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A Mixed MRAC for Adaptation of Rotor Time Constant of Induction Motor based on the Parameter Sensitivity Analysis

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Abstract: In the procedure of adaptation for rotor time constant of induction motor with Model Reference Adaptive Controller (MRAC), a mismatch of the parameter between model and motor has strong influence on the adaptation result and therefore degrade the control performance. In the study, the analytical solution between model error signals and detuned parameters are deduced, the parameter sensitivity of both d-axis voltage and reactive power-based MRAC are then analyzed theoretically and validate by a large amount of simulations, where d-axis voltage based model shows low sensitivity to mutual inductance but high to stator resistance while reactive power model just the opposite. To take full advantage of each model, a combination is then developed to construct a new MRAC. By adjusting the weighting factor for model error signals in different speed, torque region, the robustness and stability range to detuned parameters are improved and simulation followed validates the feasibility and effectiveness of the method proposed.

Key words: Vector control, MRAC, parameter sensitivity, analytical solution, weighting factor

INTRODUCTION

Since, the principle of vector control was proposed, the technology for ac drives stepped into a new stage (Santisteban and Stephan, 2001). Ideally a vector-controlled induction motor drive can obtain the decoupled control like a separately excited dc motor drive and the control performance of induction motor is consequently improved remarkably. Generally, for the simple implementation and better performance, the Indirect Rotor Flux-Oriented Vector Control (IRFOC) is frequently applied in high performance ac drives. However, the orientation in IRFOC is guaranteed by vector control equations which require the knowledge of rotor time constant (T_r), namely the ratio of rotor inductance to rotor resistance. Rotor resistance changes significantly with the operating temperature, which can even increase 50% of the rated value, while the rotor inductance depends on the flux saturation (Bose, 2002). An error between the actual T_r and the one used in the IRFOC causes disorientation of rotor flux and the decoupled relationship between the flux and torque-producing currents will no longer exist, which significantly degrades the performance of the whole system (Nordin *et al*., 1985). Therefore, on-line adaptation of rotor time constant in IRFOC is very meaningful in high performance ac drives.

Over the past three decades, various schemes have been proposed for the on-line adaptation of rotor time constant (Krishnan and Bharadwaj, 1991), of which the Model Reference Adaptive Control (MRAC) method attracts the most of interest due to its simple computation and no extra transducer requirement. The basic idea is that two models have the same output quantity. The reference model is independent of rotor time constant, while the adjustable model isn't. The difference between the two models is the error signal, which represents the error of rotor time constant used in the control system. The error signal can then be used to drive an adaptive mechanism (generally PI or I controller) which corrects the rotor time constant until the error becomes zero (Toliyat *et al*., 2003). This kind of method is heavily dependent on the steady-state model of the machine, in which more than one machine parameters are used, such as stator resistance, mutual inductance and leakage inductance. All these parameters vary with the operating condition, any mismatch between model and motor results in a wrong adaptation result of rotor time constant (Dittrich, 1994). With this method, a vast number of studies have been published. Their primary difference is with respect to which quantity is selected for adaptation. In Rowan *et al*. (1991) five specific reference models were analyzed in terms of their performance. Maiti *et al*. (2008) selected the

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reactive power as the quantity to estimate the rotor resistance, which was completely robust to the stator resistance, but the sensitivity to detuned inductance had not been analyzed. Sumner *et al.* (1993) simulated the sensitivity to detuned inductance, but the explicit expression was not given. Yu *et al.* (2002) used d-axis decoupled voltage to identify the rotor resistance, though the scheme was simple computation and almost saturation independent, the on-line compensation for stator resistance was needed, especially at low speed.

In the study, the relationship between parameter mismatch and error signal both for d-axis voltage and reactive power models are deduced, respectively.

THE RELATIONSHIP BETWEEN MODEL ERROR SIGNALS AND DETUNED PARAMETERS

Steady-state models of d-axis voltage and reactive power: In the d-q synchronous rotating reference frame, the induction motor voltages can be expressed by the following equations (Bose, 2002):

$$\begin{aligned} V_{ds} &= R_s i_{ds} + \sigma L_s p i_{ds} + \frac{L_m}{L_r} p\psi_{dr} - \sigma L_s \omega_e i_{qs} - \omega_e \frac{L_m}{L_r}\psi_{qr} \\ V_{qs} &= R_s i_{qs} + \sigma L_s p i_{qs} + \frac{L_m}{L_r} p\psi_{qr} + \sigma L_s \omega_e i_{ds} + \omega_e \frac{L_m}{L_r}\psi_{dr} \\ 0 &= \frac{R_r}{L_r}(\psi_{dr} - L_m i_{ds}) + p\psi_{dr} - (\omega_e - \omega_r)\psi_{qr} \\ 0 &= \frac{R_r}{L_r}(\psi_{qr} - L_m i_{qs}) + p\psi_{qr} + (\omega_e - \omega_r)\psi_{dr} \end{aligned} \quad (1)$$

where, the variables and parameters are defined as follows:

V_{ds}, V_{qs}	=	d-,q-axis component of stator voltage
i_{ds}, i_{qs}	=	d-,q-axis component of stator current
ψ_{ds}, ψ_{qs}	=	d-,q-axis component of rotor flux
R_s	=	Stator resistance,
R_r	=	Rotor resistance
L_m	=	Mutual inductance
$L_s = L_m+L_{ls}$	=	Stator self-inductance
$L_r = L_m+L_{lr}$	=	Rotor self-inductance
L_{ls}	=	Stator leakage inductance
L_{lr}	=	Rotor leakage inductance
σ	=	Total leakage coefficient ($\sigma = 1-L^2_m/L_sL_r$)
ω_e	=	Synchronous angular speed of d-q coordinates, viz., supply frequency
ω_r	=	Rotor angular speed
p	=	Differential operator

In the steady-state, the derivative terms are zero, meanwhile $\psi_{dr} = L_m i_{ds}$, $\psi_{qr} = 0$ in IRFOC system, the stator voltages in Eq. 1 can be simplified to:

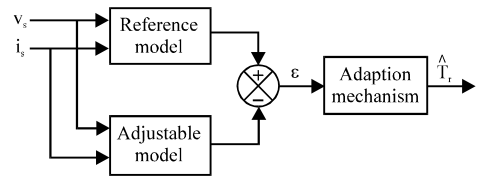

Fig. 1: Structure of model reference adaptive controller

$$\begin{aligned} V_{ds} &= R_s i_{ds} - \sigma L_s \omega_e i_{qs} \\ V_{qs} &= R_s i_{qs} + L_s \omega_e i_{ds} \end{aligned} \quad (2)$$

As known the instantaneous reactive power is expressed as:

$$Q_1 = V_{qs} i_{ds} - V_{ds} i_{qs} \quad (3)$$

Substituting Eq. 2 to 3, the expression of reactive power in steady-state is:

$$Q_2 = L_s \omega_e i_{ds}^2 + \sigma L_s \omega_e i_{sq}^2 \quad (4)$$

The basic structure of model reference controller is shown in Fig. 1, where the d-axis voltage and reactive power model are used and respectively embedded into IRFOC for rotor time constant on-line adaptation in the later simulation.

