Performance Characteristics of Inverter Controlled Three Phase Induction Motor: Teaching and Research.

C.U. Ogbuka, M.Eng.

Department of Electrical Engineering, University of Nigeria, Nsukka, Enugu State.

E-mail: ucogbuka@yahoo.com

ABSTRACT

The performance characteristics of a six-step inverter controlled three-phase induction motor is presented in this paper. Fourier-based analysis is used to determine the effect of the non-sinusoidal voltage supply on the motor currents made-up of the fundamental and the harmonic components. It is realized that the total magnetizing current is a good approximation to the fundamental component of the current thus making the induction motor respond negligibly to harmonics higher than the fundamental. Because of the half-wave symmetry, only the effect of the odd harmonics is investigated. The analysis is carried-out using MATLAB® as the programming tool.

(Keywords: induction motor, harmonics six step inverter, MATLAB)

INTRODUCTION

The induction machine is the most widely used type of machine in industry because of its robustness, reliability, low cost, high efficiency and good self-starting capability [1, 2, 3, 4]. Its low sensitivity to disturbances during operation make the squirrel cage motor the first choice when selecting a motor for a particular application [5]. In spite of this popularity, the induction motor has two inherent limitations: (1) the standard motor is not a true constant-speed machine, its full-load slip varies from less than 1% (in high-horse power motors) to more than 5% (in fractional-horsepower motors) and (2) it is not, inherently, capable of providing variable speed operations [6, 7].

These limitations can be solved through the use of adjustable speed controllers [8, 9]. The basic control action involved in adjustable speed control of induction motors is to apply a variable frequency variable magnitude AC voltage to the motor to achieve the aims of variable speed operation [10]. Both voltage source inverters and current source inverters are used in adjustable speed AC drives. The most common AC drives today are based on sinusoidal pulse-width modulation SPWM. However, voltage source inverters with constant volts/Hertz V/f are more popular, especially for applications without position control requirements, or where the need for high accuracy of speed control is not crucial [11].

INVERTER CONTROLLED INDUCTION MOTOR DRIVE

The three-phase inverter with the typical power circuit connection to a three-phase AC induction motor is shown in Figure 1 below. The power circuit consists of six self-commuted semiconductor switches S_1 to S_6 with their corresponding antiparallel diodes.

The present choice of semiconductor switches are Thynstor with External Commutator Circuit, Bipolar Junction Transistor (BJT), Metal Oxide Semiconductor Field Effect Transistors (MOSFET), Insulated Gate Bipolar Transistors (IGBT), Gate Turn-off Thyristors (GTO), MOS Controlled Thyristors (MCT) [12].

Fast recovery diodes are employed for the anti=parallel diodes while a snubber is required for each switch-diode pair. The motor, which is connected across a, b and c may have star or delta connection. The inverter may be operated as a Six-Step Inverter or a Pulse Width Modulated (PWM) Inverter

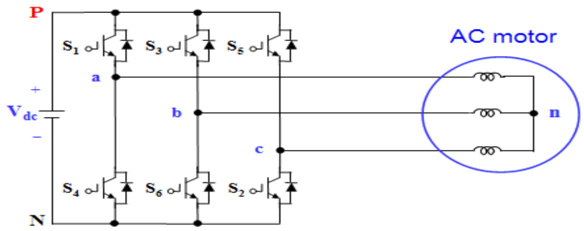

Figure 1: Three-Phase Voltage Source Inverter Connection to a 3-Phase AC Induction Motor.

When operated as a Six Step Inverter, the control signals, the switching sequence, and the line to negative voltages for the six switches of the inverter are shown in Figure 2.

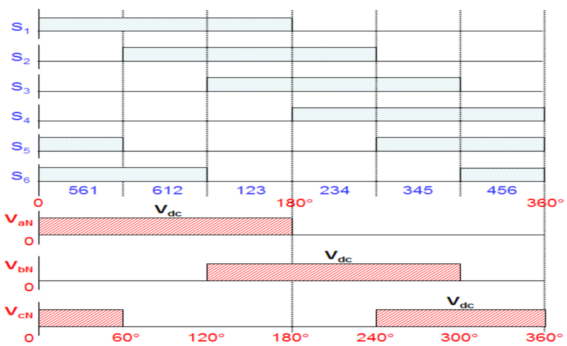

Figure 2: Waveforms of Gating Signals, Switching Sequence, Line to Negative Voltages for Six-Step Voltage Source Inverter.

