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Real Time Rotor Flux Estimation for Induction Machine Drives: an Experimental Approach

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Introduction

Squirrel cage induction motors are of major interest because of their simplicity and low cost. The rotor currents of squirrel induction machines are not accessible. In order to control the torque or speed of an induction motor, one must establish a flux observer to estimate the magnetizing currents. By using the advances of digital signal processing (DSP) technologies or the FPGA controller, the control schemes of induction motors are improved from simple scalar control strategies to field oriented control and direct torque control [2, 4, 6, 7].

Knowing that rotor flux is a not measurable, its estimate or its observation appears of capital importance for induction motor drives [1]. With an aim to improve performance control systems, a new estimation approach using the dynamic flux observer has been proposed in real time operating all transient and steady state operation [3]. In this technique, speed is calculated from the dynamic model of the machine and requires only the easily measurement machine voltage and current. The rotor flux required for speed calculation is estimated by a reduced order observer. Using computer simulation and experimental results presented in the algorithm has been found to perform well the case of control values flux machine [5, 8, 9]. However, due to direct calculation of speed from the dynamic equations, the estimation accuracy will depend on parameters that vary with temperature change during machine operation [12].

This paper explores the influence of parameter variations on estimated rotor flux by an experimental work at steady state and transient operation. The objective of newly developed notion is to propose experimental real time application for induction motor drives using DS1104 for the drives.

Mathematical model of the Induction machine

The mathematical model of induction motor is available in most literature [10, 11]. Parasitic effects such as hysteresis, eddy currents and magnetic saturation are neglected. The dynamic model for induction motor with symmetrical system is described below.
The most industrial applications of induction machine drives, need information of rotor flux in control, but the flux is not accessible, for this we need observer flux in control. The stat vector is defined [10]

$$[X]=\left[i_{s\alpha}\ i_{s\beta}\ \varphi_{r\alpha}\ \varphi_{r\beta}\right]^T . \quad (1)$$

The Dynamic model of motor is defined in fixed referential (α,β) as follows

$$\frac{d}{dt}\begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \\ \varphi_{r\alpha} \\ \varphi_{r\beta}\end{bmatrix}=\begin{bmatrix} -\gamma & 0 & \frac{K}{T_r} & pK\Omega(t) \\ 0 & -\gamma & -pK\Omega(t) & \frac{K}{T_r} \\ \frac{L_m}{T_r} & 0 & -\frac{1}{T_r} & -p\Omega(t) \\ 0 & \frac{L_m}{T_r} & p\Omega(t) & -\frac{1}{T_r}\end{bmatrix}\cdot\begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \\ \varphi_{r\alpha} \\ \varphi_{r\beta}\end{bmatrix}+\begin{bmatrix} m_1 & 0 \\ 0 & m_1 \\ 0 & 0 \\ 0 & 0\end{bmatrix}\cdot\begin{bmatrix} v_{s\alpha} \\ v_{s\beta}\end{bmatrix}. \quad (2)$$

The outputs variables are know by measurement values of stators current sensors.

Where $(T_r, K, \gamma, \sigma, m_1)$ are the motor parameters coefficients:

$$T_r=\frac{L_r}{R_r}, m_1=\frac{1}{\sigma L_s}, K=\frac{L_m}{\sigma L_s L_r}, \quad (3)$$

$$\sigma = 1 - \frac{L_m^2}{L_s L_r}, \gamma = \frac{L_r^2 R_s + L_m^2 R_r}{\sigma L_s L_r}, \tag{4}$$

where σ – the Blondel dispersion coefficient; R_s, R_r – stator and rotor resistances; L_s, L_r – stator and rotor cyclic inductances; L_m – stator-rotor cyclic mutual inductances; $V_{s\alpha\beta}$ – stator voltages in reference frame αβ; $i_{s\alpha\beta}$ – stator currents in reference frame αβ.

