A Novel 15-Level Reduced Switches in Cascaded H-Bridge Inverter For Solar Photovoltaic Application Interconnected with Grid

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***Abstract*— Renewable energy sources plays a key role in recent times as they are free from pollution, unlimited and reduces the costs related with its control. Among them Solar energy is more beneficial as the impact of solar systems on environment are significantly lower than non-solar system. Generally solar cell converts energy in the form of DC electricity. Usually we need a suitable converter for the purpose of conversion from DC to AC and then it is injected to power Grid. In this paper the inverter action is done using Eleven and fifteen level cascaded H-Bridge inverter where in we use reduced number of switches, and comparison of those inverters. The proposed inverter is used to integrate the solar system to Grid, taking into consideration of Grid requirements. In the absence of solar, we use Grid to supply the load. Eleven and fifteen level proposed Multi Level Inverters (MLI) are simulated using MATLAB/Simulink environment and the results are shown in this paper.**

***Keywords*— Solar cell, MLI, FFT, MPPT, grid integration.**

I. INTRODUCTION

The Sun is a very large of perennial source of energy, so this energy consumption can meet the present and future requirements on continues basis. This attracts attention in the world. The energy from sun i.e., Solar energy is converted to usable electricity. Solar power uses photovoltaic (PV) cells for the conversion of sunlight into electricity. The output from solar cell is in form of Direct current (DC). Then the solar panel is connected to Maximum Power Point Tracking (MPPT).

MPPT is used for extracting maximum available power from PV module under certain conditions. The obtained maximum power is then given to inverter as input.

The Inverter converts DC to alternate current (AC). For high power loads to provide accurate AC, MLIs are used. The MLI has been introduced since 1975 as alternative in high power and medium voltage situations. The conventional MLIs such as Diode Clamped MLIs need extra diodes for combination with switches, the Flying capacitor MLIs need extra Capacitors and it is also difficult to control as the levels increase and the Cascaded H-bridge MLI(CHBMLI) need separate dc sources which makes it difficult to use.

This paper proposes a latest MLI which is used to convert the dc to ac using reduced number of switches, when compared to conventional MLI. With less number of switches, switching losses can be avoided and it is also feasible. The switches used here are MOSFETs, as their switching time is less, losses associated with it are few. So for high frequency applications, where the switching loss has major impact in total power loss of the circuit, this device is the right choice.

The converted AC from proposed MLI is connected to Load. This study illustrates the development and comparison of a three phase modified H-Bridge Eleven & fifteen level inverters with 9 &11 switches respectively. The overall block model is shown in the figure1.

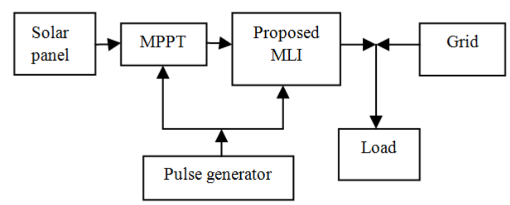

Fig.1 Block diagram of solar system with Grid connected to load

In this paper, the designed solar inverter system is interfaced to the existing conventional power grid. So that in the absence of solar power the grid supplies power to the load.

The integration of solar system to existing power system there generates associate power quality problems such as transients, harmonics, voltage fluctuations. These problems are due to irradiation, shading effects or cover of cloud makes the solar system unstable in case of grid connection which is discussed in [4]. This paper reduces these problems by integrating capacitive filter devices. Which are placed between supply and the consumer appliances hence, Improves the power quality by generating or absorbing harmonic power by the load.

The projected MLI topology can overcome some of the limitations when evaluated to the standard 2 level inverter. Harmonics decreases as the number of levels in output voltage increases. Here a higher level MLI is used so that lower order harmonics are eliminated & a comparison of 11 & 15 level MLI is also done.

Total harmonic distortion (THD) of the output voltages at load are calculated and compared to conventional MLI, thus the THD is low & power efficiency is fairly more for higher level MLI.

II. SOLAR SYSTEM

Most of the energy demands in India (and elsewhere also) can be met by simple solar systems. In addition, one of the fastest developing renewable energy sources in the last years is photovoltaic (PV) grid-connected systems [12]. However, due to the drop in the cost of PV modules (among other factors); grid interlinked photovoltaic power plants are been increasing [8] in power rating mostly now, hundreds of bulky PV based power plants with more than 10 MW [9], are working and even more are in development. Solar energy is converted into electrical energy in PV systems by PV arrays.

