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Hybrid Pulse Width Modulation Method for VSI Fed Induction Motor Drive with Reduced Complexity

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Abstract—This paper presents a generalized pulse width modulation (GPWM) algorithm for induction motor drives. In the proposed approach, by varying a constant (k_2) value from zero to one, various DPWM algorithms can be generated along with the SVPWM algorithm. As the proposed approach uses instantaneous phase voltages only for the calculation of gating times of the inverter, the complexity burden involved is very less when compared with the classical space vector approach. Then, the rms stator flux ripple, which is a measure of ripple in line current characteristics have been plotted for all the DPWM and SVPWM algorithms. From which, it is concluded that the SVPWM algorithm gives superior performance at low modulation indices, whereas the DPWM algorithm gives superior performance at higher modulation indices. Hence, to achieve the superior waveform quality at all modulation indices, a hybrid PWM (HPWM) algorithm has been presented in this paper. To validate the proposed algorithms, several numerical simulation studies have been carried out and results have been presented and compared.

Keywords—DPWM, flux ripple, GPWM, HPWM, PWM, SVPWM

I. INTRODUCTION

The variable speed drives (VSD) are becoming popular in many industrial applications due to their numerous advantages. But, the VSDs require ac voltage with controllable magnitude and frequency. To achieve the variable voltage and variable frequency ac supply, the pulse width modulation (PWM) algorithms are becoming popular. A large variety of PWM algorithms have been discussed in [1]. But, the most popular PWM algorithms as sinusoidal PWM (SPWM) and space vector PWM (SVPWM) algorithms. The SVPWM algorithm offers more degrees of freedom when compared with the SPWM algorithms. Hence, it is attracting many researchers. The SVPWM algorithm is explained in detailed in [2]. Though the SVPWM and SPWM algorithms give good performance, these give more switching losses of the inverter due to the continuous modulating signals. Hence, to reduce the switching losses of the inverter, the discontinuous PWM (DPWM) algorithms are becoming popular. Also, the classical SVPWM algorithm requires angle and sector information to generate the actual gating times of the inverter. Hence, the complexity involved is more. To reduce the complexity involved in the algorithms and for easier implementation, nowadays, the carrier based PWM algorithms are attracting many researchers. The magnitude tests based approach is presented to generate the carrier based SVPWM and various DPWM algorithms with reduced complexity in [3]. Also, by distributing the zero state time unequally, various PWM algorithms have been generated in [4]. By adding a generalized zero sequence signal to the voltages various carrier based PWM algorithms have been generated in [5]. However, the [3]-[5] gives the explanation under the linear modulation region only.

To reduce the complexity in the classical SVPWM algorithms and to extend the operation up to over modulation region, various PWM algorithms have been generated in [6]-[8] by using the concept of offset time and duty cycle. By adding the suitable offset time to the imaginary switching times, which are proportional to the instantaneous phase voltages, various PWM algorithms have been generated under both linear and over modulation regions. Though, the SVPWM and DPWM algorithms give good performance, the SVPWM algorithm gives more harmonic distortion at higher modulation indices when compared with the DPWM algorithms and DPWM algorithm gives more harmonic distortion at lower modulation indices. Hence, to reduce the harmonic distortion at all modulation indices, a hybrid PWM algorithm approach has been proposed in [9]-[12].

This paper presents a simplified approach for the generation of SVPWM and DPWM algorithms. Then, the rms stator flux ripple characteristics of all PWM algorithms is presented with reduced complexity. Based on the flux ripple characteristics, simplified hybrid PWM (HPWM) algorithm has been presented with reduced harmonic distortion at all modulation indices.

