A Novel Approach to Sensorless Control of Induction Motors

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Abstract

In this paper, sensorless control of induction motor is studied by reducing the adverse effect caused by the variation of the rotor time constant, which is the most effective parameter. For this purpose, a new robust observer for the parameter variation, is designed with the combination of sliding mode approach and Luenberger observer. Then, the observer is used in the rotor flux oriented vector control of induction motor. The control hardware is realized by using a motion control card on a computer. The current and the voltage values of the motor are transferred to the control algorithm software by means of the analog-to-digital converter on the motion control card. The actual speed of the motor is measured through the encoder and it is compared with it's estimated value. Experimental results have shown that the estimated speed successfully converged to measured one. Simulation studies are performed in MATLAB, before implementing the proposed observer with rotor flux oriented control for the induction machine. The observer constants and the control parameters are tuned based on this simulation results. The comparative results and related overall conclusions are presented accordingly.

1. Introduction

Induction motors (IM) are the most preferred electric motors due to having rigid structure, ease of maintenance and low cost. Although they were hardly used in digital applications until 1980s because of having not only slow response time but also complicated control systems, recently they are used in applications of servo systems since vector control algorithm has enabled them to have improved response time. The costs can be reduced further compared to other electric drive systems with the sensorless (without velocity feedback) control of IM. Despite the advantage of reduced costs, the complicated structure of IM involving parameter variation causes problems in transient response. This fact has limited the use of sensorless control for IM in industrial applications. There have been various efforts from the industry and academia on the structure of observers estimating the motor velocity with the aim of eliminating this limitation. Indirect flux oriented control applied to the IM by Hasse in 1968 [1]. In this study sliding mode control calculations of the motor were obtained by stator currents. On the other hand direct flux oriented control was applied by Blaschke in 1971 [2]. While this method was applied, hall effect transducers, sensing windings, third harmonic of the stator voltages used to obtain flux orientation. Joetten, using adverse emf vector u_i, had important improvements on the sensorless vector control in 1983 [3]. Sangwongwanic used sliding mode control method to the direct flux oriented control in 1990 [4]. Brdys and Du obtained Luenberger observer in 1991 [5]. Vas used fuzzy control method with using Luenberger observer in the sensorless control in 1995 [6]. Abrate et.al. also had an new approach to the Luenberger observer by using fuzzy method to the coefficients of the gain matrix of the observer in 1999 [7]. Lee also used Luenberger observer to estimate inertia torque in 2004 [8]. To derive benefit from these successful studies, in this study, a new robust observer is designed with the combination of sliding mode approach and Luenberger observer to reduce the adverse affect of the variation of the rotor time constant, which is the most effective parameter. Then, the observer is used in the rotor flux oriented vector control of IM. Mathematical model of the IM, sliding mode approach, Luenberger observer structure, and the new observer are demonstrated in section 2. Simulation setup and parameters, experimental setup and block diagram of the whole system, control and estimation of the system and the results are discussed in section 3. Findings of the simulation and experimental results and future research are presented in conclusion.

2. Theoretical Approach

The mathematical model which represents steady state and transient state machine's behavior is defined by using space vectors in order to make convenience for calculating. To ease analyze, it is accepted that in the motor air gap is smooth, iron permeability is infinite, flux density is perpendicular to the surface, there is no winding slot effect, iron loss, and point effect. Stator and rotor model of IM are obtained as below.

$$\frac{d}{dt}\begin{bmatrix} i_{sD} \\ i_{sQ} \end{bmatrix} = -C_1 \begin{bmatrix} i_{sD} \\ i_{sQ} \end{bmatrix} + C_2 \begin{bmatrix} x_r & w_r \\ -w_r & x_r \end{bmatrix} \begin{bmatrix} \Psi_{rd} \\ \Psi_{rq} \end{bmatrix} + C_3 \begin{bmatrix} u_{sD} \\ u_{sQ} \end{bmatrix} \quad (1)$$

$$\frac{d}{dt}\begin{bmatrix} \Psi_{rd} \\ \Psi_{rq} \end{bmatrix} = \begin{bmatrix} -x_r & -w_r \\ w_r & -x_r \end{bmatrix} \begin{bmatrix} \Psi_{rd} \\ \Psi_{rq} \end{bmatrix} + L_m x_r \begin{bmatrix} i_{sD} \\ i_{sQ} \end{bmatrix} \quad (2)$$

where;

$$C_1 = \left[\frac{1}{T_s'} + \frac{(1-\sigma)}{T_r'}\right],\ C_2 = \left[\frac{L_m}{L_s' L_r}\right],\ C_3 = \frac{1}{L_s'},\ \text{and}$$
$$x_r = 1/T_r$$

