

Comparative Study of Different PWM Control Techniques for a Three-phase Eleven-level Cascaded H-bridge Multilevel DC-link Inverter

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Abstract

The paper titled "Comparative study of Different PWM Control Techniques For a Three-phase Eleven-level Cascaded H-bridge Multilevel DC-link Inverter" proposes a three phase eleven-level cascaded H-bridge multilevel DC-link inverter employing three novel carrier based PWM techniques such as Constant switching frequency Pulse width modulation, Variable switching frequency multicarrier Pulse width modulation and Phase shifted carrier Pulse width modulation. The above methodologies are divided into two techniques based on the type of modulation signal. The sub harmonic pulse width modulation cascaded multilevel inverter strategy, which minimizes total harmonic distortion and the switching frequency optimal pulse width modulation cascaded multilevel inverters strategy, which enhances the output voltages. The three phase eleven-level cascaded H-bridge multilevel DC-link inverter using three novel carrier based PWM techniques is simulated using MATLAB / SIMULINK software and the output voltage THD's and the fundamental output voltages for each of the cases are tabulated and are compared.

1. Introduction

The voltage source inverters produce an output voltage or current with levels either 0 or $\pm V_{dc}$. They are known as the two-level inverter. To produce a quality output voltage or a current waveform with less amount of ripple content, they require high switching frequency. In high-power and high voltage applications these two level inverters, however, have some limitations in operating at high frequency mainly due to switching losses and constraints of device ratings. These limitations can be overcome using multilevel inverters. The multilevel inverters have drawn tremendous interest in power industry. It may be easier to produce a high-power, high voltage inverter with multi-level structure because of the way in which voltage stresses are controlled in the structure. The unique structure of multilevel voltage source inverters allows them to reach high voltages with low harmonics without use of transformers or series connected synchronized-switching devices. As the number of voltage levels increases, the harmonic content of the

output voltage wave form decreases significantly. There are 3 types of multilevel inverters named as diode clamped multilevel inverter, flying capacitor multilevel inverter and cascaded multilevel inverter. These three types of multilevel inverters requires more no of components such as switches, clamping diodes and capacitors. As the number of voltage levels 'm' grows, the number of active switches increases according to $2 \times (m-1)$ for the cascaded H-bridge multilevel inverters. Compared with the existing cascaded multilevel inverters, the cascaded Multilevel DC Link Inverters (MLDCLI) can significantly reduce the switch count as well as the number of gate drivers as the number of voltage levels increases. For a given number of voltage levels 'm', the cascaded MLDCL (Multilevel DC-link) inverter requires $m+3$ active switches as against $2 \times (m-1)$ switches required for existing cascaded multilevel inverters.

In this paper the three novel carrier based PWM techniques such as Constant switching frequency Pulse width modulation (PWM), Variable switching frequency multicarrier Pulse width modulation (PWM) and Phase shifted carrier Pulse width modulation (PWM) are employed. Based on the type of modulation signal the above methodologies are further divided into sub harmonic pulse width modulation strategy and switching frequency optimal pulse width modulation strategy. Three phase eleven-level cascaded H-bridge multilevel DC-link inverter employing different PWM techniques such as Constant Switching Frequency Multicarrier Sub Harmonic / Switching frequency optimal Pulse Width Modulation, Variable Switching Frequency Multicarrier Sub Harmonic Pulse / Switching frequency optimal Width Modulation and Phase Shifted Carrier Sub Harmonic / Switching frequency optimal Pulse Width Modulation is simulated using MATLAB / SIMULINK software. The output voltage THD's and the fundamental output voltages for each of the cases are tabulated and are compared. Figure 1 shows the general structure of a three phase 'm' level cascaded H-bridge multilevel DC-link inverter (MLDCLI) and figure 2 shows the block diagram of a cascaded H-bridge MLDCL inverter topology, which consists of a multilevel DC source to produce DC-link bus voltage 'V_{bus}' and a Single-

Phase Full Bridge (SPFB) inverter, which consists of four switches S1-S4 to alternate the polarity of DC-link bus voltage to produce an AC voltage. The DC source is formed by connecting a number of half-bridge cells in series with each cell having a voltage source controlled by two switches Sak and Sbk. The two switches operate in a toggle fashion. The cell source is bypassed with Sak on and Sbk off, or adds to the dc-link voltage by reversing the switches.

