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Online rotor time constant estimator for induction machines with optimum flux

Said Grouni[1,2] Rachid Ibtiouen[2] Madjid Kidouche[1] and Omar Touhami[2]
[1]*University M'Hamed Bougara -Laboratory of Applied Automation - Boumerdes*
[2] *High school Polytechnic Hassen Badi - Algiers*
Algeria

1. Introduction

Nowadays, the induction machines are used in many industrial applications due to their reliability, ruggedness and relatively low costs. These parameters are also attractive for use in the new generation of electrical transportation, ventilation and heating systems. With the development of control technology, these machines are being used now in variable speed drives applications. There are two forms of control vector or field oriented: direct field orientation, which need measurement or estimation of the rotor flux, and indirect field orientation, which use an inherent relationship. Though indirect field oriented control uses essentially the command reference rotor flux .Some recent works using the actual rotor flux are reported to achieve perfect decoupling (Blaschke, F. 1972; Bose, B. K. 2002; Leonhard, W. 1990; Vas, P. 1990).

The implementation of direct field oriented control via air gap flux measurement has typically been plagued by the complexities and lack of mechanical robustness associated with intrusive sensors located in machine air gap. Furthermore, a correction is required for the rotor leakage flux if the rotor flux field orientation is to be achieved. Estimation rather than measurement of the rotor flux is an alternative approach for both direct and indirect field oriented control that has received considerable attention (Holtz, J. 2006; Kennel, R. 2007; Krishnan, R. 2001).

In many popular implementations of field oriented induction machine drives, rotor flux is estimated from the terminal variables such as stator voltage and current measurements. Digital shaft position encoders are usually used to detect the rotor speed. Speed and flux sensors cause many problems, as degradation in mechanical robustness; high cost and volume lower the system reliability and require special attention to noise. In some special applications such as high speed control drives and hostile environment, difficulties arise in mounting these sensors (Bose, B. K. 2002; Holtz, J. 2006; Krishnan, R. 2001).

In the last decade, researches have been carried on the design of sensorless control schemes of induction machines. Most methods are based on the Model Reference Adaptive System schemes (MRAS) (Chang, G. W. et al. 2001; Marino, R. et al. 2008). In (Wang, et al. 2007) the authors used a reactive-power based reference model in both motoring and generating modes, but one of the disadvantages of this algorithm is its sensitivity to detuning the stator and rotor inductances. The basic MRAS algorithm is very simple but the greatest drawback is the sensitivity to uncertainties in the motor parameters (Chang, G. W. & Hespanha, J. P. et al. 2001; Marino, R. et al. 2008)

By using the advances of power electronics and Digital Signal Processing DSP technology, the control schemes of induction machine are developed from simple scalar control methods or auto-tuning control strategies to FOC and DTC. The Indirect Field Oriented Control (IFOC) is applied in real time control when dealing with high performance induction motors drives (El Refaei, et al. 2005; Holtz, J. and Thimm, T. 1991; Holtz, J. and Quan, J. 2002; Jeon, S.H., et al. 2002).

In high performance control, rotor time constant is a critical parameter for indirect field oriented control induction motor drives. Only recent works have aimed at filling in this gap by providing indirect field oriented control with a firm theoretical foundation. The influence of the rotor time constant mismatch on the stability of induction motors under indirect field oriented control. It has been shown that the speed control of induction motors through indirect field oriented control is globally asymptotically stable for any constant load torque if the rotor time constant is perfectly known or the estimated error is sufficiently small (Bezanella, A.S. and Reginetto, R. 2007; Chang, G. W. et al. 2001; Holtz, J. and Thimm, T. 1991; Matsuo, T. and Lipo, T. A. 1985).

The objective of this chapter is to present a high performance induction machines vector control that is robust against rotor time constant variations (Grouni, S., Ibtiouen, R. & Kidouche M. and Touhami, O. 2007). These variations are predicted and corrected by using the online estimator approach algorithm. This estimator is developed to simultaneously control flux and estimate rotor time constant. Simulation and experimental results are presented. In addition we consider the problem of analytically seeking a reference with optimum flux that minimizes total energy of induction machines.

