Nigerian Journal of Technology (NIJOTECH)
Vol. 31, No. 3, November, 2012, pp. 365–369.
Copyright ©2012 Faculty of Engineering,
University of Nigeria. ISSN 1115-8443

EFFECTS OF LOAD AND SPEED VARIATIONS IN A MODIFIED CLOSED LOOP V/F INDUCTION MOTOR DRIVE

C.U. Ogbuka[a], **M.U. Agu**

Department of Electrical Engineering, University of Nigeria, Nsukka, Nigeria. ***Email:*** *cosmas.ogbuka@unn.edu.ng*

Abstract

This paper investigates the effects of load and reference speed variations in a modified closed loop v/f induction motor drive. A modified approach, involving the addition of a low frequency boost voltage, is developed and adopted as an enhancement to the conventional closed loop v/f speed control of a three phase squirrel cage induction motor modelled in the stationary qd reference frame using six-step voltage source inverter waveform. The results obtained show a superior dynamic and steady state performance in the two basic mechanical characteristics: motor speed and electromechanical torque under load variation. The performance of this scheme is simulated in MATLAB/SIMULINK.

Keywords: induction motor, stationary reference frame, Volts/Hertz v/f control, reference speed, load torque

1. Introduction

Induction machine is the most used in industry because of its high robustness, reliability, low cost, high efficiency and good self-starting capability [1,2,3]. The recent improvements in power semiconductors devices and fast digital signal processing hardware have further accelerated this progress. The induction motor, particularly with a squirrel cage rotor, is the most widely used source of mechanical power fed from an AC power system. Its low sensitivity to disturbances during operation makes the squirrel cage motor the first choice when selecting a motor for a particular application [4]. 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 operation [5,6].

With respect to the control method, ac drives are classified into two basic categories. The first category motors are the ones with reduced dynamic requirements. The standard drives such as pump and fan with electric motor operating at a maximum efficiency point are the examples of this category. In the second category, dynamically high performance industrial drives are grouped [7].

During start-up and other severe motoring operations, the induction motor draws large currents, produce voltage dips, oscillatory torques and can even generate harmonics in the power system [8,9]. It is, therefore, important to be able to predict these phenomena. Various models have been developed and the qd or two axis model for the study of transient behaviours has been tested and proven to be very reliable and accurate [10]. This method of modelling has been applied by several authors in their analysis [11,12]. Since it is usually more convenient to simulate an induction machine and its converters on a stationary reference frame, the model presented in this paper is on the stationary reference frame. The complete model equations for the induction motor in the stationary reference frame is derived in [13].

2. Closed Loop V/F Controlled Induction Motor Drive

When accuracy in speed response is a concern, closed-loop speed control can be implemented with the constant v/f principle through the regulation of slip speed. A PI controller is employed to regulate the slip speed of the motor to keep the motor speed at its set value. Figure 1 shows a typical closed-loop speed control scheme which uses volts/hertz and slip regulation [14].

The major blocks consist of a DC source, a three phase inverter, and an induction motor with load. The

