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Dual Stage Boost Front-End Hybrid Inverter for Photo-Voltaic System

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Abstract*— The electrical energy crisis and its high cost paved the way to the use of renewable energy sources, out of which solar energy is commonly used. Various topologies for the photo-voltaic (PV) modules such as centralized and string topologies have drawbacks of power losses and limited power demands. The conventional PV system consists of three phase cascaded H-bridge multilevel inverters, where the number of H-bridge increases with the increasing level of the inverter that makes the system more complex and expensive. The paper describes a high efficiency photovoltaic system using a hybrid multilevel inverter circuit with multistring boost converter topology. The proposed inverter circuit is built by connecting a line frequency three-phase bridge inverter in series with three high frequency single phase H-bridge inverters. The three phase line frequency inverter bears the main output power and the three single phase H-bridge inverters are used to improve the system performance. The multistring topology with Maximum Power Point Tracking (MPPT) control achieves maximum power available from the PV which maximizes the efficiency. Compared with the traditional inverter circuit, this circuit can achieve high efficiency and low harmonics and it can reduce the voltage stress on the power switches. Since the circuit is modularized and have independent voltage control, it can be controlled easily. This paper includes the study of photo-voltaic system with independent MPPT control, inverter topology, principle of operation, switching states and its control circuit design. Simulation of a three phase proposed inverter with multistring boost converter photo-voltaic system is carried out using MATLAB-Simulink software and the result shows the feasibility of the proposed topology.

***Index Terms*— Cascaded Inverter, Multilevel Inverter, Multistring Topology, Photo-voltaic Cell.**

I. INTRODUCTION

Electrical energy crisis is an important issue. Inorder to overcome, renewable energy particularly solar and wind has been the certain choice. Solar energy is one of the favourable renewable energy source due to its distinctive advantages - simple configuration, easy allocation, free of pollution, no noise, low maintenance cost etc[1]. Photovoltaic (PV) generation is the technique which uses photovoltaic cell to convert solar energy to electric energy. There are many recommended standards for the photo-voltaic system. Present standards of PV module are EN61000 and IEC61727 and the US National Electrical code (NEC) 690. These standards deal with issues, like power quality problems, detection of islanding operation, grounding, etc. Draft IEC 62116 standards are developed in the International Electro Technical Commission Technical committee 82-Solar photo-voltaic energy systems that describes international test for inverter anti islanding [2],[3]. NEC (National Electrical Code) standards demands that the PV modules shall be the system grounded and monitored for ground faults [3],[4]. India's plan to produce 20GW solar energy by the year 2022 through India's Jawaharlal Nehru Solar Mission is one of our remarkable policies. Different types of photo-voltaic system are available- centralized topology, string topology and multistring topology. Centralized inverter topology is simple and provides connections in series and parallel according to the required voltage and power. But to achieve high power demand purpose, we need large space requirements; connections provide to the PV system become complex and high rating equipments are necessary. One of the important limitations is the single control for the whole photo-voltaic system. This paved the way for the string inverter topology. The power handling capacity of string inverter topology is limited to 2kW. Due to the limited voltage capacity of photo-voltaic modules, the power rating for single string cannot be expandable. So the next step in the evolution of string inverter topology is multistring inverters. It is considered as the state of art. Multistring topology is the symbiosis of two main competitors in the PV system-the central and string topology [5],[6]. To attain the maximum power from a PV system, maximum power point tracker is inevitable. By using multistring inverter topology separate MPPT can be possible. Different MPPT tracking algorithms are present- Perturb and Observe method (P&O), incremental conductance method (INCond.), feedback voltage or current, fuzzy logic method and neural network method. P&O method is widely applied in the MPPT controllers due to their simplicity and easy implementation [7]-[9]. A dc-dc converter is used for voltage amplification and regulation purpose. PV module oriented converters are connected in series on the DC-side and parallel on the AC side usually. A PV inverter which is an important element in the PV system is used to convert DC power from the solar panels into AC power. The performance of the power inverter depends on the control strategy adopted to generate the gate pulses. Multilevel inverters have gained much attention in the field of medium voltage and high power applications due to their many advantages, such as low voltage stress on power semiconductor, low harmonic distortions, good electromagnetic compatibility, reduced switching losses and improved reliability on fault tolerance. Comparing with two level inverter topologies at the same power ratings, multilevel inverters have the advantages that the harmonic components of line-to-line voltages fed to load are reduced owing to its switching frequencies [10]. The multilevel inverters also have lower dv/dt ratios to prevent induction or discharge failures on the loads. Also multilevel inverter is useful to reduce the cost and size of power filter and can be used for reactive compensations. Such inverter requires several number of dc power sources depending on the number of level and voltage ratio of dc buses. Multiple power sources can be easily be obtained by dividing the photovoltaic modules in groups. As a result, multilevel inverters are becoming increasingly popular in photovoltaic applications. However, there is a lot of challenge to use multilevel inverter in photovoltaic system. As the number of level of the inverter increases, the number of device also increases. The challenge of using multilevel inverter in photovoltaic application is to reduce the number of switches without compromising with power quality (number of levels) [10]-[12].

