# Comparative Study of PWM Inverters Fed 3-Phase Induction Motor

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**Abstract – In this paper the performance of three-phase induction motor, fed from SPWM & MSPWM inverters are discussed. Computer simulations are used to compare the performances. The 3 phase induction motor model is simulated with sinusoidal excitation. The line current, output power, and efficiency are compared with the experimental results. The simulated results are very close to the practical values and the difference is less than 10%. The torque developed by the motor, when fed with SPWM-inverter and that of MSPWM-inverter are compared. The distortion in the developed torque in both the cases is compared. From the simulation results it is observed that, the average value of torque developed by the motor is same when the motor is fed with SPWM and MSPWM inverters. But the distortion is less when the motor is excited with MSPWM inverter.**

**Keywords – PWM inverters, induction motor drive, 3-phase induction motor, SPWM inverter, MSPWM-inverter.**

## I. INTRODUCTION

In many modern adjustable-speed drives the demand is for precise and continuous control of speed, or position with long-term stability, good transient performance, and high quality efficiency. In power electronics, various pulse-width modulation (PWM) techniques are widely employed to control the output of static power converters. The reason for using PWM techniques is that they provide voltage and/or current wave-shaping customized to the specific needs of the application under consideration. Generally, two classes of PWM techniques for static power converters can be identified. The programmed or optimal PWM techniques that produce switching patterns based on optimization of specific performance criteria are the first. 'The other class is based on certain low-frequency reference or modulating waveform, which is compared with a high-frequency carrier waveform. These techniques are known as carrier PWM techniques [1]. To illustrate the main idea associated with the carrier PWM techniques, the sinusoidal pulse-width modulation (SPWM) technique. It is based on the principle of comparing a triangular carrier signal with a sinusoidal reference waveform [2].

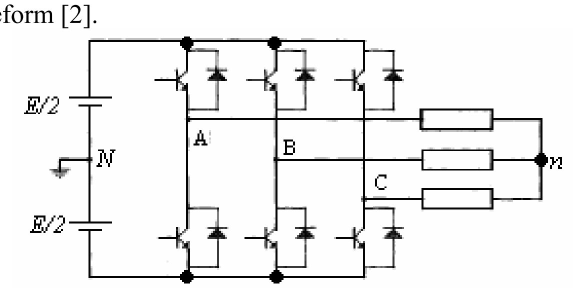


Fig. 1: Voltage source inverter

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Although the implementation of this technique is relatively simple, there are two drawbacks when compared with the six -step inverter as follows:

- Attenuation of the fundamental component of the output waveform or in other words the maximum line-to-line amplitude voltage is 0.866 pu ;
- high switching frequency, when compared with the six-step inverter, which means increased stresses on converter semiconductor elements.

To overcome these problems, improved PWM techniques have been proposed in the technical literature over the last 35 years. There are numerous technical papers dealing with PWM control in inverter-rectifier systems. Furthermore, when the microprocessors became available, significant work is reported in [3]-[6] where problems associated with the on-line computation of the switching signals had to be dealt with. However, some proposed techniques improve only the gain of the modulator, and some others improve the gain and provide reduction in the effective switching frequency. Converter effective switching frequency is defined as the number of current interruptions normalized over the output period (7-9).

In this paper a new scheme is proposed called, modified sinusoidal PWM pattern to improve the gain of the pulse-width modulator. However, this PWM technique that provides not only increased gain, but also a reduction in the effective switching frequency, since switching elements are kept inactive for a specified interval. For instance, when the neutral point of the load is floating in a voltage source inverter, converter phase legs can be "relaxed' to achieve lower effective switching frequency by avoiding intersections for some interval. This can be done by employing a special carrier waveform. Therefore, switching losses and resulting stresses of the PWM converter for the same carrier frequency are potentially reduced when comparing with continuous PWM techniques. The objective of this paper is to present and critically discuss and compare the influence of these modulation techniques on 3- phase induction motor.

