A Comparison of Single and Multi Inverter connected in Current Sharing Mode for High Power Induction Motor Drive

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Abstract: Many industrial applications require large rating induction motors to be controlled with ripple free torque for a wide speed rang in both directions. The harmonics in the output of these converters affects the speed and torque and also reduces the life of induction motor. The switching frequency has to be large to obtain acceptable quality output from single converter increasing the switching frequency losses. Larger rating single PWM converter is used extensively for high power applications and the concept of multi inverter has been introduced to reduce the rating of individual device / converter by connecting many devices / converters is series and / or parallel.

Smaller rated converters may be connected in parallel through current sharing inductors to meet the objective of ripple free torque for a range of speed and reduction in harmonic content. This paper aims to compare the performance of vector controlled induction motor drive fed by single converter and multi inverter with phase shift in triangular carrier. The switching frequency losses incurred in inverters are also compared for single and multi inverter system with implementation. The switching losses and the simulation results predict better performance of proposed multi inverter.

Key words: Current sharing inductor, multi inverter, phase shifted triangular carrier, switching frequency losses

I. INTRODUCTION

Many industrial applications require the drive fed from high-power converters. Large number of solid state switches will have to be connected in series and /or parallel to achieve megavolt-ampere rating. One method is organizing these solid state switches first in the form of three-phase bridge converters and then connecting the converters in series / parallel. This increases the megavolt-amperes rating of the system but the harmonic spectrum of the load current, voltage waveform are similar to the single sinusoidal pulse width modulation inverter.

Since the solid switches are bracketed across the each module, the solid state devices of the same phase of inverter module do not have to switch in unison; this freedom allows the phase shifted triangular carrier technique of the PWM strategy to be implemented in the control of the multi inverter modules. The important advantage of this method is that for 'N' inverter modules the effective carrier frequency is increased to ' Nf_c ' without incurring high switching losses (f_c is the switching frequency). The output waveforms are replica of the input modulating signals. All the excellent properties of the PWM strategy are found in the array of 'N' multi-inverter modules, when they operate under phase shifted triangular carrier technique. When ' Nf_c ' is sufficiently high the switching noise of the carrier frequency and the lower side band frequencies do not spread over the spectrum of the modulation signals and the ac outputs of the array are replica of the input modulating signals, which are amplified with a high constant gain without any phase shift. 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. It is observed that in case of multi- inverter operation, when even numbers of inverters (n=2, 4, 6---N) are tied up they results in output wave consisting of odd number of levels in every cycle of voltage wave, which appears more close to sinusoidal wave shape. In contrast to this when odd numbers of inverters (n=3, 5, 7, ---N) would produce even number of levels in each cycle of converter output voltage wave. This wave shape appears more close towards quasi-square wave, which contains more harmonics in comparison to earlier case even with implementation of phase shifted triangular carrier technique. Because of rich harmonic content in the inverter output there are more chances of induction motor failure due to excessive heating during operation in addition to reduced efficiency of overall system. Hence, the adoption of multi- inverter containing even number is advantageous in comparison to the multi- inverters which contain odd number of inverters. The noise components are shifted to the high frequency end where the filtering components are small and cheaper to realize.

The advantages of using multi inverters with implementation of phase shifted triangular carrier technique for large induction motor drives include the improvement in harmonic currents and lower torque pulsations due to carrier frequency multiplication effects in the multi-inverter, feasibility of practical realization of mega-volt ampere rating with the available power switching devices, switching power loss minimization by selecting suitable switching frequency modulating signals, superior reliability under dynamic loading and overloading due to better current and voltage sharing amongst inverter modules and full utilization of individual inverter module to increase the overall efficiency of the inverter system remarkably while operating at low modulation index.