II. SWITCHING SEQUENCES

The proposed GPWM algorithm may be pursued by the definition of a duty cycle or modulating signal for phase *n* (with *n* = a, b and c), which is given as the ratio between pulse width and modulation period.

$$V_n^* = \frac{Pulsewidth}{Modualtionperiod} \qquad (1)$$

Once the modulating signal V_n^* is calculated, the ON and OFF times of the inverter-leg devices can be via digital counters and comparators. For example, the duty cycle or modulating signal of SPWM algorithm can be obtained as follows [6]-[7]:

$$V_n^* = \frac{1}{2} + \frac{V_n}{V_{dc}}, \quad n = a, b\, and\, c \qquad (2)$$

where V_n is the instantaneous reference voltage of phase *n* and V_{dc} is the dc-link voltage. In the similar way, the modulating signals of the various DPWM algorithms and SVPWM algorithms can be obtained by adding a suitable zero sequence voltage (V_z) to the instantaneous phase voltages (V_n).

$$V_n^* = k_1 + \frac{V_n + V_z}{V_{dc}} \qquad (3)$$

where $V_z = k_2[\min(V_n) - \max(V_n)] - \min(V_n)$ (4)

where k_2 is the parameter that takes into account the unequal null-state sharing, can be defined as follows:

$$k_2 = 0.5(1 + \mathrm{sgn}(\cos(3\omega t + \delta)) \qquad (5)$$

where sgn(X) is 1, 0 and –1 when X is positive, zero, and negative, respectively. As previously discussed, and k_1 is an additional parameter whose value may be equal to the value of k_2 or be fixed at 0.5. Thus, the proposed approach eliminates the calculation of both the hexagon sector, in which the reference-voltage space vector is located, and the related phase.

In all the other carrier-based techniques, it must be taken that $k_1 = k_2$. The standard SVPWM algorithm can be obtained by fixing the k_2 value at 0.5. Similarly, by fixing the k_2 value at 0 and 1, the DPWMMIN and DPWMMAX algorithms can be obtained. By varying the modulation angle δ in (5), various DPWM algorithms can be generated. The DPWM0, DPWM1, DPWM2 and DPWM3 can be obtained for $\delta = \pi/6$, 0, $-\pi/6$ and $-\pi/3$ respectively.

The modulating waveforms of sinusoidal PWM (SPWM), SVPWM and all possible DPWM algorithms are given in Fig.1. In the DPWM methods, any one of the phases is clamped to the positive or negative DC bus for utmost a total of 120^0 over a fundamental cycle. Hence, the switching losses of the associated inverter leg are eliminated. Moreover, within a sampling time period three switchings will occur in SVPWM algorithm whereas two switchings in all the above DPWM algorithms. Hence, to maintain constant average switching frequency of the inverter, the frequency of DPWM algorithms is taken as 1.5 times of the switching frequency of the SVPWM algorithm.

III. PROPOSED HYBRID PWM METHOD

The SVPWM algorithm uses equal distribution of zero state times among two zero states. Whereas the proposed GPWM algorithm uses unequal distribution of zero state time and it distributes the zero state time as $T_0 = k_2 T_z, T_7 = (1 - k_2)T_z$, where T_z is the total zero state time.

