A Five Level Hybrid Multilevel Inverter With Adaptive Hysteresis Current Control Scheme For Photovoltaic Application

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Abstract— **Increasing use of renewable energy sources requires new strategies for operation and control of electricity to improve the power supply reliability and quality. Multilevel inverters (MLI) are mainly used in renewable energy sources based grid interactive generating schemes. This paper focuses on hybrid MLI topology to overcome the design related disadvantages of the three typical conventional MLIs. The proposed topology has a reduced number of switches for single phase five-level hybrid MLI utilizing only single H-bridge and an auxiliary diode bridge bidirectional switch. This enables analysis of five levels of voltages: $-V_{DC}$, $-0.5V_{DC}$, 0, $+0.5V_{DC}$ and V_{DC}. The adaptive hysteresis current controller is analyzed to keep the output current close to sinusoidal with lower THD. By using multi hysteresis bands, five level output voltage with lower harmonic output current has been examined. A simulation verification of single phase five level hybrid MLI through MATLAB is demonstrated.**

Keywords— **adaptive hysteresis current control, hybrid multilevel inverter, photovoltaic(PV), sinusoidal pulse width modulation (SPWM).**

I. INTRODUCTION

As a source of electrical energy the application of photovoltaic (PV) showed a tendency to increase generation capacity. The limited reserve of fossil fuel sources and its increasing cost has motivated the effort to find other alternative energy sources. There are many types of renewable energy sources such as wind, solar, hydro, tidal, bio-mass etc. among them the solar energy is the one , which is available free of cost where people live and it is clean source of energy. The increasing use of renewable energy sources requires new strategies for the operation and control of the electricity to improve the power supply reliability and quality. To implement the renewable generation system shows significant reduction in the high price of equipment and system of photovoltaic. IEA reported that the price of photovoltaic system have decreased by probably more than 40% [2]. Because of continuously improved technology of photovoltaic generation system causes the PV power conversion more efficient. The main advantage of PV generation compared to other renewable energy sources is more flexibility. For environment issue and global warming as important consideration for deciding the choice of energy sources for the electricity make the photovoltaic generation system as the clean and convenient energy. Photovoltaic energy conversion becomes main focus of many researches due to its promising potential as source for future electricity. Because of lower output voltage of the PV system it is most important to boost the output voltage using DC-DC boost converter. The power electronic technology plays an important role in distributed generation and synchronization of renewable energy sources into the electrical grid [1].

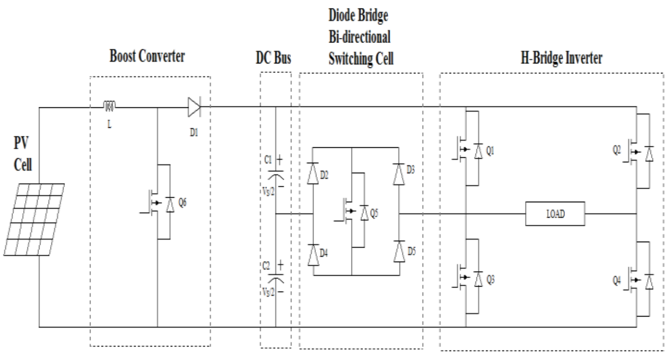

Fig.1. Single phase five level hybrid inverter

In recent years, multi level voltage source inverters have been focused on and used for various applications. They are widely used for driving high power medium voltage induction motors and var compensators. Multilevel inverters (MLI) have the main advantages that the harmonic components of line to line voltage fed to motor, switching frequency of the devices and EMI problem could be decreased and can reach the increasing demand for power quality and power ratings along with lower total harmonic distortion. Up to now the multi level inverter topologies have been classified into three categories: diode clamped multilevel inverter (DC-MLI), flying capacitor multi level inverter (FC-MLI) and cascaded H-bridge multi level inverter [1]. Among these three topologies, it is not easy to control the unbalance DC-link capacitor voltage problem. It would be a limitation to applications beyond four-level DC-MLI for reason of reliability and complexity considering the balance of capacitor voltage ad much number of clamping diodes. The cascaded H-bridge topology is another popular approach. This topology is a good choice for more than five-level output waveform. Cascaded inverters have structurally no problem of DC-link voltage unbalancing but required many separated DC sources in motor drive applications this makes it suitable for the applications of devices powering by solar cells and fuel cells. Cascaded H-bridge MLI can also be used to drive the traction motor from a set of batteries, ultra-capacitors or fuel cells. The main disadvantage associated with the cascaded inverter is their circuit complexity, requiring a high number of power switches that must be commutated in a precisely determined sequence by a driver circuit [5-6]. All these disadvantages are a drawback of this topology from an economic viewpoint.

