Identification of Most Effective Phase Shift in Triangular Carrier for Multi-(two) Inverter fed Induction Motor Drive

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Abstract - This paper presents the performance of induction motor drive fed by multi- (two) inverters with and without implementation of phase shifted triangular carrier technique with two identified phase shift patterns. Performances of the systems are compared viz. current harmonics, voltage harmonics, and total losses in inverters by implementation of discussed three methods. It is observed that the multi-inverter system with phase shifted triangular carrier with phase shift of 180^0 results in better performance of induction motor, has lower losses in the inverters and also less harmonic losses occurring in the motor. There has been a remarkable improvement in current and voltage harmonics when the phase shifted triangular carrier technique is utilized in addition to the purpose of sharing the current when compared with multi (2) inverters without any phase shift in their triangular carrier.
Key words – Harmonic profile, Inverter switching losses, Modulation index, Phase shifted triangular,

I. INTRODUCTION

The world's energy consumption is estimated to increase linearly until the year 2030. Some estimates forecast that 50% of installed motor drives will be adjustable-speed drives (ASD) in the future. The evolution in ASD's has solved many production and control issues. Their performance, reliability and efficiency have improved. Reasons for development and use of adjustable speed-drives include flexible production systems and industrial automation processes, leading to increase productivity, improved controllability, better yield, repeatability etc. Several factors have made AC ASD's the machines of choice for industrial applications vs. DC machines, including their ruggedness, reliability, and low maintenance [1, 2].

The cage induction motor is simple to manufacture, with no rotor windings or commutators for external rotor connection. There are no brushes to replace because of wear, and no brush arcing to prevent the machine from being used in volatile environments. The induction machine has a higher power density, greater maximum speed, and lower rotor inertia than the DC machine.

Present trend in the design of induction motor drive systems for wide-ratio speed control application is to use standard induction machines in conjunction with the controlled solid states. These converters are known to generate time harmonics, and efforts have, so far, been directed to design improved converter control circuits which lead to minimize harmonic generation. In induction motor drive applications, the harmonic terms result in large rotor losses and heating. The efficiency and utilization are impaired. Therefore it is important to choose a modulation strategy, which would keep the harmonic losses low. One approach to reduce the harmonic losses would be to increase the number of pulses at the inverter output where by the order of the harmonics is increased. The higher order harmonics are more easily filtered by the motor leakage reactance. However, the increased number of pulses necessitates a higher commutation rate that results in increased commutation losses. The reduction in machine losses brought about by reduction in harmonic currents can be offset by increased inverter losses. The overall system efficiency can decrease rather than improve.

Amongst various types, the pulse width modulated (PWM) voltage source inverter is an extremely effective motor controller accomplishing voltage and frequency adjustment in a single block. PWM technique has been developed for inverter circuits, to reduce the magnitude and allow the control of the fundamental component of output voltage. PWM Inverters are widely used in industrial motor drives and UPS systems. In PWM method the fundamental and harmonic components in the output voltage are controlled by the proper choice of the pulse pattern within each half cycle [3]. The harmonic components of the voltages are undesirable (though unavoidable), and are products of inverter switching and produce harmonic losses in the ac load. It is well known that higher order harmonics can be filtered out easily when compared to lower order harmonics. The latest strategies adopted in pulse width modulated inverters (phase shifted triangular carrier technique) enable shifting the lower order harmonics to higher order.

When an array of converter modules is controlled by the phase-shifted triangular carrier technique of the sinusoidal pulse width modulation strategy [4-6], besides increasing the mega volt-ampere rating, the array retains the characteristics of the three linear amplifiers.

The survey reveals that the high power converters rated tens of kilo-volt to hundreds of kilo-volt and mega-volt amperes are beyond the capacity of a single solid-state switch of maximum possible kilo-volt and kilo-amperes ratings. The high voltage, large rating PWM inverters, employing power switching devices in series and / or parallel configuration, suffers from the limitations such as an unequal voltage and current sharing, existence of high common mode voltages [7], corona discharge, voltage surges / dielectric stresses and resulting in motor winding insulation breakdown as well as motor bearing failure, mainly due to the excessive dv/dt. As the voltages and currents of the switches must be shared equally, in steady state and in transient condition, the technology for their equalization must be perfect. These limitations have been overcome to a great extent through a basic concept of using the devices ingeniously in such a way that ultimately lower dv/dt exists in the converter.