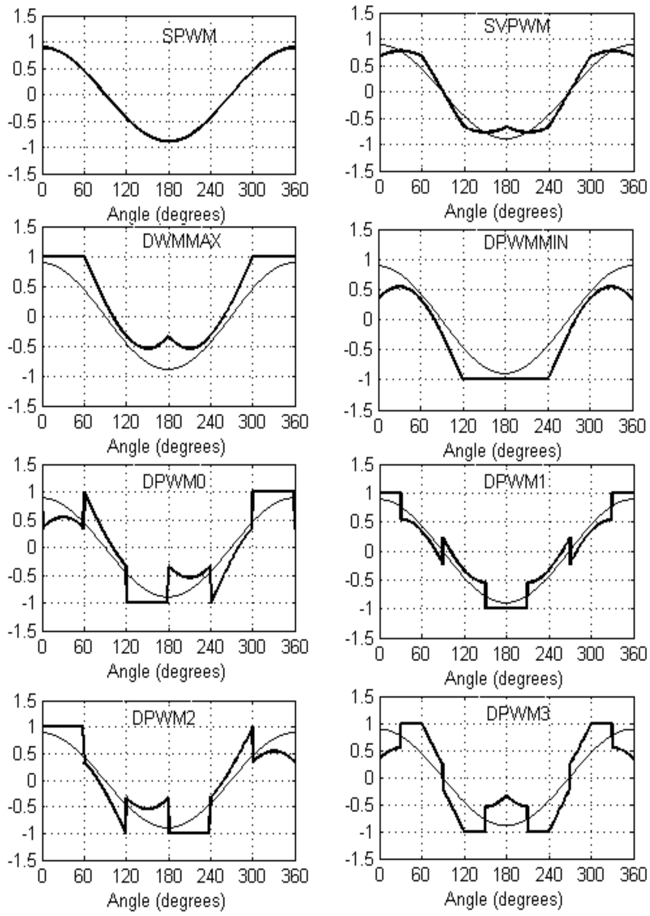

Fig. 1 Modulating waveforms of various PWM methods at $M_i = 0.7$

In the space vector approach, the applied voltage vector equals the reference voltage vector only in an average sense over the given sampling interval, and not in an instantaneous fashion. The difference between applied voltage vector and reference voltage vector is the ripple voltage vector, which depends on space and modulation index. The ripple voltage vectors and trajectory of the stator flux ripple can be represented in a complex plane as shown in Fig. 2. The corresponding d-axis and q-axis components of the stator flux ripple vector are as shown in Fig. 3, from which it is observed that the application of a zero voltage vector results in a variation of the q-axis component of the flux ripple and the application of any active voltage vector results in variation of the both the d-axis and q-axis components. The error volt-seconds corresponding to the voltage ripple vectors are given by

$$V_{r1}T_1 = \left(\frac{2}{3}V_{dc}\sin\alpha\right)T_1 + j\left(\frac{2}{3}V_{dc}\cos\alpha - V_{ref}\right)T_1 \quad (6)$$

$$V_{r2}T_2 = -\left(\frac{2}{3}V_{dc}\sin\left(60^o - \alpha\right)\right)T_2 + j\left(\frac{2}{3}V_{dc}\cos\left(60^o - \alpha\right) - V_{ref}\right)T_2 \quad (7)$$

$$V_{r0}T_0 = -jV_{ref}T_0 = -j\frac{2M_iV_{dc}}{\pi}T_0 = j\lambda_{q0} \quad (8)$$

$$V_{r7}T_7 = -jV_{ref}T_7 = -j\frac{2M_iV_{dc}}{\pi}T_7 = j\lambda_{q7} \quad (9)$$

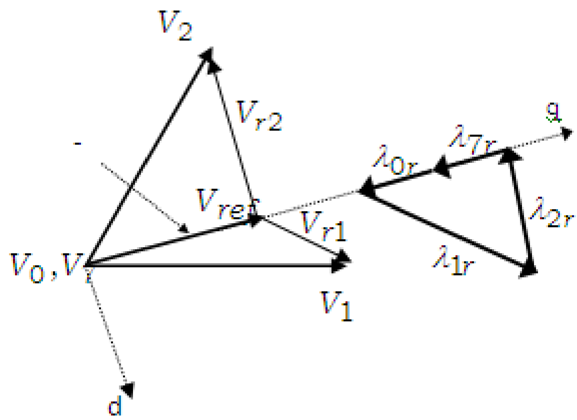

Fig. 2 Voltage ripple vectors and trajectory of the flux ripple

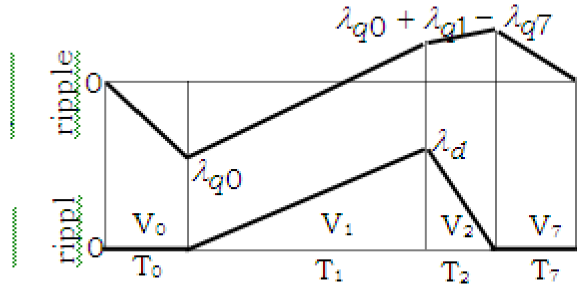

Fig. 3 q-axis and d-axis components of the flux ripple vectors

From the switching times expressions of the classical SVPWM algorithms, by substituting the values of $\sin\alpha$, $\cos\alpha$ and $\cos(60^o - \alpha)$ in (6) - (9), the following expressions can be obtained.

