VOL. 7, NO. 12, DECEMBER 2012 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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SEVEN-LEVEL THREE PHASE CASCADED H-BRIDGE INVERTER WITH A SINGLE DC SOURCE

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ABSTRACT

Multi level inverters (MLIs) have been attractive for high power applications. Among the various MLIs, the Cascaded H-Bridge inverter is promising for grid connected wind power and photovoltaic applications. This paper compares three types of MLIs namely the Neutral Point Clamped MLI, the Flying Capacitor MLI, and the Cascaded H-Bridge MLI. In addition, the Cascaded H-Bridge MLI with a single DC source is presented. These MLIs are simulated in MATLAB using multi-carrier sine pulse width modulation (MCPWM) technique. Simulated output voltages and currents for an RL load are shown for the four configurations and compared based on the total harmonic distortion (THD). Results obtained show the applicability of the Cascaded H-Bridge inverter with a single DC source for grid connected wind power applications.

Keywords: cascaded H-bridge inverter (CHB), multi carrier pulse width modulation (MCPWM), neutral point clamped inverter (NPC), flying capacitor inverter (FLC), total harmonic distortion (THD).

1. INTRODUCTION

MLIs are becoming increasingly popular for their high voltage operating capability, high power capability and reduced EMI effects. MLIs have three or more voltage levels; have lower total harmonic distortion (THD) and less switching losses compared to the classical inverters. There have been various designs for MLIs including the following:

- Cascaded H-Bridge (CHB) Inverter
- Neutral Point Clamped (NPC) Inverter
- Flying-capacitor (FLC) Inverter

Of the above, the Cascaded H- Bridge Inverter does not require any clamp diodes or capacitors. It achieves high voltage by cascading multiple single-phase inverter modules and requires the least number of components [1]. In addition, it is flexible, robust and easy to control. However, the CHB inverter has the disadvantage of requiring independent DC sources.

2. NPC, FLC AND CONVENTIONAL CHB INVERTERS

Figure-1 shows the single-phase seven-level NPC inverter, which uses a single DC source, 12 IGBT/ DIODE switches, 10 diodes and 6 capacitors.

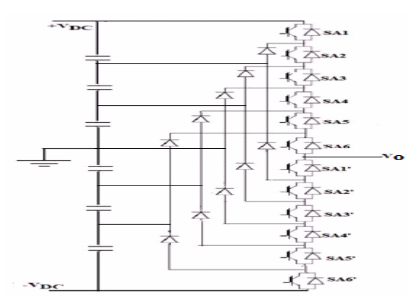

Figure-1. Seven-level NPC inverter.

Figure-2 shows the single-phase seven-level FLC inverter, which uses a single DC source, 12 IGBT/ DIODE switches and 7 capacitors.

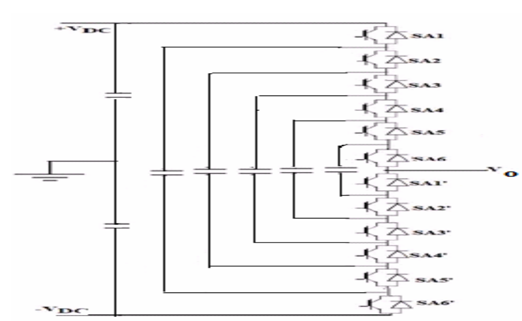

Figure-2. Seven-level FLC inverter.

Figure-3 shows the conventional single-phase seven-level CHB inverter that requires three separate DC sources and 12 IGBT/ DIODE switches. Each DC source has a single phase H-bridge [2-3].

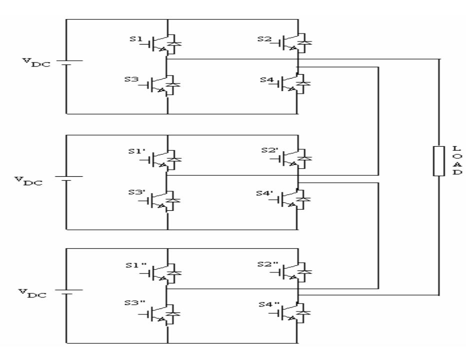

Figure-3. Conventional seven level CHB inverter.