In the inverter output voltage period of 360° (or 2π radians), each control signal has a duration of 180° (or π radians). The control signals are applied to numbers with a phase difference of 60° (or π/3 radians). The period has been divided into six equal intervals. The switches receive control signals as follows [13]: 561 (V_1) → 612(V_2) → 123 (V_3) → 234 (V_4) → 345 → (V_5) → 456 (V_6) → 561 (V_1) where 561 means that switches S_5, S_6, and S_1 are conducting and so on as shown in Figure 3.

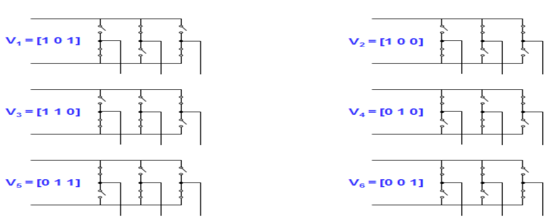

Figure 3: Six Inverter Voltage Vectors for Six-Step Voltage Source Inverter.

The switch pairs (S_1, S_4), (S_3, S_6), and (S_5, S_2) form three legs of the inverter. The switches in the same leg conduct alternately. Some time must elapse before the turn-off of one switch and turn on of another to ensure that both do not conduct simultaneously. Their simultaneous operation will cause a short circuit of the dc source resulting in a very fast rise in current. This fault, known as short-through fault can only be cleared by fast-acting fuse links. The figure below shows the line to line voltages and the line to neutral voltages resulting from the switching sequence described above.

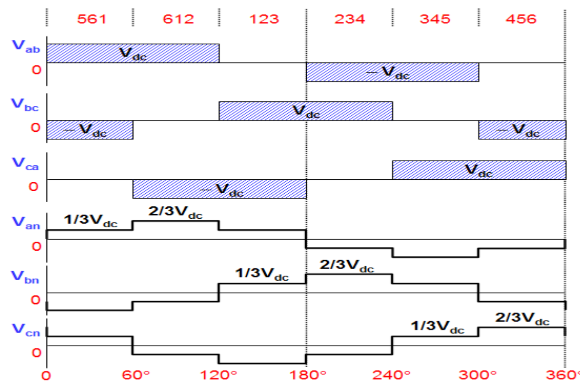

Figure 4: Waveforms of Line to Line Voltages and Line to Neutral Voltages for Six-Step Voltage Source Inverter.

Where, Line to Line Voltage:

$$V_{ab} = V_{aN} - V_{bN} \quad \textbf{(1a)}$$

$$V_{bc} = V_{bN} - V_{cN} \quad \textbf{(1b)}$$

$$V_{ca} = V_{cN} - V_{aN} \quad \textbf{(1c)}$$

Phase Voltages:

$$V_{an} = \frac{2}{3}V_{aN} - \frac{1}{3}V_{bN} - \frac{1}{3}V_{cN} \quad \textbf{(2a)}$$

$$V_{bn} = -\frac{1}{3}V_{aN} + \frac{2}{3}V_{bN} - \frac{1}{3}V_{cN} \quad \textbf{(2b)}$$

$$V_{cn} = -\frac{1}{3}V_{aN} - \frac{2}{3}V_{bN} + \frac{1}{3}V_{cN} \quad \textbf{(2c)}$$

In the operation under consideration, a cycle of the line voltage or the phase voltage is generated in six steps. Hence, when operating this way, the inverter is known as a six step inverter. The voltages V_{ab} and V_{an} are, respectively, described by the following Fourier series equations:

$$V_{ab} = \frac{2\sqrt{3}}{\pi} V_{dc}[\sin(\omega t + \frac{\pi}{6}) + \frac{1}{5}\sin(5\omega t + \frac{\pi}{6}) + + \frac{1}{7}\sin(7\omega t + \frac{\pi}{6})...] \quad \textbf{(3)}$$

$$V_{an} = \frac{2}{\pi} V_{dc}[\sin\omega t + \frac{1}{5}\sin 5\omega t + \frac{1}{7}\sin 7\omega t...] \quad \textbf{(4)}$$

Where V_{bc} and V_{ca} lag V_{ab} by 120° and 240° respectively. V_{bn} and V_{cn} also lag V_{an} by the same phase angles, respectively.

