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INDIRECT-FIELD-ORIENTATED CONTROL OF AN ASYNCHRONOUS GENERATOR WITH ROTOR-RESISTANCE ADAPTATION BASED ON A REFERENCE MODEL

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Abstract: This paper studies in detail a method for rotor-resistance adaptation for indirect-field orientated control of induction generators based on the reactive-power reference model. First of all, it will be shown how the adaptation procedure can be made independent of stator frequency and load torque. Secondly, the stability of the adaptation procedure will be demonstrated rigorously by means of Lyapunov theorem. Simulation results using data from two different machines will be presented to validate the main contributions. Finally, the sensitivity of the algorithm to errors in other machine parameters will be investigated.

Keywords: Field-Orientated Control, Induction Motors, MRAS

1. INTRODUCTION

Field-orientated control of induction motors has made it possible to extend the use of induction machines in high performance applications.

Direct-field-orientated control (DFOC) includes a closed-loop rotor-flux controller and requires the calculation of rotor-flux modulus and position. This is the standard solution for high-performance drives but requires complicated algorithms. Indirect-field-orientated control (IFOC) does not have a closed-loop rotor-flux controller and only requires the angular position of the rotor-flux vector which is calculated integrating the vector angular speed (Murphy and Turnbull, 1988). This can be computed using the rotor speed and the stator-current measurement. IFOC is a very simple and, therefore worth-to-be-considered solution in many applications. However, the calculation of the angular speed of the rotor flux is very sensitive to errors in rotor resistance which changes widely with temperature.

Several algorithms to estimate the rotor resistance have been presented in the literature. Those based on Model Reference Adaptive Systems (MRAS) are particularly well suited for IFOC systems (Rowan *et al.*, 1991). Typically:

a) Torque Reference Model. The torque reference model uses the torque equation to adapt the rotor resistance (Lorenz and Lawson, 1990). The adaptation can be utilised even during transient torque conditions. However, there is the need to know the stator resistance (variable with temperature) and L_M^2/L_R, where L_M and L_R are the magnetizing inductance and the rotor inductance, respectively. Although the implementation of this method is analysed in (Lorenz and Lawson, 1990), the convergence is not studied in detail.

b) Reactive-Power Reference Model. The reactive-power reference model uses the reactive-power equation to estimate the rotor resistance (Garcés, 1980). This method uses the stator inductance, L_S, and σ ($\sigma = 1 - L_M^2/L_S L_R$), but there is no need to know the stator resistance. A thorough analysis of the convergence of the resistance estimate to its actual value shows a strong dependency on the operating point (supply frequency and machine torque). This issue needs to be further investigated.

c) D-Axis and Q-Axis Voltage Reference Models (Rowan *et al.*, 1991). These methods use the d-axis voltage equation and the q-axis voltage equation respectively to estimate the rotor resistance. Both approaches use stator resistance, stator inductance and σ. The errors between the estimated variable and the real value obtained with the reference model are analysed in steady-state in (Rowan *et al.*, 1991). These errors drive the adaptation process. It is demonstrated that the load torque and the supply frequency also affect the algorithms convergence in this case.

The scheme proposed in this paper estimates the rotor resistance using a reactive-power-based reference model derived from (García-Cerrada and Robertson, 1999). Unlike in previous references, the algorithm convergence is rigorously studied here. Furthermore, previos references study this type of algorithm only in motoring applications while induction machines are already a very-competive alternative for generation in wind farms. Therefore, this paper also addresses the algorithm in generation mode. The reactive-power model is introduced in Section 2. An adaptation algorithm to estimate the rotor resistance, based on reactive-power model is introduced in Section 3, both in motor mode and generator mode. The algorithm has been made independent of the machine supply frequency, the initial guess for the rotor resistance value and the machine torque. The stability of this algorithm is analysed in Section 4. The main results are tested in Section 5 through simulation of two different induction machines working in generator and motor mode. Finally, the sensitivity of the proposed algorithm to errors in motor inductances is investigated through simulation.