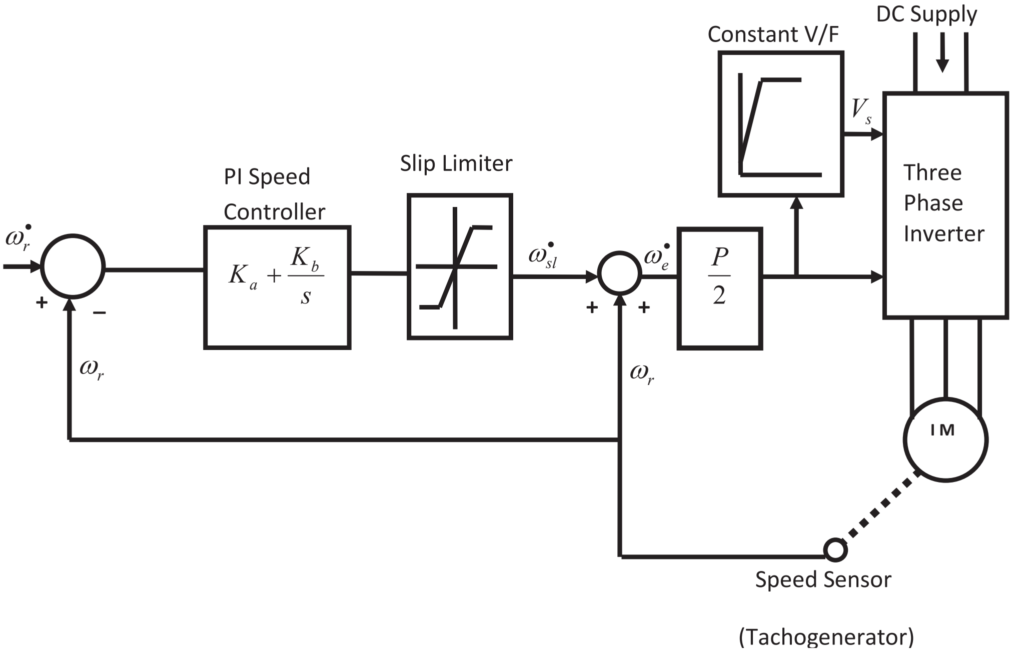

Figure 1: Closed-loop speed control scheme utilizing Volts/Hertz and slip regulation.

speed loop error generates the slip speed command ω_{sl}^* through the proportional-integral controller and limiter. The slip is added to the speed feedback signal, ω_r to generate the slip frequency command, ω_e^*. The slip frequency command generates the voltage command V_s through a Volts/Hz function generator [7, 14].

A step increase in slip frequency command, ω_e^* produces a positive speed error and the slip speed command ω_{sl}^* is set at the maximum value. The drive accelerates at the permissible inverter current, producing the maximum available torque, until the speed error is reduced to a very small value. The drive finally settles at a slip speed for which the motor torque balances the load torque.

A step decrease in slip frequency command, ω_e^* produces a negative speed error. The slip speed command is set at the maximum negative value. The drive accelerates under regenerative braking; at the maximum permissible current and the maximum available breaking torque, until the speed error is reduced to a small value. Now the operation shifts to motoring and the drive settles at the slip speed for which the motor torque equals the load torque. Several other closed loop control schemes utilizing PWM inverters are discussed in [15].

3. Modified V/F Control Versus Basic V/F Control

The major deficiency of the basic v/f control is stator impedance drop at low frequencies. The modified v/f control method, unlike the basic v/f control method, provides a boost-voltage at low frequencies thereby compensating for the stator impedance drop, enabling the motor to offer constant flux operation with maximum motoring torque from zero to rated speed. Analytical reference is made to the exact equivalent circuit of induction motor to evaluate an offset voltage which is incorporated in the v/f block of figure 1 to serve as a boost voltage during low frequency operation.

4. Evaluation of Low Frequency Boost Voltage

The voltage relationships in the exact equivalent circuit of figure 2 are analyzed to determine the low frequency boost voltage V_o needed to sustain motor flux even at zero frequency. The parameter 'a' known as the per-unit frequency, is defined as the ratio of the operating speed to the rated speed as

$$a = \frac{f_s}{f_{rated}} = \frac{\omega_s}{\omega_{sr}} \tag{1}$$

From figure 2,

$$V_s = aE_{ar} + (I_m + I_r)(r_s + jax_{ls}) \tag{2}$$

Where

$$I_m + I_r = \left(\frac{E_{ar}}{jx_m} + \frac{aE_{ar}}{\frac{r_r}{s} + jax_{lr}}\right) \tag{3}$$

Therefore,

$$V_s = aE_{ar} + (r_s + jax_{ls})\left(\frac{E_{ar}}{jx_m} + \frac{aE_{ar}}{\frac{r_r}{s} + jax_{lr}}\right) \tag{4}$$

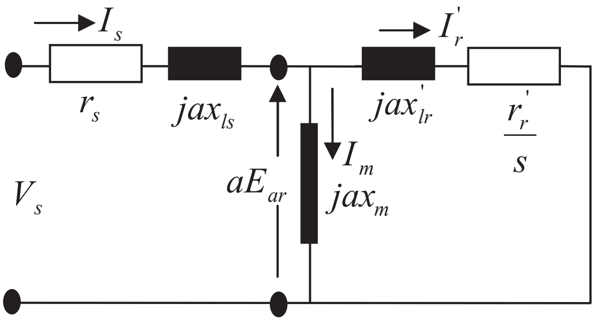

Figure 2: Steady state equivalent circuit of a squirrel cage induction motor for variable voltage and frequency control.