Base on the preceding formulas, the corresponding adaptation models can then be designed. For the sake of explicit expression, the parameter with the superscript ∧ represents the quantity used in the models hereinafter.

For d-axis voltage model, the reference model V_{ref} is defined as follows:

$$V_{ref} = \hat{R}_s \hat{i}_{ds} - \sigma \hat{L}_s \omega_e \hat{i}_{qs} \quad (5)$$

Meanwhile, the adjustable model $\hat{V}_{ds}$ is reconstructed from the inverter firing signals and measured dc-link voltage.

According to Eq. 3 and 4 for reactive power model, the reference model Q_{ref} and adjustable model Q_{adj} are written below:

$$Q_{ref} = \hat{V}_{qs} \hat{i}_{ds} - \hat{V}_{ds} \hat{i}_{qs} \quad (6)$$

$$Q_{adj} = \hat{L}_s \omega_e \hat{i}_{ds}^2 + \sigma \hat{L} \omega_e \hat{i}_{sq}^2 \quad (7)$$

So far, the MRAC with d-axis voltage and reactive power model have already been established. Using the error between reference and adjustable models, the adaptation can then be conducted.

The relationship between model error signal and detuned parameters: Assuming that the deviation angle of orientation in IRFOC is $\Delta\theta = \hat{\theta} - \theta$ and consequently the deviation of currents and voltages between model and motor occurs, expressed by Dittrich (1994):

$$\hat{i}_s = i_s e^{-j\Delta\theta} \tag{8}$$

$$\hat{V}_s = V_s e^{-j\Delta\theta} \tag{9}$$

In d-q reference frame:

$$\begin{aligned} \hat{i}_{ds} &= i_{ds}\cos(\Delta\theta) + i_{qs}\sin(\Delta\theta) \\ \hat{i}_{qs} &= i_{qs}\cos(\Delta\theta) - i_{ds}\sin(\Delta\theta) \end{aligned} \tag{10}$$

$$\begin{aligned} \hat{V}_{ds} &= V_{ds}\cos(\Delta\theta) + V_{qs}\sin(\Delta\theta) \\ \hat{V}_{qs} &= V_{qs}\cos(\Delta\theta) - V_{ds}\sin(\Delta\theta) \end{aligned} \tag{11}$$

In the steady-state, the supply frequency and rotor speed in model match their counterparts in motor. Therefore:

$$\omega_e - \omega_r = \frac{1}{\hat{T}_r}\frac{\hat{i}_{qs}}{\hat{i}_{ds}} = \frac{1}{T_r}\frac{i_{qs}}{i_{ds}} \tag{12}$$

Substituting Eq. 10 into 12, the $\Delta\theta$ is calculated as:

$$\Delta\theta = \arctan\frac{i_{ds}i_{qs}(1 - \frac{\hat{T}_r}{T_r})}{i_{ds}^2 + i_{qs}^2\frac{\hat{T}_r}{T_r}} \tag{13}$$

Combining Eq. 2, 10 and 11:

$$\begin{aligned} \hat{V}_{ds} &= R_s\hat{i}_{ds} - \sigma L_s\omega_e\hat{i}_{qs} + (1-\sigma)L_s\omega_e i_{ds}\sin(\Delta\theta) \\ \hat{V}_{qs} &= R_s\hat{i}_{qs} + L_s\omega_e\hat{i}_{ds} - (1-\sigma)L_s\omega_e i_{qs}\sin(\Delta\theta) \end{aligned} \tag{14}$$

For d-axis voltage model, the error signal ε_d between V_{ref} and $\hat{V}_{ref}$ is used to compensate the rotor time constant and:

$$\begin{aligned} \varepsilon_d = V_{ref} - \hat{V}_{ds} &= (\hat{R}_s - R_s)\hat{i}_{ds} + (\sigma L_s - \sigma\hat{L}_s) \\ &\omega_e\hat{i}_{qs} - (1-\sigma)L_s\omega_e i_{ds}\sin(\Delta\theta) \end{aligned} \tag{15}$$

Equation 15 clearly reveals the relationship between the error signal and detuned parameters. In addition to misalignment angle $\Delta\theta$, mismatch of stator resistance $\hat{R}_s$ and total leakage inductance $\hat{\sigma}L_s$ also contribute to the error signal ε_d. Once the stator resistance and leakage inductance match their counterparts in the motor, then only the last term in ε_d exists:

$$\varepsilon_d = -(1-\sigma)L_s\omega_e i_{ds}\sin(\Delta\theta)$$

Assuming that $\omega_e>0$, rotor resistance increases with the operating temperature, accordingly the d-axis is aligned behind the actual rotor flux position, $\sin(\Delta\theta)<0$, $\varepsilon_d>0_0$. Here, ε_d can be used to drive the adaptation mechanism to correct the rotor resistance in the controller until ε_d becomes zero and vice versa. This shows the feasibility of d-axis voltage model to identify the rotor resistance. However, in case of mismatch either in $\hat{R}_s$ or $\hat{\sigma}L_s$, the first two terms of Eq. 15 will no longer be zero and no doubt cause the wrong adaptation result, accordingly, the deterioration of performance occurs. Therefore, the correct convergence of rotor time constant can not be certified unless $\hat{R}_s$ and $\hat{\sigma}L_s$ match their counterparts in motor.