In present work phase shifted triangular carrier technique has been implemented in multi-inverter system. The concept of phase shifted triangular carrier can be explained as consider that '*N'* modules of converters are connected in parallel, each module receives the same modulating signal $V_m(t)$. The implementation of phase shifted triangular carrier technique consists of sending identical modulating signals 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 ($Tc = 1/f_c$) by number of inverters, *N*. Mathematically the n[th] carrier $V_{tcm}(t)$ is related to the first carrier $V_{tc1}(t)$ is given by

$$V_{tcN}(t) = V_{tc1}\left[t - \frac{(n-1)T_c}{N}\right] \quad \text{Where n=1, 2, 3----------N} \tag{1}$$

Here multi- inverters are connected in parallel to achieve increased current range and to reduce output harmonics. Previously it has been identified how careful modulation of each single-phase converter can lead to significant reduction in harmonics in the switched output voltage [1]. This harmonic reduction can now be mathematically evaluated and optimized using the analytic solutions developed. Let us consider ω_c and ω_m are angular frequencies of the triangular carrier and the modulating sinusoidal wave respectively. For PWM switched waveforms, the most effective approach is the double integral Fourier form.

ip[th] Harmonic voltage component of SPWM is given by

$$V_{ip}(t) = B_{ip}\sin(j\omega_c t + p\omega_m t + \theta_{ip}) \tag{2}$$

Equation (2) is in polar form, where B_{ip} the magnitude is represented as Bessel function and θ_{ip} is the phase angle.

When carrier is phase shifted by an angle ϕ , the Fourier series component becomes

$$V_{ip}(t) = B_{ip}\sin[j(\omega_c t + \phi) + p\omega_m t + \theta_{ip}] \tag{3}$$

When there are N identical converters whose triangular carriers are each phase shifted by

$$\phi = \frac{2\pi n}{N} \tag{4}$$

then the composite Fourier series component is

$$C_{ip} = B_{ip}\sum_{n=1}^{N}\sin[j\omega_c t + p\omega_m t + \theta_{ip} + j\frac{2\pi n}{N}] \tag{5}$$

From the trigonometric identity,

$$\sum_{n=1}^{N}[\sin\delta + i\frac{2\pi n}{N}] = 0 \tag{6}$$

For $i \neq NK$, where k=1, 2, 3---

$= N\sin\delta$

For $i = Nk$, where k=0, 1, 2, 3, ---

It can be concluded that all Fourier series harmonics are eliminated except those associated with $i = Nk$, and p in

$$C_{Nkp} = NB_{Nkp}\sin[N\omega_c t + p\omega_m t + \theta_{Nkp}] \tag{7}$$

For k=1, 2, 3,

For $p = \pm 1, \pm 2, \pm 3 ---$

It is important to recognize that, carrier sideband harmonic cancellation is a consequence of the internal phase-leg modulation strategy and the various phase shifts of the fundamental and carrier waveforms that are used. The carrier /fundamental ratio has no influence, and need not even be integer.

It is clear that due to phase shifted nature of the triangular wave applied to the inverter the same phase of all converter modules do not switch in unison. Instead the phase shifted triangular carrier wave introduce a slight staggering of switching in individual inverter and creates overall effect of high frequency switching without incurring high switching losses which would have taken place in a single inverter switched at frequency f_c . Also, the multi- inverter system utilizing phase shifted triangular carrier technique act as active power filter to the supply side and reduces the harmonics in the supply current. 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 $2f_c - 5f_m = f_m$. Here p is the 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 with the triangular carrier frequency, which must be reduced by filter inductance. When two 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. It is important to recognize that, carrier sideband harmonic cancellation is a consequence of the internal phase-leg modulation strategy and the various phase shifts of the fundamental and carrier waveforms that are used. The carrier /fundamental ratio has no influence, and need not even be integer.

It should be particularly noted that effective harmonic sideband cancellation relies on all inverters having exactly the same dc-bus voltage (i.e., well within a few percent of each other). Also, it is essential that the reference waveform for each inverter is sampled at the peak and trough of that inverter's effective triangular carrier (i.e., reference samples must be phase shifted by the carrier phase shift). Otherwise, harmonics across the multiple inverters do not have the correct magnitude or phase relationship to achieve proper cancellation.

II. SYSEM CONFIGURATION

The two identical inverter systems are having six IGBT switches in each inverter modules. The IGBT switches parameters utilized in each inverter module are of rating 600Volts and 20 Ampere. Although, due better current sharing among the each inverter module IGBT's of half of the rating would have been sufficient but
double the rating of IGBT's required is chosen to compensate for dynamic over loading effect. 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.

