Speed Sensorless Rotor Field Oriented Control of Induction Motor Drive

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Abstract: - A new speed estimation algorithm for speed sensorless rotor field oriented control of induction motor drive is presented. The proposed method is based on observing a newly defined quantity from which the rotor speed is computed. The method is simple to implement and does not require taking derivative of the measured signals. A fully digital real-time simulation, a new powerful tool for rapid prototyping of complex control systems is used to validate the estimation algorithm.

Key-Words: Induction motor, field oriented control, reduced-order observer, speed estimation, flux estimation.

1 Introduction

Field oriented control (FOC) or vector control (VC) originated from the works of Blaschke [1] and Hasse [2] has become an industry standard for controlling induction machines in high performance drive applications. However, shaft mounted speed sensors in conventional VC drives degrade the system reliability and require special attention to electrical noise. Moreover, it is difficult to mount sensors in certain applications in addition to extra expenses involved. Therefore, a lot of researches are underway to develop accurate speed estimation techniques. With sensorless vector control we have a decoupled control structure similar to that of a separately excited dc machine, retaining the inherent ruggedness of induction motor at the same time. The rotor speed has been considered as a constant by many researchers in speed estimation problem [3-12]. The idea is that the speed changes slowly compared to electrical variables. Adopting such an approach allowed speed estimation without requiring the knowledge of mechanical parameters of the drive system such as load torque, inertia etc. In [3-5] speed was estimated using Model Reference Adaptive System considering it as an unknown constant parameter. In [6-9] the speed was considered as an unknown constant state of the machine and Extended Kalman Filter was used to estimate it. Recursive least square estimation (RLSE) method was used in [10-12] for speed estimation considering speed as an unknown constant parameter and found out the value of estimated speed that best fits the measured and calculated data to the dynamic equations of the motor.

In this paper a new rotor speed estimation algorithm is proposed. The proposed method is developed by introducing a new quantity which is a function of rotor flux and speed assuming that rotor speed varies slowly in comparison to electrical states. The new quantity containing the information about the rotor flux and speed is estimated using a reduced order observer. Finally, the rotor speed is computed from the estimated quantity. The proposed method does not require taking derivative of the measured signals unlike that of [5, 10-12]. The method is also simpler to implement than implementing EKF. This work is believed to be a novel contribution. A fully digital real time simulation, a new powerful tool for rapid prototyping complex control system is used to validate the proposed estimation algorithm.

2 Rotor Flux and Speed Estimation

2.1 Induction Motor Model

Fig. 1. shows the reference frames and representation of stator current and rotor flux as space vectors. The induction motor model in stator reference frame $(\alpha - \beta)$ using complex vector notation is given as [13]:

$$\vec{v}_s = R_s \vec{i}_s + \frac{d\vec{\psi}_s}{dt} \quad (1)$$

$$0 = R_r \vec{i}_r e^{j\varepsilon} + \frac{d\vec{\psi}_r e^{j\varepsilon}}{dt} - j\omega \vec{\psi}_r e^{j\varepsilon} \quad (2)$$

$$\vec{\psi}_s = L_s \vec{i}_s + L_m \vec{i}_r e^{j\varepsilon} \quad (3)$$

$$\vec{\psi}_r e^{j\varepsilon} = L_r \vec{i}_r e^{j\varepsilon} + L_m \vec{i}_s \quad (4)$$

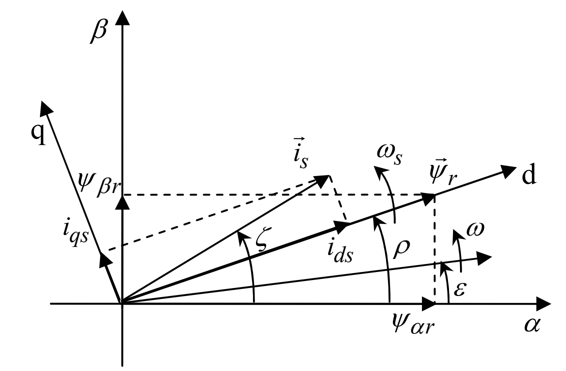


Fig. 1. Reference frames and representation of stator current and rotor flux as space vectors.

