Speed Control of Induction Motors with Loss Minimization

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Abstract— **This work presents a study of the induction motor losses in steady state (cooper and iron losses) aiming at the speed control of the machine with maximum efficiency. The classical loss model is used, with a different parameterization in terms of the magnetic parameters of the motor, its speed and slip velocity. The present work is an extension of a previous one [7] where a scalar speed controller with loss minimization is proposed. In the present work, we extend the previous results by characterizing the optimum efficiency of the machine in terms of an optimal slip velocity which is a function of the rotor speed. Some simulated and experimental results are shown which attest the feasibility of the proposed approach.**

Keywords— **Induction motor, maximum efficiency, speed regulation**

I. Introduction

There are basically two types of application of induction motor drives with variable speed: 1.) Heath, Ventilation and Air-Conditioning - HVAC, and 2.) Torque Control [1], [5]. The first application has "well behaved" loads, on one hand, and demands less accuracy than the second one. Applications, when torque control is needed, deal with highly unpredictable loads and demand higher accuracy in terms of speed (or position). This work is concerned with the first type of application, HVAC, which represents the major part of them. In this case, the control strategy can be either scalar or field oriented.

Keep the motor operating at maximum efficiency means to find the optimum relationship between flux and current which guarantees, on one side, the demanded torque, and on the other side, the minimum loss of the machine. This can be expressed in various ways as can be seen in recent papers [1], [4], [2], [6]. In [6] it has been proposed the slip velocity as the degree of liberty in choosing flux and current to achieve a certain demanded torque. The main advantage of such choice is that the slip velocity is an appropriate variable when speed control is aimed. Therefore what is at stake then, is the calculation of the optimum slip velocity for a given torque and mechanical speed. It was considered in [7] that a constant slip velocity, optimum to an average rotor speed, would ameliorate in a great extent the efficiency of the machine despite the fact that it was not optimum for speeds different from the average.

In the present work this assumption is relaxed by taking in account the impact of the rotor speed in determining the optimum slip velocity. Control schemes, either scalar or field oriented, which incorporate this optimum efficiency are shown. Finally, some previous experimental results with a scalar control scheme are provided.

II. Induction motor modelling

The synchronous $(d-q)$ reference frame has been considered for the modelling, due to the facility of deriving steady state operating conditions. The state space equations of the electrical dynamics of the motor are the following:

$$\begin{aligned}\frac{\mathrm{d}}{\mathrm{dt}}\begin{bmatrix} i_s \\ \lambda_s \end{bmatrix} &= \begin{bmatrix} -a\mathbf{I}-\boldsymbol{\omega}_{\mathbf{s}}\mathbf{J} & \mathbf{I}-\frac{\mathbf{p}\boldsymbol{\omega}_{\mathbf{r}}\mathbf{c}}{\mathbf{2}}\mathbf{J} \\ -R_s\mathbf{I} & -\omega_e\mathbf{J} \end{bmatrix}\begin{bmatrix} i_s \\ \lambda_s \end{bmatrix} \\ &\quad + \begin{bmatrix} c\mathbf{I} \\ \mathbf{I} \end{bmatrix} V_s, \end{aligned} \tag{1}$$

where

$$\mathbf{J} := \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}, \; \mathbf{I} := \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

and $\lambda_s := \begin{bmatrix} \lambda_{ds} & \lambda_{qs} \end{bmatrix}^T$, $i_s := \begin{bmatrix} i_{ds} & i_{qs} \end{bmatrix}^T$, $i_r := \begin{bmatrix} i_{dr} & i_{qr} \end{bmatrix}^T$ and $V_s := \begin{bmatrix} v_{ds} & v_{qs} \end{bmatrix}^T$ are the two elements vectors representing stator flux, current and voltage; $\omega_e := \frac{p}{2}\omega_r + \omega_s$ and ω_s, are the synchronous and the slip velocity, ω_r, the rotor angular velocity, R_s, R_r, are the stator and rotor resistances, and the parameters

$$\begin{array}{ll} a := R_s/\sigma L_s + R_r/\sigma L_r & , \; b := R_r/\sigma L_r L_s \\ c := 1/\sigma L_s & , \; \sigma := 1 - M^2/(L_s L_r), \end{array}$$

where, L_s, L_r e M, are the stator and rotor self inductances and mutual inductances, respectively.