The simplified block diagram of multi- inverter system with or without phase shifted triangular carrier will be same except the triangular carrier block for supplying vector controlled induction motor drive is shown in fig.(1). The paralleling of inverters is done through smoothening inductors. For the sake of comparison two cases are considered; induction motor is fed by a single inverter and multi inverter with phase shift in triangular carrier of the second inverter. When two inverters with phase shifted triangular carrier technique are coupled then the triangular wave amplitudes are depicted in table (1).

Table 1:Look-up table for triangular carrier wave when two inverters are connected in parallel

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

The multi- inverter system is simulated for two inverters connected in parallel with implementation of phase shifted triangular carrier technique. The paralleling of inverters is done through coupling inductors. The existence of coupling inductor is to ensure the equal current sharing and they also serve the purpose of filter in addition to limiting the current in the event of fault. The value of coupling inductor L_C is determined as a function of filter inductor [2]. Its size depends on the maximum allowable slope of the load current, which is a function of the maximum line-to-line voltage

$$\max\left|\frac{di_L}{dt}\right| = \frac{V_{LL(max)}}{2L_C} \quad (8)$$

Where, $V_{LL(max)}$ is the peak to peak line to line source voltage, and L_C is the coupling inductor and i_L is the load current (induction motor line current).To generate a current with a slope equal to the maximum slope of the load current, the upper limit on filter inductor is given by

$$Lf \le \frac{\frac{2}{3}V_{dc} - V_{jn(max)}}{\max\left|\frac{di_{Lj}}{dt}\right|} \quad (9)$$

