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Maximum Torque to Current control of a Synchronous Reluctance Machine by including cross-magnetisation

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Abstract— This paper investigates the effect of cross-magnetisation on Maximum Torque to Current control of a Synchronous Reluctance Machine. A new model of the machine based on Park's equations and including saturation effects is first developed. From this saturated model, a new maximum torque to current condition is obtained. Several experimental results are then presented to verify the accuracy of the theoretical analysis.

I. INTRODUCTION

It is now a well-established fact that a magnetic coupling exists between the fictitious d-axis and q-axis windings of an ac machine [1]-[4]. This phenomenon, which is known as cross-magnetisation, is caused by the non-linear properties of the magnetic materials. For the evaluation of an ac machine performance in term of torque, an accurate modelling of the magnetic behaviour is required.

Different methods can be used to include the magnetic saturation effects in the electrical machines models. One of them is based on the finite-element method. This approach offers a high degree of accuracy. However, it requires a great deal of computer time when the machine is fed by a PWM inverter. One can also use the reluctance networks method. This method is faster than the previous one but remains difficult to use with the simulation of a controlled machine. An alternate method is to use a modified Park model. The machine is seen as a set of coupled circuits where all the inductances depend on the stator and rotor currents. This method is more attractive in terms of computational time, especially for machines control.

The aim of this paper is to study the influence of the magnetic saturation in a maximum torque per ampere control strategy for a synchronous reluctance machine (SynRM). The goal is to minimizing the stator current amplitude for a given load torque. The experimental study is based on a small machine (600W) with a conventional salient rotor equipped with a squirrel cage. The stator is the same as an induction machine and has symmetrical three phase windings. The cross section of the experimental machine is shown in Fig.1. A photography of the rotor is given in Fig.2.

The paper is organized as follows. In the first part, a saturated model of the machine, based on modified Park's equations, is described. The magnetic saturation effects including cross-magnetisation are considered by using a single saturation factor for both d -axis and q -axis. This saturation factor is defined as a function of an equivalent

magnetising current obtained by converting an anisotropic machine into an equivalent isotropic one. In the second part, a maximum torque to current condition that takes into account magnetic saturation and determines the optimal current ratio I_{sq}/I_{sd} is derived. To show the importance of the cross-magnetisation on the electromagnetic torque, a study is made with two different expressions of the electromagnetic torque. In the first expression, the cross-magnetisation is ignored whereas in the second expression, the complete saturated model is used.

Finally, a rotor-oriented vector control of a synchronous reluctance machine is achieved with a DSP board (TMS320C31) and many experimental results are presented. These experimental results show the importance of the cross-magnetisation effect on the electromagnetic torque and the accuracy of the saturated model that we propose.

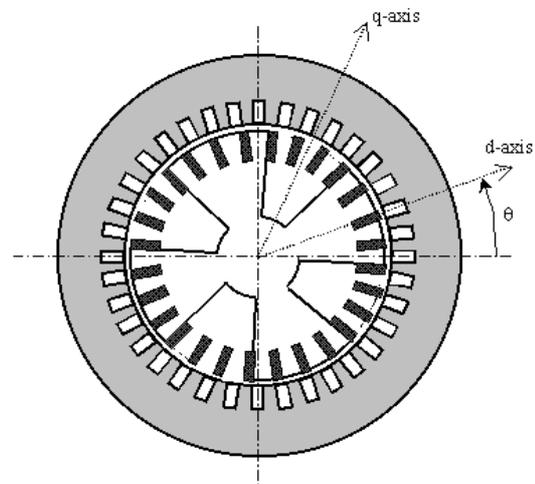


Figure 1. Cross section of the studied machine.

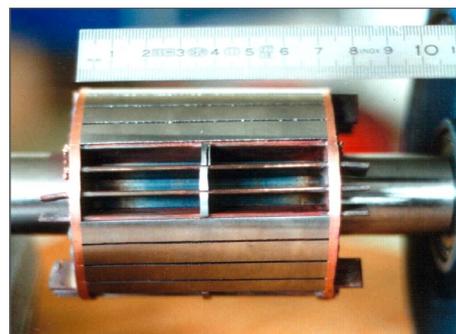


Figure 2. Rotor structure of the studied machine.