II. MULTI (2) INNVERTER CONFIGURATION

Larger industrial applications require the drive fed from high-power inverters. In these inverters many solid state switches will have to be connected in series and /or parallel. One method id connecting these switches connected in series for large voltage rating and in parallel for larger current rating then forming one module of three phase inverter and other method is organizing these solid state switches first in the form of three-phase bridge inverter module and then connecting the inverters modules in parallel. Both the techniques increases the megavolt amperes rating of the system but the harmonic spectrum of the load current and voltage waveform are similar to the single sinusoidal pulse width modulated inverter. The multi inverter systems may have phase shifted carriers to improve the output waveforms. The phase shifted carrier based multi inverter has several voltage sources SPWM inverters using common sinusoidal modulating signals and phase-shifted triangular carrier which are operated in tandem with their output coupled through current sharing inductors to meet the objective of increasing the overall rating to megawatt range. In this topology two or more (say N) SPWM inverters are connected in series and /or parallel. This not only increases the megavolt amperes rating of the system but also enables the triangular carrier frequency f_c to be increased effectively to $N.f_c$.

The implementation of phase shifted triangular carrier technique consists of sending identical modulating signal to all parallel connected inverters but the triangular carrier signal to individual inverters are phase shifted from each other. The phase-shifting is based upon dividing the carrier period T_C $(=1/f_c)$ number of inverters, N. Mathematically the n^{th} carrier $Vt_{cm}(t)$ is related to the first carrier $Vt_{c1}(t)$ by:

$$Vt_{cn}(t) = Vt_{c1}\left[t - \frac{(n-1)T_C}{N}\right], \text{ here n=1, 2, 3.......N} \quad (1)$$

By sending phase shifted triangular carrier to each of the N inverter modules, the switching instants of the devices are staggered, as the intersection points of the carriers with the common modulating signal are different for each inverter. The multi-inverter system under phase shifted triangular carrier technique act as active filter to the supply side and reduces the harmonics in the supply current.

The important advantage of this method is that the effective carrier frequency is increased to $N.f_c$ without incurring high switching losses. The output waveforms are replica of the input modulating signals. The summation of ac outputs from N inverters yields a high quality output with the low order harmonics shifted to high order harmonics, in addition the magnitude of these higher order harmonics are also reduced significantly. Thus, the noise components are shifted to the high frequency end where the filtering components are small and cheaper to realize.

When the three phases of each inverter modules are connected to a balanced delta circuit or to a balanced open star circuit, the zero sequence currents, (which include the triplen harmonics) cannot flow. When circuit has this inherent triplen discrimination, it is advantageous to choose the triangular carrier frequency to be an integral multiple of three times the modulating signal frequency. Then the harmonics in current of all the integral multiples of the triplen carrier frequency cannot exist.

The implementation of perfect phase shift in triangular carrier technique in multi inverter for large power rating industrial drives has many advantages:

- Reduction in torque pulsations and better voltage and current harmonics spectrum due to inherent carrier frequency multiplication effect.
- The small rating switches can configured for realization of mega-volt ampere.
- Superior reliability under dynamic loading and overloading due to better current sharing amongst individual modules.
- Full utilization of individual module to increase the overall efficiency of the inverter system remarkably, specially operating at low modulation index.

A very important property of the phase shifted carrier technique is that the amplified modulating signals in all the inverter modules have the same constant gain and there is no phase shift. For low value of carrier ratio, such as (carrier frequency) $f_c = 3f_m$, the two sideband components have the same fundamental frequency f_m (modulation frequency), as the amplified modulating signal. They are sideband frequency $(p \pm 2, 2p \pm 1, 2p \pm 5.....)$, $f_c - 2f_m = f_m$ and $2f_c - 5f_m = f_m$. Where 'p' is number of pulses in a cycle. The phasor addition of the two sideband components to the amplified modulating signal yield fundamental frequency output voltage, which are unbalanced. Consequently the modules cannot be connected directly in parallel for low-value of the carrier ratio, because the resultant unbalanced currents will be unacceptably high.

Large value of the carrier ratio permits the connection of the inverter modules in parallel without serious ac current unbalance from the individual modules. The ripple currents in the composite station have been annulled by harmonic self cancellation. The equivalent carrier to modulation frequency ratio $N.f_c$ is reflected in the high quality waveform of the total current. When $f_c = 9$ and higher the sideband harmonics do not interface with the modulating signals, all the fundamental components are equal in magnitude and in phase, so that the inverter nodules can be connected directly in parallel. The currents through individual modules will still contain the harmonics associated will the triangular carrier frequency, which must be reduced by filter inductance. When two or more inverter modules are connected in parallel then the rating of inverters which are connected in parallel must be same and it is necessary to ensure that the voltage stresses and the current loading are evenly shared by the individual modules. The lower order harmonics are cancelled for the composite station but the harmonic currents still flow in the individual inverter modules.

In present multi inverter is considered to have two inverters connected in parallel. The paralleling of inverter is done through an inductor which is called the coupling inductor or current sharing inductor (L_c).Phase shifted triangular technique has been used for the control of multi inverter system. For N=2 i.e. two inverter connected in parallel, the triangular carrier wave to second inverter is

$$Vt_{c2}(t) = Vt_{c1}\left[t - \frac{T_C}{2}\right] \quad (2)$$

Due to phase shifted nature of the triangular wave applied to the inverter the same phase of all the inverter modules does not switch in unison. Instead the phase shifted triangular carrier waves introduce a slight staggering of switch in individual inverters and creates overall effect of high frequency switching without incurring high switching losses which would have taken place in a single equivalent inverter switched frequency f_c.