The expressions of stator and rotor fluxes are defined bellow:

$$\begin{cases} \varphi_{s\alpha} = L_s i_{s\alpha} + L_m i_{r\alpha}, \\ \varphi_{s\beta} = L_s i_{s\beta} + L_m i_{r\beta}, \\ \varphi_{r\alpha} = L_r i_{r\alpha} + L_m i_{s\alpha}, \\ \varphi_{r\beta} = L_r i_{r\beta} + L_m i_{s\beta}. \end{cases} \tag{5}$$

The electromagnetic torque expression presents high coupling [5]

$$C_{em} = p \frac{L_m}{L_r} (\varphi_{\alpha r} i_{\beta s} - \varphi_{\beta r} i_{\alpha s}), \tag{6}$$

where $v_{s\alpha}, v_{s\beta}$ are the α-axis and β-axis equivalent phase voltages of stator winding; Ω_s, Ω are the synchronous and mechanecal rotor speeds of machine; R_s, R_r are the resistance of the stator winding and rotor; $i_{s\alpha}, i_{s\beta}$ and $i_{r\alpha}, i_{r\beta}$ are the α-axis and β-axis equivalent stator and rotor currents; $\varphi_{s\alpha}, \varphi_{s\beta}$ and $\varphi_{r\alpha}, \varphi_{r\beta}$ are the α-axis and β-axis equivent flux linkages of the stator widing and rotor.

Dynamic model of the proposed estimation methods on rotor flux

Model of estimation flux based on current model. For squirrel cage induction machines, the rotor current is not accessible. Therefore, the estimation equation of rotor fluxes based on current model is defined by expressions follows:

$$\begin{cases} \dfrac{d\hat{\varphi}_{r\alpha\_i}}{dt} - \dfrac{\hat{L}_m \hat{R}_r}{\hat{L}_r} i_{s\alpha} + \dfrac{\hat{R}_r}{\hat{L}_r} \hat{\varphi}_{r\alpha\_i} + \omega_r \hat{\varphi}_{r\beta\_i} = 0, \\ \dfrac{d\hat{\varphi}_{r\beta\_i}}{dt} - \dfrac{\hat{L}_m \hat{R}_r}{\hat{L}_r} i_{s\beta} - \omega_r \hat{\varphi}_{r\alpha\_i} + \dfrac{\hat{R}_r}{\hat{L}_r} \hat{\varphi}_{r\beta\_i} = 0, \end{cases} \tag{7}$$

where the phase estimation and norm flux are:

$$\begin{cases} |\hat{\varphi}_r| = \hat{\varphi}_r = \sqrt{\hat{\varphi}_{r\alpha\_i}^2 + \hat{\varphi}_{r\beta\_i}^2}, \\ \hat{\theta} = arctg\left(\dfrac{\hat{\varphi}_{r\beta\_i}}{\hat{\varphi}_{r\alpha\_i}}\right), \end{cases} \tag{8}$$

where $(\hat{R}_r, \hat{L}_r, \hat{L}_m)$ are estimated parameters of dynamic model: The variation effects are calculated by the signals errors as follows:

$$\begin{cases} e_\varphi = |\varphi_r| - |\hat{\varphi}_{r\_i}|, \\ e_\theta = \theta - \hat{\theta}. \end{cases} \tag{9}$$

Model of estimation flux based on voltage model. Estimation of rotor flux based on voltage model is defined by two expressions as follows:

$$\begin{cases} v_{s\alpha} - \dfrac{d\hat{\varphi}_{s\alpha\_v}}{dt} - \hat{R}_s i_{s\alpha} = 0, \\ v_{s\beta} - \dfrac{d\hat{\varphi}_{s\beta - v}}{dt} - \hat{R}_s i_{s\beta} = 0, \end{cases} \tag{10}$$

where rotor fluxes are obtained:

$$\begin{cases} \hat{\varphi}_{r\alpha\_v} = \dfrac{\hat{L}_r}{\hat{L}_m}\left(\hat{\varphi}_{s\alpha\_v} - \hat{L}_{\sigma s} i_{s\alpha}\right), \\ \hat{\varphi}_{r\beta\_v} = \dfrac{\hat{L}_r}{\hat{L}_m}\left(\hat{\varphi}_{s\beta\_v} - \hat{L}_{\sigma s} i_{s\beta}\right), \end{cases} \tag{11}$$