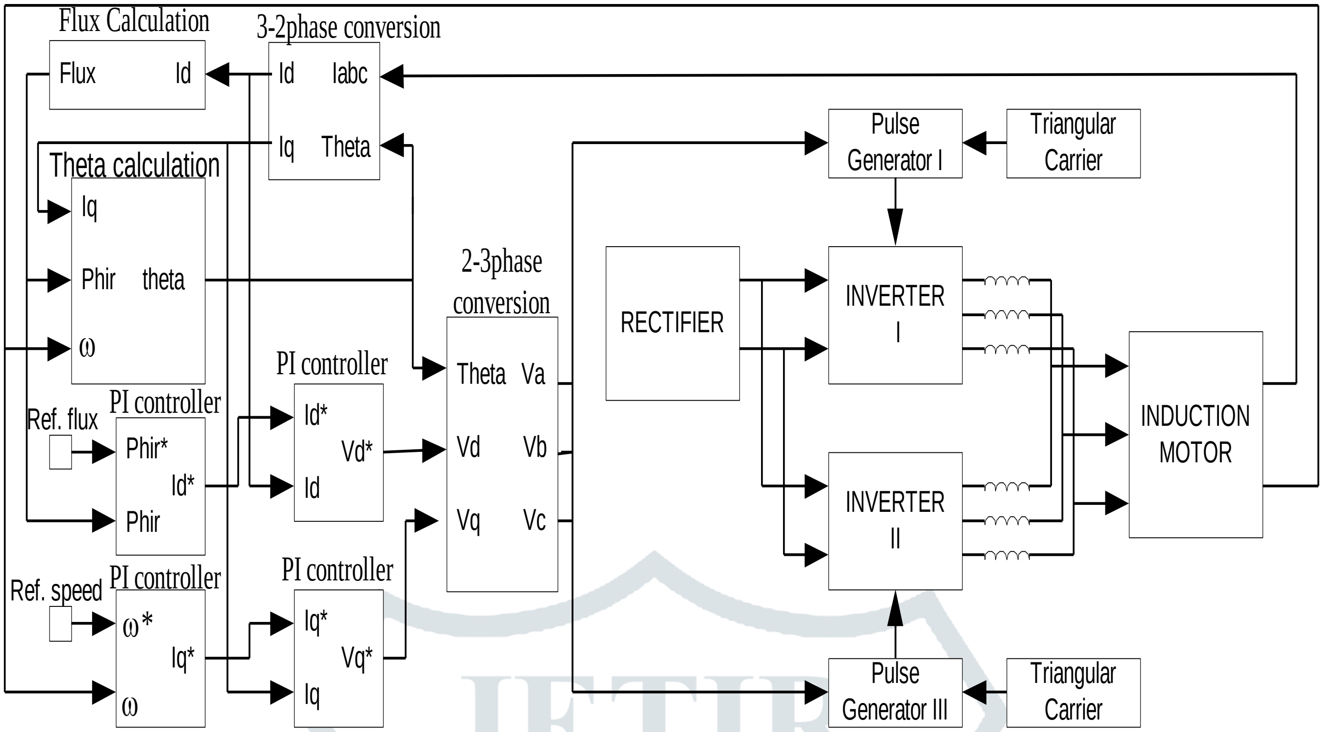

Fig. (1): Vector controlled Induction motor drive fed by multi-inverter system

Where, $V_{jn(max)}$ and i_{Lj} are the peak line to neutral source voltage and the load current of phase 'j' respectively. The lower limit on filter inductor size is described by the acceptable value of the switching frequency ripple current.

The value of coupling inductor is determined as a function of the filter inductor L_f, by substituting the maximum rate of change of load current from equ. (8) & (9).

$$L_C \geq \left[\frac{3m}{4-2(\sqrt{3})m}\right] L_f \qquad (10)$$

Where, $m = \frac{V_{LL(max)}}{V_{dc}}$

From above design method value of L_C comes out to be 2.012mh. For convenience sake $L_C = 2mh$ is selected.

The single and multi- inverter system was simulated for two similar inverters connected in parallel. In each case, the performance variables of induction motor such as current harmonics and torque harmonics of the machine were analyzed using MATLAB SIMULINK.

III. RESULTS

The switching losses amounting significant part in high power applications are calculated for the case of induction motor fed by single inverter and multi inverter with and without phase shift in triangular carrier. The calculation of total losses incurred in inverter employing IGBTs is done utilizing the data sheets of individual IGBT switch [3]. The sum of turn on losses, turn off losses and recovery losses constitutes the losses that would be incurred by one IGBT switch. There are six IGBT switches in one inverter module hence the total losses incurred in one inverter module will be six times the losses incurred by one IGBT switch. The losses incurred in individual inverter module at different switching frequencies are measured analytically listed in table (2). The carrier frequencies of each module in case of single and multi-inverter without phase shifted triangular carrier wave is same as depicted in the table but in case of multi-inverter with implementation of phase shifted triangular carrier wave switching frequency of each module is kept half of the switching frequencies of single and multi-inverter without phase shifted triangular carrier to take into account that the effective carrier frequency will be twice (because in this case only two inverters are connected) the carrier frequency of individual inverter module. This is shown by multiplication of

Table (2): Total switching losses incurred in single inverter and multi-inverter with and without phase shifted triangular carrier wave

Single inverter			Multi (2)-inverter without phase shifted triangular carrier			Multi (2)-inverter with phase shifted triangular carrier		
Applied Carrier Freq. (KHz)	Effective carrier Freq. (KHz)	Losses (watts)	Applied Carrier Freq. (KHz)	Effective carrier Freq. (KHz)	Losses (watts)	Applied Carrier Freq. (KHz)	Effective carrier Freq. (KHz)	Losses (watts)
1	1	2.136	1	1	2.060	0.5	1	1.030
2	2	4.274	2	2	4.120	1	2	2.060
3	3	6.140	3	3	6.181	1.5	3	3.091
4	4	8.547	4	4	8.242	2	4	4.121
5	5	10.684	5	5	10.302	2.5	5	5.151
6	6	12.820	6	6	12.362	3	6	6.181
7	7	14.957	7	7	14.423	3.5	7	7.211
8	8	17.094	8	8	16.483	4	8	8.242
9	9	19.231	9	9	18.540	4.5	9	9.272
10	10	21.367	10	10	20.064	5	10	10.302

switching frequency of each module in table (2). All the losses are calculated when the motor will run at its rated speed. The difference in calculated and actual losses will definitely be visible due to the fact that manufacturer supplies a common data of all the switches of same rating but this cannot be true due to some inherent difference while fabricating switches.