The simplified block diagram of multi-inverter system in which two inverters are connected in parallel and feed the induction machine load is shown in fig.1. The paralleling of inverters is done through coup-ling inductors. The control circuit of two inverters is similar to that of the single SPWM inverter. Here only difference is that the triangular carrier wave for the second inverter is $T_C/2$ period phase shifted with respect to triangular wave of the first inverter. Accordingly when two inverters are connected in parallel then there must be a phase shift of 180 degrees in triangular carrier wave of second inverter. For the sake of comparison three cases are considered (i) when there is no phase shift in the triangle carrier of both the inverters, (ii) when there is an introduction of phase shift of $T_C/2$ period in triangular carrier wave of the second inverter, (iii) when there is an introduction of phase shift of $T_C/4$ period in triangular carrier wave of the second inverter. For two inverters connected in parallel with an introduction of phase shift of $T_C/2$ period in triangular carrier wave of the second inverter the triangular wave amplitudes are depicted in table1. For two inverters connected in parallel with an introduction of phase shift of $T_C/4$ period in triangular carrier wave of the second inverter the triangular wave amplitudes are depicted in table2. Here T_C is the time period of one cycle of carrier wave and maximum amplitude of carrier wave is 1.

Table (1): Look-up table for triangular carrier wave when two inverters are connected in parallel with $T_C/2$ period (180^0) phase shift

Time instant	Inverter 1	Inverter 2
0	0	-1
Tc/4	1	0
Tc/2	0	1
3Tc/4	-1	0
Tc	0	-1

Table (2): Look-up table for triangular carrier wave when two inverters are connected in parallel with $T_C/4$ period (90^0) phase shift

Time instant	Inverter 1	Inverter 2
0	0	0
Tc/4	1	-1
Tc/2	0	0
3Tc/4	-1	1
Tc	0	0

The calculation of total losses incurred in a PWM inverter employing IGBTs using a relatively simple method [9] from manufacturer's catalogue parameter can be done very accurately, employing the following equations

Turn on losses $$P_{on} = \frac{1}{8} V_{CC} t_{rN} \frac{I_{CM}^2}{I_{CN}} \quad (3)$$

Turn off losses $$P_{off} = V_{cc} I_{CM} t_{fN} F_s \left(\frac{1}{3\pi} + \frac{I_{CM}}{24 I_{CN}} \right) \quad (4)$$

Recovery losses are given by

$$P_{rr} = V_{cc} F_s \left[\begin{array}{l} \left(0.28 + \frac{0.38 I_{CM}}{\prod I_{CN}} + 0.015 \left(\frac{I_{CM}}{I_{CN}} \right)^2 \right) Q_{rrN} \\ + \left(\frac{0.8}{\pi} + 0.05 \frac{I_{CM}}{I_{CN}} \right) I_{CM} t_{rrN} \end{array} \right] \quad (5)$$

where V_{cc} is applied voltage to semiconductor device, Fs is switching frequency, t_{rn} is rated rise time at rated current, I_{CM} is maximum current through device, I_{CN} is rated current of device, t_{fN} is rated fall time, Q_{rrN} is rated recovery charge and t_{rrN} is rated recovery time.

III. RESULTS

The table (3) shows the switching losses incurred in the multi-inverters in all the cases i.e. when there is no phase shift in the triangular carrier wave of second inverter, when there is a phase shift of $T_C/4$ period (90^0) in the triangular carrier wave of second inverter and when there is a phase shift of $T_C/2$ period (180^0) in the triangular carrier wave of second inverter. In case when multi inverters are fed with a phase shift of $T_C/2$ period (180^0) in the triangular carrier wave of second inverter there is carrier multiplication effect. In case when multi inverters are fed with a phase shift of $T_C/2$ period (180^0) in the triangular carrier wave of second inverter then each inverter is fed with a carrier frequency of half of the carrier frequency as mentioned in the table yet the effective carrier frequency will be as mentioned in the table itself due to the fact of carrier multiplication effect which is not possible in this case.

