Harmonic Cancellation Technique of Four Pole Induction Motor Drive by using Phase Shifted Carrier Space Vector PWM Technique

Kiran Kumar Nallamekala
Department of Electrical and Eletronics Engineering, Vardhaman College of Engineering, Hyderabad, India.
Email: kiraneee227@gmail.com

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ABSTRACT:
The conventional two-level inverter fed induction motor drive causes pulsating torque because of harmonics present in the inverter output voltage. Therefore, minimization of harmonics content is the major challenge in two-level inverter supplied drives. In this paper, a harmonic reduction technique for multiple pole-pair induction motor drive is presented. A modified carrier based space vector PWM technique is used with suitable phase shift between different (modulating and carrier) signals to cancel the harmonic content. In order to use this PWM technique, each pole-pair winding coil of a four-pole induction motor is supplied with two-level inverters separately as dual inverter fed drives. Two dc voltage sources are used to feed all these two-level inverters and by connecting in proper sequence zero sequence currents can be eliminated. By using proposed PWM technique to the inverter configuration, all harmonics will appear at four times of the switching frequency. The proposed inverter concept is tested with 5hp four-pole induction motor in MATLAB/Simulink and experimentally also verified with laboratory prototype. Simulation and experimental results demonstrate the performance of the proposed inverter topology and also show the improvement in harmonic profile.

KEYWORDS: Carrier based SV PWM Technique, Induction Motor, Multi-level Inverters.

1. INTRODUCTION

In recent years, requirement for the inverter fed ac drives is growing considerably because of the advances in power electronics. Mostly two-level inverter configurations are used for speed control of the AC motor drives. But the two-level inverter output voltage consists of more harmonics along with necessary fundamental voltage component [1-2]. The harmonics present in the two-level inverter output voltage will causes torque ripple and current ripple and it will cause the damage (reduce the life time) of stator winding and power electronic switches [3-4]. Hence the minimization of harmonics is the important issue in two-level inverter supplied ac drives. The harmonic elimination concepts presented in paper [5-7] will minimize the effect of harmonics on the load by transferring all harmonics to switching frequency. But, the harmonics near switching frequency will also cause problem to the stator winding of the motor and to power electronic devices. To minimize this effect of harmonics present at switching frequency, the carrier signal frequency has to be increased. But, increasing carrier signal frequency will cause to increase the switching losses especially in high power applications. An interesting PWM technique is proposed in [8-11] that will shift all harmonics to two times switching frequency without increasing carrier signal frequency. To implement this pwm technique, a dual inverter configuration is required where both sides of stator winding of induction motor are connected with two-level inverters. Here the modulating signals of both the inverters may be phase shifted by 180^0 or carrier signals of both the inverters may be phase shifted by 180^0 [11]. To push all harmonics to further higher levels, another interesting pwm technique is available in the literature [12-15]. By using proper phase shift between carrier signals and modulating signals, all harmonics can be transferred to 4-times of switching frequency. It means that the first center band harmonics are situated at four times the switching frequency. But this pwm technique can be used in a circuit where four two-level inverters are connected as two dual inverter configurations. Till now this concept is used to the inverter configurations which are supplying to RL load. But, it is difficult to use for inverter fed motor drives because it is difficult to use such a configuration to drives application.

In this paper, the above concept is applied to the induction motor drive by disconnecting pole-pair winding coils of the stator winding. There exist two pole-pair winding coils in a four pole induction motor stator winding [16-18]. Generally in induction motors, these two pole-pair windings are connected either in series or parallel. However in the present work, two pole-pair windings are detached at middle. Then each winding will have two terminals and total winding will have four terminals per phase. All these four terminals will be connected to four two-level inverters and it will be explained clearly in the next section.