In a similar way, the reference model of reactive power is:

$$Q_{ref} = V_{qs}i_{ds} - V_{ds}i_{qs} = \hat{V}_{qs}\hat{i}_{ds} - \hat{V}_{ds}\hat{i}_{qs}$$

Substituting Eq. 14 into 6 results:

$$Q_{ref} = L_s\omega_e\hat{i}_{ds}^2 + \sigma L_s\omega_e\hat{i}_{qs}^2 - (1-\sigma)L_s\omega_e(\hat{i}_{ds}i_{qs} + i_{ds}\hat{i}_{qs})\sin(\Delta\theta) \tag{16}$$

According to Eq. 7, the adjustable model in steady-state is:

$$Q_{adj} = \hat{L}_s\omega_e\hat{i}_{ds}^2 + \sigma\hat{L}_s\omega_e\hat{i}_{sq}^2$$

The error signal can now be derived as:

$$\begin{aligned} \varepsilon_Q = Q_{ref} - Q_{adj} &= (L_s - \hat{L}_s)\omega_e\hat{i}_{ds}^2 + (\sigma L_s - \sigma\hat{L}_s)\omega_e\hat{i}_{qs}^2 - (1-\sigma) \\ &L_s\omega_e(\hat{i}_{ds}i_{qs} + i_{ds}\hat{i}_{qs})\sin(\Delta\theta) \end{aligned} \tag{17}$$

Similar to Eq. 15, it can be seen that except the angle deviation $\Delta\theta$, the stator inductance and total leakage inductance also have connection with error signal. Independent to stator resistance is the most attractive advantage of reactive power model. From Eq. 17, any mismatch of $\hat{R}_s$ or $\hat{\sigma}L_s$ will cause the wrong adaptation result.

The analysis above is based on the operating condition which is $\omega_e>0$, $i_{ds}>0$, $i_{qs}>0$, other cases can similarly be analyzed from Eq. 15 and 17.

PARAMETER SENSITIVITY ANALYSIS OF ON-LINE ADAPTATION

In the steady-state, the reference and adjustable model have equal output value, namely the error signal such as ε_d, ε_q is zero. Consequently, parameter sensitivity can now be discussed based on the equation Eq. 15 and 17.

Parameter sensitivity analysis of d-axis voltage model: Here, the error signal of d-axis voltage model has been deduced as:

$$\varepsilon_d = (\hat{R}_s - R_s)\hat{i}_{ds} + (\sigma L_s - \sigma\hat{L}_s)\omega_e\hat{i}_{qs} - (1-\sigma)L_s\omega_e i_{ds}\sin(\Delta\theta)$$

The mismatch of stator resistance and total leakage inductance cause the wrong adaptation of rotor time constant, so the parameter sensitivity to stator resistance and total leakage inductance are analyzed respectively below.

Parameter sensitivity to stator resistance: Assuming that $\sigma L_s = \hat{\sigma}L_s$, $\Delta r_s = \hat{R}_s - R_s$, ε_d in Eq. 15, which results in:

$$\Delta R_s\hat{i}_{ds} = (1-\sigma)L_s\omega_e i_{ds}\sin(\Delta\theta)$$

Combining the first equation in Eq. 10 and 13, in addition, after a series of rearrangement, the following expression can be obtained (Dittrich, 1994):

$$\frac{\hat{T}_r}{T_r} = 1 - \frac{\Delta R_s[1 + (\frac{i_{qs}}{i_{ds}})^2]}{(1-\sigma)L_s\omega_e\frac{i_{qs}}{i_{ds}}} \tag{18}$$

Three conclusions can be deduced from Eq. 18:

- Assuming that the stator resistance increases with operating temperature, ωe>0 namely. When motor rotates clockwise , which results in $\hat{T}_r < T_r$ thus, the d-axis of the reference frame is aligned behind the actual rotor flux position. When motor rotates in reverse, which results in $\hat{T}_r < T_r$, the d-axis of the reference frame is aligned ahead of the actual rotor flux position
- The influence on the adaptation due to stator resistance mismatch is in inverse proportion to the synchronous angular speed and will almost vanish at high speed
- For the part:

$$\frac{1}{\frac{i_{qs}}{i_{ds}}} + \frac{i_{qs}}{i_{ds}}$$

it can be regarded as the function of load:

$$g = \frac{i_{ds}}{i_{qs}} + \frac{i_{qs}}{i_{ds}}$$

is assumed, when: $i_{ds}/i_{ds} = 1$ the minimum of g returns and $g_{min} = 2$:

when $i_{ds}/i_{ds} \in (0, 1]$, g is an increasing ascend function

when $i_{ds}/i_{ds} \in (1, +\infty]$, g is a decreasing descend function

It can be predict that the detune of T_r is serious at light load and with the increase of load, the effect will minish first and then continue to deteriorate. Though the i_{ds} and i_{qs} here is still the function of T_r, the analysis above is available all the same.

Parameter sensitivity to total leakage inductance: Assuming that $\hat{R}_s = R_s$, $\Delta(\sigma L_s) = \hat{\sigma}L_s - \sigma L_s$, $\varepsilon_d = 0$ in Eq. 15, the equation is simplified as:

$$\Delta(\sigma L_s)\omega_e\hat{i}_{qs} = (\sigma - 1)L_s\omega_e i_{ds}\sin(\Delta\theta)$$

Substituting the equation in Eq. 10 as well as 13 into above equation, the following result is obtained (Dittrich, 1994):

$$\frac{\hat{T}_r}{T_r} = 1 + \frac{\frac{\Delta(\sigma L_s)}{\sigma L_s}}{\frac{i_{ds}^2}{i_s^2}\frac{1-\sigma}{\sigma} - \frac{\Delta(\sigma L_s)}{\sigma L_s}}. \tag{19}$$

Similarly, two conclusions are developed as follows:

- The influence is not speed dependent and at certain load, the detune of T_r is somehow proportional to the leakage inductance mismatch error
- With the increase of load, it is hard to say how i_{ds}/i_s effects the adaptation result $\hat{T}_r/T_r$. Using the coordinate transformation in Eq. 10, the actual d-axis component of stator current i_{ds} in Eq. 19 can be replaced by $\hat{i}_{ds}$ in the controller. Due to its computational intensity, only the result is formulated as follows:

$$\frac{\hat{T}_r}{T_r} = \frac{1 + \sqrt{1 + 4\Delta(\sigma L_s)\frac{L_s - \sigma L_s - \Delta(\sigma L_s)}{(L_s - \sigma L_s)^2}(\frac{\hat{i}_{qs}}{\hat{i}_{ds}})^2}}{2\frac{L_s - \sigma L_s - \Delta(\sigma L_s)}{L_s - \sigma L_s}}. \tag{20}$$

In IRFOC system, the $\hat{i}_{ds}$ is kept constant under rated speed. From Eq. 20 the relationship between $\hat{i}_{qs}$ and $\hat{T}_r/T_r$

seems clear, as the load increases, the detune of rotor time constant also deteriorates.