II. MAGNETIC SATURATION IN SYNCHRONOUS RELUCTANCE MACHINE

The two-axis representation of the SynRM is given in Fig.3.

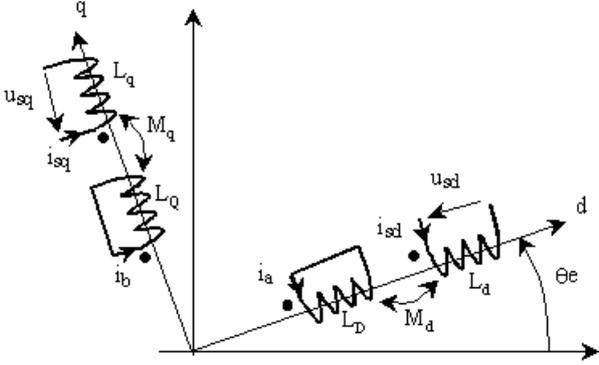


Figure 3. Two-axis model in the rotor reference frame

From Fig.3, the d - q voltage equations in the rotor reference frame are as follows:

$$u_{sd} = R_s \cdot i_{sd} + \frac{d\Psi_{sd}}{dt} - \omega_e \cdot \Psi_{sq} \quad (1)$$

$$u_{sq} = R_s \cdot i_{sq} + \frac{d\Psi_{sq}}{dt} + \omega_e \cdot \Psi_{sd} \quad (2)$$

$$0 = R_D \cdot i_a + \frac{d\Psi_{rd}}{dt} \quad (3)$$

$$0 = R_Q \cdot i_b + \frac{d\Psi_{rq}}{dt} \quad (4)$$

The stator and rotor flux linkages are related to the currents by:

$$\Psi_{sd} = L_d \cdot i_{sd} + M_d \cdot i_a \quad (5)$$

$$\Psi_{sq} = L_q \cdot i_{sq} + M_q \cdot i_b \quad (6)$$

$$\Psi_{rd} = L_D \cdot i_a + M_d \cdot i_{sd} \quad (7)$$

$$\Psi_{rq} = L_Q \cdot i_b + M_q \cdot i_{sq} \quad (8)$$

Introducing magnetizing currents I_{md} and I_{mq} , the stator flux linkages become:

$$\Psi_{sd} = L_d \cdot I_{md} \quad \text{with} \quad I_{md} = i_{sd} + \frac{M_d}{L_d} \cdot i_a \quad (9)$$

$$\Psi_{sq} = L_q \cdot I_{mq} \quad \text{with} \quad I_{mq} = i_{sq} + \frac{M_q}{L_q} \cdot i_b \quad (10)$$

As the machine is of anisotropic magnetic structure, space vectors of stator flux linkages $\underline{\Psi}_s$ and magnetizing current \underline{I}_m are no longer aligned as shown in Fig.4.

To obtain a saturated model with a single saturation factor, the synchronous reluctance machine must be converted into an equivalent isotropic machine [5]. The equivalent isotropic machine is represented in Fig.5 by two

equivalent space vectors \underline{I}'_m and $\underline{\Psi}'_s$ which are spatially aligned. The transformation of \underline{I}_m and $\underline{\Psi}_s$ in Fig.4 to \underline{I}'_m and $\underline{\Psi}'_s$ in Fig.5 is obtained by using the following matrix transformations:

$$\begin{pmatrix} I'_{md} \\ I'_{mq} \end{pmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & k \end{bmatrix} \cdot \begin{pmatrix} I_{md} \\ I_{mq} \end{pmatrix} \quad (11)$$

$$\begin{pmatrix} \Psi'_{sd} \\ \Psi'_{sq} \end{pmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1/k \end{bmatrix} \cdot \begin{pmatrix} \Psi_{sd} \\ \Psi_{sq} \end{pmatrix} \quad (12)$$

where k is the saliency factor defined as:

$$k = \sqrt{\frac{L_q}{L_d}} \quad (13)$$

Introducing now the saturation factor $K_s(I'_m)$, the d - q axis stator flux linkages can be written as:

$$\Psi_{sd} = K_s(I'_m) \cdot L_d \cdot I_{md} \quad (14)$$

$$\Psi_{sq} = K_s(I'_m) \cdot L_q \cdot I_{mq} \quad (15)$$

where I'_m is the equivalent rotor magnetizing current:

$$I'_m = \sqrt{I_{md}^2 + k^2 \cdot I_{mq}^2} \quad (16)$$

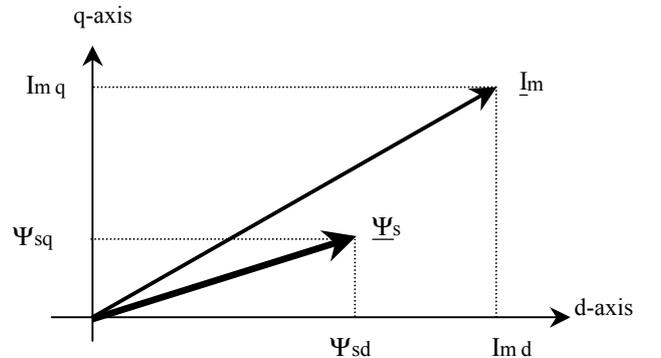


Figure 4. Anisotropic machine

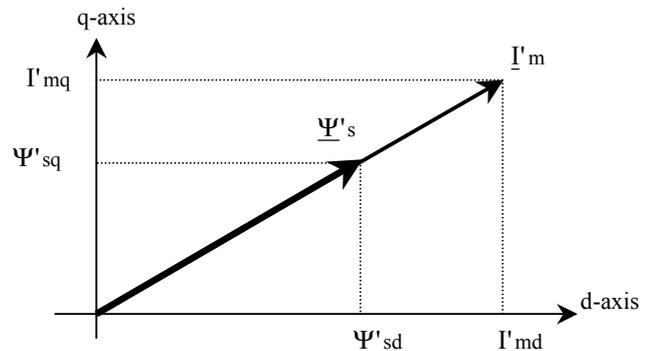


Figure 5. Equivalent isotropic machine

The saturation factor can be measured from the no-load test or the d-c test at standstill along the d-axis under saturated conditions. The result obtained for the studied machine is shown in Fig.6 [6].

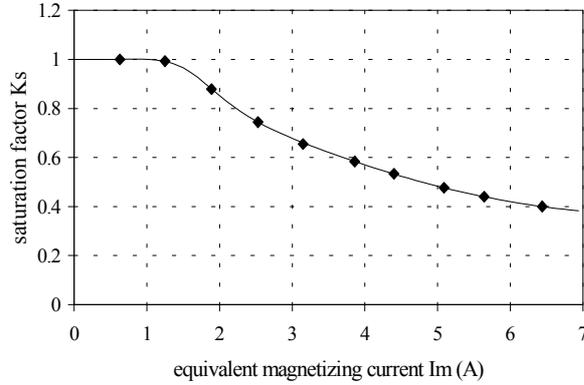


Figure 6. Saturation factor $K_s(I'_m)$.

A simple mathematical expression is used for the representation of the saturation factor:

$$K_s(I'_m) = 1 \quad \text{with } I'_m < 1.5A \quad (17)$$

$$K_s(I'_m) = \frac{2.35}{1 + 0.9 \cdot I'_m} \quad \text{with } I'_m \geq 1.5A$$

The stator inductances L_d and L_q which appear in equations (14) and (15) have been measured under unsaturated conditions by using the d.c test along *d-axis* and *q-axis* with the machine at standstill [7]. The results obtained with the experimental synchronous reluctance machine are summarized in Table I.