2. Induction Machine Model and Control Problem Formulation

The induction machine mathematical model, in space vector notation, established in d-q rotating coordinates frame system is based on the Park's transformation. Dynamic models of induction machines are available in the literature (Bose, B.K. 2002; Krishnan, R. 2001). Parasitic effects such as hysteresis, eddy currents, magnetic saturation and others are generally neglected. Consider a state-space model of equations system related to the indirect method of vector field control is described below. In the rotating reference frame at synchronous speed ω_s , d-q-axis voltage equations are (Krause, P. 1986):

$$v_{ds} = R_s i_{ds} + \frac{d\varphi_{ds}}{dt} - \omega_s \varphi_{qs} \tag{1}$$

$$v_{qs} = R_s i_{qs} + \frac{d\varphi_{qs}}{dt} + \omega_s \varphi_{ds} \tag{2}$$

$$0 = R_r i_{dr} + \frac{d\varphi_{dr}}{dt} - (\omega_s - \omega)\varphi_{qr} \tag{3}$$

$$0 = R_r i_{qr} + \frac{d\varphi_{qr}}{dt} - (\omega_s - \omega)\varphi_{dr} \tag{4}$$

where ω_s and ω are the synchronous and rotor angular speeds.
In the same way, we define the stator and rotor fluxes by the following magnetic equations:

$$\varphi_{ds} = L_{ls} i_{ds} + L_m (i_{ds} + i_{dr}) = L_s i_{ds} + L_m i_{dr} \tag{5}$$
$$\varphi_{qs} = L_{ls} i_{qs} + L_m (i_{qs} + i_{qr}) = L_s i_{qs} + L_m i_{qr} \tag{6}$$
$$\varphi_{dr} = L_{lr} i_{dr} + L_m (i_{dr} + i_{qr}) = L_r i_{dr} + L_m i_{ds} \tag{7}$$
$$\varphi_{ds} = L_{lr} i_{qs} + L_m (i_{qs} + i_{qr}) = L_r i_{qr} + L_m i_{qs} \tag{8}$$

where L_{ls} , L_{lr} are the stator and rotor leakage inductances and L_m is the mutual inductance.

In d-q rotating reference frame components, the expressions of electromagnetic torque and mechanical speed are stated by:

$$C_{em} = p \frac{L_m}{L_r} (\varphi_{dr} i_{qs} - \varphi_{qr} i_{ds}) \tag{9}$$

where ***p*** is the pair pole number
This expression presents a high coupling between fluxes and electromagnetic torque.

$$J \frac{d\omega}{dt} + f_r \omega = C_{em} - C_r \tag{10}$$

From (7) and (8), d-q rotating reference frame the rotor currents are given:

$$i_{dr} = \frac{1}{L_r} (\varphi_{dr} - L_m i_{ds}) \tag{11}$$
$$i_{qr} = \frac{1}{L_r} (\varphi_{qr} - L_m i_{qs}) \tag{12}$$

Substituting (11) and (12) into (3) and (4) we get yields

$$\frac{d\varphi_{dr}}{dt} + \frac{R_r}{L_r} \varphi_{dr} - \frac{L_m}{L_r} R_r i_{ds} - \omega_{sl} \varphi_{qr} = 0 \tag{13}$$

$$\frac{d\varphi_{qr}}{dt}+\frac{R_r}{L_r}\varphi_{qr}-\frac{L_m}{L_r}R_r i_{qs}-\omega_{sl}\varphi_{dr}=0 \tag{14}$$

where $\omega_{sl}=\omega_s-\omega$ is the slip angular speed.