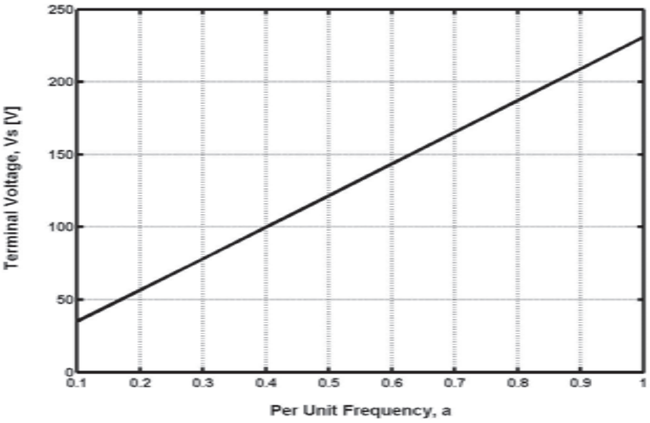

Figure 3: Variation of terminal voltage against per unit frequency.

A plot of the terminal voltage V_s as a varies in the range $0.1 \leq a \leq 1$ is shown in figure 3. where slip $s = s_r/a$ and s_r is the rated slip.

By extrapolation, it can readily be shown that the terminal voltage V_o at $a = 0$ is 13.3261V. This low frequency boost voltage is utilized in the constant Volts/Hertz generator in the closed loop arrangement of figure 1.

5. Induction Machine Model in Stationary Reference Frame

Making reference to the induction machine model in the arbitrary reference frame and substituting $\omega = 0$, the induction machine model in the stationary reference frame is realized. This is called the stationary reference frame because the qd axis does not rotate and is said to be fixed in the stator. The analysis done above recognizes that in a vast majority of cases, the machine is connected in delta or wye such that the neutral current does not flow. In this case, the neutral axis voltages and currents are identically zero. The machine model in stationary reference frame for a squirrel cage induction machine is well known and given by

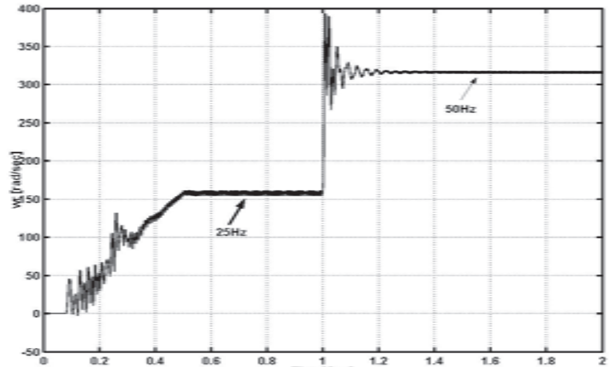

Figure 4: Rotor speed for step change in reference speed.

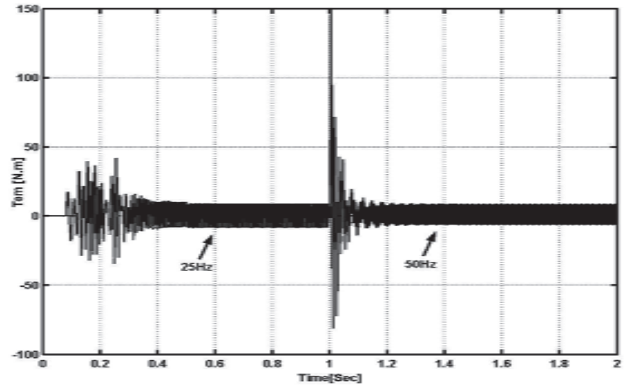

Figure 5: Electromechanical torque for step change in reference speed.