Parameter sensitivity of reactive power model: For reactive power model, the error signal is derived as:

$$\varepsilon_Q = (L_s - \hat{L}_s)\omega_e \hat{i}_{ds}^2 + (\sigma L_s - \sigma\hat{L}_s)\omega_e \hat{i}_{qs}^2 - (1-\sigma) L_s \omega_e (\hat{i}_{ds} i_{qs} + i_{ds}\hat{i}_{qs})\sin(\Delta\theta)$$

Reactive power model is completely without sensitivity to stator resistance, but the stator inductance and total leakage inductance are expected. Assuming that $\Delta L_s = \hat{L}_s - L_s$, $\Delta(\sigma L_s) = \Delta\hat{L}_s - \sigma L_s$, $\varepsilon_Q = 0$ and Eq. 17 is simplified as:

$$\Delta L_s \omega_e \hat{i}_{ds}^2 + \Delta(\sigma L_s)\omega_e \hat{i}_{qs}^2 = (\sigma - 1) L_s \omega_e (\hat{i}_{ds} i_{qs} + i_{ds}\hat{i}_{qs})\sin(\Delta\theta)$$

Considering Eq. 10 and 13, i_{ds} and i_{qs} can be replaced by $\hat{i}_{ds}$, $\hat{i}_{qs}$, the following expression is derived as:

$$\frac{\hat{T}_r}{T_r} = \sqrt{\frac{[\hat{L}_s - (\sigma\hat{L}_s)](\hat{i}_{ds}^4\hat{i}_{qs}^2 + \hat{i}_{ds}^2\hat{i}_{qs}^4) + \Delta(\sigma L_s)(\hat{i}_{qs}^6 + 2\hat{i}_{ds}^2\hat{i}_{qs}^4 + \hat{i}_{ds}^4\hat{i}_{qs}^2)}{[\hat{L}_s - (\sigma\hat{L}_s)](\hat{i}_{ds}^4\hat{i}_{qs}^2 + \hat{i}_{ds}^2\hat{i}_{qs}^4) - \Delta L_s(\hat{i}_{ds}^6 + 2\hat{i}_{ds}^4\hat{i}_{qs}^2 + \hat{i}_{ds}^2\hat{i}_{qs}^4)}} \quad (21)$$

There is no item ω_e in Eq. 21, which means the adaptation result has nothing to do with the synchronous angular speed. The errors ΔL_s and $\Delta(\sigma L_s)$ against adaptation result $\hat{T}_r/T_r$ are analyzed, respectively as follows (Noguchi *et al*., 1997).

Parameter sensitivity to stator inductance: Assuming that $\Delta(\sigma L_s)$ in Eq. 21, the equation can be rewritten as:

$$\frac{\hat{T}_r}{T_r} = \frac{1}{\sqrt{1 - \frac{\Delta L_s}{\hat{L}_s - (\sigma\hat{L}_s)}\frac{\frac{\hat{i}_{ds}^4}{\hat{i}_{qs}^2} + 2\hat{i}_{ds}^2 + \hat{i}_{qs}^2}{\hat{i}_{ds}^2 + \hat{i}_{qs}^2}}} = \frac{1}{\sqrt{1 - \frac{\Delta L_s}{\hat{L}_s - (\sigma\hat{L}_s)}\left(1 + \frac{\hat{i}_{ds}^2 + \frac{\hat{i}_{ds}^4}{\hat{i}_{qs}^2}}{\hat{i}_{ds}^2 + \hat{i}_{qs}^2}\right)}} \quad (22)$$

From the formula above, the following conclusions can be obtained:

- Under a certain load, once $\Delta L_s<0$, the $\hat{T}_r < T_r$ happens, which means the d-axis of the reference frame is aligned ahead of the actual rotor flux position. While $\Delta L_s<0$ causes $\hat{T}_r < T_r$, the d-axis of the reference frame is aligned behind the actual rotor flux position
- Considering that under the same error ΔL_s, with the increase of $\hat{i}_{qs}$ which indicates the increase of load, the detuned influence against $\hat{T}_r < T_r$ decreases on the contrary

Parameter sensitivity to total leakage inductance: Assuming $\Delta L_s = 0$ in Eq. 21, the equation is modified as:

$$\frac{\hat{T}_r}{T_r} = \sqrt{1 + \frac{\Delta(\sigma L_s)}{\hat{L}_s - (\sigma\hat{L}_s)}\frac{\frac{\hat{i}_{qs}^4}{\hat{i}_{ds}^2} + 2\hat{i}_{qs}^2 + \hat{i}_{ds}^2}{\hat{i}_{ds}^2 + \hat{i}_{qs}^2}} = \sqrt{1 + \frac{\Delta(\sigma L_s)}{\hat{L}_s - (\sigma\hat{L}_s)}\left(1 + \frac{1 + \frac{\hat{i}_{qs}^2}{\hat{i}_{ds}^2}}{1 + \frac{\hat{i}_{ds}^2}{\hat{i}_{qs}^2}}\right)} \quad (23)$$

The same analyses are made as follows:

- Under a certain load, the error $\Delta(\sigma L_s)<0$ causes $\hat{T}_r < T_r$ while $\Delta(\sigma L_s)>0$ results in $\hat{T}_r > T_r$, which is very much alike to the conclusion with respect to ΔL_s
- Different to ΔL_s, under the same error $\Delta(\sigma L_s)$, as $\hat{i}_{qs}$ increases, the distortion of $\hat{T}_r/T_r$ also increases

All the analyses and conclusions above are derived in steady-state, which means the error signal can be driven to zero. In fact, due to the mismatch of parameters, the disorientation in IRFOC will cause inaccurate current track to the command trajectory, furthermore, the rotor speed may fall in respect that no enough current can be supplied. In addition, the parameters vary within a certain range, otherwise the stability of the whole system is lost. Consequently, the simulation of parameter sensitivity is inevitable for more detailed results.

SIMULATION STUDY OF PARAMETER SENSITIVITY

A digital simulation is developed in MATLAB/ SIMULINK with IRFOC to examine sensitivity against stator resistance, mutual inductance and leakage inductance both for d-axis voltage model and reactive power model. The ratings and parameters of simulated induction machine are shown in Table 1. To evaluate the effect of one parameter in the motor independent change of others, one varied while others are kept constant. In the simulation, the variation range for stator resistance is investigated from -50 to +50%, whereas the range of -30 to +30% is investigated for inductance. In the simulation results, only the range the curve covers could the stability of the whole system be obtained.