$$V_{r1}T_1 = \frac{\pi V_{dc}}{3\sqrt{3}M_i}\frac{T_1T_2}{T_s} + j\left(\frac{2V_{dc}\pi(T_1 + 0.5T_2)}{9M_iT_s} - \frac{2V_{dc}M_i}{\pi}\right)T_1 \quad (10)$$
$$= \lambda_d + j\lambda_{q1}$$

$$V_{r2}T_2 = -\frac{\pi V_{dc}}{3\sqrt{3}M_i}\frac{T_1T_2}{T_s}$$
$$+ j\left(\frac{2V_{dc}\pi(0.5T_1 + T_2)}{9M_iT_s} - \frac{2V_{dc}M_i}{\pi}\right)T_2 \quad (11)$$
$$= -\lambda_d + j\lambda_{q2}$$

Then the mean square stator flux ripple over a sampling interval can be calculated as

$$\lambda^2{}_{(rms)} = \frac{1}{T_s}\int_0^{T_s}\lambda_q^2 dt + \frac{1}{T_s}\int_0^{T_s}\lambda_d^2 dt$$
$$= \frac{1}{3}\left\{\lambda_{q0}^2\frac{T_0}{T_s} + \left[\lambda_{q0}^2 + (\lambda_{q0} + \lambda_{q1})^2 + \lambda_{q0}(\lambda_{q0} + \lambda_{q1})\right]\frac{T_1}{T_s}\right.$$
$$+ \left[(\lambda_{q0} + \lambda_{q1})^2 - \lambda_{q7}(\lambda_{q0} + \lambda_{q1}) + \lambda_{q7}^2\right]\frac{T_2}{T_s}$$
$$\left. + \lambda_{q7}^2\frac{T_7}{T_s} + \lambda_d^2\frac{(T_1 + T_2)}{T_s}\right\}$$
(12)

By using (12), the mean square flux ripple can be easily computed and graphically represented for all PWM methods. The mean square stator flux ripple characteristics obtained from (12) for various PWM algorithms and for different modulation indices are shown in Fig.4 – Fig.7.

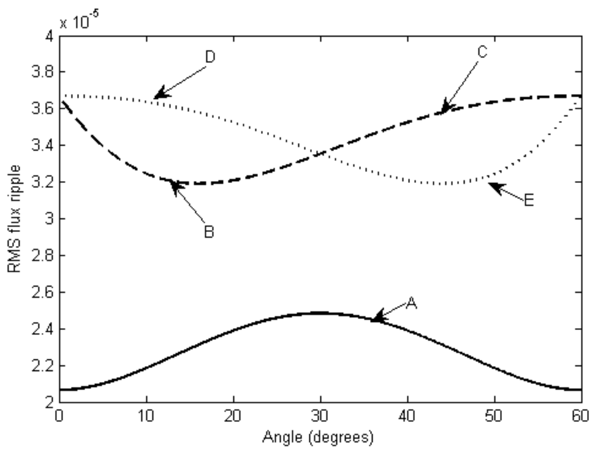

Fig. 4 RMS flux ripple over a subcycle against the angle α at M_i=0.**4**
(A: SVPWM, CD: DPWM1, BE: DPWM3, DE: DPWMMAX, DPWM2 and BC: DPWMMIN, DPWM0).