Table 3: Total switching losses incurred per devices in Single inverter and Multi-inverter (two inverters without and with $T_C/2$ period (180^0) and $T_C/4$ period (90^0) phase shifted triangular carrier)

Effective Carrier frequency (KHz)	Losses (W) in Multi- Inverters without phase shift in triangular carrier of second inverter	Losses (W) in Multi- Inverters (2) and with a phase shift of $T_C/4$ period (90^0) in triangular carrier of second inverter	Losses (W) in Multi- Inverters (2) with phase shift of $T_C/2$ period (180^0) in triangular carrier of second inverter
1	0.330092	0.330092	0.165046
2	0.660182	0.660182	0.0.330091
3	0.990274	0.990274	0.495137
4	1.32	1.32	0.660182
5	1.65	1.65	0.825227
6	1.981	1.981	0.99072
7	2.311	2.311	1.155
8	2.641	2.641	1.32
9	2.971	2.971	1.485
10	3.3	3.3	1.65

The multi-inverter system was simulated for single, two similar inverters with $T_C/4$ and $T_C/2$ phase shift in triangular carrier in parallel. In each case, the performance variables of induction motor such as current harmonics, voltage harmonics and speed harmonics of the machine were analyzed using pc 386. The switching devices used in the inverters were IGBTs.

Fig. (1, 4,7) depicts respectively the current, voltage and speed harmonics spectrum of the induction motor supplied by single inverter at rated speed. Fig. (2, 5, 8) and Fig. (3, 6, 9) shows the current, voltage and speed harmonics spectrum of the induction motor supplied by multi inverter at rated speed with phase shift of $T_C/4$ and $T_C/2$ respectively.

The comparison of voltage harmonic spectrum as depicted Fig. (1, 2, 3) it is clear that THD with single, multi inverter with phase shift of $T_C/4$ and $T_C/2$ are 5.48%, 3.69 %, and 1.51%. The comparison of current harmonic spectrum as depicted Fig. (4, 5, 6) it is clear that THD with single, multi inverter with phase shift of $T_C/4$ and $T_C/2$ are 44.12%, 29.42 %, and 25.58%.The speed harmonic spectrum as depicted Fig. (7, 8, 9) it is clear that THD with single, multi inverter with phase shift of $T_C/4$ and $T_C/2$ are 0.09%, 0.02 %, and 00.01%. The harmonic spectrum of voltage, current and speed improves with multi inverter may be with a phase shift in triangular of $T_C/4$ and $T_C/2$. Furthermore it also is evident from the result that the harmonic spectrum is best for voltage, current and speed in case of multi inverter fed by triangular phase shift of $T_C/2$ period when compare to other discussed method of supply.

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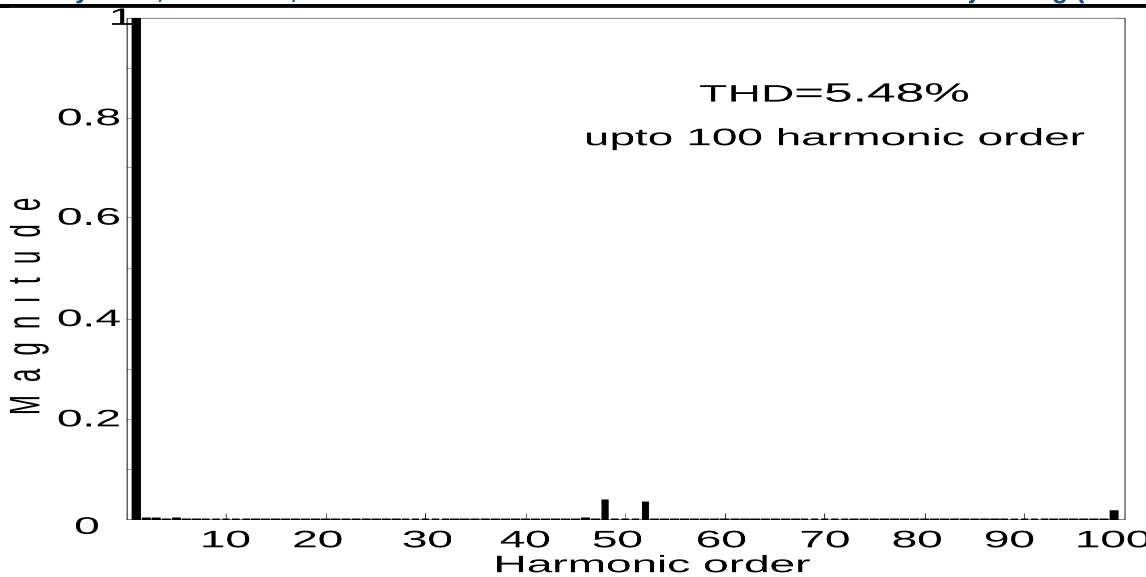

Fig (1) Current harmonic spectrum at rated speed of Induction motor fed Multi inverter without any phase shift in triangular carrier wave

