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Modified Vector Control for Saturated Induction Machine by considering a series iron losses equivalent circuit

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Abstract: - Vector controlled induction machine drives are increasingly used in industrial drive systems, but the drive performance often degrades with the machine parameter variations. In this paper, a modified vector control system is proposed to achieve decoupling when saturation and iron losses are taking into account. The simulated and experimental results of the modified controller are presented to verify the effectiveness of the proposed approach.

Key-Words: Induction machine, modified vector control, iron losses, saturation

1. Introduction

The vector control system of an induction motor requires well known motor parameters. To perform this type of control, a Park transformation is used. Unfortunately, a highly coupling between the two axis remains. Moreover, depending on the operating point, the electric parameters vary. A phenomenon's such as: saturation, heating, iron losses or deep bar etc, can be considered as the main causes of errors [1].

Saturation, as one of the parameter variation causes, is a subject of considerable interest; its modelling has been investigated by various authors [1-4]. All of them propose that the magnetising inductance should be a function of magnetising current, and hence, different models have been established. It is shown that saturation causes additional coupling in dynamic equations of the machine. A number of schemes derived from developed models have been proposed to compensate the effect of saturation [5,6]. In addition, iron losses, as a cause of detuning, have been studied by many authors [2,7-9]. Two major main approaches for iron losses modelling have emerged in literature, the first represents iron losses by an equivalent resistance placed in parallel with the magnetising branch [2,7,8], while the second one models iron losses by an equivalent resistance placed in series to the magnetising branch [9]. On the basis of these models, most vector controllers that compensate iron losses effect have been reported. All of them are little more complex with respect to the basic vector control.

This paper presents an approach for including iron losses and saturation in the induction machine model. A new alternative to vector control elaboration based on the use of saturated induction machine model that includes, in addition, iron losses in serial form is presented. The proposed scheme is developed and compared to the basic one. In this paper, we will show that this proposed controller is insensitive to saturation effect as well as to iron losses. This is due to the fact that these effects are directly considered in the controller. The validity of the proposed scheme is verified through simulation and experimental investigation.

2. Induction machine modelling

The equations of the induction machine model [6,7] that takes into account iron losses, written in a d-q synchronous reference frame, are given by:

$$\underline{V}_s = R_s \underline{I}_s + \frac{d\underline{\Phi}_s}{dt} + j\omega_s \underline{\Phi}_s \quad (1)$$

$$\underline{V}_r = R_r \underline{I}_r + \frac{d\underline{\Phi}_r}{dt} + j(\omega_s - \omega_r)\underline{\Phi}_r \quad (2)$$

$$\underline{\Phi}_s = L_{\sigma s} \underline{I}_s + \underline{\Phi}_m \;, \quad \underline{\Phi}_r = L_{\sigma r} \underline{I}_r + \underline{\Phi}_m \quad (3)$$

$$\underline{\Phi}_m = L_m \underline{I}_m \;, \quad \underline{I}_m + \underline{I}_{Fe} = \underline{I}_s + \underline{I}_r \quad (4)$$

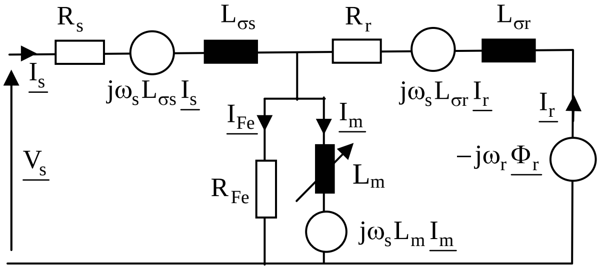

Fig.1: Equivalent circuit of an induction machine by considering iron losses

$$R_{Fe}\underline{I_{Fe}} = L_m \frac{d\underline{I_m}}{dt} + j\omega_s L_m \underline{I_m} \quad (5)$$

$$Tem = P\frac{L_m}{L_r}\left[\Phi_{dr}(I_{qs} - I_{qFe}) - \Phi_{qr}(I_{ds} - I_{dFe})\right] \quad (6)$$