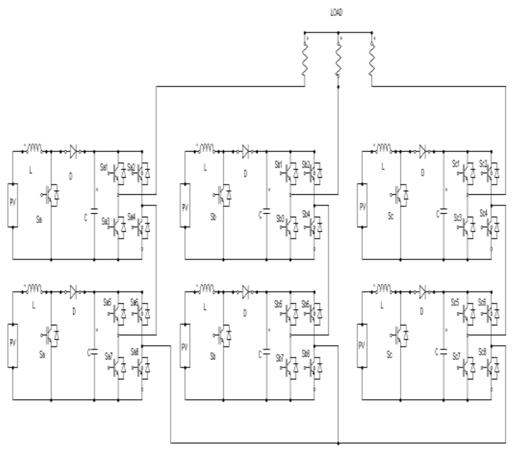

Fig.1: Conventional Inverter

Different types of multilevel inverters have been studied- diode clamped (neutral clamped) inverter, flying capacitor (capacitor clamped) inverter and cascaded inverter with separate DC source [7],[8],[10]. Diode clamped (neutral clamped) inverter was proposed by Nabae *et al*. [5]have a wide popularity in motor drive applications, would be a limitation of complexity and number of clamping diodes when the level exceeds the three. Also this inverter have capacitor voltage imbalance problem. The main limitations of flying capacitor (capacitor clamped) inverter is the requirement of large number of capacitors and their efficient control. Conventional cascaded multilevel inverter is shown in fig.1.Compared with the other multilevel inverters, cascaded multilevel inverter has lower total harmonic distortion, it requires only less number of components comparative to the diode clamped or the flying capacitor. But it needed separate H-bridge according to the output voltage level. So the number of switching devices required is more. In effect the switching losses are more, efficiency is reduced, and expense and complexity is increased. Hence a novel cascaded multilevel inverter topology is introduced. In this paper, Section II presents the principle of operation of the proposed inverter and its control part. Section III includes multi-string photovoltaic system with boost front-end converter and MPPT control strategy. Simulation works and result analysis of a three phase novel system using MATLAB-Simulink software is included in section IV. Conclusions are given in section V. The analytical and simulated results show the superiority of the proposed system compared with conventional system

II. PROPOSED INVERTER AND ITS CONTROL STRATEGY

Proposed system is designed for obtaining a 5-level output and it is shown in fig.2