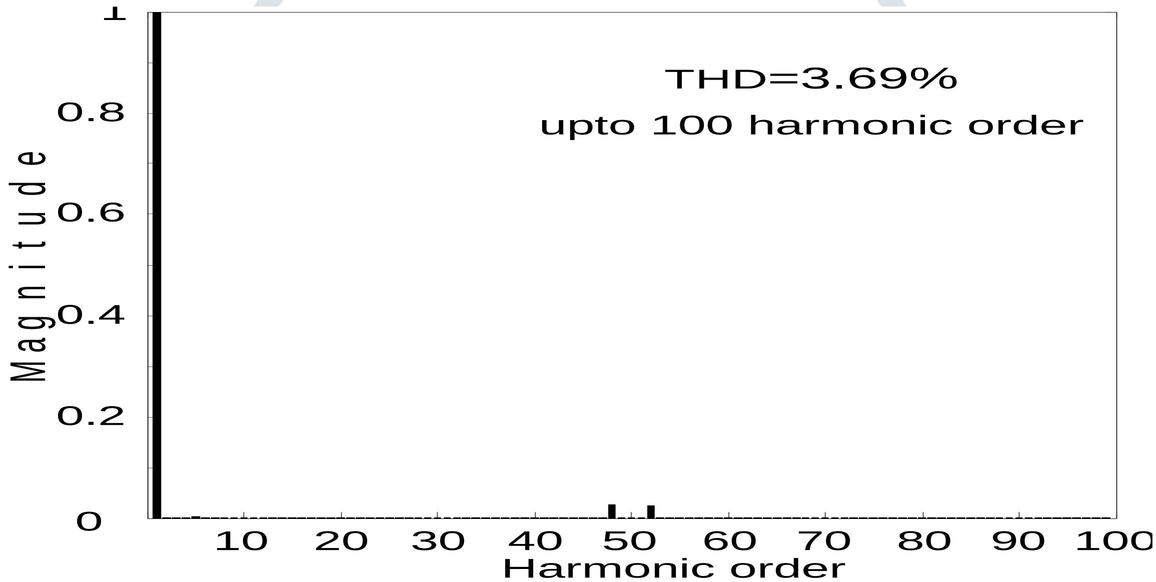

Fig (2) Current harmonic spectrum at rated speed of Induction motor fed Multi inverter phase shift of Tc/4 period in triangular carrier wave

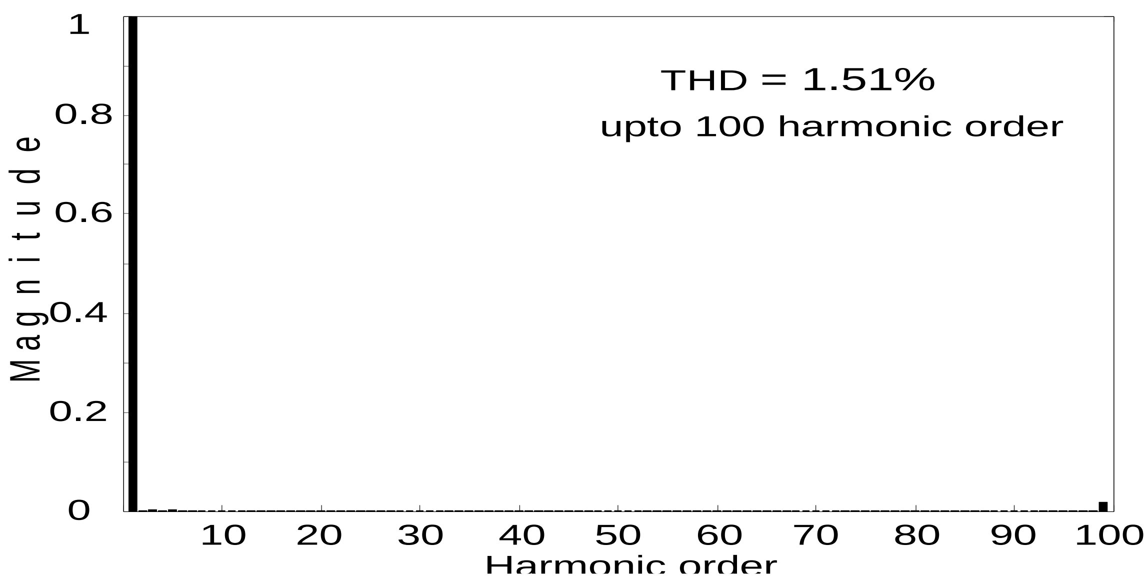

Fig (3) Current harmonic spectrum at rated speed of Induction motor fed Multi inverter phase shift of Tc/2 period in triangular carrier wave