2. REACTIVE-POWER REFERENCE MODEL

The state-variable model of an asynchronous motor referred to a reference frame rotating with an arbitrary angular speed can be written as (Vas, 1990),

$$\frac{d}{dt}\begin{bmatrix} i_{Sd} \\ i_{Sq} \\ \psi_{Rd} \\ \psi_{Rq} \end{bmatrix} = \begin{bmatrix} A & \omega_e & B & C\omega_R \\ -\omega_e & A & -C\omega_R & B \\ D & 0 & E & \omega_{Slip} \\ 0 & D & -\omega_{Slip} & E \end{bmatrix} \begin{bmatrix} i_{Sd} \\ i_{Sq} \\ \psi_{Rd} \\ \psi_{Rq} \end{bmatrix} + \\ + \begin{bmatrix} F & 0 \\ 0 & F \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} v_{Sd} \\ v_{Sq} \end{bmatrix} \tag{1}$$

$$\frac{d\omega_R}{dt} = \frac{P}{J}\left(T_e - T_L\right) - \frac{B}{J}\omega_R \tag{2}$$

with

$$\begin{array}{ll} A = -\frac{R_S}{L_S\sigma} - \frac{R_R(1-\sigma)}{L_R\sigma} & B = \frac{L_M R_R}{\sigma L_S L_R^2} \\ C = \frac{L_M}{\sigma L_S L_R} & D = \frac{L_M R_R}{L_R} \\ E = -\frac{R_R}{L_R} & F = \frac{1}{L_S} \\ T_e = G\left(\psi_{Rd} i_{Sq} - \psi_{Rq} i_{Sd}\right) & G = \frac{P L_M}{L_R} \\ \omega_{Slip} = \omega_e - \omega_R & \end{array} \tag{3}$$

where i_{Sd}, i_{Sq}, ψ_{Rd}, ψ_{Rq}, v_{Sd} and v_{Sq} are the d and q components of stator currents (i_S), rotor flux (ψ_R) and stator voltage (v_S). ω_e is the angular speed of the reference frame used to model the machine. ω_R is the rotor speed in electric rad/s. T_e is the electro-mechanical torque. T_L is the load torque. P is the number of pole pairs. J is the total motor and load inertia. B is the total damping coefficient. R_S is the stator resistance and R_R is the rotor resistance.

This state-variable model can be written using a reference frame which moves at the same angular speed that the rotor-flux vector. Moreover, the d axis of this frame can always be taken in the direction of the rotor flux vector ($\psi_{Rq} = 0$). This is the field-orientated reference frame. If the stator-current components (d and q) in this frame are controlled and the rotor-flux modulus is kept constant: i_{Sd} is equal to i_{Sd}^*, i_{Sq} is equal to i_{Sq}^* and the rotor-flux modulus becomes $L_M i_{Sd}^*$ in steady-state. Note that i_{Sd}^* and i_{Sq}^* stand for the reference values of stator currents. If stator-current references are made constant, stator equations lead to:

$$L_S\sigma\frac{di_{Sd}^*}{dt} = -R_S i_{Sd}^* + L_S\sigma\hat{\omega}_S i_{Sq}^* + v_{Sd} = 0 \tag{4}$$

$$L_S\sigma\frac{di_{Sq}^*}{dt} = -L_S\hat{\omega}_S i_{Sd}^* - R_S i_{Sq}^* + v_{Sq} = 0 \tag{5}$$

where $\hat{\omega}_S$ is the estimated value for the angular speed of the rotor flux in steady state.

Equations (4) and (5) may be used to calculate $\hat{\omega}_S$ eliminating R_s, giving:

$$\hat{\omega}_S = \frac{v_{Sq} i_{Sd}^* - v_{Sd} i_{Sq}^*}{L_S\left(i_{Sd}^{*2} + \sigma i_{Sq}^{*2}\right)} = \frac{Q}{L_S\left(i_{Sd}^{*2} + \sigma i_{Sq}^{*2}\right)} \tag{6}$$

where Q is the instantaneous reactive power of the machine. It is worth pointing out that (6) only contains machine parameters which do not undergo significant changes (L_S and σ) during operation. This is a clear advantage.

The angular speed estimated in this way, $\hat{\omega}_S$, is equal to the angular speed of the rotor-flux vector only when the reference frame rotates synchronously with the rotor-flux vector and $\psi_{Rq} = 0$ during steady-state operation.