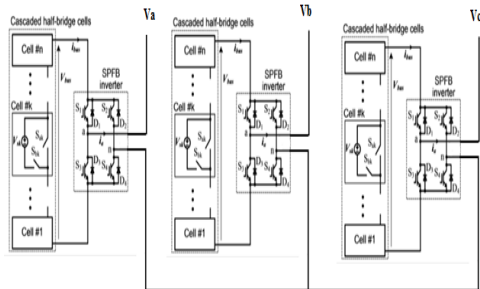


Fig.1: Three Phase 'm' level Cascaded H-bridge MLDCI

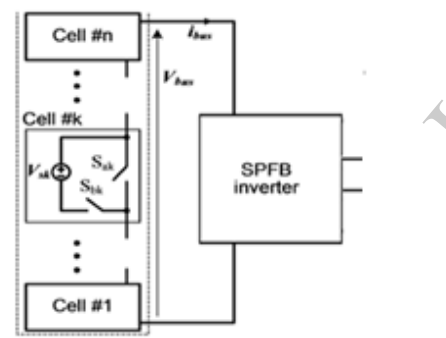


Fig.2: Block diagram of cascaded H-bridge MLDCI

2. Carrier based Pulse Width Modulation Techniques

Pulse Width Modulation control is the most widely used method of controlling the active devices in a multilevel inverter. A significant amount of research has been published on various ways of implementing PWM control. The focus here is on carrier-based sinusoidal PWM techniques for controlling a Cascaded H-bridge DC-link Multilevel Inverter.

2.1 Sub Harmonic Pulse Width Modulation Method

Carrara extended Sub Harmonic Pulse Width Modulation (SH-PWM) to multiple levels as follows: For an m-level inverter, m-1 carriers with the same frequency 'fc' and the same amplitude 'Ac' are disposed such that the bands they occupy are contiguous. The reference waveform has peak-to-peak amplitude 'Am', frequency 'fm', and its zero centered in the middle of the carrier set. The reference is continuously compared with each of the carrier signals. If the reference is greater than a carrier signal, then the active device corresponding to that carrier is switched on and if the reference is less than a carrier signal, then the active device corresponding to that carrier is switched off.

In multilevel inverters, the amplitude modulation index 'ma', and the frequency ratio, 'mf', are defined as

$$ma = Am / (m-1) \cdot Ac \quad (1)$$

$$mf = fc / fm \quad (2)$$

Figure 3 shows a set of carriers for a six-level diode-clamped inverter and a sinusoidal reference or a modulation waveform. The resulting output voltage of the inverter is also shown in figure 3.

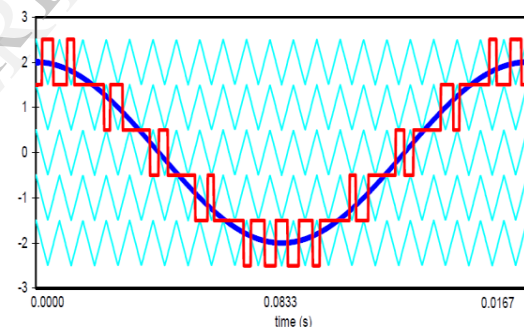


Fig.3: Multilevel carrier-based Sub Harmonic PWM showing carrier bands, modulation waveform, and inverter output waveform