L_m, L_r and L_s are magnetizing, rotor and stator inductances respectively. $L_s' = L_s - L_m^2/L_r$ is stator transient inductance. Stator and rotor transient time constant are defined as $T_s' = L_s'/R_s$ and $T_r' = L_r'/R_r$ respectively. R_s and R_r are stator and rotor resistances. L_r' is defined as $L_r' = L_r' - L_m^2/L_s$. Leakage factor, σ, is given as $\sigma = 1 - L_m^2/(L_s L_r)$.

Sensorless vector control is realized by taking the flux and torque as references for the system. θ is angle of the rotor flux vector between the D-axis. This angle value is obtained by the components of the rotor flux vector via the observer. θ is necessary for the transformation between (D-Q) stationary reference frame and (d-q) rotating reference frame. The accuracy of the angle is so important that it affects the vector control. Phasor diagram in connection with these transformations is shown in Fig. 1.

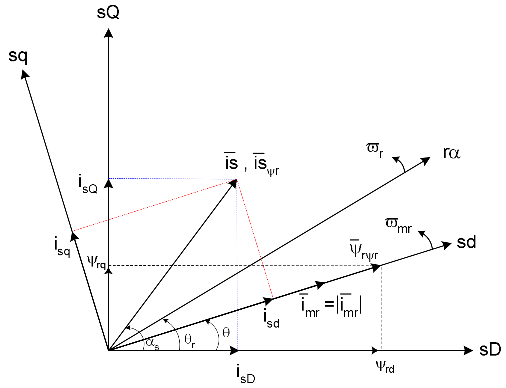

Fig. 1. Stator currents in D-Q and d-q axis.

2.1. Observer Method

Motor's model can be represented in state space, $\dot{X}(t) = A.X(t) + B.U(t)$, where, state variables, A, B and u are described as follows,

$$X = \begin{bmatrix} i_{sD} & i_{sQ} & \psi_{rd} & \psi_{rq} \end{bmatrix}^T, U = \begin{bmatrix} u_{sD} \\ u_{sQ} \end{bmatrix}, B = \begin{bmatrix} \frac{1}{L_s'} & 0 & 0 & 0 \\ 0 & \frac{1}{L_s'} & 0 & 0 \end{bmatrix}^T \tag{3}$$

$$A = \begin{bmatrix} -\left[1/T_s' + (1-\sigma)/T_r'\right]I_2 & \left[L_m/(L_s'L_rT_r)\right]\left[I_2/T_r - w_rJ\right] \\ (L_m/T_r)I_2 & -(1/T_r)I_2 + w_rJ \end{bmatrix} \tag{4}$$

where I_2 is 2x2 identity matrix and J matrix is

$$J = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \tag{5}$$

To estimate the rotor speed, Luenberger observer method can be used and given as,

$$\frac{d\hat{x}}{dt} = \hat{A}x + Bu + G(i_s - \hat{i}_s) \tag{6}$$

This dynamics is similar to the motor model except $\hat{x}$, $\hat{A}$, G, and $\hat{i}_s$. And it's convergence properties well studied in literature [6], [7], [8]. $\hat{A}$ can be partioned as,

$$\hat{A} = \begin{bmatrix} -\left[1/T_s' + (1-\sigma)/T_r'\right]I_2 & \left[L_m/(L_s'L_rT_r)\right]\left[I_2/T_r - \hat{w}_rJ\right] \\ (L_m/T_r)I_2 & -(1/T_r)I_2 + \hat{w}_rJ \end{bmatrix} \tag{7}$$

G matrix in the observer equation is known as observer gain matrix and written as a two-by-four matrix with constants values.