In an induction motor with IFOC, the angular speed of the stator-current vector is forced to be:

$$\omega_e = \omega_R + \frac{\hat{R}_R}{L_R} \frac{i_{Sq}^*}{i_{Sd}^*} \tag{7}$$

where $\hat{R}_R$ stands for the estimated value of the rotor resistance and all d and q components are referred to the field-orientated frame.

Obviously, this is also the angular speed of the rotor-flux vector in steady-state. In addition, the angular position of the rotor-flux vector can be calculated as

$$\theta_e = \int \omega_e dt \tag{8}$$

Under stator-current control conditions, correct field-orientation using an IFOC is only achieved if $\hat{R}_R = R_R$ (Sugimoto, 1983). Therefore, (6) and (7) will give the same result only in this circumstance. The difference between those values can be used to drive the adaptation process.

3. ROTOR-RESISTANCE-ADAPTATION ALGORITHM

The machine-control system (IFOC) is depicted in figure 1 whereas the calculus of the angular position θ_e is depicted in figure 2. The estimated angular speed, $\hat{\omega}_S$, is compared with the speed of reference frame, ωe, to form an error, e. This error is then used by the rotor-resistance-adaptation algorithm to adjust the rotor resistance estimate, $\hat{R}_R$, used to calculate the speed of the reference frame (see equation (7)) and the angular position (see (equation 8)).

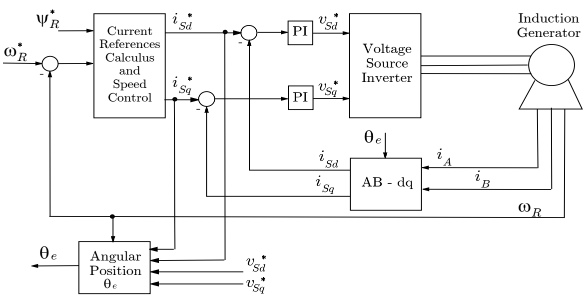

Fig. 1. Indirect field-orientated control scheme

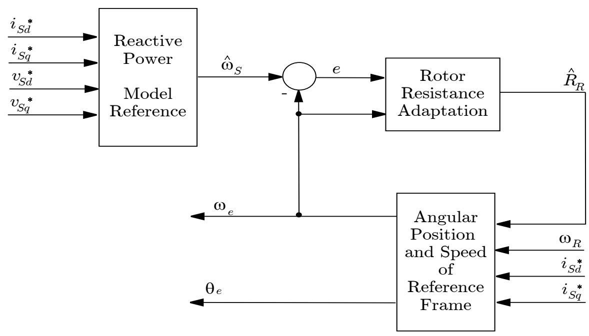

Fig. 2. Rotor resistance adaptation process

The error between the estimated angular speed of the rotor flux, $\hat{\omega}_S$ and the angular speed of the reference frame used in the IFOC, ω_e is given by:

$$e = \hat{\omega}_S - \omega_e \tag{9}$$

If v_{Sd} and v_{Sq} are calculated from (1) and they are taken to (6), one obtains in steady-state:

$$\hat{\omega}_S = \omega_e \frac{R_R^2 i_{Sd}^{*^2} + \sigma \hat{R}_R^2 i_{Sq}^{*^2}}{R_R^2 i_{Sd}^{*^2} + \hat{R}_R^2 i_{Sq}^{*^2}} \frac{i_{Sd}^{*^2} + i_{Sq}^{*^2}}{i_{Sd}^{*^2} + \sigma i_{Sq}^{*^2}} \tag{10}$$

Substituting (10) in (9), the error equation yields

$$e = \alpha \frac{\omega_e \left(R_R^2 - \hat{R}_R^2\right)}{R_R^2 i_{Sd}^{*^2} + \hat{R}_R^2 i_{Sq}^{*^2}};\ \alpha = \frac{(1-\sigma) i_{Sd}^{*^2} i_{Sq}^{*^2}}{i_{Sd}^{*^2} + \sigma i_{Sq}^{*^2}} \tag{11}$$

When the induction machine operates in motor mode, the angular rotor speed, ω_R and the q component of the stator current, i_{Sq}^* are positive or negative simultaneously. Therefore the error will be zero only when $\hat{R}_R$ is equal to R_R. But when the induction machine operates in generator mode, the angular rotor speed and the q component of the stator current have opposite signs, therefore the error will be zero when $\hat{R}_R$ is equal to R_R or when $\omega_e = 0$ (see equation (7)).