Recent advances in cascaded H-bridge inverters include utilizing different DC voltages on each series H-bridge and cascading different types of inverters together, such as cascading H-bridge with diode clamped MLI, in order to increase the number of voltage levels and improve the power quality. However, these methods bring some issues at the same time, such as more complexity of control and power circuit [5-8]. This paper presents a single phase five-level hybrid inverter using single H-bridge with an auxiliary diode bridge bidirectional switch, drastically reduces number of components to generate same number of voltage level. Thereby the power circuit complexity of proposed inverter reduces compared to conventional MLIs. This topology achieves 37.5% reduction in the number of main power switches required.

There are several types of control strategies to control MLIs. The voltage control strategies are mainly used for motor drive applications. The performance of multilevel inverter mainly depends on the quality of current control strategy. For grid connected inverters the total harmonics must be reduced to predefined limit. The basic strategies of current control can be classified as ramp comparator, hysteresis controller and predictive control. The current control approach based on the comparison technique is the ramp comparison control. It compares the control signal according to the current error to a triangular waveform, to generate switching pulses. The switching frequency is fixed but the system response is affected by load parameters. The predictive controllers calculate the inverter voltages required to force the measured currents to follow the current reference. The system stability is affected by load parameters and it is very complex control strategy. The system response affected by load parameters is eliminated by the hysteresis control scheme. This strategy uses hysteresis comparators to select the proper switching states based on the comparison of the current error with switching boundaries defined as a hysteresis band. The proposed hybrid inverter utilizes adaptive hysteresis current control strategy to reduce the total harmonic distortion of load current. To get the multi level output voltage hysteresis current controller use multi-band hysteresis control scheme.

II. PRINCIPLE OF OPERATION FOR PROPOSED HYBRID INVERTER

The proposed single phase five-level hybrid multilevel inverter topology will use a single phase cascaded H-bridge with an auxiliary diode bridge bidirectional switching cell. The modified H-bridge hybrid inverter topology is significantly advantageous over other topologies i.e., less number of power switches, power diodes and capacitors for the same number of voltage levels. A bi-directional switch has to be capable of conducting currents and blocking voltages of both polarities, depending on control signal.

The basic principle of operation for the proposed inverter has single sinusoidal reference with two triangular carriers having same switching frequency but have different offset. This topology will use only two carriers' waveform instead of four carriers in the conventional level shifted PWM MLI. The input voltage of inverter is boosted up by DC-DC boost converter to provide more output voltage to the inverter. Two capacitors with equal capacitance rating are used as the DC bus for converting single output of boost converter into multilevel.

By comparing a sinusoidal reference with two carriers at different offset used to generate switching pulses for proposed inverter. The carrier 1 can generate full level of input voltage of positive and negative amplitude. The carrier 2 can generate half voltage of positive and negative amplitude. The operating principle to generate five level output voltage as: $+V_{DC}$, $+1/2V_{DC}$, 0 $-1/2V_{DC}$, $-V_{DC}$ for proposed inverter is shown in fig (2). Thereby proper controlling an auxiliary circuit switching pattern can generate half of voltage level [3, 9, 12].

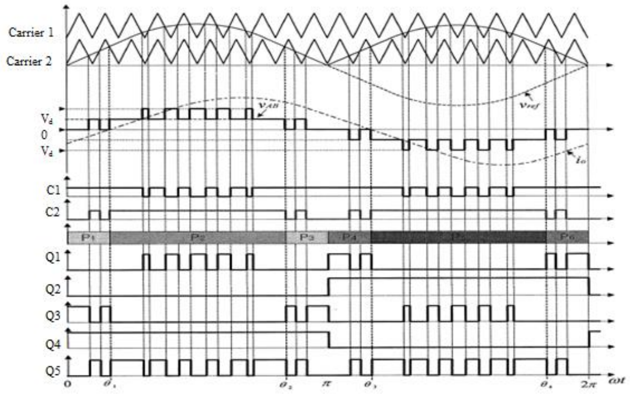

Fig.2. Switching pattern of the proposed single-phase five-level hybrid PWM inverter.

