International Journal on
"Technical and Physical Problems of Engineering"
(IJTPE)
Published by International Organization of IOTPE

ISSN 2077-3528
IJTPE Journal
www.iotpe.com
ijtpe@iotpe.com

June 2012 Issue 11 Volume 4 Number 2 Pages 1-6

EXPERIMENTAL AND ANALYTICAL PARAMETER SENSITIVITY ANALYSIS OF INDIRECT FIELD ORIENTED CONTROL OF INDUCTION MACHINE

A. Shiri H.P. Nabi A. Shoulaie

Electrical Engineering Department, Iran University of Science and Technology, Tehran, Iran
abbas_shiri@iust.ac.ir, h_pairo@elec.iust.ac.ir, shoulaie@iust.ac.ir

Abstract- The paper discusses on parameter sensitivity analysis of indirect vector controlled induction motor drive. As known, the variation of the motor parameters deteriorates the performance of the system. The analytical equations are provided to investigate the effect of the variations or wrong instrumentation of the parameters of the motor on the performance of the indirect vector controller. A laboratory prototype of indirect vector controlled induction machine is constructed to confirm the analytical and simulation results. The experimental results under load and no-load conditions are in good agreement with the results of the analytical equations and simulations.

Keywords: Parameter Sensitivity, Induction Motor Drive, Indirect Field Oriented Control.

I. INTRODUCTION

Several control strategies have been proposed by researchers to control the induction machines. One of them is scalar control strategy which is more suitable for low power applications [1]. To achieve a better performance, other control strategies such as direct torque control [2] and vector control have been developed by researchers [3-4]. In vector control theory, AC motors are controlled similar to dc machines. The vector control is divided into two general methods entitled direct and indirect vector control which the latter is adopted in industry because of its better implementation possibility.

Different control methods are used in indirect vector control such as PI, fuzzy logic, etc. [5-7]. Besides its proper performance, the major drawback of the indirect vector control scheme is that it is dependant to machine parameters, since the model of the motor is used for flux estimation. The machine parameters are affected by the temperature variations and the saturation levels of the machine. Any mismatch between the parameters in the motor and that instrumented in the vector controller will result in the deterioration of the performance in terms of steady state error and transient oscillations of rotor flux and torque. These types of oscillations are not desired for some exact uses. Regarding the importance of sensitivity of vector control drive to the motor parameters, many investigations have been carried out in this field. In [8], the effects of rotor resistance and mutual inductance variations on output torque and rotor flux have been discussed qualitatively.

In other work, the effect of the machine parameters variations on its outputs, based on simulation results has been investigated and two techniques for rotor resistance estimation have been proposed [9]. Krishnan in Reference [10] has derived approximate equations for parameter sensitivity of indirect vector control; and finally in some references, motor parameter estimation and compensation techniques and their effect on machine outputs have been described [11-17]. Shiri et al. [18] using approximate analytical functions, have investigated the output torque and rotor flux of indirect vector controlled induction motor drives. In the latter work, the analytical functions have been compared with some simulation results. In addition, in Reference [19] a standstill parameter identification method for vector-controlled induction motors has been presented by means of two simple current injection tests in which the parameters of the motor can be accurately identified.

In this paper, the analytical equations for output torque and motor flux are derived and the vector control system is simulated in Matlab/Simulink in speed controlled mode. To confirm the validity of analytical functions as well as simulation results, the vector controlled induction motor drive is constructed in laboratory. The experimental results under load and no-load conditions show the validity of analytical functions and simulation results.