The electromagnetic torque of the induction motor is given as

$$\tau_m := \frac{p}{2}\left(i_{qs}\lambda_{ds} - i_{ds}\lambda_{qs}\right) = \frac{pM}{2L_r}\left(i_{qs}\lambda_{dr} - i_{ds}\lambda_{qr}\right) \tag{2}$$

where p is the pole number.

Consider also the following linear relationship:

$$\begin{aligned} \lambda_s &= \sigma L_s i_s + \tfrac{L_{sr}}{L_r}\lambda_r \\ \lambda_r &= L_{sr} i_s + L_r i_r \end{aligned}$$

where λ_r and i_r are the rotor flux and current vectors.

A. Motor losses at steady state

The steady state operation of an induction motor corresponds to $\frac{\mathrm{d}}{\mathrm{d}t} i_s = 0$ and $\frac{\mathrm{d}}{\mathrm{d}t}\lambda_s = 0$ in Eq. (1). Using this fact and manipulation the equations in (1) it is possible, as it has been done in [7], to obtain interesting relationships between torque, current, voltage and flux which bring forth nice characteristics of the machine. Consider the following relations and definitions:

$$\begin{aligned}
&\phi_r = \frac{MRr}{\sqrt{L_s^2R_r^2+\sigma^2L_s^2L_r^2\omega_s^2}}\phi_s,\ \phi_r := \sqrt{\lambda_{dr}^2+\lambda_{qr}^2},\\
&\phi_s := \sqrt{\lambda_{ds}^2+\lambda_{qs}^2}\\
&I_s^2 = \frac{2\left(\omega_s^2+(R_r/L_r)^2\right)}{pR_r(M/L_r)^2\omega_s}\tau_m \quad , \quad I_s := \sqrt{i_{sd}^2+i_{sq}^2}\\
&\phi_r^2 = \frac{2R_r}{p\omega_s}\tau_m \qquad , \quad I_r := \sqrt{i_{rd}^2+i_{rq}^2}
\end{aligned} \tag{3}$$

Through some algebraic manipulation and model insight it is possible to come up with the following relationship (see [7] for details):

$$\tau_m = \begin{cases} \frac{p\omega_s}{2R_r}\phi_r^2 \\ \frac{pR_r(M/L_r)^2\omega_s}{2\left(\omega_s^2+(R_r/L_r)^2\right)} I_s^2 \\ \frac{p\beta(1-\sigma)\omega_s}{2\sigma L_s(\beta^2+\omega_s^2)}\phi_s^2 \end{cases} \tag{4}$$

where $\tau_m = \frac{pM}{2L_r}\left(i_{qs}\lambda_{dr} - i_{ds}\lambda_{qr}\right) = \frac{pM}{2L_r} I_s\phi_r \sin(\delta)$ and $\beta = R_r/(\sigma L_r)$.

III. Minimum loss and speed regulation

As it has mentioned before in this text, minimum loss is achieved by finding the appropriate amount of flux and current on the motor for a given demanded torque and rotor speed. The purpose of the present work is to obtain a more accurate criterion for optimum loss steady state operation of the motor. This will be done by obtaining the optimum slip frequency for a given operation state.

In a previous work, this study has been carried to the point of obtaining the expression for the total power loss of the machine, given as a function of the motor parameters, the electromagnetic torque, the slip and the rotor speed [7]. Some results have been obtained by adopting a constant slip velocity while performing the speed regulation.

A. The induction motor losses

Consider the following simplified loss model for the induction motor [3], assuming sinusoidal flux in a limited frequency range:

$$P_l = \left[R_s I_s^2 + R_r I_r^2 + K_h\omega_e\phi^2 + K_e\omega_e^2\phi^2\right] \tag{5}$$

where I_r and I_s are the rotor and stator currents as defined in (3), K_h and K_e are the hysteresis and eddy current loss coefficients. ϕ, is the air gap flux which satisfies:

$$\phi \simeq \frac{M}{L_r}\phi_r = \frac{M^2Rr}{L_r\sqrt{L_s^2R_r^2+\sigma^2L_s^2L_r^2\omega_s^2}}\phi_s\ .$$

