JOURNAL OF SEMICONDUCTOR TECHNOLOGY AND SCIENCE, VOL.16, NO.4, AUGUST, 2016
http://dx.doi.org/10.5573/JSTS.2016.16.4.451
ISSN(Print) 1598-1657
ISSN(Online) 2233-4866

Cascaded H-Bridge Five Level Inverter for Grid Connected PV System using PID Controller

M. S. Sivagamasundari and P. Melba Mary

Abstract—**Photovoltaic energy conversion becomes main focus of many researches due to its promising potential as source for future electricity and has many advantages than the other alternative energy sources like wind, solar, ocean, biomass, geothermal etc. In Photovoltaic power generation multilevel inverters play a vital role in power conversion. The three different topologies, diode-clamped (neutral-point clamped) inverter, capacitor-clamped (flying capacitor) inverter and cascaded h-bridge multilevel inverter are widely used in these multilevel inverters. Among the three topologies, cascaded h-bridge multilevel inverter is more suitable for photovoltaic applications since each pv array can act as a separate dc source for each h-bridge module. This paper presents a single phase Cascaded H-bridge five level inverter for grid-connected photovoltaic application using sinusoidal pulse width modulation technique. This inverter output voltage waveform reduces the harmonics in the generated current and the filtering effort at the input. The control strategy allows the independent control of each dc-link voltages and tracks the maximum power point of PV strings. This topology can inject to the grid sinusoidal input currents with unity power factor and achieves low harmonic distortion. A PID control algorithm is implemented in Arm Processor LPC2148. The validity of the proposed inverter is verified through simulation and is implemented in a single phase 100W prototype. The results of hardware are compared with simulation results. The proposed system offers improved performance over conventional three level inverter in terms of THD.**

Index Terms—**Multilevel inverter, cascaded H-bridge multilevel inverter, total harmonic distortion, sinusoidal pulse width modulation, MATLAB, PID controller**

I. INTRODUCTION

In the recent years, the demand for clean and green energy requires high quality output power with low switching losses. It is also seen that the soft switching technology develop showing that the demand further increases by improving efficiency. This trend is expected to continue in coming years because the energy produced by renewable sources is expected to satisfy 20% and 50% of the total needs in 2020 and 2050 respectively. It is also witnessed that among these renewable energy sources, solar photovoltaic energy is found to be a promising energy.

An important consequence of this situation is a change of the electric power system from the present one, consisting of a relatively low number of very high power ac generators, to a distributed one, characterized by an extremely large number of small and medium power dc and ac generators supplied by renewable energy sources connected to the grid through electronic power converters, the latter adapting the produced energy to grid specifications.

This new scenario introduces many technical, economic, and political challenges because it is changing the way in which the electrical energy resources

Manuscript received Jul. 23, 2015; accepted Feb. 29, 2016
Department of EEE, V V College of Engineering, Tisaiyanvilai,TamilNadu, India
E-mail : mssivagamasundari@gmail.com

(generation, transmission and distribution networks) are designed and managed. From the technical viewpoint, the use of electronic power converters introduces new and challenging issues, including increased topological complexity, additional power losses, and electromagnetic interferences, thus reducing the overall quality of service, efficiency, and network stability.

Franquelo and Rodriguez [1] introduced the pulse width modulated (PWM) multilevel inverter is an effective alternative to current inverter topologies and provides an introduction of the modeling techniques and the most common modulation strategies and also addressed the operational and technological issues.Lai and Peng [2] have described three recently developed multilevel voltage source converters and the techniques to balance the voltage between different levels in multilevel converters. Rodriguez **,** Lai and Peng [3] have described the most relevant control and modulation methods developed for this family of converters: multilevel sinusoidal pulse width modulation, multilevel selective harmonic elimination, and space-vector modulation. Tolbert and Peng [4] have experimentally demonstrated that traditional 2-level high frequency pulse width modulation inverters for motor drives have several problems associated with their high frequency switching and two different multilevel topologies are identified for use as a converter for electric drives. Rodriguez and Dixon [5] have introduced the PWM regenerative rectifiers with reduced input harmonics and improved power factor. In early stages, multilevel active rectifier were employed mainly in high-voltage high-power industrial and traction applications because they distribute the applied voltage among a number of cascaded power devices, thus overcoming their voltage limits and allowing the elimination of output transformers in medium–high voltage systems. Since their output voltage is a modulated staircase, they outperform two-level PWM inverters in terms of total harmonic distortion (THD), without the use of bulky expensive and dissipative passive filters has been demonstrated in [6, 7]. Kjaer [8] have focused on various inverter technologies for connecting photovoltaic (PV) modules to a single-phase grid , compared, and evaluated against demands, lifetime, component ratings, and cost. Calais [9] have described an overview of different multilevel topologies and investigated their suitability for single-phase grid connected photovoltaic systems regarding issues such as component count and stress, system power rating and the influence of the photovoltaic array earth capacitance. Calais and Agelidis [10, 19] have developed Unipolar SPWM full-bridge with transformer less grid connected inverter, a lot of depth researches, where new freewheeling paths are constructed to separate the PV array from the grid in the freewheeling period.