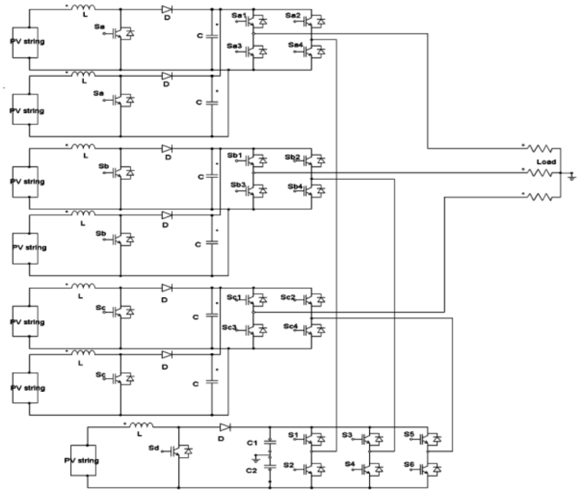

Fig.2: Proposed Inverter

Dual stage process system consists of multistring topology for dc-dc conversion and an inverter connected to load for dc-ac conversion. Separate PV strings as dc source and each string is connected to a boost converter. Since multistring topology is used the boost converters output are connected in parallel. This boosted dc supply is fed to three phase five level novel cascaded H-bridge multilevel inverter. An H-bridge is connected to each leg of the three phase inverter and the output is connected to the load. Three-phase inverter circuit works at line-frequency, which provides the main output power [14]. Since the switches of the three phase inverter work at line frequency, the switching loss is small and the efficiency of output system is high. Double frequency control is implemented for photo-voltaic inverter configuration. Fundamental switching scheme is used to do modulation control for the main inverter and an independent voltage control is used for H-bridges. Considering the fig.3, the switch S1 is ON for positive half cycle produces +Vdc/2 and S2 is ON for negative half cycle which produces-Vdc/2. Similarly other switches in the main inverter conducts for 180 degree in turn in each cycle. For each H-bridge inverter, when Sa1 and Sa4 is ON produces +Vdc/2 and when Sa2 and Sa3 is ON produces –Vdc/2. Main inverter uses dc link voltage to generate a modulated voltage at the output terminals. The total output voltage for proposed inverter is obtained by the

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sum of each individual output voltage. Thus proposed inverter is able to produce five output voltage levels, such as, +Vdc, +Vdc/2, 0, -Vdc/2 and –Vdc.

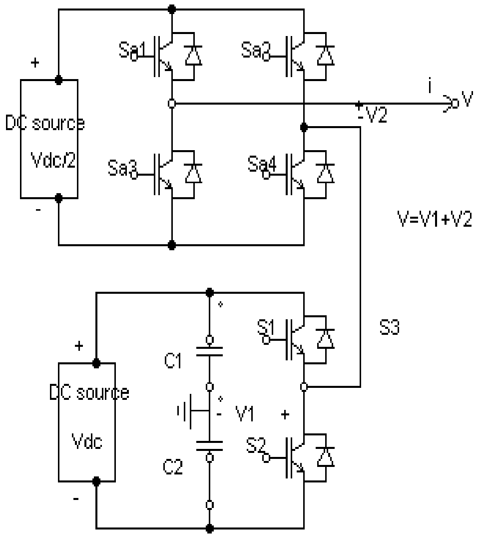

Fig.3: Single Phase Structure of Proposed Inverter [28]

Table I: Output Voltages and Switching States of Single Phase Structure

Main inverter switches	H-bridge inverter switches	Output voltage
S_1	S_{a2},S_{a3}	0
S_1	S_{a3},S_{a4}	$V_{dc}/2$
S_1	S_{a1},S_{a4}	V_{dc}
S_1	S_{a3},S_{a4}	$V_{dc}/2$
S_2	S_{a1},S_{a4}	0
S_2	S_{a1},S_{a2}	$-V_{dc}/2$
S_2	S_{a2},S_{a3}	$-V_{dc}$
S_2	S_{a1},S_{a2}	$-V_{dc}/2$

The output voltages attained and the switching sequence are shown in table I. For the same operation in conventional cascaded inverter needed four switches. In proposed inverter topology, only three switches are conducting at a time. Thus the switching losses are reduced. As the number of switches reduced, the efficiency of the system is improved. At the same time distortions are reduced. This will reduce the filter requirements. Since double mode frequency control is carried out, this makes the inverter control simple. The same principle of operation is employed in the other two phases. In proposed system, the three phase inverter works at line frequency and at the same time three single-phase H-bridge inverters work at high frequency. Modulating signal shown in fig.4 has to be formed to attain the switching pulses for the proposed inverter and it is obtained from the sinusoidal waveform.