TABLE I 600 W, FOUR POLES SRM PARAMETERS

| Symbol | Quantity |
|------------------------|--------------------------------------|
| $R_s = 7.8\Omega$ | stator resistance |
| $L_d = 0.54 \text{ H}$ | d-axis stator unsaturated inductance |
| $L_q = 0.21 \text{ H}$ | q-axis stator unsaturated inductance |

From equations (14) and (15), two family of curves are obtained for the d and q axis as shown in Fig.7 and Fig.8. Each family shows, for each axis winding, the magnetization curves obtained with various fixed values of current in the other winding. We can observed that a change in the quadrature-axis magnetizing current I_{mq} cause a change of stator flux linkage in the direct axis winding and a change in the direct axis magnetizing current I_{md} cause a change of stator flux linkage in the quadrature winding. These characteristics demonstrate the importance of the cross-magnetisation effect for the studied machine.

The expression of the electromagnetic torque is given by (18). This expression is still valid in saturated condition but in this case, we must use the magnetic characteristics given in Fig.7 and in Fig.8 to calculate the electromagnetic

torque. In the torque equation (18), p is the number of pole pairs.

$$T = p \cdot (\Psi_{sd} \cdot I_{sq} - \Psi_{sq} \cdot I_{sd}) \quad (18)$$

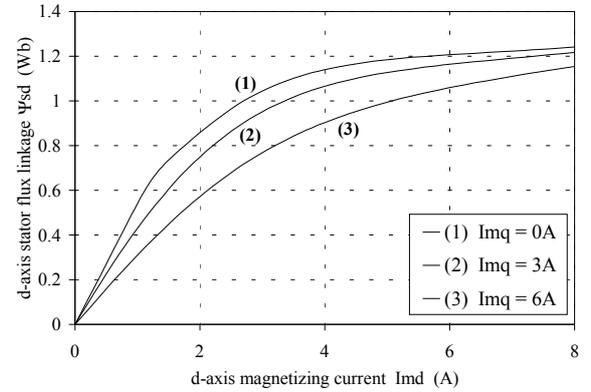


Figure 7. d-axis magnetic characteristics.

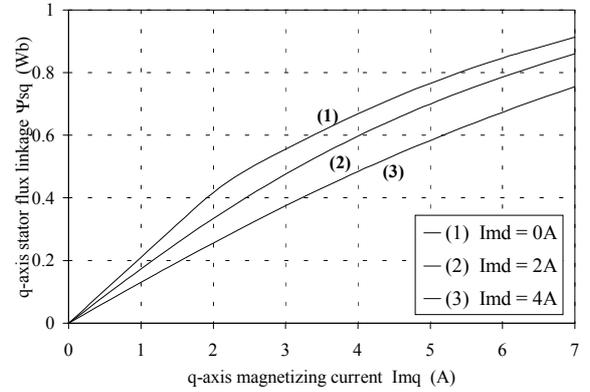


Figure 8. q-axis magnetic characteristics.

III. MAXIMUM TORQUE-TO CURRENT CONDITION

It is desirable to achieve maximum torque per ampere operation of a SynRM. This can be achieved by selecting an appropriate current angle $\alpha = \tan^{-1}(I_{sq}/I_{sd})$ with respect to the rotor d-axis. When magnetic saturation is ignored, the electromagnetic torque in steady state condition can be written as follows:

$$T_0 = p \cdot (L_d - L_q) \cdot I_{sd} \cdot I_{sq} \quad (19)$$

The torque of synchronous reluctance motors depends of the two components of the stator current vector I_{sd} and I_{sq} . For a given value of the electromagnetic torque in steady state condition, there exist various combinations of d-axis and q-axis current for one value of the stator current. When magnetic saturation is ignored (19), the well known relation $\alpha = 45^\circ$ ($I_{sd} = I_{sq}$) which provides minimum stator current is obtained [8]

When magnetic saturation is taken into account, the steady state expressions of the electromagnetic torque (no

current in the rotor bars) with or without cross-magnetisation are given respectively by (20) and (21):

$$T_2 = p \cdot K_s(I_m) \cdot (L_d - L_q) \cdot I_{sd} \cdot I_{sq} \quad (20)$$

$$T_1 = p \cdot \{K_s(I_{sd}) \cdot L_d \cdot I_{sd} \cdot I_{sq} - K_s(k \cdot I_{sq}) \cdot L_q \cdot I_{sq} \cdot I_{sd}\} \quad (21)$$

In steady state condition, the equivalent magnetizing current I_m (16) is given by:

$$I_m = \sqrt{I_{sd}^2 + k^2 \cdot I_{sq}^2} \quad (22)$$

Fig.9 presents the torque versus current angle α for three values of the stator current module (the rated value of the stator current is equal to 3A). The expressions of the electromagnetic torque T_0 , T_1 and T_2 are given above.