Ertl and Kolar [11] have proposed a novel multicell DC–AC converter for applications in renewable energy systems and cells are operated in an interleaved pulse width modulation mode which, in connection with the low voltage level of each cell , significantly reduces the filtering effort on the ac output of the overall system. Alonso and Sanchis [12] have introduced a new control method and proportional PWM modulation of the cascaded H-bridge multilevel converter for grid-connected photovoltaic systems and this control makes each H-bridge module supply different power levels, allowing therefore for each module an independent maximum power point tracking of the corresponding photovoltaic array. Walker and Sernia [13] have proposed an alternative topology of nonisolated per-panel dc-dc converters connected in series to create a high voltage string connected to a simplified dc-ac inverter and buck, boost, buck-boost, and Cu´k converters are considered as possible dc-dc converters that can be cascaded. Rahiman and Kumar [14] have developed a fifteen level cascaded H-Bridge Configuration, equal dc voltages are selected for each of the units, with step modulation and fundamental frequency switching which has reduced conduction loss and switching loss. Kang and Park [15] have developed multilevel PWM inverters suitable for the use of stand-alone photovoltaic power grid-connected inverters for photovoltaic modules and have a series-connected secondary, the amplitude of an output voltage appears at the rate of an integer to an input dc source. Alepuz [16] have described a three level inverter that can be used to interface distributed dc energy sources with a main ac grid or as an interface to a motor drive and the controller simultaneously regulates the dc-link voltage the mains power factor, and the dc-link neutral-point voltage balance. Ozdemir and Tolbert [20] have proposed a five level DMLI(Diode Clamped Multilevel Inverter) fundamental frequency switching strategy for three phase stand-alone photovoltaic systems by selecting the switching angles such that the lower order harmonics are eliminated. Besides being able to maximize the power obtained from the PVAs, the multilevel converter usually presents the advantages of reducing the device voltage stress, being more efficient and generating a lower output a voltage harmonic distortion. Among the following three main families of multilevel converters; diode-clamped , capacitor-lamped and cascaded H-Bridge , the latter is usually considered in the literature for PV applications [17, 18].

Fortunato [21] have proposed an improved maximum power point tracking with better performance to solve a fast changing irradiation problem and by means of a multiobjective strategy to optimize inverter performance at both high and low insolation levels. Shanthi.B [22] have proposed multilevel inverter control strategies are implemented in real time using FPGA for linear and non-linear loads and produced regulated output voltage with low distortion under all loading conditions. Shuitao yang [23] have analyzes the stability problem of the grid-connected voltage-source inverter (VSI) with LCfilters and introduced H∞ controller with explicit robustness in terms of grid-impedance variations to incorporate the desired tracking performance and stability margin. F.T. Josh [24] have proposed multilevel inverter in the field of renewable energies, reduces output filter dimensions and influence of perturbations caused by cloud darkening or seasonal variations. Jun Mei, Bailu xiao [25] have proposed an improved phase disposition pulse width modulation (PDPWM) for a modular multilevel inverter which is used for Photovoltaic grid connection to achieve dynamic capacitor voltage balance without the help of an extra compensation signal.

Bailu xiao [26] have introduced a modular cascaded h-bridge multilevel inverter for grid connected applications to improve the efficiency and flexibility of pv systems and a distributed MPPT control scheme is applied to get unbalanced grid current and supplied power. Jaysing [27] have described a five level inverter where the output current of the inverter can be adjusted according to the voltage of the pv array. Coppola [28] have described an advanced control strategy for grid tied photovoltaic cascaded h-bridge inverter using staircase PWM and assuring good performance in terms of harmonic distortion and power factor in both standard and mismatch conditions.Balasundaram [29] have proposed a modern cascaded nine level inverter topology using one voltage source for a nearly sinusoidal voltage and reduces total harmonic distortion. Farivar [30] have introduced a decoupled control system for a static synchronous compensator based on a cascaded h-bridge multilevel inverter to improve the transient performance of the STATCOM and enables the linearization of a cluster voltage control loop. Bosun [31] have described the integration of both cascaded multilevel inverter and two level h-bridge inverter so as to achieve the low losses of two level h-bridge inverter and low grid connected current THD advantages of cascaded multilevel inverter. Diego [32] have proposed a new converter topology for integrating pv plants constituted by many panels into the grid and the output voltage presents a very low ripple. Coppola [33] have proposed a new control which is able to efficiently track the maximum power point while assuring good performance in terms of harmonic distortion and power factor in both standard and mismatch conditions.

It is clear from the above literatures that many researchers are addressing their efforts in proposing new inverter topologies or in modifying the existing ones, aiming at improving the quality of the energy available at the inverter terminals. Among the available multilevel inverter topologies, Cascaded H-bridge multilevel inverter is proven to be the best for its high power handling capacity and reliability due to its modular topology and constitutes a promising alternative that can be extended to allow a transformer less connection to the grid. The Cascaded H-bridge multilevel inverter requires separate dc source, is a drawback when a single dc source is available but it becomes a very attractive feature in the case of PV systems, because solar cells can be assembled in a number of separate generators. The CHB-MLI supports different Pulse Width Modulation (PWM) techniques like Sinusoidal PWM (SPWM), Selective Harmonic Elimination (SHEPWM) and Optimized Harmonic Stepped Waveform (OHSW).

A typical single-phase three-level inverter adopts full-bridge configuration by using approximate sinusoidal modulation technique as the power circuits. The output voltage has the following three values: zero, positive (+Vdc) and negative(−Vdc) supply dc voltage (assuming that Vdc is the supply voltage). The harmonic components of the output voltage are determined by the carrier frequency and switching functions. Therefore, their harmonic reduction is limited to a certain degree. To overcome this limitation, this paper presents a five-level inverter whose output voltage can be represented in five levels. As the number of output levels increases, the harmonic content can be reduced. The SPWM switching strategy and cascaded inverter structure are employed in this work. This inverter topology uses two reference signals, instead of one reference signal, to generate PWM signals for the switches.

In this paper, a single-phase Cascaded H-bridge five level inverter for grid-connected photovoltaic application using PID controller is proposed. Results confirm the effectiveness of the proposed controller. Experimental results are presented to confirm the simulation results.

This paper has been arranged as follows. After the introduction in section I, Section II gives an outline of cascaded h-bridge multilevel inverter topology. Proposed control algorithm is explained in section III. Power balance between the H-Bridge inverters is described in Section IV. The two sections V,VI and VII show the simulation,experimental setup and experimental results that validate the proper operation of the inverter. Conclusion and final remarks are made in Section VIII.