A. *PV array*

Individual PV cells are interconnected in series forming a PV module. Solar PV system is formed by many thin film PV modules. These construct the Solar panel for installation. The principles of operation of the PV cell was discovered by Becquerel in 1839 later, Ohl discovered the PV effect at p-n junction of two semiconductors in 1941.

Solar Cell is a p-n semiconductor material made of silicon, when photons of light energy from sun, fall on the cell a part of them will be reflected back. The nonreflected photons incident on the surface of the cell enter the thin outer layer of the semiconductor are either converted into heat or produce ion-pair by stripping the valance electrons from the semiconductor atoms. Ion-pairs are produced when the incoming energy is in excess of excitation energy. Some carriers escape the electric field of the junction and contribute to decreased electric field at the junction and this in turn decrease the flow of the majority carriers producing the current flow, this generates DC current [6]. The equivalent solar cell is shown in the below figure2. The Solar Cell block represents a solar cell current source.

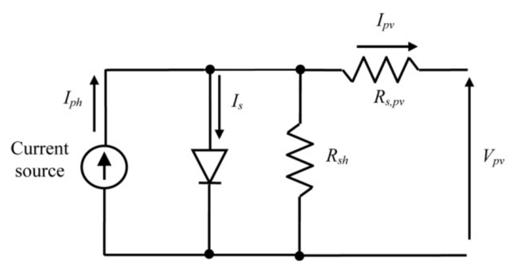

Fig.2 The equivalent circuit diagram of Solar Cell

The following equations explain current-voltage characteristics of PV cell:

PV cell output current I_{pv}:

$$I_{pv} = I_{ph} - I_s - I_{sh}$$

$$I_{pv} = I_{ph} - I_s * \left[e^{\left(\frac{V+I*R_s}{N*V_t}\right)} - 1\right] - \left(\frac{V + I * R_s}{R_{sh}}\right)$$

Where:

- I_{ph} is the solar-induced current:

$$I_{ph} = I_{ph0} * \frac{I_r}{I_{r0}}$$

- V_t is the thermal voltage, *kT/q*, where:
  - o *k* is the Boltzmann constant.
  - o *T* is the Device simulation temperature parameter value.
  - o *q* is the elementary charge on an electron.
- *N* is the quality factor (diode emission coefficient) of the first diode.
- I_s is the saturation current of the diode.
- I_{sh} is the current through parallel resistance
- *V* is the voltage across the solar cell electrical ports.
- R_s Series resistance.
- R_p Parallel resistor.

This paper presents solar panel of 36 Solar cells connected in series. This gives an open-circuit voltage of about 21V under standard test conditions. The P-V and V-I characteristics are show in below figure 3.

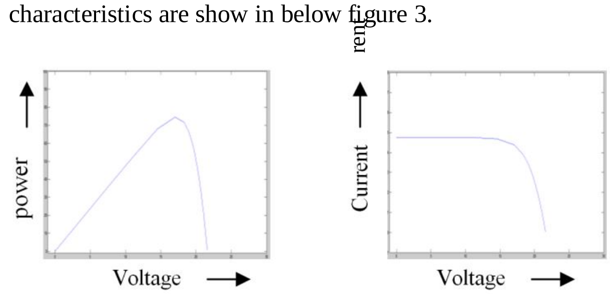

Fig.3 P-V and V-I characteristics of Solar panel

The actual DC energy from the solar array = the derated output power of the module x number of modules x irradiation for the tilt and azimuth angle of the array. Solar irradiance is a measure of the irradiance (power per unit area on the Earth's surface) produced by the Sun in the form of electromagnetic radiation, which is perceived by humans as sunlight. As the temperature goes on increasing that leads to decrease in voltage and power and by increase in sun irradiation the current, voltage and power values will increase[3].

The output from solar panel is low so there is a need to improve the voltage. Hence solar panel is connected to the dc-dc power converter, and this converter is a boost converter [5].

B. *MPPT:*

The maximum power can be extracted from solar panel when the load resistance is equal to the solar cell internal resistance. So if we can vary the resistance, maximum power can be drown.