2.2 Switching Frequency Optimal Pulse Width Modulation Method

Another carrier based method that was extended to multilevel applications by Menzies is termed switching frequency optimal PWM (SFO-PWM), and it is similar to SH-PWM except that a zero sequence (triplen harmonic) voltage is added to each of the carrier waveforms. This method takes the instantaneous average of the maximum and minimum of the three reference voltages (Va^* , Vb^* , Vc^*) and subtracts this value from each of the individual reference voltages, i.e.

$$V_{offset} = ((\max(Va^*, Vb^*, Vc^*) + \min(Va^*, Vb^*, Vc^*)) / 2) \quad (3)$$

$$V_{aSFO*} = V_{a*} - V_{offset}$$

$$V_{bSFO*} = V_{b*} - V_{offset} \quad (4)$$

$$V_{cSFO*} = V_{c*} - V_{offset}$$

The addition of this triplen offset voltage centres all of the three reference waveforms in the carrier band, which is equivalent to using space vector PWM. SFO-PWM is illustrated in figure 4 for the same reference voltage waveform that was used in figure 3. The resulting output voltage of the inverter is also shown in figure 4.

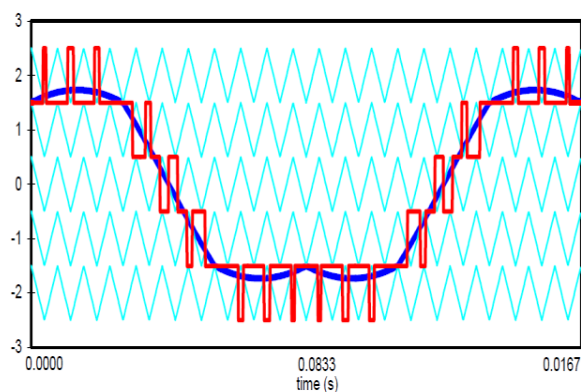


Fig.4: Multilevel carrier-based SFO-PWM showing carrier bands, modulation waveform, and inverter output waveform

3. Constant Switching Frequency Multicarrier PWM

In constant switching frequency multicarrier pulse width modulation, the frequency of all the level shifted carrier waves are kept constant. This is again subdivided into constant switching frequency multicarrier sub harmonic pulse width modulation and constant switching frequency multicarrier switching frequency optimal pulse width modulation.

3.1. Constant Switching Frequency Multicarrier Sub harmonic Pulse Width Modulation (CSFMC-SH-PWM)

For an 'm' level inverter, 'm-1' carriers with the same frequency 'fc' and the same amplitude 'Ac' are disposed such that the bands they occupy are contiguous. The reference waveform has peak to peak amplitude 'Am', the frequency 'fm', and its zero centred in the middle of the carrier set. The reference is continuously compared with each of the carrier signals. If the reference is greater than a carrier signal, then active device corresponding to that carrier is switched

on. Figure 5 shows constant switching frequency multicarrier sub harmonic pulse width modulation for three phase with three reference signals.

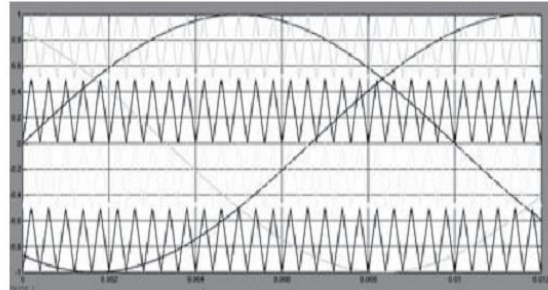


Fig.5: Constant Switching Frequency Multicarrier Sub harmonic Pulse Width Modulation (CSFMC-SH-PWM)

3.2. Constant Switching Frequency Multicarrier Switching Frequency Optimal Pulse Width Modulation (CSFMC-SFO-PWM)

Figure 6 shows the CSFMC-SFO-PWM in which triplen harmonic voltage is added to each of the carrier waveforms. The method takes the instantaneous average of the maximum and minimum (Va*, Vb*, Vc*) and subtracts the value from each of the individual reference voltages to obtain the modulation waveforms. Figure 6 shows the CSFMC-SFO-PWM for three phases.