Table 1: Ratings and parameters of induction motor

Parameters	Values
Power rating	5.5 kW
Voltage rating	350 V
Current rating	13 A
Rated speed	1430 r m^{-1}
Stator resistance R_s	0.813 Ω
Rotor resistance R_r	0.531 Ω
Mutual inductance L_m	102.4 mH
Stator leakage inductance L_{ls}	3.86 mH
Rotor leakage inductance L_{lr}	6.35 mH

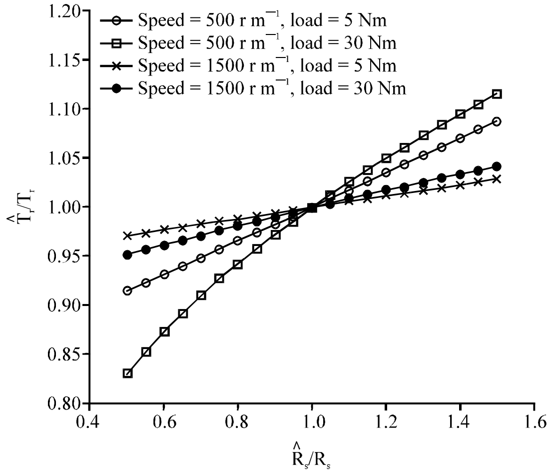

Fig. 2: Sensitivity to stator resistance with d-axis voltage model

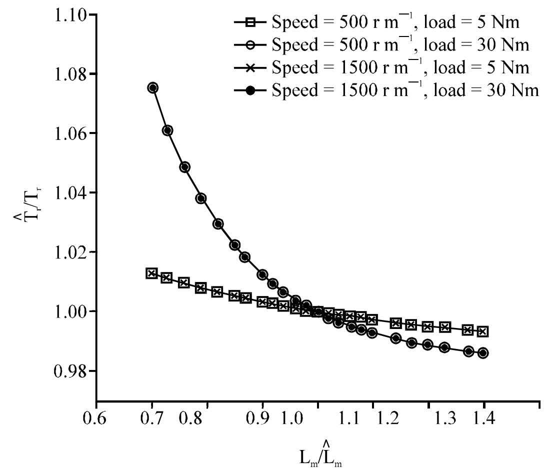

Fig. 4: Sensitivity to mutual inductance with d-axis voltage model

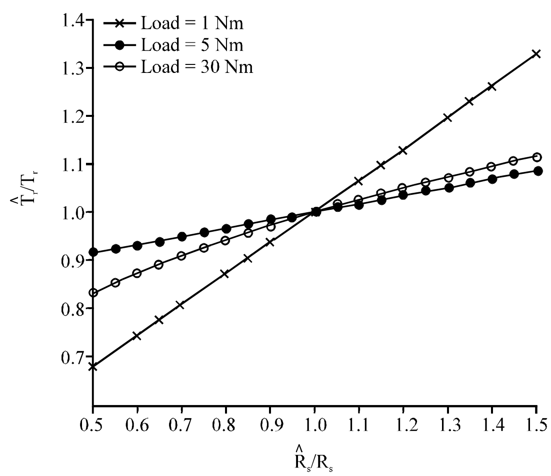

Fig. 3: Sensitivity to stator resistance with d-axis voltage model at different loads

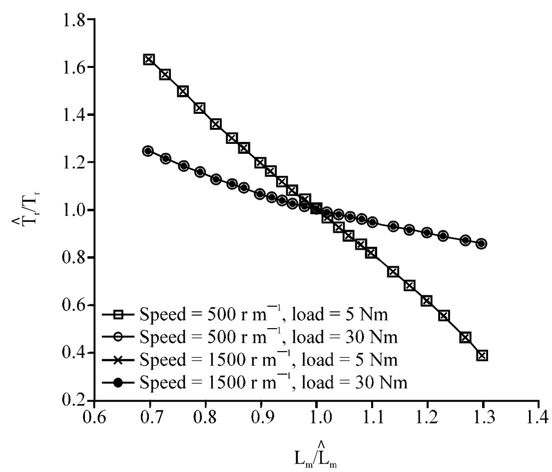

Fig. 5: Sensitivity to mutual inductance with reactive power model

Sensitivity to stator resistance: From Fig. 2, the distortion of $\hat{T}_r/T_r$ due to the stator resistance mismatch is decreased in a higher rotor speed. When motor rotates at speed of 500 r/m with 50% detune of stator resistance, nearly 10% adaptation error is produced. The lower the rotor speed is, the more deterioration adaptation yields. In the conclusions from Eq. 18, at certain $R_s/\hat{R}_s$ with the increase of load, $\hat{T}_r/T_r$ decreases first and then continues to increase. To validate this analysis, the simulation with constant rotating speed of 500 r m^{-1} is developed at different loads of 1, 5 and 30 Nm, respectively. The results in Fig. 3 indicate the validity of the analysis. The reactive power model is totally robust to the stator resistance, so the simulation result is not presented.

Sensitivity to mutual inductance: As shown in Eq. 19, $\Delta(\sigma L_s)$ has great influence on the adaptation result in d-axis voltage model. Considering that $\sigma L_s \approx L_{ls}+L_{lr}$, the variation of mutual inductance barely effects the σL_s and thus the d-axis voltage model has little sensitivity to mutual inductance which is identical to the simulation result in Fig. 4. Though $\hat{T}_r/T_r$ is motor speed independent, it increases at higher loads.

Different to the d-axis voltage model, the reactive power model has strong sensitivity to mutual inductance and that the sensitivity is lower at higher loads which is still great than that in d-axis voltage model, as depicted in Fig. 5, which also approves the analysis to Eq. 22.