After eliminating the rotor current and stator flux the model of the motor is as given below:

$$\frac{d\vec{\psi}_r e^{j\varepsilon}}{dt} = -a\vec{\psi}_r e^{j\varepsilon} + j\omega\vec{\psi}_r e^{j\varepsilon} + aL_m \vec{i}_s \quad (5)$$

$$\frac{d\vec{i}_s}{dt} = -bd\vec{i}_s + acd\vec{\psi}_r e^{j\varepsilon} - j\omega cd\vec{\psi}_r e^{j\varepsilon} + d\vec{v}_s \quad (6)$$

where $a = \frac{R_r}{L_r}$, $b = R_s + \frac{R_r L_m^2}{L_r^2}$, $c = \frac{L_m}{L_r}$ and $d = \frac{1}{L_s - L_m^2 / L_r}$.

2.2 Rotor Flux Estimation

Using (1), (3) and (4) we obtain the equation commonly known as voltage model of induction motor given below:

$$\vec{\psi}_r e^{i\varepsilon} = \frac{1}{c}\left\{ \int (\vec{v}_s - R_s \vec{i}_s) dt - \frac{1}{d}\vec{i}_s \right\} \quad (7)$$

The rotor flux can be estimated using (7). However, the integration in (7) produces a problem of dc off-set and drift component in low speed region. Therefore, a first order low pass filter (LPF) is used instead of integration. The phase error in the low speed region produced due to LPF is approximately compensated by adding low pass filtered reference flux with the same time constant as above, and producing the estimated rotor flux [14]. The estimator equation is given as:

$$\hat{\psi}_r e^{j\hat{\rho}} = \frac{1}{c}\left\{ (\vec{v}_s - R_s \vec{i}_s)\frac{\tau}{1+\tau s} - \frac{1}{d}\vec{i}_s \frac{\tau s}{1+\tau s} \right\} + \Psi_r^* e^{j\rho^*} \frac{1}{1+\tau s} \quad (8)$$

where τ is the LPF time constant and $\Psi_r^* = L_m i_{ds}^*$. The rotor flux angle command ρ^* is computed as follows:

$$\rho^* = \int \omega_s^* dt \quad (9)$$

where $\omega_s^* = \omega_{sl}^* + \hat{\omega}$ is the command rotor flux speed. The command slip speed is as given below:

$$\omega_{sl}^* = \frac{R_r i_{qs}^*}{L_r i_{ds}^*} \quad (10)$$

2.3 Speed Estimation

First of all let's define a new quantity:

$$\vec{Z} = a\vec{\psi}_r e^{j\varepsilon} - j\omega\vec{\psi}_r e^{j\varepsilon} \quad (11)$$

Then, after introducing the new quantity the induction motor model may be written as:

$$\frac{d\vec{\psi}_r e^{j\varepsilon}}{dt} = -\vec{Z} + aL_m \vec{i}_s \quad (12)$$

$$\frac{d\vec{i}_s}{dt} = -bd\vec{i}_s + cd\vec{Z} + d\vec{v}_s \quad (13)$$

$$\frac{d\vec{Z}}{dt} = e\vec{Z} + f\vec{i}_s \quad (14)$$

where $e = -a + j\omega$ and $f = a^2 L_m - jaL_m\omega$.

The proposed speed estimation algorithm is based on observing the newly defined quantity which is a function of rotor flux and speed. The last two equations (13) and (14) are used for constructing a Gopinath's reduced-order observer [15] for estimating the newly defined quantity $\vec{Z}$. The observer equation is as given below:

$$\frac{d\hat{\vec{Z}}}{dt} = e\hat{\vec{Z}} + f\vec{i}_s + G\left(\frac{d\vec{i}_s}{dt} - \frac{d\hat{\vec{i}}_s}{dt}\right) \quad (15)$$

Using equation (13) for $\frac{d\hat{\vec{i}}_s}{dt}$ the observer equation becomes:

$$\frac{d\hat{\vec{Z}}}{dt} = e\hat{\vec{Z}} + f\vec{i}_s + G\left(\frac{d\vec{i}_s}{dt} - bd\vec{i}_s - cd\hat{\vec{Z}} - d\vec{v}_s\right) \quad (16)$$

where $G = g_1 + jg_2$ is the observer gain. The observer poles can be placed at the desired location in the stable region of the complex plane by properly choosing the values of G.

