J. Indian Inst. Sci., July–Aug. 1987, 67, pp. 271–277
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Modulation strategies for variable speed induction motor drives*

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Abstract

In this paper a description of some of the available modulation strategies and their suitability for induction motor drives is discussed. Comparison of various schemes is undertaken by defining suitable performance indices. Comparison charts are presented to illustrate the effectiveness of each scheme.

Key words: Induction motor drives, modulation strategies.

1. Introduction

The recent advancement in power semiconductor technology coupled with technological improvements in power control techniques now provide means for effectively using pulse width modulation (PWM) techniques for variable speed motor drive applications. PWM-inverter-fed induction motor drive is favored for its improvements in motor system dynamics, efficiency, power factor and ease in control[1]. Also the PWM method of control permits the use of a fixed voltage DC link and thus facilitates parallel operation of several inverters. Several modulation strategies are available in the literature[2,3]. However, the choice of a modulation strategy should be so chosen to minimize the effect of unwanted harmonics of the motor terminal voltage. The presence of these undesirable voltage components can cause torque pulsations[4–6], speed disturbances, acoustic noise which could be undesirable for many domestic and industrial environments[3], motor over heating due to excessive copper and iron losses[5,7,8] and current transients which can overtax the inverter switches. Unless the modulation approach is carefully selected to contain within reasonable limits these harmful side effects of the modulation process, full practical advantage of the favorable features of the PWM drive cannot be taken.

This paper discusses some aspects of the modulation problems encountered in the development of a practical ac drive without regard to a particular power circuit configuration. Suitable performance indices based on the harmonic loss factor, rms value

*First presented at the Platinum Jubilee Conference on Systems and Signal Processing held at the Indian Institute of Science, Bangalore, India, during December 11–13, 1986.

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of the harmonics in the audible range (mainly to evaluate the noise performance) and pulsating torques caused by current harmonics are defined. The performance indices are used to effectively evaluate the PWM schemes for the induction motor drive.

2. Description of the available PWM schemes

Figure 1 illustrates the general arrangement of the rectifier inverter induction motor drive system. Inverter switches are opened and closed according to a predefined PWM strategy. In this section a brief description of the available PWM schemes is presented along with their corresponding spectrum.

2.1 The sine PWM technique

This scheme is most popular and widely used in industry. The PWM pulses are derived from the intersection of the triangular carrier wave and the low frequency sinusoid. Figure 2 illustrates the waveforms of the sine PWM scheme, line-to-line voltage and the corresponding frequency spectrum. The magnitude of the fundamental can be varied by varying the amplitude of the intersecting low-frequency sinusoid. The maximum amplitude of the fundamental obtainable with this scheme is 0·866 pu which contributes to low-inverter utilization. This is the main disadvantage of this scheme. Synchronization of the carrier with the reference sinusoid eliminates subharmonic components at the output. However, suitable ratio changing schemes have to be adopted if wide variation in speed is required.

2.2 The modified sine PWM technique[9]

In this scheme (fig. 3) only first and last 60° intervals (per half-cycle) are generated through the intersection of the triangular carrier and the reference sinusoid. This technique has the advantage of producing a magnitude of the fundamental close to unity at the output.

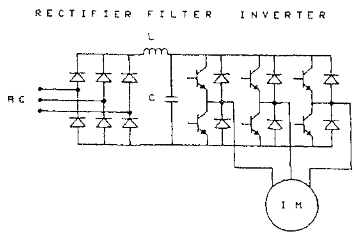

Fig 1. Rectifier inverter induction motor drive system.

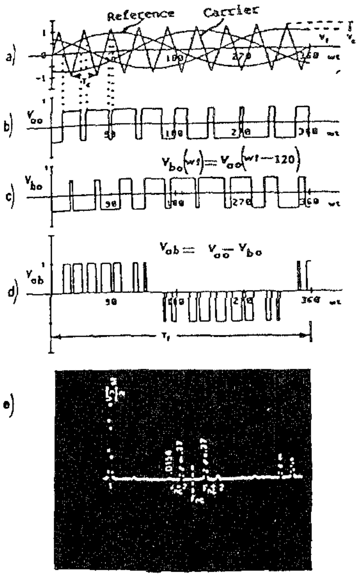

FIG 2. SPWM waveforms. (a) Carrier and reference sinusoid; (b), (c) Line-to-neutral voltages; (d) Line-to-line voltages; (e) Frequency spectrum of (d).

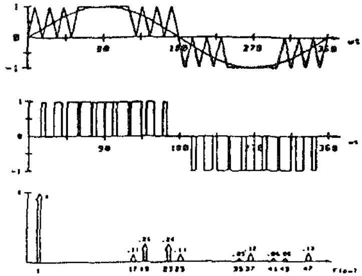

FIG 3. MSPWM waveforms. (a) Carrier and reference sinusoid; (b) Line-to-line voltages; (c) Frequency spectrum of (b).