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3. MULTI CARRIER PWM

The most popular control technique used in MLIs is the sinusoidal or "sub harmonic" natural pulse width modulation (PWM) method. Its popularity is due to its simplicity and to the good results it guarantees at all operating conditions, including "over-modulation," which allows the first harmonic. It can be used for any MLI and can be easily implemented. For an m-level inverter, m-1 carrier (triangular) waves with same amplitude and frequency are required. The frequency modulation index, which is the ratio of the carrier frequency to the modulating signal frequency, is expressed by equation (1).

$$m_f = \frac{f_{cr}}{f_m} \quad (1)$$

Where, f_m is the frequency of the modulating signal and f_{cr} is the frequency of the carrier waves. The amplitude modulation index m_a is defined by equation (2).

$$m_a = \frac{v_m}{v_{cr}(m-1)} \quad (2)$$

Where, v_m is the peak value of the modulating wave and v_{cr} is the peak value of each carrier wave. Four carrier PWM strategies, available in literature, with different phase relations are [4-7]:

a) Phase Disposition (PD)
b) Phase Opposition Disposition (POD)
c) Alternate Phase Opposition Disposition (APOD)
d) Phase Shift (PS).

In this paper, PD modulation scheme is used for pulse generation because it provides the lowest harmonic distortion for line voltages [8].

4. SIMULATION USING MATLAB

Seven-level three-phase NPC, FLC and conventional CHB MLIs are simulated with MATLAB for an RL load. In PD technique, for an m level inverter, m-1 carrier waves are used which are in phase with each other. These carrier waves are arranged to have vertical shifts. Hence, for a seven-level inverter six carrier waves are used to generate the switching pulses. These six carrier waves are compared with a reference to obtain the switching pulses. The PD scheme is shown in Figure-4.

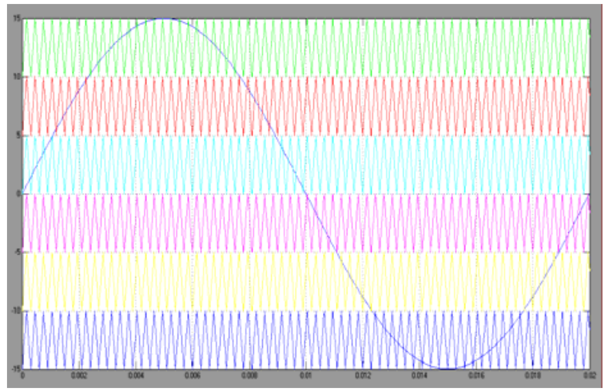

Figure-4. PD modulation scheme for the seven-level inverter.

MLIs are simulated for a star connected RL load of 50+j7.53 Ω/phase. Figures 5 and 6 show the output voltage and output current waveforms of the three-phase seven-level NPC inverter. Figures 7 and 8 show the output voltage and output current waveforms of the three-phase seven-level FLC inverter. Figures 9 and 10 show the output voltage and output current waveforms of the three-phase seven-level CHB inverter with separate DC sources.

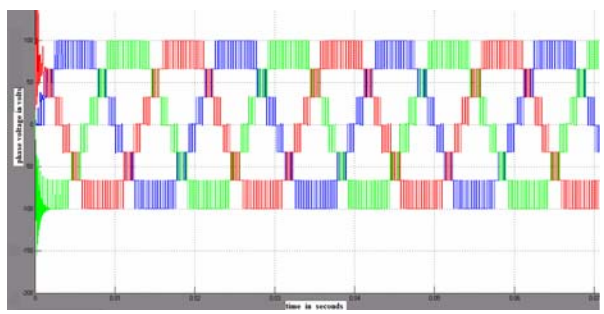

Figure-5. Simulated output voltage of the NPC inverter.

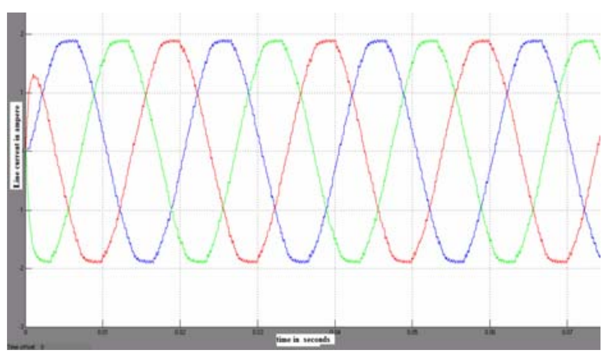

Figure-6. Simulated output current of the NPC inverter.

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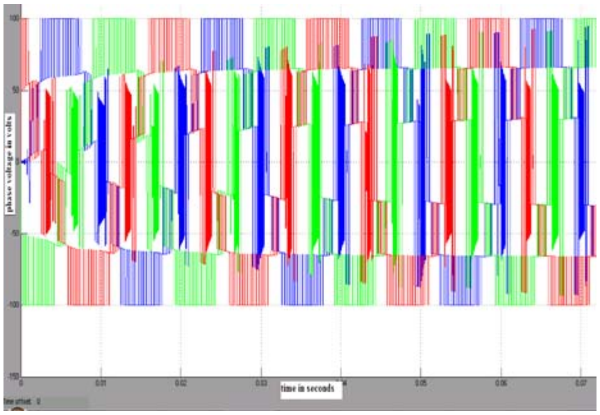

Figure-7. Simulated output voltage of the FLC inverter.

