energy resources. Out of these Pv Energy has been used in most number of cases as it is distributed over the whole area of the earth and it is available in sufficient amount.

Previously the PV systems was generally consisted of a dc-dc converter or boost chopper followed by a PWM or pulse width modulated inverter, but this cascade of converters presents some problems in efficiency, complexity, interaction between the stages and Maximum Power Point Tracking, addition power losses, harmonics etc.

Due to this reason now our focus is on inventing new tropologies of improved inverters. Among these tropologies multilevel inverter with PWM control is gaining more importance. They have many additional advantages over the other tropologies and are more efficient. Detailed discussion of this cascaded multilevel inverter and why this multilevel inverter is used in Photovoltaic systems ,are discussed below. The PWM inverter used do not produces the exact waveform reather the waveform is distorted, so this gives birth of harmonics and distortion which in turn reduces the system performance and heating effect.Not only that when this waveform is fed to a motor this can even produce some reverse torque and causes overloading of the motor if this torque is very high[3].Improvement and advancement of new breed of inverter tropologies can be used in high power applications without the use of transformers.

2. MULTILEVEL INVERTER

The Cascaded H-Bridge MLIs [4]-[7] are simply the cascade of some two-level inverter where each cells have 3 levels Vdc,0,-Vdc.Here in place of DC source we are integrating PV cell in the supply side of the inverter. The diagram of the Cascaded H-Bridge MLIs are shown below in figure1.As each cell basically represents +Vdc,0,-Vdc so by any four combination of cells we can constructs multiple levels.

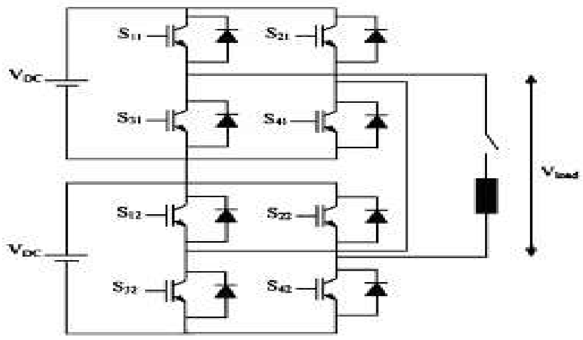

Fig.1 5 Level Cascaded H-Bridge MLI

The no of output levels depends on the no of dc sources being used .It follows the formula n=2N+1, where N is the no of Dc sources being used. The higher the no of levels the better will be the shape of the sinusoidal output waveform. But as we increase the no of levels the complexity and the cost of the sys- tem as the no of switches is being increased and also the swit - ching frequency will also be reduced. It can be seen that even if the switching loss is increased the transistor i.e the MOSFE- T or the IGBT conductance resistance is decreased while using devices with lower maximum applicable voltage so the total losses can be lower than the two level inverter.

The wave form of a 11 level Cascaded Multilevel [2] inverter is shown here in the fig-2 below. This is stepped waveform and by this we can determine the Fourier Transform and the Fourier coefficient of the output.