As PV module is connected directly to load, the operating point will be at the common point of the load line and V-I curve. As a result load impedance orders system operating condition. Normally the operating point does not lie solar module Maximum power point (MPP), so there is no maximum power. To keep away from this problem, a maximum power point track is placed to maintain operating point. A MPPT (maximum power point tracker) is an electronic DC to DC converter that optimizes the match between the solar array (PV panels), and the Inverter. The boost converter performs the MPPT of the generator solar side. The impedance matching of solar module and the load to obtain maximum power can be modelled by Boost network. The DC-DC Boost circuit is shown in below figure4. The boost converter is composed of inductor L, capacitor C, Power electronic switch S and a diode D.

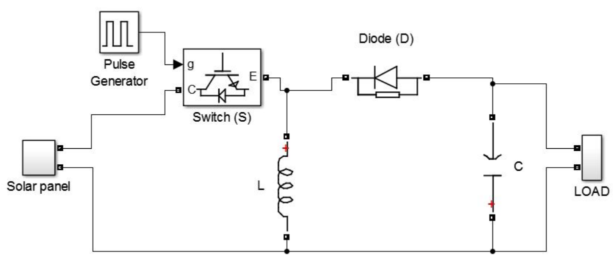

Fig.4 DC-DC Boost converter

By varying the pulse width of the gate signal of the switch S the impedance seen by the solar panel will also vary thus solar panel will be able to supply maximum power. If the pulse width is less than 50 converter acts as buck network, otherwise Boost network. Here in this paper we use only boost to increase the output of solar panel.

When switch S is turned ON, the current flows through the inductor L stores the energy. During this, diode D is blocked. When switch S is turned OFF, inductor L will provide energy to the load and the capacitor C. The stored energy in capacitor will supply energy to load when switch S is turned ON. In this way the maximum power is delivered to the load. The solar panel connected to MPPT module forms a solar system. Here the designed solar system is connected as DC supply input to the Inverter.

III. MULTILEVEL INVERTER

A. Cascaded H-Bridge MLI

Generally an Inverter converts a fixed dc voltage to an ac voltage of variable frequency and of fixed or variable magnitude. Inverters are designed using semiconductor devices such as power transistors, MOSFETs, IGBTs, GTOs and thyristors.

Now-a-days many industrial applications require high power. This requirement is met by MLI. The multilevel inverter has been introduced since 1975 as alternative in high power and medium voltage situations. MLIs comprise semiconductors, voltage sources, capacitors generate voltages of stepped waveforms. MLIs have numerous advantages when compared with two level converters. MLI generates output stepped voltages with less dv/dt stress and little distortion. These can manage system dynamic behaviour, decrease the power quality problems. MLI with renewable energy sources can be interfaced to the grid, using several low voltage DC sources like solar energy. The different formats of Multilevel inverter: Diode clamped multilevel inverter, Flying capacitors multilevel inverter, Cascaded H-bridge multilevel inverter. Among these topologies, the most accepted inverter is cascaded H-bridge MLI [7]. It exhibits most attractive features as: no capacitor voltage problems, simple circuit, less components. The series connection of multiple H-bridge inverters forms to Cascaded H-bridge MLI. Each H-bridge has similar configuration as a typical full bridge inverter of single phase. Cascaded H-bridge MLI uses separate DC source, each H-bridge inverter is connected to its own DC source. Depending on the number of voltage levels H-bridges are connected in series with individual DC sources. The number of output voltage levels is given by:

$$V=2n+1$$

Where V is the number of voltage levels and n the number of separate DC sources [14]. The number of output voltage levels are more than the double number of DC sources.

The solar power conversion is the finest suitable applications for cascaded H-bridge MLI, as each inverter require separate DC source.

The main disadvantage of CHBMLI is increase in number of power semiconductor switches, complication in gate driver circuit and switching losses. These complications can be reduced by minimizing the reliability of the inverter [15]. It can be solved effectively by reducing the number of switches for same levels of voltages. The required number of voltage levels to the number of switches is important element[2]. For the application of solar system a new topology is introduced where the same voltage levels are maintained with reduced switches is designed in this paper.

B. Proposed Multilevel Inverter Topology

The main objective is to improve the MLI voltage output quality with less number of switches [1]. A key issue in MLI design is generating sinusoidal voltage waveform. The major concern in switching technique is finding proper switching angles to produce the fundamental frequency. This paper presents an appropriate topology for MLI with less number of switches which suites for renewable energy (solar) source interface.