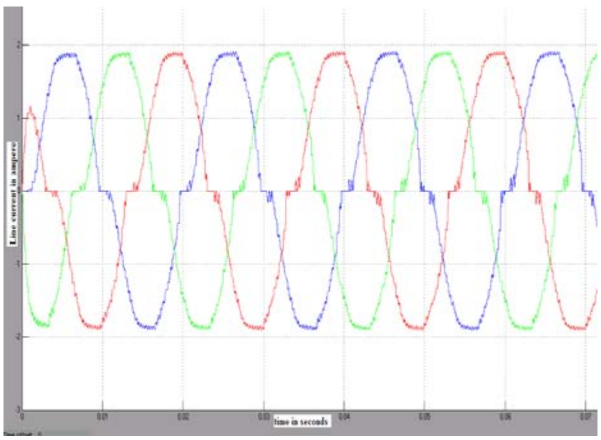

Figure-8. Simulated output current of the FLC inverter.

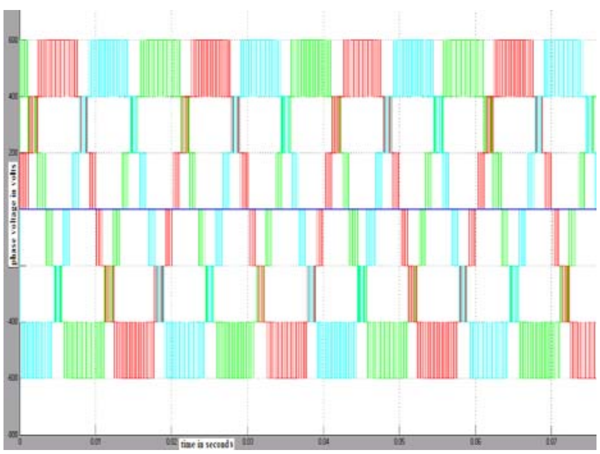

Figure-9. Simulated voltage of the traditional CHB inverter.

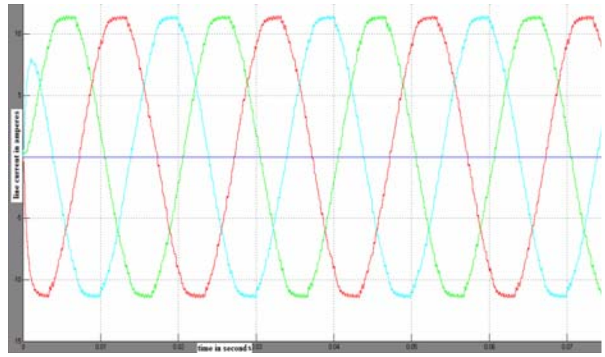

Figure-10. Simulated output current of the traditional CHB inverter.

5. COMPARISON OF THE THDs

The FFT analysis obtained by simulating MLIs are shown for the three configurations. Figures 11 and 12 respectively show the FFT analysis for the phase 'a' output voltage and output current for the NPC inverter. Figures 13 and 14 respectively show the FFT analysis of the phase 'a' output voltage and output current for the FLC inverter. Figures 15 and 16 respectively show the FFT analysis of the phase 'a' output voltage and output current for the conventional CHB inverter.

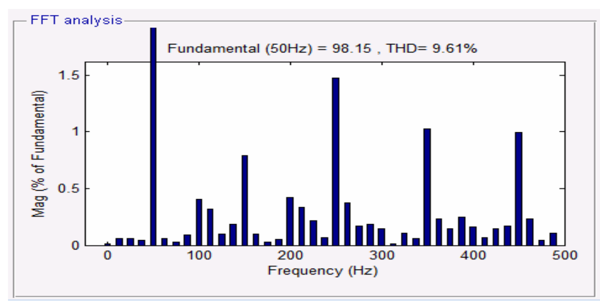

Figure-11. FFT analysis of the output voltage of the NPC inverter.

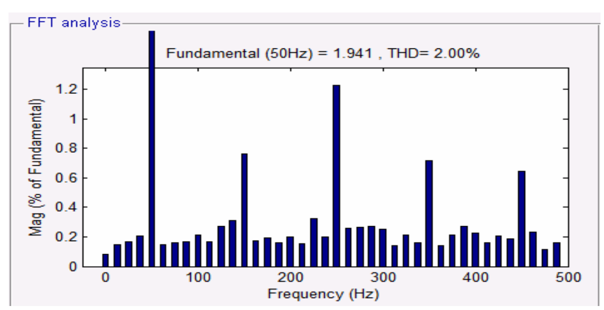

Figure-12. FFT analysis of the output current of the NPC inverter.