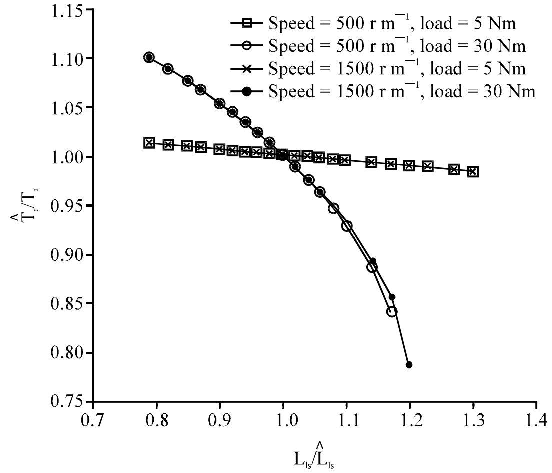

Fig. 6: Sensitivity to stator leakage inductance with d-axis voltage model

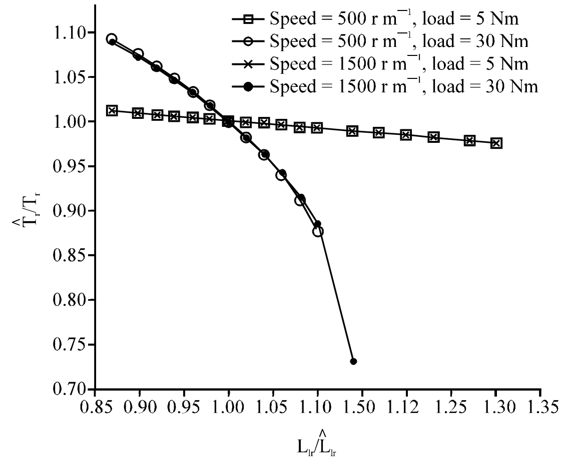

Fig. 8: Sensitivity to rotor leakage inductance with d-axis voltage model

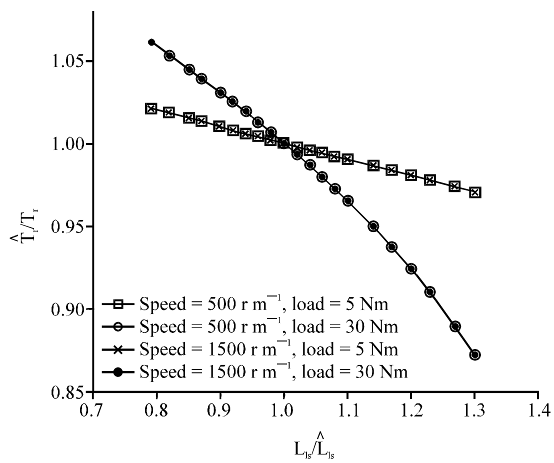

Fig. 7: Sensitivity to stator leakage inductance with reactive power mode

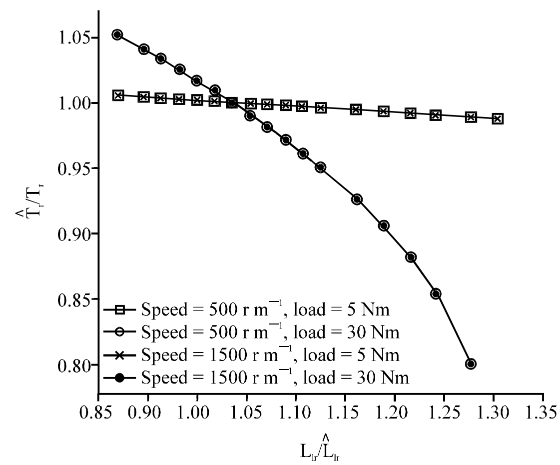

Fig. 9: Sensitivity to rotor leakage inductance with reactive power model

Sensitivity to stator leakage inductance: The d-axis voltage model and reactive power model have the similar sensitivity to stator leakage inductance, shown in Fig. 6 and Fig. 7, which confirmed the analysis to Eq. 20 and 21. But with the increase of load, the sensitivity in d-axis voltage model is more or less great than that in reactive power model and the variation has great influence on the stability of the entire system. In Fig. 6, with the load of 30 Nm, the system with d-axis voltage model is instable in case over 20% increase of stator leakage inductance exists.

Sensitivity to rotor leakage inductance: The simulation results are similar to that of stator leakage inductance. In d-axis voltage model, with the load of 30 Nm, the stability of entire system becomes deteriorative when over 10% increase of rotor leakage inductance occurs, whereas the stability range of reactive power model is a little wider, as indicated in Fig. 8 and 9.

After a number of simulations above, it can be seen that d-axis voltage model and reactive power model each has its strong points and weaknesses. The d-axis voltage model is low sensitivity to mutual inductance, however a great adaptation distortion occurs in low speed due to the stator resistance voltage drop and the stability range is shortened with the variation of leakage inductance at high load. The reactive power model is absolutely stator resistance independent, but unfortunately with high sensitivity to mutual inductance especially at low load. If a new model is found which holds advantages of both models, the robustness to motor parameters in MRAC can surely be improved.

A MIXED MRAC COMBINING D-AXIS VOLTAGE MODEL WITH REACTIVE POWER MODEL

No matter which method is used in the procedure for on-line adaptation of rotor time constant, the main objectives are the suppression of the sensitivity to stator resistance at low speed and robustness to inductance under any load. Based on the analyses and simulations in the previous sections, a mixed MRAC is proposed in the study combining d-axis voltage model and reactive power model. The weighting factor k is introduced and adjusted in different speed-torque range to change the weighting of each model, which makes full use of advantages in each model to improve the robustness to motor parameters. A consideration of Eq. 15 and 17 show that a possible combination might be defined as follows (Bose, 2002),

$$\varepsilon = k\varepsilon_d + (1-k)\varepsilon_Q \quad (0 \le k \le 1) \tag{24}$$

Because of great different magnitude of ε_d, ε_Q in different speed and torque, the exact expression of k is hard to obtain, which is still under investigation at present. But a possible adjustment law of k can be made. Accordingly, the speed, load range is divided into four subregions, which are low speed, low load; low speed, high load; high speed, low load; high speed, high load.

In low speed, low load subregion, the sensitivity to L_m in reactive power model is higher than that in d-axis voltage model and almost same low sensitivity to leakage inductance. But the lower the speed is, the more sensitive to stator resistance d-axis voltage model holds. Therefore, almost equal weighting for each model is available.

In low speed, high load subregion, the influence on adaptation due to leakage inductance deviations in d-axis voltage model is a little higher, compared with reactive power model and short stability range is also produced. So, the weighting leans a little to reactive power model, in which the effect caused by detune of L_m decreases with the increase of load.

In high speed, low load subregion, the d-axis voltage model has the most remarkable advantages with lower sensitivity to all the parameters. Oppositely, the reactive power model is high sensitive to L_m, as shown in Fig. 5, the compensation to L_m is necessary, otherwise the great adaptation error is obtained. Consequently, the weighting leans to d-axis voltage model.