II. CASCADED H-BRIDGE FIVE LEVEL INVERTER TOPOLOGY

The block diagram of proposed Cascaded H-bridge inverter topology with SPWM is shown in Fig. 1. This system consists of several PV modules, DC/DC power converter, a multilevel DC/AC power inverter and a grid. The PV modules arrangements are considered with multi-string technology. Each string of the PV array is connected to a DC/DC boost converter with a maximum power point tracking. As the irradiance level is inconsistent throughout the day, the amount of power generated by the PV modules is always changing with weather conditions. The Perturb and Observe algorithm is used to extract maximum power from the PV array. The DC power from the PV array is boosted using the DC-DC boost converter with dc bus capacitors. The output of these converters is the DC power supply of the multilevel DC/AC power converter. The output of five level inverter is ac voltage which is connected to grid system utility feeder through filtering inductor. The

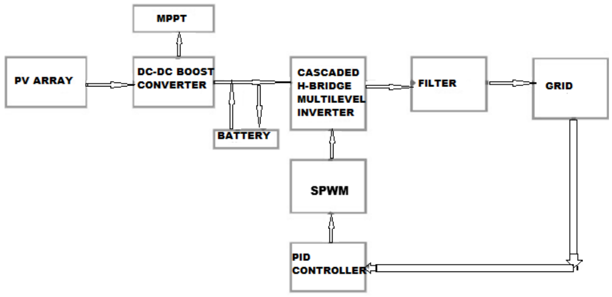

Fig. 1. Block diagram of Cascaded H-bridge inverter topology.

injected current must be sinusoidal with low harmonic distortion. The power factor is also maintained at near unity. The above proposed SPWM with the closed loop control is implemented using MATLAB software.

A schematic diagram of cascaded h-bridge inverter topology of grid connected photovoltaic system is shown in Fig. 2. The cascaded multilevel inverter topology consists of *n* H-bridge inverters connected in series. Each individual full bridge has 16 possible inverter states. Of these 16 inverter states only 4 inverter states allow bi-directional current flow and a fixed inverter output voltage. Each dc link is fed by a short string of PV panels. By considering cells with the same dc-link voltage, the inverter can synthesize an output voltage *v*HT with *n* levels. The power electronic switches (S11, S21) are in the on-state, and the power electronic switches (S31, S41) are in the off-state during the positive half cycle. On the contrary, the power electronic switches (S11, S21) are in the off-state, and the power electronic switches (S31, S41) are in the on-state during the negative half cycle and vice versa. The output voltage has 5 voltage levels 0, +Vdc, +Vdc/2,−Vdc, −Vdc/2. The ac outputs of each of the different full-bridge inverter levels are connected in series such that the synthesized voltage waveform is the sum of the inverter outputs.

The number of output phase voltage levels m in a cascaded inverter is defined by

$$m = 2s+1 \quad (1)$$

where s is the number of separate dc sources.

This high-quality voltage waveform enables the reduction of the harmonics in the generated current, reducing the filtering effort at the input. The cascaded multilevel inverter is connected to the grid through a L filter, which is used to reduce the switching harmonics.

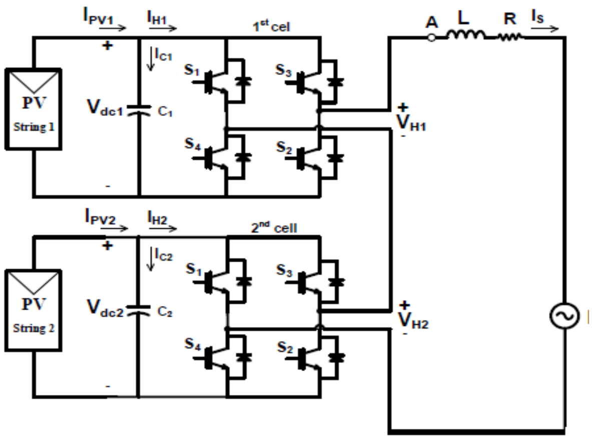

Fig. 2. Cascaded h-bridge inverter topology of grid connected photovoltaic system.

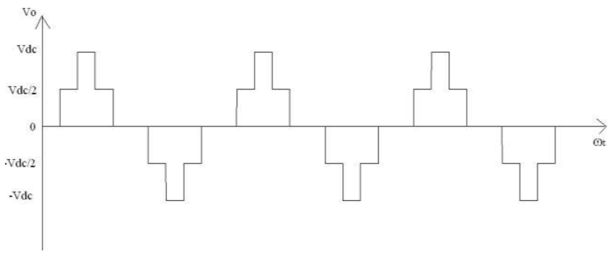

Fig. 3. Output voltage (phase) waveform of 5-Level Inverter.

Table 1. Switching sequence of single leg CMLI for 5-level

Output Voltage	Switching				Sequence			
	S11	S31	S41	S21	S12	S32	S42	S22
0	1	1	0	0	0	0	1	1
V_{dc}	1	0	0	0	0	1	1	1
2 V_{dc}	1	0	1	0	0	1	0	1
-V_{dc}	0	1	1	1	1	0	0	0
-2V_{dc}	0	1	0	1	1	0	1	0

There is also a local load connected in parallel. PV power is delivered to the load/grid according to the system operation conditions. This topology can inject to the grid sinusoidal input currents with unity power factor, even under conditions of unequal solar radiation of the string of PV cells. The output voltage (phase) waveform of 5-Level Inverter is shown in Fig. 3. Table 1 shows the switching sequence of five level inverter.

Several switching strategies have been proposed for Cascaded H-Bridge(CHB) converters. PWM technique is extensively used for eliminating harmful low-order harmonics in inverters. In PWM control, the inverter switches are turned ON and OFF several times during a half cycle and output voltage is controlled by varying the pulse width. This paper adopts the sinusoidal Pulse Width Modulation(PWM) technique strategy because instead of maintaining the width of all pulses the same as in the case of multiple PWM, the width of each pulse is varied in proportion to the amplitude of a sine wave evaluated at the same pulse. The distortion is reduced significantly compared to multiple PWM.

III. PROPOSED CONTROL ALGORITHM

The Proposed Cascaded H-bridge multilevel inverter topology is used for grid-connected photovoltaic application, so that the power is injected to the grid and maintained the power factor at near unity. As the irradiance level is inconsistent throughout the day, the amount of electric power generated by the PV modules are always changing with weather conditions. To overcome this problem, MPPT algorithm is used. The Perturb and Observe algorithm is used to extract maximum power from the PV modules. The feedback controller used in this application utilizes the PID algorithm.