In order to avoid the derivative of the stator current in the algorithm we introduce another new quantity $\vec{F} = \vec{Z} - G\vec{i}_s$. The observer after introduction of the new quantity is of the following form:

$$\frac{d\vec{F}}{dt} = \left(e - cdG\right)\vec{F} + \left(f + bdG + eG - cdG^2\right)\vec{i}_s$$
$$-dG\vec{v} \quad (17)$$

$$\hat{\vec{Z}} = \vec{F} + G\vec{i}_s \quad (18)$$

The block diagram of the $\vec{Z}$ estimator is shown is Fig. 2.

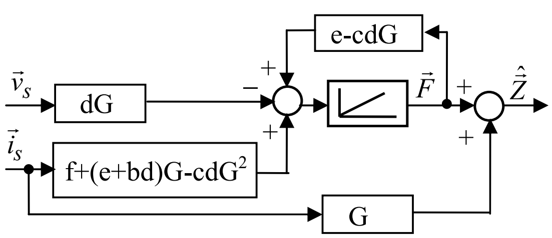


Fig. 2. Block diagram of the $\vec{Z}$ observer.

Assuming that there are no parameter variations and no speed error, the equation of the error dynamics is given by:

$$\frac{d\tilde{Z}}{dt} = \frac{d}{dt}\left(\vec{Z} - \hat{\vec{Z}}\right) = \left(e - cdG\right)\tilde{Z} \quad (19)$$

Eigenvalues of $\left(e - cdG\right)$ are the observer poles which are as given below:

$$p_{obs1,2} = -\left(a + cdg_1\right) \pm j\left(\omega - cdg_2\right) \quad (20)$$

The desired observer dynamics can be imposed by proper selection of observer gain G.

Next, we present how the rotor speed is computed. We see that the observed quantity is a function of rotor flux and speed. Taking cross product of (11) with $\vec{\psi}_r e^{j\varepsilon}$ we obtain a simple equation as given below:

$$Z_\alpha \psi_{r\beta} - Z_\beta \psi_{r\alpha} = \left(\psi_{r\alpha}^2 + \psi_{r\beta}^2\right)\omega \quad (21)$$

This equation does not involve derivative or integration. To use this equation directly for speed estimation we need to know rotor flux and Z. The estimated values of Z and rotor flux are used for computing the rotor speed. Rearranging the above equation we have the equation used for rotor speed computation as given below:

$$\hat{\omega} = \frac{\hat{Z}_\alpha \hat{\psi}_{r\beta} - \hat{Z}_\beta \hat{\psi}_{r\alpha}}{\hat{\psi}_{r\alpha}^2 + \hat{\psi}_{r\beta}^2} \quad (22)$$

It is to be noted here that the model of the motor used in implementing the observer algorithm has been developed assuming that the derivative of the rotor speed is zero. It is valid to make such an assumption since the dynamics of rotor speed is much slower than that of electrical states. Moreover, such an assumption allows estimation without requiring the knowledge of mechanical quantities of the drive such as load torque, inertia etc.

3 Real-Time Digital Simulation

The estimation algorithms are incorporated into the induction motor drive control scheme. The sensorless vector control induction motor drive thus obtained is shown in Fig.3. A PC cluster based fully digital real-time simulation using RT-Lab software package [16] is carried out to analyze the performance of the proposed scheme.

Initially, the drive is run at no load. The machine is accelerated to 150 rad/s at 0.3 s and the speed is reversed at 3 s. The speed of the motor (ω), estimated speed $(\hat{\omega})$, reference speed (ω^*) and speed estimation error $(\omega - \hat{\omega})$ are shown in Fig. 4.

Next, we test the performance of the estimator on loading and unloading. Full load is applied at 1 sec to the machine operating at no load at a speed of 150 rad/s and then the load is removed completely at 2 s Later, after speed reversal, full load is applied at 4 s and the load is fully removed at 5 s. The response of the drive on application and removal of load is shown in Fig. 5.

Then, we test the performance of the estimator under fully loaded condition of the drive at various operating speed. The fully loaded machine is accelerated to 150 rad/s at 0.3 s, then the speed is reduced in steps to 100 rad/s, 50 rad/s and 10 rad/s at 2.5 s, 3.5 s and 4.5 s respectively. Fig. 6 shows the estimation results during the operation of the drive.