2.3 *Third harmonic injection PWM technique*[10]

In this scheme, 17% third harmonic component is added to the low-frequency sinusoid. The resulting flat-topped waveform (fig. 4) which intersects the triangular carrier wave allows a boost in the magnitude of the fundamental component while maintaining minimum harmonic voltage components at the output.

2.4 *Harmonic elimination PWM*[11]

This scheme was proposed by Patel and Hoft[11] and is based on selecting particular switching instants in the PWM waveform such that a set of unwanted harmonic components are completely eliminated. Figure 5 shows an experimental PWM switching pattern to eliminate 5,7,11,13,17,19,23,25 (N = 9) harmonics and its corresponding frequency spectrum. The triplen harmonics do not have any effect in a three-phase

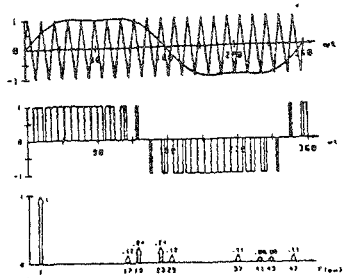

FIG 4. Harmonic injection PWM. (a) Carrier and reference waves; (b) Line-to-line voltage; (c) Frequency spectrum of (b).

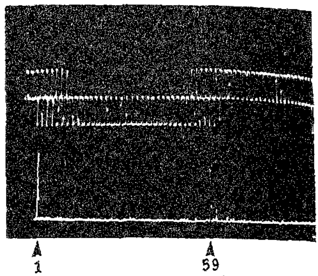

FIG 5. Switching pattern for eliminating 5,7,11,13,17,19,23,25 $V_{pu} = 1$ (for three phase). (a) Line to line voltage V_{ab}; (b) Frequency spectrum of (a).

unconnected neutral load. The most dominant harmonic in the present case is 29. This scheme is particularly suitable to operate the motor at base speed and results in excellent performance of the drive. However, at lower frequencies the number of switchings has to be increased to achieve good performance. Also computation of the various switching instants to eliminate a set of harmonics is quite cumbersome even on a mainframe computer.

3. Comparison of PWM schemes

In this section the available PWM schemes are evaluated for the induction motor drive. A carrier frequency ratio of 15 is assumed for sine PWM schemes. These are compared with harmonic elimination PWM with N = 5 and N = 9. Various performance indices are defined to make this comparison possible.

3.1 *Performance index based on harmonic losses*

The additional losses incurred in the motor due to the unwanted voltage harmonics contribute to the motor heating and as a result considerable derating of the motor may be required. Thus an optimum PWM technique should minimize additional harmonic losses in the motor. These are primarily harmonic copper losses and can be computed as follows.

The magnitude of the kth harmonic current in the motor is given by,

$$I_k = \frac{V_k}{k \cdot f \cdot X} \tag{1}$$

where V_k is the pu kth harmonic voltage and f is the pu fundamental frequency. The kth harmonic copper loss is $I_k^2 \cdot R_k$, where R_k is the resistance of the motor of the kth harmonic. Therefore the harmonic copper loss can be expressed as,

$$P_L = I_k^2 \cdot R_k. \tag{2}$$

The skin effect on the resistance at harmonic frequencies can be taken into consideration for more accurate loss prediction. Therefore,

$$P_L = \frac{1}{X^2} \cdot \sum_{k \neq 1} \frac{V_k^2 \cdot R_k}{(k \cdot f)^2}. \tag{3}$$

Figure 6 shows the pu harmonic loss for various PWM waveforms. The superiority of selective harmonic elimination PWM for n = 9 is quite evident despite having fewer switching instants per cycle. Harmonic injection PWM is found to be superior to sine PWM above 0·6 pu voltage. However, MSPWM and harmonic elimination PWM with N = 5 exhibit higher losses. Previous theoretical and experimental investigations have confirmed that increase in core losses due to time harmonic main fluxes is negligible[8].

3.2 *Noise factor*

Acoustic noise of the PWM-fed induction motor drive is caused by harmonic currents in the audible range[3]. Accordingly, to minimize the acoustic power, it is necessary to reduce the harmonic current as much as possible. Thus a noise factor is defined based on the rms value of the harmonic components in the audible range of a particular PWM strategy. These harmonic currents are determental in causing acoustic noise in the motor. Such factors are becoming increasingly important in the present wide-spread application of ac motor drives in industrial, domestic and office environments. Thus an optimum PWM technique should generate minimum noise due to harmonics[3]. Figure 7 illustrates the noise factor of various PWM schemes. From this comparison sine PWM is superior in terms of noise performance below 0·6 pu voltage. MSPWM and harmonic elimination PWM with N = 5 exhibit higher noise factors than all other schemes. This is mainly due to the amplification of higher order harmonics.