From (18), the electromagnetic torque is controlled only by q- axis stator current, and the rotor flux is controlled by d-axis stator current. In vector field oriented control we have :

$$\varphi_{qr}=0 \tag{15}$$

$$\frac{d\varphi_{dr}}{dt}=0 \tag{16}$$

$$\frac{d\varphi_{qr}}{dt}=0 \tag{17}$$

$$C_{em}=p\frac{L_m}{L_r}\varphi_{dr}i_{qs} \tag{18}$$

Substituting (15)-(17) into (3) and (11)-(14) it yields

$$i_{dr}=0 \tag{19}$$

$$i_{qr}=-\frac{L_m}{L_r}i_{qs} \tag{20}$$

$$\varphi_{dr}=L_m i_{ds} \tag{21}$$

$$\omega_{sl}=\frac{L_m}{T_r}\frac{i_{qs}}{\varphi_{dr}}=\frac{1}{T_r}\frac{i_{qs}}{i_{ds}} \tag{22}$$

$$T_r=\frac{L_r}{R_r} \tag{23}$$

in which:

ω is the rotor speed, T_r is the rotor time constant and (i_{ds}, i_{qs}) are the components of stator currents, ($\varphi_{dr},\varphi_{qr}$) are the rotor linkaqges fluxes, [(ω, i_{ds}, i_{qs}, $\varphi_{dr},\varphi_{qr}$) are the state variables] and (v_{ds}, v_{qs}) are stator voltages (control inputs). In reference frame the outputs to be controlled are the rotor speed, the rotor flux modulus tracking $(\varphi_{dr}^2+\varphi_{qr}^2)^{\frac{1}{2}}$ and the electromagnetic torque C_{em}.

3. Rotor Field Orientation Control

There are many categories of vector control strategies (Bose, B.K. 2002; Krishnan, R. 2001; Vas, P. 1990). We are interested in this work to indirect field oriented control (IFOC). We have shown in equation (9) that the electromagnetic torque expression, in the dynamic regime, presents a coupling between stator current and rotor flux. The main objective of the vector field oriented control of induction machines is to obtain the decoupling between flux and electromagnetic torque (Blaschke, F. 1972). This is done by using a d-q rotating reference frame at synchronous speed with the rotor flux is space vector orientation. The d-axis is aligned with the rotor flux space vector. Under this condition we have; $\varphi_{dr} = \varphi_r$ and $\varphi_{qr} = 0$, rotor flux has only the real component which is constant in steady state. In this case, combining equations (13), (14) and (22), we obtain the following references:

$$i_{ds}^* = \frac{1}{L_m}\left(T_r \frac{d\varphi_r^*}{dt} + \varphi_r^*\right) \tag{24}$$

$$i_{qs}^* = \frac{L_r}{pL_m}\frac{T_e^*}{\varphi_r^*} \tag{25}$$

$$\omega_{sl}^* = \frac{L_m}{T_r}\frac{i_{qs}^*}{\varphi_r^*} \tag{26}$$

The function of electromagnetic torque with the reference slip speed frequency is:

$$C_{em} = p\frac{\varphi_r^{*2}}{R_r}\omega_{sl}^* \tag{27}$$

These equations are functions of some structural electric parameters of induction machines (R_s, R_r, L_s, L_r, L_m), which are in reality approximate values. We will come back thereafter to the influence of the rotor time constant parameter T_r. In this control method, the electromagnetic torque C_{em}^* and flux φ_r^* are used as references signals and (i_{ds}, i_{qs}) are the stator currents as control inputs variables (Bose, B. K. 2002; Krishnan, R. 2001; Vas, P. 1990).
The dynamic model represented in equations (1)-(4) is applied with pulse width modulation (PWM) voltage or current control inverter. The schematic block diagrams of a real control system are represented in figures 1 and 2. The following models of control are used on closed loop in field oriented control systems which depend on the loading conditions.