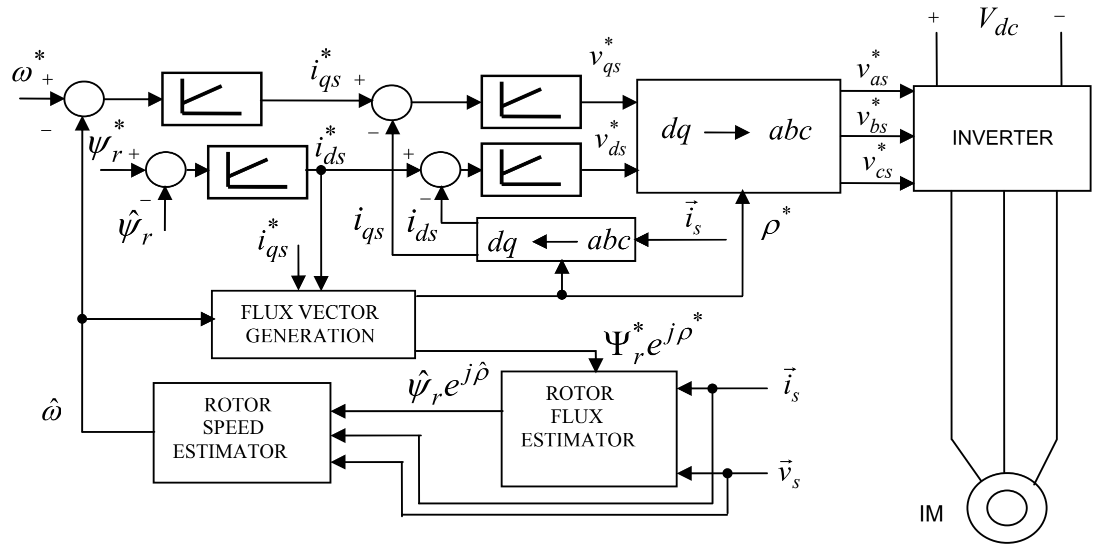
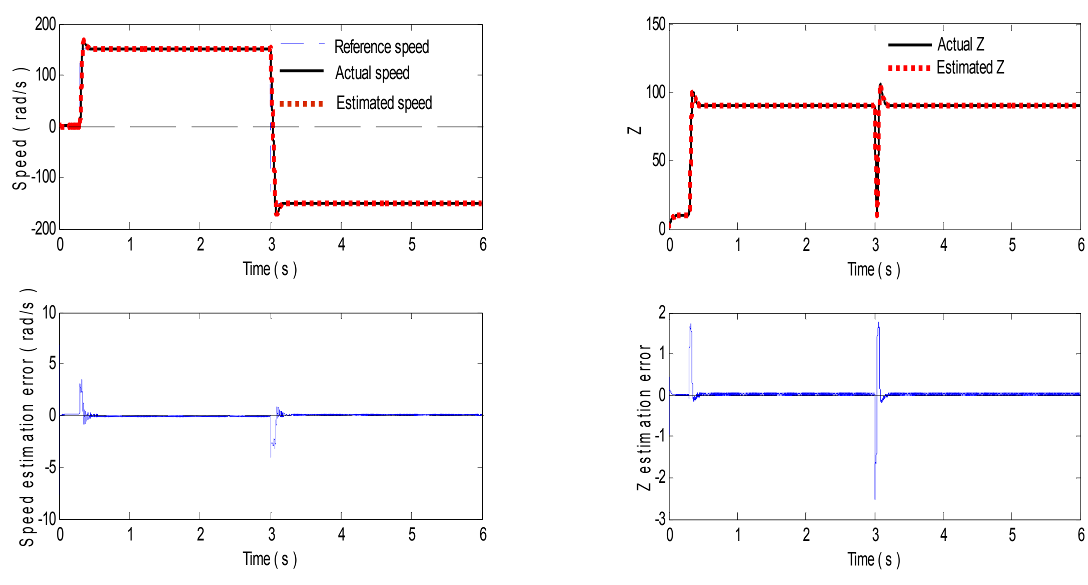
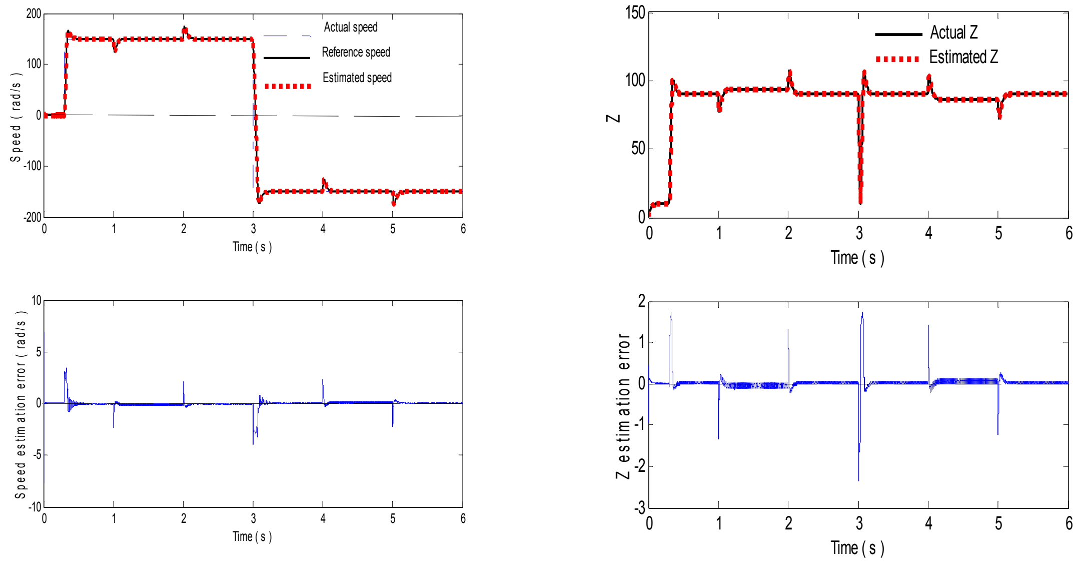