The general structure of the proposed MLI circuit is as shown in figure 5. The switches are positioned in a manner such that there is decrease in cost and the overall weight of MLI. This circuit requires only nine, eleven switches for single phase eleven, fifteen level inverters respectively. For this topology, we just need to insert one switch for every increase in level.

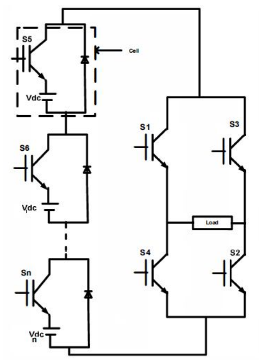

Fig.5 General structure of the proposed MLI circuit

Each DC source is replaced with solar system. By turning ON switches S_1, S_2 generates $+V_{dc}$, for $-V_{dc}$ turn ON switches S_3,S_4.

IV. COMPARISON OF ELEVEN & FIFTEEN LEVEL MULTILEVEL INVERTER

A. *Eleven Level MLI*

Eleven level voltage is obtained by proper gating pulse of inverter switches ($+5V_{dc}$,$+4V_{dc}$,$+3V_{dc}$,$+2V_{dc}$,$+V_{dc}$,0,$-V_{dc}$,$-2V_{dc}$,$-3V_{dc}$,$-4V_{dc}$,$-5V_{dc}$).

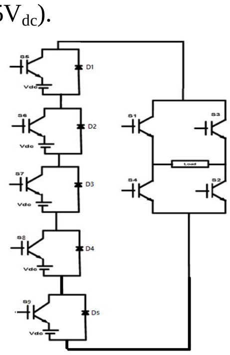

Fig.6 Circuit diagram of proposed eleven level MLI

The proposed eleven level MLI uses switches, diodes and DC sources as shown in figure 6. MOSFETs are used as switches. Table I shows the switching sequence of proposed eleven level inverter.

TABLE I
SWITCHING SEQUENCE OF PROPOSED ELEVEN LEVEL MLI

Load Voltage	S1	S2	S3	S4	S5	S6	S7	S8	S9
$+5V_{dc}$	ON	ON	OFF	OFF	ON	ON	ON	ON	ON
$+4V_{dc}$	ON	ON	OFF	OFF	ON	ON	ON	ON	OFF
$+3\ V_{dc}$	ON	ON	OFF	OFF	ON	ON	ON	OFF	OFF
$+2\ V_{dc}$	ON	ON	OFF	OFF	ON	ON	OFF	OFF	OFF
$+\ V_{dc}$	ON	ON	OFF	OFF	ON	OFF	OFF	OFF	OFF
0	OFF	ON	OFF	ON	OFF	OFF	OFF	OFF	OFF
$-\ V_{dc}$	OFF	OFF	ON	ON	ON	OFF	OFF	OFF	OFF
$-2\ V_{dc}$	OFF	OFF	ON	ON	ON	ON	OFF	OFF	OFF
$-3\ V_{dc}$	OFF	OFF	ON	ON	ON	ON	ON	OFF	OFF
$-4\ V_{dc}$	OFF	OFF	ON	ON	ON	ON	ON	ON	OFF
$-5V_{dc}$	OFF	OFF	ON	ON	ON	ON	ON	ON	ON

The output waveform of eleven level proposed MLI is shown in below figure 7 with different voltage levels: $0V_{dc}$,±Vdc, ±2Vdc, ±3Vdc, ±4Vdc, ±5Vdc

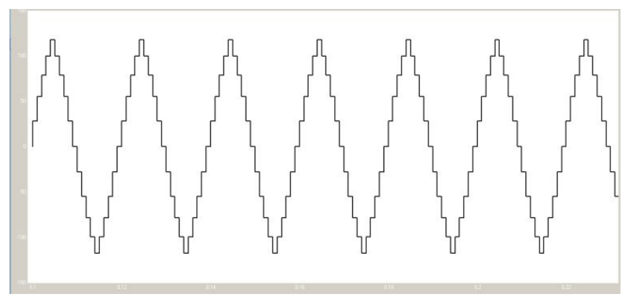

Fig.7 Eleven level Load voltage of proposed MLI

By switching the MOSFETs firing angle, we obtain the desired eleven level output voltage with fast switching.