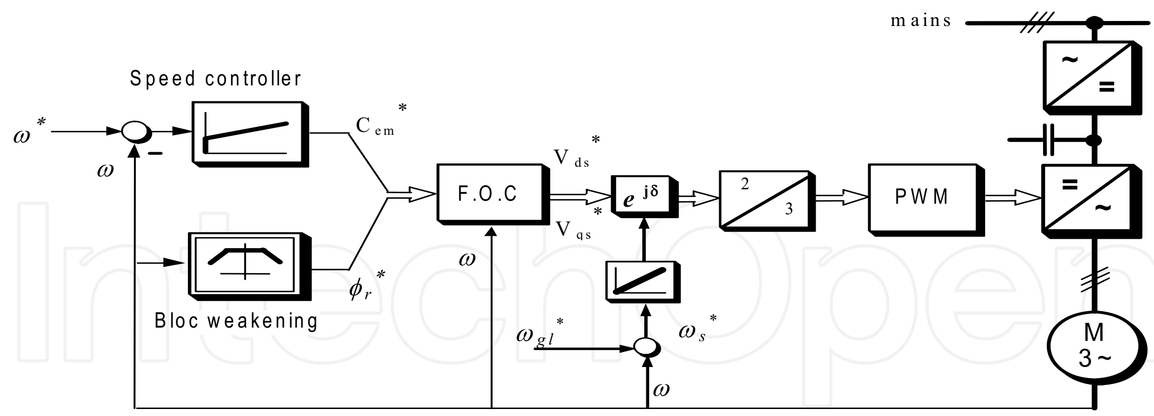

Fig. 1. Block scheme of indirect field oriented control on voltage control inverter

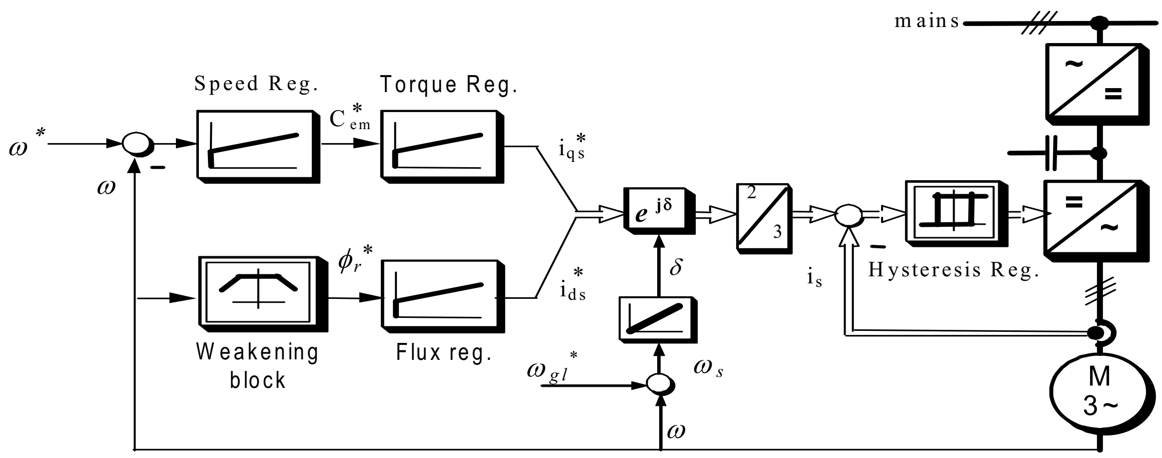

Fig. 2. Block scheme of indirect field oriented control on current control inverter

The current and voltage controls of indirect field oriented control are represented in Figures 3 and 4. It is noticed that the decoupling flux is maintened null in q-axis rotor flux. The fluxes circular locus show a good improvement of the proposed control.