Where V, I and Φ denote, respectively, voltage, current and flux vector. P is the number of poles pairs of the machine. ω_s is the reference axis speed. ω_r is the electrical rotor speed. T_{em} is the electromagnetic torque. Fe is the index associated to iron losses branch. These losses are traditionally modelled with parallel resistance R_{Fe} to the magnetising branch [2,7,8], as shown in Fig.1. In this case, it can be shown that an additional mutual coupling between the axis components (d-q) is introduced and leads to an increase of the system order. To avoid this problem, the equivalent circuit can be transformed from the parallel form to a serial form [9], as shown in Fig.2. Using the relationships between the flux linkages and currents, the induction machine equations, in the synchronous reference frame, can be expressed as follow:

$$\underline{V_s} = R_s\underline{I_s} + L_{\sigma s}\frac{d\underline{I_s}}{dt} + L_m\frac{d\underline{I_m}}{dt} + j\omega_s(L_{\sigma s}\underline{I_s} + L_m\underline{I_m}) \quad (7)$$

$$\underline{V_r} = R_r\underline{I_r} + L_{\sigma r}\frac{d\underline{I_r}}{dt} + L_m\frac{d\underline{I_m}}{dt} + j\omega_{sl}(L_{\sigma r}\underline{I_r} + L_m\underline{I_m}) \quad (8)$$

Substituting (5) into (4) gives:

$$\underline{I_s} + \underline{I_r} = \frac{L_m}{R_{Fe}}\left(\frac{d\underline{I_m}}{dt} + j\omega_s\underline{I_m}\right) + \underline{I_m} \quad (9)$$

Except during the phase when the flux is set, it is known that the rate of change of I_m is small compared with the terms in (9). As a consequence, equation (9) can be written as:

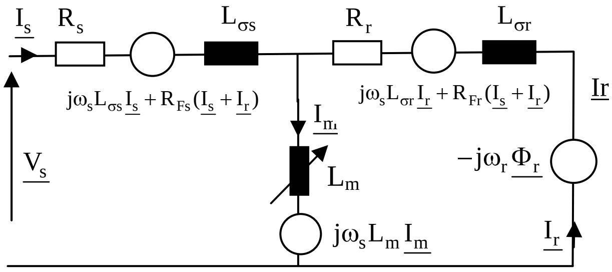

Fig.2: Modified equivalent circuit of an induction machine by considering iron losses

$$\underline{I_m} = \frac{R_{Fe}}{R_{Fe} + j\omega_s L_m}(\underline{I_s} + \underline{I_r}) \quad (10)$$

Introducing, (10) into the equations (7) and (8), the serial model of an induction machine that includes iron losses can be obtained as:

$$\underline{V_s} = R_s\underline{I_s} + L_{\sigma s}\frac{d\underline{I_s}}{dt} + \left(L_M - \frac{jR_{Fs}}{\omega_s}\right)\frac{d(\underline{I_s}+\underline{I_r})}{dt} + j\omega_s L_{\sigma s}\underline{I_s} + (j\omega_s L_M + R_{Fs})\ (\underline{I_s}+\underline{I_r}) \quad (11)$$

$$\underline{V_r} = R_r\underline{I_r} + L_{\sigma r}\frac{d\underline{I_r}}{dt} + \left(L_M - \frac{jR_{Fr}}{\omega_{sl}}\right)\frac{d(\underline{I_s}+\underline{I_r})}{dt} + j\omega_{sl} L_{\sigma r}\underline{I_r} + (j\omega_{sl} L_M + R_{Fr})\ (\underline{I_s}+\underline{I_r}) \quad (12)$$

Knowing that generally $R_{Fe} \gg \omega_s L_m$, the serial mutual inductance L_M is given by:

$$L_M = \frac{L_m R_{Fe}^2}{R_{Fe}^2 + \omega_s^2 L_m^2} \approx L_m \quad (13)$$