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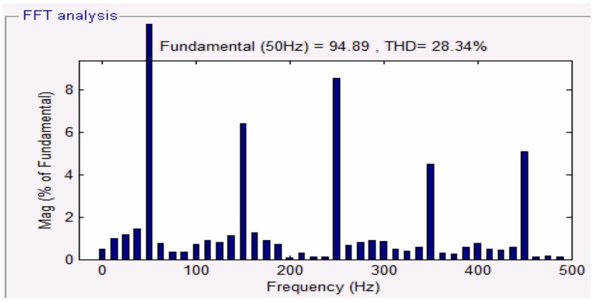

Figure-13. FFT analysis of the output voltage of the NPC inverter.

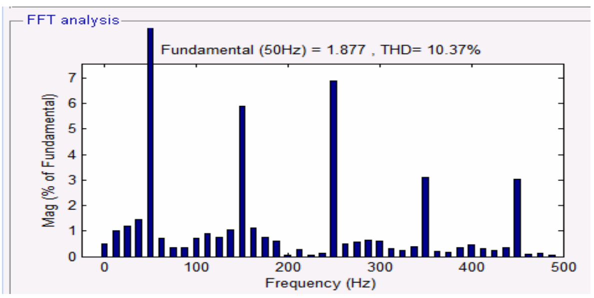

Figure-14. FFT analysis of the output current of the FLC inverter.

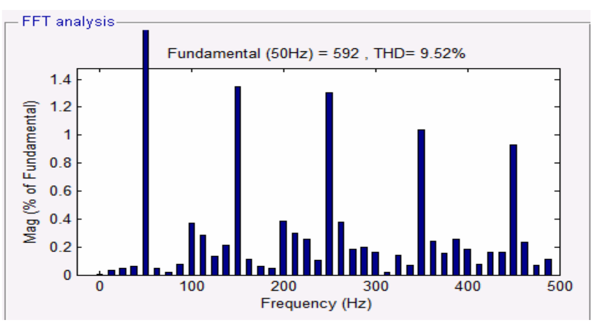

Figure-15. FFT analysis of the output voltage of the conventional CHB inverter.

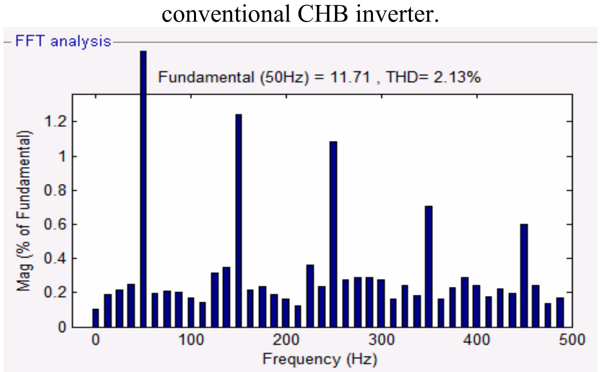

Figure-16. FFT analysis of the output current of the traditional CHB inverter.

From Figures 11-16, it can be seen that the THD for four cycles of the output voltage for the NPC, FLC, and traditional CHB are 9.61%, 28.34%, and 9.52%, respectively. The THD for four cycles of the output current of NPC, FLC, and traditional CHB are 2%, 10.37%, 2.13%, respectively. Figure-17 shows the voltage and current THDs for all the three inverters.

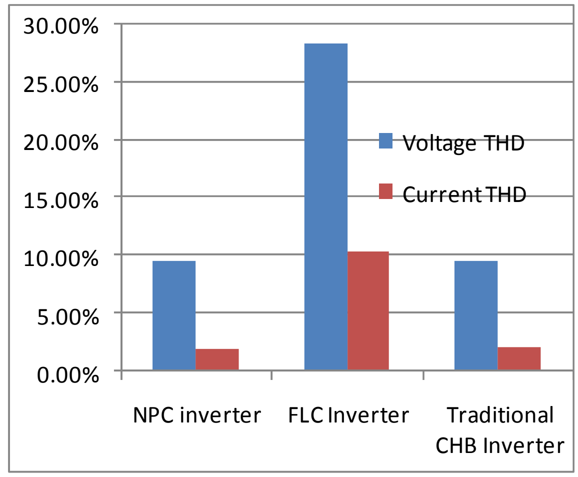

Figure-17. Voltage and current THDs for the NPC, FLC, and CHB inverters.

From the simulated waveforms, it is seen that for high power applications, CHB inverter is better suited as its fundamental output voltages and currents are high. In addition, the CHB inverter requires less number of components compared to the NPC and the FLC inverters. However, the CHB inverter has the disadvantage of requiring separate DC sources for each level, which increases the cost of the inverter. This disadvantage is not present in the proposed CHB MLI as it uses only a single DC source.