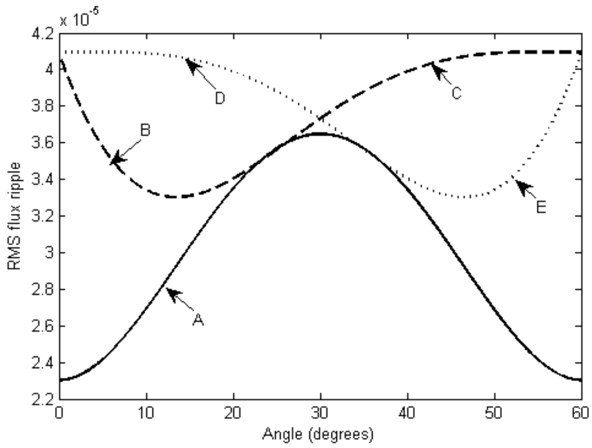

Fig. 5 RMS flux ripple over a subcycle against the angle α at M_i=0.55
(A: SVPWM, CD: DPWM1, BE: DPWM3, DE: DPWMMAX, DPWM2 and BC: DPWMMIN, DPWM0).
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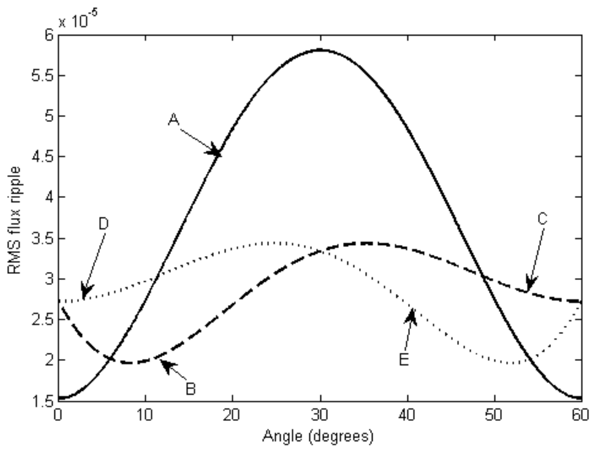

Fig. 6 RMS flux ripple over a subcycle against the angle α at M_i=0.75
(A: SVPWM, CD: DPWM1, BE: DPWM3, DE: DPWMMAX, DPWM2 and BC: DPWMMIN, DPWM0).
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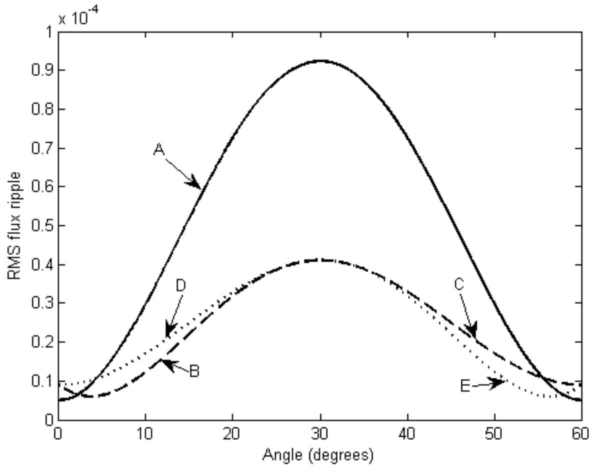


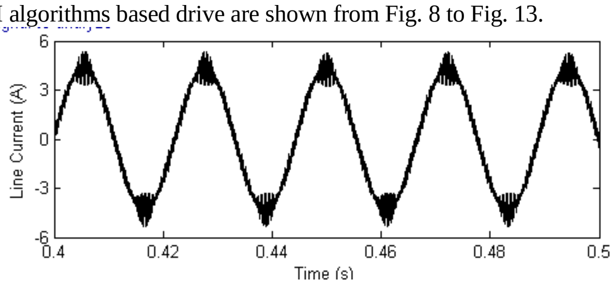
Fig. 7 RMS flux ripple over a subcycle against the angle α at M_i =0.906
(A: SVPWM, CD: DPWM1, BE: DPWM3, DE: DPWMMAX, DPWM2 and BC: DPWMMIN, DPWM0).