II. INDIRECT VECTOR CONTROL

In this section, the indirect vector controller is derived from the dynamic equations of the induction machine in the synchronously rotating reference frame. The rotor equations of the induction machine are given by:

$$R_r i_{qr}^{e} + p\lambda_{qr}^{e} + \omega_{sl}\lambda_{dr}^{e} = 0 \qquad (1)$$

$$R_r i_{dr}^{e} + p\lambda_{dr}^{e} - \omega_{sl}\lambda_{qr}^{e} = 0 \qquad (2)$$

where

$$\omega_{sl} = \omega_s - \omega_r \qquad (3)$$

$$\lambda_{qr}{}^{e} = L_m i_{qs}{}^{e} + L_r i_{qr}{}^{e} \tag{4}$$

$$\lambda_{dr}{}^{e} = L_m i_{ds}{}^{e} + L_r i_{dr}{}^{e} \tag{5}$$

In the above equations, the various symbols denote the following: R_r, the per phase stator referred rotor resistance; L_m, the per phase mutual inductance; L_r, the per phase stator referred rotor self inductance; $i_{dr}{}^{e}$ and $i_{qr}{}^{e}$, the stator referred direct and quadrature axes currents, respectively; *p*, the differential operator; ω_{sl}, slip speed in rad/sec, ω_s and ω_r are synchronous speed and electrical rotor speed both in rad/sec, and $\lambda_{dr}{}^{e}$ and $\lambda_{qr}{}^{e}$ are rotor direct and quadrature axes flux linkages, respectively. The resultant rotor flux (λ_r) is assumed to be on the direct axis, to reduce the number of variables in the equations. Hence, aligning the d axis with rotor flux phasor yields:

$$\lambda_r = \lambda_{dr}{}^{e} \tag{6}$$

$$\lambda_{qr}{}^{e} = 0 \tag{7}$$

$$p\lambda_{qr}{}^{e} = 0 \tag{8}$$

Substituting Equations (6)-(8) in Equations (1) and (2) and using Equations (4) and (5), the followings are obtained for i_f and ω_{sl}:

$$i_f = \frac{1}{L_m}[1 + pT_r]\lambda_r \tag{9}$$

$$\omega_{sl} = (L_m / T_r)(i_T / \lambda_r) \tag{10}$$

where

$$i_f = i_{ds}{}^{e} \tag{11}$$

$$i_T = i_{qs}{}^{e} \tag{12}$$

$$T_r = L_r / R_r \tag{13}$$

The q and d axis currents are labeled as torque (i_T) and flux (i_f) producing components of the stator current phasor, respectively. T_r denotes the rotor time constant. Also using Equations (6-8), we can summarize the induction machine torque equation as:

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}(\lambda_r i_{qs}) = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}\lambda_r i_T = K_{te}\lambda_r i_T \tag{14}$$

where, P is the number of poles and K_{te} is torque constant and is equal to:

$$K_{te} = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r} \tag{15}$$

Note that the torque is proportional to the product of the rotor flux linkages and the stator q axis current. This resembles the torque expression of dc motor, which is proportional to the product of the field flux linkages and the armature current. If the rotor flux linkage is kept constant, then the torque is simply proportional to the torque producing component of the stator current (i_T), as in the case of the separately excited dc machine, where the torque is proportional to the armature current when the field current is constant. The rotor flux linkage and torque equations given in (9) and (14), respectively, complete the transformation of the induction machine into an equivalent separately excited dc machine from a control point of view. Figure 1 shows the indirect vector controller block diagram.

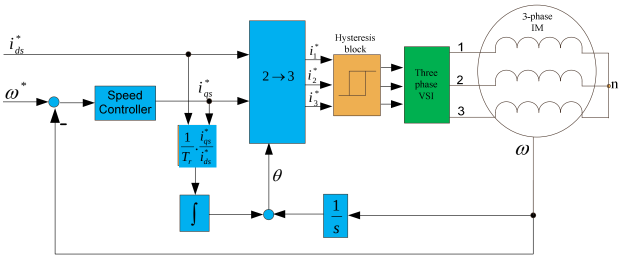

Figure 1. Indirect vector controller block diagram

III. SENSITIVITY ANALYSIS

A mismatch between the vector controller and induction motor occurs as a result of the motor parameters changing with operating conditions such as temperature rise and saturation or of the wrong instrumentation of the parameters in the vector controller. The mismatch produces a coupling between the flux and torque producing channels in the machine and degrades the performance of the controller.