For obtained the flux estimation we need resolving these differential equations:

$$\begin{cases} v_{s\alpha} - S\dfrac{\hat{L}_m}{\hat{L}_r}\hat{\varphi}_{r\alpha\_v} - \left(\hat{R}_s + \hat{L}_{\sigma s} S\right) i_{s\alpha} = 0, \\ v_{s\beta} - S\dfrac{\hat{L}_m}{\hat{L}_r}\hat{\varphi}_{r\beta\_v} - \left(\hat{R}_s + \hat{L}_{\sigma s} S\right) i_{s\beta} = 0, \end{cases} \tag{12}$$

where estimation parameters are given by

$$\hat{L}_{\sigma s} = \hat{L}_s - \frac{\hat{L}_m^2}{\hat{L}_r} = \hat{L}_s \cdot \left(1 - \frac{\hat{L}_m^2}{\hat{L}_s \hat{L}_r}\right) = \hat{L}_s \cdot \hat{\sigma}, \tag{13}$$

where $S = \dfrac{d}{dt}$ is the Laplace operator; $(\hat{R}_s, \hat{L}_s, \hat{L}_r, \hat{L}_m, \hat{L}_{\sigma s})$ are the estimated parameters of motor model.

The modulus rotor flux rotorique and the phase are defined as follows:

$$\begin{cases} |\hat{\varphi}_r| = \hat{\varphi}_r = \sqrt{\hat{\varphi}_{r\alpha\_v}^2 + \hat{\varphi}_{r\beta\_v}^2}, \\ \hat{\theta} = arctg\left(\dfrac{\hat{\varphi}_{r\beta\_v}}{\hat{\varphi}_{r\alpha\_v}}\right). \end{cases} \tag{14}$$

Model of estimation flux based on elimination model. This estimation of rotor flux based on elimination model is defined by these equations

$$\begin{bmatrix} \hat{\varphi}_{r\alpha\_el} \\ \hat{\varphi}_{r\beta\_el} \end{bmatrix} = \begin{bmatrix} \dfrac{\hat{L}_m \hat{R}_r}{\hat{L}_{\sigma s}\hat{L}_r^2} & \omega_r \cdot \dfrac{\hat{L}_m}{\hat{L}_{\sigma s}\hat{L}_r} \\ -\omega_r \cdot \dfrac{\hat{L}_m}{\hat{L}_{\sigma s}\hat{L}_r} & \dfrac{\hat{L}_m \hat{R}_r}{\hat{L}_{\sigma s}\hat{L}_r^2} \end{bmatrix}^{-1} \cdot \left(-\frac{1}{\hat{L}_{\sigma s}}\begin{bmatrix} v_{s\alpha} \\ v_{s\beta} \end{bmatrix} + \left(S + \frac{\hat{R}_{sr}}{\hat{L}_{\sigma s}}\right)\begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix}\right), \tag{15}$$

where $\hat{R}_{sr} = \hat{R}_s + \hat{R}_r \dfrac{\hat{L}_m^2}{\hat{L}_r^2}$; and $\left(\hat{R}_r, \hat{R}_s, \hat{L}_s, \hat{L}_r, \hat{L}_m, \hat{L}_{\sigma s}\right)$ are estimation parameters of motor on dynamic mode.

The modulus of rotor flux and phase are obtained by:

$$\begin{cases} \left|\hat{\varphi}_r\right| = \hat{\varphi}_r = \sqrt{\hat{\varphi}_{r\alpha\_el}^2 + \hat{\varphi}_{r\beta\_el}^2}, \\ \hat{\theta} = \tan^{-1}\left(\dfrac{\hat{\varphi}_{r\beta\_el}}{\hat{\varphi}_{r\alpha\_el}}\right). \end{cases} \quad (16)$$

The signals errors are given by:

$$\begin{cases} e_\varphi = \left|\varphi_r\right| - \left|\hat{\varphi}_{r\_el}\right|, \\ e_\theta = \theta - \hat{\theta}. \end{cases} \quad (17)$$

Estimation rotor flux in real time

Combining equations (18) and (19) with introduction error signal of estimated flux signal we obtain the following observer flux:

The validation of estimation based on current model is implemented in real time application. The proposed scheme in real time when we take into account the estimation of error in speed and rotor flux is described below:

$$\begin{cases} \dfrac{d\hat{\varphi}_{r\alpha\_i}}{dt} - \dfrac{\hat{L}_m \hat{R}_r}{\hat{L}_r} i_{s\alpha} + \dfrac{\hat{R}_r}{\hat{L}_r}\hat{\varphi}_{r\alpha\_i} + \omega_r \hat{\varphi}_{r\beta\_i} = 0, \\ \dfrac{d\hat{\varphi}_{r\beta\_i}}{dt} - \dfrac{\hat{L}_m \hat{R}_r}{\hat{L}_r} i_{s\beta} - \omega_r \hat{\varphi}_{r\alpha\_i} + \dfrac{\hat{R}_r}{\hat{L}_r}\hat{\varphi}_{r\beta\_i} = 0. \end{cases} \quad (18)$$