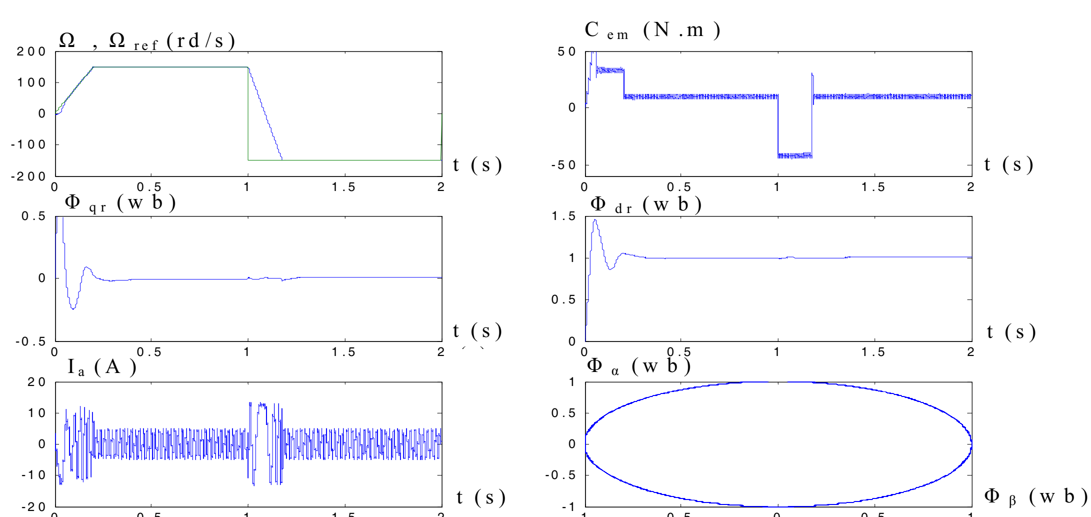

Fig. 3. Simulation results with current control inverter

With respect to the proposed control, the speed response follows perfectly the reference speed while the curves of torque show good dynamic behavior for both transient and steady state. The stator current waveform shows a fast rise time response.

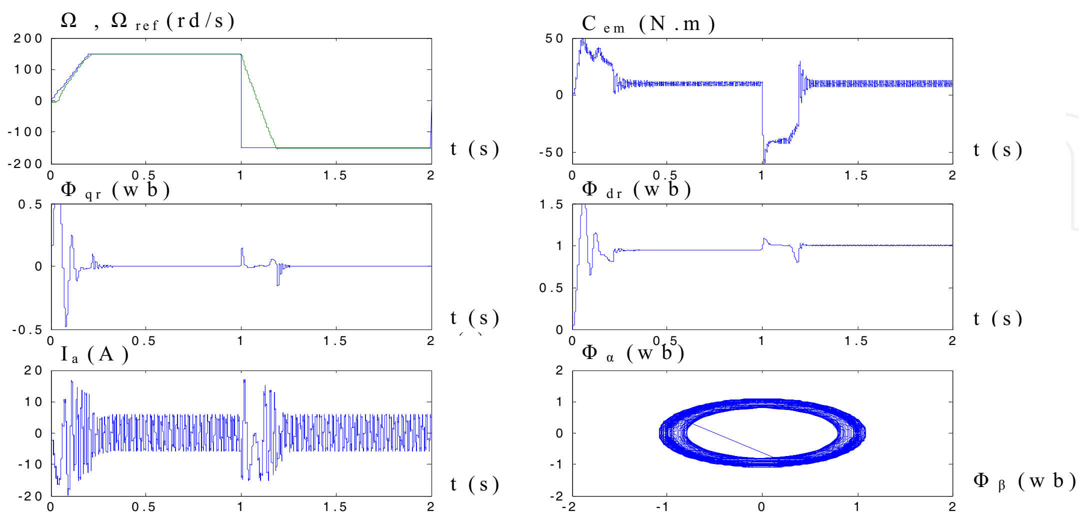

Fig. 4. Simulation results with voltage control inverter

4. Online Rotor time constant estimator

As stated in the introduction, the interest study is in online tracking of the value of rotor time constant T_r as it changes due to ohmic heating. The electrical parameters L_s, L_m, and σ are assumed to be known and constant. Measurements of stator currents and voltages as well as the position of the rotor are assumed to be also known; velocity is then deduced from the position measurement. The influence on rotor time constant variation is an important parameter for studying the dynamic response and robustness of control particularly for the stability of a system (Bezanella, A. S. et al. 2001; Chang, G. W. et al. 2001; Marino, R., Tomei, Verrelli, C. M. 2008).

4.1 Variation effect of rotor time Constant (9 pt, bold)

Several research tasks (Bezanella, A. S., Reginetto, R. 2001; Holtz, J. & Thimm, T. 1991; Jeon, S. H. et al. 2002; Marino, R., Tomei, Verrelli, C. M. 2008; Matsuo, T. & Lipo, T. O. 1985; Novotny, D. & Lorenz, R. 1986) and (Wensen, Wang, et al. 2001,) showed that effectiveness of the control in oriented flux depend strongly on the knowledge and accuracy of the machine parameters. The simulation of mathematical equations given by (28) and (29) are plotted in Figure 5.