In order to study the effect of machine parameters variation on drive outputs, the mathematical analyses are employed. To do this, the machine equations which were derived in previous section are used. The motor electromagnetic torque from Equation (14) is equal to:

$$T_e = K_{te}\lambda_r i_T \tag{16}$$

Replacing λ_r and K_{te} from Equation (9) and Equation (15) in Equation (16), respectively, we get:

$$T_e = \frac{1}{K_{it}}\frac{L_m}{L_r}\frac{L_m}{1 + pT_r} i_f i_T \tag{17}$$

where $K_{it} = (2/3)(2/P)$. Referring to the Figure 2, following equations are achievable:

$$\tan\theta_T = \frac{i_T}{i_f} \tag{18}$$

$$i_T = i_s \sin\theta_T \tag{19}$$

$$i_f = i_s \cos\theta_T \tag{20}$$

Replacing Equations (18)-(20) in Equation (17) produces:

$$T_e = \frac{1}{K_{it}}\frac{L_m}{L_r}\frac{L_m}{1 + pT_r} i_s{}^2 \sin\theta_T \cos\theta_T \tag{21}$$

Also the slip speed derived from Equation (10) as:

$$\begin{aligned}\omega_{sl} &= \frac{L_m}{T_r}\frac{i_T}{\lambda_r} = \frac{L_m}{T_r}\frac{i_T}{\dfrac{L_m ids}{1 + pT_r}} = \\ &= \frac{1 + pT_r}{T_r}\frac{i_T}{i_f} = \frac{1 + pT_r}{T_r}\tan\theta_T\end{aligned} \tag{22}$$

Rearranging the above equation for $\tan\theta_T$ we can get:

$$\tan\theta_T = \omega_{sl}T_r / (1 + pT_r) \tag{23}$$

From which sine and cosine of the torque angle are defined as:

$$\sin\theta_T = (\omega_{sl} T_r)/(1+pT_r)/\sqrt{1+\left(\frac{\omega_{sl} T_r}{1+pT_r}\right)^2} \tag{24}$$

$$\cos\theta_T = 1/\sqrt{1+\left(\frac{\omega_{sl} T_r}{1+pT_r}\right)^2} \tag{25}$$

Replacing $\sin\theta_T$ and $\cos\theta_T$ from Equation (24) and Equation (25), respectively in Equation (21) we have:

$$T_e = \frac{1}{K_{it}} \frac{L_m^{\,2}}{[R_r(1+pT_r)^2][1+(\frac{\omega_{sl} T_r}{1+pT_r})^2]} \omega_{sl} i_s^{\,2} \tag{26}$$

where $T_r = L_r / R_r$. Similar to the motor torque equation, commanded torque can be defined as:

$$T_e^* = \frac{1}{K_{it}} \frac{L_m^{*2}}{[R_r^*(1+pT_r^*)^2][1+(\frac{\omega_{sl}^* T_r^*}{1+pT_r^*})^2]} \omega_{sl}^* i_s^{*2} \tag{27}$$

The command values are denoted with asterisks.

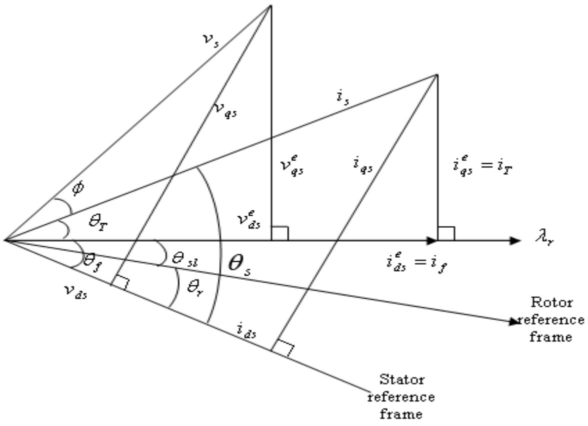

Figure 2. Vector control phasor diagram

For rotor flux linkages following equation can be derived:

$$\lambda_r = \frac{L_m}{(1+pT_r)\sqrt{1+\left(\frac{\omega_{sl} T_r}{1+pT_r}\right)^2}} i_s \tag{28}$$