R_{Fs} and R_{Fr} are, respectively, equivalent serial resistances associated to the stator and to the rotor, which are equal to:

$$R_{Fs} = \frac{\omega_s^2 L_m^2 R_{Fe}}{R_{Fe}^2 + \omega_s^2 L_m^2} \approx \frac{\omega_s^2 L_m^2}{R_{Fe}} \quad (14)$$

$$R_{Fr} = \frac{\omega_{sl}\omega_s L_m^2 R_{Fe}}{R_{Fe}^2 + \omega_s^2 L_m^2} \approx \frac{\omega_{sl}\omega_s L_m^2}{R_{Fe}} \quad (15)$$

In addition we have:

$$\frac{R_{Fs}}{\omega_s} = \frac{R_{Fr}}{\omega_{sl}} = \frac{\omega_s L_m^2 R_{Fe}}{R_{Fe}^2 + \omega_s^2 L_m^2} \le \frac{\omega_s L_m^2 R_{Fe}}{2R_{Fe}\omega_s L_m} \ll L_m$$

So, the terms (R_{Fs}/ω_s) and (R_{Fr}/ω_{sl}) in (11) and (12) are small compared to L_M and they can be neglected. Then, the equations (11)-(12) become:

$$\underline{V}_s = R_s \underline{I}_s + L_{\sigma s}\frac{d\underline{I}_s}{dt} + L_m \frac{d(\underline{I}_s + \underline{I}_r)}{dt} + j\omega_s L_{\sigma s}\underline{I}_s + (j\omega_s L_M + R_{Fs})\ (\underline{I}_s + \underline{I}_r) \quad (16)$$

$$\underline{V}_r = R_r \underline{I}_r + L_{\sigma r}\frac{d\underline{I}_r}{dt} + L_m \frac{d(\underline{I}_s + \underline{I}_r)}{dt} + j\omega_{sl} L_{\sigma r}\underline{I}_r + (j\omega_{sl} L_M + R_{Fr})\ (\underline{I}_s + \underline{I}_r) \quad (17)$$

As can be seen, these equations are quite similar to the corresponding equations of the basic model. Equations (16-17) show that, even with the consideration of iron losses, the order of the system does not change. On the opposite, the system order increases from four to six with the parallel model.

Saturation effect in induction machines is generally associated with the magnetising flux or with the leakage flux [2-4]. In the following, the leakage flux path saturation is neglected. Including saturation effect in d-q axis model consist in expressing the mutual inductance and its derivative as function of the magnetising current [2].

Iron losses and saturation are now considered simultaneously. In this case, the principle of magnetising flux saturation modelling and derivation procedure remain the same as for induction machine without iron losses. The derivation procedure is presented in details in [4,6]. After arrangement and development of the set of equations (16-17), considering the saturation effect, the model of a saturated induction machine, that incorporates iron losses in serial form, may be given in matrix form as:

$$[V] = [L]\ [\dot{I}] + [R]\ [I] \quad (18)$$

Where:

$$[I] = \left[I_{ds}\ ,\ I_{qs}\ ,\ I_{dr}\ ,\ I_{qr}\right]^T$$

$$[V] = \left[V_{ds}\ ,\ V_{qs}\ ,\ 0\ ,\ 0\right]^T$$

$$[L] = \begin{bmatrix} L_{\sigma s}+M_d & M_{dq} & M_d & M_{dq} \\ M_{dq} & L_{\sigma s}+M_q & M_{dq} & M_q \\ M_d & M_{dq} & L_{\sigma r}+M_d & M_{dq} \\ M_{dq} & M_q & M_{dq} & L_{\sigma r}+M_q \end{bmatrix}$$

$$[R] = \begin{bmatrix} R_s+R_{Fs} & -\omega_s L_s & R_{Fs} & -\omega_s L_m \\ \omega_s L_s & R_s+R_{Fs} & \omega_s L_m & R_{Fs} \\ R_{Fr} & -\omega_{sl} L_m & R_r+R_{Fr} & -\omega_{sl} L_r \\ \omega_{sl} L_m & R_{Fr} & \omega_{sl} L_r & R_r+R_{Fr} \end{bmatrix}$$