From Fig. 4– Fig. 7, it can be observed that replacing α by $(60^o - \alpha)$ in the rms stator flux ripple expressions of SVPWM does not change its value. However, the rms ripple over a subcycle is not symmetric about the center of the sector for the other PWM sequences. Moreover, it can be observed that the DPWM3 algorithm gives less harmonic distortion when compared with the other DPWM algorithms. In order to minimize the harmonic distortion in the line current, the rms current ripple or rms stator flux ripple over every sampling time period should be reduced. The proposed hybrid PWM (HPWM) algorithm employ the best PWM algorithm among the SVPWM and DPWM3 algorithms to minimize the rms current ripple in every sampling time period.

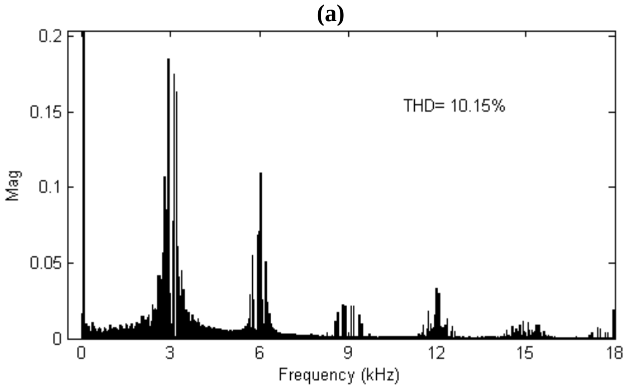
In the proposed HPWM algorithm, in every sampling time period the rms stator flux ripples of SVPWM and DPWM3 are compared with each other and the PWM algorithm, which has less rms stator flux ripple is applied to minimize the THD. Thus, the proposed HPWM algorithm uses the DPWM3 algorithm in conjunction with SVPWM algorithm.

IV. SIMULATION RESULTS AND DISCUSSION

To verify the proposed HPWM algorithm, numerical simulation studies have been carried out on v/f controlled induction motor drive and results have been presented. Simulation studies have been carried out at different supply frequencies (different modulation indices). The steady state current waveforms along with the total harmonic distortion (THD) values for SVPWM and proposed HPWM algorithms based drive are shown from Fig. 8 to Fig. 13.

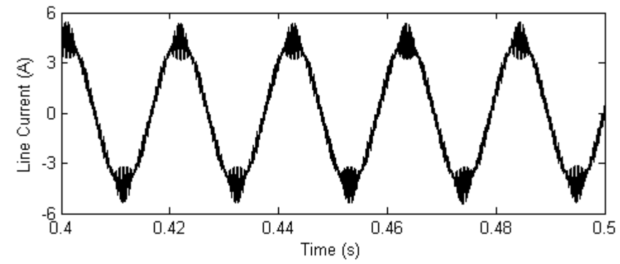


(a)

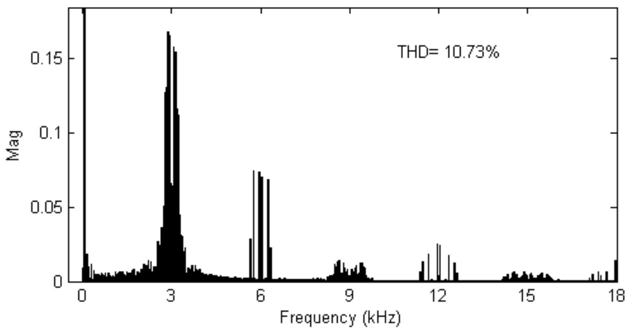


(b)

Fig. 8 simulation results of SVPWM based drive (f=45 Hz or M_i = 0.8154) (a) current (b) Harmonic spectra of current