2.2. The New Approach

In the sliding mode method, control which makes the derivative of the slide function zero is called equivalent control. Disadvantage of the equivalent control is it contains numerous operations. To solve this problem, a calculation method was improved, based on estimation of the equivalent solution u_{eq}. In this method, first order filter is used for estimation. These filter dynamics is,

$$\tau_i \dot{\hat{u}}_{eq_i}(t) + \hat{u}_{eq_i}(t) = \hat{u}_i(t), \; \hat{u}_{eq_i} = \frac{1}{\tau_i.s + 1}u_i \tag{8}$$

where $\hat{u}_{eq_i}$ is the estimated u_{eq_i} and "s" is the laplace operator. Consequently control rule can be written in discrete time,

$$u_{(t)} = u_{(t-T)} + \frac{1}{B.T}\left((D.T+1).S_{(t)} - S_{(t-T)}\right) \tag{9}$$

where B and D are constant value, T is period of the control, S is slide function. Rotor time constant vector matrix can be defined as a part of Eq. 1, and can be written as,

$$f = \begin{bmatrix} f_D \\ f_Q \end{bmatrix} \triangleq \begin{bmatrix} x_r & w_r \\ -w_r & x_r \end{bmatrix} \begin{bmatrix} \Psi_{rd} \\ \Psi_{rq} \end{bmatrix} \tag{10}$$

thus estimated values of stator model,

$$\frac{d}{dt}\begin{bmatrix} \hat{i}_{sD} \\ \hat{i}_{sQ} \end{bmatrix} = -C_1\begin{bmatrix} \hat{i}_{sD} \\ \hat{i}_{sQ} \end{bmatrix} + C_2\begin{bmatrix} \hat{f}_D \\ \hat{f}_Q \end{bmatrix} + C_3\begin{bmatrix} u_{sD} \\ u_{sQ} \end{bmatrix} \tag{11}$$

Difference of these two models can be obtained by subtracting Eq. 11 from Eq. 1,

$$\begin{bmatrix} \Delta i_{sD} \\ \Delta i_{sQ} \end{bmatrix} = -C_1\begin{bmatrix} \Delta i_{sD} \\ \Delta i_{sQ} \end{bmatrix} + C_2\begin{bmatrix} \Delta f_D \\ \Delta f_Q \end{bmatrix} \tag{12}$$

Variation of currents and its derivation can be obtained as zero by controlling the vector $\hat{f}$ ($\Delta i_s = 0, \Delta \dot{i}_s = 0$) [11, 13].This control vector $\hat{f}$ can be written as,

$$\hat{f} = \begin{bmatrix} \hat{f}_D \\ \hat{f}_Q \end{bmatrix} \triangleq \begin{bmatrix} \beta & \hat{w}_r \\ -\hat{w}_r & \beta \end{bmatrix} \begin{bmatrix} \hat{\Psi}_{rd} \\ \hat{\Psi}_{rq} \end{bmatrix} = \begin{bmatrix} \hat{\Psi}_{rd} & \hat{\Psi}_{rq} \\ \hat{\Psi}_{rq} & -\hat{\Psi}_{rd} \end{bmatrix} \begin{bmatrix} \beta \\ \hat{w}_r \end{bmatrix} \tag{13}$$

β in Eq. 13 is the control variable, which tunes the variations of the rotor time constant. Because of the variation of the flux components is slower than the current's, this tune operation can be written like Eq. 9,

$$\beta_{(t)} = \beta_{(t-T)} + \frac{L'_s.L_r}{L_m.T.\left|\hat{\Psi}_r\right|}.\begin{bmatrix} \cos\hat{\theta}.\left[(D.T+1)\Delta i_{sD(t)} - \Delta i_{sD(t-T)}\right] \\ +\sin\hat{\theta}.\left[(D.T+1)\Delta i_{sQ(t)} - \Delta i_{sQ(t-T)}\right] \end{bmatrix} \quad (14)$$

Δ is the differences in real and estimated values ($\Delta i_{sD} = i_{sD} - \hat{i}_{sD}$ and $\Delta i_{sQ} = i_{sQ} - \hat{i}_{sQ}$).