Fig. 3. Block diagram of sensorless VC induction motor drive.



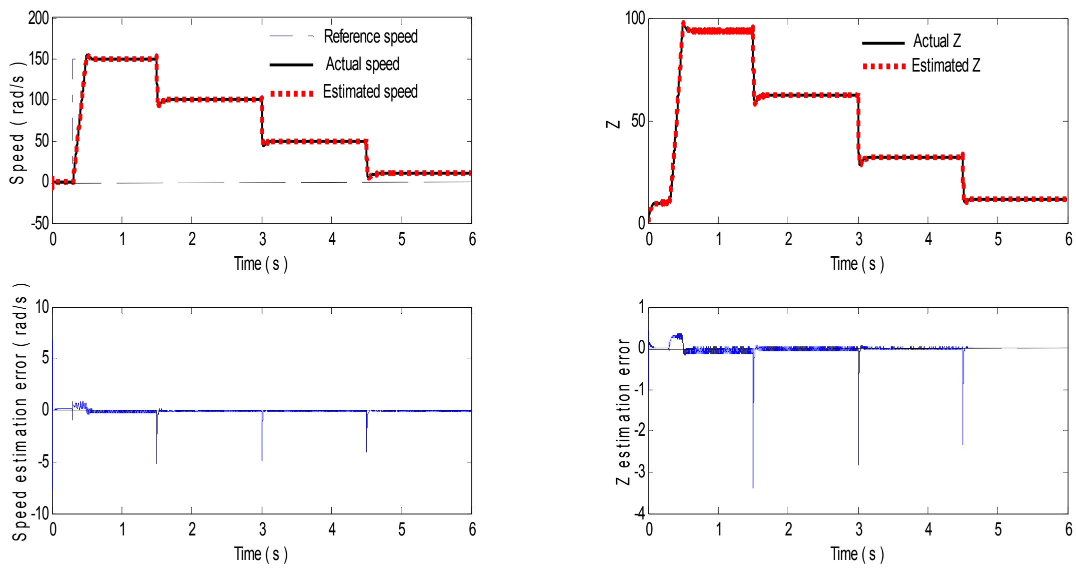
(a) (b)

Fig. 4. Starting and speed reversal at no load; (a) reference (ω^*), actual (ω), estimated ($\hat{\omega}$) speed and speed estimation error ($\omega - \hat{\omega}$); (b) actual (Z), estimated ($\hat{Z}$) and Z estimation error ($Z - \hat{Z}$).



(a) (b)

Fig. 5. Response of the drive on application and removal of load; (a) reference (ω^*), actual (ω), estimated ($\hat{\omega}$) speed and speed estimation error ($\omega - \hat{\omega}$); (b) actual (Z), estimated ($\hat{Z}$) and Z estimation error ($Z - \hat{Z}$).