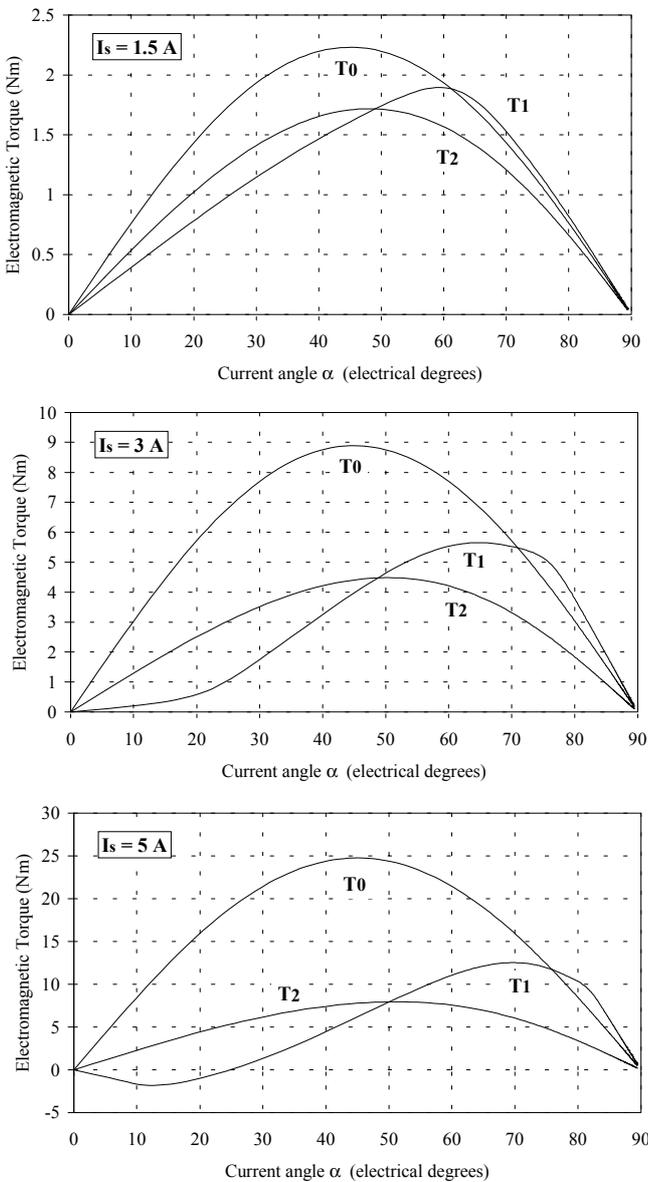


Figure 9. Torque versus current angle α at different current modules. T_0 : linear model; T_1 : saturated model without cross-magnetisation; T_2 : saturated model with cross-magnetisation.

These curves clearly illustrate the influence of magnetic saturation in motor performance. We can see that the maximum value of the electromagnetic torque is widely reduced when the magnetic saturation is taken into account.

When the cross-magnetisation is disregarded (T_1), we can observe that the optimal current angle is shifted toward values upper to 45° (which is the value predicted by a linear magnetic model). The optimal current angle depends of the stator current. This result corresponds with that obtained by [8], [9] and [10].

When the cross-magnetisation is included (T_2), we can observe that the optimal current angle is close to $\alpha = 45^\circ$ for all the values of the stator current. This result is important. It shows that a Maximum Torque to Current control strategy with $\alpha = 45^\circ$ is still valid when magnetic saturation occurs. This result is available for the studied synchronous reluctance machine where the saliency ratio L_d/L_q is small ($L_d/L_q \approx 2.5$).