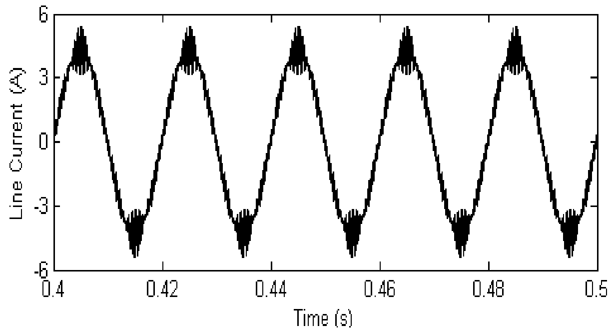


(a)

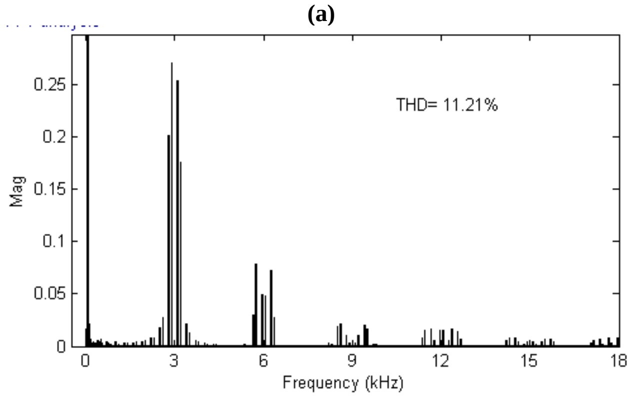


(b)

Fig. 9 simulation results of SVPWM based drive at (f=48 Hz or $M_i = 0.87$ (a) current (b) Harmonic spectra of current

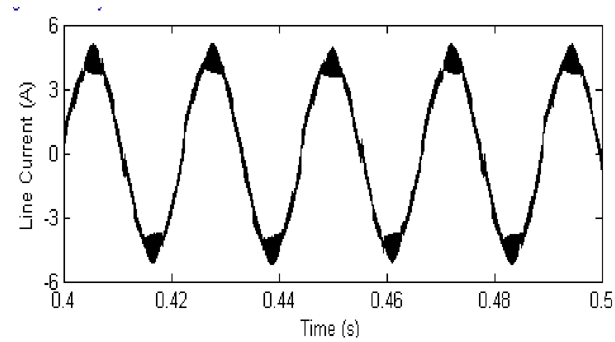


(a)

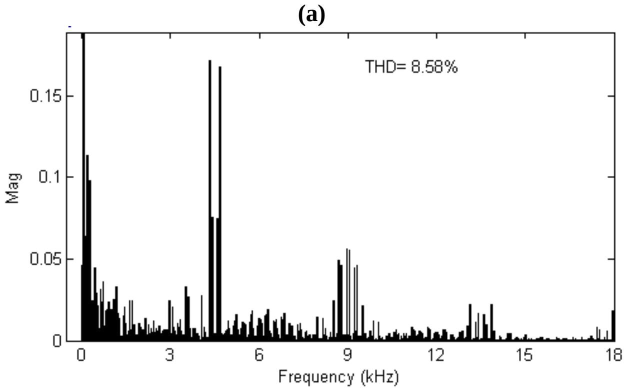


(b)

Fig.10 simulation results of SVPWM based drive (a) current (f=50 Hz or $M_i = 0.906$) (b) Harmonic spectra of current

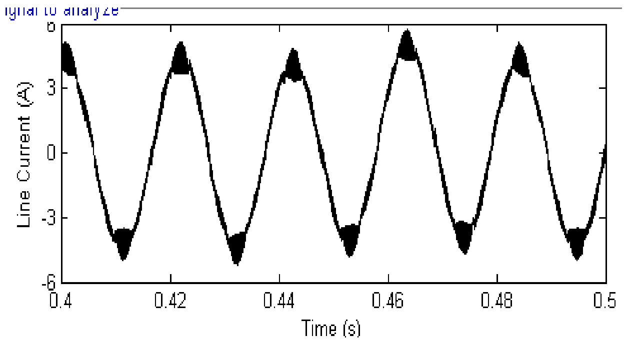


(a)