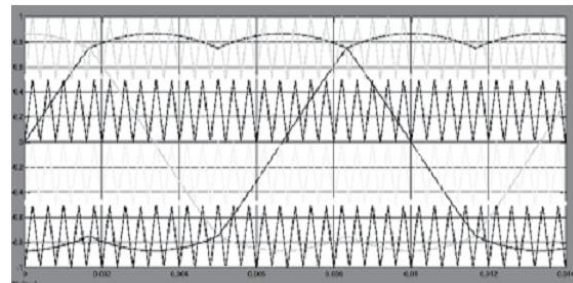


Fig.6: Constant Switching Frequency Multicarrier Switching Frequency Optimal Pulse Width Modulation (CSFMC-SFO-PWM)

4. Variable Switching Frequency Multicarrier PWM

In variable switching frequency multicarrier pulse width modulation, the frequencies of the level shifted carrier waves are varied. This is again subdivided into variable switching frequency multicarrier sub harmonic pulse width modulation and variable switching frequency multicarrier switching frequency optimal pulse width modulation.

4.1. Variable Switching Frequency Multicarrier Sub harmonic Pulse Width Modulation (VSFMC-SH-PWM)

For a multilevel inverter with 'm' levels, there will be 'm-1' carrier set with variable frequency which will be compared with the sinusoidal reference. The carriers are in phase across all the bands. In this technique, significant harmonic energy is concentrated at the carrier frequency. Figure 7 shows the above modulation process for three phases.

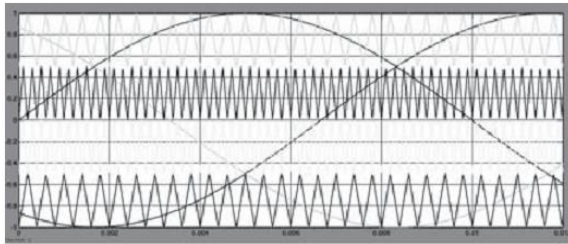


Fig.7: Variable Switching Frequency Multicarrier Sub harmonic Pulse Width Modulation (VSFMC-SH-PWM)

4.2. Variable Switching Frequency Multicarrier Switching Frequency Optimal Pulse Width Modulation (VSFMC-SFO-PWM)

For 'm' level multilevel inverter, there will be 'm-1' carrier set with variable switching frequency and these are compared with the third harmonic injection reference. The third harmonic injection is given as,

$$Y=1.15\sin\theta+1.15/6\sin3\theta \quad (5)$$

The resulting flat topped waveform allows over modulation while maintaining excellent AC term and DC term spectra. This is an alternative to improve the output voltage without entering the over modulation range. Figure 8 shows the variable Switching Frequency Multicarrier Switching Frequency Optimal Pulse Width Modulation for three phases.

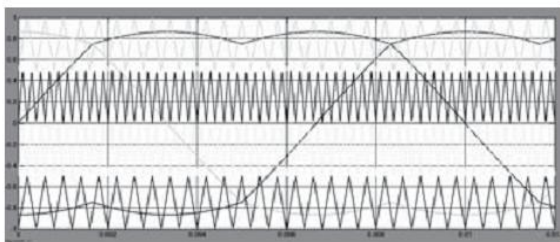


Fig.8: Variable Switching Frequency Multicarrier Switching Frequency Optimal Pulse Width Modulation (VSFMC-SFO-PWM)

5. Phase Shifted Carrier Pulse Width Modulation

In phase shifted carrier pulse width modulation, the frequency of all the carrier waves are kept constant and it is phase shifted by each other. This is again subdivided into phase shifted carrier sub harmonic pulse width modulation and phase shifted carrier switching frequency optimal pulse width modulation.