IV. EXPERIMENTAL RESULTS

A functional block diagram of the synchronous reluctance machine vector control is given in Fig.10. The SynRM is fed by a voltage-source PWM inverter. The control is achieved with a DSP board (TMS320C31). Conventional PI controllers are used for current loops (d-axis and q-axis current controllers). These controllers allow to obtain good dynamic performances (a response time of 3ms in both d-axis and q-axis current loops). For the speed loop, an IP controller with an integrator antiwindup is used. IP algorithm is executed to generate the needed I_{sqref} current reference. A current limiter is used to ensure that stator current remains within rated value. Hall effect current transducers and a rotor position sensor provide the information to monitor the current vector I_{sd} and I_{sq} .

The 600W synchronous reluctance machine is coupled to a DC generator. For a constant output speed (maintained by the speed loop), the load torque T_r is maintained constant with a fixed load resistor on the DC generator and a fixed field excitation.

Several experimental results are presented to validate the effectiveness of the theoretical results.

Fig.11 illustrates the variations of the measured stator current versus d-axis current for different values of the speed (250, 500 and 800 r/mn) and different values of the load torque T_r (0, 1.2, 2 and 3 Nm). To obtain these curves, the d-axis current reference I_{sdref} is varied, and the corresponding stator current is measured with an ammeter. It can be observed that the optimal value of the d-axis current increase with the loading and is not subject to the speed value.

Fig.12 illustrates the variations of the measured stator current versus current angle α for a speed maintained at 250 r/mn, 500 r/mn and 800 r/mn and for different values of the load torque T_r . It can be observed that in all cases, the optimal current angle is close to 45° ($I_{sd} = I_{sq}$). This result confirms the theoretical study and validates the effectiveness of the proposed model.

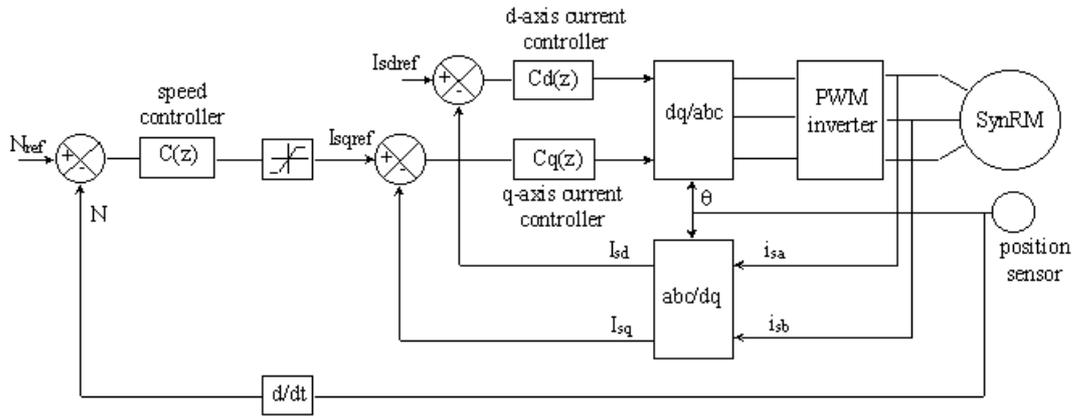


Figure 10. Block diagram of the experimental system.