The variable terms in (18) are [4,6]:

$$\begin{aligned} M_d &= M_{dy}\cos^2\alpha + L_m \sin^2\alpha \\ M_q &= M_{dy}\sin^2\alpha + L_m \cos^2\alpha \\ M_{dq} &= (M_{dy} - L_m)\cos\alpha\sin\alpha \end{aligned} \quad (19)$$

M_{dy} and L_m are, respectively, the dynamic and the static mutual inductances. M_{dq} is the term that explains the "cross effect" between the d and q axis. α is the angle between the d axis and the magnetising current. The electromagnetic torque is written in terms of stator and rotor currents as:

$$T_{em} = PL_m(I_{dr}I_{qs} - I_{qr}I_{ds}) \quad (20)$$

The magnetising curve and equivalent iron losses resistance must be known. They are determined by standard no-load tests on an induction machine with sinusoidal supply. R_{Fe} represents only stator iron losses and varies with frequency. So, it must be introduced as a function of frequency in the induction machine model.

3. Modified vector controller

A decoupling scheme is based on stator currents and rotor speed measurements. Derivation of the modified adaptative vector control model is obtained from the systems (1-5) and (16-17) by introducing the saturation effect. To include saturation effect in the controller model, assuming the constraints: $\Phi_{dr} = \Phi_r$, $\Phi_{qr} = 0$ and introducing the magnetizing flux, the equations of a rotor flux oriented induction machine can be written as [6]:

$$T_{\sigma r}\frac{d\Phi_r}{dt} + \Phi_r = \Phi_{dm} \quad , \quad \omega_{sl} = \frac{\Phi_{qm}}{T_{\sigma r}\Phi_r} \quad (21)$$

Using the magnetising flux, the torque is given as:

$$T_{em} = P\frac{\Phi_r \Phi_{qm}}{L_{\sigma r}} \quad (22)$$

With the previous assumptions, equation (17) gives

$$\Phi_{dr} = (L_m - \frac{R_{Fr}L_r}{R_r + R_{Fr}})I_{ds} \quad (23)$$

$$\omega_{sl}\Phi_{dr} = \frac{(L_m(R_r + R_{Fr}) - L_r R_{Fr})}{L_r} I_{qs} \quad (24)$$