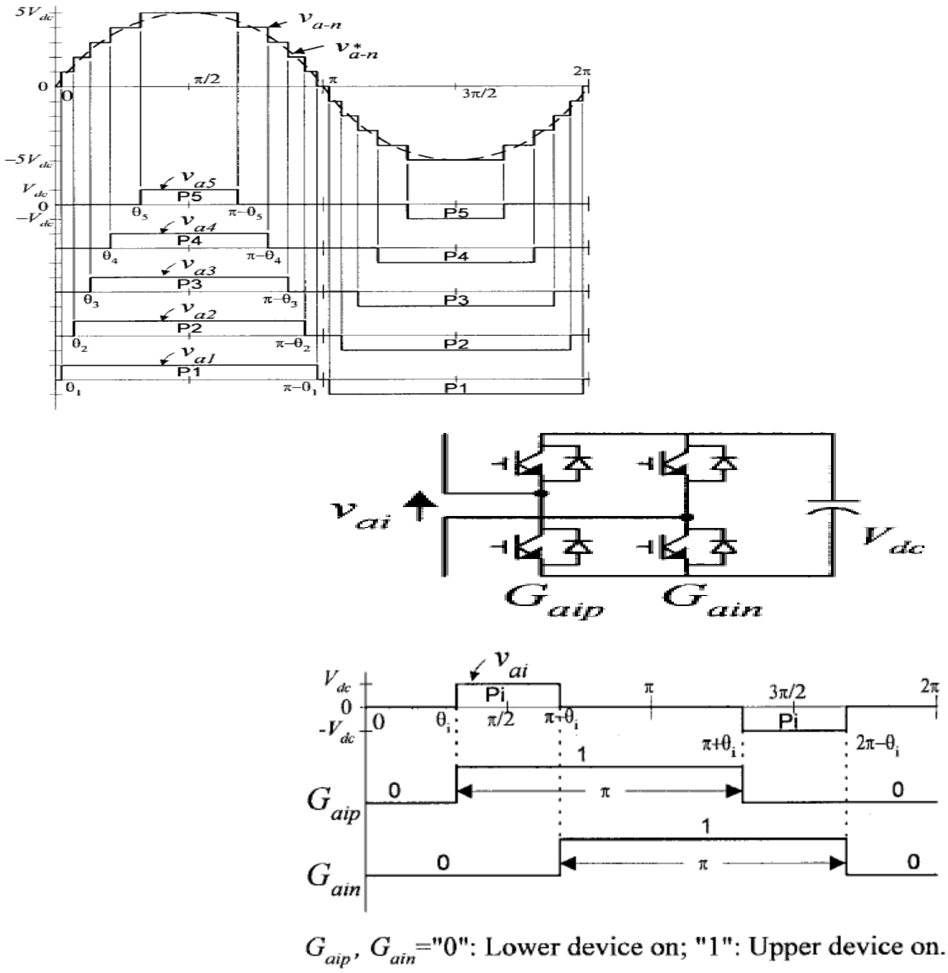

Fig-2 Waveform and Switching methods of a 11 level CHB MLI

The Fourier Transform of the waveform shown in fig is as follows:-

$$V(\omega t)=(4V_{dc}/\pi)\sum_n[\cos(n\theta_1)+\cos(n\theta_2)+.........+\cos(n\theta_s)] \times\{\sin(n\omega\theta)/n\} ; \quad \text{Where } n=1,3,5..... \qquad (1)$$

Thus from this we can get the magnitude of the Fourier co-efficient by normalizing it with respect to V_{dc} and it becomes

$$H(n)=(4/\pi n)[\cos(n\theta_1)+\cos(n\theta_2)+\ldots\ldots\ldots+\cos(n\theta_s)]$$
Where n=1,3,5,7……… (2)

The conduction angle θ_1, $\theta_{2,}$ $\theta_{3,\ldots\ldots,}$ θ_s are chosen such that the THD of the voltage will be the minimum. These angles are choosen such that the predominant lower order odd harmonics i.e the 5^{th},7^{th}….,11^{th} harmonics gets cancel out or reduced.The Modulation Index **m** which is defined as the ratio of $V_L/V_{L\ max}$,where V_L is the amplitude of the Inverter output phase voltage and V_{Lmax} is the maximum output of the of the converter i.e $V_{Lmax}=sV_{dc.}$So the equation 2 can be reduced to

$$\cos(5\theta_1)+\cos(5\theta_2)+\cos(5\theta_3)+\ldots\ldots.+\cos(5\theta_5) =0$$
$$\cos(7\theta_1)+\cos(7\theta_2)+\cos(7\theta_3)+\ldots\ldots+\cos(7\theta_5) =0$$
$$\cos(11\theta_1)+\cos(11\theta_2)+\ldots\ldots\ldots\ldots\ldots+\cos(11\theta_5) =0$$
$$\cos(13\theta_1)+\cos(13\theta_2)+\cos(13\theta_3)+\ldots..+\cos(13\theta_5) =0$$
and
$$\cos(\theta_1)+\cos(\theta_2)+\cos(\theta_3)+\cos(\theta_4)+\cos(\theta_5) =5m \quad (3)$$

Solving this equation 3 in Newton-Raphson Method by taking a fixed value of modulation index(m) we can get the values of $\theta_{1,}$ $\theta_{2,}$ $\theta_{3,\ldots,}$ θ_5 and by finding all these values we can see that the output will not contain any 5^{th},7^{th},11^{th},13^{th} harmonics.Switching patterns swaping of 11-level CHB MLI is given neatly in the fig 3 below.

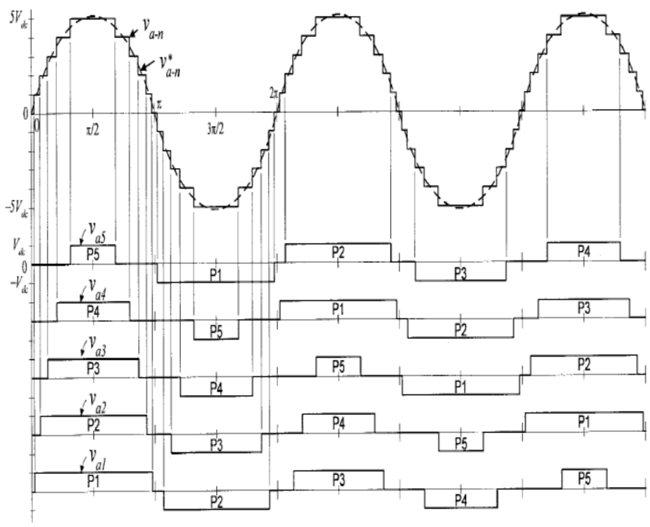

Fig -3 Switching patterns swaping of 11-level CHB MLI for balancing battery change