In the proposed inverter topology, the current is injected into the grid, grid current Ig is sensed and fedback to a comparator which compares it with the reference current Iref. Iref is obtained by sensing the grid voltage and converting it to reference current and multiplying it with constant m. This is to ensure that Ig is in phase with grid voltage Vg and always at near unity power factor.

PID control is developed in this work to obtain desired output voltage and minimize the harmonics of the chosen inverter.

IV. POWER BALANCE BETWEEN THE H-BRIDGE INVERTERS

The power balance between the two H-bridge inverters depends on the dc-link voltages and the individual modulation signals. To evaluate the steady-state power balance in the cells of a cascaded inverter, the cells have been replaced by voltage sources with values $v1$ and $v2$ that are equal to the rms values of the fundamental harmonic of the voltages. Moreover, to have a stable operation, it is necessary to ensure that, for a total amount of active power supplied to the 2Cell-Cascaded

H-Bridge inverter, both cell loads are between the maximum and minimum allowed.

V. SIMULATION RESULTS

The effectiveness of the CHB-based grid-connected PV inverter in Fig. 2 with a PID control algorithm has been evaluated in the MATLAB/SIMULINK environment. Each CHB cell is connected to an array of five series-connected panels. In this simulation, a 10μF capacitor is used as a smoothing capacitor in each cell to keep the dc voltage ripples below 8.5% [12]. The Perturb and Observe algorithm is used for MPPT which updates the reference voltages every $\Delta t = .5s$ by $\Delta V = .5V$. The simulations have been done with the initial conditions of $G = 200$ W/m^2 for the solar irradiation and $T = 25^{\circ}$C for each PV array.

To evaluate the effectiveness of the proposed control scheme to follow the MPP in the first simulation the temperature of the first array is changed from $T_1 = 25^{\circ}$C to 15°C at $t_1 = 9s$, the temperature of the second array is changed from $T_2 = 25^{\circ}$C to 35°C at $t_2 = 12s$. In this paper, the reference voltage of the dc links has been set to $V_{refdc} = 75V$ at first. Then, the MPPT algorithm sets the reference voltage of the PV arrays close to the MPP point which is almost $72V$ for the initial test condition. In addition, when the temperature of a cell decreases, the voltage of the corresponding cell increases and when the cell temperature increases, the corresponding cell voltage decrease in order to extract the maximum power from the connected PV array. After starting with the standard initial conditions, at $t_1 = 1s$, the irradiation level of the first PV array is changed from $G_1 = 800$ W/m^2 to 500 W/m^2. Then, at $t_2 = 3s$, a step change from $G_2 = 800$ W/m^2 to $G_2 = 200$ W/m^2 occurs in the irradiation level of the second PV array. As a result of the first change, the maximum power point current of the first PV array changes from $I_{MPP1} = 6.72A$ to $I_{MPP1} = 3.36A$. A simulation is carried out in MATLAB/SIMULINK software for a five level cascaded H-bridge inverter with isolated dc sources supplied from PV arrays. The elements and the parameters considered for simulation are presented in Table 2 for the cascaded h-bridge five level inverter topology.

The simulation model of cascaded H-bridge five level inverter topology is shown in Fig. 4. The power circuit consists of two H-bridges whose nominal dc voltage is considered to be 18 V and the five level stepped output voltage is obtained and the harmonics are reduced. Also it consists of PWM generator block which has parameters as amplitude, pulse width period and phase delay which is used to determine the shape of the output .Therefore the efficiency of the inverter is increased. The inverter must perform reliably and efficiently to supply a wide range of ac loads with the voltage and required power quality necessary for reliable and efficient load and system performance. The advantages of the system are high power high voltage capacity, low harmonics and low switching loss. The output voltage and output current has five levels. It can be achieved by using SPWM technique. The output five level inverter fundamental frequency is 50 Hz. The loads are connected across the cascaded H-bridge five level inverter.

Table 2. Parameters of the Cascaded H-Bridge Inverter

Parameters	Values
No. of H-Bridge levels	5
No. of Switches	20
DC source voltage for individual H- bridge	65.02 V
Fundamental frequency	50 Hz
Load resistor	30 Ohm
Load Inductor	20 mH
Filter Inductor	10 H
Filter capacitor	10 μF
Grid voltage	230 V

The response of the MLI with SPWM is satisfactory and the load voltage and grid current waveforms are shown in Fig. 5 and 6. The Total Harmonic Distortion waveforms for voltage and current are shown in Fig. 7 and 8. It is observed from the results that the total harmonic distortion for voltage is 10.54 % and current is 8.09% which is low, when compared with conventional three level inverter, the total harmonic distortion for voltage is 18.01% and current is 15.05% shown in Fig. 9 and 10. When the temperature of a cell decreases, the voltage of the corresponding cell increases and when the cell temperature increases, the corresponding cell voltage decrease in order to extract the maximum power from the connected PV array. Fig. 12. shows the grid voltage and grid current are in phase at unity power factor.

