Investigations on Single and Multi-Inverter Fed Induction Motor Drive

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***Abstract* - This paper compares the simulation results of induction motor drive in open loop fed by single PWM inverter, two similar inverters connected in current sharing mode and four similar inverters connected in current sharing mode. Performances of all three systems are compared viz. current harmonics, torque harmonics waveforms and total losses in inverters. It is observed that the multi-inverter system results in better performance of induction motor drives and also has lower losses.**

***Index Terms* - PWM inverter, multi-inverter, and induction motor drive, phase shifted carrier.**

I.INTRODUCTION

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 [1]. The harmonic components of the voltages are undesirable (though unavoidable) and are products of inverter switching and produce harmonic losses in the ac load.

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 whereby 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. 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 [5], 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.

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II. MULTI- INVERTER

In the past, multilevel operation was achieved by summing the output of several inverters operating in parallel through phase shifting transformers [2].

Transformer-less multilevel inverters are uniquely suited for large electric drives [3] because of the high volt-ampere ratings possible with these inverters. Multilevel inverters also solve problems with some present two-level PWM adjustable speed drives (ASD). Motor damage and failure have been reported by industry as a result of some ASD inverter's high voltage change rates (dv/dt), which produces a common mode voltage across the motor winding. High frequency switching can exacerbate the problem because of the numerous times this common mode voltage is impressed upon the motor each cycle. The main problems reported have been "motor bearing failure and motor winding insulation breakdown", because of circulating currents, dielectric stresses, voltage surge and corona discharges.

As the number of levels increases, the synthesized output waveform has more steps, which produces a staircase wave that approaches a desired waveform. Also, as more steps are added to waveform, the harmonic distortion of the output wave decreases, approaching zero as the number of levels increases.

The main advantages of using multilevel converters for large induction motor drives include the following

- They are suitable for large volt-ampere rated and / or high voltage motor drives.
- Power factor is close to unity for multilevel inverters used as a rectifier to convert generated ac to dc.
- No EMI problems or common mode voltage/current problems exists.
- No charge unbalance problem results when the converters are in either charge mode (rectification) or drive mode (inversion)

In addition to above, small voltages steps lead to production of high-quality waveforms and also reduce dv/dt stress on the load. Another important feature of multilevel inverter is that semiconductors are wired in series type connection, which allows operation at higher voltages. However, series connection is typically made with clamping diodes, which eliminates the over voltage concern.

Further, the switches are not series connected, hence there switching can be staggered, which reduces the switching frequency and switching losses. The lower rating switches can be used in multilevel inverter and therefore active semiconductor cost is not appreciably increased, when compared with the two-level cases.

In multi converter topology, several voltage source PWM inverters using common sinusoidal modulating signal and phase shifted triangular carriers operate as linear power amplifier with their output coupled through current sharing inductors. The high voltage rating is obtained through series connection of low voltage converter module structures, whereas high current rating is obtained by parallel connection of the multiple low voltage converter modules.

For high rating ac drives, ac machines particularly induction motor fed through multi-converter system seems to be the best proposition provided a detailed study of such a drive is carried out with respect to following factors

- Improvement in harmonic currents and torque pulsations, due to carrier frequency multiplication effects in the multi-converter.
- 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 LCVM's
- Full utilization of individual LCVM to increase the overall efficiency of the converter system drastically while operating at low modulation index.
- Techno-economic feasibility

III. SIMULATION OF MULTI-INVERTER

A multi-inverter system is considered to have two or more inverters connected in parallel. The paralleling of inverter is done through an inductor called coupling inductor or current sharing inductor (L_c). When N modules of inverters are connected in parallel, each module receives the same modulating signal V (t). However, in each module (n=1, 2, 3, 4, ---------N) the triangular carrier wave $V_{cn}(t)$ is phase shifted by a time Tc/N where Tc=1/fc. Mathematically the n^{th} N^{th} carrier wave of N^{th} modules $V_{cn}(t)$ is related to first carrier $V_c(t)$ by

$$V_{Cn}(t) = V_{C1}(t)\left[t - \frac{(n-1)T_C}{N}\right] \qquad n=1, 2, 3, -----N \text{ (i)}$$

For N=2 i.e. two inverter connected in parallel, the triangular carrier wave to second inverter is

$$V_{C2}(t) = V_{C1}\left[t - \frac{T_C}{2}\right] \qquad \text{(ii)}$$

Due to phase shifted nature of the triangular wave applied to the inverter the same phase of all the inverter modules not switches in unison. Instead, phase shifted triangular carrier waves introduces a slight staggering of switch in individual converters 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 fc.