The instantaneous output voltage of the n-level inverter can be given by:-$V_{AN}=\sum_{k=1}^{n} V_{out,i.}$Where $V_{out,i}$ is the output voltage of the i-th stage.Each H-Bridge can be driven by a square waveform of suitable duty produced by the PWM inverter.The switching states of a five level inverter is given below:-

S1 1	S2 1	S3 1	S4 1	S1 2	S2 2	S3 2	S4 2	LEVELS
1	0	0	1	0	0	0	0	Vdc
1	0	0	1	1	0	0	1	2Vdc
0	0	0	0	0	0	0	0	0
0	1	1	0	0	0	0	0	-Vdc

0	1	1	0	0	1	1	0	-2Vdc

3. PHOTOVOLTAIC ARRAYS

The Photovoltaic Cells converts the solar energy of the sun to electrical energy i.e electricity.The basic unit of a PV array is a PV cell.The PV cells grouped together to form a PV panels and these PV panels can be further grouped together to form a PV array. The PV cells[11] can be either circular or rectangular in shape.Each PV cells can be considered as a simple p-n junction diodes and the surface of these diodes are exposed directly to the sunlight and in turn the charge carriers are generated which produces electricity.

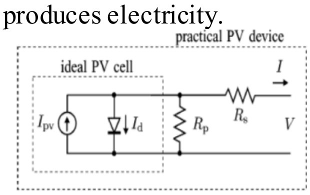

Fig.4 Basic Ckt diagram of a PV cell using one diode

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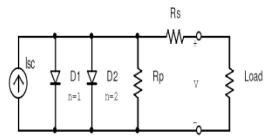


Fig.5 PV cell using two diode model.

The basic diagram of a PV cell is shown in fig.4 and to compensate the error the two diode model is also given in fig.4.In this fig the PV cell is represented by a current source and the R_p and R_s is the parallel and series resistance respectively.V and I are the output voltage and output current respectively.From the fig it is evident that the net current I is the summation of I_{pv} and I_d so

$$I=I_{pv}-I_d \quad (4)$$

Where
$I_d=I_0\exp(qV/akT)$
I_0=Leakage current of the diode.
q=Electronic charge
k=Boltzmann Constant
T=Temperature of the pn junction
a=Diode identity constant
The equation(4) is the ideal equation which is a bit different from the practical one.Acutally the practical PV array is composed of more then one PV cells and so the basic equation requires some additional terms.The actual eq is given below

$$I=I_{pv}-[\exp\{V+(R_sI/V_ta)\}-1]-(V+R_sI/R_p) \quad (5)$$

Where
$V_t=N_skT/q$

This the the thermal voltage of the cell with N_s no of cells connected in series.The cells connected in parallel increases the current and cells connected in series increases the voltage.The I-V characteristic [13]-[14] is shown in figure 6 below.From this figure we can easily find that the voltage and current is maximum at some poin let it be called as MPP.Here as the voltage and current is maximum we can get the maximum power at this point.The voltage and current corresponding to this point is V_{mp} and I_{mp} respectively.

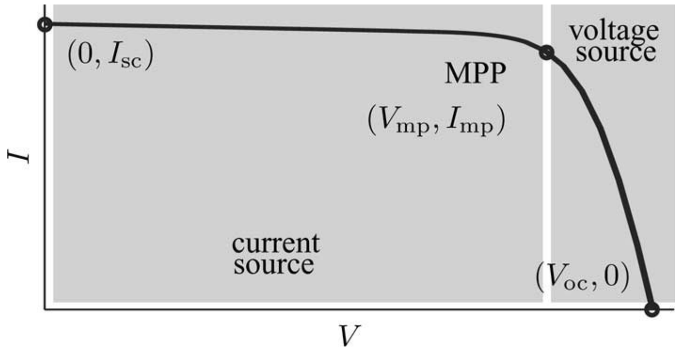


Fig-6 V-I characteristics of an PV cell

Here in this diagram I_{sc} is known as the short circuit current i.e the current is maximum when the output terminal is short circuited and V_{oc} is known as the open circuited voltage i.e the voltage is maximum when the output terminal is open.Actually the output of the solar cell is not constant as the irradiance and temperature changes throughout the day and so it becomes very important for us to track this MPP i.e maximum power point to get a very efficient and robust system.

4. INTEGRATED PI CONTROLLER AND CONTROL

The complete block diagram and its control is given blow in fig 7.In this the PV Array is connected to the Multilevel inverter as a source and the MLI is connected to the load.In closed loop control the output of the load is sensed by a voltage sensor and fed to the FPGA to generate the gate pulse for the MLI switches through a feedback path.The load connected can be of any type i.e R,RL any type.To get the closed loop control of the system first of all the transfer function of the system is to be derived by using laplace transform and then it can be implemented.PI contol is implemented here.PI implies Proportional and Integral control.