In this study, the new approach incorporates β to the observer matrix. β is reducing the adverse effect caused by the variation of the rotor time constant. Rotor resistance can change from nominal values by about 20% to 50% [9],[10]. Although observer dynamics is similar as given Eq. 6, $\hat{A}$ matrix with β can be described as below,

$$\hat{A} = \begin{bmatrix} -\left[1/T'_s + (1-\sigma)/T'_r\right]I_2 & \left[L_m/(L'_s L_r)\right]\left[\beta I_2 - \hat{w}_r J\right] \\ L_m \beta I_2 & -\beta I_2 + \hat{w}_r J \end{bmatrix} \quad (15)$$

To reduce calculation time of the algorithm, four entries of the observer gain matrix are taken zero. Other entries are constant as shown below.

$$\begin{aligned} g_{12} &= g_{21} = g_{31} = g_{41} = 0 \\ g_{11} &= g_{22} = c_1 \\ g_{32} &= -g_{42} = c_2 \end{aligned} \quad (16)$$

Speed is calculated with an error signal, which is composed of d and q components and can be written as,

$$e_w = \hat{\Psi}_{rq} e_{sD} - \hat{\Psi}_{rd} e_{sQ} \quad (17)$$

where $e_{sd} = i_{sD} - \hat{i}_{sD}$ and $e_{sq} = i_{sQ} - \hat{i}_{sQ}$.

Next, to accomplish the estimation of the rotor speed, e_w signal is used (substituted) in the PI controller,

$$\hat{w}_r = K_p e_w + K_i \int (e_w) dt \quad (18)$$

Fig. 2, demonstrates speed estimation, basically measured voltage and currents are used for flux and current estimation those estimated values are used to estimate motor speed.

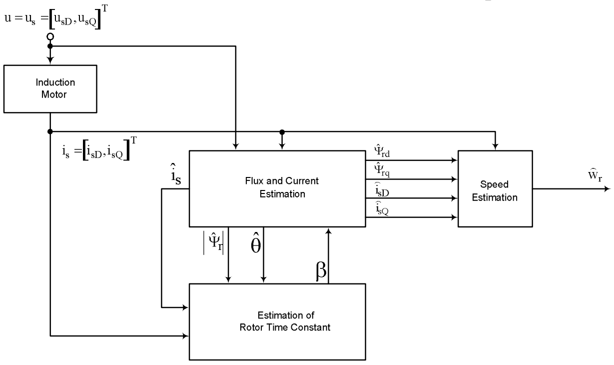

Fig. 2. Block diagram of the speed estimation.

3. Experimental Studies and Results

Since it has been proven in the literature that rotor flux oriented control has better stability, it has been implemented in this study. A new observer is proposed to estimate rotor flux and so the rotor speed. These estimations are used in the vector control. This control block is shown in Fig. 3.

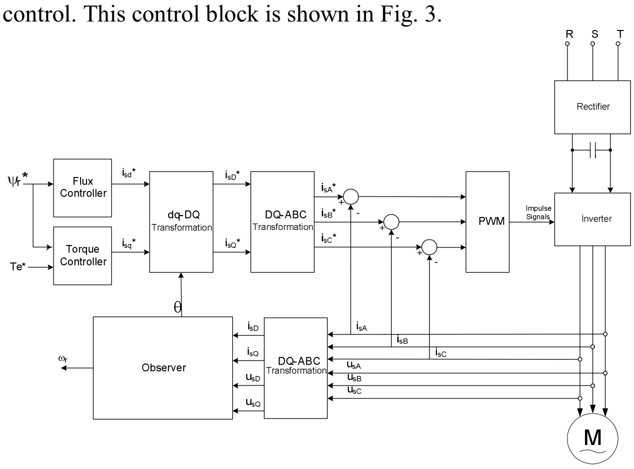

Fig. 3. Block diagram of sensorless speed control.

In the rotor-flux-oriented control, determination of the rotating frame axes is ground on that rotor flux vector is over the one of the axis. As shown from the Fig. 1 the rotor flux vector is on top of the d-axis. Components of the flux vector in the stationary reference frame are shown in the figure ψ_{rd} and ψ_{rq} in D and Q axis respectively. Components of the reference stator current in the stationary reference frame are obtained by θ angle and flux reference with torque reference using in the rotating reference frame. PWM signals are used switch to IGBT's in inverter to drive the motor, These signals generated by comparing measured current with the estimated current.

3.1. Simulations

MATLAB is used for calculation and simulation. In the contributed software, sampling time is 100µs and 11000 loops are used in the software. As a result, total time of the simulation is 1.1s. Note that, this duration is enough for the steady state status for the motor speed.