The harmonic content of line and phase voltages is the same. The different waveforms are due to a different phase relationship between the harmonics and the fundamental. Only odd harmonics of the order K=6n±1 are present, Where n is an integer. The triplen (multiples of 3) harmonics are absent, hence there is no circulating current in a delta-connected stator winding [10, 13].

The drawbacks of the six step inverter described above are eliminated if the inverter control is by Sinusoidal Pulsewidth Modulation SPWM. Increase of switching losses due to high PWM frequency is the major drawback of this PWM method. This method and the other PWM techniques, namely: Pulsewidth Modulation with Uniform Sampling, Pulsewidth Modulation with Selective Harmonic Elimination, and Pulsewidth Modulation with Minimum Loss in Motor are exhaustively discussed in [10].

MOTOR ANALYSIS FOR SIX STEP INVERTER CONTROL

The figure below shows the per-phase steady state equivalent circuit of a controlled three phase induction motor.

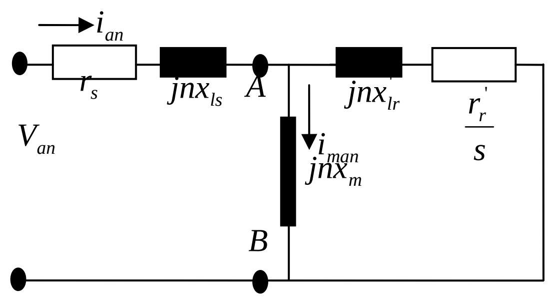

Figure 5: The RMS Equivalent Circuit of Squirrel Cage Induction Motor.

The impedance looking through the points A and B is,

$$Z_{in} = \frac{(r_r'/s + jnx_{lr}')(jnx_m)}{(r_r'/s + jnx_{lr}' + jnx_m)} \quad \textbf{(5)}$$

Let us define $r = r_r'/s$, then

$$Z_{in} = \frac{(r + jnx_{lr}')(jnx_m)}{(r + jnx_{lr}' + jnx_m)} \quad \textbf{(6)}$$

$$Z_{in} = \frac{jrnx_m - n^2 x_{lr}' x_m}{r + j(nx_{lr}' + nx_m)} \quad \textbf{(7)}$$

Also, defining $x = x_{lr}' + x_m$, then

$$Z_{in} = \frac{jrnx_m - n^2 x_{lr}' x_m}{r + jnx} \quad \textbf{(8)}$$

$$Z_{in} = \frac{(jrnx_m - n^2 x_{lr}' x_m)(r - jnx)}{(r + jnx)(r - jnx)} \quad \textbf{(9)}$$

Expanding and collecting like terms

$$Z_{in} = \frac{rn^2 x_m - (x - x_{lr}')}{r^2 + n^2 x^2} + j\frac{nx_m (r^2 + n^2 x x_{lr}')}{r^2 + n^2 x^2} \quad \textbf{(10)}$$

Since $x - x_{lr}' = x_m$, therefore,

$$Z_{in} = \frac{rn^2 x_m^2}{r^2 + n^2 x^2} + j\frac{nx_m (r^2 + n^2 x x_{lr}')}{r^2 + n^2 x^2} \quad \textbf{(11)}$$

Now the total impedance looking through the stator terminals is,

$$Z_T = Z_s + Z_{in} \quad \textbf{(12)}$$

Where,

$$Z_s = r_s + jnx_{ls} \quad \textbf{(13)}$$

Therefore,

$$Z_{in} = r_s + jnx_{ls} + \frac{rn^2 x_m - (x - x'_{lr})}{r^2 + n^2 x^2} + j\frac{nx_m (r^2 + n^2 x x'_{lr})}{r^2 + n^2 x^2} \quad \textbf{(14)}$$