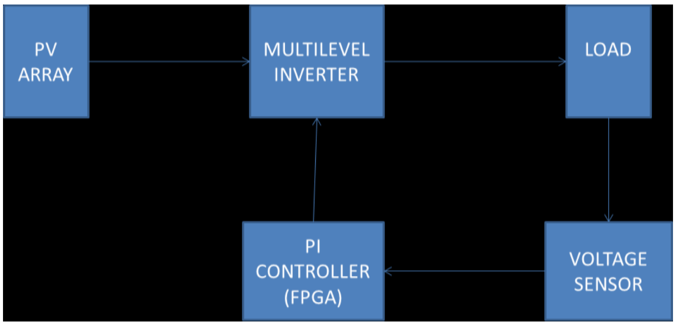


Fig-7 Block Diagram of the proposed syatem

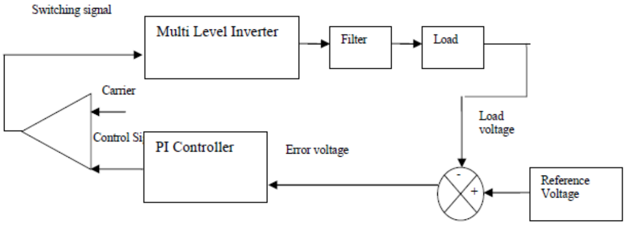


Fig-8 PI control for Cascaded Multilevel Inverter.

Here we have implemented PWM technique[6]-[7].Actually some amount of harmonics are produced in the output so to reduce this harmonics we have used PWM control.The PWM pulses are basically some square wave pulses with varring width and this width can be varied by varring the T_{ON} and T_{OFF} period.The pulses are produced by comparision of a reference wave and a modulating signal.By calculating the switching angle we will have to vary the width of the pulses.

5. SIMULATION AND ANALYSIS

Simulation of the entire system is done my using MATLAB Simulink 's Sim Power Systems tool box and M-File.The Simulation is done step by step.The performance and THD of different levels of the Cascaded Multilevel inverters is done starting from 3 level to 11 levels.

5.1. Simulation Of PV Module

In this analysis the resistance R_p is eliminated.The output voltage V can be obtain by simplifying the equation(2) which gives:-

$$V=(akT/e)\ln\{(I_{ph}+I_d-I)/I_d\}-(R_sI) \quad (6)$$

Where
k=boltzmann Constant(1.38*10^-23*J/K*)
e=electronic Charge(1.602*10^-19*C*)
T=Reference operating temperature(20 C)
R_s=Series resistance(0.001 ohm)
I_d=Reverse saturation current of the diode(0.0002 A)
The ambient temperature T_a effects the output voltage and photocurrent of the cell and this can be represented by two temperature coefficient C_{TV} and C_{TI} and can be represented by

$$C_{TV}=1+\beta_T(T_a-T_x) \quad (7)$$
$$C_{TI}=1+\gamma_T/S_c(T_a-T_x) \quad (8)$$

Where β_T=0.004 and γ_T=0.06 and another cell ambient temperature is T_x.Based on this two equatin the Simulation is carried out.
The temperature change ΔT_c occurs due to the change in solar irradiation level and can be given by:-

$$\Delta T_c = \alpha_c(S_x-S_c) \quad (9)$$

Where the constant α_c represents the change in slope of the cell operating temperature due to change in solar irradiation level.
The new value of cell voltage V_{cx} and photocurrent I_{phx} can be obtained for new value of tempeture T_x and solar irradiation S_x by the given equation:-

$$V_{cx}=C_{SV}C_{TV}V_c \quad (10)$$

$$I_{phx}=C_{SI}C_{TI}I_{ph} \quad (11)$$

Where $C_{SV,}C_{TV,}C_{SI,}C_{TI}$ are the correlation coefficients.

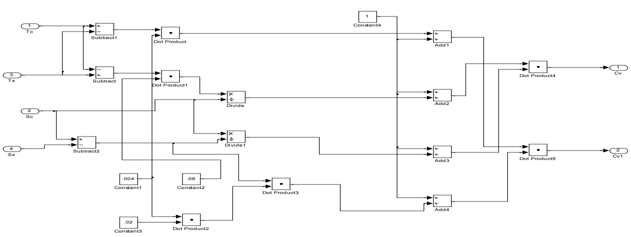


Fig-9 PV Sub-module for correction factor for current.