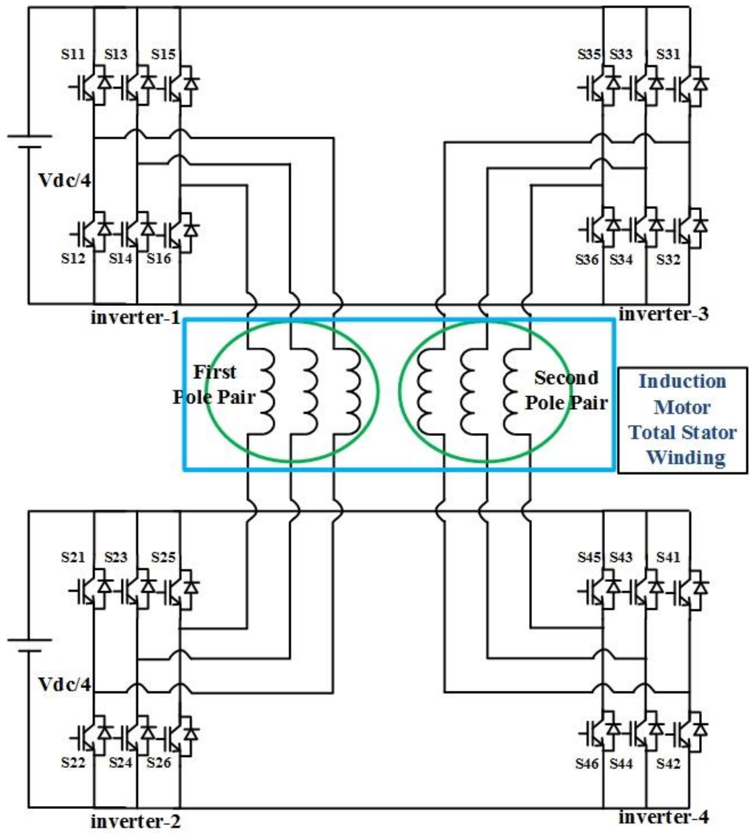


Fig. 1. The proposed multi-level inverter.

These two-level inverters are switched in such a way that same average voltage must be applied across each pole-pair winding. Modified carrier based space vector PWM technique is used to produce gating signals to the inverter. It will cause to shift the first center band harmonics to four times higher frequencies compared to harmonics of conventional inverter fed induction motor drives, thus the current ripple and torque ripple will be significantly reduced.

2. INVERTER CONFIGURATION AND PHASE SHIFTED CARRIER SVPWM

The inverter configuration is modelled based on stator winding configuration of four-pole induction motor. As explained in the previous section, two pole-pair windings of stator winding are detached and connected to four two-level inverters and it is shown in Fig.1. Two-level inverter-1 and 2 are supplying first pole pair instead of inverter-1 and 3. If inverter-1 and 3 are connected to first pole pair, then zero sequence currents will flow through the winding because of common dc voltage source. These zero sequence currents will not produce torque component. Moreover zero sequence currents will cause to produce more losses in the machine and it will raise the temperature of the machine. In order to disconnect the path for zero sequence currents, inverter-1 and inverter-2 are connected to two different isolated dc voltage sources. Similarly inverter-3 and inverter-4 are connected to different two different isolated dc voltage sources which are also connected to inverter-1 and 2. Voltage across first winding is equal to the difference between inverter-1 and 2 pole voltages. Since inverter-1 & inverter-2 are connected to two different dc voltage sources, voltage across first winding consists of different between two pole voltages and also difference of voltages between two dc voltage sources and it is clearly shown in results section. Similarly, voltage across other winding is equal to potential difference between inverter-3 & inverter-4 poles. The sum of voltage across both windings will give total voltage across stator winding per phase. The voltage across total motor phase winding is equal to the sum of voltage across each winding. Each two-level inverter will have two switches in each phase leg. These two switches are complimentary switches which mean that when one switch is turned ON, other should be turned OFF.