Now let $Z_T = r_n + jx_n$

where, $r_n = r_s + \frac{rn^2 x_m^2}{r^2 + n^2 x^2}$ **(15)**

and

$$x_n = nx_{ls} + \frac{nx_m (r^2 + n^2 x x'_{lr})}{r^2 + n^2 x^2} \quad \textbf{(16)}$$

$$Z_n = \sqrt{(r_n^2 + x_n^2)} \quad \textbf{(17)}$$

$$\phi = \tan^{-1}(\frac{x_n}{r_n}) \quad \textbf{(18)}$$

As defined for the six-step three-phase inverter supply,

$$V_{an} = \sum_{n=6p\pm1}^{\infty} \frac{2V_d}{n\pi} \sin n\omega t \quad \textbf{(19a)}$$

$$V_{bn} = \sum_{n=6p\pm1}^{\infty} \frac{2V_d}{n\pi} \sin n(\omega t - \frac{2\pi}{3}) \quad \textbf{(19b)}$$

$$V_{cn} = \sum_{n=6p\pm1}^{\infty} \frac{2V_d}{n\pi} \sin n(\omega t - \frac{4\pi}{3}) \quad \textbf{(19c)}$$

Where, $p = 1,2,3,4...$

Now referring to Figure 5, for the phase a, the stator current i_{an} and the magnetizing current i_{man} are, respectively, as shown below:

$$i_{an} = \frac{2V_d}{n\pi Z_n} \sin(n\omega t - \phi) \quad \textbf{(20)}$$

$$i_{man} = i_{an} * \frac{r + jnx'_{lr}}{r + jnx} \quad \textbf{(21)}$$

Generally, $n = 1$ and $n = 6p + 1$ present positive sequence supply while $n = 6p - 1$ presents negative sequence supply. This affects the nth harmonic equivalent circuit of the induction motor. For the harmonic frequency $n\omega_s$ that presents positive sequence for a motoring speed of ω_m, then slip s_n is given by:

$$s_n = \frac{n\omega_s - \frac{p}{2}\omega_m}{n\omega_s} \quad \textbf{(22)}$$

$$s_n = \frac{(n-1)\omega_s + \omega_s - \frac{p}{2}\omega_m}{n\omega_s} \quad \textbf{(23)}$$

At fundamental frequency, let slip, s, be given by

$$s = \frac{\omega_s - \frac{p}{2}\omega_m}{\omega_s} \quad \textbf{(24)}$$

This gives the positive sequence slip, s_n, as

$$s_n = \frac{n - 1 + s}{n} \quad \textbf{(25)}$$

Similarly, for the negative sequence,

$$s_n = \frac{-n\omega_s - \frac{p}{2}\omega_m}{-n\omega_s} = \frac{n\omega_s + \frac{p}{2}\omega_m}{n\omega_s} \quad \textbf{(26)}$$

$$s_n = \frac{(n+1)\omega_s - \omega_s + \frac{p}{2}\omega_m}{n\omega_s} \quad \textbf{(27)}$$

This gives the negative sequence slip, s_n, as,

$$s_n = \frac{n+1-s}{n} \quad \textbf{(28)}$$

Therefore, the nth harmonic Equivalent Circuit of Induction Motor is:

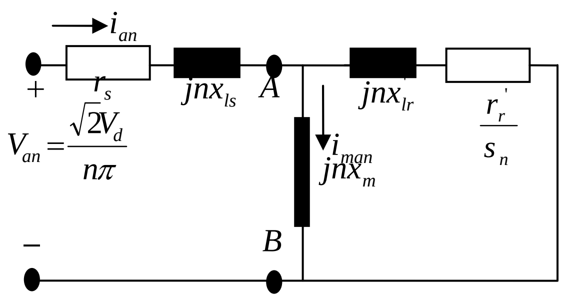

Figure 6: The nth Harmonic Equivalent Circuit of Squirrel Cage Induction Motor.

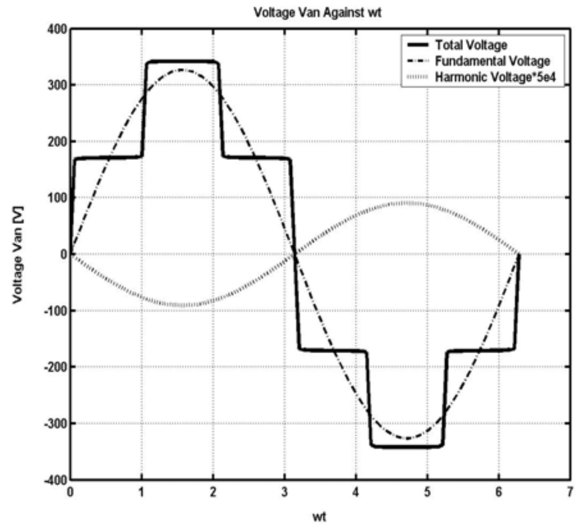

Figure 7: Plot of Voltage V_{an} Against ωt.