Similarly its command value is:

$$\lambda_r^* = \frac{L_m^*}{(1+pT_r^*)\sqrt{1+\left(\frac{\omega_{sl}^* T_r^*}{1+pT_r^*}\right)^2}} i_s^* \tag{29}$$

Now by having the equations of torque and flux, we can define sensitivity functions in respect to the machine parameters. The ratio of torque to its command value is obtained as:

$$\frac{T_e}{T_e^*} = \frac{L_m^{\,2}}{L_m^{*2}} \frac{R_r^*(1+pT_r^*)^2[1+(\frac{\omega_{sl}^* T_r^*}{1+pT_r^*})^2]}{R_r(1+pT_r)^2[1+(\frac{\omega_{sl} T_r}{1+pT_r})^2]} \frac{\omega_{sl}}{\omega_{sl}^*} \frac{i_s^{\,2}}{i_s^{*2}} \tag{30}$$

Also the ratio of actual to command rotor flux linkages is:

$$\frac{\lambda_r}{\lambda_r^*} = \frac{L_m}{L_m^*} \frac{1+pT_r^*}{1+pT_r} \frac{\sqrt{1+(\frac{\omega_{sl}^* T_r^*}{1+pT_r^*})^2}}{\sqrt{1+(\frac{\omega_{sl} T_r}{1+pT_r})^2}} \frac{i_s}{i_s^*} \tag{31}$$

Derived sensitivity functions are applicable for both transient and steady states. In steady state p=0, so we get:

$$\frac{T_e}{T_e^*} = \alpha\beta \frac{[1+(\omega_{sl}^* T_r^*)^2]}{[1+(\alpha\omega_{sl} T_r^*)^2]} \frac{\omega_{sl}}{\omega_{sl}^*} \frac{i_s^{\,2}}{i_s^{*2}} \tag{32}$$

$$\frac{\lambda_r}{\lambda_r^*} = \beta \frac{\sqrt{1+(\omega_{sl}^* T_r^*)^2}}{\sqrt{1+(\alpha\omega_{sl} T_r^*)^2}} \frac{i_s^{\,2}}{i_s^{*2}} \tag{33}$$

where $T_r / T_r^* = \alpha$ and $L_m / L_m^* = \beta$ and the following approximation was accepted (leakage inductance is supposed to be negligible compared to the mutual inductance): $L_r^* / L_r \approx L_m^* / L_m$.

Working conditions of the machine such as temperature rise, magnetic saturation and operation of the induction motor drive in the linear portion of the iron B-*H* characteristics can cause changes of α and β in the following manner [10], $0.5 \le \alpha \le 1.5$ and $0.8 \le \beta \le 1.2$.

In the speed control mode, as the speed and load torque are kept constant, T_e / T_e^* is constant. So, by changing the motor parameters, ω_{sl} and i_s change according to Equation (32). In no-load condition, due to zero value of the speed slip, the changes of the parameters have no effect on the performance of the system.

IV. SIMULATION RESULTS

In this section, the indirect vector control of a three-phase induction machine is simulated in Matlab/Simulink. The parameters of three-phase machine are represented in Appendix. Figure 3 and Figure 4 are related to the simulation of the motor in speed control mode under no-load condition. The speed command is 400rpm. In simulations, the parameters of the machine used in implementation of the indirect vector controller are halved after *t*=5s. Figure 3 shows the speed of the motor before and after parameter variations. As shown in this figure, the speed of the motor with correct and wrong parameters is constant. Also, as expected, after and before t=5s, the phase currents are unchanged (Figure 4). It means that the parameter variation has no effect on the drive performance under no-load condition.

To study the effect of parameter variations on the performance of the motor under load, a 12 N.m torque is applied to the motor and the speed command is set to 400 rpm. The results of the simulations are depicted in Figure 5 and Figure 6. The parameter changes are applied in this condition like no-load condition. So, the parameters of the machine are halved after *t*=5s. The speed of the motor is illustrated in Figure 5. Although, there is a transient in the motor speed after *t*=5s, it remains constant in steady state operation. The phase a current is shown in Figure 6. This figure shows that after *t*=5s, the phase currents are increased whereas load and speed are remained constant.