Motor parameters are;

R_s=7; R_r=5.4; L_{ls}=20*1e-3; L_{lr}=20*1e-3; L_m=382*1e-3; (L_s=L_{ls}+L_m, L_r=L_{lr}+L_m);

P = 4 (Number of the motor poles)

J = 0.01 (Inertia of the motor)

V_{dc} = 311 Volts (DC bus voltage).

Furthermore, flux reference and torque reference are taken as 0.5Wb and 2Nm respectively.

It should be mentioned that the most effective parameter in the mathematical model of IM is the rotor time constant. The variation of the rotor time constant is a negative effect for the realization of the sensorless control of IM. Thus, simulations are carried out for five different rotor time constant (T_r) values for the new observer.

The nominal value of the rotor time constant is,

$$T_r = \frac{L_r}{R_r} = \frac{L_{lr} + L_m}{R_r} = \frac{0.402}{5.4} = 0.0744 \quad (19)$$

Simulations are realized for Tr = (Tr)n = 0.0744, Tr = 0.8*(Tr)n , Tr = 1.5*(Tr)n and it has been shown in Figures 4-6 that the estimated speed is obtained from the observer, the motor speed, and the error between those for Tr = (Tr)n , Tr = 0.8*(Tr)n , Tr = 1.5*(Tr)n respectively.

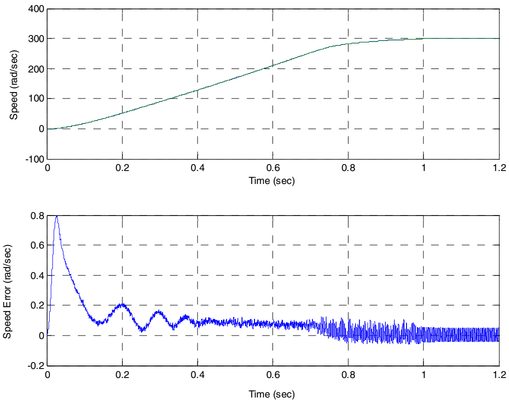

Fig. 4. The estimated speed, the motor speed, and the error between the two speed for Tr = (Tr)n = 0.0744.

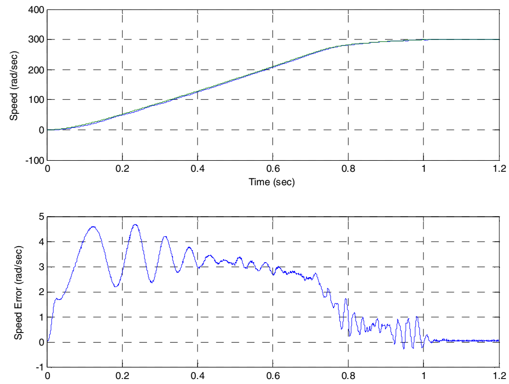

Fig. 5. The estimated speed, the motor speed, and the error between the two speed for Tr = 0.8*(Tr)n.

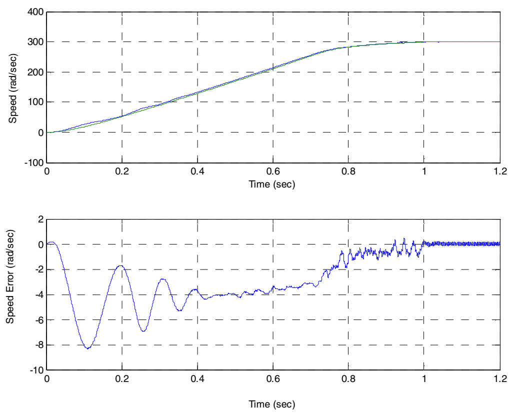

Fig. 6. The estimated speed, the motor speed, and the error between the two speed for Tr = 1.5*(Tr)n.

3.2. Implementation

In the experimental circuit, a rectifier (6RI30G160) which is three phase uncontrolled rectifier and produces a dc voltage across the filter capacitor (2200µF). and an inverter which is an intelligent power module (IPM-7MBP25RA120) are used in the power circuit. Control algorithm is run with a Pentium based PC. ADC and Encoder card are connected to the selectable addresses of a standard 64-bit I/O card (DESICION) which is on the ISA slot of the PC. Control and input/output signals are generated by this card.