A rotor resistance update algorithm can be chosen as in (García-Cerrada and Robertson, 1999)

$$\frac{d\hat{R}_R}{dt} = \gamma i_{Sq}^* e \tag{12}$$

where γ is a positive constant that affects the convergence rate of the controller. This is a design parameter and can be changed during operation to keep γi_{Sq}^* constant in (12) so that the motor torque current does not affect the convergence dynamics. For practical reasons γ cannot be made arbitrarily big and the algorithm does not work when i_{Sq}^* is very small. Substituting (11) in (12) yields,

$$\frac{d\hat{R}_R}{dt} = \gamma \alpha \frac{\omega_e i_{Sq}^* \left(R_R^2 - \hat{R}_R^2\right)}{R_R^2 i_{Sd}^{*^2} + \hat{R}_R^2 i_{Sq}^{*^2}} \tag{13}$$

During motor-mode operation, this algorithm always converges to the real value of the rotor resistance because $\omega_e \cdot i_{Sq}^* > 0$. However, during generator-mode operation, if $\omega_e \cdot i^*_{Sq} < 0$, $\hat{R}_R$ increases when $\hat{R}_R > R_R$ and decreases when $\hat{R}_R < R_R$. Therefore the actual value of the rotor resistance will never be reached. It is clearly shown that in motor mode the convergence rate is a function on the angular speed of the reference frame, ω_e. It is also shown that the adaptation process might be affected by the torque reference current (i^*_{Sq}).

The algorithm proposed in this paper is applicable in motor and generator modes. Up to certain extend, its convergence rate can be kept constant regardless of ω_e and i^*_{Sq}. If

$$\frac{d\hat{R}_R}{dt} = \frac{\gamma}{\omega_e} e \tag{14}$$

substituting (11) in (14) yields

$$\frac{d\hat{R}_R}{dt} = \gamma\alpha \frac{\left(R_R^2 - \hat{R}_R^2\right)}{R_R^2 i_{Sd}^{*2} + \hat{R}_R^2 i_{Sq}^{*2}} \tag{15}$$

Section 4 demonstrates that this algorithm estimates the rotor resistance correctly for any operation mode. However, it does not work when the angular speed of the reference frame is equal to zero in steady-state: Fortunatelly, the induction machine never operates in these conditions. The algorithm is also badly conditioned if i^*_{Sq} is very small because α tends to zero and the inital estimate for the rotor resistance does not change.

4. ADAPTATION ALGORITHM STABILITY

The differential equation (15) is clearly nonlinear dynamical system. Lyapunov theorem for global stability is used to demonstrate its stability (Slotine and Li, 1991).

The rotor-resistance-estimation error can be defined as, h

$$h = R_R - \hat{R}_R \tag{16}$$

If R_R is constant during the adaptation process, its time derivative yields

$$\frac{dh}{dt} = -\frac{d\hat{R}_R}{dt} \tag{17}$$

Substituting (15) and (16) into (17) yields

$$\frac{dh}{dt} = -\gamma\alpha \frac{\left(R_R + \hat{R}_R\right) h}{R_R^2 i_{Sd}^{*2} + \hat{R}_R^2 i_{Sq}^{*2}} \tag{18}$$

The following Lyapunov function candidate can be proposed

$$V = h^2 \tag{19}$$

which is positive definite and $V(h) \to \infty$ when $\|h\| \to \infty$.

Its time derivative is:

$$\frac{dV}{dt} = \frac{dV}{dh}\frac{dh}{dt} = -2\gamma\alpha \frac{\left(R_R + \hat{R}_R\right) h^2}{R_R^2 i_{Sd}^{*2} + \hat{R}_R^2 i_{Sq}^{*2}} \tag{20}$$

Therefore

$$\frac{dV}{dt} = -2\gamma\alpha \frac{\left(R_R + \hat{R}_R\right)}{R_R^2 i_{Sd}^{*2} + \hat{R}_R^2 i_{Sq}^{*2}} V \tag{21}$$

Thus, $\dot{V} < 0$ as long as $h \neq 0$, so that $h = 0$ ($\hat{R}_R = R_R$) is a globally aymptotically stable equilibrium point.