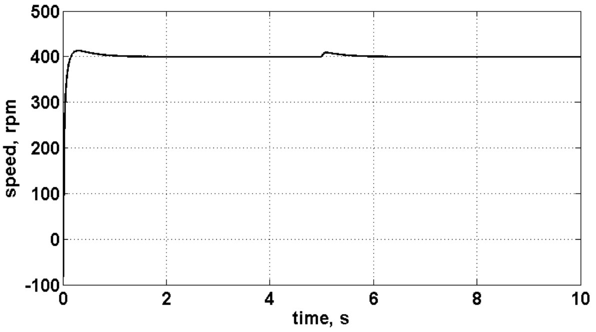

Figure 3. Motor speed under no-load condition

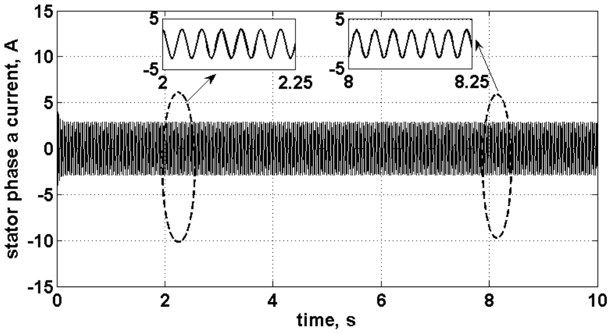

Figure 4. Stator phase a current under no-load condition

V. EXPERIMENTAL RESULTS

An experimental setup is constructed to verify the analytical investigations about parameter sensitivity in indirect vector control. In this section, the experimental results are presented. The microcontroller used in controller board is dspic30f4011. The inverter phase currents are measured using LEM sensors. The experimental tests have been done on an 8-pole, 50Hz, three-phase induction machine. The per phase motor parameters are those appeared in appendix. This machine is coupled with a dc generator as load.

Motor phase currents are sampled by data acquisition apparatus (USB-4711A) and the motor speed is measured using digital tachometer RM-1501. Speed and current samples are plotted with Matlab.

The experimental setup is shown in Figure 7. Figures 8 and 9 show the experimental results related to indirect vector control under no-load condition. To investigate the parameter sensitivity in indirect vector control, the correct parameters are applied between t=0s and t=5s. After t=5s, the rotor time constant is halved in microcontroller which results in wrong parameter estimation (the rotor resistance is doubled). In this test, microcontroller which results in wrong parameter estimation (the rotor resistance is doubled). In this test, the speed command is equal to 400rpm. The machine speed is shown in Figure 8 and the current samples of phase a are shown in Figure 9. Because of low sampling rate of digital tachometer, the transients in the speed response are not observable. These results obviously show that wrong parameter estimation has no effect on indirect vector control under no load condition.