The gating pulse for the switches of proposed inverter configuration is generated with the help of phase shifted carrier space vector pulse width modulation technique. By using this PWM method, gating pulses for every two-level inverter is independently generated. In this technique, gating signals for inverter-1 is produced by using carrier based SV PWM technique where phase shift of space vector based modulating signal and carrier signal are equal to zero as shown in Fig.2. Gating signals for inverter-2 is generated with the help of space vector based modulating signal and carrier signal where phase shift of modulating signal is 180^0 and phase shift of carrier signal is zero. Since inverter-1 and 2 modulating signals are phase shifted by 180^0 and voltage across first winding is the difference of inverter-1 and 2 pole voltages, the voltage across first winding is equal to two times inveter-1 pole voltage. Moreover, due to 180^0 phase shift between modulating signals, all harmonics at odd multiples of m_f (where m_f- is frequency modulation ratio i.e. the ration between frequency of carrier signal to frequency of modulating signal) will be cancelled. Where center band harmonics means, harmonics present around switching frequency. In case of incerter-3 gating pulses, phase shift of modulating signal frequency is zero and phase shift of carrier signal is 90^0. Similarly for inverter-4 gating pulses, modulating signal frequency is 180^0 and carrier frequency is 90^0. The phase shift of carrier signal will not have any impact on magnitude of output voltage, magnitude of total voltage across second winding is equal to two times of inverter-3 pole voltage. But, due to the 90^0 phase shift provided to carrier signal, harmonics at second center band will be cancelled. Hence, all harmonics at odd multiples of m_f are cancelled due to 180^0 phase shift between modulating signals and harmonics at second center band are cancelled because of 90^0 phase shift between carrier waves. Hence with combined effect of phase shift due to modulating and carrier waves, all harmonics are present at four times frequency modulation ratio (m_f).

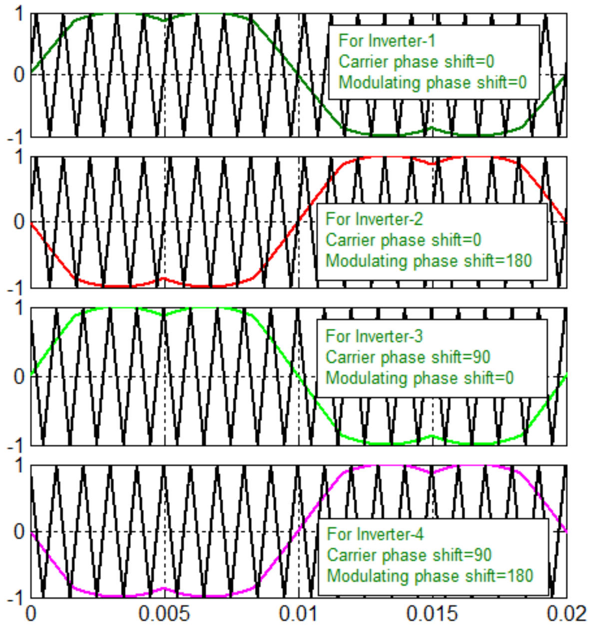


Fig. 2. Novel PWM method suitable for proposed inverter.

For 2 kHz switching frequency, all harmonics are shifted to 8kHz whereas in conventional PWM, same harmonics are present at 2kHz and it is clearly demonstrated in results section. The theoretical justification for the harmonics cancellation is presented below section and similar analysis is carried out in [19] for RL load. The concept presenting for RL load is simple, applying it to induction motor is difficult unless pole pair windings are disconnected.

3. HARMONIC CANCELLATION

In this section harmonic cancellation in motor phase winding is explained as follows. The complete pole voltage equation (fundamental and harmonic components) of each inverter can be written as [19]:

$$V_{A1} = \frac{V_{dc}}{4} M cos(w_o t + k\pi) + \frac{4}{\pi}\frac{V_{dc}}{4} \sum_{m=1}^{\infty}\sum_{n=-\infty}^{\infty} \frac{1}{m} \left\{ \sin\left[\frac{(m+n)\pi}{2}\right] J_n\left(\frac{m\pi M}{2}\right) \cos[m(w_c t) + n(w_o t + k\pi)] \right\} \quad (1)$$