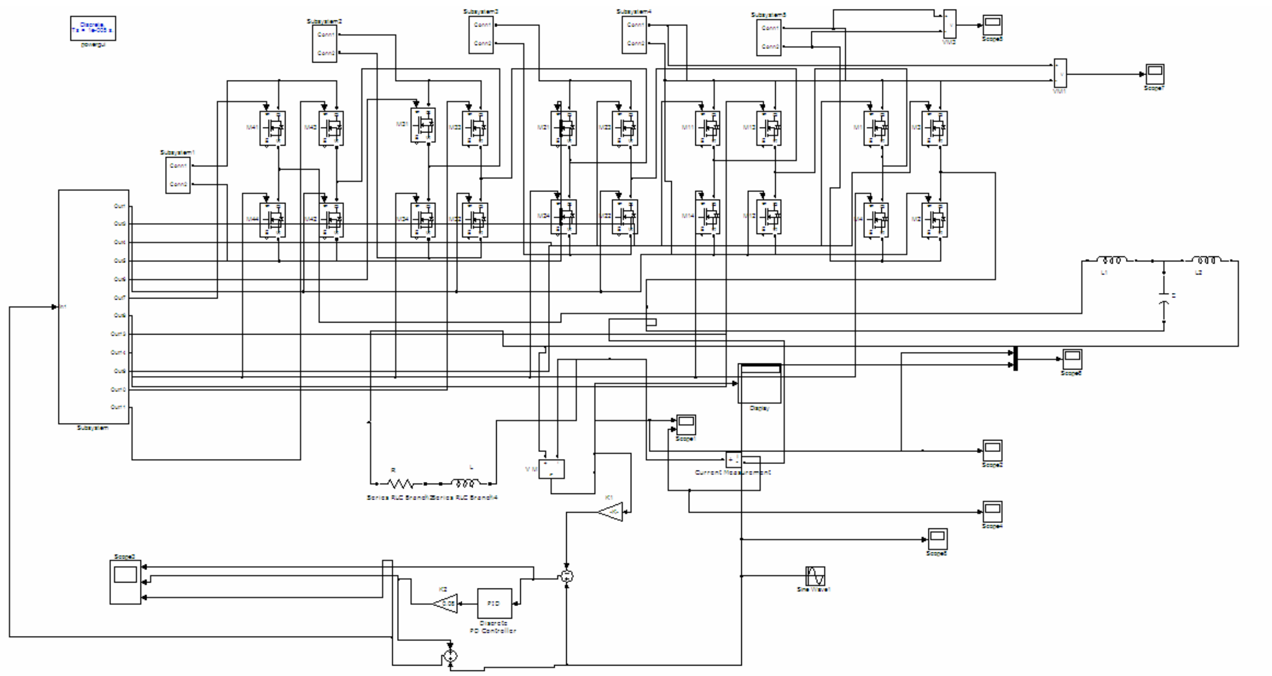

Fig. 4. Simulink model of the Cascaded MLI.

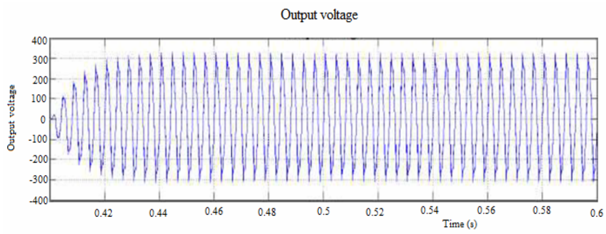

Fig. 5. Load voltage.

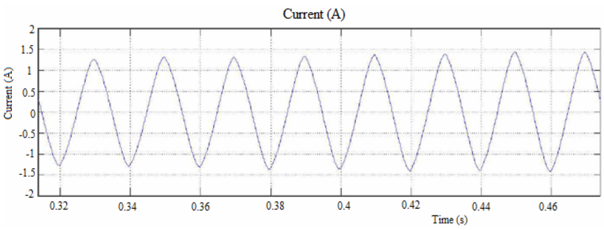

Fig. 6. Grid current.

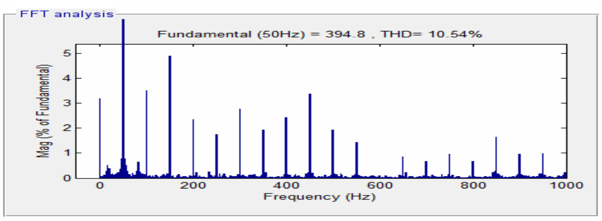

Fig. 7. Voltage THD(five level inverter).

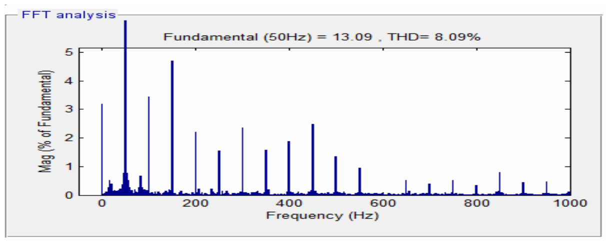

Fig. 8. Current THD(five level inverter).

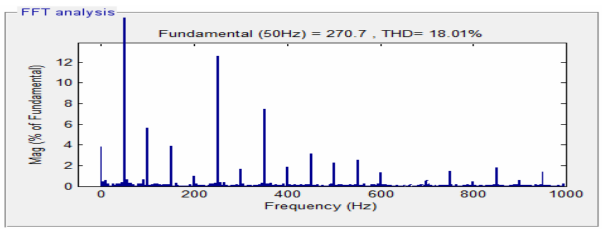

Fig. 9. Voltage THD(three level inverter).

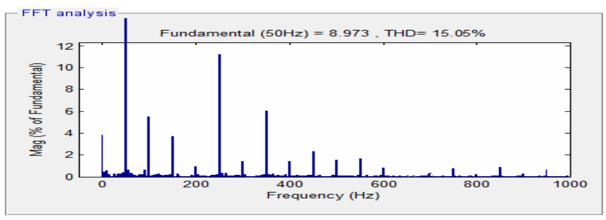

Fig. 10. Current THD(three level inverter).

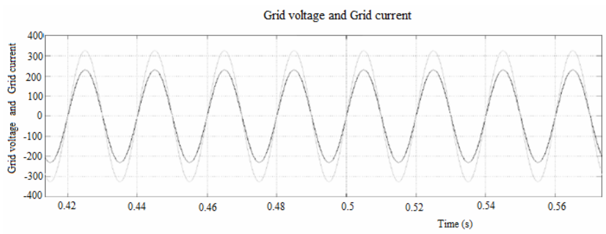

Fig. 11. Grid voltage and Grid current are in phase at unity power factor.