$$\frac{C_{em}}{C_{em}^*} = \frac{T_r}{T_r^*} \frac{1+\left(\frac{i_{qs}^*}{i_{ds}^*}\right)^2}{1+\left[\left(\frac{T_r}{T_r^*}\right)\left(\frac{i_{qs}^*}{i_{ds}^*}\right)\right]^2} \tag{28}$$

$$\frac{\varphi_r}{\varphi_r^*} = \left[\frac{1+\left(\frac{i_{qs}^*}{i_{ds}^*}\right)^2}{1+\left[\left(\frac{T_r}{T_r^*}\right)\left(\frac{i_{qs}^*}{i_{ds}^*}\right)\right]^2}\right]^{\frac{1}{2}} \tag{29}$$

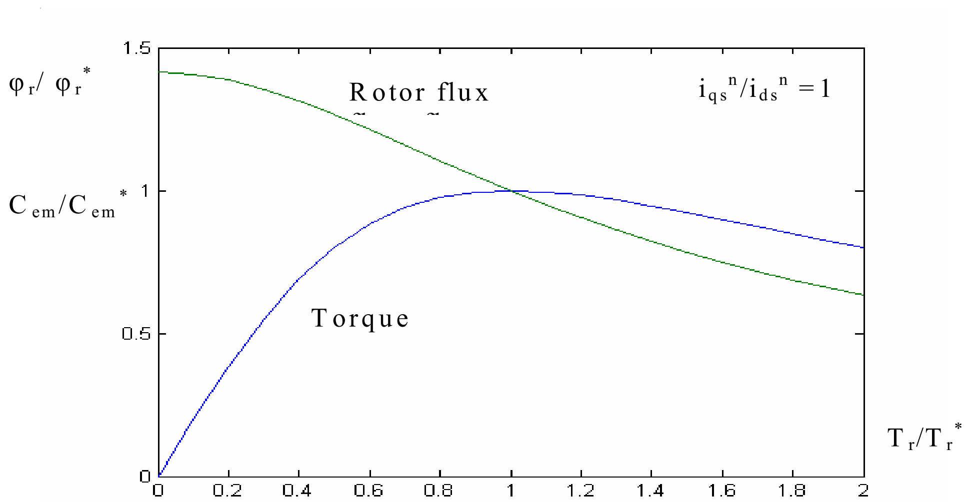

Fig. 5. Detuning of steady-state effect parameter of flux and torque current commands

These curves show that the actual value of the rotor time constant is smaller than the predicted (T_r/T_r^* <1). The identification method of rotor time constant is studied and simulated.

4.2 Rotor time constant estimation according to Garces method

The simulation results in Figure 6 have shown the estimation method according to Garces based on the comparison of two expressions of the machine reactive power (Garces, J. L. 1980; Okuyama, T. Nagase, H., Kubota, Y., et al. 1983). The simulation results applied for low load represent a good dynamic behavior for both transient and steady state responses in large scale of time. The flux curves show the decoupling between torque and flux, and (α, β) axis of rotor fluxes show clearly circular locus. The control drives are applied for resistant torque value C_r = 2 *N.m* while speed and torque show a good dynamic behavior.