IV. SYSTEM CONFIGURATION

The control circuit of the two and four inverters is similar to that of the single SPWM inverter. Here only difference is that triangular carrier wave for the second inverter is phase shifted by Tc/2 period with respect to triangular carrier wave of first inverter in case when two inverters are coupled. In case when four inverters are coupled then triangular carrier wave for all four inverters are phase shifted by Tc/4 period with respect to triangular carrier wave of consequent inverter. Thus for two and four inverters connected in parallel, the triangular wave amplitudes at different instants are depicted in table [1] and table [2] respectively Here Tc is the time period of the 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

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

Table 2:Look-up table for triangular carrier wave when four inverters are connected in parallel

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

V. RESULTS & DISCUSSIONS

The multi-inverter system was simulated for single inverter, two and four 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. The system parameters are depicted in Appendix-A.

Induction motor is run at 25 Hz with carrier frequency of 1 kHz by a single inverter, by two similar inverters connected in parallel through current sharing inductors and by four similar inverters connected in parallel through current sharing inductors fig.(1), fig.(2), fig.(3) show the voltage harmonics waveforms and fig.(4), fig.(5), fig.(6) show the current harmonics waveforms of an induction machine when run by single inverter, by two similar inverters connected in parallel through current sharing inductors and by four similar inverters connected in parallel through current sharing inductors respectively.

Induction motor is run at 50 Hz with carrier frequency of 1 kHz by a single inverter, by two similar inverters connected in parallel through current sharing inductors and by four similar inverters connected in parallel through a current sharing inductors fig.(7), fig.(8), fig.(9) show the voltage harmonics waveforms and fig.(10), fig.(11), fig.(12) show the current harmonics waveforms of an induction machine when run by single inverter, by two similar inverters connected in parallel through current sharing inductors and by four similar inverters connected in parallel through current sharing inductors respectively.

The calculation of total losses incurred in a PWM inverter employing IGBTs is done experimentally.

This can also be verified using [4] manufacturer catalogue where, the parameters of IGBT are provided by employing the following equations

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

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

Recovery losses are given by

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

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.

This calculation yields the losses which would take place in a device. To find out total losses in an inverter total loss of a device is multiplied by the number of devices which are used in an inverter under consideration.

Table3: Total losses incurred in Single inverter, two-inverters and four-inverters

Induction motor Freq. (Hz)	Carrier freq (KHz).	Single Inverter losses (W)	Two Inverter losses (W)	Four Inverter losses (W)
25	1	10.314	5.052	8.508
	2.5	25.782	12.642	21.264
	5	51.564	25.290	42.522
	1	3.438	10.116	17.010
	2.5	51.564	25.29	42.534
	5	103.128	50.568	85.062

The measured losses in inverters at all the considered frequency and at different carrier frequencies for all the cases i.e. when induction motor is fed from single inverter, from two similar inverters connected in parallel through current sharing inductors and from four similar inverters connected in parallel through current sharing inductors are calculated and listed in table [3]. It can be seen from the table that at all the considered frequencies and at all the considered carrier frequencies the total losses are more in case of single inverter compared with two-inverters and four inverters. Although losses are more in case of four inverters when compared with that of two inverters implementation but there is significant improvement in the current and torque harmonic waveforms when four inverters are implemented instead of two inverters.. Individual device rating is reduced for the four inverters when compared with device rating for two inverters and the individual device rating for two inverters is reduced when compared with device ratings for single inverter. Thus, the overall cost incurred for four inverters, two inverters and single inverter is fairly justified. The fraction by which the individual device rating is reduced is the design parameter.

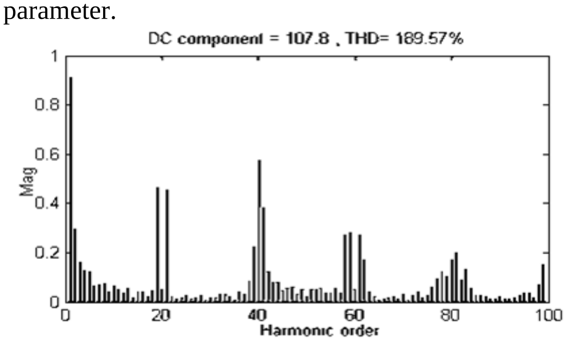

Fig. (1) Voltage harmonics when Induction motor is run at 25 Hz, with carrier frequency of 1 kHz by single inverter

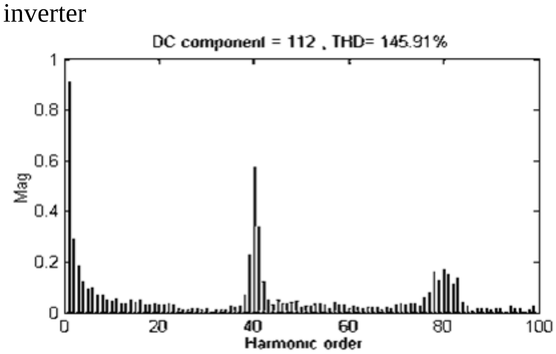

Fig. (2) Voltage harmonics when Induction motor is run at 25 Hz, with carrier frequency of 1 kHz by two inverters