The voltage estimated model is defined:

$$\begin{cases} S\dfrac{\hat{L}_m}{\hat{L}_r}\hat{\varphi}_{r\alpha\_v} = v_{s\alpha} - \left(\hat{R}_s + \hat{L}_{\sigma s}S\right)i_{s\alpha}, \\ S\dfrac{\hat{L}_m}{\hat{L}_r}\hat{\varphi}_{r\beta\_v} = v_{s\beta} - \left(\hat{R}_s + \hat{L}_{\sigma s}S\right)i_{s\beta}. \end{cases} \quad (19)$$

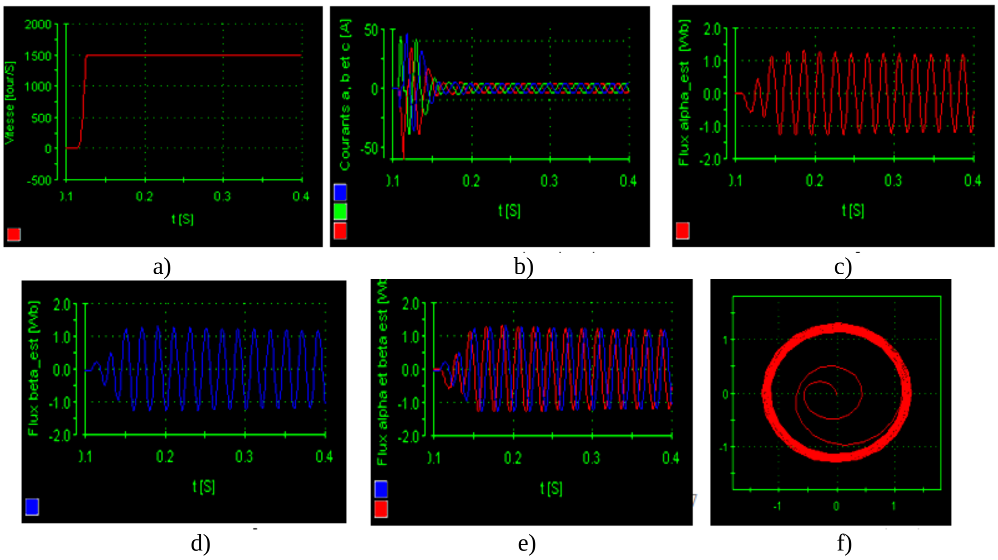

Fig.1. Experimental results of estimation rotor flux in real time application induction motor drives: a) speed response; b) current measurements: i_{sa}, i_{sb}, i_{sc}; c) observed flux $\hat{\varphi}_{r\alpha}$; d) observed flux $\hat{\varphi}_{r\beta}$; e) observed flux: $\hat{\varphi}_{r\alpha}$, $\hat{\varphi}_{r\beta}$; f) flux circle $\hat{\varphi}_{r\beta} = f\left(\hat{\varphi}_{r\alpha}\right)$

$$\begin{cases} \hat{\varphi}_{r\alpha\_obs} = \dfrac{\hat{L}_r}{\hat{L}_m}\left[\dfrac{1}{S}\left(v_{s\alpha} - \hat{R}_s . i_{s\alpha} + \left(K_p + \dfrac{K_i}{S}\right)\Delta\hat{\varphi}_{r\alpha}\right) - \hat{L}_{\sigma s} . i_{s\alpha}\right], \\ \hat{\varphi}_{r\beta\_obs} = \dfrac{\hat{L}_r}{\hat{L}_m}\left[\dfrac{1}{S}\left(v_{s\beta} - \hat{R}_s . i_{s\beta} + \left(K_p + \dfrac{K_i}{S}\right)\Delta\hat{\varphi}_{r\beta}\right) - \hat{L}_{\sigma s} . i_{s\beta}\right]. \end{cases} \quad (20)$$

$$\begin{cases} C = K_p + \dfrac{K_i}{S}, \\ \Delta\hat{\varphi}_{r\alpha} = \hat{\varphi}_{r\alpha\_obs} - \hat{\varphi}_{r\alpha\_i}, \\ \Delta\hat{\varphi}_{r\beta} = \hat{\varphi}_{r\beta\_obs} - \hat{\varphi}_{r\beta\_i}, \end{cases} \quad (21)$$

where $\left(\hat{R}_r, \hat{R}_s, \hat{L}_s, \hat{L}_r, \hat{L}_m, \hat{L}_{\sigma s}\right)$ are observer motor parameters.