Most of the industrial applications need adjustable speed drive and hence, the simulation results of induction motor performance viz. current, and torque harmonics at rated and half of rated speeds are depicted. The current harmonics of induction motor running at half of rated speed and at rated speed fed by single and multi inverter are shown in Fig. (2 & 3) and Fig. (4 & 5) respectively. The torque harmonics of induction motor running at half of rated speed and at rated speed fed by single and multi inverter are shown in Fig. (6 & 7) and Fig. (8 & 9) respectively. It is evident from the harmonics spectrum of current and torque that the significant lower order harmonic shifts to double the significant lower order harmonic because of the doubling effect with implementation of phase shifted triangular carrier both at rated speed and half of rated speeds.

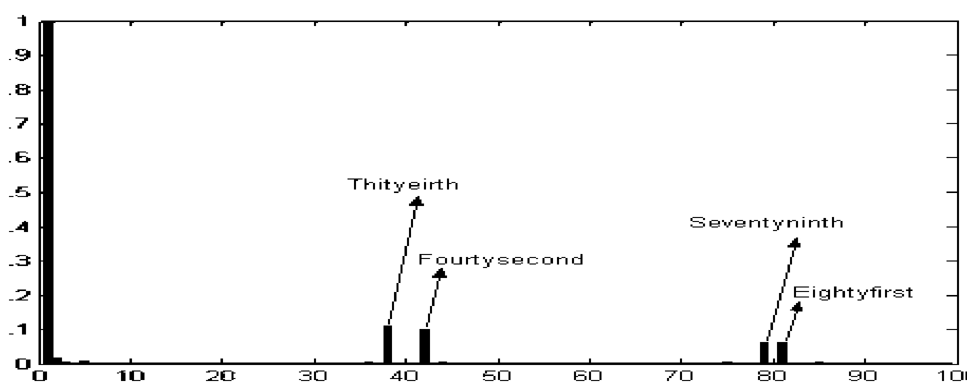

Fig. (2): Current harmonic spectrum of Induction motor running at half of rated speed by single inverter

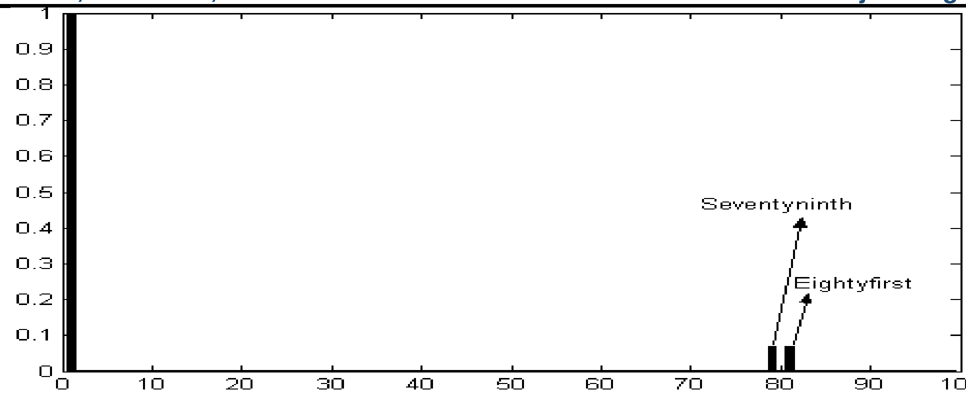

Fig (3): Current harmonic spectrum of Induction motor running at 25 Hz by Multi inverter