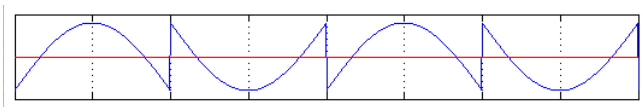

Fig.4: Modulated Sine Wave [14]

Consider the phase 'a' of three phase waveform. PWM control is given to the H-bridge inverter. The waveform in fig.4 is compared with triangular carrier wave with equal amplitude and frequency and obtains the gate pulses A and B for switches Sa1 and Sa2 shown in fig.5.

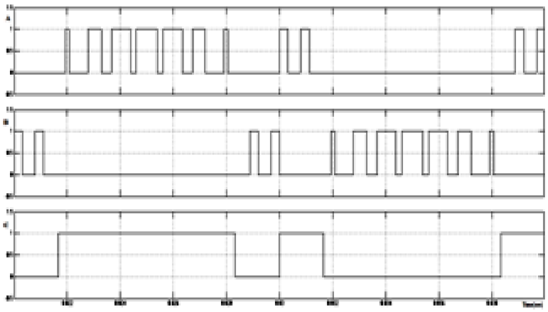

Fig.5: PWM Pulses of Single Phase Bridge Inverter

The modulated sine wave (fig.4) is passed through a zero level comparator and obtains the signal C shown in fig.5. This signal is then combined using logic gates and attain the gate pulses for the other two switches of H-bridge inverter ie, the driving signals for the high frequency switches Sa1, Sa2, Sa3 and Sa4 are obtained as Sa1=A, Sa2=B, Sa3= $\overline{A}+C$, Sa4= $\overline{B}+C$ respectively [14]. The gate pulses for one leg of the main inverter switches S1 and S2 are achieved by comparing the sine wave with a relational operator. The same procedure is repeated for the other two phases. The switches logic connections are shown in fig. 6.

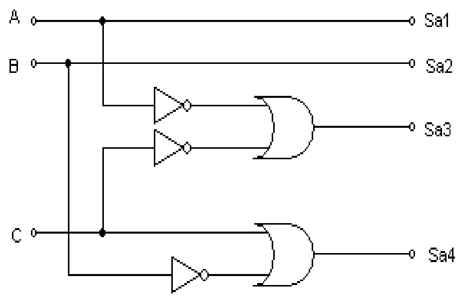

Fig.6: Switches Logic Control Schematics [14]

III. MULTISTRING FRONTEND BOOST CONVERTER WITH MPPT CONTROL FOR PHOTOVOLTAIC SYSTEM

A. Photovoltaic System

The photovoltaics are attractive sources of renewable energy for electric power generation. dc supply used for the new inverter topology is supplied using photovoltaic modules since solar energy is widely available and completely free of cost. The electromagnetic radiation of solar energy can be directly converted to electricity through photovoltaic effect. PV cell is the basic unit of photo voltaic system. The cells must be connected in series-parallel configuration on a module to produce enough high power. PV module has nonlinear characteristics. A PV array is a group of several PV modules which are electrically connected in series and parallel circuits to generate the required voltage and power [15], [16]. The characteristics and performance of PV cell is varied by varying the irradiance and temperature. The open

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circuit voltage increases logarithmically with the ambient irradiation, while the short circuit current is a linear function of the ambient irradiation. The dominant effect with increasing cell's temperature is the linear decrease of the open circuit voltage, the cell being thus less efficient. The short circuit current slightly increases with the cell temperature [17]. The equivalent circuit for the solar module is shown in fig.7 which consists of a photo current, a diode, a parallel resistor representing a leakage current and a series resistor describing an internal resistance to the current flow. Shunt resistance denoted by R_p, and R_s is a series resistance.