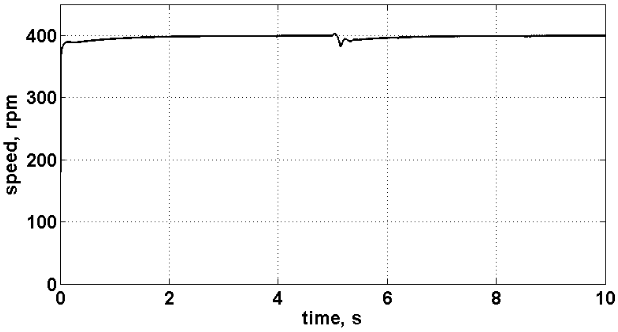

Figure 5. Motor speed under load

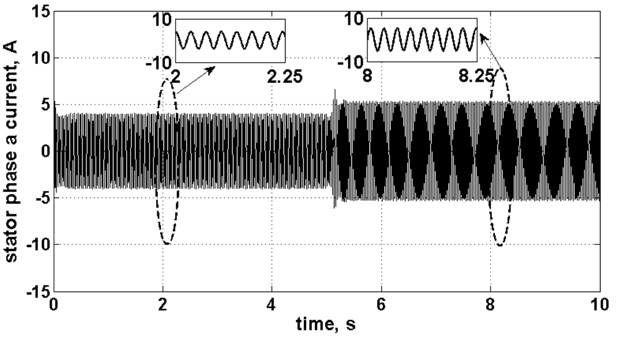

Figure 6. Stator phase a current under load

The test results of indirect vector control under load are shown in Figures 10 and 11. In this test, between t=0s to t=5s, the correct parameters and after t=5s, wrong parameters are applied in microcontroller. The speed command is 400 rpm and the load torque is 12 N.m. The speed of the motor is shown in Figure 10 and the phase a current is shown in Figure 11. These results show that after applying wrong parameters, the speed of the motor and consequently, the output power of DC generator remains unchanged. However, wrong parameters causes the stator current to increase and consequently leads to increasing the stator copper loss in constant power.

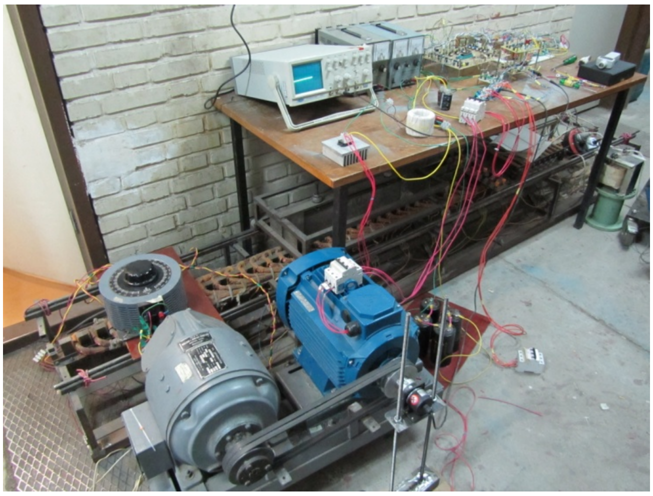

Figure 7. Experimental setup

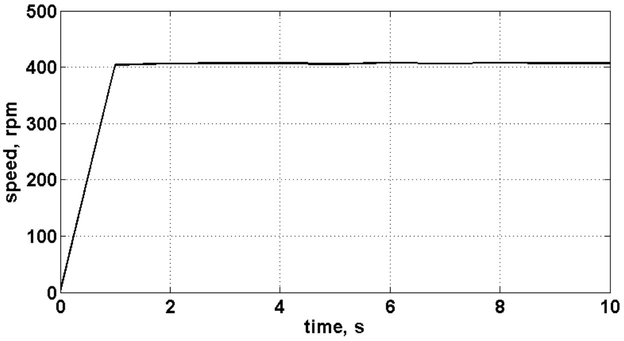

Figure 8. Motor speed under no-load condition (experiment)

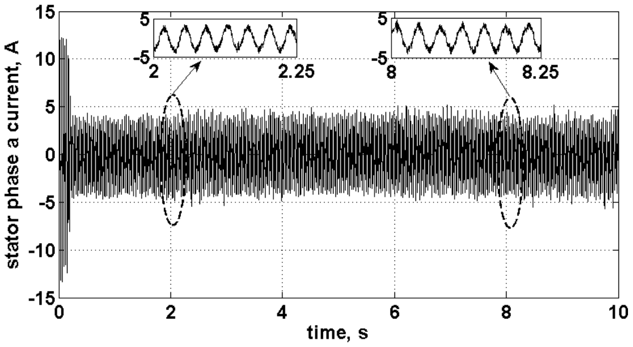

Figure 9. Stator phase a currents under no-load condition (experiment)

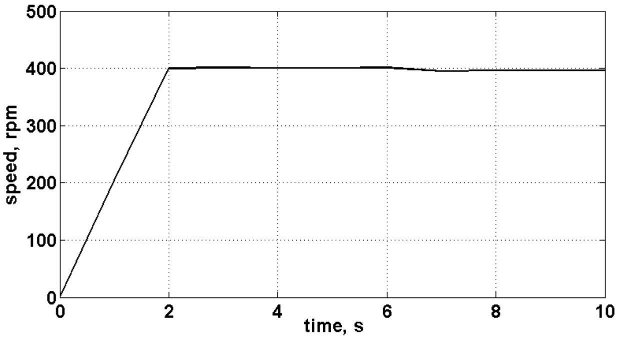

Figure 10. Motor speed under load (experiment)