The simulation time, for four cycles of output, for the three MLI configurations, vary between 1.5 s and 2.5 s, and is given in the Table-1. It can be seen that simulation time for the CHB MLI of 1.75 s is comparable to the least simulation time taken by the FLC MLI, which is 1.5 s.

Table-1. Simulation time for four cycles of output for the three inverters.

Type of inverter	NPC MLI	FLC MLI	CHB MLI
Simulation time in seconds (s)	2.5	1.5	1.75

6. CHB MLI WITH A SINGLE DC SOURCE

Figure-18 shows the proposed single-phase seven-level CHB MLI that uses a single DC source. The output of the inverter is connected through transformers to the load. The inverter uses three transformers per phase, the secondary of each transformer being connected in series. The load is connected across the series connected secondary of the transformer [9-11].

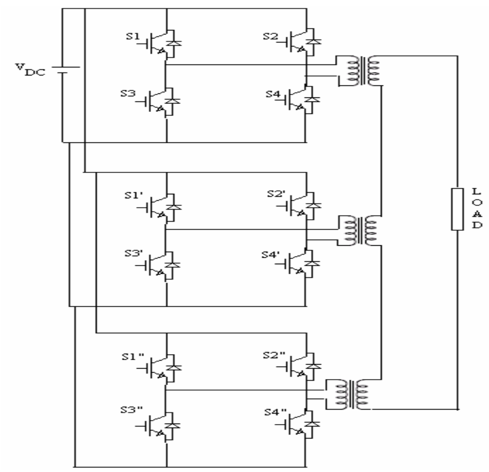

Figure-18. Seven-level CHB inverter with a single DC Source.

The proposed seven-level three-phase CHB inverter is simulated in MATLAB. Output voltage and current waveforms are shown in Figures 19 and 20, respectively.

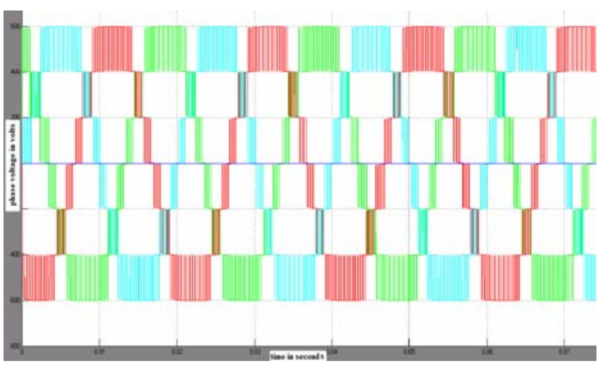

Figure-19. Simulated output voltages of the proposed CHB inverter.

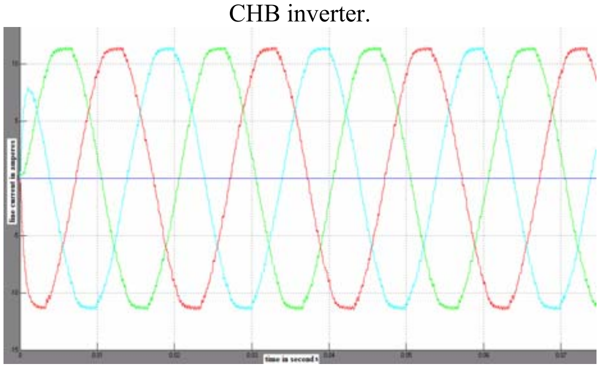

Figure-20. Simulated output currents of the proposed CHB inverter.

The FFT analysis of the output voltage and the output current, obtained by simulation of the proposed CHB inverter, is shown in Figures 21 and 22, respectively.

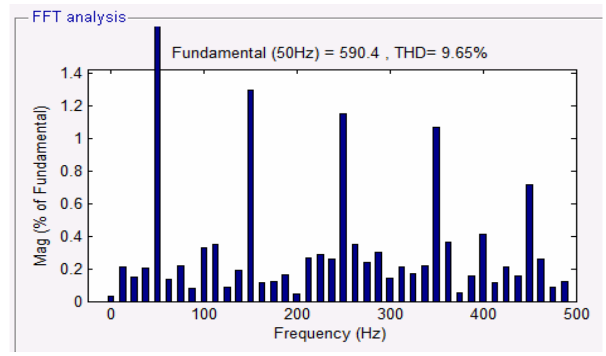

Figure-21. FFT analysis of the output voltage of the proposed CHB inverter.