The flux modulus and phase are given by:

$$\begin{cases} \left|\hat{\varphi}_r\right| = \hat{\varphi}_r = \sqrt{\hat{\varphi}_{r\alpha\_obs}^2 + \hat{\varphi}_{r\beta\_obs}^2}, \\ \hat{\theta} = arctg\left(\dfrac{\hat{\varphi}_{r\beta\_obs}}{\hat{\varphi}_{r\alpha\_obs}}\right). \end{cases} \quad (22)$$

The resolution of this equation, gives rotor flux in real time application:

Experimental results of estimation rotor flux

The estimation rotor flux method developed is given by these experimental results in Fig.1. With respect to the proposed experimental approach, α and β axis rotor fluxes show clearly circular while the speed shown the good dynamic behavior for transient and steady state response.

The curves of currents show the good response of currents and voltages sensors. The implementation becomes more effective in control drives.

Conclusions

In this paper, we have demonstrated the estimation approach of rotor flux based of current and voltage and elimination models for induction motor drives.

The implementation in real time of estimation approach has successfully demonstrated the design of control with observer flux using only the stator currents and voltages measurements. Method has successfully demonstrated the control design with optimum flux using only the stator currents, voltages and position measurements.

The Advantage of our approach is directly applicable to electric drive and other application.

Appendix

Induction motor parameters: P_n= 3 kW, U_n= 380 V, Ω_n= 1420 tr/mn, I_n= 3.64 A(Y) 6.31A(Δ), R_s= 4.85Ω, R_r= 3.805Ω, L_s= 0.274 H, L_r= 0.274 H, p= 2, L_m= 0.258 H, J= 0.031 kg.m^2, f_r= 0.008 Nm.s/rd.

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The objective of this paper deals in introducing how to obtain the rotor flux estimation in real time for induction motor drives. The accuracy of flux estimation algorithm depends on the motor parameters variation. These parameters as stator and rotor resistance vary as temperature changes during motor operation. The practical usefulness of our control models are evaluated and confirmed through experiments using an induction machine (3kW/380V). Experimental investigation tests are provided to evaluate the consistency of the proposed control model using DS1104 with MATLAB - Simulink. Ill. 1, bibl. 12 (in English; abstracts in English, Russian and Lithuanian).

С. Гроуни, Р. Ибтиоуэн, М. Кидоуче, О. Тоухами. Экспериментальные исследования состоянии асинхронных двигателей в реальном времени // Электроника и электротехника. – Каунас: Технология, 2010. – № 8(104). – С. 69–72.

Предлагается новый способ определения параметров двигателей в реальном времени. Практическую полезность предложенного метода доказывают проведенные эксперименты с двигателем типа (3kW/380V) на основе DS1104 модели контроля. Ил. 1, библ. 12 (на английском языке; рефераты на английском, русском и литовском яз.).

S. Grouni, R. Ibtiouen, M. Kidouche, O. Touhami. Asinchroninio variklio rotoriaus srauto apskaičiavimo realiu laiku eksperimentinis tyrimas // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2010. – Nr. 8(104). – P. 69–72.

Aprašomas būdas asinchroninių variklių rotoriaus srautui apskaičiuoti realiu laiku. Srauto skaičiavimo algoritmo tikslumas priklauso nuo variklio parametrų. Veikiant varikliui statoriaus ir rotoriaus varžos turi temperatūrinę priklausomybę. Kontrolės modelio praktinę naudą įrodo eksperimentai su asinchroniniu varikliu (3kW/380V). MATLAB aplinkoje atlikti eksperimentiniai tyrimai taikant siūlomą DS1104 kontrolės modelį. Il. 4, bibl. 12 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).