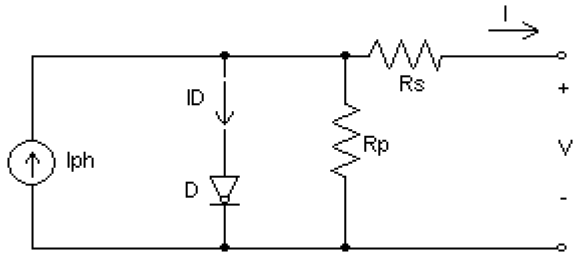

Fig.7: Equivalent Circuit for the Solar Module [19]

The PV module current can be obtained by using Kirchhoff's law as

$$I = I_{ph} n_p - n_p I_{sr}\left[\exp\left(\frac{qV}{kTAn_s}\right) - 1\right] \quad (1)$$

where I_{ph} is a light-generated current or photocurrent, I_{sr} is the cell saturation of dark current, q (= 1.6 ×10^{-19}C) is an electron charge, k (= 1.38 ×10^{-23}J/K) is a Boltzmann's constant, n_p is the number of parallel cells, n_s is the number of series cells, T is the cell's working temperature, A is an ideal factor. Due to the photo-voltaic (PV) effect, the voltage of a PV cell is not very high. More number of PV modules are to be connected in series or parallel to meet the inverter input demands. This increases the component requirements and space requirements. Considering the multistring topology, separate PV strings can be designed so that it can meet higher power demands and provide separate MPPT control. [18]-[21].

B. DC-DC Converters

DC-DC converters can be used as switching mode regulators to convert an unregulated dc voltage to a regulated dc output voltage. The regulation is achieved by PWM at a fixed frequency and the switching device is generally BJT, MOSFET or IGBT. There are five topologies for the switching regulators: Buck converter, Boost converter, Buck-Boost converter, Cuk converter and SEPIC converter. In this paper, a high step-up converter [22] is implemented to provide voltage amplification, reduce the series-connected numbers of PV modules, to maintain a constant dc bus voltage for the inverter utilization, and to decouple and simplify the inverter control design. The inductor and capacitor provides filtering requirements that reduce the output ripple. The voltage conversion ratio of boost converter is given by:

$$\frac{V_o}{V_d} = \frac{1}{1-D} \quad (2)$$

C. Control Algorithm for MPPT

Maximum Power Point Tracking(MPPT) is the algorithm that included in electronic control device for extracting maximum available power from PV panels, which the maximum power change according to the variations in parameters such as solar radiation, ambient temperature and solar cell temperature[23]. The MPPT algorithm is implemented by using microprocessor to check the PV panels output at all time that there is no other higher output power from PV panels in form of current and voltage from the solar radiation at that time. Different algorithms are present and fig.4 shows the algorithm for P&O method which is used for tracking the maximum power [9], [24], [25].

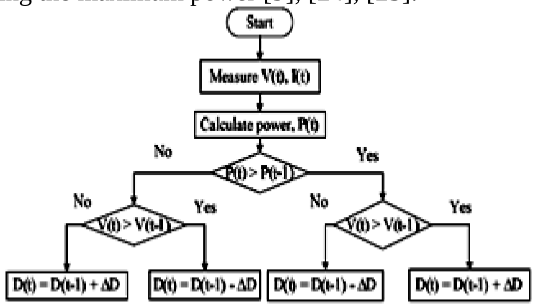

Fig.8: Flowchart for P& O algorithm [9]

According to the structure of MPPT system shown in fig. 8, the required parameters of the power-feedback type MPPT algorithms are only the voltage and current of PV modules. Power is calculated from the measured voltage and current and algorithm is operated by perturbing (i.e., incrementing or decrementing) the array terminal voltage periodically and comparing the PV output power with that of the previous perturbation cycle. If the power is increasing the perturbation will continue in the same direction in the next cycle, otherwise the perturbation direction will be reversed. Compared with Incremental Conductance algorithm, Perturb and Observe algorithm is preferred due to its simplicity and easy implementation. Once maximum power attained, then the operating point oscillate around MPP throughout the process and this will result in loss of energy. These oscillations can be minimized by reducing the perturbation step size but it slows down the MPP tracking system [9],[26],[27].

IV. SIMULATION RESULTS AND ANALYSIS

The Sun Power SPR-327NE-WHT-D model, 327W PV module was chosen for modelling and simulation using MATLAB/Simulink. The module has 96 maxeon cells which are connected in series. The electrical specifications are shown in table II.

