Indirect Field Oriented Control with rotor time constant adaptation

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Abstract - This work deals with the design of an Adaptive Reference model Controller for (MRAC) for parameters adaptation apply to an indirect field oriented controller for induction motor control. The parameters behavior was analyzed using three different reference models. The considered reference models were: direct (d) axis voltage, the quadrature (q) axis voltage and the reactive power. For each reference model the adaptation error was analyzed. Using these equations the parameters convergence was analyzed and discussed under several motor conditions. The results were presented and the simulation for all the reference models considered, illustrating the parameters behavior under several motor operating conditions. The analysis and simulation results show the superiority of the dynamic reference models using quadrature (q) axis voltage and reactive power model.

Keywords: Field Oriented Controller, Field Oriented MRAC Control, Induction motor, Field Orientation Drive Systems, Parameter Adaptation for the Speed Controlled, Field-Oriented Induction Machine Drives

1. Introduction

The field oriented control is the most popular method to obtain the best dynamic benefits in industrial applications with induction motors. Two basic schemes of field oriented controllers exist: the direct and the indirect method. The main difference is that the direct method achieves the field orientation by means of direct measurements or calculations (estimation) of the electric flux of the rotor, while the indirect method achieves it by means of the measurements of the speed and the slip calculation with the reference values. Typically, both schemes use some kind of stator current regulation.

The indirect method has been the preferred one, mainly because it is not needed to measure or to estimate the flux, simplifying the controller and then reducing the costs. However the slip frequency calculation depends on the rotor time constant which varies mainly with the rotor temperature, and if their exact value is not know, the dynamic performance indicators deteriorate.

It has been proposed several schemes using MRAC controllers to adapt such variations [7] - [11]. As it is known in this technique (MRAC) the required behavior of the motor it is specified by a reference model. To achieve the adaptation it is use the error signal, difference between the model reference output and the motor terminal measurements. Several reference models have been presented in

the literature, in [7] the reference model corresponds to an modified function of the reactive power. In [9] a reference model is used, based on the motor torque. In [10] 3 reference models are based on the voltages. All these reference models are algebraic, and most of them based on induction motor steady state operation.

2. Adaptation Method for MRAC

Figure 1 shows the basic structure of an MRAC scheme with slip frequency gain adaptation, similar to generalized MRAC scheme, used in [10] and [11].

The variable Y^* is the model reference output and represents the value of some motor magnitudes, Yis the variable current value, the one, obtain by means of measurements in the terminals of the motor. The Y^*-Y difference produces the adaptation error (e_a) , which is multiplied by the reference of the torque producing current, and then is integrated to produce the slip frequency gain (\hat{k}_s) , that is used directly by the field oriented control, to compute the slip frequency (w_{sl}) .

The goal of this method is to adapt the gain \hat{k}_s to achieve the convergence to zero of the adaptation error. The reference model plays a leading roll in this adaptation structure, since the behavior of the system is specified, in this case the behavior of the induction motor with field oriented control. The reference model should be this way able to predict this behavior so that the gain \hat{k}_s converges to its nominal value, the same to say that the adaptation error converges to zero.



Fig. 1. Block diagram of the Field Oriented MRAC Control

All these models are based on induction motor model with lineal magnetic circuit and constant reference flux.

3. Algebraic reference model

The algebraic reference models are those that only contain algebraic operations. They don't include integral or differential operations.

The algebraic reference models that we will consider in this work are obtained only from steady state operations. In this case the stator voltage in reference to the synchronous axes are given from the following equations:

$$v_{qs} = R_s i_{qs} + w_e \lambda_{ds} \tag{1}$$

$$v_{ds} = R_s i_{ds} - w_e \lambda_{qs} \tag{2}$$

Where the symbols are defined in the annexes. The stator flux in field oriented condition are:

$$\lambda_{qs} = L_{\sigma} i_{qs} \tag{3}$$
$$\lambda_{ds} = L_s i_{ds} \tag{4}$$

The direct (d) axis voltage reference model was obtained by means of the substituting (2) in the field oriented condition (3) [10]:

$$v^*_{ds} = R_s i^c_{ds} - w_e L_\sigma i^c_{qs} \tag{5}$$

The cuadrature (q) axis voltage reference model was obtained by means of the substituting (1) in the field oriented condition (4). [10]:

$$v_{qs}^{*} = R_{s}i_{qs}^{c} + w_{e}L_{s}i_{ds}^{c}$$
(6)

The reactive power is obtained by means of:

$$Q = v_{qs}i_{ds} - v_{ds}i_{qs} \tag{7}$$

The reactive power reference model was determined by means of the substitution of the equation (1) and (2) in (7), and applying the field oriented conditions 3 and 4. [10]:

$$Q^* = w_e \left(L_s i_{ds}^{c^2} + L_{\sigma} i_{qs}^{c^2} \right) \tag{8}$$

The equations (5) to (8), produce the Y^* variable (fig. 1) and Y is obtained directly by means of the measurements of v_{ds} and v_{qs} of the *d* and *q* axis in the voltage reference models and with the equation (7) the reactive power reference model was obtained.