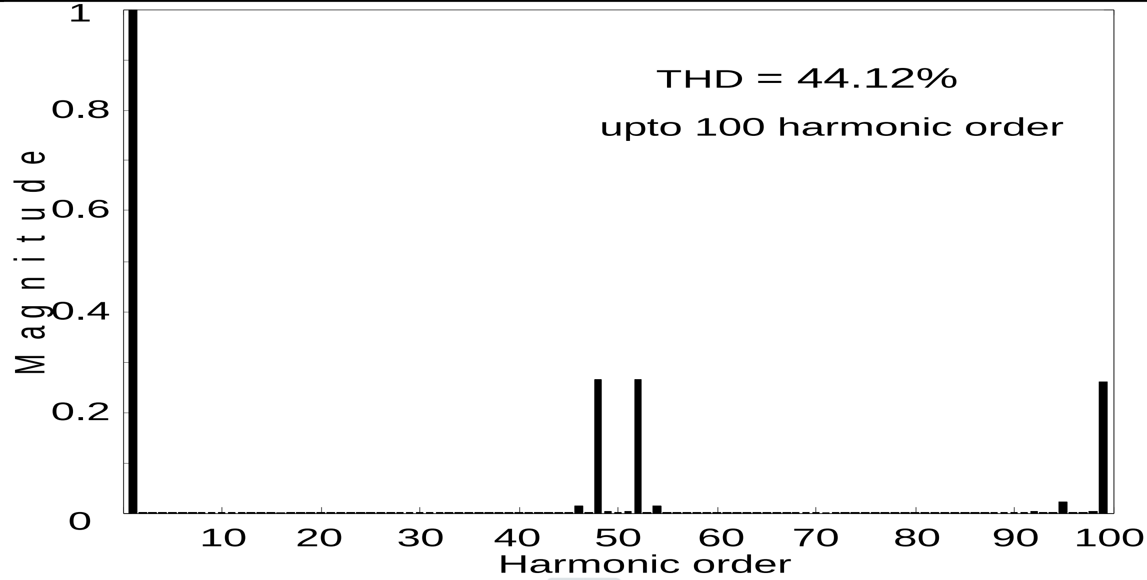

Fig (4) Voltage harmonic spectrum at rated speed of Induction motor fed Multi inverter without any phase shift in triangular carrier wave

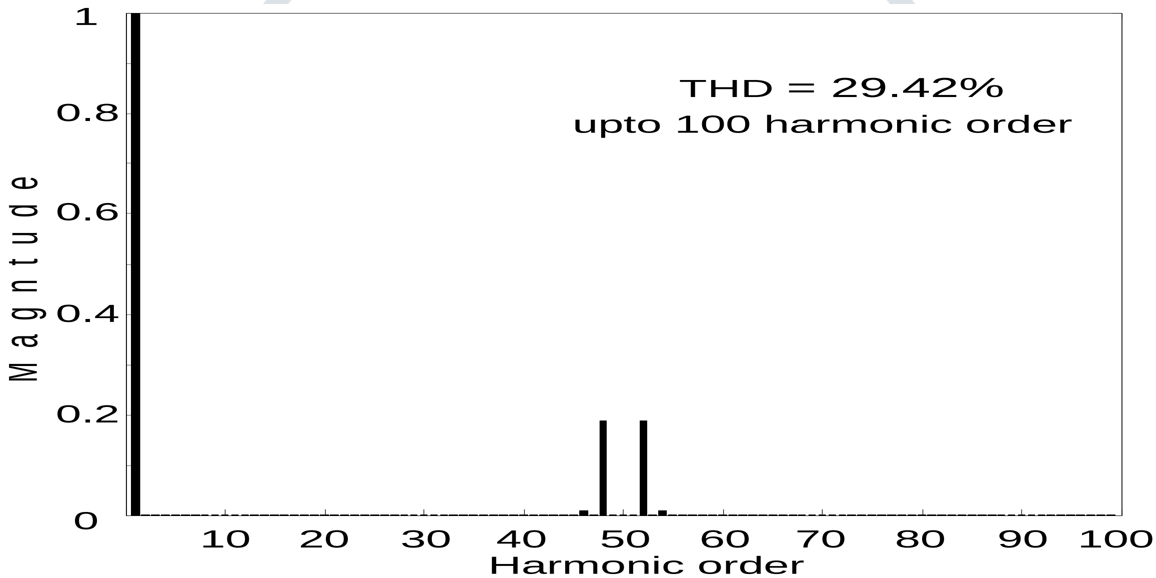

Fig (5) Voltage harmonic spectrum at rated speed of Induction motor fed Multi inverter phase shift of Tc/4 period in triangular carrier wave