SAMPLE MOTOR DATA

Table 1: Sample Machine Data

Rated Voltage	400V
Winding Connection	Star
Rated Frequency	$50H_z$
Number of Poles	6
Rated Speed	960rpm
Stator Resistance	0.4Ω
Rotor Referred Resistance	0.2Ω
Stator Reactance	1.5Ω
Rotor Referred Reactance	1.5Ω
Magnetizing Reactance	30Ω

ANALYSIS AND RESULTS

Per cycle variation of V_{an}, i_{an}, and i_{man} are programmed and plotted in MATLAB using Equations 19, 20, and 21. The results are shown below. The plots are made as ωt varies from 0 to 2π in steps of $2\pi/100$ while p varies from 0 to 100 in steps of 1.

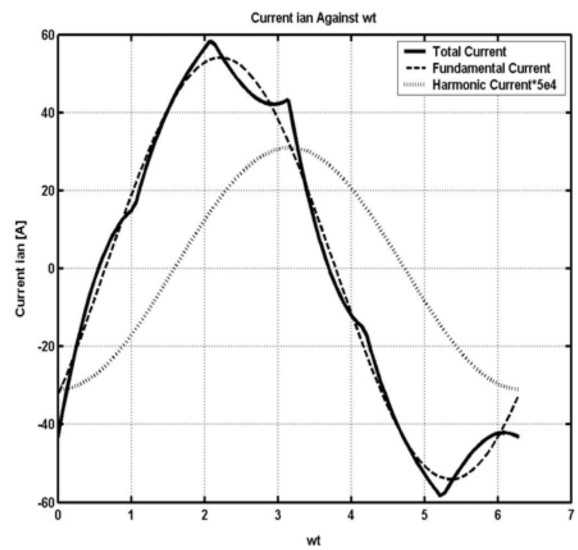

Figure 8: Plot of Current i_{an} Against ωt.

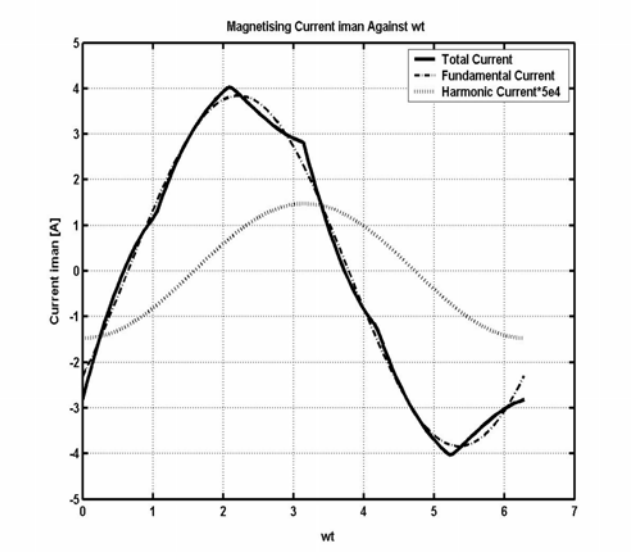

Figure 9: Plot of Magnetizing Current i_{man} Against ωt.

OBSERVATIONS AND CONCLUSION

The results obtained show the per cycle variations of the supply voltage and motor currents for the sample induction motor. It has been observed that for harmonics other than the fundamental, that the harmonic components are very negligible in comparison with the fundamental components. This makes possible the safe operation of the motor even in the presence of these harmonic components. By applying the six-step waveform of Figure 7, a comparison of Figures 8 and 9 shows that while i_{an} is visibly non-sinusoidal, i_{man} is almost sinusoidal thus making the induction motor respond negligibly to harmonics higher than the fundamental.

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ABOUT THE AUTHOR

Engr. Ogbuka, **Cosmas Uchenna** received his B.Eng. (First Class Honors) and M.Eng. degrees in 2004 and 2008, respectively, in the Department of Electrical Engineering University of Nigeria, Nsukka where he presently works as a

Lecturer/Research Student. His research interests are in Adjustable Speed Drives of Electrical Machines: (DC and AC Electric Machine Torque/Speed Control with Converters and Inverters) and Power Electronics.

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