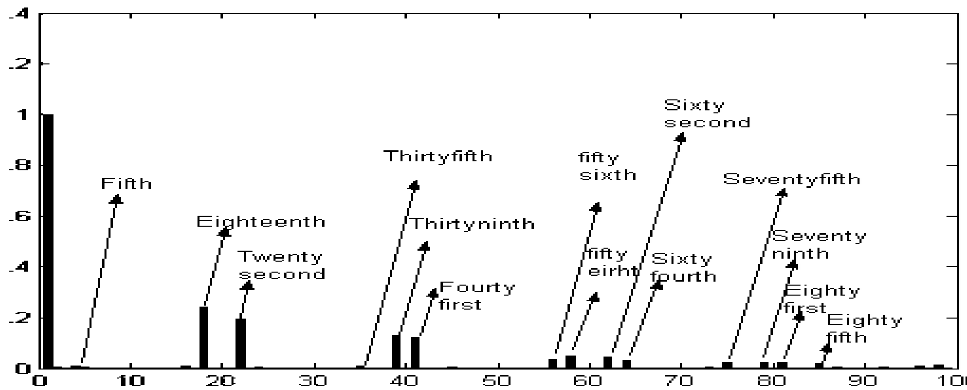

Fig. (4): Current harmonic spectrum of Induction motor running at 50 Hz by single inverter

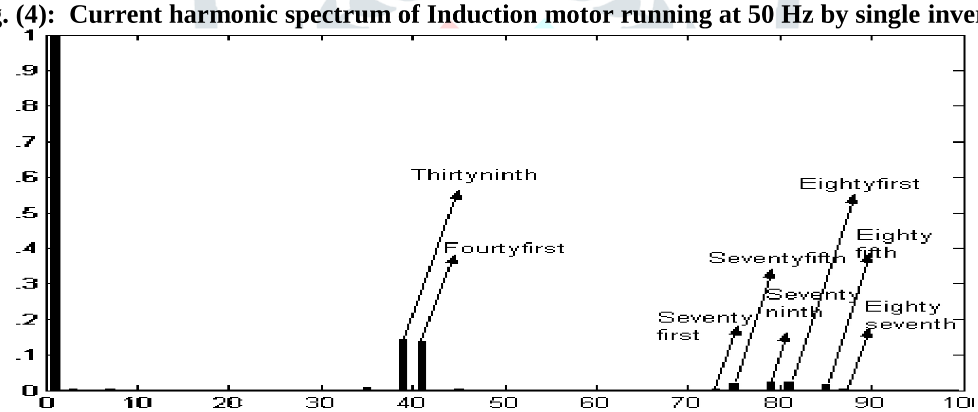

Fig. (5): Current harmonic spectrum of Induction motor running at 50 Hz by Multi inverter

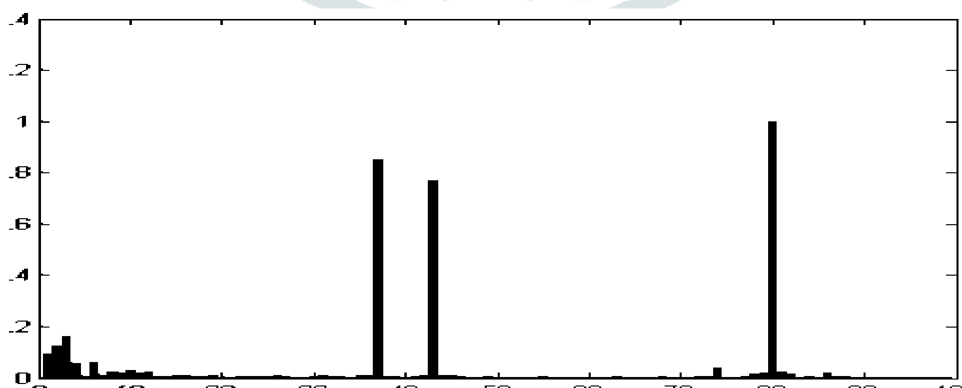

Fig.(6): Torque harmonic spectrum of Induction motor running at 25 Hz by single inverter