5.1. Phase Shifted Carrier Sub harmonic Pulse Width Modulation (PSC-SH-PWM)

In Phase Shifted Carrier Pulse Width Modulation the frequency of the all the carrier waves are kept constant and are phase shifted by each other. Figure 9 illustrates the phase shifted carrier sub harmonic pulse width modulation. In phase shifted carrier pulse width modulation all the triangular carriers have the same frequency and the same peak-to-peak amplitude but there is a phase shift between each other. In general, a multilevel inverter with 'm' voltage levels requires 'm-1' triangular carriers. The phase shifted carrier sub harmonic pulse width modulation for three phase is shown in figure 10.

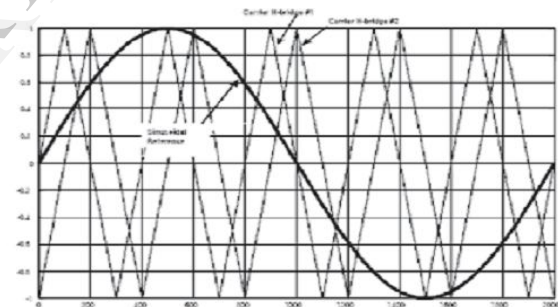


Fig.9: Phase Shifted Carrier Sub harmonic Pulse Width Modulation (PSC-SH-PWM)

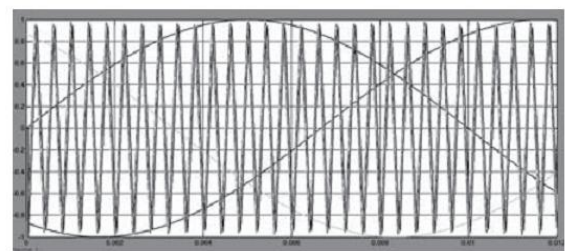


Fig.10: Phase Shifted Carrier Sub harmonic Pulse Width Modulation (PSC-SH-PWM) for three phases

5.2. Phase Shifted Carrier Switching Frequency optimal Pulse Width Modulation (PSC-SFO-PWM)

The method takes the instantaneous average of the maximum and minimum of the three reference voltages (V_a^* , V_b^* , V_c^*) and subtracts this value from each of the individual reference voltages to obtain modulation waveforms, which uses equations (3) & (4). The carrier voltage is the average of maximum and minimum value of V_a , V_b , V_c . The phase voltage using SFO is the difference between reference voltages to carrier voltage. Figure 11 shows the phase shifted carrier switching frequency optimal pulse width modulation for three phases.

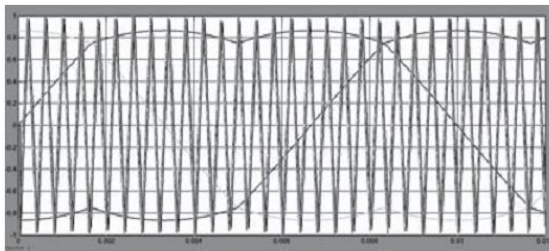


Fig.11: Phase Shifted Carrier Switching Frequency optimal Pulse Width Modulation (PSC-SFO-PWM)

6. Simulation Results

Various modulation techniques output voltage and THD (Total Harmonic Distortion) values for a three phase eleven-level cascaded H-bridge multilevel DC-link inverter are shown in table below.

Modulation Technique	Voltage THD %	V_{ac}
CSFMC-SH-PWM	23.15	123.5
CSFMC-SFO-PWM	26.39	126.8
VSFMC-SH-PWM	21.28	124.3
VSFMC-SFO-PWM	26.73	128.2
PSC-SH-PWM	20.3	126.9
PSC-SFO-PWM	26.92	125.4

To verify the proposed schemes, a simulation model for a three phase eleven-level cascaded H-bridge multilevel DC-link inverter is implemented and simulated using MATLAB / SIMULINK software. The Simulation parameters for constant switching frequency multicarrier PWM are as following: each source voltage is 30 V and switching frequency is 1 KHz. The simulation parameters for variable switching frequency multicarrier PWM are as follows: each source voltage is 30 V and switching frequencies are 1 KHz, 2KHz and 2.5 KHz. The simulation parameters for phase shifted carrier PWM are as follows: each source voltage is 30 V and switching frequency is 1 KHz.