(Where V_{dc} - DC source voltage, W_o - fundamental frequency, W_c - Carrier frequency' k - harmonic order, m - Carrier component, n - fundamental component, Jn - Bessel functions of the first kind of order n, M - Modulation depth). Similarly, pole voltage of inverter-2, 3 and 4 can be written just by changing phase angle of modulating and carrier wave signals. Since the inverter-1 and inverter-2 are connected to the DC sources with same magnitude and V_{r2} is phase shifted by 180^0 from V_{r1}, therefore the total voltage appearing across first IVPWC is the difference between inverter-1 and inverter-2 pole voltages. [19]

$$V_{A12} = \frac{V_{dc}}{4} 2M cos(w_o t) + \frac{8}{\pi}\frac{V_{dc}}{4} \sum_{m=1}^{\infty} \sum_{\substack{n=-\infty \\ n\neq 0}}^{\infty} \frac{1}{2m} \left\{\cos[(m+n+1)\pi] J_{2n-1}\left(\frac{2m\pi M}{2}\right) \cos[2m(w_c t) + (2n-1)(w_o t)]\right\} \quad (2)$$

(Where k=0 for the inverter-1 and k=1 for the inverter-2). In the same way voltage across the second IVPWC is the difference between the inverter-3 and inverter-4 pole voltages. But the carrier wave for inverter-1 is 90^0 phase shifted from carrier wave for inverter-3. From the equation (2) it can be noticed that all even side band harmonics and odd carrier multiples are cancelled for any modulation index (i.e. ratio of magnitude of modulating signal to carrier signal) and frequency modulation ratio. Therefore all harmonics are transferred near to two times the switching frequency. Therefore voltage equation across the second IVPWC is given by [19]:

$$V_{A34} = \frac{V_{dc}}{4} 2MN cos(w_o t) + \frac{8}{\pi}\frac{V_{dc}}{4} \sum_{m=1}^{\infty} \sum_{\substack{n=-\infty \\ n\neq 0}}^{\infty} \frac{1}{2m} \left\{\cos[(Nm+n+1)\pi] J_{2n-1}\left(\frac{2Nm\pi M}{2}\right) \cos[2mN(w_c t) + (2n-1)(w_o t)]\right\} \quad (3)$$

(where N=4). By providing 90^0 phase shift between carrier waves, side band harmonic of second center band will be cancelled [19], therefore by adding voltage across both the windings, all lower order harmonics are shifted near to four times the switching frequency (i.e. first center band is moved to four times switching frequency). Even though this process of harmonic cancellation is explained earlier in [19], this method is not applied to induction motor drive. Application of this method to induction motor drive is giving good results. i.e. if 1kHz switching frequency is used to produce gating pulses, all lower order harmonics must be appear around 1kHz frequency. But, by using this method to induction motor drive, all lower order harmonics will appear around 4kHz frequency for the same switching frequency. From the above discussion it can be observed that the harmonics near to second center band will flow through each IVPWC, but when both windings are connected, these second band harmonics are shifted to four times switching frequency, therefore the air gap flux is free from these harmonics (i.e. the harmonics up to third center band are cancelled).

4. RESULTS AND DISCUSSION

The effectiveness of proposed topology is verified by using MATLAB/Simulink and experimentally verified with laboratory prototype. Control signals for the switching devices of the proposed inverter configuration is generated using phase shifted carrier PWM technique. The same gating pulses are generated with dSPACE (DS1104) and given to every conventional two-level inverters independently which are shown in Fig.1. The dead band circuits are designed to provide 2μs delay between the gating pulses of the complimentary. The voltages from each pole to ground are presented and voltage across each winding and total voltage across total winding and current through winding are also presented. All above mentioned results are presented for different modulation indices to show performance of drive in entire linear modulation region.

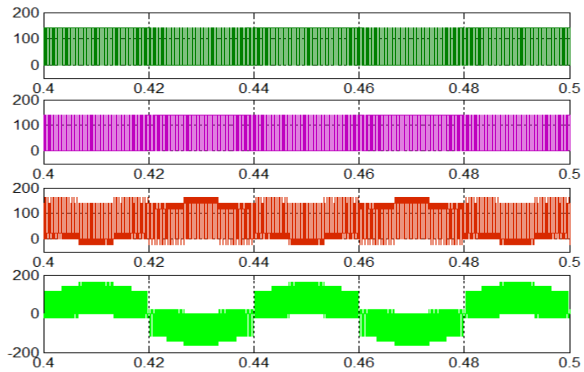


Fig. 3. First waveform is inverter-1 pole voltage, second waveform is inverter-2 pole voltage, third waveform is voltage between two dc voltage sources and bottom waveform is voltage across first winding for modulation index 0.433.