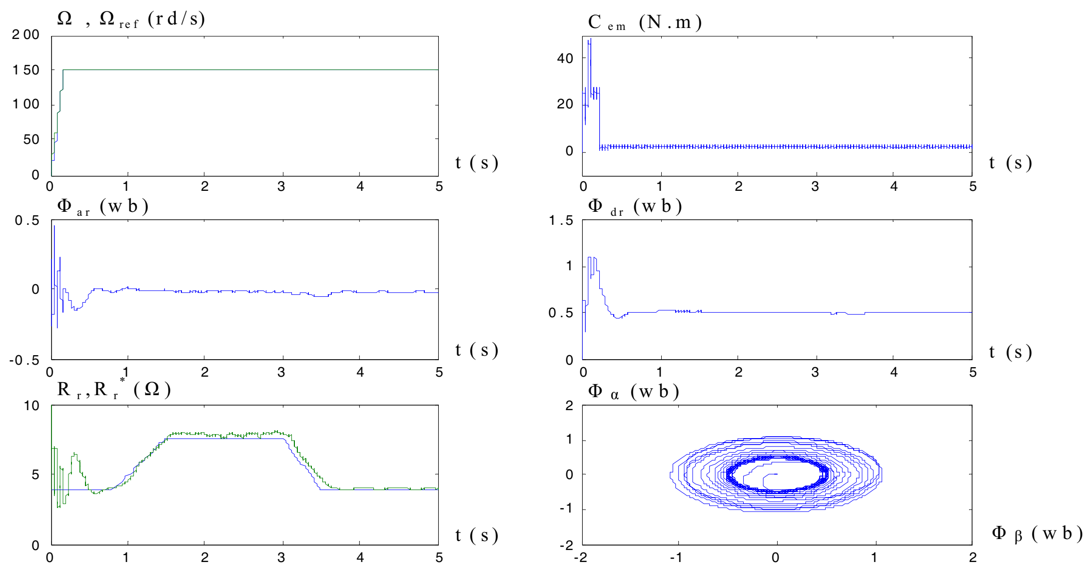

Fig. 6. Simulation results of Adaptation T_r for C_r=2 *N.m* for flux variation

4.3 Estimation approach of rotor time constant with optimum flux

The estimation approach of rotor time constant is based on error signal of real and optimum rotor flux. This approach has been used to optimize rotor flux for optimum control trajectory tracking. It depends largely on the machine parameters where optimum rotor flux is function of copper loss minimization (Grouni, S., Ibtiouen, R. & Kidouche, M. and Touhami, O. 2008):

$$\varphi_r = f(C_{em}) \tag{30}$$

Optimum control of rotor flux is calculated by using equation:

$$u_1^{opt} = \frac{L_r}{R_r L_m}\left(\frac{d\varphi_r^{opt}}{dt} + T_r \varphi_r^{opt}\right) \tag{31}$$

Developing this expression, and calculating optimum flux according to the function of electromagnetic torque, we get the following expression:

$$\varphi_r^{opt} = \beta\sqrt{|C_{em}|} \tag{32}$$

$$\beta = \left(\frac{R_s L_r^2 + R_r L_m^2}{p^2\left(R_s + R_f\right)}\right)^{\frac{1}{4}} \tag{33}$$

where R_f is the resistance of copper and p number of pole pair of machine.

The d-axis component of rotor flux φ_{dr} is used to identify the rotor resistance and the slip speed frequency which is calculated from the error signal of rotor flux. In steady state, the expression of estimated signal (S) is defined as follows:

$$S = \varphi_{dr} = \frac{V_{qs} - R_s i_{qs}}{\omega_s} - \sigma L_s i_{ds} \tag{34}$$

The reference signal S^* is defined as:

$$S^* = \varphi_{dr}^* = \varphi_{dr}^{opt} \tag{35}$$

The expression of estimated stator resistance is given by the following equation:

$$R_s = \frac{V_{ds} + \omega_s i_{qs}\left(\sigma L_s + L_m\right) + L_m i_{qr}}{i_{ds}} \tag{36}$$

The control scheme presented is shown as a dotted block in figure 7. This is used to improve the estimator of rotor time constant with optimum flux.