3.1 Adaptation error

To formulate the adaptation error, all the motor parameter who describe the reference models are supposed known and should exist an exact match between the real currents and those of reference in the motor. The saturation effect were not considered.

The expressions of the adaptation error were obtained taking the difference for each reference model. The stator measured voltage in the motor terminals is given by equations (18) and (19). Using these two equations and equation (7) yields: [11] Direct (d) axis voltage reference model:

$$e_a^{\nu ds} = \frac{L_m}{L_r} \Big(w_e \,\lambda_{qr} - p \,\lambda_{dr} \Big) \tag{9}$$

Quadrature (q) axis voltage reference model:

$$e_a^{vqs} = -\frac{L_m}{L_r} \Big[w_e \big(\lambda_{qr} - L_m i_{ds} \big) + p \lambda_{qr} \Big] - L_\sigma p i_{qs}$$
(10)

Reactive Power reference model:

$$\begin{aligned} z_a^{pr} &= -\frac{L_m}{L_r} w_e \Big[i_{ds} \left(\lambda_{qr} - L_m i_{ds} \right) + i_{qs} \lambda_{qr} \Big] \\ &- \frac{L_m}{L_r} \Big(i_{ds} p \lambda_{qr} - i_{qs} p \lambda_{dr} \Big) - L_\sigma i_{ds} p i_{qs} \end{aligned}$$
(11)

These equations predict the adaptation error in both cases, steady and transient state.

3.2 Steady state analysis

In steady state, the derivative term that appears in the equations (9) to (11) are zero. The steady state adaptation error is expressed better by means of the detuning reason:

$$x = \frac{\hat{k}_s}{k_s^0} \tag{12}$$

Writing the adaptation error in steady state operation as a function of equation (12), we obtain in this case:

Direct (d) axis voltage reference model:

$$e_a^{vds} = v_0 \left[\tau_r w_r + x \cdot \left(\frac{i_{qs}}{i_{ds}} \right) \right] \cdot \frac{\left(1 - x \right) \cdot \left(\frac{i_{qs}}{i_{ds}} \right)}{1 + \left(\frac{i_{qs}}{i_{ds}} \right)^2}$$
(13)

Quadrature (q) axis voltage reference model:

$$e_a^{vqs} = v_0 \left[\tau_r w_r + x \cdot \left(\frac{i_{qs}}{i_{ds}} \right) \right] \cdot \frac{x(x-1) \cdot \left(\frac{i_{qs}}{i_{ds}} \right)^2}{1 + \left(\frac{i_{qs}}{i_{ds}} \right)^2} \quad (14)$$

Reactive Power reference model:

$$e_a^{pr} = Q_0 \left[\tau_r w_r + x \cdot \left(\frac{i_{qs}}{i_{ds}} \right) \right] \cdot \frac{\left(x^2 - 1 \right) \cdot \left(\frac{i_{qs}}{i_{ds}} \right)^2}{1 + \left(x \cdot \frac{i_{qs}}{i_{ds}} \right)^2} \quad (15)$$

Where:

$$v_0 = R_r i_{ds} \left(\frac{L_m}{L_r}\right)^2$$
 and $Q_0 = v_0 i_{ds}$ (16, 17)

The ratio i_{qs} / i_{ds} is strategic in the equations (13) to (15). As this ratio is a torque's function demanded by the load, this expressed the load dependence with the adaptation errors. Of course, small values of the ratio i_{qs} / i_{ds} , imply small values adaptation error converge to zero when $i_{qs} = 0$, that is way, there in not adaptation without load. This is not a peculiar problem of the MRAC method, other schemes have the same problem [12].

The adaptation error also depends on frequency, as is shown in equations from (13) to (15). At rated speed the adaptation error will be bigger that in low speed. The adaptation error dependence is nonlinear. For adaptation error x = 1 doesn't take place the adaptation process and this determines an equilibrium point for gain \hat{k}_s . This corresponds to the tuned condition.