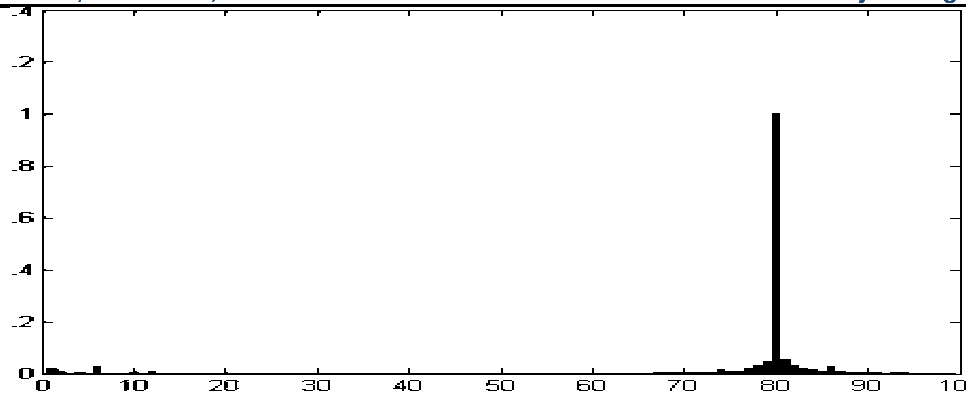

Fig.(7): Torque harmonic spectrum of Induction motor running at 25 Hz by multi inverter

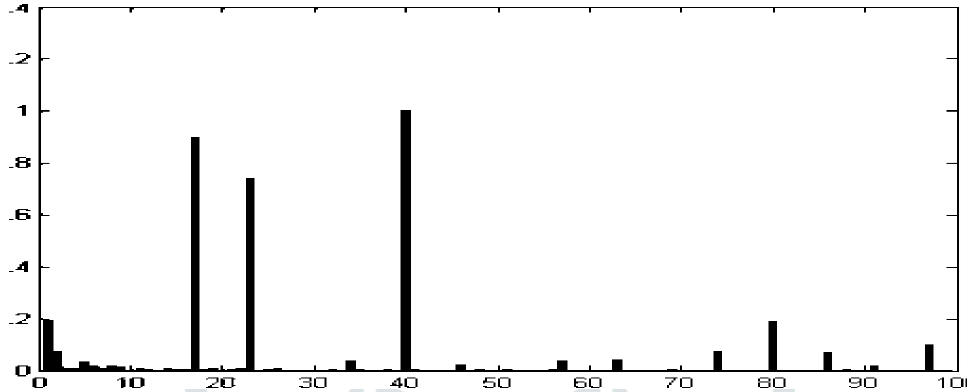

Fig. (8): Torque harmonic spectrum of Induction motor running at 50 Hz by single inverter

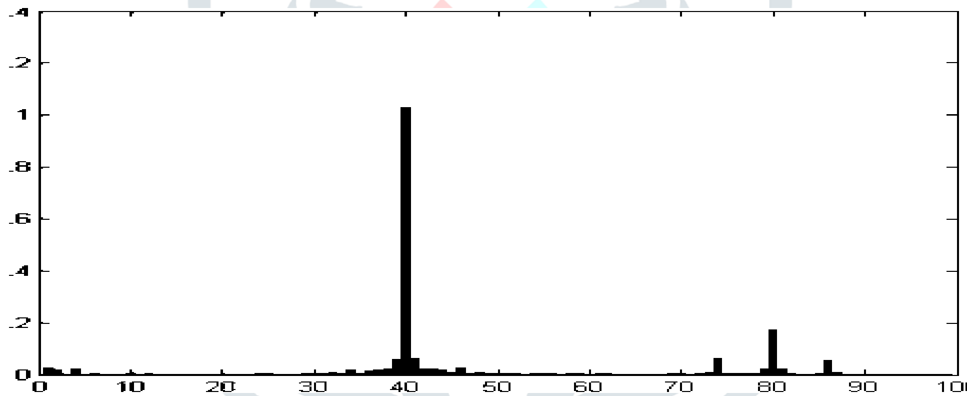

Fig. (9): Torque harmonic spectrum of Induction motor running at 50 Hz by multi inverter

IV CONCLUSION

Total losses in multi-inverter with a phase shift in triangular carrier of second inverter is found to be very less when compared with single inverter and multi-inverter without any phase shift in the triangular carrier. Staggering of switching instants in the individual inverter due to the phase shift in triangle carrier creates an overall high frequency switching effect at the ac side of the paralleled module structure of the multi-inverter system. The devices are operated at reduced switching frequency resulting in better efficiency due to the reduced switching losses. Multi-inverter system possesses high reliability under over loading due to better current sharing [4].