It has been shown in [7] that, for steady state operation, (5) can be written in terms of the electromagnetic torque, the motor parameters and the rotor velocity as:

$$\begin{aligned}
P_l = \tau_m \{&\left[c_1 + c_{ke2}\right]\omega_s + \\
&\left[c_1c_2 + c_3 + c_{kh}\omega_r + c_{ke1}\omega_r^2\right]\frac{1}{\omega_s} + \\
&+2c_{kh}/p + c_{ke2}\omega_r p - d_1\sqrt{1+d_2/\omega_s^2}\}
\end{aligned} \quad , \tag{6}$$

where

$$\begin{aligned}
&c_1 = \frac{2}{p}\left[\frac{R_s}{R_r}\left(\frac{L_r}{M}\right)^2 + 1\right], && c_2 = \left(\frac{R_r}{L_r}\right)^2,\\
&c_3 = \frac{2}{p}\left(\frac{R_r}{L_r}\right)^2, && c_{kh} = K_hR_r\left(\frac{M}{L_r}\right)^2,\\
&c_{ke1} = K_eR_r\frac{p}{2}\left(\frac{M}{L_r}\right)^2, && d_1 = \frac{4R_r}{pL_r}\ ,\\
&c_{ke2} = K_eR_r\frac{2}{p}\left(\frac{M}{L_r}\right)^2, && d_2 = \left(\frac{R_r}{L_r}\right)^2 - 1.
\end{aligned}$$

Note the Eq. (6) is convex in ω_s, for a given rotor speed ω_r. This implies that optimum value for the slip frequency, ω_s^*, can be obtained by making $\partial P_l/\partial\omega_s = 0$. The derivative of (6) is given as

$$\begin{aligned}
\partial P_l/\partial\omega_s \ &= \ (c_1 + c_{ke2}) + \frac{d_1d_2}{\omega_s^2\sqrt{\omega_s^2+d_2}}\\
&-\frac{1}{\omega_s^2}(c_1c_2 + c_3 + c_{kh}\omega_r + c_{ke1}\omega_r^2)
\end{aligned} \tag{7}$$

Making (7) equal to zero gives:

$$(c_1 + c_{ke2})\omega_s^2 + \frac{d_1d_2}{\sqrt{\omega_s^2+d_2}} = (c_1c_2 + c_3 + c_{kh}\omega_r + c_{ke1}\omega_r^2) \tag{8}$$

Solving Eq. (8) gives the optimum slip frequency, *i.e.*, the value of ω_s which minimizes (6), for each rotor speed, ω_r.

Figure 1 shows ten different loss curves (6) as functions of ω_s, for a constant load torque, τ_m, of 1 N.m and for ten different speed, ranging from zero to 200 rad/s, in constant intervals of 20 rad/s. The motor used in simulation has the following parameters: Rated power: 1.5 kW; Pole pair no.: 2, Rated speed: 1430 rpm , Rated voltage: 220 V, Rated current: 6.1 A, Rated $\cos(\phi)$: 0,82; Electrical parameters: $R_s = 1.47\ \Omega$, $R_r = 0.79\ \Omega$, $L_s = 0.105\ H$, $L_r = 0.094\ H$, $M = 0.094\ H$, $K_h = 0.00191\ W.s/Wb^2.rad$, $K_e = 0.00191\ W.s^2/Wb^2.rad^2$;

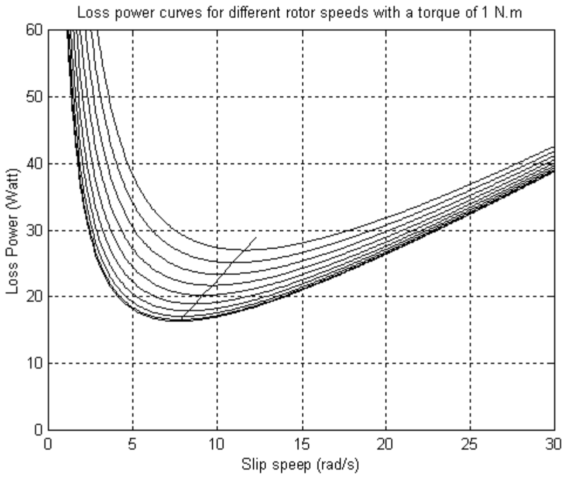

Fig. 1. The total motor loss as a function of the slip speed for ten different rotor speed