3.3 Transient analysis

The derivative terms of i_{qs} in the equations (10) and (11) demonstrates that the adaptation error depends on i_{qs} transients. Such a derivative term appears because the reference models were based on steady state considerations and it cannot predict the transient behavior of the induction motor in field orientation. The equation (9) doesn't demonstrate such dependence because e_a^{vds} depends on the derivative of i_{qs} and constant flux condition is supposed.

The dependence of the adaptation error in i_{qs} transients introduces an significant problem. The problem that arises for any i_{qs} transient of an adaptation error will take place independently of the tune condition. This can be seen as a wrong

adaptation error and it will cause an adaptation of \hat{k}_s to an erroneous value. For this reason, the system can abandon the tune condition due to these transients [11].

As the tuning sensibility is bigger at low flux levels, the problem will be larger in this situation. Also, the problem will be more significant if frequently torque changes is required, e.g., Robotics Applications.

4. Dynamic model formulation

To develop a dynamic model of the induction motor in field orientation, it should be considered their behavior in this situation, as follows:

The stator voltage of the induction motor is:

$$v_{qs} = R_r i_{qs} + w_e L_\sigma i_{ds} + p L_\sigma i_{qs} + \frac{L_m}{L_r} \left(w_e \lambda_{dr} + p \lambda_{qr} \right) (18)$$

$$v_{ds} = R_s i_{ds} - w_e L_\sigma i_{qs} + p L_\sigma i_{ds} - \frac{L_m}{L_r} \left(w_e \lambda_{qr} + p \lambda_{qr} \right) (19)$$

Field orientation, supposing constant flux operation:

$$\lambda_{qr} = p\lambda_{qr} = 0 \tag{20}$$

$$\lambda_r = L_m i_{ds} \tag{21}$$

Substituting (20) and (21) in (18) and (19) yields: $v_{qs} = R_s i_{qs} + w_e L_s i_{ds} + p L_\sigma i_{qs}$ (22)

$$v_{ds} = R_s i_{ds} - w_e L_\sigma i_{as} \tag{23}$$

The equations (22) and (23) describe the behavior of the stator voltage of the induction motor in both cases, in transient and steady state. The only difference between them and the equations (5) and (6) is the i_{as} derivative that appears in the equation

(22). To consider such a derivative a similar model can be build, as is shown in figure 2.

In the figure G(p) is standard PID controller. It has the same role that the CRPWM inverter, producing the stator voltage v_{qs}^m to achieve that i_{qs}^m continues

closely to i_{qs}^c , if G(p) were designed to achieve this approach.



Fig. 2. Dynamic model block diagram $i_{qs}^m \approx i_{qs}^c$

(24)

This can be declared as:

$$v_{qs}^{m} = R_{s}i_{qs}^{m} + w_{e}L_{s}i_{ds}^{c} + pL_{\sigma}i_{qs}^{m}$$

$$\approx R_{s}i_{qs}^{c} + w_{e}L_{s}i_{ds}^{c} + pL_{\sigma}i_{qs}^{c}$$
(25)

$$v_{ds}^{m} = R_{s}i_{ds}^{c} - w_{e}L_{\sigma}i_{qs}^{m} \approx R_{s}i_{ds}^{c} - w_{e}L_{\sigma}i_{qs}^{c}$$
(26)

Now, like it was established before, that $i_{qs} = i_{qs}^c$ and $i_{ds} = i_{ds}^c$, the equation (25) declare that stator voltage in the q axis of the dynamic model v_{qs}^m corresponds to the current motor voltage v_{qs} . For this reason, the dynamic model predicts the behavior of the stator voltage of the induction motor in both cases, in transient and steady state. Thus the dynamic model can be written as:

$$i_{qs}^{m} = \frac{1}{R_s + pL_{\sigma}} \left(v_{qs}^{m} - w_e L_s i_{ds}^{c} \right)$$
(27)

$$v_{qs}^{m} = G_{c}\left(p\right) \cdot \left(i_{qs}^{c} - i_{qs}^{m}\right)$$
(28)

$$v_{ds}^m = R_s i_{ds}^c - w_e L_\sigma i_{qs}^m \tag{29}$$

4.1 Dynamic reference models

The dynamic model obtained in the previous section can be use to build a similar reference model to the algebraic one. The direct and cuadrature voltages reference models should be obtained directly as:

$$v_{ds}^* = v_{ds}^m \tag{30}$$

$$v_{qs}^* = v_{qs}^m \tag{31}$$

Reactive power reference model is obtained by means of:

$$Q^* = v_{qs}^m i_{ds}^c - v_{ds}^m i_{qs}^m \tag{32}$$

These models will be called as dynamic reference models because they are based on the induction motor dynamic model.