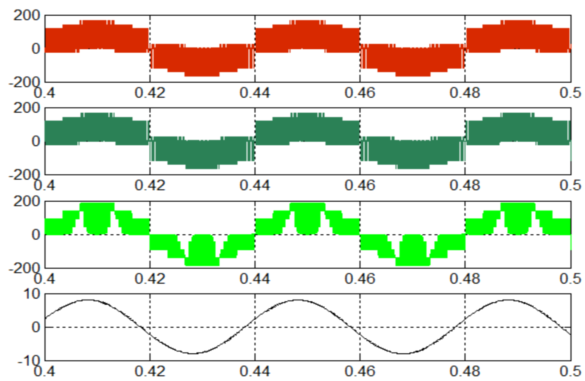
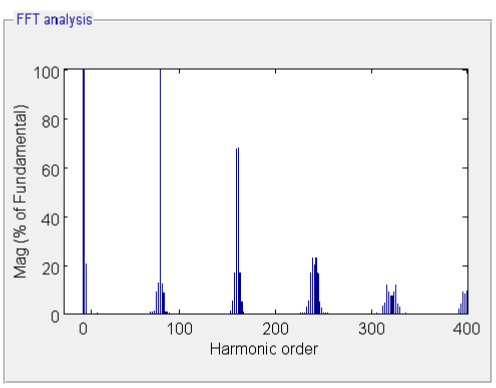
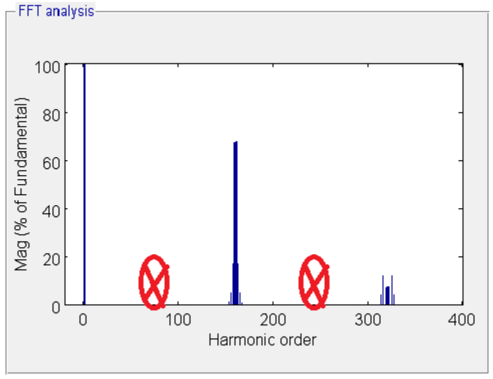


Fig. 4. First waveform is voltage across first winding, second waveform is voltage across second winding, third waveform is voltage across total stator winding and bottom waveform is current through stator for modulation index 0.433.

Top trace in Fig. 3 indicates pole voltage of inerter-1 with respect to Vdc1 and second trace indicates the pole voltage of inerter-2 with respect to Vdc2. Third trace from top indicates pole voltage of inerter-2 with respect to Vdc1. Here, as inverter-2 is connected to Vdc2, third trace contains sum of pole voltage and voltage difference between two dc voltage sources and it can be easily observed from Fig.3. Bottom trace indicates voltage across one winding and it is equal to difference of inerter-1 and inverter-2 pole voltages. Fig.4 shows the voltage each winding and voltage across total winding and current through total winding. Third trace from top in Fig.4 shows the total voltage which is equal to sum of voltages across two windings. It can be noticed from Fig that, multi-level voltage waveform can be generated across total winding. Bottom trace in Fig.4 indicates current through motor phase winding. It can be observed from Fig.4 that, current is almost pure sinusoidal because the voltage across the winding is free from first, second and third center band harmonics and it will be explained using next three figures. Fig.5 (a) represents the harmonic spectrum of pole voltage for modulation index of 0.433 and it contains lower order harmonics at first center band which is equal to the ratio of switching frequency to fundamental frequency. Fig.5(b) shows the harmonic spectrum of voltage across each winding for modulation index 0.433. It can be noticed from Fig. 5(b) that, all odd center band harmonics are cancelled by using this pwm technique. Fig.5(c) shows the harmonic spectrum of voltage across total stator winding and it can be noticed that harmonics at first, second and third multiples of m_f are cancelled and all appearing at fourth multiple of m_f. When compared with harmonics of output voltage using conventional pwm technique, harmonics are shifted four times higher levels using this pwm technique.