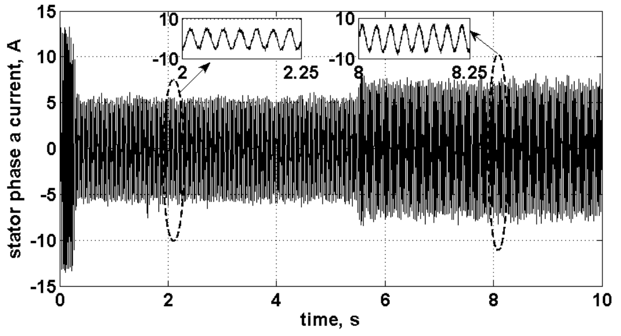

Figure 11. Stator phase a current under load (experiment)

VI. CONCLUSIONS

In this paper, the effect of parameter variations on the performance of indirect vector control is investigated. Analytical equations are derived for sensitivity analysis and indirect vector controlled induction motor drive is simulated in Matlab/Simulink. An indirect vector controller has been implemented in laboratory. The experimental results confirm the results of the analytical equations and simulations. In addition, the results show that the parameter variation has no effect on the performance of the system under no-load condition; while under load, parameter variations cause the stator current to increase. This leads to decreasing the efficiency of the motor as the output power and torque are remained constant in speed control mode.

APPENDIX

The motor parameters are as:

$n_s = 750$ rpm, $n_m = 690$ rpm, $p_n = 3$ hp, $r_r = 2.66\ \Omega$, $r_s = 3\ \Omega$, $L_m = 0.179$ H, $L_{lr} = L_{ls} = 14.8$ mH, $J = 0.028\ \text{kg.m}^2$

REFERENCES

[1] I. Kioskeridis, N. Margaris, "Loss Minimization in Scalar-Controlled Induction Motor Drives with Search Controllers", IEEE Trans. on Power Electronics, Vol. 11, No. 2, March 1996.

[2] J.N. Nash, "The Direct Torque Control, Induction Motor Vector Control without an Encoder", IEEE Trans. on Industry Applications, Vol. 33, No. 2, March/April 1997.

[3] F. Blaschke, "The Principle of Field Orientation as Applied to the New Transvector Closed Loop Control System for Rotating Machinery", Siemens Rev., 34, pp. 217-220, 1972.

[4] K. Hasse, "About the Dynamics of Adjustable-Speed Drives with Converter-Fed Squirrel-Cage Induction Motors", Ph.D. Dissertation, Darmstadt Technische Hochschule, 1969 (in German).

[5] E. Cerruto, A. Consoli, A. Raciti, A. Testa, "Fuzzy Adaptive Vector Control of Induction Motor Drives", IEEE Trans. on Power Electronics, Vol. 12, No. 6, November 1997.

[6] S.M. Gadoue, D. Giaouris, J.W. Finch, "MRAS Sensorless Vector Control of an Induction Motor Using New Sliding-Mode and Fuzzy-Logic Adaptation Mechanisms", IEEE Trans. on Energy Conversion, Vol. 25, No. 2, June 2010.

[7] M.N. Uddin, T.S. Radwan, M.A. Rahman, "Performances of Fuzzy-Logic-Based Indirect Vector Control for Induction Motor Drive", IEEE Trans. on Industry Applications, Vol. 38, No. 5, September/October 2002.

[8] R. Krishnan, A.S. Baharadwaj, "A Review of Parameter Sensitivity and Adaptation in Indirect Vector Controlled Induction Motor Drive Systems", IEEE Trans. on Power Electronics, Vol. 6, No. 4, pp. 695-703, October 1991.

[9] B. Karanayil, M.F. Rahman, C. Grantham, "PI and Fuzzy Estimators for On-line Tracking of Rotor Resistance of Indirect Vector controlled Induction Motor Drive", IEEE Conference on Electric Machines and Drives, pp. 820-825, 2001.