Table II: Specification of Sun power E20/327model

At temperature	25^{0}C
Open circuit voltage, V_{oc}	64.9V
Short circuit current, I_{sc}	6.46A
Voltage at maximum power, V_{mpp}	55.87V
Current at maximum power, I_{mpp}	5.85A
Maximum power, MPP	326.8W

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Fig.9 shows the configuration of PV system built in Simulink. It consists of a set of PV module model, a boost converter and MPPT algorithm. The inputs of the PV module are the solar irradiance and the ambient temperature. The output produced by the PV module is the PV current, which acts as a controlled current source for the input of the boost converter. The input capacitance of the converter is 0.5198mF, the inductance, L is 2.632mH and the output capacitance is set to be 599.17 μF. The load resistance, R is 69.372 Ω. The MPPT block consists of MPPT algorithm, namely perturb and observe algorithm. Frequency, f_s is set to be 1 kHz in this simulation. The sampling time of the simulations is assumed to be 0.5 seconds.

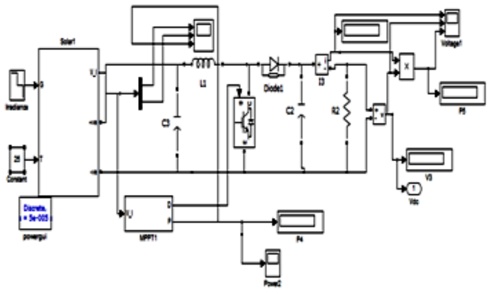

Fig.9: Configuration of PV System in Simulink

Fig.10 show the configuration of MPPT algorithm in Simulink according to the flow chart of P&O method explained in fig. 8.

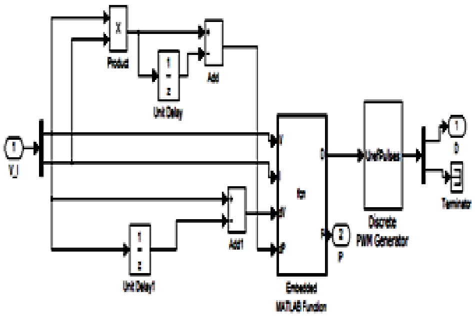

Fig.10: Configuration of MPPT P &O Algorithm in Simulink

Fig.11 shows the simulated V-I characteristics and V-P characteristics of the PV model at temperature-25^{o}C and irradiance -1kW/m^2. The maximum power attained from the PV model is 306.6W with Vmpp-50.2V and Impp- 6.11A.

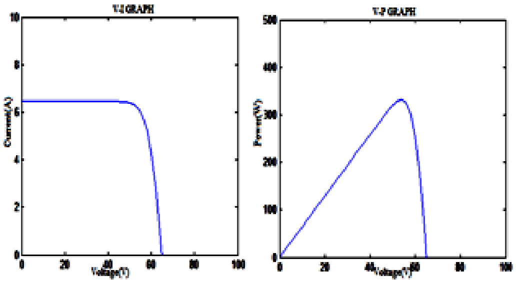

Fig.11: V-P and V-I output characteristics of PV module at T-25^{0}C and s=1kW/m^2

Fig.12 shows the photo-voltaic power waveform obtained using the Perturb and Observe (P&O) algorithm. The incremental and the decremental perturbation step size of P&O algorithm is 0.01.Algorithm was tested at temperature of 25^{o}C and solar irradiance of 1 kW/m2. The maximum PV power obtained by algorithm is 306.6W.