$$\begin{bmatrix} v_{qs} \\ v_{ds} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} r_s + L_s p & 0 & L_m p & 0 \\ 0 & r_s + L_s p & 0 & L_m p \\ L_m p & -\omega_r L_m & r_r + L_r p & -\omega_r L_r \\ -\omega_r L_m & L_m p & -\omega_r L_r & r_r + L_r p \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} \tag{5}$$

where, $v_{qs} = \sqrt{2} V_s \cos \omega_e t$, $v_{ds} = -\sqrt{2} V_s \sin \omega_e t$, $L_s = L_{ls} + L_m$ and $L_r = L_{lr} + L_m$. The electromechanical torque developed is given by

$$T_{em} = T_L + \frac{2}{P} J \frac{d\omega_r}{dt} \tag{6}$$

Where p is the operator d/dt, r_s is the stator resistance, r_r is the rotor resistance referred to the stator side, L_{ls} and L_{lr} are the stator and rotor leakage inductance respectively. L_m is the magnetizing inductance, T_l is the load torque, P is the number of pole pairs, J is the moment of inertia, ω_r is the rotor electrical speed, and ω_e is the supply synchronous speed.

6. Dynamic Performance Under Reference Speed Variation

A closed loop v/f controlled induction motor is simulated in the stationary reference frame using MATLAB/SIMULINK. The parameters of the sample motor are shown in Table 1 below.

Table 1: Sample machine data.

Motor Rating	2 Hp
Rated Voltage	400V
Winding Connection	Star
Rated Frequency	50Hz
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
Moment of Inertia	2.1kgm^2

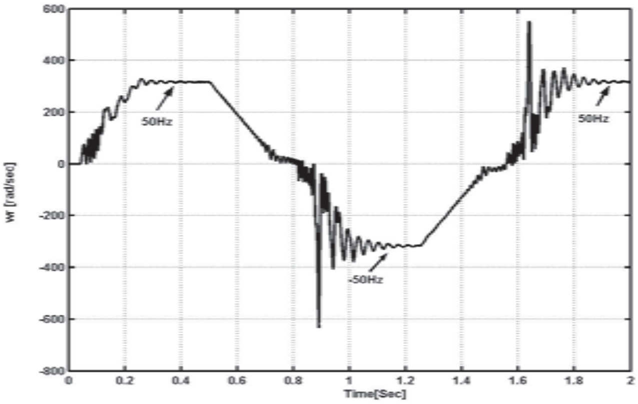

Figure 6: Speed reversal due to change in reference speed.

6.1. *Effect of a step change in reference speed*

The speed reference is changed from 25Hz to 50Hz at load torque $T_L = 0\text{Nm}$. The effect on motor speed is observed in figure 4, while the effect on electromechanical torque delivered by the motor is shown in figure 5. A sudden jerk is noticed on the load torque at the time the sudden change in reference speed occurred.

6.2. *Effect of reversal in speed reference*

With a load torque of 0Nm, Figure 6 shows the rotor speed due to the reference speed reversal in the sequence [0 50 -50 50 0]Hz while figure 7 shows the effect on the electromechanical torque. The speed and torque transients are, as expected, observed each time the reference speed crosses the zero point. The transient effects need definite time to settle as can be observed in the curves.

7. Dynamic Performance Under Load Torque Variation

7.1. *Sequential changes in load torque at reference speed of 50Hz*

Dynamic performance is observed when load torque changes in the sequence [0 30 15 30 0] Nm at a reference speed of 50Hz. Figure 8 shows the speed changes due to the programmed sequence of load torque variation while figure 9 shows the change in electromechanical torque due to the load torque changes.