Figure 2 (a) shows the optimum ω_s, versus the rotor speed, ω_r. It suggests us to use a linear relationship, given as:

$$\omega_s^* = \omega_r \sqrt{\frac{c_{ke1}}{(c_1 + c_{ke2})}} + \omega_{s0} = k_o \omega_r + \omega_{s0} \qquad (9)$$

which is the approximation of (8) when $\omega_s, \omega_r \gg 1$. This is a quite reasonable assumption given that, as the speed gets lower and lower, so does the load, and therefore, the optimum value of flux tends to zero. This is something to be avoided, by restraining the flux to a minimum reference value. It will be discussed in the next section.

Finally, Figure 2 (b) shows the optimum rotor flux as a function of the rotor speed, for a constant 1 N.m magnetic torque. It can be clearly seen the optimum stator flux tends to decrease as the rotor speed increases.

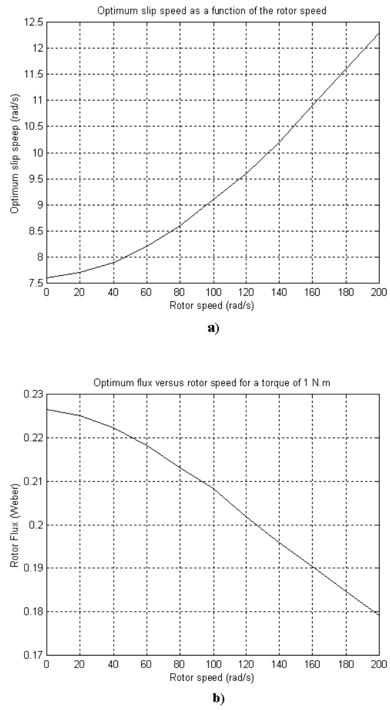

Fig. 2. (a) Optimum slip speed as a function of rotor speed; (b) Optimum rotor flux as a function of the rotor speed

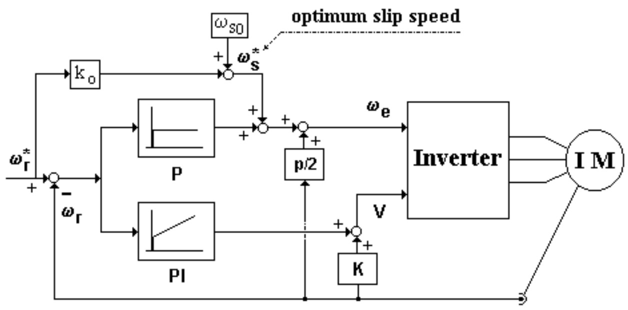

Fig. 3. Block diagram of the scalar controller with minimum loss

B. Control strategies taking minimum loss into account

For the HVAC type of application considered here, a scalar control strategy is a simple and sufficient alternative for the speed control of induction motor drives. Figure 3 shows a feasible controller which takes into account loss minimization. Here, the optimum value ω_s^* is taken to be a linear function of ω_r, as in (9).

As it has been mentioned in [7], the main difference between standard U/f controllers is that, in that case, flux is kept constant, around its rated value for all speed and load conditions, whereas, in our case, the flux is adjusted with respect to the rotor speed and motor load as to assure minimum electrical losses.

The main drawback of such an strategy is that the impulse torque available when the flux is low, is also low. This should not be a serious problem when talking of HVAC applications. Nevertheless, in the scalar scheme presented in Figure 3, a rather larger motor torque is guaranteed during speed transitions via the P action which, as long as the speed error persists, varies the slip frequency in order to achieve torque. When the desired speed is attained, the sleep frequency will accommodate to its optimum value.

The slip speed is to be understood as the degree of freedom in choosing pairs of current and flux sets (as we speak of three-phase motors) which give a desired torque. Therefore, for a certain torque there is a combination of flux and current which is optimal.