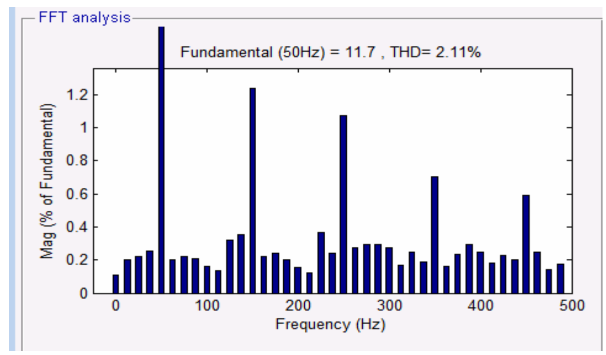

Figure-22. FFT analysis of the output current of the proposed CHB inverter.

Figures 23-34 show the switch currents and switch voltages for 12 switches of one leg (phase) of the proposed CHB inverter.

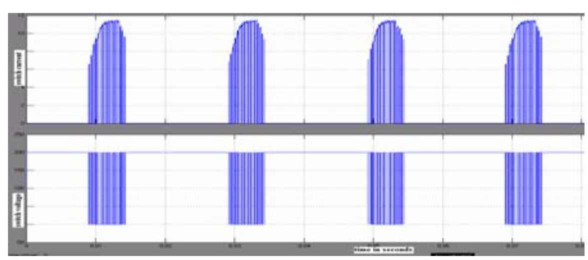

Figure-23. Switch current and voltage for S_1.

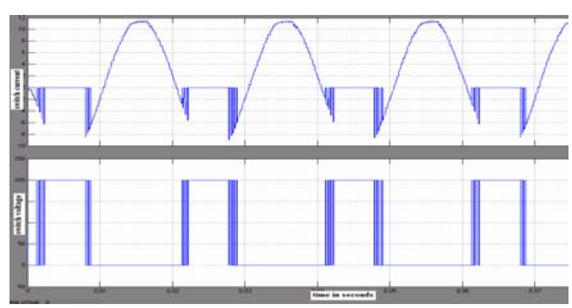

Figure-24. Switch current and voltage for S_2.

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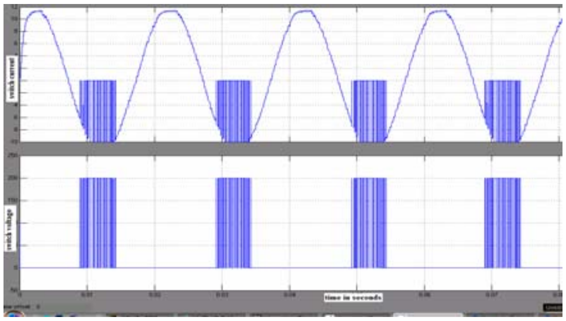

Figure-25. Switch current and voltage for S_3.

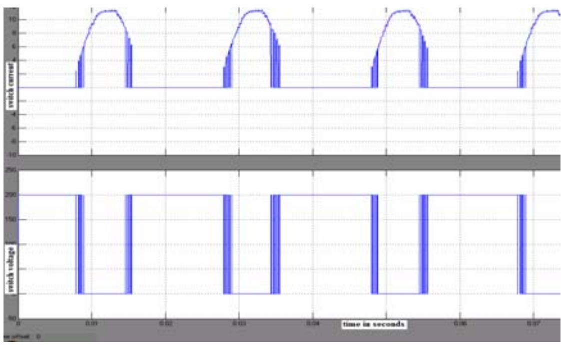

Figure-26. Switch current and voltage for S_4.

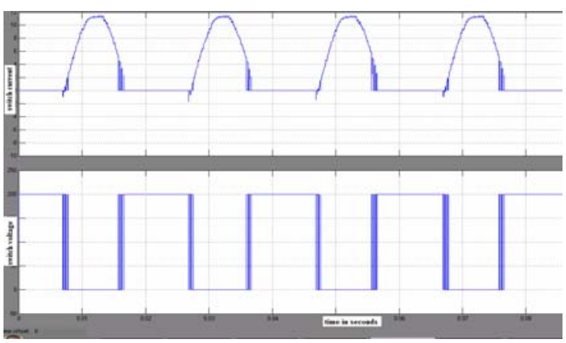

Figure-27. Switch current and voltage for S_1'.

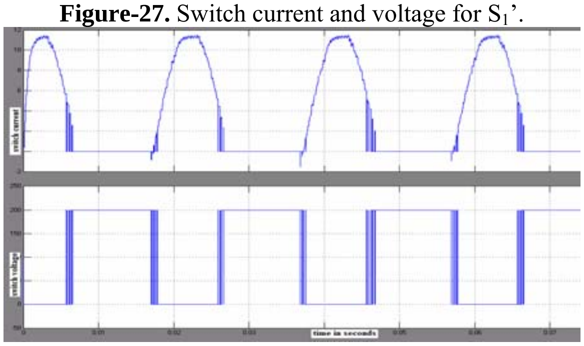

Figure-28. Switch current and voltage for S_2'.