5. SIMULATION RESULTS

The simulation results have been obtained using two different induction motor, whose parameters are given in Appendix A (250 W) and in Appendix B (3 kW), to compare the adaptation dynamics. Both machines use an IFOC for rotor-speed control. Rotor resistances in the machine simulator have been made 50% bigger than their nominal values which have been used as the initial estimates. Adaptation algorithm begins to update the rotor resistance at 5 s.

Figure 3 shows the simulation results of the 250 W induction machine working in generator mode with a load torque $T_L = -1,5$ N·m (85% of nominal torque) and with changes in rotor speed reference. The adaptation algorithm updates the rotor resistance to the correct value. Once the rotor resistance is correct, the speed transients improve substantially.

Figure 4 shows the simulation results of the 250 W induction machine working in motor mode with a load torque $T_L = +1,5$ N·m and with changes in rotor speed reference. The adaptation algorithm also updates the rotor resistance to the correct value.

Figure 5 shows the simulation results of the 250 W induction machine working in generator mode at low rotor speed (about 50 rad/s) with a load torque $T_L = -1,5$ N·m. The adaptation algorithm updates the rotor resistance to the correct value again and the convergence rate is similar to that on Figure 3 where the motor speed was much higher.

The same simulation experiments have been carried out with a larger-size machine.

Figure 6 shows the simulation results of the 3 kW induction machine working in generator mode with a load torque $T_L = -15$ N·m (75% of nominal torque) and with changes in rotor speed reference. Figure 7 shows the simulation results of the 3 kW induction machine working in motor

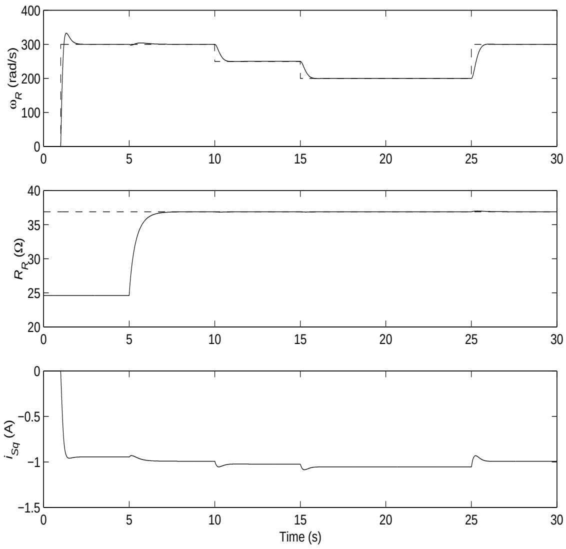

Fig. 3. Adaptation algorithm response in generator mode (250 W motor)

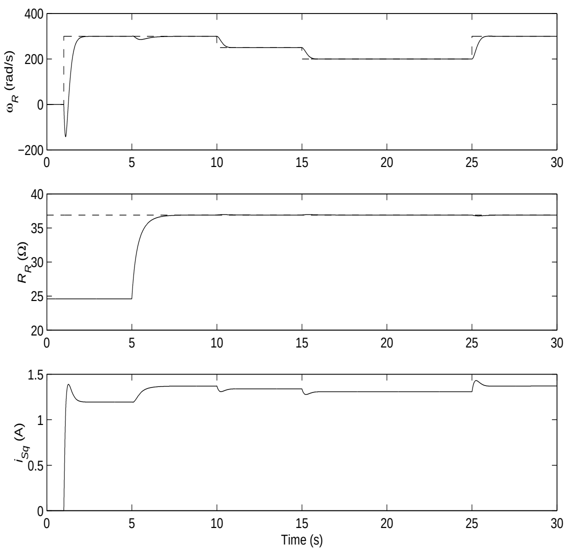

Fig. 4. Adaptation algorithm response in motor mode (250 W motor)

mode with a load torque $T_L = +15$ N·m and with changes in rotor speed reference. Figure 8 shows the simulation results of the 3 kW induction machine working in generator mode at low rotor speed (about 50 rad/s) with a load torque $T_L = -5$ N·m (25% of nominal torque). The adaptation algorithm updates the rotor resistance to the correct value again.