[10] R. Krishnan, "Electric Motor Drives: Modeling, Analysis and Control", Prentice Hall, pp. 411-477, 2001.

[11] A. Dittrich, “Parameter Sensitivity of Procedures for On-Line Adaptation of the Rotor Time Constant of Induction Machines with Field Oriented Control”, IEE Proc., Electr. Power Appl., Vol. 141, No. 6, pp. 353-359, November 1994.

[12] R.W. De Doncker, “Parameter Sensitivity of Indirect Universal Field-Oriented Controllers”, IEEE Trans. on Power Electronics, Vol. 9, No. 4, pp. 367-376, July 1994.

[13] H.A. Toliyat, E. Levi, M. Raina “A Review of RFO Induction Motor Parameter Estimation Techniques”, IEEE Trans. on Energy Conversion, Vol. 18, No. 2, pp. 271-283, June 2003.

[14] A. Ba-Razzouk, P. Sicard, V. Rajagopalan, “A Simple On-Line Method for Rotor Resistance Updating in Indirect Rotor Flux Orientation”, IEEE Trans. on Power Electronics, Vol. 1, pp. 317-322, Nov. 2002.

[15] R.S. Pena, G.M. Asher, “Parameter Sensitivity Studies for Induction Motor Parameter Identification Using Extended Kalman Filters”, The Fifth European Conference on Power Electronics Application, Vol. 4, pp. 306-311, Sep. 1993.

[16] M. Mahdavi, H. Monsef, “Advanced Particle Swarm Optimization Used for Optimal Design of Single-Phase Induction Motor”, International Journal on Technical and Physical Problems of Engineering (IJTPE), Issue 2, Vol. 2, No. 1, pp. 55-59, March 2010.

[17] Z.A. Mamedova, “Numerical Simulation of Transients Processes in Nonlinear Electric Drive System with Induction Electromagnetic Clutch”, International Journal on Technical and Physical Problems of Engineering (IJTPE), Issue 6, Vol. 3, No. 1, pp. 53-56, March 2011.

[18] A. Shiri, A. Vahedi, A. Shoulaie, “The Effect of Parameter Variations on the Performance of Indirect Vector Controlled Induction Motor Drive”, IEEE International Symposium on Industrial Electronics, Montreal, Quebec, Canada, pp. 2377-2381, 2006.

[19] Y. Kwon, J. Lee, S. Moon, B. Kwon, C. Choi, J. Seok, “Standstill Parameter Identification of Vector-Controlled Induction Motors Using the Frequency Characteristics of Rotor Bars”, IEEE Trans. on Industry Applications, Vol. 45, No. 5, pp. 1610-1618, September/October 2009.

BIOGRAPHIES

Abbas Shiri was born in Hashtrood, Iran in 1980. He received the B.Sc. degree from University of Tabriz (Tabriz, Iran) and M.Sc. degree from Iran University of Science and Technology (Tehran, Iran) both in Electrical Engineering in 2004 and 2006, respectively. He is currently working toward Ph.D. degree in Electrical Engineering at Iran University of Science and Technology. His areas of research interests include linear electric machines, electromagnetic systems and actuators, electrical machine design and modeling.

Hamidreza Pairodin Nabi was born in Tehran, Iran in 1986. He received the B.Sc. and M.Sc. degrees from Iran University of Science and Technology (Tehran, Iran) both in Electrical Engineering. He is currently working toward Ph.D. degree in Electrical Engineering at Iran University of Science and Technology. His main research interests include electrical machine design and modeling, design and control of power electronic converters and motor drive systems and multiphase variable speed drives.

Abbas Shoulaie was born in Isfahan, Iran, in 1949. He received the B.Sc. degree from Iran University of Science and Technology (Tehran, Iran) in 1973, and the M.Sc. and Ph.D. degrees in Electrical Engineering from U.S.T.L., Montpellier, France, in 1981 and 1984, respectively. He is a Professor at the Department of Electrical Engineering, Iran University of Science and Technology. He is the author of more than 100 journal and conference papers in the field of power electronics, electromagnetic systems, electrical machine, linear machine and HVDC.