In the realized control system, control period Ts is chosen 30µsec. Two phase currents and DC link voltage are sampled by ADC in every 30µsec. To obtain the control period, PB4 port in the 0x61 address of the PC is used. The control software is written with C code. Calculated switch signals drives the IPM by using I/O card. It should be underlined that isolation between the PC and the power circuit is obtained fully.

Desired reference speed value is an input to the control algorithm. After the reference flux and torque, reference stator currents are calculated by using the reference speed value. Comparison of the measured current values and the reference values is used for the drive signals of the IPM by using the hysteresis control method. Band width is taken as 0.1sec. in the hysteresis. Experimental block diagram is given in Fig. 7.

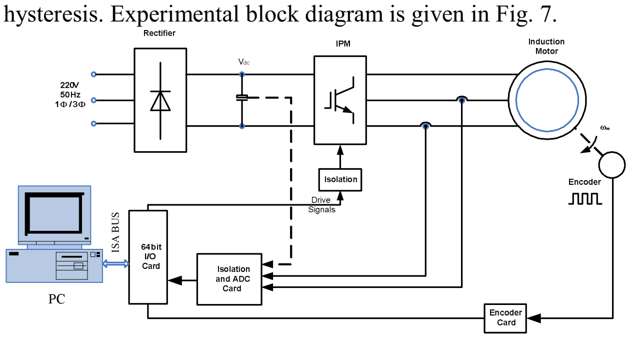

Fig. 7. Block diagram of experimental study.

Reference speed values are taken as 250 and, 500 rpm. In the control part one cycle is taken as 5500 period which means that it is sampled 5500 times. Sampling value is limited because of the capacity of the system. The estimated and the measured values of the speed values are taken from the I/O card.

Estimated and measured speed for reference 250 and 500 rpms are shown in Fig. 8 and 9.

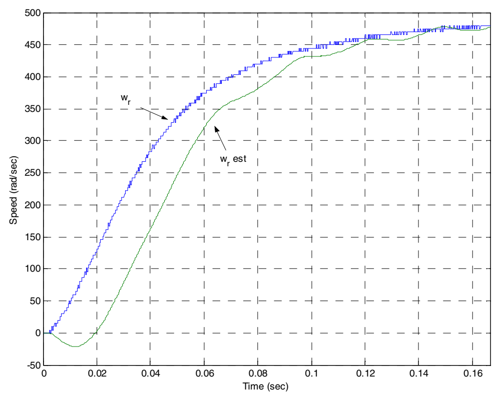

Fig. 8. The estimated and the measured speed for 250 rpm of reference speed.

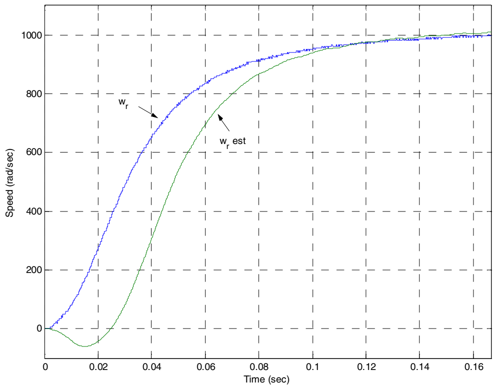

Fig. 9. The estimated and the measured speed for 500 rpm of reference speed.

4. Conclusion

In this study, changes of the components of the stator currents ($\hat{i}_{sD}$ and $\hat{i}_{sQ}$) and rotor flux ($\hat{\psi}_{rd}$ and $\hat{\psi}_{rq}$) are obtained by using the new designed observer. It is known that the IM mathematical model strongly dependent on the rotor time constant. In this paper, to reduce this dependency, a new approach to the Luenberger observer is suggested. The proposed method is both simulated and experimentally validated.

In the simulation, the amplitude and the angle of the rotor flux are obtained from the components of the estimated rotor flux. To obtain the angle in this way is very difficult when using microcontroller because this process takes lots of time. Thus sinus and cosines tables are composed in the experiment. Consequently tangent of the rotor flux and transformation of the axis are obtained. Estimated values of the rotor time constant (β) are updated in every period of the control. In the estimation of the speed, the components of the estimated rotor flux and the difference between the measured and the estimated stator currents in DQ-axis are input values. Estimation of the speed is obtained by imposing the signal from a PI controller finally. PI parameters in the controller are tuned.