In all six cases treated the adaptation dynamics are very similar.

5.1 *Sensivity of the Proposed Algorithm*

One of the disadvantages of the reactive-power reference model is the sensivity to detuning in the stator and rotor inductances.

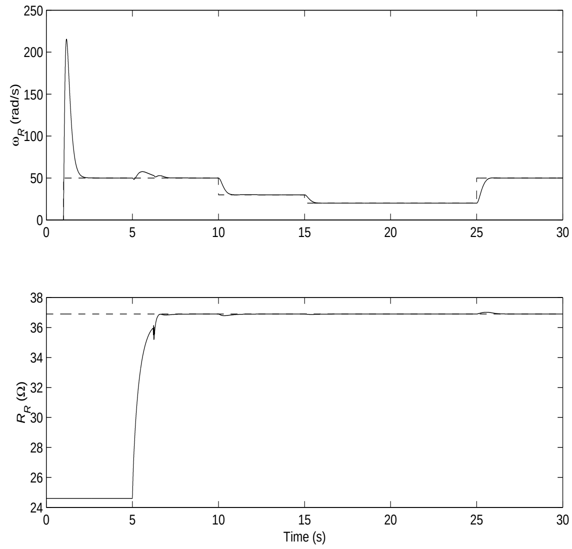

Fig. 5. Adaptation algorithm response in generator mode at low speed rotor (250 W motor)

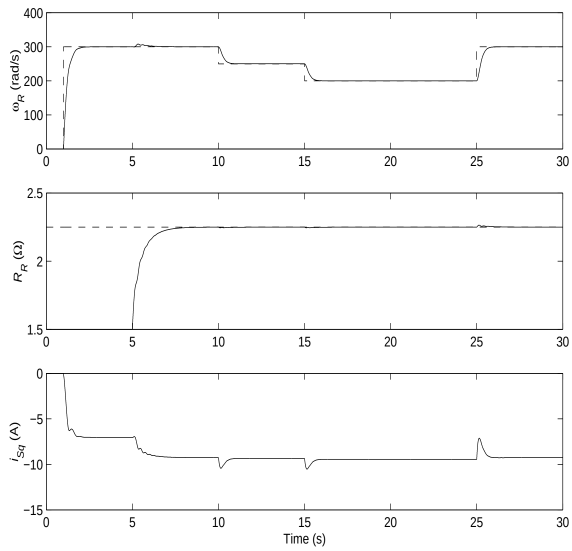

Fig. 6. Adaptation algorithm response in generator mode (3 kW motor)

Simulations have been carried out to analyse this sensivity. The machine power is 250 W, the load torque is $T_L = -1,5$ N·m and the rotor speed is $\omega_R = 300$ rad/s. Inductances have been varied ±4% with respect to their nominal values. The results obtained are showed in Table 1 and in Table 2. In all cases, the errors produced in the current-stator components are higher when the rotor resistance is not estimated.

$\Delta\%$	$\varepsilon_{R_R}\%$	$\varepsilon_{i_{Sd}}\%$	$\varepsilon_{i_{Sq}}\%$	$\varepsilon_{T_e}\%$
$\Delta L_R = +4\%$	$6,12$	$8,20$	$1,93$	$10,38$
$\Delta L_R = -4\%$	$2,89$	$4,85$	$2,06$	$6,78$
$\Delta L_S = +4\%$	$17,10$	$13,65$	$2,95$	$10,30$
$\Delta L_S = -4\%$	$11,11$	$8,00$	$3,50$	$4,78$

Table 1. Errors produced by inductance detuning. The error of the variable x is $\varepsilon_x = \left|(x_{real} - x_{measured})/x_{real}\right|$