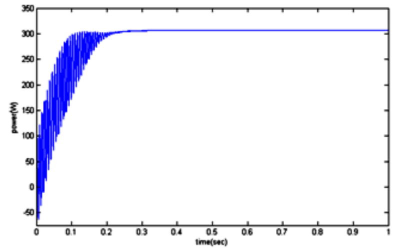

Fig.12: Maximum Power Obtained From MPPT

For two-stage PV generation system, boost converter circuit is used as the DC-DC converter. Since the output voltage of PV cell is low, the use of boost circuit will enable low-voltage PV array to be used, as a result, the voltage amplification takes place, power becomes steady and unchanged and current reduced. The simulation results of PV fed multi-string boost converter is shown in fig.13.The converter is designed for boosting the PV model voltage-50V to 200V with total output power 654W. The values obtained are output power, Po – 576.4W, output voltage Vo – 200V, output current, Io – 2.882A. By using multi-string topology the voltage becomes steady, current is doubled and the power is increased. The obtained input voltage and current from a single PV system are Vd – 50.2V and Id – 6.11A.

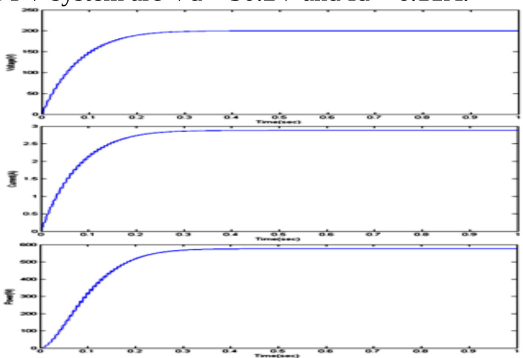

Fig.13: Output Voltage, Current and Power of Multistring PV Boost Converter

The simulink model of conventional cascaded H-Bridge multilevel inverter is shown in fig. 14. It consists of six subsystems for the inverter design and six subsystems for its controlling techniques. Subsystems which specify inverter design consists of six H-bridge inverters and its dc input is multi-string boost converter. The controlling section subsystem includes the phase opposition pulse width modulation control pulses.

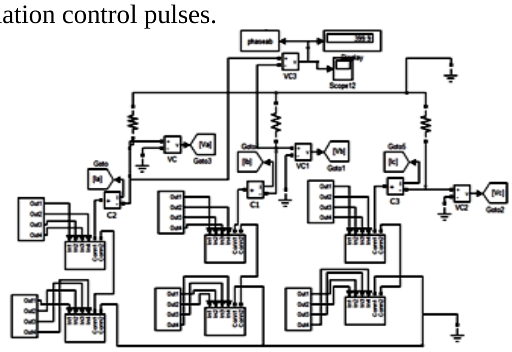

Fig.14: Simulink Model of Conventional Cascaded Inverter with Multi-String PV System

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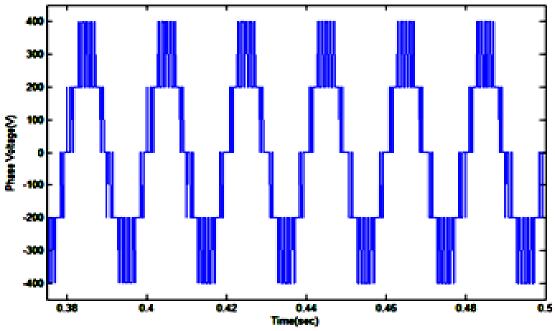

Fig.15: Output Phase Voltage of Conventional Cascaded Inverter

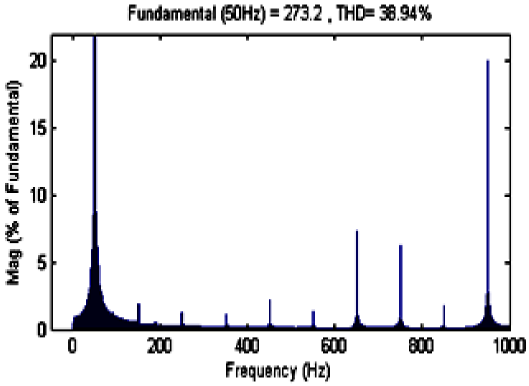

Fig.16: FFT Analysis of Conventional Cascaded Inverter

The output phase voltage is shown in fig.15 and FFT analysis is carried out to find the THD of the conventional system. The power obtained for conventional system is 1072.4W. FFT analysis result for 'phase a' of conventional inverter is shown in figure 16.The obtained THD value is 38.94%. The simulink model of proposed cascaded H-Bridge multilevel inverter with multi-string boost converter is shown in fig.17.