4.2 Adaptation error

The adaptation error $e_a = Y^* - Y$ for the dynamic reference models is obtained in the same way that the algebraic ones. The variable Y^* is given by the equations from (30) to (32) while the variable Y is given by the equations (18), (19) and (7). Direct (d) axis voltage reference model:

$$e_a^{vds} = \frac{L_m}{L_r} \left(w_e \lambda_{qr} - p \lambda_{dr} \right)$$
(33)

Quadrature (q) axis voltage reference model:

$$e_a^{vqs} = -\frac{L_m}{L_r} \Big[w_e \big(\lambda_{dr} - L_m i_{ds} \big) + p \lambda_{qr} \Big]$$
(34)

Reactive Power reference model:

$$e_{a}^{\mathrm{Pr}} = -w_{e} \frac{L_{m}}{L_{r}} \left[i_{ds} (\lambda_{dr} - L_{m} i_{ds}) + i_{qs} \lambda_{qr} \right] - \frac{L_{m}}{L_{r}} \left(i_{ds} p \lambda q_{r} - i_{qs} p \lambda_{dr} \right)$$
(35)

The equations (33) to (35) can be compared with the equations (9) to (11) to conduct a comparative analysis.

4.3 Stable state analysis

In steady state operation, the derivative terms of equations (33) to (35) are zero. This way decreases the adaptation error obtained by means of the algebraic reference model (equations (9) to (11) in steady state), so both reference models, the dynamic and the algebraic one have the same behavior in steady state and they produce the same adaptation error. This can seem obvious because both reference models predict the same behavior for the induction motor in steady state.

Also, the adaptation error in the d axis dynamic reference model and the algebraic model of the same axis, are the same one, because the d axis stator voltage doesn't depend on the transients of i_{as} , like it was mentioned before.

4.4 Transient analysis

The equations (34) and (35) shows that the adaptation error, through the q axis voltage and the power reactive dynamic reference models don't depend on the transients of i_{qs} like it was in the case of the algebraic reference model. This is the main advantage from the reference model dynamic envelope to the algebraic one. They are able to predict the behavior wanted for the induction motor in both cases, steady state and transitory, false adaptation error doesn't take place this way during the transients of i_{qs} .

The equation (26) demonstrates that the d axis voltage dynamic reference model is similar to the algebraic one. This way, in both cases the same behavior is obtained, in transient and steady state, this because the d axis voltage in the transients doesn't depend of i_{as} like it was mentioned before.

It only depends on the i_{ds} transients and they were not considered supposing constant flux operation.

5. Motor parameters dependence

Both dynamic and algebraic reference models is dependent of the motor parameters, the motor parameters contains R_s , L_s and L_{σ} , and. The stator resistance changes with the temperature, while the inductances L_s and L_{σ} varies with the magnetic circuit saturation of the motor. [3, 10].

The q axis voltage and the reactive power dynamic reference models contains these parameters, while the algebraic models only contains two of these parameters. Thus expressing superior robust behavior of the algebraic reference model that the dynamic one. Also, it is observed that the dynamic reference models are much more complex that the algebraic ones, because it contains integral operations.

6. Simulation results

The simulations results were obtained in an indirect field oriented control of an induction motor with speed closed loop. A speed reference change at t = 0.1 seg was applied and the k_s vs t graph was obtained. They were carried out for both, q axis voltage and reactive power algebraic and dynamic models. The system initially is tuned and working to rated flux with 20% of the load.



Fig. 3. Adaptation behavior simulation during a reference change. Q Axis Voltage and Reactivate Power Algebraic Reference Models.

Figure 3 shows the behavior of \hat{k}_s for the case of the algebraic reference models. The figure also shows that the \hat{k}_s abandons its tune value during the transient of speed for both models. That is way, a reference speed change produces a transient of i_{qs} which introduces an adaptation error, although the system was tuned initially.



Fig. 4. Adaptation behavior simulation during a reference change. Q Axis Voltage and Reactivate Power Dynamic Reference Models.

Figure 4 shows the behavior of \hat{k}_s for the dynamic reference models. The detuning characteristics introduced in this case is smaller than in the case of algebraic reference models. Comparing both results it can be notices that the dynamic references models have better behavior that their algebraic equivalent.



Fig. 5. Adaptation behavior simulation during a reference change. D Axis Voltage Reference Models.

Figure 5 shows the behavior of \hat{k}_s for the d axis voltage reference model. It is observed that their behavior is similar to the case of the dynamic reference models (figures 4), this allows to conclude that the detuning introduced in this case is not consequence of the transients of i_{qs} , but to other errors that are not included. So the derivative of i_{qs} was exactly predicted with the dynamic reference models.