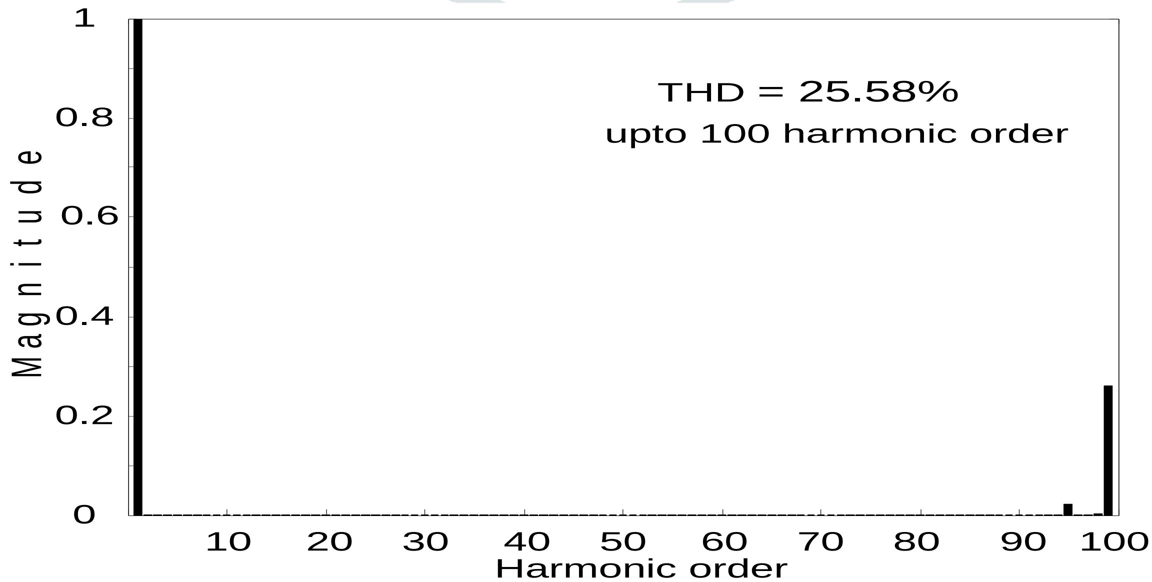

Fig (6) Voltage harmonic spectrum at rated speed of Induction motor fed Multi inverter phase shift of Tc/2 period in triangular carrier wave

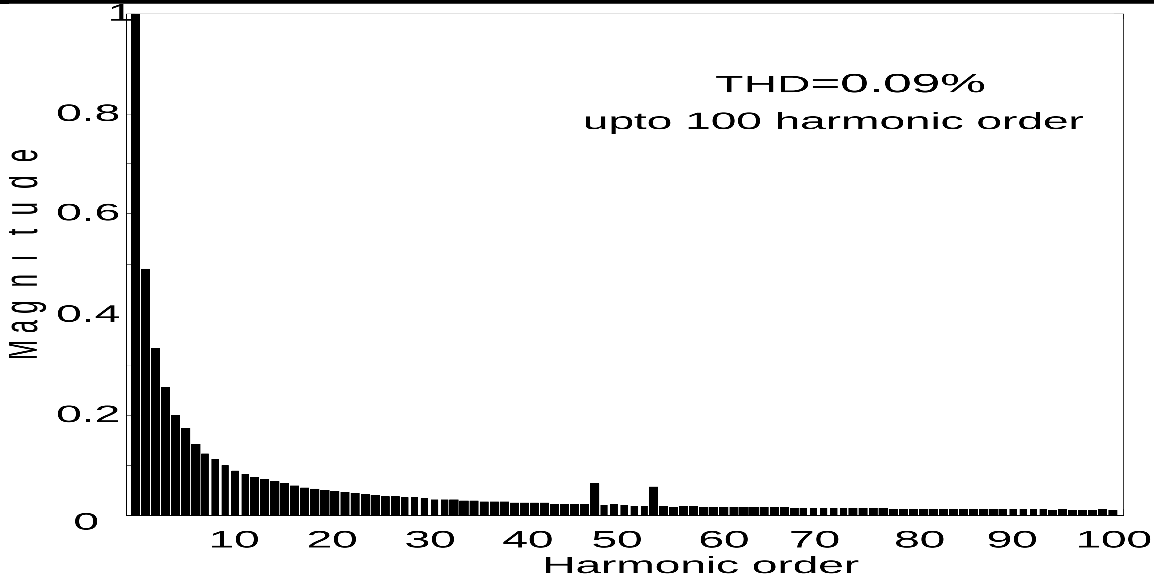

Fig (7) Speed harmonic spectrum at rated speed of Induction motor fed Multi inverter without any phase shift in triangular carrier wave