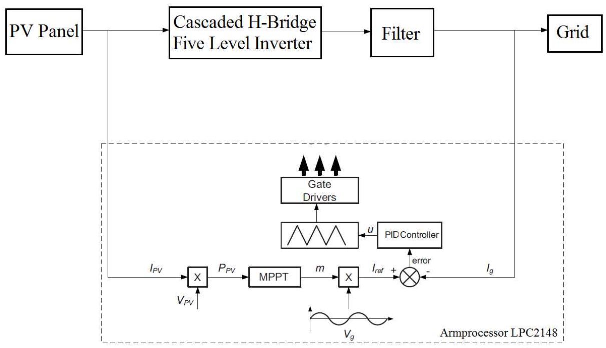

Fig. 12. Experimental block diagram.

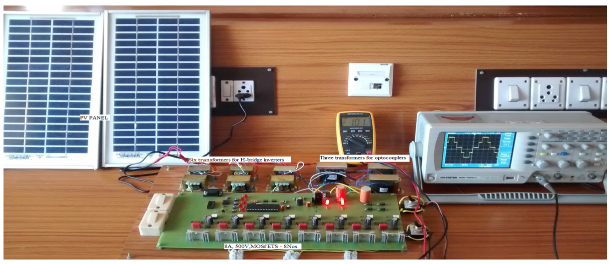

Fig. 13. Structure of the experimental prototype.

VI. Experimental Setup

The experimental block diagram of proposed Cascaded H-bridge inverter topology with SPWM is shown in Fig. 12. This block diagram consists of a multilevel DC/AC power inverter, Optocoupler, Arm Processor LPC2148, filter and a grid. The isolated dc power sources from the pv array are connected to the Cascaded H-bridge inverter. The output of the five level inverter is ac voltage which is connected to grid through filter.

A single phase 100W hardware prototype 5-level inverter as shown in Fig. 13 is built. It consists of two full-bridge inverters that are connected in a series form. The inverter uses 8-A, 500-V MOSFETs as the switching devices and the DC source voltage of each H-bridge

Table 3. Parameters of the Solar Panels

Parameters		Values
DC Side	MPP voltage	17.7 V
	MPP current	6.5 A
	Open circuit voltage	22.2 V
	Short circuit current	7.97 A
	Temperature	25°C
	Solar Irradiance	1000 W/m^2
AC Side	Rated grid voltage	230 V
	Rated grid current	0.5 A
	Switching frequency	20 Khz
	Inductor filter	0.9 μH

Table 4. Experimental Prototype Specifications

Parameters	Values
No. of H-Bridge levels	2
No. of Switches MOSFET IRF840 – 8Nos.	500 V, 8 A
DC source voltage for individual H- bridge	34.8 V/2 A
Fundamental frequency	50 Hz
R Load	100 Ohm
RL Load	100 Ohm, 10 mH
Optocouplers MCT2E (8 Nos.)	30 V, 3 A
Filter Capacitor	1000 μF
Transformers(6 Nos.)	0-24 V, 2 A
Transformers(3 Nos.)	6 V-0-6 V, 500 mA
Rated grid voltage	230 V
Rated grid frequency	50 Hz
Inverter rated power	1000 W

inverter from the PV panel is constant and is selected to be 34.8 V. Also, the frequency of the output is assumed to be 50 Hz. Six transformers (0-24 V, 2 A) are used to power up the individual H- bridge inverters. Three transformers (6 V-0-6 V, 500 mA) are used to power up the optocouplers. The real time implementation for chosen inverter using Arm Processor LPC2148 is carried out in this work. SPWM generation and also the control strategies for the chosen inverter are developed using MATLAB software. Furthermore, the dc link of each H-bridge is connected to an array of series-connected panels, whose parameters are listed in Table 3. The other principal parameters of the prototype are given in Table 4. In this experiment, the average voltage of each cell is around 85V and the maximum power is extracted from the PV strings. The proposed controller also provides a rapid and accurate tracking of the MPP for PV strings without an additional dc/dc converter. The elimination of intermediate dc/dc converters and independent control of the PV strings improves the system efficiency when

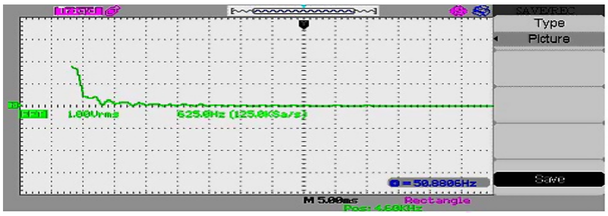

Fig. 14. Harmonic spectrum of the five level inverter output voltage.

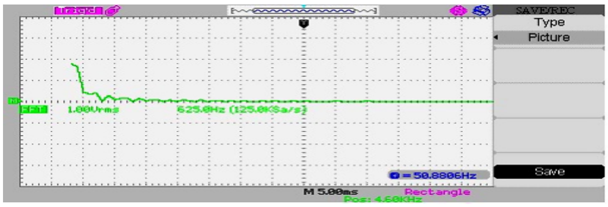

Fig. 15. Harmonic spectrum of the three level inverter output voltage.

compared to the conventional systems.

VII. EXPERIMENTAL RESULTS

To prove that the proposed Cascaded H-bridge five level inverter topology has advantages over the conventional three level inverter in terms of THD and power factor and the corresponding measurements were made on both inverters. A clamp type THD meter UT243 was used for this purpose. The THD for the proposed five level inverter is 8.02% for current and 10.47% for voltage while the power factor is 0.98.

The results from the five level inverter are compared to those from the conventional three level inverter in terms of THD. The same SPWM technique is used to control the overall performance of the inverter. The THD measurement of the conventional three level inverter is 14.98% for current and 17.92% for voltage. The result was taken at almost the same environment conditions to ensure Ig to be similar to measurement made for the five level inverter. By comparison, the THD measurement for the three level inverter is much higher when compared to the five level inverter. This proves that multilevel inverters can reduce the THD which is an essential criterion for grid connected PV systems.

Fig. 14 and 15 which shows the harmonic spectrum of the five level and three level inverter output voltage. Fig. 16 and 17 which shows the output voltage waveform of the five level and three level inverter. The resulting PF is close to 0.98 and the current THD is nearer which satisfies the IEEE-519 constraints. The measured grid side voltage is 67*V* for the first cell, 65*V* for the second cell, whereas the voltage of each PV string is close to 85*V*.