An other point to be made is that, the lower the load is, the larger is going to be the saved energy using this optimum criterion. In other words, when the motor is operating below 60% of its rated load capacity, the impact in operating with optimum flux will be greater [1]. When delivering near rated torques, the optimum flux will be close to its rated value, in most of the cases.

The same ideas can be easily incorporated into vector control approaches, even in *sensorless* controllers of induction motors. This can be done by generating a flux reference which varies (slowly) with load and speed, as in the scalar case, leading to an optimum motor operation at steady-state, in terms of electrical losses. A vector control approach with minimum loss is depicted in Figure **??** where a *sensorless* speed control scheme is presented. The flux and speed estimator follows the approach presented in [8]. Although the purpose of this paper is not to focused in the sensorless vector control of the induction machine, some details of the simulation will be presented here. The main idea of the decoupled control of flux and torque of the vector control is kept, when working with stator current and flux in the synchronous frame as the machine variables. In the speed loop the desired i_{qs}^* is derived through a PI, then the correspondent voltage, $V_{qs'}$ is obtained through a second PI. The decoupler term is then added to obtain the necessary V_{qs}. In the flux loop, it is the optimal slip frequency rather than the reference flux which determines the desired V_{ds}, which is obtained thorough a PI plus the voltage drop on the stator resistance, R_s. This voltage corresponds to the minimum loss power as derived in (9). Finally, the voltages fed to the motor are obtained from a reference frame transform, based on the *sensorless* flux estimator, which derives de desired voltage space vector in the stationary frame and then, the correspondent PWM.

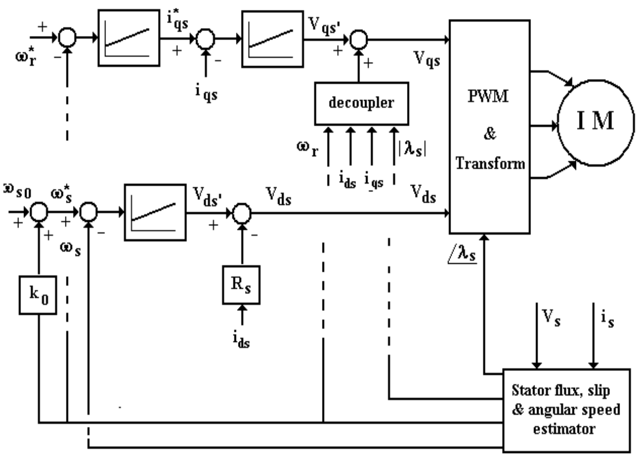

Fig. 4. Sensorless speed control block diagram with optmized efficiency

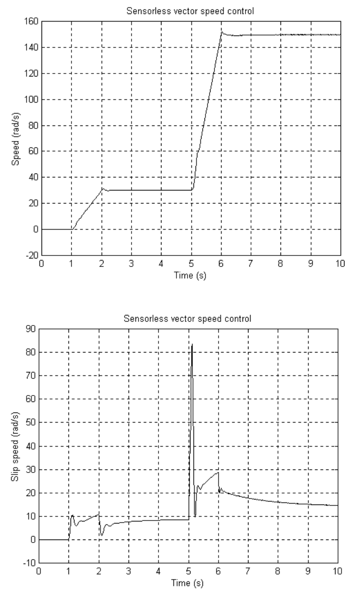

Fig. 5. Speed response (up) and the slip speed response (down)

IV. Simulation and Experimental Results

A. Simulation of the Sensorless Control

Simulations were made using this scheme applied to a 1.5 kW, 4 pole machine whose parameters are given at the end of Section III-A. First, a speed ramp from 0 to 30 rad/s was imposed, from 1 to 2s, then a second speed ramp from 30 to 150 rad/s was imposed from 5 to 6s. Figure 5 shows the speed response and the slip speed. It can be noticed that during the sped transient, there is no imposition of the optimal slip speed whereas, when the speed and the load are kept constant, the slip speed tends smoothly to its optimal reference.

The effect of regulating the slip speed is noticed in the stator flux of the machine, as shown in Figure 6 where, in the upper part are shown the stationary frame orthogonal currents and in the lower part, the stator fluxes. It can be seen that the fluxes accommodate in values which are optimal in terms of efficiency, with respect to the speed and the machine load or delivered power.