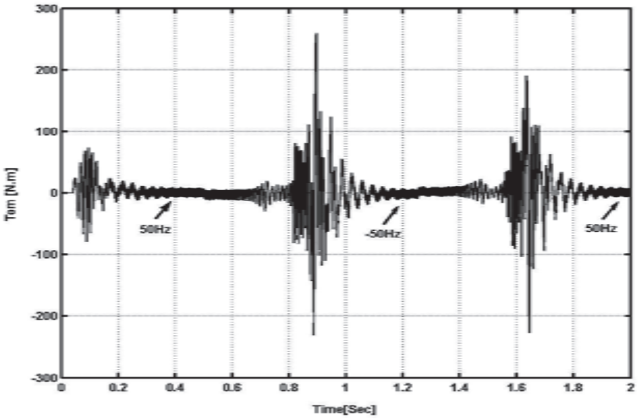

Figure 7: Electromechanical torque due to change in speed reference.

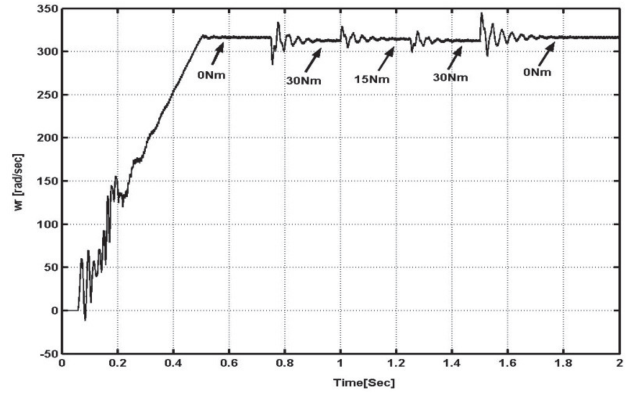

Figure 8: Rotor speed for programmed changes in load torque.

7.2. *Step change in load torque at a reference speed of 25Hz*

Figures 10 and 11 show the rotor speed and electromechanical torque respectively due to the load torque changes from 0 Nm to 50 Nm at a reference speed of 25Hz.

8. Conclusion

The scheme presented here has successfully incorporated the estimated low frequency boost voltage to the conventional closed loop v/f control modelled in the stationary qd reference frame. The choice of the stationary reference frame is made because of its compatibility with the three phase six step inverter waveform used in place of actual inverter model. This modification is validated for the dynamic performance by subjecting it to reference speed and load torque variations. The ripple in motor speed and electromechanical torque due to sudden changes in reference speed

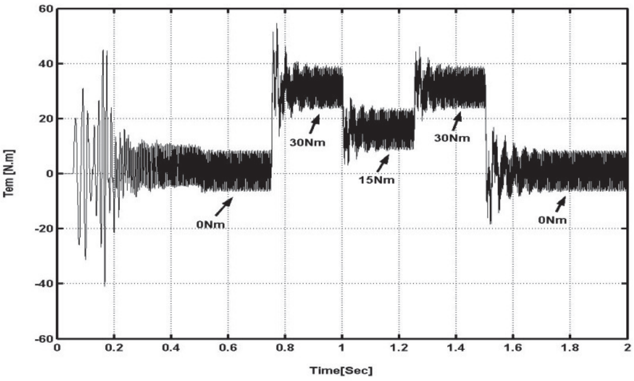

Figure 9: Electromechanical torque for programmed changes in load torque.

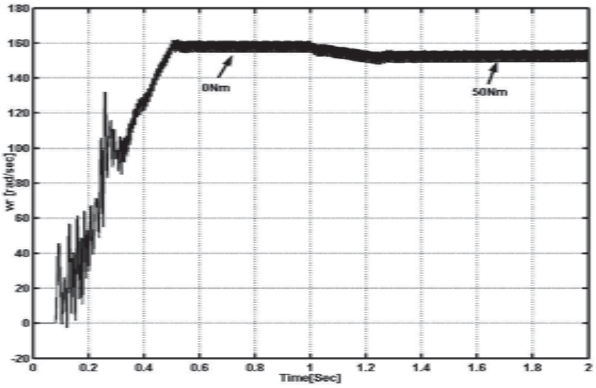

Figure 10: Rotor speed for step change in load torque from 0Nm to 50Nm at Reference speed of 25Hz.

and load torque are observed as expected. This modified closed loop v/f control method shows a better dynamic and steady state performance when compared to the conventional v/f control method of three phase squirrel cage induction motors.