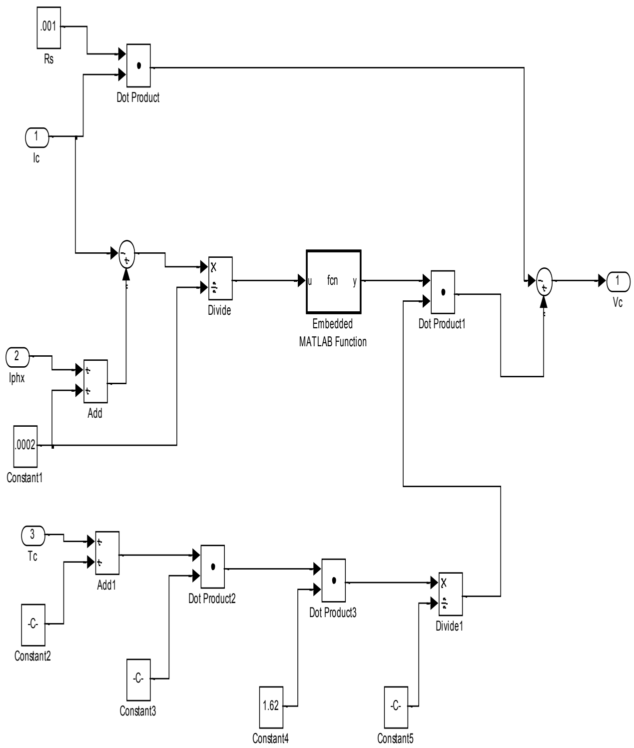


Fig-10 PV Sub module for determining the PV cell output voltage

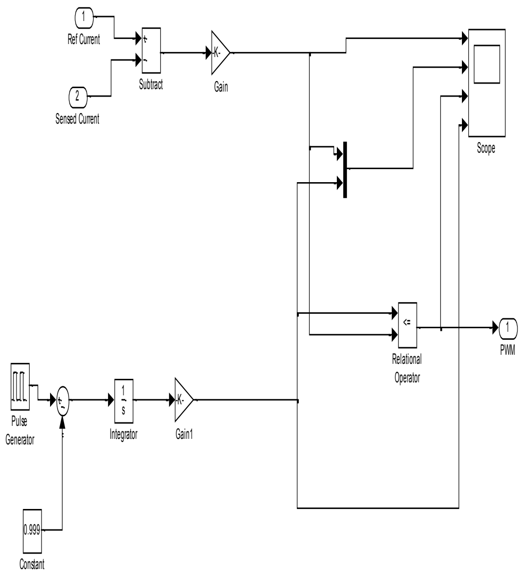


Fig-11 Internal Sub module for PWM generator

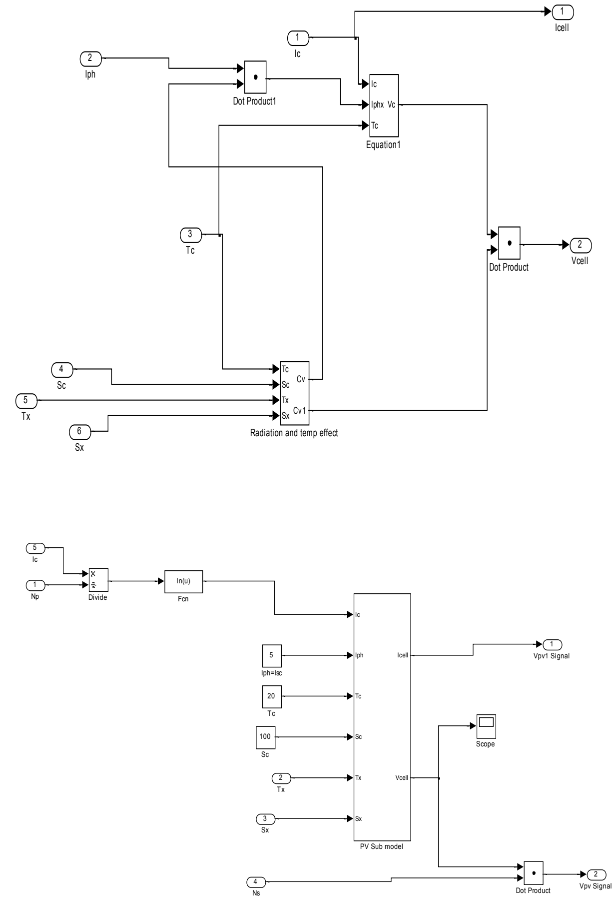


Fig-12 PV sub module that gives output voltage and output current

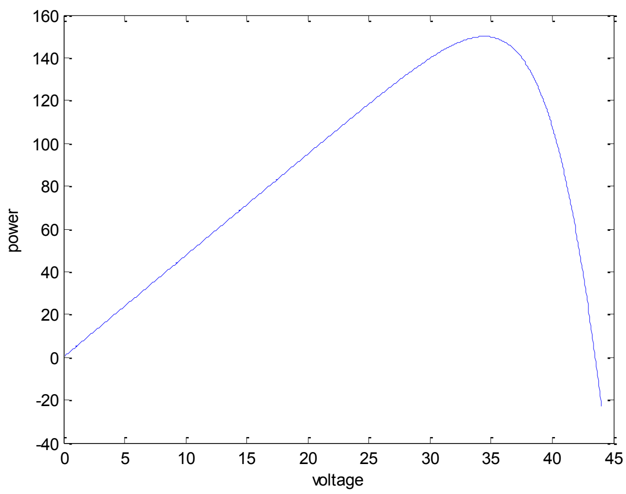


Fig-13 Power vs Voltage curve of PV cell

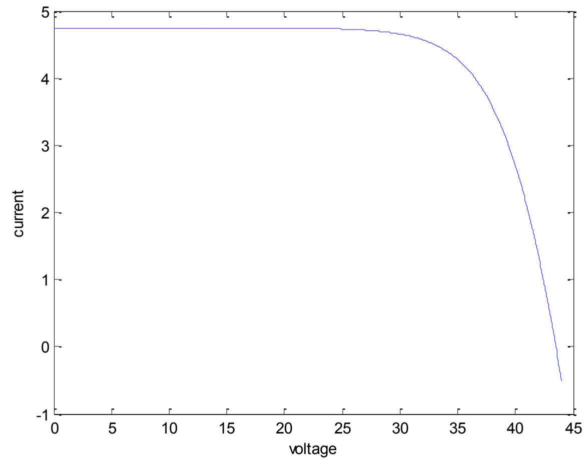
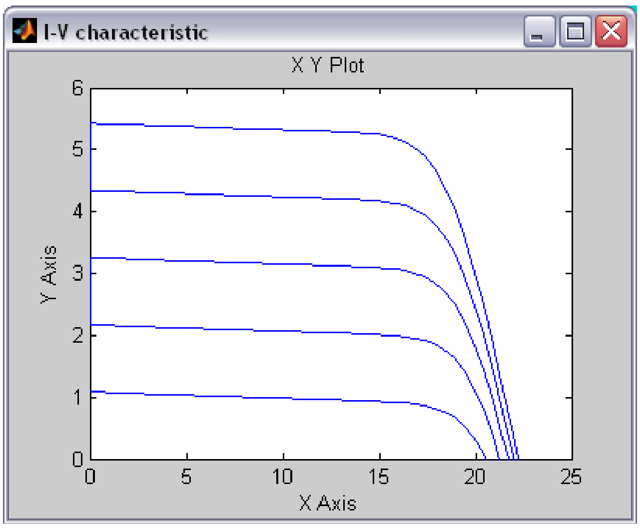


Fig-14 Voltage vs Current curve of PV cell



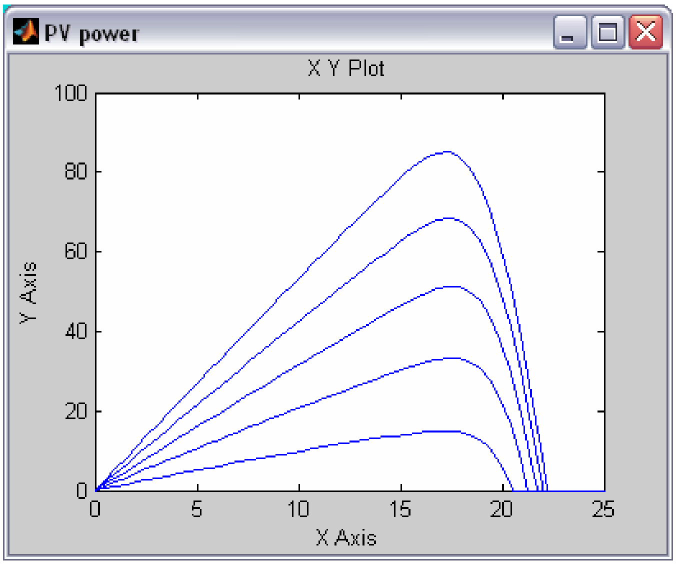


Fig-15 P-V and I-V characracteristic and for different values of isolation

TABLE 1

PARAMETERS FOR PV CELL

Parameters used	values	Parameters used	values	Parameters used	values
Q	1.602*10^-19	K	1.38*10^-23	Irradiation	100%
Iph=Isc	5A	Identity factor (a)	1.62	Np	1
Ns	15	T	20 C	Rp	415.405 ohm

5.2. Simulation of Multilevel Inverter

Simulation analysis of 3-level to 11 level multilevel inverter has been done here and by this their THD i.e harmonic content, voltage stress across the switches and no of switches has been analysed.Firstly their closed loop control is done and then their closed loop analysis is also carried out and the result is analysied.