## II. SPWM TECHNIQUE AND ITS INFLUENCE ON 3-PHASE INDUCTION MOTOR

In sinusoidal pulse width modulation a high frequency triangular carrier wave $v_c$ is compared with a sinusoidal reference wave $v_r$ of the desired frequency. The intersection of $v_c$ and $v_r$ waves determines the switching instants and commutation of the modulated pulse. The carrier and reference waves are mixed in a comparator. When he sinusoidal reference wave has magnitude higher than the triangular wave, the comparator output is high otherwise it is low. The ratio of $v_r$ / $v_c$ is called the amplitude modulation index ($m_a$) and it controls the harmonic content of the output voltage waveform.

$$m_a = \frac{V_{r.}}{V_c} \tag{1}$$

The pulse widths and the RMS value of voltage depend upon $\frac{v_r}{v_c}$. The frequency of reference wave decides the output frequency. The carrier frequency decides number of pulses per half cycle. More the number of pulses the smoother is the waveform.
The RMS value of output voltage can change from 0 to maximum value by changing the modulation index.

The RMS value of output voltage is

$$V_0 = V_d[\sum_{M=1}^{p}\left(\frac{M}{\pi}\right)]^{\frac{1}{2}} \tag{2}$$

where 'p' is number of pulses per half cycle.

$$V_0 = \sum_{m-1}^{p} C_n \sin n\omega t \tag{3}$$

where $C_n = \sqrt{A_n^2 + B_n^2}$

The voltage waveform can be expanded in to Fourier series.

$$A_n = \sum_{m=1}^{p}\left(\frac{2V_d}{n\pi}\right)[\sin n(\alpha_m + \delta_m) - \sin(n\alpha_m)] \tag{4}$$

$$B_n = \sum_{m=1}^{p}\left(\frac{2V_d}{n\pi}\right)[\cos(n\alpha_m) - \cos n(\alpha_m + \delta_m) \tag{5}$$

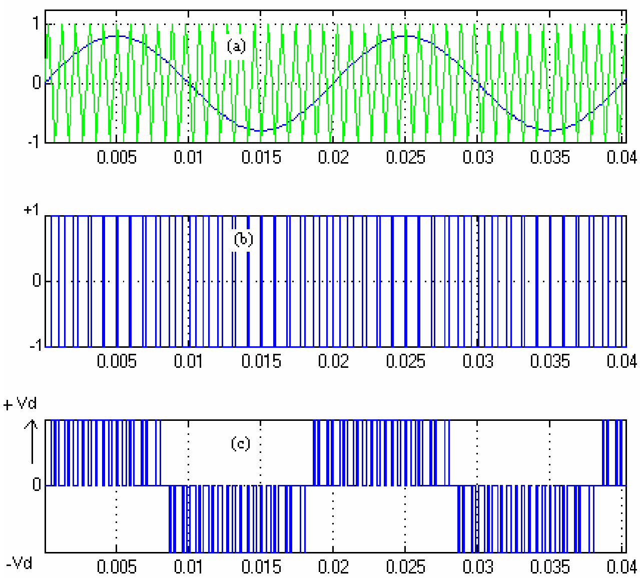

Fig. 2: a) Reference and carrier waveforms. b) line-to-neutral voltage. C) line-to-line output voltage

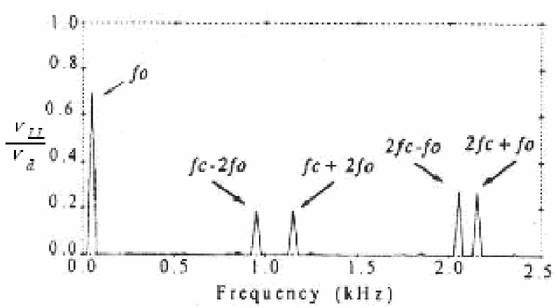

Fig. 3: Harmonic spectrum of line-to-line voltage

In the linear region $(m_a \le 1.0)$, the fundamental-frequency component in the output voltage varies linearly with the amplitude modulation ratio $m_a$. Fig. 2 and Fig. 3 show the waveforms of SPWM and harmonic spectrum of line-to-line voltage, respectively. The peak value of the fundamental-frequency component in one of the inverter leg is,