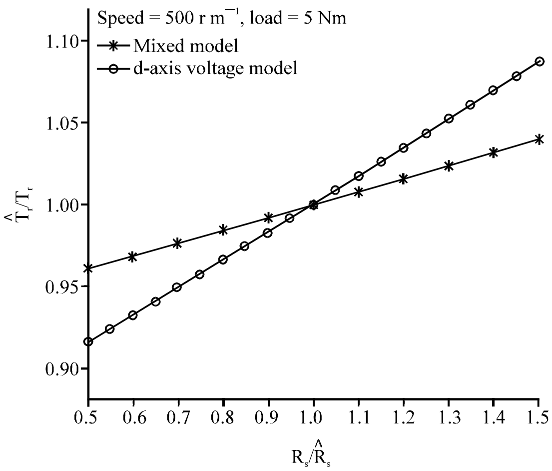

Fig. 10: Comparison of sensitivity to stator resistance at low speed, low load

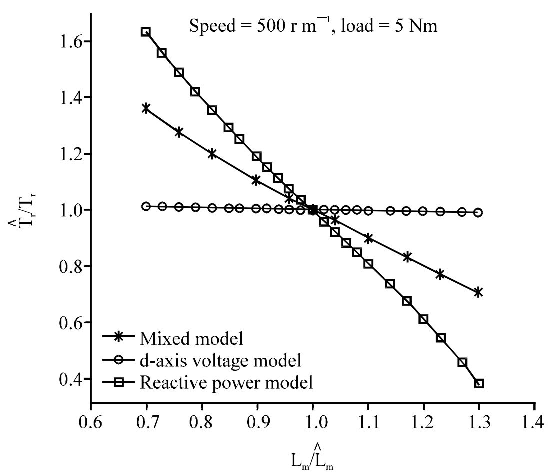

Fig. 11: Comparison of sensitivity to mutual inductance at low speed, low load

In high speed, high torque subregion, the stability is easily influenced at higher loads by the deviation of leakage inductance in d-axis voltage model. A compromised solution is reduction the weighting of d-axis voltage model.

Based on a number of tests and simulations, a compromised value of k is chosen and the conclusion can provide reference for succeeding intelligent control design.

- Speed = 500 r m^{-1}, load = 5 Nm, k = 0.85
- Speed = 500 r m^{-1}, load = 30 Nm, k = 0.95
- Speed = 1500 r m^{-1}, load = 5 Nm, k = 1
- Speed = 1500 r m^{-1}, load = 30 Nm, k = 0.97

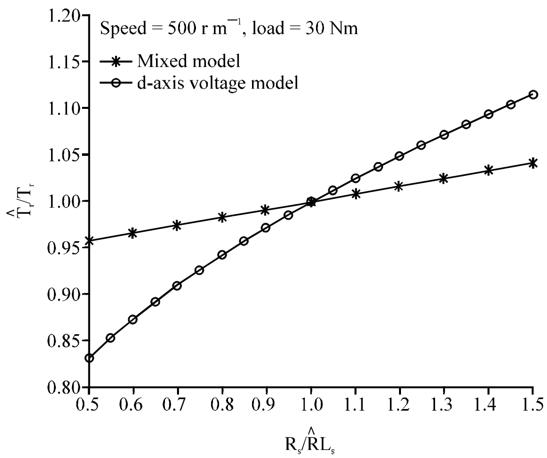

Fig. 12: Comparison of sensitivity to stator resistance at low speed, high load

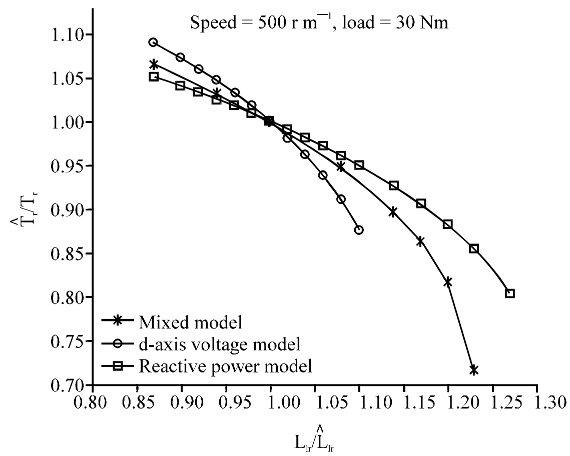

Fig. 15: Comparison of sensitivity to rotor leakage inductance at low speed, high load

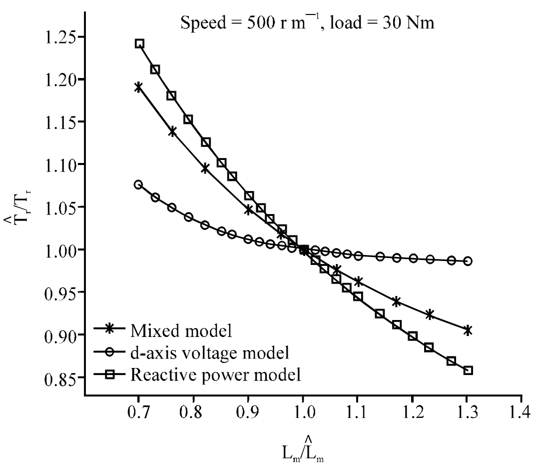

Fig. 13: Comparison of sensitivity to mutual inductance at low speed, high load

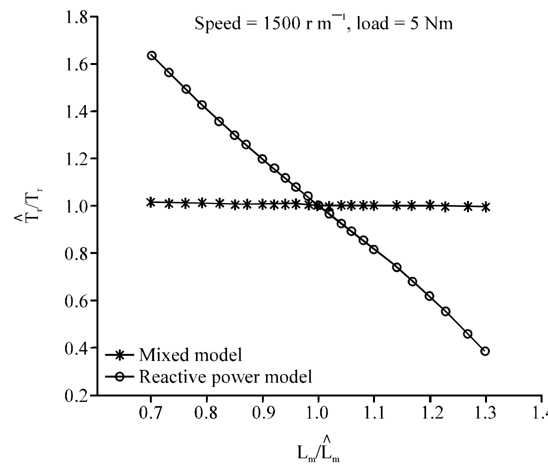

Fig. 16: Comparison of sensitivity to mutual inductance at high speed, low load

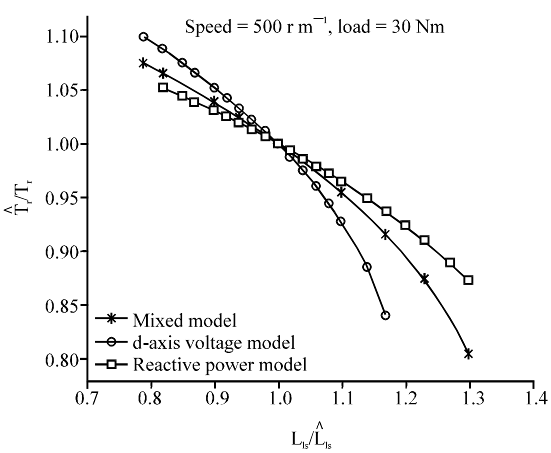

Fig. 14: Comparison of sensitivity to stator leakage inductance at low speed, high load