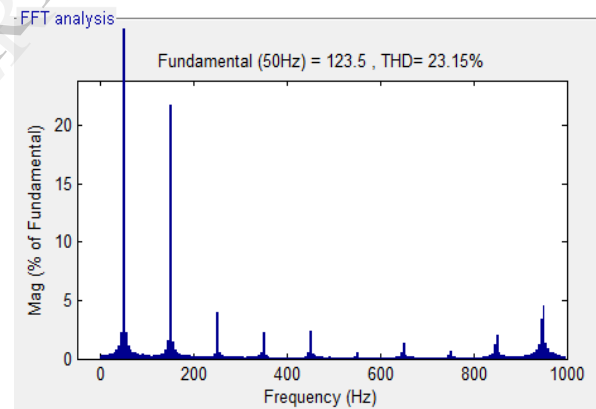
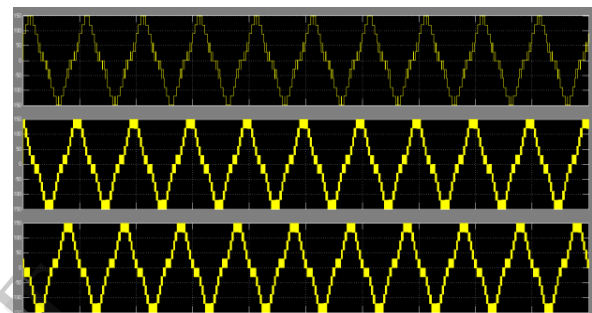
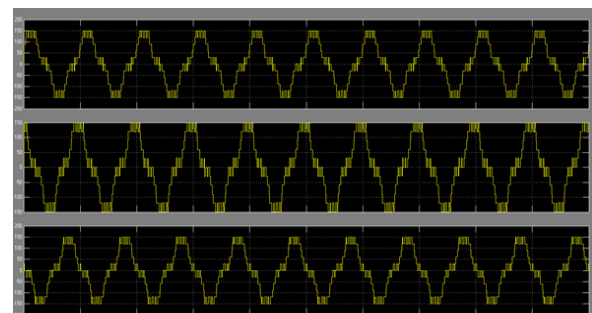