$$(V_{AN})_1 = m_a \frac{V_d}{2} \tag{6}$$

The line-to-line rms voltage at the fundamental frequency, due to $120^0$ phase displacement between phase voltages can be written as

$$V_{LL,rms} = \frac{\sqrt{3}}{\sqrt{2}}(V_{AN})_1 \tag{7}$$

$$= \frac{\sqrt{3}}{2\sqrt{2}} m_a V_d \tag{8}$$

$$= 0.612 m_a V_d \quad (m_a \le 1.0) \tag{9}$$

From equation 9 we observe that the fundamental rms value of output voltage varies linearly with the modulation index.

## III. Modified Sinusoidal Pulse Width Modulation

The technique of generation of waveform is the further improvement of the sinusoidal pulse modulation. In SPWM technique it is observed that the pulse width in the range of $60^o$ to $120^o$ does not vary much and is constant for a longer duration. Instead of providing the number of pulses in the $60^o$ to $120^o$ interval by comparing a reference wave with the carrier wave a single pulse of that duration is introduced in that space so that the switching losses of the power transistor is reduced during this interval and there by improving the wave form as suitable for induction motor drives .So to generate the gating pulses for the switching devices the carrier wave is applied during the first and last $60^o$ intervals per half cycle. This type of modulation is known as Modified Sinusoidal Pulse Width Modulation (MSPWM). This type of switching the sine wave reserves components with minimal number of switching there by giving a grater performance and efficiency of the inverter.

The number of pulses '$q$'in the $60^o$ is normally related to the frequency ratio by $\frac{f_C}{f_0} = 6q$.

In a three phased Delta /Star connected network, even harmonic are absent in star connected network the third harmonic and its multiples will be absent. The remaining present are $5^{th}$, $7^{th}$ $11^{th}$, $13^{th}$, etc which can be eliminated by properly positioning the pulses in the first and last $60^o$ intervals of the half cycle. Any number of unwanted harmonics at the out put of the single phase inverter can be eliminated by introducing the number of symmetrically placed voltages notches i.e., by suitably modifying the MSPWM wave form to calculate the positioning of the notches we will consider the Fourier analysis of the output voltage waveform which is given by

$$V_0 = \sum_{n=1,3,5}^{\infty} B_n \sin \omega t. \tag{10}$$

where

$$B_n = \frac{4V_s}{\pi}\left[\int_0^{\alpha_1} \sin n\omega t\, d\omega t + \int_{\alpha_2}^{\frac{\pi}{2}} \sin n\omega t\, d\omega t + .........\right] \quad (11)$$

Considering only for two notches

$$B_n = \frac{4V_s}{\pi}\,\frac{1-\cos n\alpha_1 + \cos n\alpha_2}{n} \quad (12)$$

The third and fifth harmonics would be eliminated if

$$1-\cos 3\alpha_1 + \cos 3\alpha_2 = 0$$

$$1-\cos 5\alpha_1 + \cos 5\alpha_2 = 0$$

Solving the above equations by iterations we get

$\alpha_1 = 17.83^0$ and $\alpha_2 = 37.07^0$

Therefore the MSPWM technique can be applied to generate the notches, which would eliminate certain harmonics effectively in the output voltage.