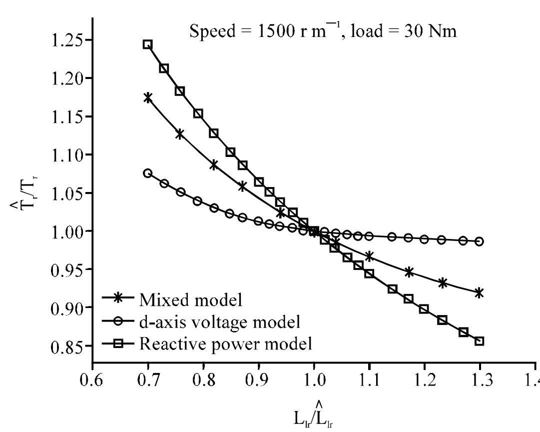

Fig. 17: Comparison of sensitivity to mutual inductance at high speed, high load

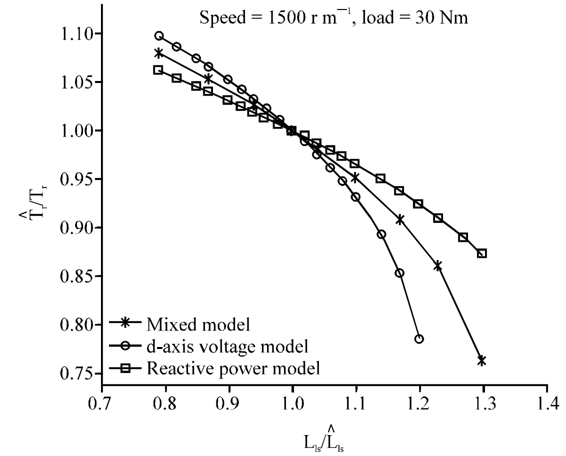

Fig. 18: Comparison of sensitivity to stator leakage inductance at high speed, high load

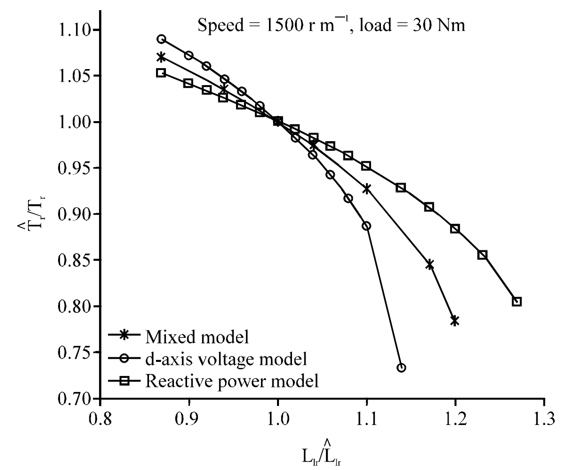

Fig. 19: Comparison of sensitivity to rotor leakage inductance at high speed, high load

The sensitivities to stator resistance, mutual inductance and leakage inductance using mixed model are shown in Fig. 10-19. The comparison to d-axis voltage model and reactive power model is also developed. From the simulation results, robustness to mutual inductance is improved, with the extensive suppression of stator resistance, considering the instability problem caused by detune of leakage inductance, the stability range is correspondingly extended.

CONCLUSION

In the procedure of MRAC identification for rotor time constant in IRFOC induction machine drives, the mismatch of stator resistance and inductance between model and motor can degrade the adaptation result and thus orientation accuracy. The parameter sensitivity is analyzed based on d-axis voltage model and reactive power model respectively, parameter sensitivities of each model are then indicated in section 3 and confirmed by simulations in section 4. Correspondingly, a new MRAC is proposed in section 5 combining d-axis voltage with reactive power models. The weighting factor k is then introduced and adjusted in different speed, torque region to change the weighting of each model, which makes full use of their advantages. The simulations show the improved robustness to parameters and extended stability range.

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REFERENCES

Bose, B.K., 2002. Modern Power Electronics and AC Drives. 2nd Edn., Prentice Hall, Upper Saddle River, New Jersey, USA., ISBN-10: 013016743, pp: 736.

Dittrich, A., 1994. Parameter sensitivity of procedures for on-line adaptation of the rotor time constant of induction machines with field oriented control. IEEE Proc. Electric Power Appl., 141: 353-359.

Krishnan, R. and A.S. Bharadwaj, 1991. A review of parameter sensitivity and adaptation in indirect vector controlled induction motor drive system. IEEE Trans. Power Electr., 6: 695-703.

Maiti, S., C. Chakraborty, Y. Hori and M.C. Ta, 2008. Model reference adaptive controller-based rotor resistance and speed estimation techniques for vector controlled induction motor drive utilizing reactive power. IEEE Trans. Indus. Electr., 55: 594-601.

Noguchi, T., S. Kondo and I. Takahashi, 1997. Field-oriented control of an induction motor with robust on-line tuning of its parameters. IEEE Trans. Indus. Appl., 33: 35-42.

Nordin, K.B., D.W. Novotny and D.S. Zinger, 1985. The influence of motor parameter deviations in feedforward field orientation drive systems. IEEE Trans. Indus. Appl., 21: 1009-1015.

Rowan, T.M., R.J. Kerkman and D. Leggate, 1991. A simple on-line adaption for indirect field orientation of an induction machine. IEEE Trans. Indus. Appl., 27: 720-727.

Santisteban, J.A. and R.M. Stephan, 2001. Vector control methods for induction machines: An overview. IEEE Trans. Educ., 44: 170-175.

Sumner, M., G.M. Asher and R. Pena, 1993. The experimental investigation of rotor time constant identification for vector controlled induction motor drives during transient operating conditions. Proceedings of the 5th European Conference on Power Electronics and Applications, Sep. 13-16, Brighton, pp: 51-56.

Toliyat, H.A., E. Levi and M. Raina, 2003. A review of RFO induction motor parameter estimation techniques. IEEE Trans. Energy Convers., 18: 271-283.

Yu, X., M.W. Dunnigan and B.W. Williams, 2002. A novel rotor resistance identification method for an indirect rotor flux-orientated controlled induction machine system. IEEE Trans. Power Electr., 17: 353-364.