B. *Fifteen Level MLI*

Fifteen level voltage is obtained by proper gating pulse of inverter switches ($+7V_{dc}$, $+6V_{dc}$, $+5V_{dc}$, $+4V_{dc}$, $+3V_{dc}$, $+2V_{dc}$, $+V_{dc}$,0,$-V_{dc}$,$-2V_{dc}$,$-3V_{dc}$,$-4V_{dc}$,$-5V_{dc}$,$-6V_{dc}$,$-7V_{dc}$).

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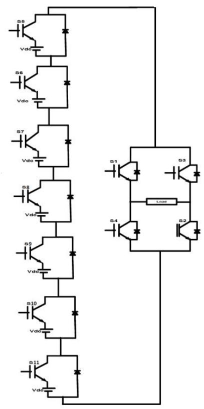


Fig.8 Circuit diagram of proposed fifteen level MLI

The proposed fifteen level MLI uses switches, diodes and DC sources as shown in figure 8. MOSFETs are used as switches. Table II shows the switching sequence of proposed fifteen level inverter.

TABLE III
SWITCHING SEQUENCE OF PROPOSED FIFTEEN LEVEL MLI

Load Voltage	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11
$+7V_{dc}$	ON	ON	OFF	OFF	ON	ON	ON	ON	ON	ON	ON
$+6V_{dc}$	ON	ON	OFF	OFF	ON	ON	ON	ON	ON	ON	OFF
$+5V_{dc}$	ON	ON	OFF	OFF	ON	ON	ON	ON	ON	OFF	OFF
$+4V_{dc}$	ON	ON	OFF	OFF	ON	ON	ON	ON	OFF	OFF	OFF
$+3\ V_{dc}$	ON	ON	OFF	OFF	ON	ON	ON	OFF	OFF	OFF	OFF
$+2\ V_{dc}$	ON	ON	OFF	OFF	ON	ON	OFF	OFF	OFF	OFF	OFF
$+\ V_{dc}$	ON	ON	OFF	OFF	ON	OFF	OFF	OFF	OFF	OFF	OFF
0	OFF	ON	OFF	ON	OFF	OFF	OFF	OFF	OFF	OFF	OFF
$-\ V_{dc}$	OFF	OFF	ON	ON	ON	OFF	OFF	OFF	OFF	OFF	OFF
$-2\ V_{dc}$	OFF	OFF	ON	ON	ON	ON	OFF	OFF	OFF	OFF	OFF
$-3\ V_{dc}$	OFF	OFF	ON	ON	ON	ON	ON	OFF	OFF	OFF	OFF
$-4\ V_{dc}$	OFF	OFF	ON	ON	ON	ON	ON	ON	OFF	OFF	OFF
$-5V_{dc}$	OFF	OFF	ON	ON	ON	ON	ON	ON	ON	OFF	OFF
$-6V_{dc}$	OFF	OFF	ON	ON	ON	ON	ON	ON	ON	ON	OFF
$-7V_{dc}$	OFF	OFF	ON	ON	ON	ON	ON	ON	ON	ON	ON

The output waveform of fifteen level proposed MLI is shown in below figure 9 with different voltage levels:
0Vdc, ±Vdc, ±2Vdc, ±3Vdc, ±4Vdc, ±5Vdc, ±6Vdc, ±7Vdc

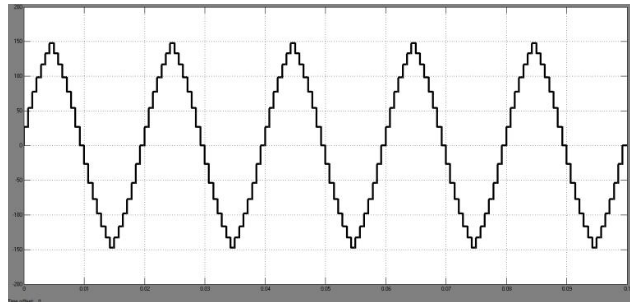


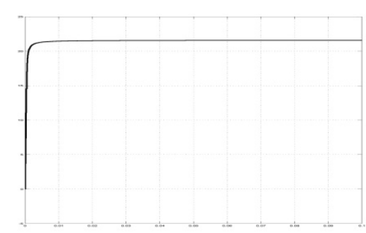
Fig.9 Eleven level Load voltage of proposed MLI