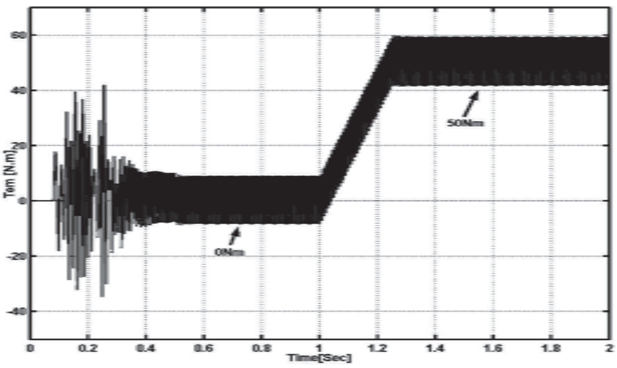

Figure 11: Electromagnetic torque for step change in load torque at reference speed of 25Hz.

References

1. Leonhard, W. *Controlled AC Drives, A Successful Transfer from Ideas to Industrial Practice.* CETTI 95, Brazil, 1995, pp. 1-12.
2. Okoro, O.I. Dynamic Modelling and Simulation of Squirrel-Cage Asynchronous Machine with Non-Linear Effects. *Journal of ASTM International*, Vol. 2, No. 6, 2005, pp. 1-16.
3. MacDonald, M.L. and Sen, P.C. Control Loop Study of Induction Motor Drive Using D-Q Model. *IEEE Transaction on Industrial Electronics and Control Instrumentation*, Vol. 26, No. 4, 1979, pp. 237-241.
4. Ostovic, V. *Computer-Aided Analysis of Electric Machines.* Prentice Hall International (UK) Ltd, 1994.
5. Okoro, O.I. MATLAB Simulation of Induction Machine with Saturable Leakage and Magnetizing Inductances. *Botswana Journal of Technology*, No. 2, Vol.13, 2004, pp. 20-28.
6. Fitzgerald, A.E. *Electric Machinery.* 5th Edition, McGraw-Hill Inc, New York, 1990.
7. Mulay, S.P. and M.V. Aware. V/F Control of an Induction Machine Predicting Inverter Machine Interaction. *International Journal of Innovation in Energy Systems and Power*, Vol.3, No. 1, 2008, pp.27-31.
8. Landy, C.F. The Predictions of Transient Torques Produced in Induction Motors due to Rapid Reconnection of Supply. *Trans. S. Africa Inst. Electr. Eng.*, (63), 1972, pp.178-185.
9. Pillay, P. and Harley, R.G,. *Comparison of Models for Predicting Disturbances Caused by Induction Motor Starting.* SAIEE Symposium on Power Systems Disturbances, Pretoria. 1983.
10. Lee, R.J, Pillay P, and Harley, R.G. D,Q Reference Frame for the Simulation of Induction Motors. *Electric Power Systems Research*, (8), 1985, pp.15-16.
11. Jordan, H.E. Digital Computer Analysis of Induction Machines in Dynamic Systems. *IEEE Transaction on Power Apparatus and System*, Vol. PAS-86, No.6, 1967, pp. 722-728.
12. Chattopadhyay, A.K. Digital Computer Simulation of an Adjustable-Speed Induction Motor Drive with a Cycloconverter-Type Thyristor-Commutator in the Rotor. *IEEE Transactions on Industrial Electronics and Control Instrumentation*, Vol. IECI-23, Issue 1, 1976, pp. 86-92.
13. Ong, C.M. *Dynamic Simulation of Electric Machinery Using MATLAB and SIMULINK.* Prentice Hall PTR, New Jersey. 1997.
14. Yu, Z. and D. Figoli. *AC Induction Motor Control Using Constant V/Hz Principle and Space Vector PWM Technique with TM320C240.* Texas Instrument, 1998.
15. Bose, B.K. *Power Electronics and AC Drives.* Englewood Cliffs, Prentice-Hall, 1986.