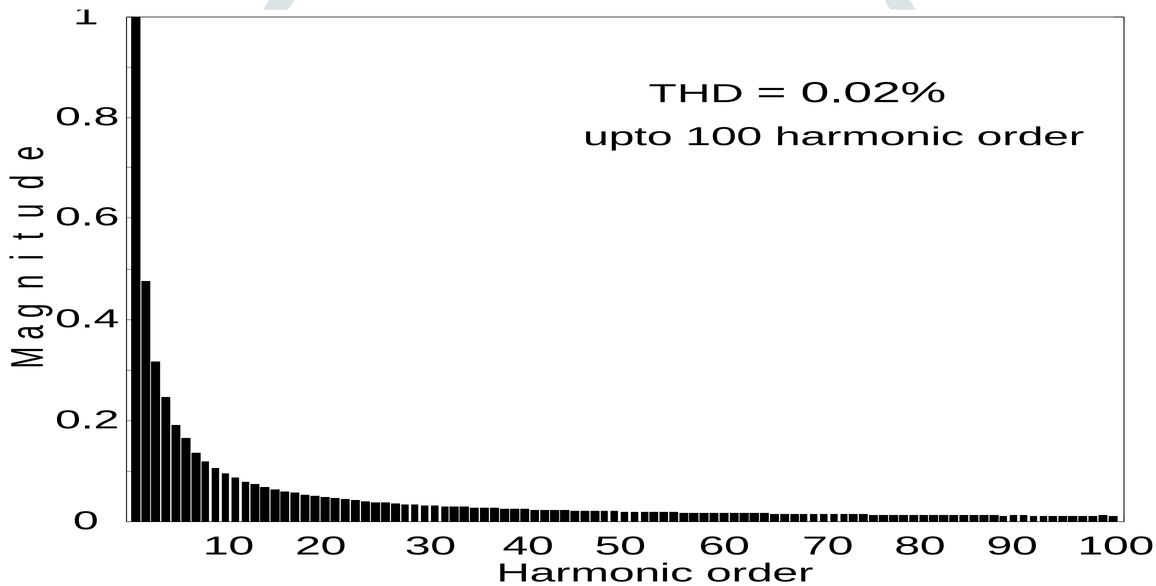

Fig (8) Speed harmonic spectrum at rated speed of Induction motor fed Multi inverter phase shift of Tc/4 period in triangular carrier wave

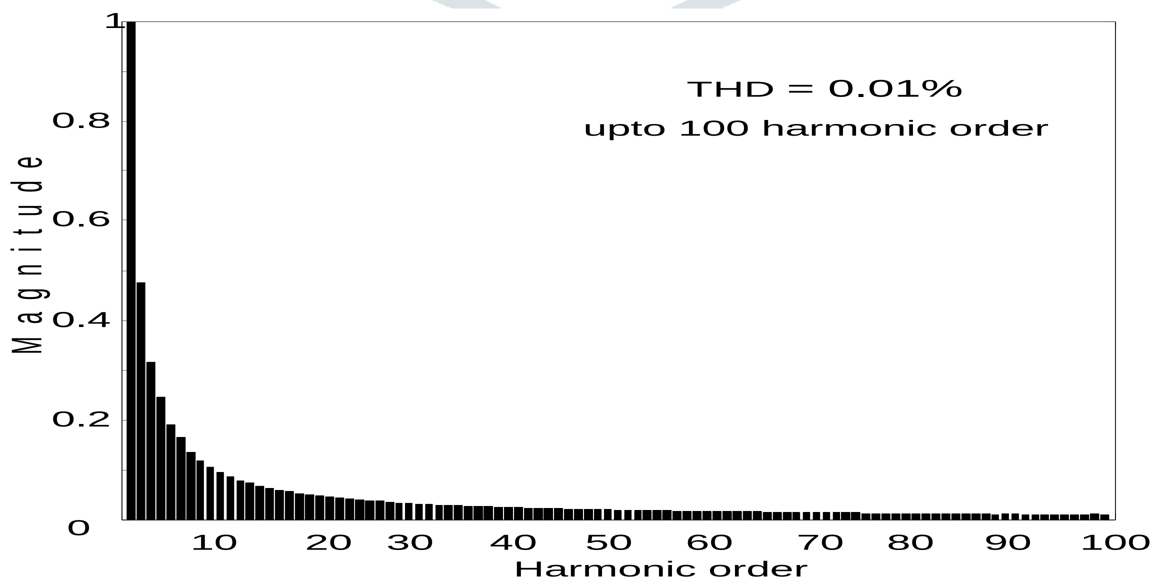

Fig (9) Speed harmonic spectrum at rated speed of Induction motor fed Multi inverter phase shift of Tc/2 period in triangular carrier wave

IV. CONCLUSION

The performance of induction motor is found to be better when it is supplied by multi-inverter with phase shifted triangular carrier technique rather than a single inverter. There has been improvement in harmonic spectrum of currents, voltage and speed which would result in steady torque, when multi-inverter with phase shifted triangular carrier technique is used to supply the induction motor. The phase shift of Tc/2 rather than phase shift of Tc/4 in phase shift of triangular carrier yields better harmonic profile of voltage, current, speed and thereby of torque. The losses in single inverter when compared to multi inverters are quiet less also the multi inverter losses with phase shift of Tc/2 are lesser than phase shift of Tc/4 in phase shift if triangular carrier in case of two inverters. The number of inverters studied are two in present case but the increase of number of inverters will further improve the voltage, current and torque harmonic spectrum and also reduce the switching losses in inverter because the multiplication effect in triangular carrier frequency will increase the effective carrier frequency and hence reduction in the switching losses in inverter.

The lower order harmonics are shifted to higher order harmonics in addition to reduction of magnitude of higher order harmonics significantly. The higher order harmonics are easier to filter out when compared with lower order harmonics.

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