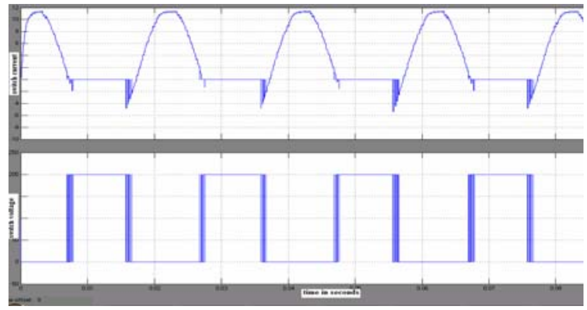

Figure-29. Switch current and voltage for S_3'.

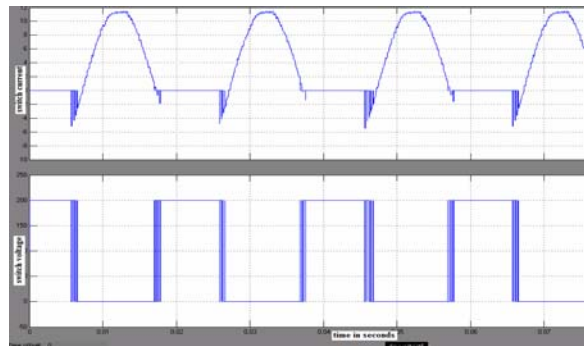

Figure-30. Switch current and voltage for S_4'.

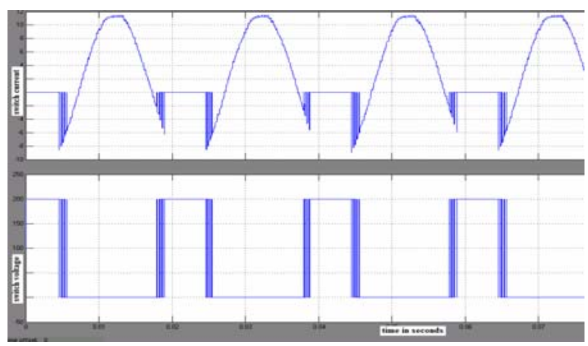

Figure-31. Switch current and voltage for S_1".

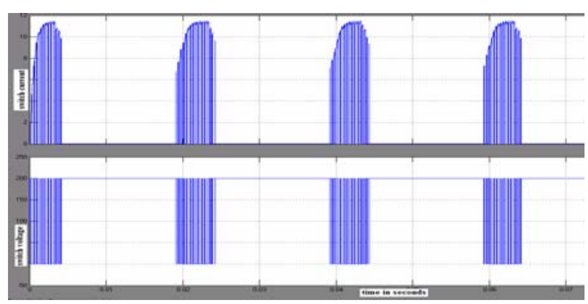

Figure-32. Switch current and voltage for S_2".

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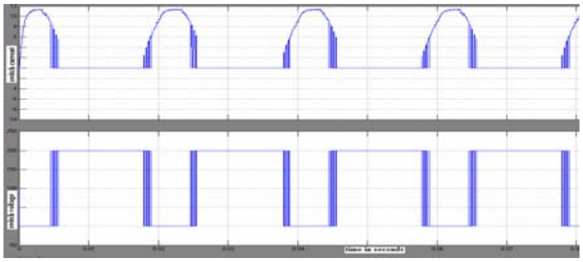

Figure-33. Switch current and voltage for S3".

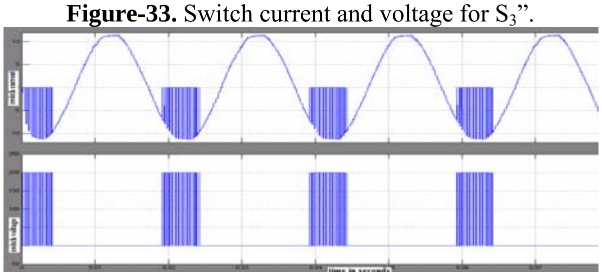

Figure-34. Switch current and voltage for S4".

Figure-21 shows that the THD of the output voltage of the proposed CHB inverter is 9.65% and Figure-22 shows that the THD of the output current of the proposed CHB inverter is 2.11%. The voltage THD of the proposed inverter is slightly higher than that of the conventional CHB inverter and the current THD of the proposed CHB inverter is slightly lower than that of the conventional CHB inverter. The proposed CHB may be considered better as it costs less due to the requirement of only one DC source, with performance comparable to the conventional CHB inverter.