(a)



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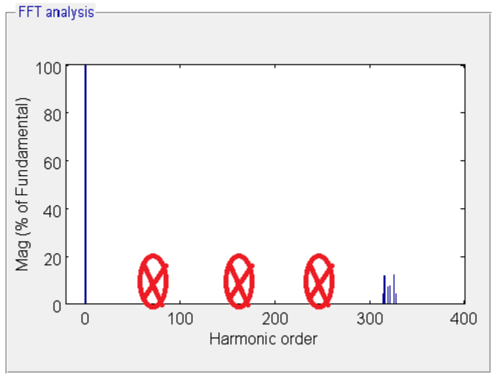


(c)

Fig. 5. (a) Harmonic spectrum of inverter-1 pole voltage, (b) Harmonic spectrum voltage across first winding and (c) Harmonic spectrum of voltage across total stator winding for modulation index of 0.433.

Pole voltages and phase voltage for modulation index 0.866 is shown in Fig.6. The phase voltage across each winding is similar to a three-level voltage waveform. Fig. 7 shows simulation results of phase voltage across every winding and total voltage across phase winding and current through it. It can be noticed from Fig.7 that, total voltage is similar to a five-level voltage waveform. Experimental results for modulation index 0.866 are shown in Fig.8. From Fig.7 and 8 it can be noticed that, simulation results are validating experimental results. Harmonic spectrum for pole voltage, phase voltage across each winding and total winding are shown in Fig. 9(a), (b) and (c) respectively. The results for different modulation indices are presented to show the performance of drive in entire linear modulation region.

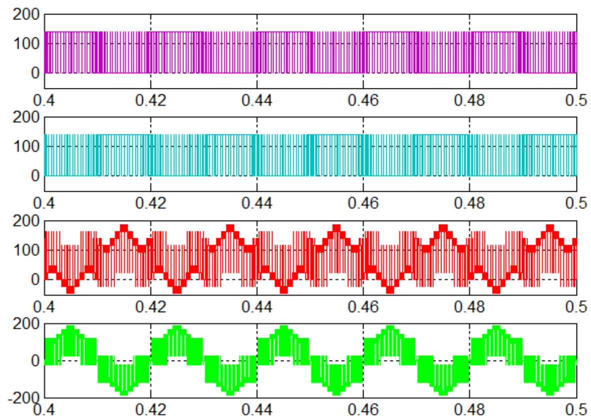


Fig. 6. First waveform is inverter-1 pole voltage, second waveform is inverter-2 pole voltage, third waveform is voltage between two dc voltage sources and bottom waveform is voltage across first winding for modulation index 0.866.

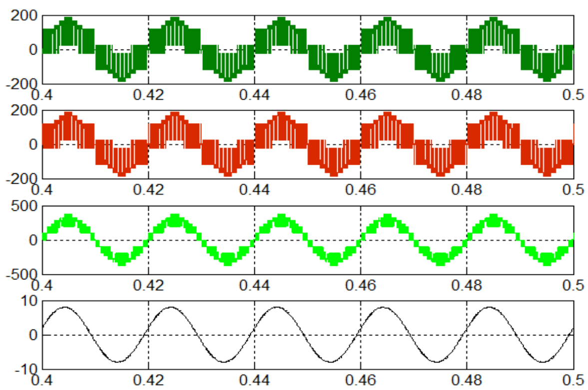


Fig. 7. First waveform is voltage across first winding, second waveform is voltage across second winding, third waveform is voltage across total stator winding and bottom waveform is current through stator for modulation index 0.866.