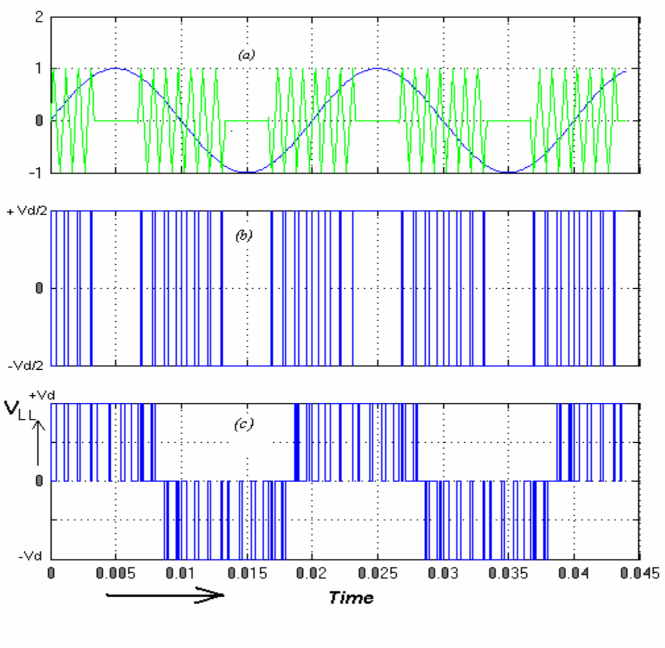


Fig. 4: a) Reference and carrier waveforms. b) line-to-neutral voltage. c) line-to-line output voltage

Fig. 4 and Fig. 5 show the waveforms of MSPWM technique and harmonic spectrum of line-to-line voltage, respectively. Here the carrier frequency $f_c$ is 1050Hz. modulation index $m_a$ is 0.8 and reference signal frequency is 50 Hz. The DC bus voltage is 508 volts. Modulation index is varied from 0 to 1 (Linear modulation) to vary the rms value of the output voltage.

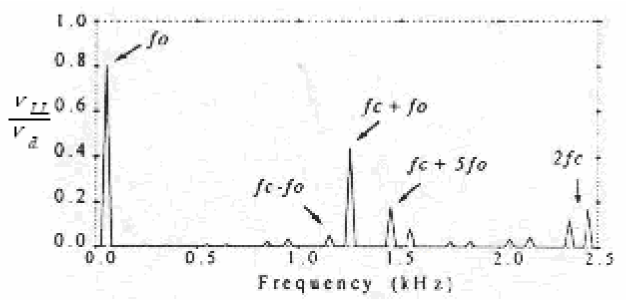


Fig. 5: Spectrum of line-to-line output voltage

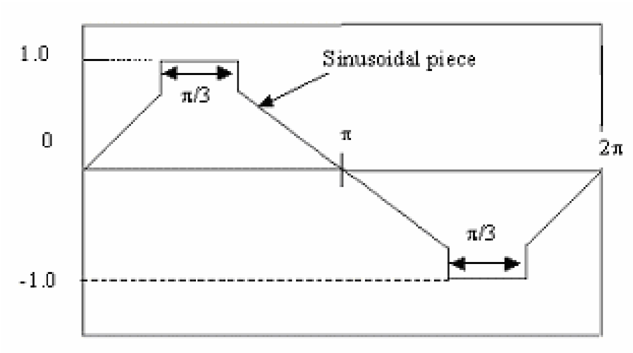


Fig. 6: Reference waveform for MSPWM technique

Referense wave form for MSPWM tecnique is as shown above and is defined as,

$$f_A(\omega t) = \begin{cases} m\sin(\omega_0 t) & 0 \le \omega_0 t \le \frac{\pi}{3} \\ 1 & \frac{\pi}{3} \le \omega_0 t \le \frac{2\pi}{3} \\ m\sin(\omega_0 t) & \frac{2\pi}{3} \le \omega_0 t \le \pi \end{cases} \quad (13)$$

$$V_{rms} = \sqrt{\frac{1}{T}\int_0^T (v(t))^2\, dt} \quad \text{(General Form)} \quad (14)$$

$$V_{rms} = \sqrt{\frac{1}{T}\int_0^T (f_A(\omega t))^2\, dt} \quad (15)$$

$$V_{rms} = \sqrt{\frac{1}{\pi}\left[\begin{array}{l}\int_0^{\frac{\pi}{3}} (m_a \sin \omega_0 t)^2\, d\omega_0 t + \int_{\frac{\pi}{3}}^{\frac{2\pi}{3}} (1)^2\, d\omega_0 t\; + \\ \int_{\frac{2\pi}{3}}^{\pi} (m_a \sin \omega_0 t)^2\, d\omega_0 t\end{array}\right]} \quad (16)$$