Fig.12: CSFMC-SH-PWM output voltage and harmonic spectra



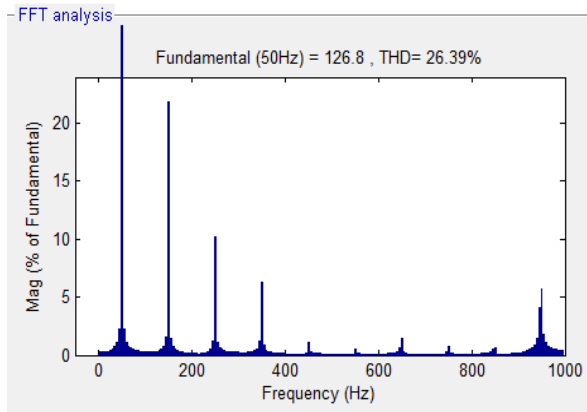


Fig.13: CSFMC-SFO-PWM output voltage and harmonic spectra

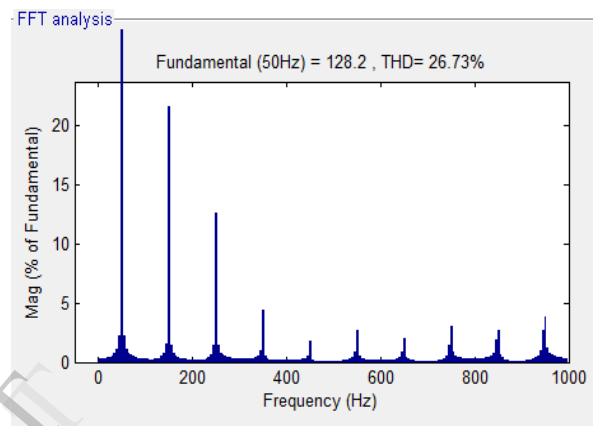
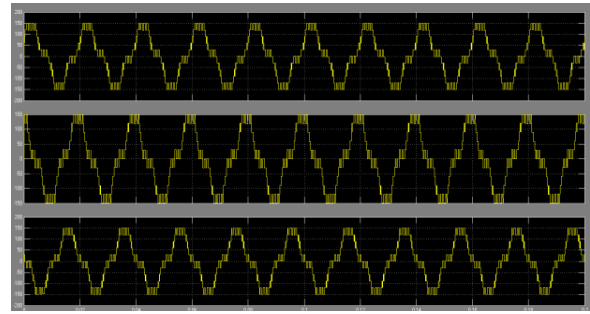
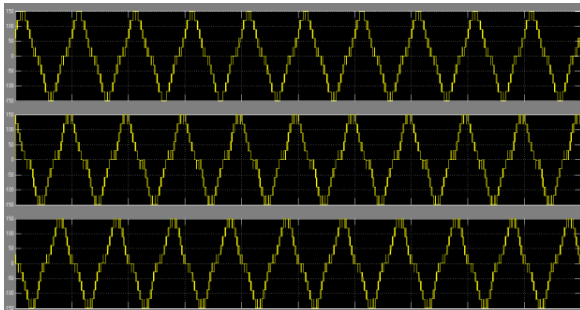


Fig.15: VSFMC-SFO-PWM output voltage and harmonic spectra

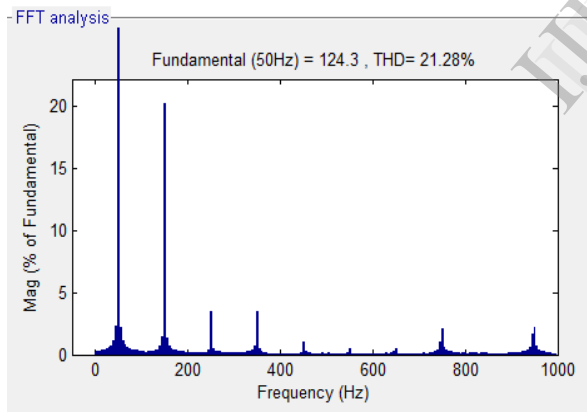
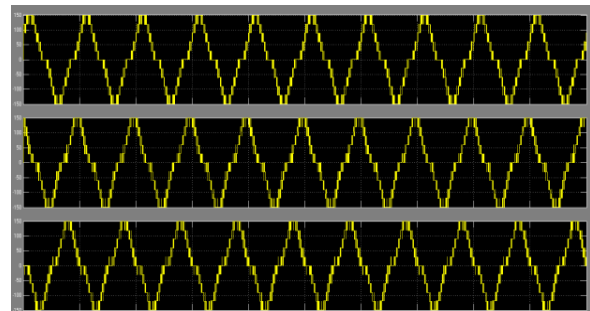