C. *Comparisons*

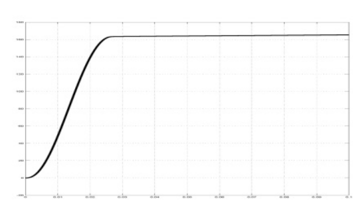
Parameters	11 Level MLI	15 Level MLI
MOSFET	9	11
Diodes	5	7
Output Voltage	$+5V_{dc}$,$-5V_{dc}$	$+7V_{dc}$,$-7V_{dc}$
DC Sources	5	7
THD	0.34%	0.26%

V. SIMULATION RESULTS

Simulation results of the solar connected proposed eleven and fifteen level inverters integrated with grid is done with MATLAB/Simulink. This project consists of solar panel of 36 solar cells connected in series, with irradiance of 1000 W/m^2 which produced a DC voltage of 21V. As the output from solar panel is insufficient to connect the inverter, the panel output is boosted with a DC-DC boost converter to produce voltage of 160V as shown in figure 10. Due to the changes in solar radiation and fast switching there affects the output voltage of the boost converter. To reduce the effect capacitors are placed in parallel.



(a)



(b)

Fig.10. Output voltage waveforms. (a) solar panel. (b) Boost converter.

The DC supply from solar system is connected as input to the proposed MLI to convert DC to AC. With proper MOSFETs firing, the gate signals to the switches is obtained. The gating signals are as shown in Table III & Table IV

TABLE IIIII
11 LEVEL PULSE GENERATOR VALUES OF SWITCHES

SWITCHES	Period (secs)	Pulse Width (% of period)	Phase delay (secs)
S1	0.02	50	0
S2	0.02	50	0
S3	0.02	50	0.01
S4	0.02	50	0.01
S5	0.01	90	0
S6	0.01	70	0.001
S7	0.01	50	0.002
S8	0.01	30	0.003
S9	0.01	10	0.004

TABLE IVV
15 LEVEL PULSE GENERATOR VALUES OF SWITCHES

SWITCHES	Period (secs)	Pulse Width (% of period)	Phase delay (secs)
S1	0.02	50	0
S2	0.02	50	0
S3	0.02	50	0.01
S4	0.02	50	0.01
S5	0.01	650/7	0
S6	0.01	550/7	1/1400
S7	0.01	450/7	1/700
S8	0.01	50	3/1400
S9	0.01	250/7	1/350
S10	0.01	150/7	1/280
S11	0.01	50/7	3/700

The MATLAB simulated circuit of 11 level MLI this system is as shown in the figure 11.

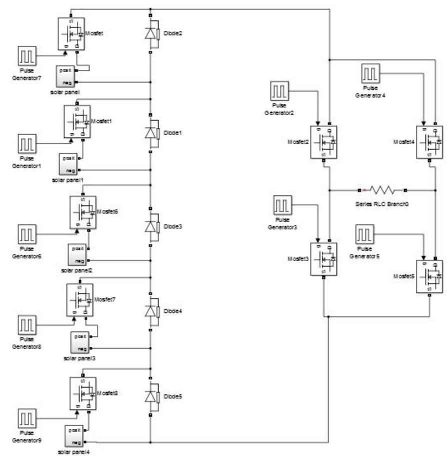


Fig.11 Simulation circuit of PV based single phase proposed eleven level inverter

Three phase MLI circuit is also designed similar to the single phase MLI circuit. The figure 12 & 13 shows the three phase output load voltage waveforms of proposed solar interfaced MLI. Proposed inverter produces an accurate eleven & fifteen levels stepped sinusoidal voltage waveform. Thus the proposed solar based MLI is successfully simulated.