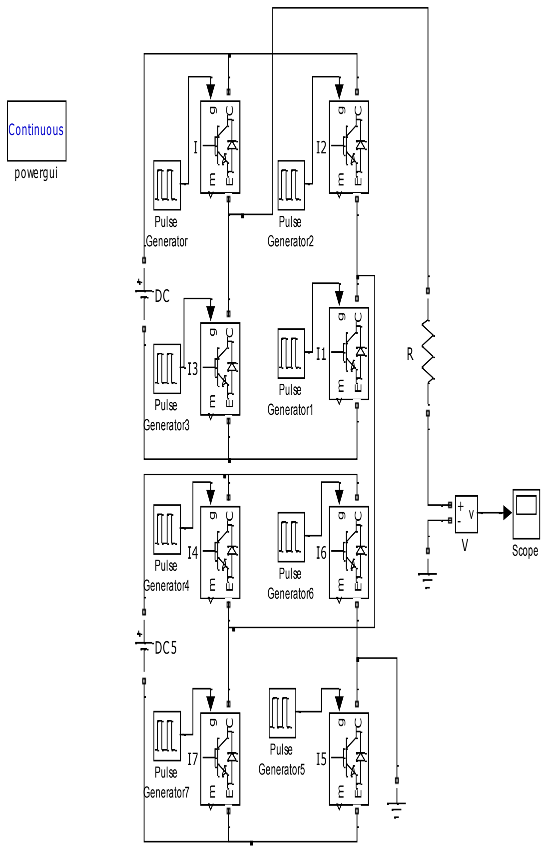


Fig-16 Cascaded 5-level multilevel inverter.

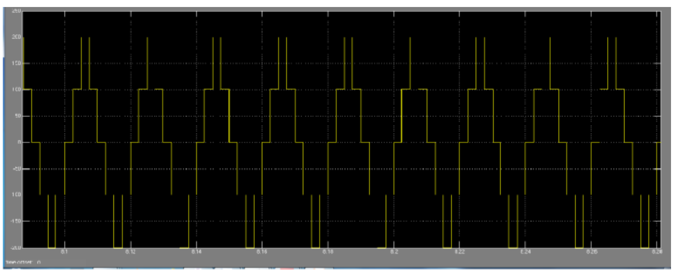


Fig-17 Output waveform of 5 level Cascaded inverter with r load.

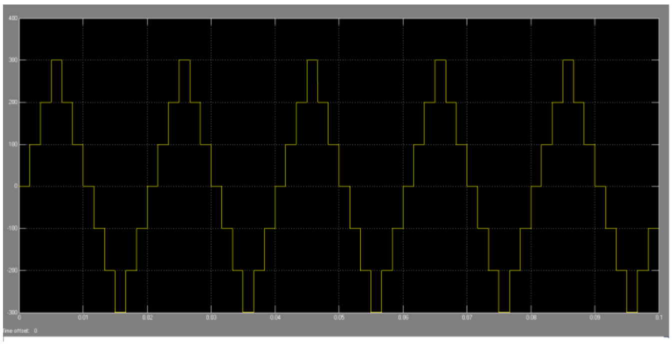


Fig-18 Output voltage waveform of 11-level inverter.

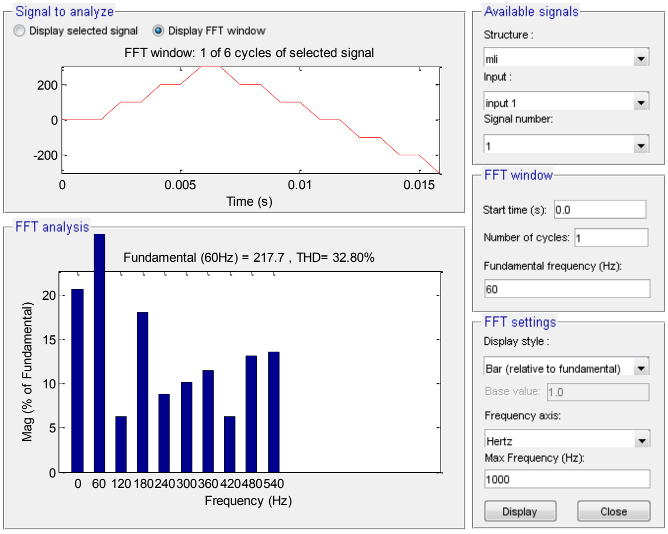


Fig-19 THD Value of 7 level inverter

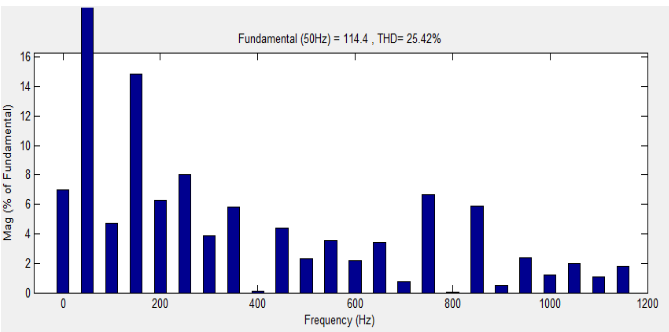


Fig-20 THD analysis of 9 level inverter.