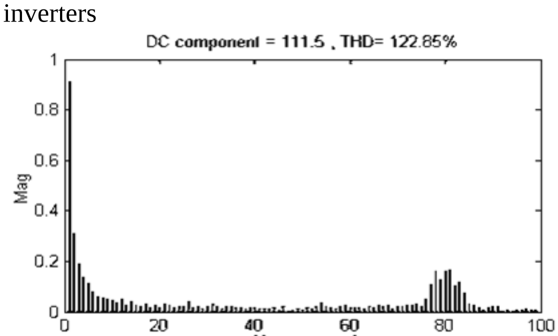

Fig. (3) Voltage harmonics when Induction motor is run at 25 Hz, with carrier frequency of 1 kHz by four inverters

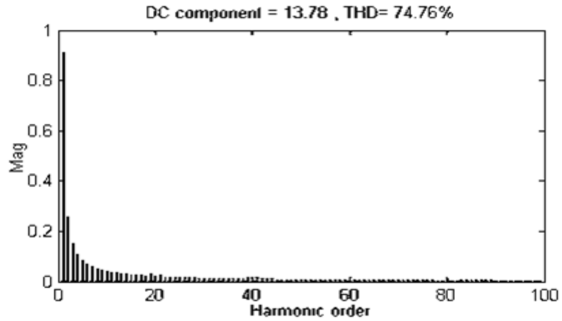

Fig. (4) Current harmonics when Induction motor is run at 25 Hz, with carrier frequency of 1 kHz by single inverter

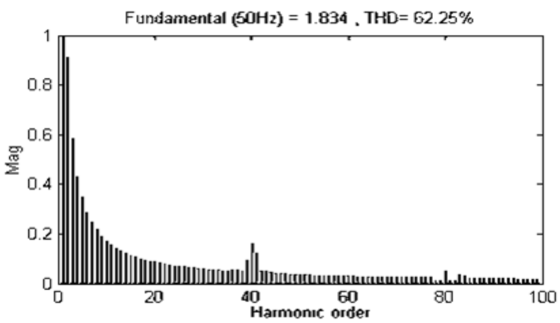

Fig. (5) Current harmonics when Induction motor is run at 25 Hz, with carrier frequency of 1 kHz by two inverters

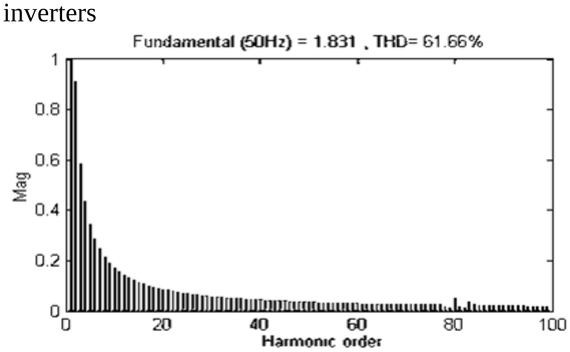

Fig. (6) Current harmonics when Induction motor is run at 25 Hz, with carrier frequency of 1 kHz by four inverters

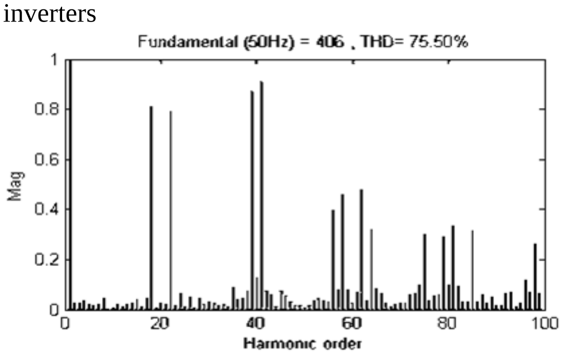

Fig. (7) Voltage harmonics when Induction motor is run at 50 Hz, with carrier frequency of 1 kHz by single inverter

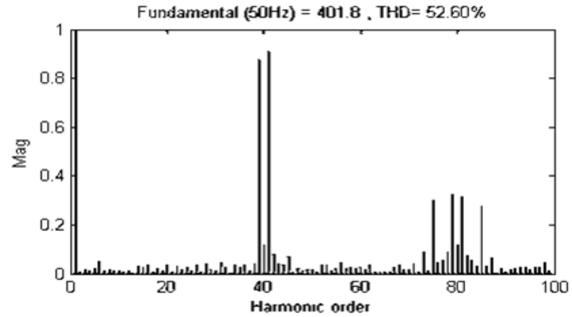

Fig. (8) Voltage harmonics when Induction motor is run at 50 Hz, with carrier frequency of 1 kHz by two inverters