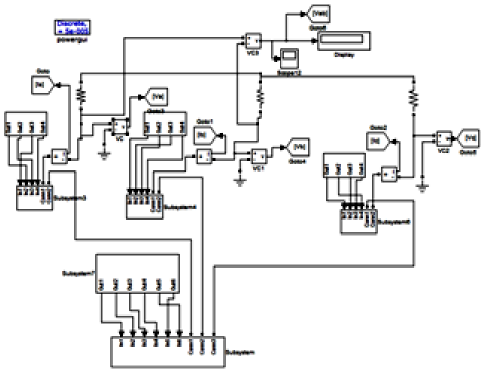

Fig.17: Simulink Model of Proposed Cascaded Inverter with Multi-String PV System

Separate MPPT is given to each PV string. Seven PV fed boost converters are necessary for the proposed inverter. It consists of four subsystems for the proposed inverter design and four subsystems for its controlling techniques shown in fig.17. Subsystem which specifies inverter design consists of three H-bridge inverter and a main inverter. The controlling section subsystem includes the fundamental switching frequency control pulses and the high switching frequency control pulses. The proposed inverter is fed to a three phase load. Each phase is designed to get five output levels- 0, 200V,-200V, 400V, -400V.

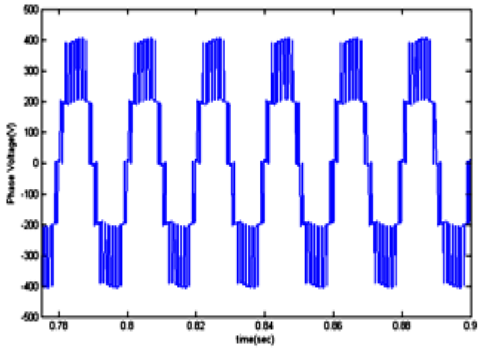

Fig.18: Output Phase Voltage of Proposed Cascaded Inverter System

The output phase voltage waveforms are shown in fig.18 and FFT analysis is carried out to find the harmonic distortion of the proposed system. FFT analysis result for phase a of proposed inverter is shown in fig.19.The obtained output power is 1041W and THD value is 33.37%.

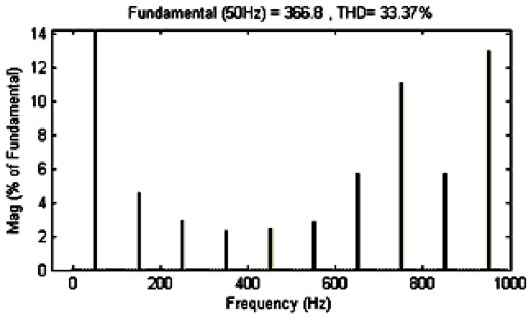

Fig.19: FFT Analysis of Proposed Cascaded Inverter

The conventional and proposed inverter topologies are designed and done simulations using MATLAB/Simulink software. Feasibility of the proposed inverter is verified through detailed FFT analysis. The table III shows the effectiveness of the proposed inverter as compared with the conventional inverter.

Table III: Comparison of Five Level Proposed Inverter with Conventional Cascaded Inverter

	conventional inverter	proposed inverter
Number of switches	24	18
Switching losses	More	Less
Energy conversion efficiency	Less	More
Switching stress	More	Less
THD%	38.94	33.37

V. CONCLUSION

A study on photovoltaic system is done and different types of multilevel inverter topologies are studied to obtain an efficient three phase inverter topology that provide high efficiency and high quality outputs. Multistring topology provides higher power rating capacity. Novel three phase multilevel inverter with multistring boost converter topology has been proposed. Circuit topology, operating principle, control algorithm of the proposed inverter have been analyzed. Maximum power tracking is achieved by using P&O algorithm having a maximum power of 306.6W. Compared with the conventional three phase topology, the new topology have lower THD-33.37% and switching losses, better efficiency, high quality voltage and current waveforms. The simulation model of the proposed inverter is done using MAT LAB Simulink software.

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