$$V_{rms} = \sqrt{\frac{1}{3}\left(m_a^{\,2} + 1\right)} \quad (17)$$

$$V_{rms} = 0.816\ m_a V_d \quad (18)$$

If $m_a = 1$,

$V_{rms} = 0.816\ V_d$

From equation (14)-(18), we observe that the fundamental rms value of output voltage varies linearly with the modulation index.

## IV. Experimental Results

To experimentally validate the proposed MSPWM technique, mathematical models of three-phase SPWM & MSPWM inverter have been developed and simulated using MATLAB. A 3-phase induction motor is selected with the specifications shown in the table below.

**Table 1: Specifications of the motor**

| | |
|---|---|
| Type of the motor | 3-ϕ Induction motor |
| Rated output power | 3.7 kW (5 HP) |
| Rated line-to-line voltage | 415 V |
| Rated current | 8.4 A |
| Number of poles | 4 |
| Frequency of the supply voltage | 50 Hz |
| Rated speed | 1485 rpm |
| Type of winding | Y-connected |

The parameters of this motor are calculated by conducting No-load test, Blocked Rotor test and Retardation test. This motor model is simulated using MATLAB and the simulated results are compared with that of practical results. It is found that these two results are very close to each other. Then the motor model is simulated with the proposed SPWM and MSPWM inverters. Table 2 shows the readings of load test from no-load to full-load.

**Table 2: Experimental results of motor on load test at rated voltage (415V)**

| $I_L$ Amps | $W_1$ Watts | $W_2$ Watts | $T_L$ N-m | N rpm | I/p Watts | O/p Watts | %η |
|---|---|---|---|---|---|---|---|
| 4.5 | 1000 | -800 | 0 | 1480 | 200 | 0 | 0 |
| 4.9 | 1400 | -500 | 2.53 | 1463 | 900 | 387.6 | 43 |
| 5.5 | 1700 | -100 | 7.6 | 1413 | 1600 | 1124.5 | 70.2 |
| 6.1 | 2100 | 0 | 10.96 | 1376 | 2100 | 1579 | 75.2 |
| 6.8 | 2400 | 700 | 15.18 | 1320 | 3100 | 2098 | 67.6 |

**Table 3: Simulation results of motor model on load test at rated voltage (415V)**

| S.No. | $I_L$ Amps | $T_L$ N-m | N rpm | O/p Watts | I/p Watts | %η |
|---|---|---|---|---|---|---|
| 1. | 4.52 | 0 | 1482 | 0 | 195 | 0 |
| 2. | 4.6 | 2.53 | 1463 | 287 | 859 | 45 |
| 3. | 5.3 | 7.6 | 1423 | 1133 | 1523 | 74 |
| 4. | 5.7 | 10.96 | 1448 | 1547 | 2048 | 75.5 |
| 5. | 6.7 | 15.18 | 1293 | 2055 | 3034 | 67.7 |

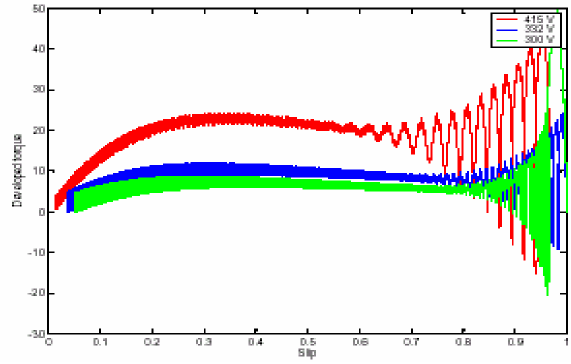


Fig. 7: Slip-Torque chars. of the motor for different voltages fed from SPWM inverter