TABLE-2
A.PERFORMANCE COMPARISION AND VOLTAGE STRESS IN DIFFERENT LEVELS OF MLIS

Levels	**Output voltage in volts**	**No of switches used**	**Voltage stress across the switches in volts**
5	$2V_{in}$	8	41.4

7	$3V_{in}$	12	70
9	$4V_{in}$	16	100.2

B.HARMONICS AND THD IN VARIOUS LEVELS OF CASCADED MULTILEVEL INVERTERS

Levels in MLIs	**THD Calculated in %**
5	35.70
7	32.80
9	25.42
11	22.10
13	17.32

C. Simulation of PI controller and Closed Loop Control

PI Controller Modelling.

PI controller is basically a combination of Proportional and Intregral controller.PI control is one of the most efficient control tropologies other then FUZZY Logic control.This increases the system performance under steady state but is not that much satisfactory under dynamic conditions.

The transfer function of PI controller is given by:-

$H(s)=K_p+(K_i/s)$

Where K_p and K_i are known as proportional and integral constant.The simulation diagram of this is shown here.

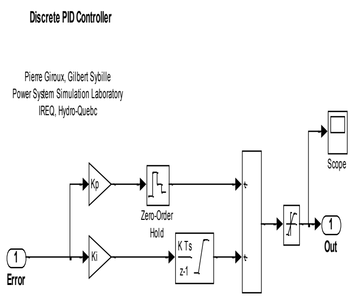


Fig-21 PI controller block.

D. Closed loop control of the system.

The closed loop control of the system is given here by first of finding out its transfer function and providing a feedback from its output loop.

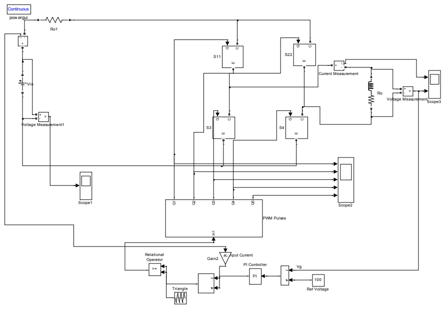


Fig-22 Closed loop control of the CHB MLI for 3 level

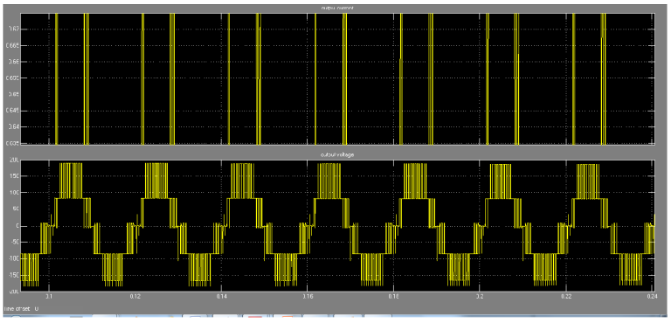


Fig-23 Output Current and Voltage waveform of closed loop control of CHB MLI 3 level

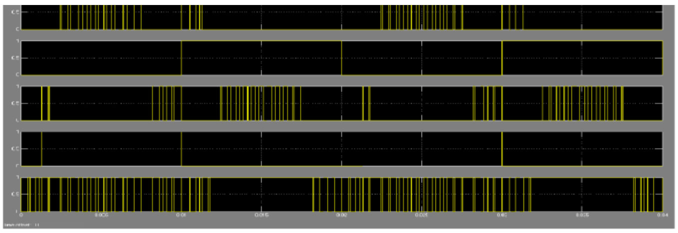


Fig-24 PWM pulses generated.

6. CONCLUSION

In this paper, a Cascaded H-Bridge Multilevel inverter for PV cell application with PI control has been proposed wich can successfully satisfy the demand of clean and flexible power requirement. The use of Cascaded Multilevel Inverter in the proposed system increases the efficiency, reduces the stress on the switches, fastens the response time and decreases the complexity and it can easily be integrated to the renewable energy resources i.e PV, Fuel cell etc. As we have seen that the harmonics can also be reduced to a desired level as we increase the no of levels of the multilevel inverter and this in turn also reduces the THD. The use of FPGA to generate the pulses for the switches allows designing the controller at a very high speed and in a very compact way and there by increases the system performance and also becomes more efficient then the Microcontroller based implementation of the System. So based on the results and discussion of components of the system and the whole system we can easily conclude the the use of Multilevel Inverter in renewable energy application is much more efficient then the other methods and hopefully it is expected that this system will be more widely used in filling up our demand for power.

7. ACKNOWLEDGEMENTS

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