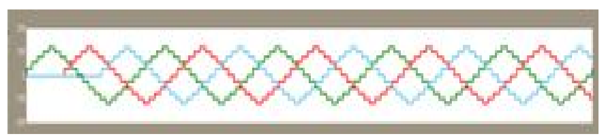


Fig.12 Three phase eleven level voltage waveforms of proposed MLI

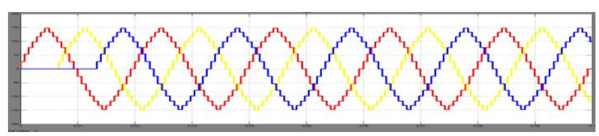


Fig.13 Three phase fifteen level voltage waveforms of proposed MLI

The generated AC voltage is connected to a RL load. In the absence of solar radiation, system does not supply the load (consumers). To overcome this problem, this paper interconnects the PV based proposed MLI system to the Grid. Figure 14 shows it in the form of MATLAB simulation. The AC grid supplies energy to the load in the absence of solar energy.

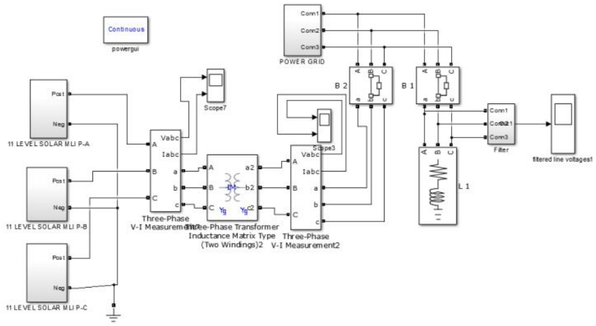


Fig.14 Simulation model of Grid connected proposed multi level inverter with the application of solar system

Interfacing grid to the solar MLI system produces distortions at the load. This problem is solved by connecting a LP filter[16] at the load end. The figure 15 shows the simulated output waveform at the load of our system. It can be observed that a continuous and reduced harmonic wave is achieved.

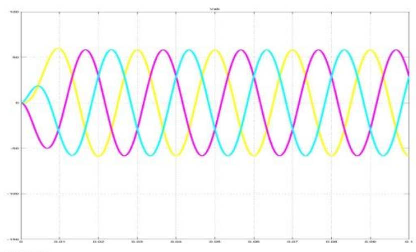


Fig.15 Output of load voltage when solar and grid system are connected

The line spectrum of output voltage waveform is taken to determine the Total harmonic distortion present in the waveform. Figure 16 & 17 shows that the total harmonic distortion, for the output voltage of proposed eleven & fifteen level inverter with resistive and inductive load is 0.26% & 0.34% respectively. Which is very less compared to normal Cascaded H-Bridge Inverter [10],[13].

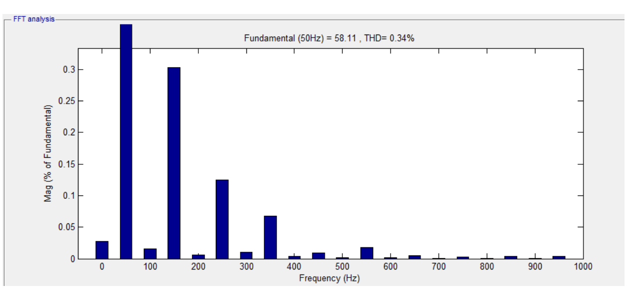


Fig.16 FFT analysis of output voltage waveform of eleven level MLI with RL load

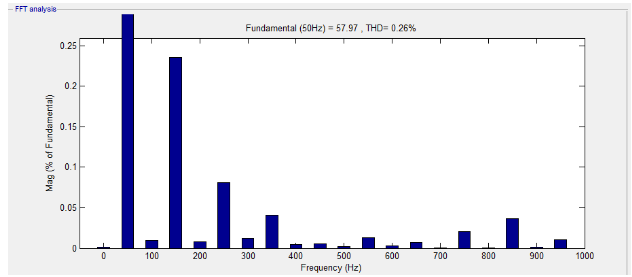


Fig.17 FFT analysis of output voltage waveform of fifteen level MLI with RL load

VI. CONCLUSION

A PV based modified MLI of eleven & fifteen level with reduced switches, integrated scheme for power grid is proposed in this paper. This topology eliminates the harmonics at the solar system by expanding and increasing the number of output levels with less number of switches through which the initial cost is also reduced. This MLI presents nearly same sinusoidal output voltage with minimum (0.34% & 0.26%) & harmonic content. Hence it is proved that with increased number of levels the output is closer to sinusoidal waveform resulting reduced harmonic content. Simulation results are presented to validate the efficiency of the proposed scheme.

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