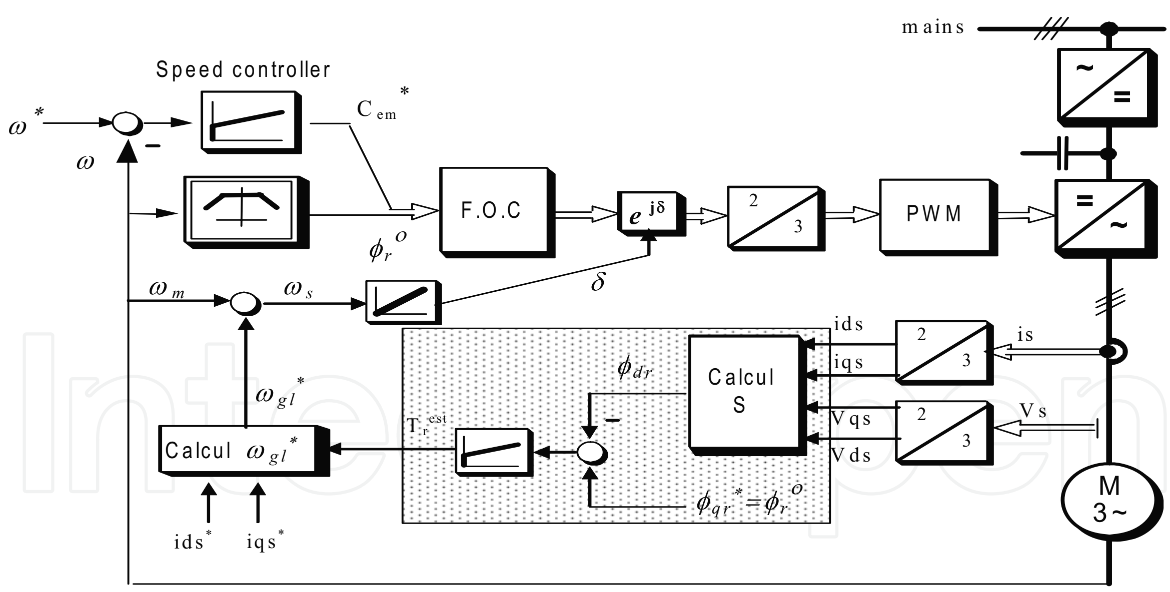

Fig. 7. Block scheme diagram of online estimator T_r with optimum flux

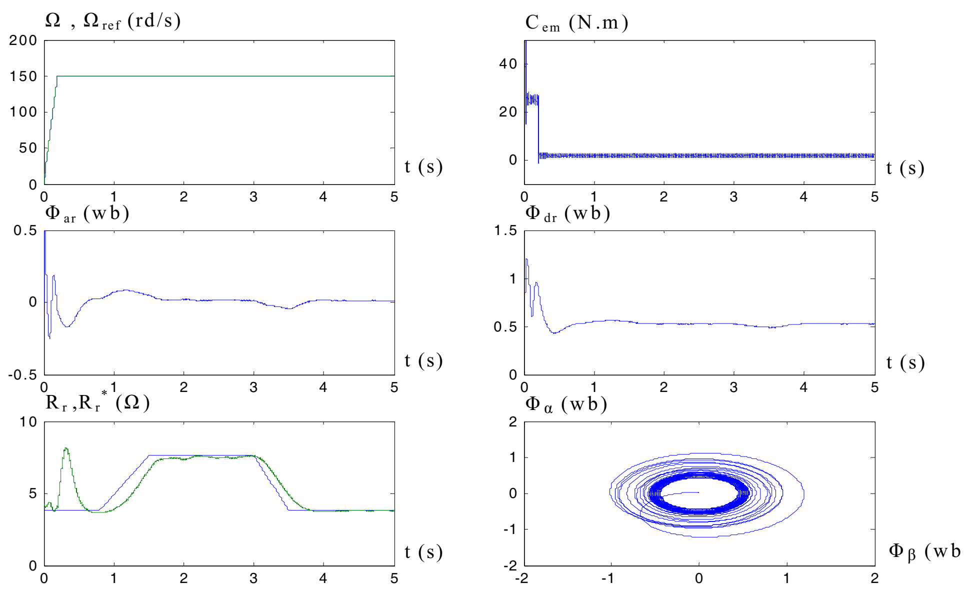

Fig. 8. Simulation results of rotor time constant with optimum flux

We have tested the proposed scheme diagram with the estimation approach of rotor time constant. The responses of rotor flux and electromagnetic torque show that the decoupling is maintained. The speed signal has a good dynamic behavior in transient and steady state. The response follows perfectly the reference. The estimation approach has obtained a perfect response behavior of rotor time constant in large scale of time.

5. Conclusion and Further Research

In this chapter, we have presented the estimation approach of rotor time constant variation with optimum flux. The Garces method is applied for several applications of load torque. The estimation approach predicts and tune the rotor time constant to the actual value rapidly. Now, it is possible to say that this approach can be applied to reduce losses in low load application for induction machines. Further research can address the effectiveness rotor time constant which remains an important parameter for stability and robustness in high application vector controlled machines in presence of load disturbance.

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This book provides an overview of subjects in various fields of life. Authors solve current topics that present high methodical level. This book consists of 13 chapters and collects original and innovative research studies.