7. OUTPUT POWER CALCULATION

The Fourier series expansion of the phase voltage of the CHB inverter is given by equation (3) [12].

$$v_{an} = \frac{4V_{DC}}{n\pi}[\sum_{j=1}^{3}\cos(n\alpha_j)]\sin(n\omega t) \tag{3}$$

Where α is the conduction angle and n = 1, 5, 7, etc.

The Fourier series expansion of the phase current, which is also the line current for the star connected load, is given by equation (4).

$$i_a = \frac{4V_{DC}}{n\pi Z_n}[\sum_{j=1}^{3}\cos(n\alpha_j)]\sin(n\omega t - \phi_n) \tag{4}$$

The equation (4) can be rewritten as given by equation (5).

$$i_a = I_n[\sum_{j=1}^{3}\cos(n\alpha_j)]\sin(n\omega t - \phi_n) \tag{5}$$

Where $I_n = \frac{4V_{DC}}{n\pi Z_n}$

Z_n is the per phase load impedance given by equation (6) and ϕ_n is the power factor angle given by equation (7).

$$Z_n = \sqrt{(R^2 + (n\omega L)^2} \tag{6}$$

$$\phi_n = \tan^{-1}(\frac{n\omega L}{R}) \tag{7}$$

The rms value of the phase current I_a is given by equation (8).

$$I_a = \sqrt{\frac{\sum_{n=1}^{\infty} I_n^2}{2}} \tag{8}$$

The output power is given by equation (10)

$$P_{out} = 3I_a^2 R \tag{9}$$

For the conventional CHB inverter, the rms value of the phase current is 8.28 A. The output power is given by:

$$P_{out} = 3*8.28^2*50$$
= 10284 W

For the proposed CHB inverter, the rms value of the phase current is found to be 8.27 A. Hence, the output power is given by:

$$P_{out} = 3*8.27^2*50$$
= 10259 W

8. COMPARISON OF CHB MLI HAVING SEPARATE DC SOURCES WITH CHB MLI HAVING A SINGLE DC SOURCE

The two CHB inverters are simulated in MATLAB with PD modulation with a star connected RL load of 50+j7.53 Ω/phase. The output voltage, output current and FFT analysis of voltage and current waveforms of the CHB inverter with separate DC sources were shown in the Figures 9, 10, 15 and 16 respectively. Figures 19-21 show the output voltage, output current, and FFT analysis of voltage and current of CHB with a single DC source.

Table-2 shows the comparison of the proposed CHB inverter with the conventional MLI. From Table-2, it can be seen that THD values and power output of the CHB MLI are comparable with the conventional one. It requires one DC source, which reduces the cost of the proposed CHB inverter.

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9. PARAMETERS FOR PROPOSED CHB

Input DC Voltage $V_{DC} = 200$ V

Load Impedance/phase = 50+j7.53 Ω

IGBT/Diode voltage/current rating = 400 V/15A

Transformer rating = 200V/200V, 15A/15A

Table-2. Comparison of the conventional and the proposed CHBs.

Parameters	Conventional CHB MLI	Proposed CHB MLI
No. of DC sources required	Nine DC sources	One DC source
Number of IGBT/Diode pairs	36	36
Voltage THD	9.52 %	9.65 %
Current THD	2.13 %	2.11 %
Output power	10284 W	10259 W
Cost	US $ 5,500	US $ 3,600
Voltage rating of power switches	400 V	400 V
Current rating of power switches	15 A	15 A

10. CONCLUSIONS

The simulation of three Multi-level Inverters (MLIs) namely the Neutral Point Clamped (NPC), the Flying Capacitor (FLC) and the Cascaded H-Bridge (CHB) is presented in this paper. These inverters are simulated in MATLAB using multi-carrier sine pulse width modulation (MCPWM) technique. The simulated output voltage and current waveforms for an RL load are shown for the three configurations and the total harmonic distortion (THD) is compared. For high power applications, CHB inverter is better suited as its fundamental output voltages and currents are high. In addition, the CHB inverter requires less number of components compared to the NPC and the FLC inverters. However, the CHB inverter has the disadvantage of requiring separate DC sources for each level, which increases the cost of the inverter.

The proposed Cascaded H-Bridge with a single DC source is simulated in MATLAB using multi-carrier sine pulse width modulation (MCPWM) technique. The simulated output voltage and current waveforms, FFT analysis and switching voltages and currents for an RL load are shown for the proposed Cascaded H-Bridge with a single DC source. The total harmonic distortion (THD), output power and the cost for the two CHB Inverter configurations are compared. The proposed CHB inverter does not require separate DC sources and hence the cost of the system is lesser. In addition, this system eliminates the possibility of short circuit of the DC sources, which may occur in the conventional CHB inverter.

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