The level of output voltage is dependent on the value of modulation index. If the value of modulation index is equal to or less than 0.5 then the behavior of proposed inverter is similar to the conventional three-level inverter. The harmonic content in output voltage is similar to that of conventional three-level inverter. If the value of modulation index greater than 0.5 then it will behave like five-level inverter. According to the amplitude of the sinusoidal reference, the operational interval of each mode varies within a certain period. The modes are separated as [9]:

Mode 1: $0 < \omega t \leq \theta_1$, $\theta_2 \leq \omega t \leq \pi$

Mode 2: $\theta_1 < \omega t \leq \theta_2$,

Mode 3: $\pi < \omega t \leq \theta_3$, $\theta_4 < \omega t \leq 2\pi$

Mode 4: $\theta_3 < \omega t \leq \theta_4$ (1)

When the value of modulation index is less than 0.5, the value of phase angle displacement is given by:

$\theta_1 = \theta_2 = \pi/2$

$\theta_3 = \theta_4 = 3\pi/2$ (2)

When the value of modulation index is greater than 0.5, the value of phase angle displacement is given by:

$\theta_1 = \sin^{-1}(A_c/A_m)$

$\theta_2 = \pi - \theta_1$

$\theta_3 = \pi + \theta_1$

$\theta_4 = 2\pi - \theta_1$ (3)

Where Ac is peak to peak value of carrier and Am is peak value of sinusoidal reference.

The phase angle displacement is dependent on the modulation index Ma. For proposed hybrid inverter, the equation of modulation index Ma can be given as [9]:

$M_a = A_m/2*A_c$ (4)

The switching pulses for the proposed converter can be generated by the use of logical AND, OR, NOT gates.

$S1 = \overline{C1} \cdot A2 + \overline{C2} \cdot A4 + \overline{C2} \cdot A6$

$S2 = A4 + A5 + A6$

$S3 = \overline{C2} \cdot A2 + \overline{C2} \cdot A3 + \overline{C1} \cdot A5$

$S4 = A1 + A2 + A3$

$$S5=C1\cdot A1+C1\cdot C2\cdot A2+C2\cdot A3+C2\cdot A4+C1\cdot C2\cdot A5+C2\cdot A6 \quad (5)$$

TABLE 1 Output of inverter according to switch ON-OFF

Q1	Q2	Q3	Q4	Q5	V_{OUT}
ON	OFF	OFF	ON	OFF	$+V_D$
OFF	OFF	OFF	ON	ON	$+0.5V_D$
ON	ON	OFF	OFF	OFF	0
OFF	ON	OFF	OFF	ON	$-0.5V_D$
OFF	ON	ON	OFF	OFF	$-V_D$

III. ADAPTIVE HYSTERESIS CURRENT CONTROL

The performance of the inverter systems which are supplied by DC sources largely depends on the quality of the applied current control strategy [8]. Various methods have been presented to reduce harmonic contents using current control for active power filter or PV applications of MLIs. The basic strategies of current control can be classified as (1) ramp comparator (2) hysteresis controller and (3) predictive controller [8]. The current control approach based on the comparison technique is the ramp-comparison controller. It compares the control signal according to the current error to a triangular carrier waveform, to generate the switching pulses. The main advantage of ramp-comparison controller is that the inverter operates at a fixed switching frequency defined by the triangular carrier waveform. However, the system response is affected by load parameters. It has an inherent phase and amplitude error even in steady-state operation [18]. The predictive controllers calculate the inverter voltages required to force the measured currents to follow the current reference. The system stability is affected by load parameters. The dynamic response of predictive current control is fast but it is very complex control strategy. The system response affected by load parameters is eliminated by the hysteresis control approach. This strategy uses hysteresis comparators to select the proper switching states based on the comparison of the current error with switching boundaries defined as a hysteresis band. The hysteresis current control strategy is simple and extremely robust [14-16].