3.3 *Pulsating torque factor*

PWM power supplies produce dominant harmonics at certain frequencies, and torque fluctuations due to such harmonics may be large particularly at low speeds. In order to compare the low-speed capability of various PWM techniques, the dominant pulsating torque developed by each waveform is calculated. The effects of rotor speed fluctuations and dc link voltage variations are not taken into consideration for simplicity. Robertson and Hebbar[4] have outlined the procedure for computing the pulsating torque due to harmonics based on the equivalent circuit of the induction motor. Air gap flux levels at harmonic frequencies are very small[12] and the dominant torque fluctuations are those due to the interaction of the fundamental flux in the air gap with the harmonic rotor currents. Thus the kth rotor current I_k reacts with the fundamental flux ϕ_1 to produce a pulsating torque component whose pu amplitude is given by,

$$T_{k \pm 1} = \phi_1 \cdot I_k \cdot \tag{4}$$

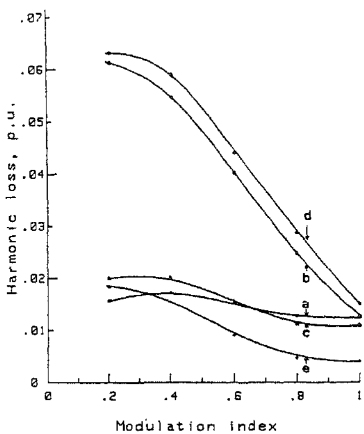

FIG 6. Harmonic losses as function of pu fundamental frequency. (a) Sine PWM; (b) MSPWM; (c) Harmonic injection PWM; (d) Harmonic elimination PWM (N = 5); (e) Harmonic elimination PWM (N = 9).

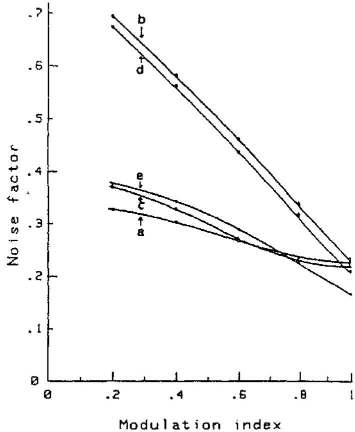

FIG 7. Noise factor as function of pu fundamental frequency. (a) Sine PWM; (b) MSPWM; (c) Harmonic injection PWM; (d) Harmonic elimination PWM (N = 5); (e) Harmonic elimination PWM (N = 9).

It should be noted that the torque harmonic is of order $(k + 1)$ for negative sequence rotor currents and of order $(k - 1)$ for positive sequence currents. Substituting for I_k from (1) in (4) we have,

$$T_{k+1} = \frac{\phi_1 \cdot V_k}{k \cdot f \cdot X}. \tag{5}$$

Thus the dominant pulsating torque component is computed using the above expression for each PWM waveform, sine PWM with a carrier frequency ratio of n is characterized by large amplitude voltage harmonics at $(n \pm 2)$ and $(2n \pm 1)$ times the fundamental frequency. The $(2n \pm 1)$th harmonics both develop pulsating torques of order 2n and are approximately in phase, thus contributing to a major hunting torque component. In the present case with a carrier frequency ratio of 15 the dominant torque harmonic is 30 times the frequency of the fundamental and its worst case value is $T_p(max) = 0{\cdot}45$ pu at Vpu = 0·2. In the case of harmonic injection PWM $T_p(max) = 0{\cdot}51$ of order 30 at Vpu = 0·2. For MSPWM $T_p(max) = 0{\cdot}56$ of the order 12. The pulsating torque is predominant in the case of harmonic elimination PWM for N = 5 $T_p(max) = 0{\cdot}87$ pu at Vpu = 0·2 and of the order 18, for N = 9 $T_p(max) = 0{\cdot}525$. The pulsating torque component $T_p(max)$ increases with the decrease in the carrier frequency ratio which contributes to the pulsating torque.

4. Conclusions

Comparison charts presented illustrate the effectiveness of each PWM scheme. Sine PWM, harmonic injection PWM and harmonic elimination PWM (N = 9) are found to provide minimum losses due to harmonics and the sine PWM scheme is found to be particularly suitable for silent operation of the drive below 0·8 pu of the base speed.

Acknowledgement

The authors would like to thank Dr. Manias and Mr. M. Boost for providing the data for sine PWM techniques. Also interesting discussions with Dr. P.D. Ziogas are gratefully acknowledged.

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