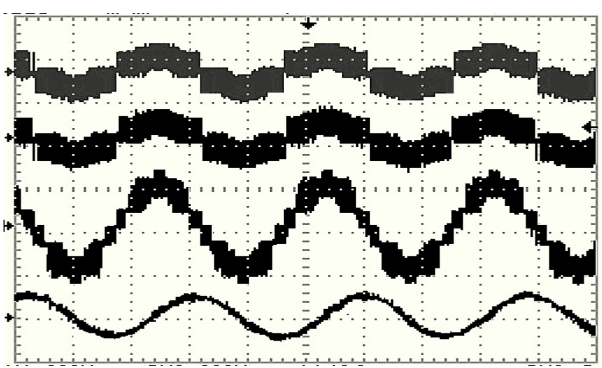
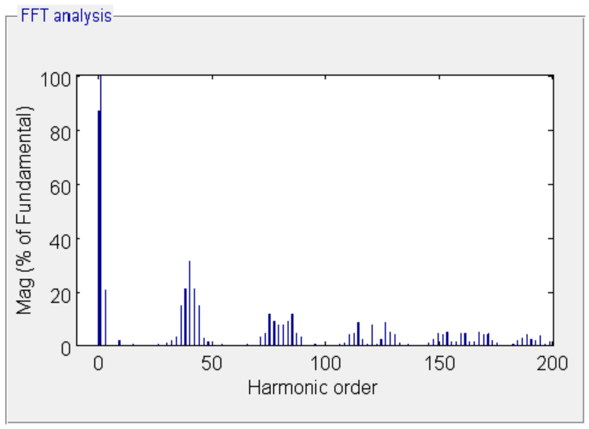
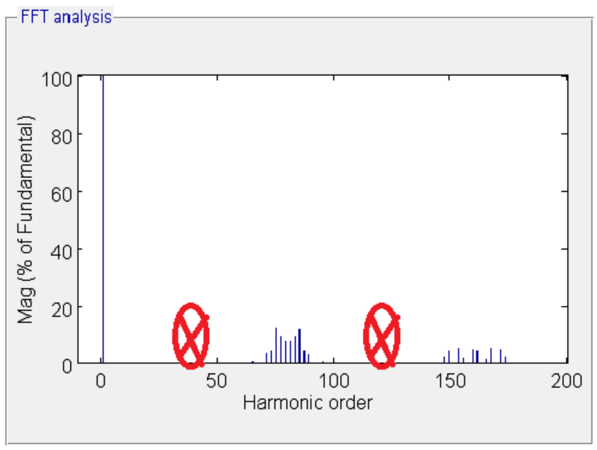


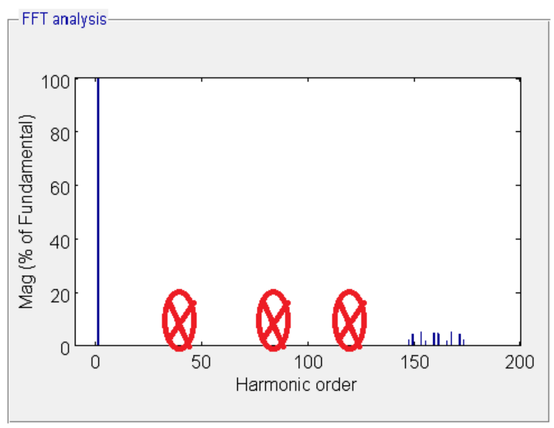
Fig. 8. [Experimental results] First waveform is voltage across first winding, second waveform is voltage across second winding, third waveform is voltage across total stator winding and bottom waveform is current through stator for modulation index 0.866. [Y-axis 200V/div, 2A/div, X-axis 10ms/div].



(a)



(b)



(c)

Fig. 9. (a) Harmonic spectrum of inverter-1 pole voltage, (b) Harmonic spectrum voltage across first winding and (c) Harmonic spectrum of voltage across total stator winding for modulation index of 0.866.

5. CONCLUSION

In this paper a phase shifted carrier space vector pwm technique is presented for the inverter configuration supplying to a four pole induction motor drive. By using this pwm technique and inverter configuration, all harmonics are cancelled up to three center bands and appear at fourth center band (m_f). Utilisation of dc bus voltage is also increased by 15% as space vector pwm is used for this inverter configuration. By increasing number of pole pairs of induction motor stator winding, it is possible to transfer the lower order harmonics to further more number of higher levels. The drawback with increasing more number of pole pairs is that it requires more number of isolated dc voltage sources. As harmonic content in the inverter output voltage is reduced, the torque ripple of induction motor will also be reduced because, torque ripple is proportional to current ripple. Simulation and also experimental results are presented to validate the proposed pwm concept for the inverter circuit. This pwm technique can only be applied to inverter configurations where two-level inverters are connected to both sides of the load terminals. Disconnection of induction motor stator winding at its pole pairs is also very easy. Hence this configuration can be extended to induction motors with any number of pole pairs.

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