Equations (23)-(24) are used to determine the rotor

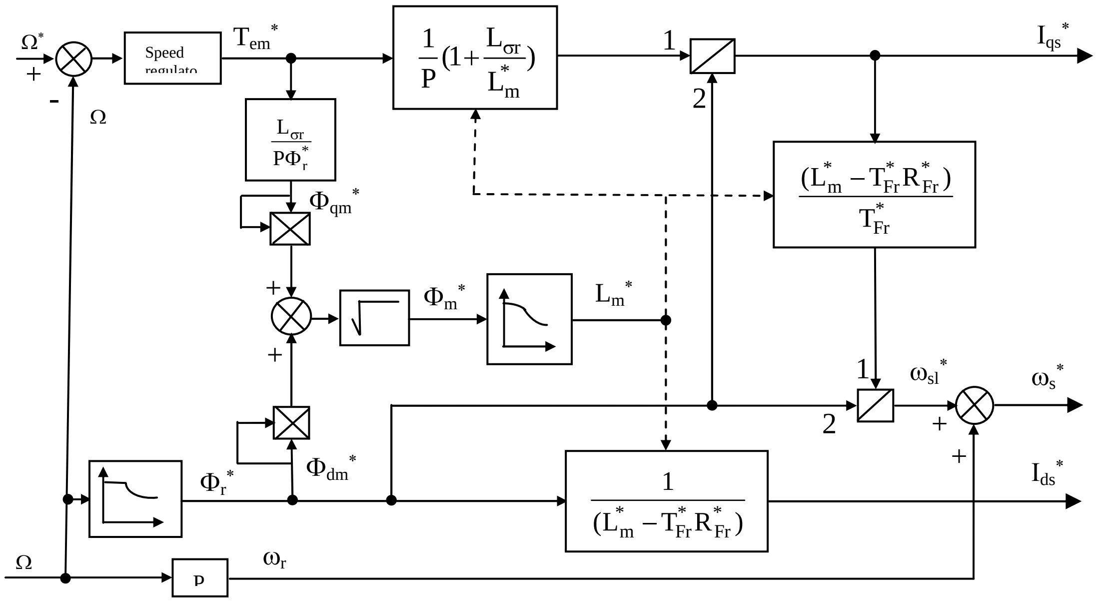

Fig.3. Proposed vector controlled induction machine with iron losses and saturation compensation

flux reference value and the slip in the synchronous reference frame. As one can see, these equations are quite similar to the corresponding equations of the classical field oriented control. The complete serial modified vector controller that takes into account saturation and iron losses, assuming steady-state operating conditions, can be given by the following system:

$$\Phi_{dm}^* = \Phi_r^* \quad , \quad \Phi_{qm}^* = \frac{L_{\sigma r} T_{em}^*}{P\Phi_r^*}$$

$$\Phi_m^* = \sqrt{\Phi_{dm}^{*\,2} + \Phi_{qm}^{*\,2}} \quad , \quad L_m^* = L_m^*(\Phi_m^*)$$

$$L_r^* = L_m^* + L_{\sigma r} \quad , \quad L_s^* = L_m^* + L_{\sigma s}$$

$$I_{ds}^* = \frac{\Phi_r^*}{(L_m^* - R_{Fr}^* T_{Fr}^*)} \quad , \quad I_{qs}^* = \frac{T_{em}^* L_r^*}{P L_m^* \Phi_r^*}$$

$$\omega_{sl}^* = \frac{(L_m^* - T_{Fr}^* R_{Fr}^*) I_{qs}^*}{T_{Fr}^* \Phi_r^*} \quad , \quad \omega_s^* = \omega_{sl}^* + \omega_r$$

* indicates reference values. If the machine is fed by a voltage inverter the stator voltages can be given as:

$$V_{ds}^* = V_{ds1}^* - \sigma L_s^* \omega_s^* I_{qs}^* + \frac{R_{Fs}^*}{L_r^*} \Phi_r^*$$

$$V_{qs}^* = V_{qs1}^* + \omega_s^* (\sigma L_s^* I_{ds}^* + \frac{L_m^*}{L_r^*} \Phi_r^*) \qquad (25)$$

V_{ds1}^* and V_{qs1}^* are current regulators outputs and:

$$R_{Fs}^* = \frac{\omega_s^{*2} L_m^{*\,2}}{R_{Fe}}, \; R_{Fr}^* = \frac{\omega_{sl}^* \omega_s^* L_m^{*\,2}}{R_{Fe}}, \; T_{Fr}^* = \frac{L_r^*}{R_{Fr}^* + R_r}$$

The bloc diagram of this controller is shown in Fig.3.

4. Simulation and experimental results

A 5.5 KW, 12 A, 380 V, four-pole cage induction machine is used in simulation and experimentation setup. The value of mutual inductance used in the basic controller is equal to its nominal rated value, the inverter is assumed to be ideal in simulation. In order to test the validity of the basic controller with the variations of saturation level, we carried out an operation at high speed with flux weakening. It is well known that the mutual inductance increases when the magnetising current decreases. Fig.4 shows the results of simulation for a ramp reference of speed. The presented results show that the basic vector control is not able to eliminate detuning caused by saturation. The controller forces the machine to operate at a half of rated flux; hence, the d axis current and reference flux are inversely proportional to the increase of speed. The flux in the machine decreases less than the flux imposed by the controller. It is equal to 0.65 Wb at 120% of rated speed instead of 0.5 Wb. In this case, the magnetizing inductance of motor L_m is increased and it is larger than the magnetizing inductance of the controller L_m^*, this last is kept constant and equal to its nominal value while in weakening mode Hence, the magnetizing current, is larger