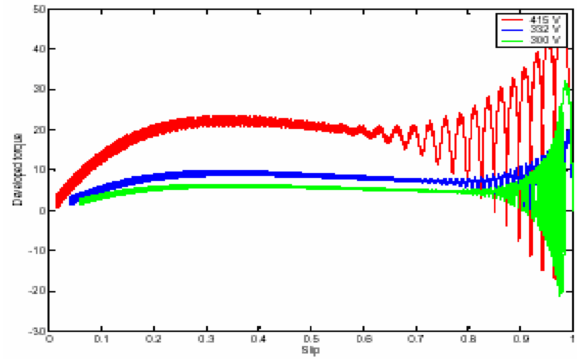


Fig. 8: Slip-Torque chars. of motor fed with MSPWM inverter for different voltages

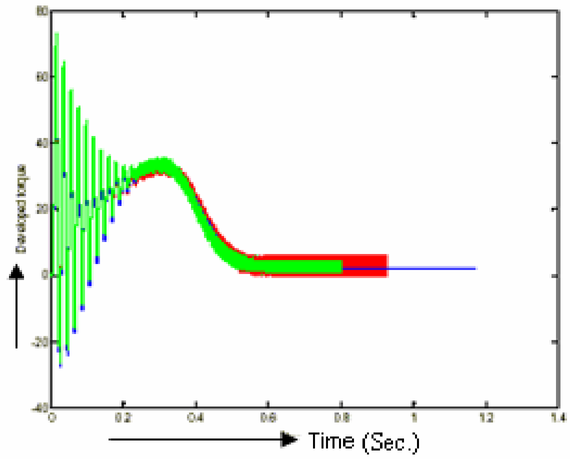


Fig. 9: Torque developed by the motor fed with sine voltage, SPWM and MSPWM inverters

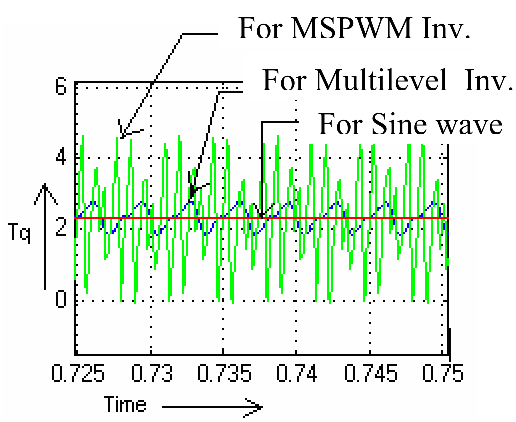


Fig. 10: Torque developed by the motor in steady state fed with sine voltage, SPWM and MSPWM inverters

## V. CONCLUSION

The comparison is made on the basis of ripple in the developed torque of the motor on steady state. Fig. 9 and 10 shows simulation results of the torque developed by the motor excited at rated voltage with sinusoidal voltage, SPWM-inverter and MSPWM-inverter. All the three graphs have been plotted on the same axis. The blue colour graph is plotted for sinusoidal excitation, red colour graph is plotted for SPWM inverter excitation, and green colour graph is plotted for MSPWM inverter excitation at rated voltage. From the graph it is observed that, the average value of torque developed by the motor is same when the motor is fed with SPWM and MSPWM inverters. But the ripple (distortion) magnitude is more when the motor is excited with SPWM inverter compared with that of MSPWM inverter (*i.e.* There is 75% reduction in the ripple magnitude). Hence MSPWM technique is the best suitable for a 3-phase induction motor compared to SPWM inverter technique.

Fig. 10: Photograph of Experimental setup

In the fig. 10, there are three rows of switching devices. Each row consists of four devices (i.e. one full bride inverter), one bridge is used for Sinusoidal PWM technique, one bridge is used for Modified SPWM technique and the second row of three bridges are used for multilevel inverter technique. The Multilevel inverter techniques are not discussed in this paper.

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## BIOGRAPHIES


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