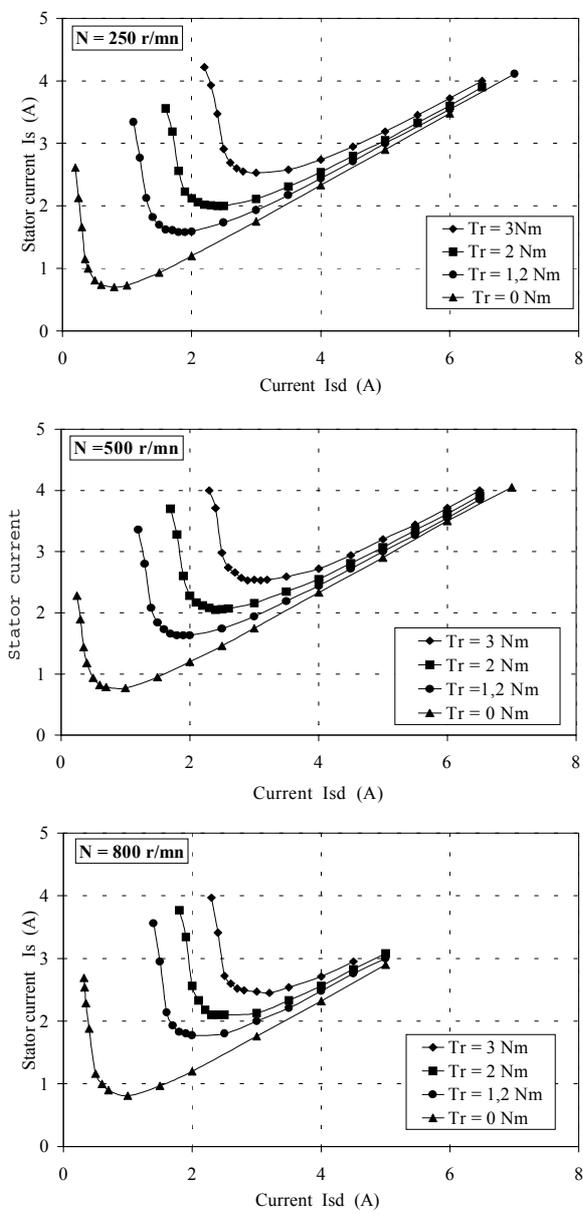


Figure 11. Stator current versus d-axis current for different values of the load torque. Experimental results

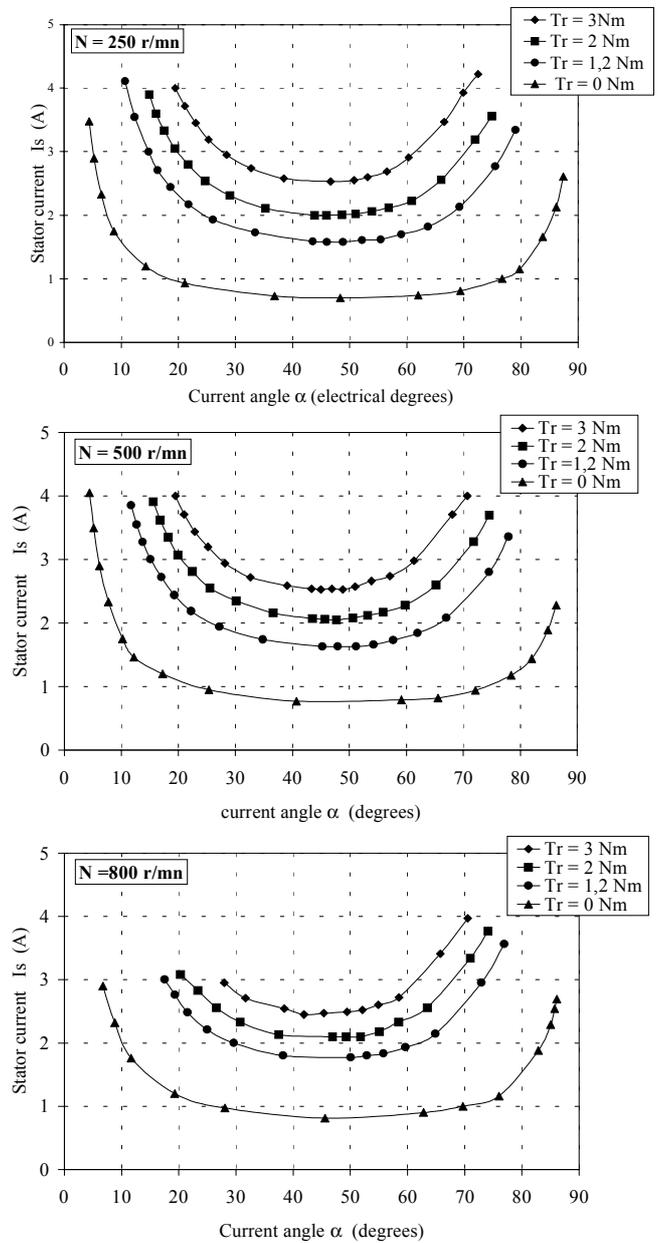


Figure 12. Stator current versus current angle α for different values of the load torque. Experimental results