As shown from the figures of the simulations, the estimated speed is very similar to the motor speed when the rotor time constant equals to the original value. In the transient condition, the growing error is below the 1%. Notwithstanding in the steady state condition, the error is around 0.1%. When the rotor time constant changes, the error is growing up 1% slightly. But in the steady state, the error is descending below 1%.

As shown in the experimental results, performance of the observer is very successful in the steady state. The estimation of the speed is nearly following the measured one. But in the transient the observer is not following the real one perfectly. This adverse effect can be reduced with soft start. Instead of hysteresis control method, space vector modulation method can be used with implementation of DSP. Furthermore, coefficients of the gain matrix of the observer are taken as constant values. In further studies, these coefficients can be taken different values for different speed region or using neural network, fuzzy-neural or genetic algorithm for specifying the coefficients of the gain matrix will be better solutions to sensorless control.

5. References

[1] K. Hasse, "Zum Dynamischen Verhalten der Asynchronmachine bei Betrieb mit variable Standerfrequenz und Standerspannung," *ETZ-A, Bd.89, H.4, pp.77-81,* 1968.

[2] F. Blaschke, "Das Prizip der Feldorientierung , Die Grundlage fur die TRNSVEKTOR-Regelung von Asynchnmachinen," *Siemens Zeitschrift, 45, p.757,* 1971.

[3] R. Joetten, G. Maeder, "Control Methods for Good Dynamic Performance IM Drives Based on Current and Voltage as Measured Quantities", *IEEE Trans. on Ind. Appl. Vol. 19, No.3: 356-363,* 1983.

[4] S. Sangwongwanic, S. Doki, T. Yonemoto, S. Okuma, "Adaptive Sliding Observer for Direct Field-Oriented Control of Induction Motors", *Int. Conf. on Ind. Elec. Cont. and Instr., IECON'90,: 915-920,* Asilomar, 1990.

[5] M.A. Brdys, T. Du, "Algorithms for joint state and parameter estimation in induction motor drive systems", Control '91., *International Conference on , Vol.2: 915 – 920,* 25-28 Mar,1991.

[6] P. Vas, A.F. Stronach, M. Neuroth, "A fuzzy-controlled speed-sensorless induction motor drive with flux estimators", *Electrical Machines and Drives, Seventh International Conference on (Conf. Publ. No. 412) : 315 – 319,* 11-13 Sep, 1995.

[7] M. Abrate, G. Griva, F. Profumo, A. Tenconi, "High speed sensorless fuzzy-like Luenberger observer", *Power Electronics Specialists Conference, PESC 99. 30th Annual IEEE , Volume. 1: 477 – 481,* 27 June-1 July 1999.

[8] K.B. Lee, J.Y. Yoo, J.H. Song, I. Choy, "Improvement of low speed operation of electric machine with an inertia identification using ROELO", *Electric Power Applications, IEE Proceedings, Vol.151, Issue. 1: 116 - 120,* 9 Jan. 2004.

[9] M.A. Valenzuela, J.A. Tapia, and J.A. Rooks, "Thermal evaluation of TEFC induction motors operating on frequency-controlled variable-speed drives", *IEEE Trans. Ind. Appl., vol. 40, no. 2, pp. 692-698,* Mar./Apr. 2004.

[10] T.H. Bishop, "Temperature monitoring is key to motor reliability", *Maint. Technol. Mag., p. 34,* Jul. 2004.

[11] A.K. Pradeep, J.P. Lyons, S.R. MacMinn, "Application of sliding mode observer for state estimation in rotating machines", *Proc.VARSCON'91, pp. 57-64,* 1991.

[12] P.L. Jansen, C.O. Thompson, R.D. Lorenz, "Observer-based direct field orientation for both zero and very high speed operation", *Proc.of Power Conv. Conf., PCC Yokohama, pp. 432-437, ISBN: 0-7803-0471-3,* 19-21 April 1993.

[13] F. Alogne, T. Raimondi, "Indirect adaptive speed control of induction motor systems based on model reference identifiers", *Proc.IECON'93, vol:2, pp. 1035-1040, ISBN: 0-7803-3026-9,* 6-10 November 1995.