7. Conclusion

In this work it were analyzed the effects of the i_{qs} transients in the performance of the adaptation by means of voltages and reactive power algebraic reference models.

Also, a dynamic model of the indirect field oriented induction motor that considers its transient behavior, dynamic reference models based on the voltages and in the reactive power were obtained.

Finally, a comparative analysis of the behavior of algebraic and dynamic reference models was presented, including the simulation results, which show an performance increase through these last ones.

References:

- [1].- F. Blaschke, "The Principle of Field Orientation ace Applied to New the Transvector Closed-Loop Control System for Rotating-Field Machines", Siemens Review, Vol.XXXIX, pp.217-220,1972.
- [2].- D. W. Novonty and P.C.Sen, "Introduction to Field Orientation and High Performance AC Drives", Tutorial course presented at IEEE Ind. Applic. Soc. Annual Meeting, Sep. 1986.

- [3].- R. Krishnan, F. C. They gild, "Study of Parameter Sensitivity in High-Performance Inverter-Fed Induction Motor Drive Systems", IEEE Trans. Ind. Appl, Vol. IA-23, pp. 623-635, Jul/Aug.1987.
- [4].- K. B. Nordin, D. W. Novonty and D. S. Zinger, "The Influence of Motor Parameter Deviations in Feed-forward Field Orientation Drive Systems", IEEE Trans. Ind. Appl., Vol. IA-21, pp. 1009-1015, July/Aug. 1985.
- [5].- R. Krishnan, A.S. Bharadwaj, "A Review of Parameter and Adaptation in Vector Indirect Controlled Induction Motor Drive Systems", IEEE Transaction or Power Electronics, Vol.6, pp. 695-703, Oct.1991.
- [6].- R. D. Lorenz and D. W. Novonty, "Saturation Effects in Field-Oriented Induction Machines", IEEE Trans. Ind. Appl., Vol. IA-26, pp. 283-289, Mar/Apr. 1990.
- [7].- L. J. Garcès, "Parameter Adaptation for the Speed Controlled Static AC Drive with to Squirrel-Cage Induction Motor", IEEE Trans. Ind. Appl., Vol. IA-16, pp. 173-178, Mar/Apr. 1990.
- [8].- K. Ohnishi, Y. Ueda and K. Miyachi, "Model Reference Adaptive System Against Rotor Resistance Variation in Induction Motor Drive", IEEE Trans. Ind. Elect. Appl., Vol. IE-33, pp. 217-223, Aug. 1986.
- [9].- R. D. Lorenz and D.B Lawson, "TO Simplified Approach to On-line Continuous Tuning of Field-Oriented Induction Machine Drives", IEEE Trans. Ind. Appl., Vol. 26, pp. 420-424, May/June. 1990.
- [10].- T. M. Rowan, R. J. Kerkman and D. Leggate, "A Simple On-line Adaptation for Indirect Field-Orientation of Induction Machine", IEEE Trans. Ind. Appl., Vol. 27, pp. 720-727, July/Aug. 1991.
- [11].- R. Reginatto, "Control por Campo Orientado Indireto do Motor of Indução com Adaptação of Parâmetros Via MRAC", M. Sc. Dissertation, LCMI, UFSC.
- [12].- H. Sugimoto and S. Tamai, "Secondary Resistance Identification of Induction - Motor Applied Model Reference Adaptive System and Its Characteristics", IEEE Trans. Ind. Applic., Vol. IA-23, pp. 296-303, March/April. 1987.

Annexes

Induction motor parameters: Three-phase induction motor, star connected, 220

Volt, 4 poles, 60 Hz, 1710 rpm. $X_m = 26.13 \Omega$, $X_s = 0.754 \Omega$, $X_r = 0.754 \Omega$

Symbols and Notations:

 v_{ds} , v_{qs} d and q axis Stator Voltages

 i_{ds} , i_{qs} d and q axis Stator Currents.

 i_{dr} , i_{qr} d and q axis Rotor Currents.

 λ_{ds} , λ_{qs} d and q axis Stator Fluxes.

 λ_{dr} , λ_{qr} d and q axis Rotor Fluxes.

c Supra index of the reference variables.

* Supra index of output of the ref models.

m Supra index of the variables of the dyn. models.

 w_{ρ} Synchronous frequency.

 w_r Rotor electric angular speed.

- w_{sl} Slip frequency.
- k_s Slip frequency gain.
- k_s^0 Tuning value of the slip frequency.
- \hat{k}_s Adaptation value of the slip frequency.
- *x* Detuning ratio.
- e_a Adaptation error.