The performance of induction motor is found to be better when it is supplied by multi-inverter with phase shifted triangular carrier technique while comparing its performance when motor is fed by single inverter. There has been improvement in harmonic currents and torque pulsations, when multi-inverter with phase shifted triangular carrier technique is used to supply the induction motor. The harmonic spectrum of line current of induction motor shows that for the carrier ratio of p, effective carrier has increased to NP. In this case two similar inverters are used if more numbers of inverters are paralleled then the harmonic spectrum of current would be still better. The torque pulsations would still be reduced and the waveforms of current, voltage, and torque would be smooth. It can be summarized that the use of multi-inverter with phase shifted triangular carrier technique results in improvement in harmonic of currents, harmonics of voltage and torque pulsations when compared with single inverter system also the lower order harmonics are shifted to higher order harmonics. If four and six inverters are connected in parallel then the triangular carrier wave for individual inverter are phase shifted by $T_C/4$ period and $T_C/6$ period respectively. The significant lower order harmonic will shift in multiplication of number of inverter and higher order harmonics are easier to filter out when compared with lower order harmonics. Increase in number of inverters with phase shifted triangular carrier would further reduce the switching losses because the system will run at lower carrier frequency but with higher effective carrier frequency depending on the number of inverters.

REFRENCES

[1] Liang, Y.; Nwankpa, C. O.; "A New type of Statcom based on Cascading Voltage Source Inverters with phase-shifted Uniploar SPWM", IEEE IAS Annual Meeting, pp.1447-1453, 1998,

[2] Al-Zamil, Adil, M.; Torrey, D. A.; "A Passive Series Active Shunt Filter for High Power Application", IEEE Transactions on Power Electronics, Vol.16, No.1, pp.101-109, Jan. 2001.

[3] Casanellas, F.; "Losses in PWM Inverters using IGBTs", IEE Proceedings Electric Power Applications, pp.235-239, 141, 1994

[4] Singh, D.K.P.; Singh, G.K.; "Multi-Inverter System fed Induction Motor Drive", 2nd International Conference on Emerging Technology, KIIT, Bhubaneswar, 21-24 December, 2004

[5] Zhang, H.; Jouanne, A., V.; Dai, S.; Walace, A., K.; Fellow, and Wang, F.; "Multilevel Inverter Modulation Scheme to Eliminate Common-Mode Voltages", IEEE Transactions on Industry Applications, Vol.36, No.6, pp.1645-1653, Nov./Dec.2000

[6] Leon, M., Tolbert; Fang, Zheng, Peng; Thomas, G., Mabetler; "Multilevel Converters for Large Electric Drives", IEEE Transactions on Industry Applications, Vol.35, No.1, pp.36-44, Jan/Feb 1999

[7] Zhang, Z.C.; Kuang, J.; Wang, X.; Ooi, B.T.; "Force Commutated HVDC and SVC Based on Phase Shifted Multi-Converter Modules", IEEE Transactions on Power Delivery, Vol.8, No.2, pp.712-718, April 1993

[8] Flairty, C., W.; "A 50 Kw Adjustable-Frequency 23 Phase Controlled Rectifier Inverter", IEE Industrial Electronics Symposium, Boston, MA, Sept 20-21, 1961

[9] Tolbert, L., M.; Peng, F., Z.; Habetler, T., G.; "Multilevel PWM Method at low Modulation Indices", IEEE Transactions on Industry Applications, Vol.36, No.4, pp.719-725, July.2000

[10] Mwinyiwiwa, B.; Wolanski, Z.; Ooi, B., T.; "Microprocessor-Implemented SPWM for Multi-Converter with Phase-Shifted Triangle Carriers", IEEE Transactions on Industry Applications, Vol.34, No.3, pp.487-494, May./June.2000

[11] Singh, D.K.P.; Singh, G.K.; "Multi-Inverter System fed Induction Motor Drive", 2nd International Conference on Emerging Technology, KIIT, Bhubaneswar, 21-24 December, 2004.

[12] Singh G. K., Singh D. K. P., et al, "A Simplified Indirect Field-Oriented Control Scheme for Multi-Converter fed Induction Motor", IEEE Transactions on Industrial Electronics vol. 52, No. 6, Dec.2005 pp. 1653-1659