With reference to Table 5 a comparison of THD of the output voltage have been done. It is evident that the results of simulation are closer to the experimental values.

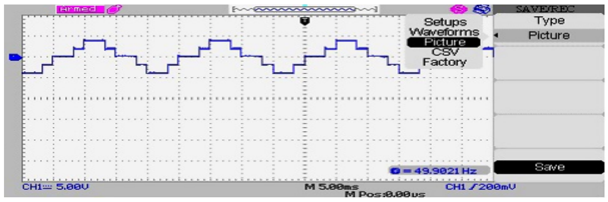

Fig. 16. Output voltage waveform (five level inverter).

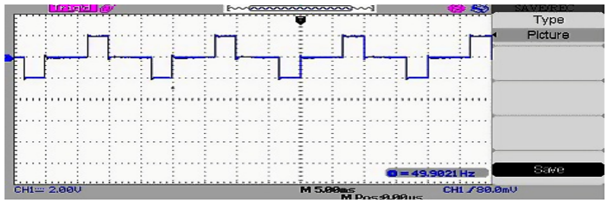

Fig. 17. Output voltage waveform (three level inverter).

Table 5. Comparison of THD of the output voltage

THD(%)			
Experimental		Simulation	
Current	Voltage	Current	Voltage
8.02	10.47	8.09	10.54

VIII. CONCLUSION

This paper presented a single phase cascaded H-bridge five level inverter with a sinusoidal pulse width modulation technique for photovoltaic applications. The proposed inverter topology, control algorithm and principle of operation were analyzed in detail. A PID control algorithm is implemented to optimize the performance of the inverter. Comparison has been made between three level and five level inverters in terms of THD and the results show that the THD of five level inverter is lesser than that of the conventional three level inverter. Also, both the grid voltage and grid current are in phase at unity power factor.

ACKNOWLEDGEMENT

The authors are thankful to the Institution of Engineers(India), Kolkata for the financial grant for carrying out the research work in real time application.

REFERENCES

[1] L. G. Franquelo, J. Rodriguez, J. I. Leon, S. Kouko, R. Portillo, M. A. M. Prats, "The age of multilevel converters arrives," *IEEE Ind. Electron. Mag*. 2, 28–39(2008).

[2] J.-S. Lai, F. Z. Peng, "Multilevel converters—A new breed of power converters," *IEEE Trans. Ind. Appl*., 32, 509–517(1996).

[3] J. R. Rodriguez, J.-S. Lai, F. Z. Peng, "Multilevel inverters: A survey of topologies, control, and application," *IEEE Trans. Ind. Electron.*, 49, 724–738(2002).

[4] L. M. Tolbert, F. Z. Peng, T. G. Habetler, "Multilevel converters for large electric drives," *IEEE Trans. Ind. Appl*., 35, 36–44(1999).

[5] J. R. Rodriguez, J. W. Dixon, J. R. Espinoza, J. Pontt, P. Lezana, "PWM regenerative rectifiers: State of the art," *IEEE Trans. Ind. Electron.*, 52, 5–22(2005).

[6] C. Cecati, A. Dell'Aquila, M. Liserre, V. G. Monopoli, "Design of H-bridge multilevel active rectifier for traction systems," *IEEE Trans. Ind. Appl.,* 39, 1541–1550(2003).

[7] C. Cecati, A. Dell'Aquila, M. Liserre, V. G. Monopoli, "A passivity based multilevel active rectifier with adaptive compensation for traction applications," *IEEE Trans. Ind. Appl.,* 39, 1404–1413(2003).

[8] S. B. Kjaer, J. K. Pedersen, F. Blaabjerg, "A review of single-phase grid-connected inverters for photovoltaic modules," *IEEE Trans. Ind. Appl.,* 41, 1292–1306(2005).

[9] M. Calais, V. G. Agelidis, "Multilevel converters for single-phase grid connected photovoltaic systems—An overview," *Proc. ISIE.* 1, 224–229(1998)

[10] M. Calais, V. G. Agelidis, L. J. Borle, M. S. Dymond, "A transformer less five level cascaded inverter based single phase photovoltaic system," *Proc. IEEE 31st Annu. Power Electron. Spec. Conf.* 3, 1173–1178(2000).

[11] H. Ertl, J. W. Kolar, F. C. Zach, "A novel multicell DC–AC converter for applications in renewable energy systems," *IEEE Trans. Ind. Electron.,* 49, 1048–1057(2002).

[12] O. Alonso, P. Sanchis, E. Gubia, L. Marroyo, "Cascaded H-bridge multilevel converter for grid connected photovoltaic generators with independent maximum power point tracking of each solar array," *Proc. 34th IEEE Power Electron. Spec. Conf.* 2, 731–735(2003).

[13] G. Walker, P. Sernia, "Cascaded DC/DC converter connection of photovoltaic modules," *IEEE Trans. Power Electron.,* 19, 1130–1139(2004)

[14] A. Rahiman, U. Kumar, V. Ranganathan, "A novel fifteen level inverter for photovoltaic power supply system," *Conf. Rec. IEEE IAS Annu. Meeting*, 1165–1171(2004)

[15] F. S. Kang, S. J. Park, S. E. Cho, C. U. Kim, T. Ise, "Multilevel PWM inverters suitable for the use of stand-alone photovoltaic power grid-connected inverters for photovoltaic modules," *IEEE Trans. Energy Convers*., 20, 906–915(2005).

[16] S. Alepuz, S. Busquets-Monge, J. Bordonau, J. Gago, D. Gonzalez, J. Balcells, "Interfacing renewable energy sources to the utility grid using a three-level inverter," *IEEE Trans.Ind. Electron.,* 53, 1504–1511(2006).