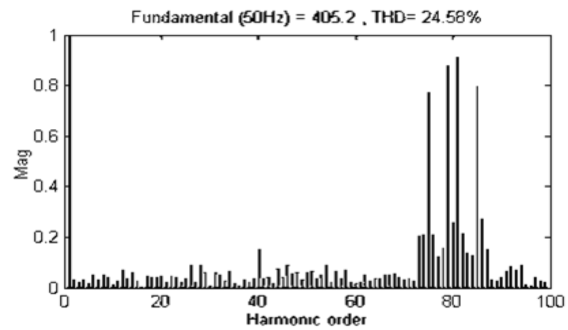

Fig. (9) Voltage harmonics when Induction motor is run at 50 Hz, with carrier frequency of 1 kHz by four inverters.

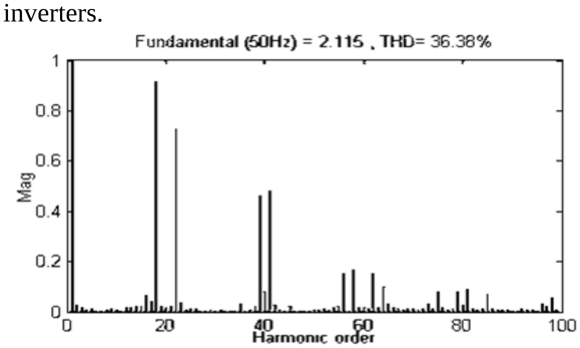

Fig. (10) Current harmonics when Induction motor is run at 50 Hz, with carrier frequency of 1 kHz by single inverter

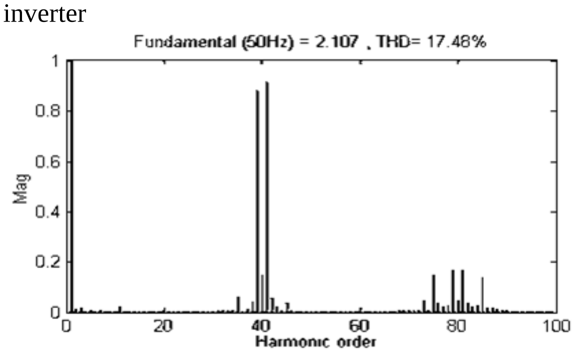

Fig. (11) Current harmonics when Induction motor is run at 50 Hz, with carrier frequency of 1 kHz by two inverters

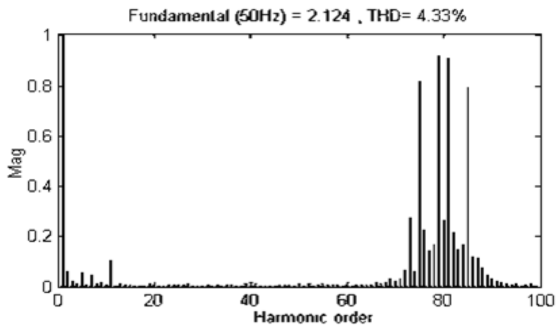

Fig. (12) Current harmonics when Induction motor is run at 50 Hz, with carrier frequency of 1 kHz by four inverters

VI. CONCLUSION

The performance of induction motor is found to be better when it is supplied by multi-inverter system. They are found to be suitable for large volt-ampere rated and/or high voltage motor drives. Multi-inverter system possesses high reliability under dynamic loading and overloading due to better current sharing. There has been improvement in harmonic currents and torque pulsations, when multi-inverter 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 N_P. The turn on and switching frequency losses in multi-inverter is found to be very less when compared to its counterpart i.e. single inverter. Although two inverters have less losses when compared with four inverters but implementation of four inverters gives better results as can be seen from the torque and current harmonic waveforms. The devices are operated at reduced switching frequency resulting in better efficiency due to the reduced switching losses. 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**.** In this case single inverter, two similar inverters and four similar inverters are used if more number of inverters are coupled through coupling inductor then the harmonic spectrum would be still better. The current and torque pulsations would still be reduced and the waveforms of current and torque would be smooth. The summary is that the multi-inverter results in improvement in harmonic currents and torque pulsations. The cost of multi-inverter system is not increased as lower rated switches are used with increase in number of inverters in case of multi-inverter system.

Appendix-a
The induction motor used for simulation purpose has following parameters
Power = 1.5 kW
Voltage = 400V
Frequency = 50 Hz
Stator resistance = 2.2 ohms per phase
Stator leakage inductance = 0.0111 H/ phase
Rotor resistance referred to stator = 2.2 ohms per phase
Rotor leakage inductance referred to stator = 0.0133 henry per phase
Mutual inductance = 0.0334 henry per phase
Inertia = 0.089
Number of pairs of poles = 3

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