The basic concept of hysteresis current control is to switch the output voltage level appropriately whenever the output current goes above or below a given tolerance band. By comparing a reference current and actual load current, the current controller can generate switching pulses for the power semiconductor devices. This decreases the current error and provides the desired current waveform for a load. In the hysteresis current control method, the reference current is surrounded by several bands. When the load current is between upper and lower bands, no switching occurs. When the load current crosses one of the bands to pass the upper limit (lower limit) the output voltage is decreased (increased) [20].

The hysteresis current control technique is a type of variable switching pattern which causes wide range of switching frequency variations. The variable switching frequency has been recognized to minimize mechanical noise for motor drive applications. But for power system application the switching frequency has to be in certain limitation to reduce the sub and lower order harmonics. This strategy proposes a multi-band hysteresis current control for a single phase five level hybrid inverter. The multi-band hysteresis current control for an "n" level inverter based on the magnitude error can be associated with a number of bands around the reference current [23]. There are two different types of hysteresis bands for five-level inverter. The first band consists of a main zone near the reference current that the load current always has to be inside the main zone to minimize total harmonic distortion. The second set of switching band has different zone surrounding the first hysteresis band to provide a reliable and a robust control for an "n" level inverter. The output current traces the reference current. If the output current crosses the additional band then the higher level output voltage will come [20].

The concept behind multi-band where the reference and load current determine the switching pattern is as shown in fig (3). If the load current crosses first hysteresis band the output voltage will half of Vdc in both positive and negative direction. Whereas the load current crosses the second band then the output voltage will be full Vdc in positive and negative direction.

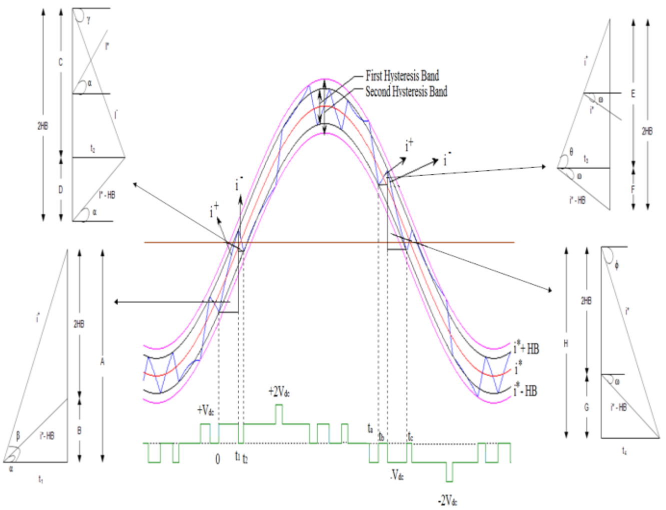

Fig.3. analysis of current and voltage waveforms with multi hysteresis bands.

The derivation for proposed multi-band hysteresis current controller for voltage level (+Vdc, 0) [20]:

$$di^{+}/dt = 1/L\,(V_{dc} - V_s) \quad (6)$$

$$di^{-}/dt = (-1/L)\,V_s \quad (7)$$

From analyses of first two triangles:

$$2HB = A - B = t_1\cdot\tan\beta - t_1\cdot\tan\alpha = t_1\cdot di^{+}/dt - t_1\cdot di^{*}/dt \quad (8)$$

$$2HB = C + D = -t_2\cdot\tan\gamma - t_2\cdot\tan\alpha = -\,t_2\cdot di^{-}/dt + t_2\cdot di^{*}/dt \quad (9)$$

We can get total switching time and thus switching frequency as follows:

$$t_1 + t_2 = T_c = 1/f_c \quad (10)$$

Adding and subtracting Eq (5.3) and Eq (5.4),

$$4HB = (t_2 - t_1) \cdot di^*/dt + t_1 \cdot di^+/dt - t_2 \cdot di^-/dt \quad (11)$$

$$(t_2 + t_1) \cdot di^*/dt - t_1 \cdot di^+/dt - t_2 \cdot di^-/dt = 0 \quad (12)$$