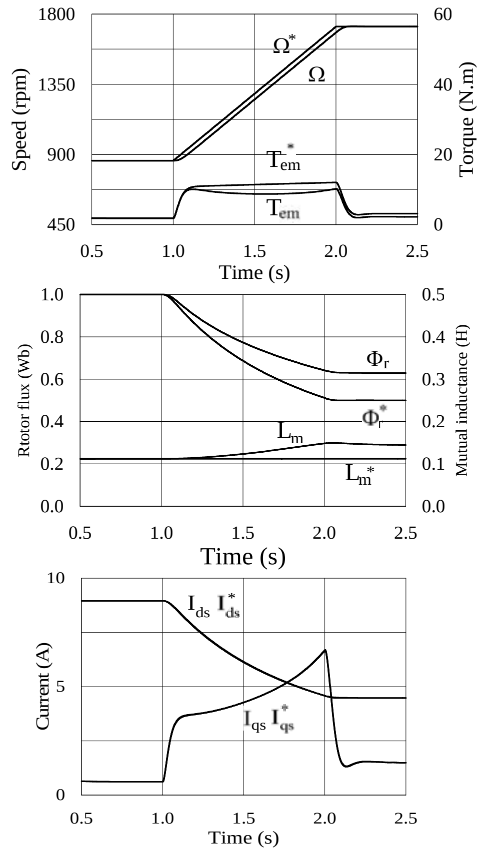

Fig.4: Field weakening operation: Simulated results without consideration of iron losses and saturation in vector control

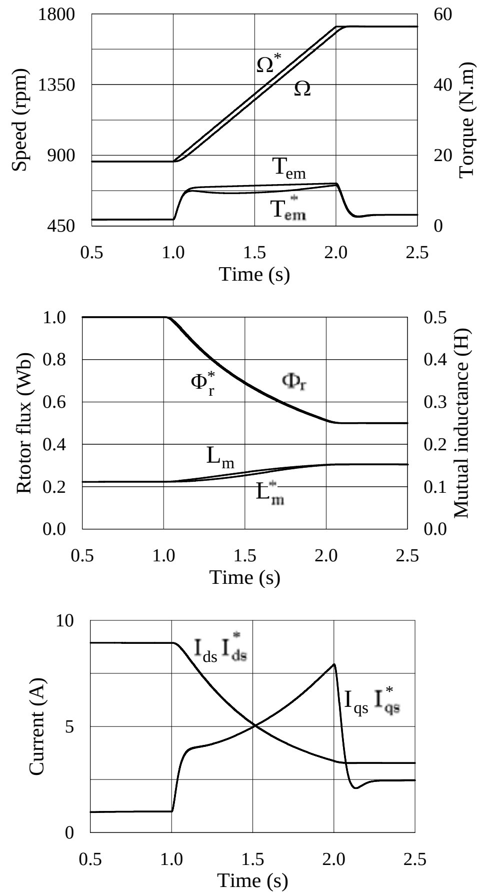

Fig.5: Field weakening operation: Simulated results with consideration of iron losses and saturation in vector control