Fig.14: VSFMC-SH-PWM output voltage and harmonic spectra



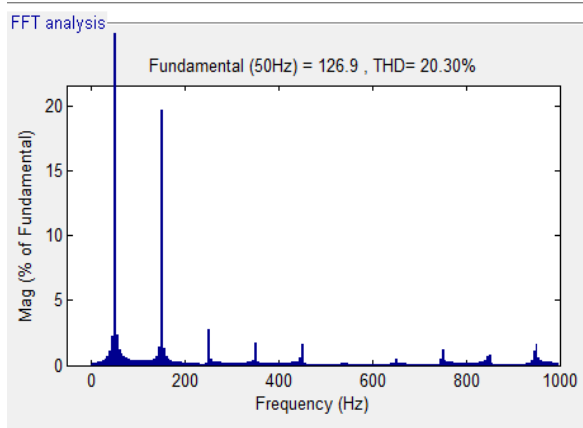


Fig.16: PSC-SH-PWM output voltage and harmonic spectra

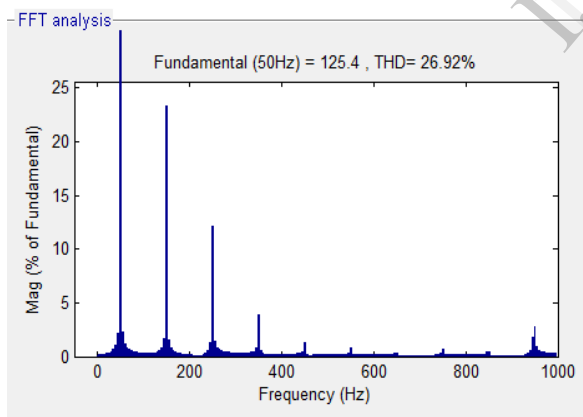
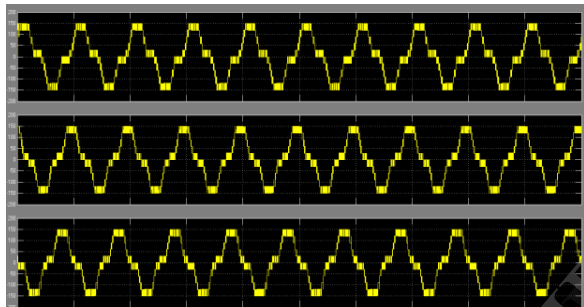


Fig.17: PSC-SFO-PWM output voltage and harmonic spectra

7. Conclusion

In this paper the three PWM schemes such as constant switching frequency multicarrier, variable switching frequency multicarrier and phase shifted carrier pulse width modulation techniques are implemented. The sub harmonic pulse width

modulation strategy reduces the THD and switching frequency optimal pulse width modulation enhances the output voltage. From the tabulated results it can be concluded that the phase shifted carrier sub harmonic PWM gives best results both in terms of the % THD and the output voltage.

8. References

- [1] N.Booma, Nagisetty Sridhar, "Nine level Cascaded H-bridge Multilevel DC-link Inverter", Emerging Trends in Electrical and Computer Technology (ICETECT), International Conference, March 2011.
- [2] Gui-Jia Su, "Multilevel DC-Link Inverter", IEEE Trans. Industrial Applications, vol. 41, no. 3, May/June 2005.
- [3] B.P.McGrath and Holmes, "Multicarrier PWM strategies for multilevel inverter," IEEE Trans.Ind-Electron., vol.49, no.4, pp.858, 867. Aug.2002.
- [4] J. Rodriguez, J. Lai, F.Z. Peng: "Multilevel inverters: a survey of topologies, controls, and applications", IEEE Trans. on Industrial Electronics, vol.49, issue 4, pp.724-738, 2002.
- [5] L.M.Tolber, T.G.Habetler, "Novel Multilevel Inverter Carrier based PWM Method," IEEE Ind.Appli., vol.35. pp.1098, 1107. Sep/Oct 1999.
- [6] Roozbeh Naderi, and Abdolreza rahmati, "Phase shifted carrier PWM technique for general cascaded inverters," IEEE Trans. Power Electron., vol.23, no.3, pp.1257, 1269. May.2008.
- [7] P.Palanivel, Subhransu Sekhar dash, "Comparative study of constant switching frequency and variable switching frequency multicarrier pulse width modulation for three phase cascaded multilevel inverter", International Journal of Recent Trends in Engineering, Vol 2, No.7, November 2009.