As for the motor load, a quadratic load with the motor speed has been such that, for nominal speed, nominal load torque is achieved. It can be seen in Fig. 7 where the electromagnetic torque of the motor is shown.

Finally, the total and the loss power are shown in Fig. 8 where, in the upper part these powers are shown with respect to the first speed ramp and in the lower part, with respect to the second speed ramp. Notice that, different from the conventional vector control approaches, the loss power is relatively small when the load torque is small because, in this case, the optimum flux is also small, reducing both the core losses and the current necessary to maintain flux. Whenever magnetic torque is demanded from the load, the flux is corrected to achieve optimum efficiency, as it can be seen when speed is increased from 30 to 150 rad/s and the load torque from less than 1 to 16 N.m.

B. Experimental results with the Scalar Control

In order to illustrate the proposed technique, some experimental tests have been made. It was not possible to validate the simulated results shown in [7], where a scalar control approach has been proposed, with respect to the amount of power gained with our approach, because the experimental setup was not ready yet to measure and separate losses and mechanical power. The

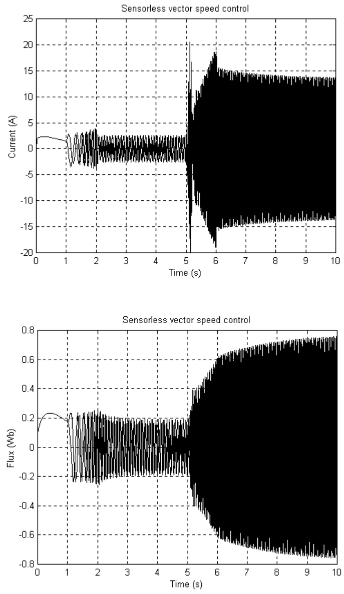

Fig. 6. Orthogonal stationary frame currents (up) and orthogonal stationary frame stator fluxes (down)

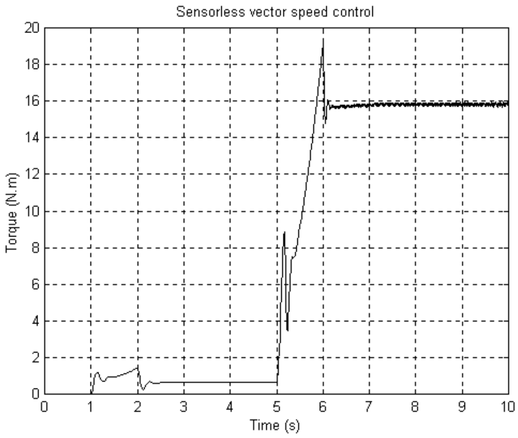

Fig. 7. Eletromagnetic motor torque, τ_m

preliminary results shown here, verify two important aspects of the control: i) its stability in the presence of load perturbations; ii) the lower voltage levels when in steady-state, for the optimum control.

These experimental tests are quite simple. First, a reference speed ramp was established for both, a standard scalar controller and the optimum scalar controller. Fig. 9 shows the speed response when optimum sleep frequency is (optimum flux) is applied, and the respective low supplied voltage level in the motor. When conventional scalar control is used, the speed response and the voltage level are shown in Fig. 10. Notice that in this case the motor is with no load.

Next, Figure 11 shows the motor speed response when load disturbances are applied to the motor in the case of regular and optimum scalar control. What we notice here is that, in the optimum scalar control case, the

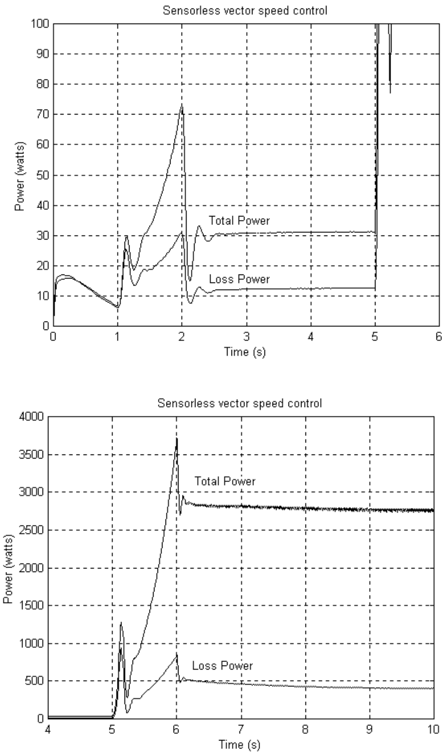

Fig. 8. Total and loss power for the first speed ramp (0 - 30 rad/s) in the upper part and to the second speed ramp (30 - 150 rad/s) in the lower part