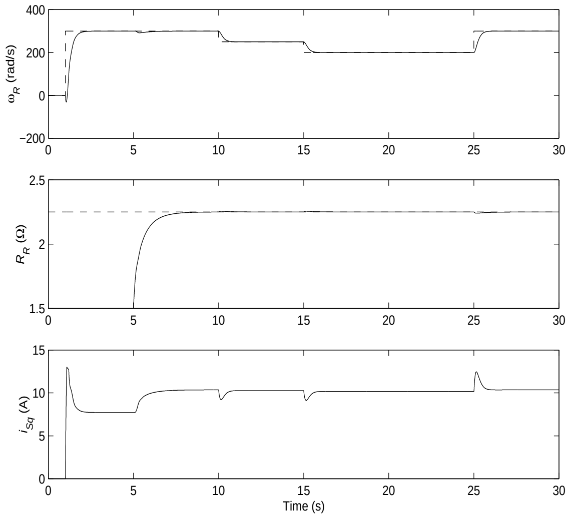

Fig. 7. Adaptation algorithm response in motor mode (3 kW motor)

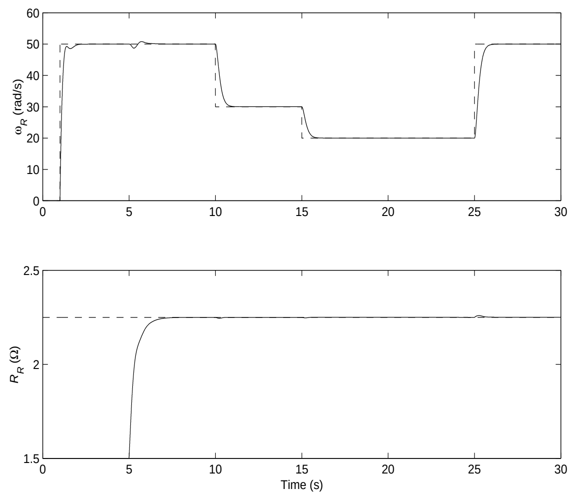

Fig. 8. Adaptation algorithm response in generator mode at low speed rotor (3 kW motor)

$\Delta\%$	$\varepsilon_{R_R}\%$	$\varepsilon_{i_{Sd}}\%$	$\varepsilon_{i_{Sq}}\%$	$\varepsilon_{T_e}\%$
$\Delta L_R = +4\%$	50	$21,03$	$13,85$	$6,46$
$\Delta L_R = -4\%$	50	$23,40$	$19,68$	$11,98$
$\Delta L_S = +4\%$	50	$22,26$	$16,62$	$9,35$
$\Delta L_S = -4\%$	50	$22,26$	$16,62$	$9,35$

Table 2. Errors produced by inductance detuning without adaptation algorithm

6. CONCLUSIONS

An adaptation algorithm to estimate the rotor resistance based on a reference model is studied in this paper (MRAS). This algorithm is used in a IFOC scheme, which is a simple and valuable solutions in many applications. The adaptation algotithm works properly in motor and generator modes. Previously-presented studies would only consider motoring operation mode. The algorithm stability has been demonstrated rigorously by means of Lyapunov theorem. The proposed adaptation algorithm is globally aymptotically stable. Up to certain extend the convergence speed can be made independent of the supply frequency and the motor torque current.

Finally, a simulator has been developed to validate the main results. Important errors are produced when the rotor resistance is not estimated, therefore, this algorithm improves the IFOC scheme.

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Appendix A. 250 W INDUCTION MACHINE PARAMETERS

$R_S = 48\Omega$	$R_R = 24,6\Omega$
$L_S = 1,1338$ H	$L_R = 1,1338$ H
$L_M = 1,0282$ H	$P = 2$
$J = 1,1 \cdot 10^{-3}$ kg·m^2	$B = 1,6 \cdot 10^{-3}$ kg·m^2·s^{-1}

Appendix B. 3 KW INDUCTION MACHINE PARAMETERS

$R_S = 2,5\Omega$	$R_R = 1,5\Omega$
$L_S = 0,33$ H	$L_R = 0,33$ H
$L_M = 0,32$ H	$P = 2$
$J = 25 \cdot 10^{-3}$ kg·m^2	$B = 5,6 \cdot 10^{-3}$ kg·m^2·s^{-1}