From above two equations we can find positive Hysteresis band as:

$$HB = [V_{dc}(L\cdot m+V_s)-(L\cdot m+V_s)^2]/(2\cdot f_c\cdot V_{dc}\cdot L) \quad (13)$$

where $m = di^*/dt$

For voltage level (0, -Vdc):

$$HB = [-V_{dc}(L\cdot m+V_s)-(L\cdot m+V_s)^2]/(2\cdot f_c\cdot V_{dc}\cdot L) \quad (14)$$

Similarly for second hysteresis band values can be analyzed that [13]:

For voltage level (+Vdc, +2Vdc) positive hysteresis band:

$$HB = [V_{dc}(5(L\cdot m+V_s)-V_{dc})-(L\cdot m+V_{dc}+V_s)^2]/(2\cdot f_c\cdot V_{dc}\cdot L) \quad (15)$$

For voltage level (-Vdc, -2Vdc) negative hysteresis band:

$$HB = [-V_{dc}\,(L\cdot m+V_{dc}+V_s)-(L\cdot m+V_{dc}+V_s)^2]/(2\cdot f_c\cdot V_{dc}\cdot L) \quad (16)$$

From equations (13), (14), (15) and (16) we can find out the upper and lower hysteresis bands for fixed frequency.

IV. SIMULATION RESULTS FOR PROPOSED HYBRID INVERTER

V.

The developed MATLAB models/Simulations have been carried out for a single phase hybrid inverter using MATLAB/Simulink software. In the simulations, the DC input and output voltage of the inverter is 28V, and the grid voltage is 18V and grid frequency is 50Hz. fig (4), Shows the simulation diagram done in MATLAB for the proposed hybrid inverter with sinusoidal PWM technique and for the same the output voltage and current waveform is shown in fig (5).

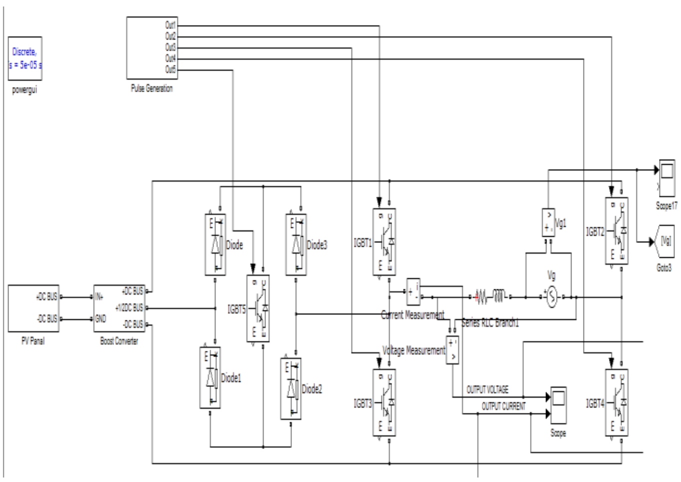

Fig.4. simulation of hybrid inverter with SPWM

As the output voltage has five-level and peak amplitude is 28V. The switching frequency for the SPWM is 10 KHz. The THD of the current using SPWM is 7.76%.

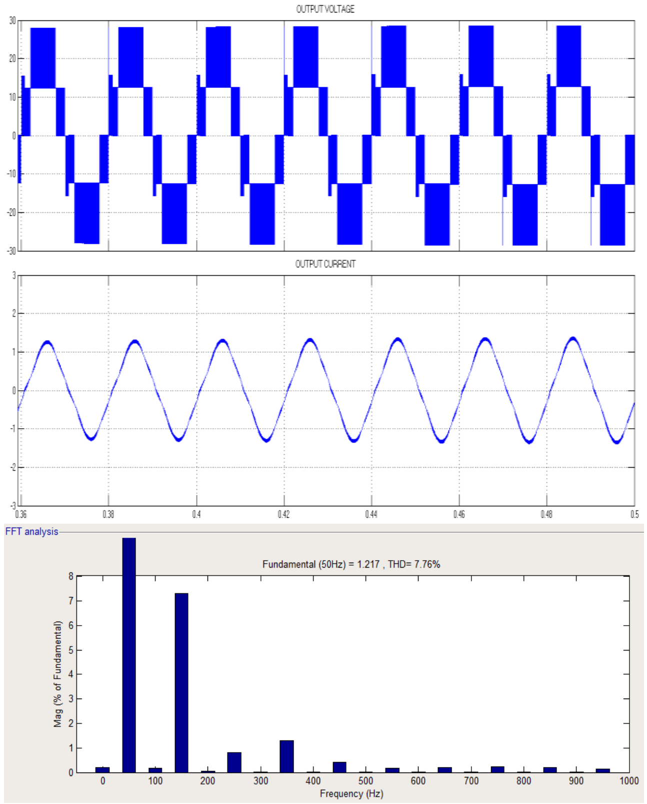

Fig.5. Five-level inverter output voltage and current waveforms with THD analysis