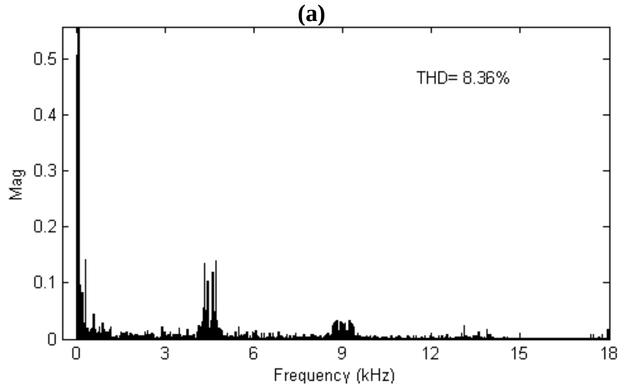


(b)

Fig. 11 simulation results of proposed HPWM based drive at f=45 Hz or $M_i = 0.8154$ (a) current (b) Harmonic spectra of current

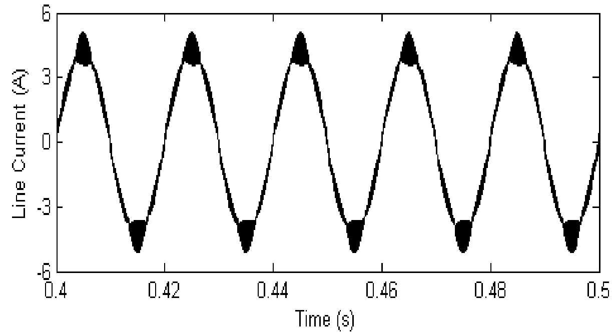


(a)

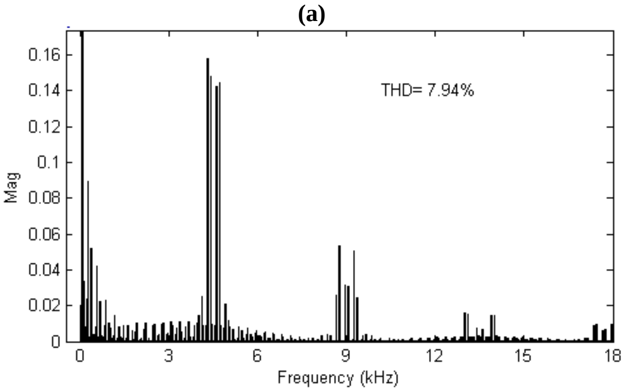


(b)

Fig. 12 simulation results of proposed HPWM based drive at f=48 Hz or $M_i = 0.87$ (a) current (b) Harmonic spectra of current



(a)



(b)

Fig.13 simulation results of SVPWM based drive (a) current (f=50 Hz or $M_i = 0.906$) (b) Harmonic spectra of current

From the simulation results, it can be observed that the proposed HPWM algorithm gives superior waveform quality when compared with the SVPWM algorithm. Also, proposed PWM algorithm gives spread spectra and hence reduces the acoustical noise of the induction motor. Thus, the proposed algorithm reduces both the harmonic distortion and acoustical noise.

V. CONCLUSIONS

A simple and novel GPWM algorithm for VSI fed induction motor drives is presented in this paper. The proposed algorithm generates a wide range of DPWM algorithms along with SVPWM algorithm by using the instantaneous phase voltages only. By utilizing the concept of stator flux ripple, the harmonic analysis of various PWM algorithms has been carried out and the flux ripple characteristics are presented. By comparing these characteristics, best PWM algorithm has been used in the proposed HPWM algorithm. Thus, the proposed HPWM algorithm gives reduced harmonic distortion when compared with the SVPWM algorithm. The simulation results confirm the effectiveness of the proposed PWM algorithm.

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