(a) (b)

Fig. 6. Operation at full load at various reference speeds; (a) reference (ω^*), actual (ω), estimated ($\hat{\omega}$) speed and speed estimation error ($\omega - \hat{\omega}$); (b) actual (Z), estimated ($\hat{Z}$) and Z estimation error ($Z - \hat{Z}$).

The results show that the estimation accuracy of the proposed estimation algorithm is good and the response of the drive is satisfactory.

4 Conclusions

A new speed estimation algorithm for speed sensorless vector controlled induction motor drive has been proposed. The proposed algorithm is based on observing a newly defined quantity from which rotor speed is computed. The method is simple and involves no derivative. The proposed scheme was validated by the results of real-time digital simulation. The method has good estimation accuracy under both transient and steady state conditions, and the performance of the sensorless vector controlled induction motor drive was found to be satisfactory.

Acknowledgement

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References:

[1] F. Blaschke, The principle of Field Orientation as Applied to the New Transvector Closed-Loop Control System for Rotating Field Machines, *Siemens review,* Vol. XXXIX, No.5, 1972, pp. 217-219.

[2] K. Hasse*, On the Dynamics of Speed Control of a Static AC Drive with a Squirrel-cage induction machine*, PhD dissertation, Tech. Hochsch. Darmstadt, 1969.

[3] Colin Schauder, Adaptive speed Identification for Vector Control of Induction Motors without Rotational Transducers, *IEEE Trans. Ind. App.,* Vol. 28, No. 5, 1992, pp. 1054-1061.

[4] H. Tajima, Y. Hori, Speed Sensorless Field Orientation Control of the Induction Machine, *IEEE Trans. Ind. App.,* Vol. 29, No. 1, 1993, pp. 175-180.

[5] Fang-Zheng Peng, and Tadashi Fukao, Robust Speed Identification for Speed Sensorless Vector Control of Induction Motors, *IEEE Trans. Ind.. App.,* Vol. 30, No. 5, 1994, pp. 1234-1240.

[6] Y.R. Kim, S.K. Sul and M.H. Park, Speed Sensorless Vector Control of Induction Motor Using Extended Kalman Filter, *IEEE Trans. Ind. Appl.,* Vol. 30, No. 5, 1994, pp. 1225-1233.

[7] V. Comnac, M. Cernat, M. Cotorogea and I. Draghici, Sensorless Direct Torque and Stator Flux Control of Induction Machines Using an Extended Kalman Filter, *Proc. IEEE Int. Conf. on Control Appl.,* Mexico, 2001, pp. 674-679.

[8] X. Ma and Y. Gui, Extended Kalman Filter for Speed Sensorless DTC Based on DSP, *Proc. 4th World Cong. on Intelligent Control and Automation*, Shanghai, China, 2002, pp. 119-122.

[9] T. Du, P. Vas and F. Stronach, Design and Application of Extended Observers for Joint State and Parameter Estimation in High Performance AC Drives, *IEE Proc. Elec. Power App.,* Vol.142, No. 2, 1995, pp. 71-78.

[10] K. Minami, M. Veley-Reyez, D. Elten, G. C.Verghese, and D. Filbert, Multi-stage Speed and Parameter Estimation for Induction Machines, *IEEE Power Electronics Specialists Conf.*, Boston MA, 1991, pp. 596-604.

[11] M. Veleyez-Reyes and G. C. Verghese, Decomposed Algorithms for Speed and Parameter Estimation in Induction Machines, *IFAC Symposium on Nonlinear Control System Design*, Bordeaux, France, 1992, pp. 77-82.

[12] M. Velez-Reyes, K. Minami and G. C. Verghese, Recursive Speed and Parameter Estimation for Induction Machines, *IEEE/IAS Ann. Meet. Conf. Rec.*, San Diego, 1989, pp. 607-611.

[13] W. Leonhard, *Control of Electrical Drives*, Springer-Verlag, Berlin, 2001.

[14] T. Ohtani, N. Takada and K. Tanaka, Vector Control of Induction Motor without Shaft Encoder, IEEE Trans. Ind. Appl., Vol. 28, No. 1, Jan/Feb 1992, pp. 157-164.

[15] B. Gopinath, On the Control of Linear Multiple Input-Output Systems, *Bell Sys. Tech. J.*, Vol. 50, March 1971.

[16] Opal RT Technologies, RT Lab 7.1 User's Manual.