To reduce the THD of propose hybrid inverter the hysteresis current control simulation is shown in fig (6). For the adaptive hysteresis current control technique the values of first and second hysteresis bands are 0.0643 and 0.1357 respectively.

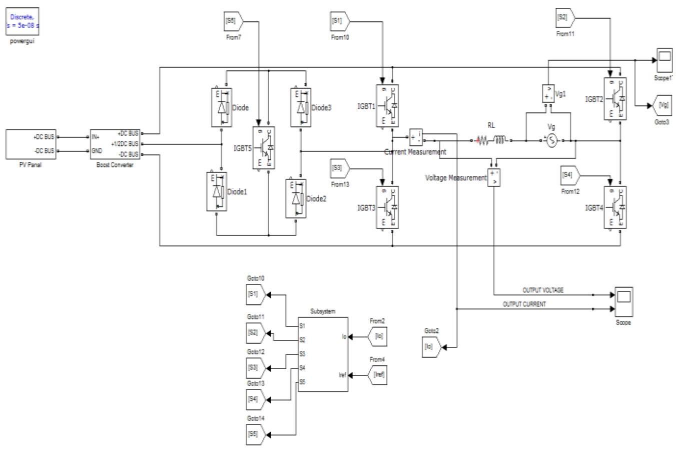

Fig.6. Simulation of hybrid inverter with hysteresis current control scheme

The output voltage and current waveform using adaptive hysteresis current controller is shown in fig (7). The THD of HCC for the current can be reduced to 5.98%.

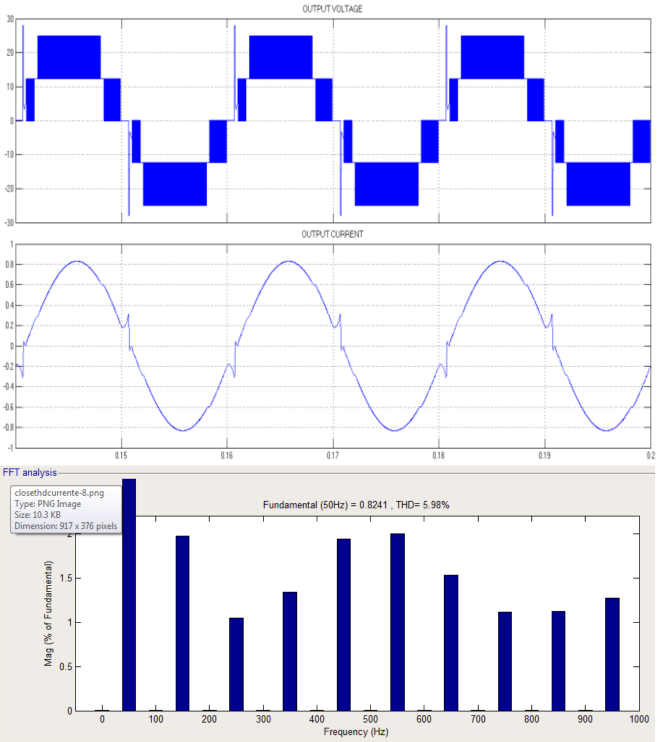

Fig.7. Five-level output voltage, current and FFT Analysis waveforms with THD analysis

VI. CONCLUSION

This paper presents a single phase five level hybrid MLI with SPWM and HCC. The effectiveness of the current control scheme is verified by the simulation results. The importance of hybrid inverter topology compared to conventional MLIs for the same number of voltage levels is also presented. The total harmonic content in the output current is reduced effectively using HCC. This method is more robust and effective then other current control techniques.

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