Fig.13 shows the results obtained when the control law $I_{sdref} = I_{sq}$ is include in the control algorithm. This figure shows from top to bottom, the d-axis and q-axis current, the stator current and the speed. The motor is running with a constant speed command of 400 r/mn, under a constant load torque of 3 Nm and with the rated value of the d-axis current ($I_{sdref} = 2.5$ A). At $t = 0$ s, the control law $I_{sdref} = I_{sq}$ is activate to obtain the minimum value of the stator current. We can observe that after a transient, the average value of the stator current decreases from 3.3 A to 2.6 A, that corresponds about a reduction of 20%. The average value of the d- and q -axis current is then equal to 3.1 A

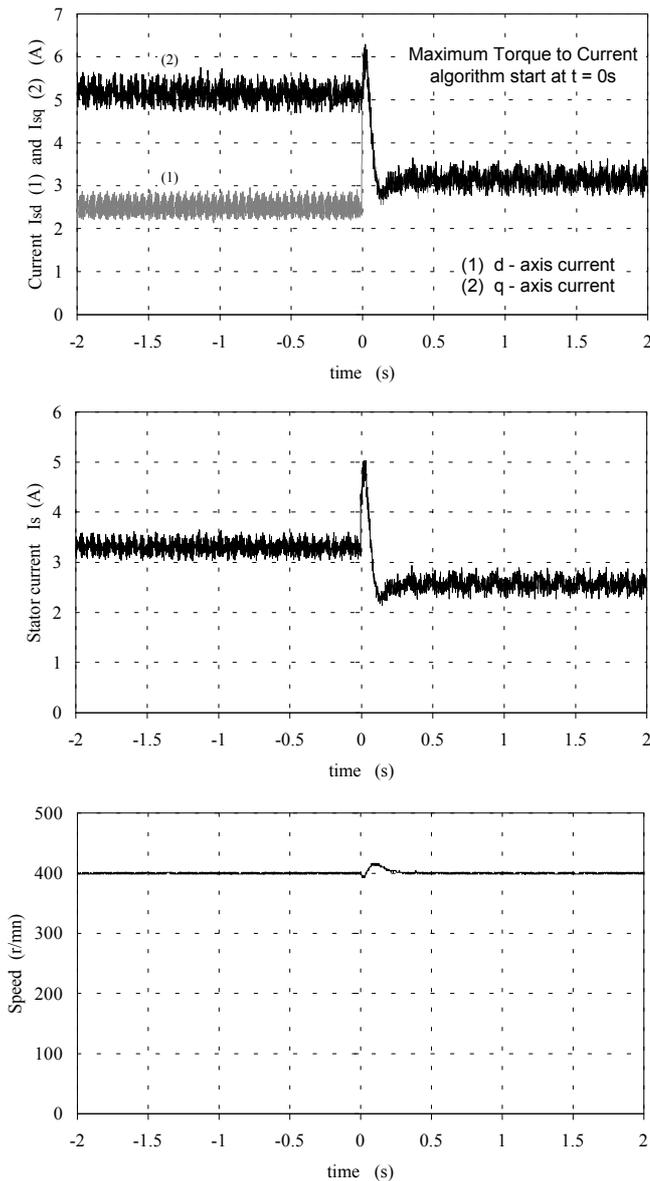


Figure 13. Experimental results of the Maximum Torque to Current control ($I_{sdref} = I_{sq}$) of the SynRM

V. CONCLUSION

The results presented in this paper clearly show the importance of cross-magnetisation in establishing optimal current angle for vector control of a synchronous

reluctance machine. We have shown by using a new saturated model that a Maximum Torque to Current control strategy with $\alpha = 45^\circ$ ($I_{sdref} = I_{sq}$) is still valid when magnetic saturation occurs. The experimental results have validate the effectiveness of the proposed model

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