flux levels are very low when the motor is operating with very light load. The impulse torque is also low. This explains the poorer dynamic performance of the optimum scalar control when compared to the standard one. Nevertheless, the optimum controller is shown to be robust.

V. Conclusions

An approach to obtain the speed regulation of the induction motor including loss minimization has been presented. The total motor losses include hysteresis, eddy current and cooper losses, given in a standard model. It has been shown that, for a given torque and rotor speed there exists an optimum slip frequency which minimizes the motor losses. Furthermore, the relationship between the optimum slip and rotor speeds tends to be practically linear for speed not close to zero. Having that in mind, two speed regulation schemes have been proposed which incorporate this optimization feature. One of them is a scalar type speed control and the other is

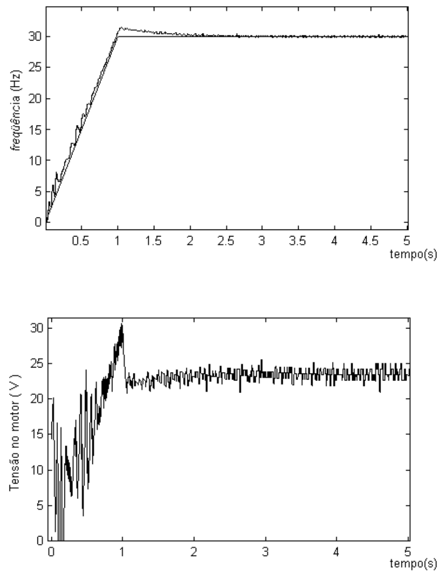

Fig. 9. Speed response and voltage level of the optimum scalar control

a *sensorless* vector speed control. Simulation results of this last approach were presented.

The work is complemented with some experimental results for the scalar speed control, which show the approach robustness with respect to load perturbation.

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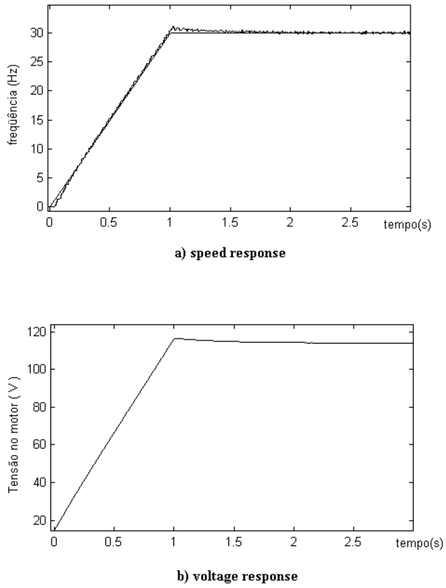

Fig. 10. Speed response and voltage level of the stardard scalar control

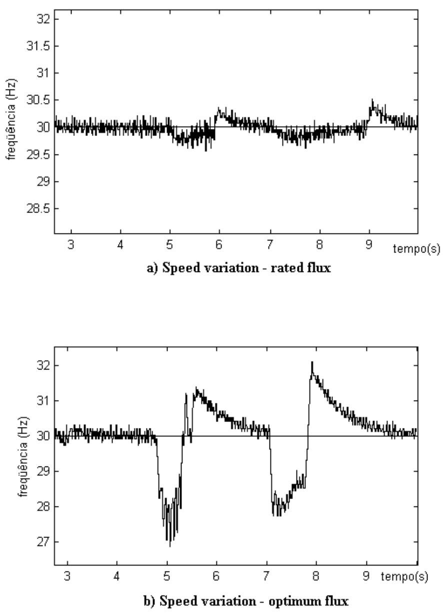

Fig. 11. Motor speed variation due to load disturbance