than that the necessary magnetizing current and the motor is overexcited. Furthermore, if I_{ds} is actually higher and actual magnetizing inductance L_m increases, the latter term of q axis voltage equation increases considerably because of the rotor speed factor. Therefore, the voltage margin is reduced and it is difficult to control the torque smoothly. In addition, the position information of rotor flux is extremely important for indirect vector control system. This information needs rotor time constant that is closely related to the magnetizing inductance. If the controller has an incorrect magnetizing inductance value, it can not provide an adaptation to flux changes caused by saturation. As consequence, rotor flux and electromagnetic torque are greater than the reference values. To prove the effectiveness of the proposed scheme that takes into account saturation and iron losses we present a simulation of this system on Fig.5. One can see that the flux weakening operation is performed with a good agreement between flux and torque in the machine and flux and torque of the controller. Moreover, the current I_{ds} decreases from nominal value of 8.94 A to 3.27 A instead 4.47 A. The magnetizing inductance used in the controller L_m* follows the variation of real magnetising inductance L_m. These results demonstrate that the proposed control algorithm is able to keep the torque and the flux at its reference values. Experimental investigation has been carried out in a laboratory setup. The whole vector control scheme has been implemented in C language with the use of dSpace RTLib (Real Time Library) of the DS1104 DSP Board. The main sampling period is of 200 μs with a 10 kHz PWM and a low sampling period of 1 ms for the speed controller. In order to verify the proposed approach, Fig.6 and Fig.7 show the experimental results of field weakening operation in same conditions as the ones of the simulation. In the conventional scheme, the drive can not operate properly according to the variation of the magnetizing inductance, the flux component current I_{ds} is larger than that of the proposed scheme in the field weakening region. Thus, the decoupling term of the q-axis stator voltage is decreased, and voltage margin is enlarged. In basic controller, V_{qs}* reaches limitation (Fig.6), in opposite, with proposed controller, V_{qs}* is lower about 16% in comparison with the limitation voltage (Fig.7). So, it is possible to increase speed without exceeding further voltage limitation. We gained in d axis current and q axis voltage but q axis current increases slightly. Therefore, q-axis voltage margin has been sufficiently large and q-axis stator current has become more stable.

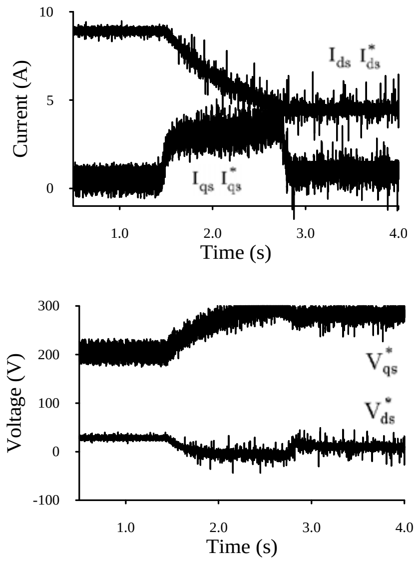

Fig.6: Experimental results: Current and voltage for a flux weakening operation (basic vector control)

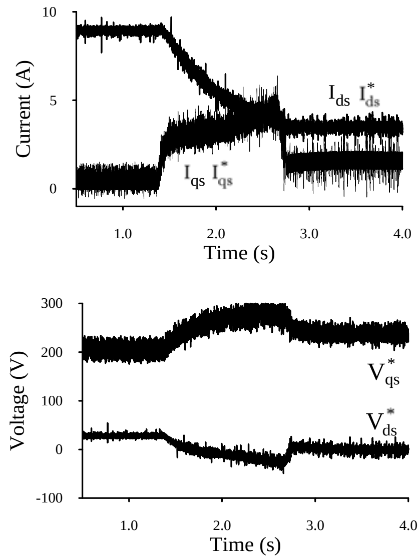

Fig.7: Experimental results: Current and voltage for a flux weakening operation (proposed vector control)

5. Conclusion

Advanced motor model for vector controlled drives has been proposed. It takes into account both iron losses and magnetic saturation. The developed model is based on modification of parallel form to serial form of iron losses resistance. And next, the magnetic saturation, which affects inductances, is incorporated into the model.

Due to the dependency of the vector controlled variables, flux and torque, in the model of induction motor, we showed that it is necessary to introduce iron losses and saturation on the model to perfect the control response. Therefore, a modified adaptative vector controller was developed. The proposed algorithm has only small additional complexity than the conventional one. However, this scheme requires good knowledge of the equivalent iron losses resistance and magnetizing curve. The most important advantage of the new controller is to provide only a little additional computational time compared to the linear one. Moreover, the proposed controller eliminates the detuning caused by saturation and iron losses and the machine is better used in current and in voltage. As a consequence, it can operate in field weakening at higher speed without exceeding voltage limitations. The experimental results demonstrate the effectiveness of the proposed method.

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