[17] J. I. Leon, S. Vazquez, A. J. Watson, L. G. Franquelo, P. W. Wheeler, J. M. Carrasco, "Feed-forward space vector modulation for single-phase multilevel cascaded converters with any DC voltage ratio," *IEEE Trans. Ind. Electron.,* 56, 315–325(2009).

[18] F. J. T. Filho, T. H. A. Mateus, H. Z. Maia, B. Ozpineci, J. O. P. Pinto, L. M. Tolbert, "Real-time selective harmonic minimization in cascaded multilevel inverters with varying DC sources," *Proc. IEEE Power Electron. Spec. Conf.* , 4302–4306(2008).

[19] R. Gonzalez, E. Gubia, J. Lopez, L. Marroyo, "Transformerless single-phase multilevel based photovoltaic inverter," *IEEE Trans. Ind. Electron*., 55, 2694–2702(2008).

[20] E. Ozdemir, S. Ozdemir, L. M. Tolbert, "Fundamental frequency modulated six-level

diodeclamped multilevel inverter for three-phase standalone photovoltaic system," *IEEE Trans. Ind. Electron.,*56, 4407–4415(2009).

[21] M. Fortunato, A. Giustiniani, G. Petrone, G. Spagnuolo, M. Vitelli, "Maximum power point tracking in a one-cycle-controlled single-stage photovoltaic inverter," *IEEE Trans. Ind. Electron*., 55, 2684–2693(2008).

[22] Shanthi. B, S. P. Natarajan, "FGPA based fuzzy logic control for single phase multilevel inverter", *International journal of computer applications*, 9, 10-18(2010).

[23] Shuitao yang, Fang Z. Peng, Zhaoming Qian, "A robust control scheme for grid connected voltage source inverters," *IEEE Trans. Ind. Electron*., 58, 202-212(2011).

[24] F. T. Josh, Jovitha Jerome, J. Arulwilson, "Fuzzy Logic based nine level Inverter for photovoltaic systems," *European Journal of Scientific Research*, 78(3), 522-533(2012).

[25] Jun Mei, Bailu xiao, Ke shen, Leon M.Tolbert, Jian Yong Zheng, "Modular Multilevel Inverter with New Modulation Method and Its Application to Photovoltaic Grid-Connected Generator," *IEEE Trans. on Power Electron*., 28, 5063–5073(2013).

[26] Bailu xio, Lijun Hang, Jun Mei, Riley.c, "Modular Cascaded H-Bridge Multilevel PV inverter with distributed MPPT for grid connected applications," *IEEE Trans. on Industry Applications*, 51, 1722-1731(2014).

[27] Jaysing Ashok Kshirsagar, K. Vadirajacharya, "Performance evaluation of five level inverter for solar grid connected system," *International Journal of Current Engineering and Technology*, special issue 3, 222-225(2014).

[28] Coppola. M, Di Napoli. P, Guerriero. P, Lannuzzi. D, "An FGPA based advanced control strategy of a grid tied PV CHB inverter," *IEEE Trans. on Power Electron*., 31, 806-816(2015).

[29] G. Balasundaram, Dr. S. Arumugam, C. Dinakaran, "Design and Simulation of single phase Cascaded multilevel grid connected inverter using photovoltaic system," *Journal of Chemical and Pharmaceutical Science*, 8, 441-449(2015).

[30] Farivar. G, Hredzak. B, Agelidis. V. G., "Decoupled control system for cascaded h-bridge multilevel converter based STATCOM," *IEEE Trans. on Industrial Electronics*, 63, 322-331(2015).

[31] Bo sun, Fengjiang wu, Mehdi saraghebi, Joseph M.Guerrero, "A flexible five level cascaded h-bridge inverter for photovoltaic grid connected systems," *Proceedings of the 9th International Conference on Power Electronics and ECCE Asia*, 2369-2375(2015).

[32] Diego lannuzzi, Mario Pagano, Luigi Piegari, Pietro Trioli, "Current balancing of Cascaded H-Bridge converters for PV systems with partial shading," *COMPEL- The International Journal for computation and mathematics in Electrical and Electronic Engineering*, 34, 1879-1895(2015).

[33] Mariono Coppola, Fabio Di Napoli, Pierluigi Guerriero, Adolfo Dannier, Diego lannuzzi, Santolo Daliento, Andrea Delpizzo, "Maximum power point tracking algorithm for grid tied photovoltaic cascaded h-bridge inverter," *Electric Power Components and systems*, 43, 951-962(2015).

M. S. Sivagamasundari (born May 14, 1977) took her B.E in Electrical and Electronics Engineering from the C.S.I Institute of Technology, Thovalai, MBA in finance from Annamalai University, Chidambaram M.E in Power Electronics & Industrial Drives from the Sathyabama University, Chennai in 1999, 2002 and 2010 respectively. Currently she is pursuing P.hd in Anna University. She is a member in various professional bodies like ISTE, ISOI, IE(I), IAENG and SESI. She has more than ten years of teaching experience and one year of industrial experience. She has presented more than 25 papers in various national and international conferences and published more than 28 papers in various National and International journals. Currently, she is working as an Asst.professor in Electrical and Electronics department in V V College of Engineering, Tisaiyanvilai. Her research interests include power electronics and renewable energy sources.

P. Melba Mary (born October 7, 1969) took her B.E in Electrical and Electronics from the Government College of Engineering, Tirunelveli, M.E in Control and Instrumentation from the College of Engineering, Guindy, Ph.D in Anna University, Chennai in 1990,1995 and 2009 respectively. She worked as lecturer in National Engineering College, Kovilpatti and as Professor and Head of the Electrical and Engineering department at National College of Engineering, Maruthakulam. She has more than 21 years of teaching experience and few years of industrial experience too. Her main research interests on hybrid control system theory, industrial process control, robotics and various intelligent techniques used in the design of controllers. She has presented more than 30 papers in various national and international conferences and published more than 40 papers in National and International journals. She is a member in various professional bodies like ISTE, IEEE, IET,IE(I) and a Fellow of the Institution of Electronics and Telecommunication Engineers (IETE). Currently, she is working as Principal in V V College of Engineering, Tisaiyanvilai.