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ASPECTS REGARDING INFLUENCES OF RELUCTANCE SYNCHRONOUS MOTORS PARAMETERS ON THE ELECTROMAGNETIC TORQUE

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Abstract – **This paper analyzes the way in which the parameters of the reluctance synchronous motors influence the value of the electromagnetic torque in steady state. In order to do this there are presented the necessary computation relations and a series of characteristics obtained by simulation with the help of a Matlab program. The paper closes with a few experimental results, confirming the simulations validity and with emerging conclusions.**

Keywords: *reluctance synchronous motors, parameters, electromagnetic torque.*

1. INTRODUCTION

The efforts of the electrical motors designers and builders always aims to obtain as simple as possible constructive solutions, in order to reduce the cost price and to ensure at the same time as good as possible performances, both at starting and in operation.

The reluctance synchronous motors have many unchallenged advantages:
- they do not have sliding contacts (brushes and rings miss);
- they do not allow to occur sparks;
- their construction is very simple;
- they are silent;
- they have high reliability etc.
- they have not magnets, which is an advantage over the machines with permanent magnets in high temperatures applications, the demagnetization phenomenon does not occur and they are cheaper.

These advantages have made possible to use them in explosive or corroding medium, in mining industry, in petroleum industry or in chemistry.
In the case of the reluctance synchronous motors, the electromagnetic torque is produced owing to the tendency of its mobile part to move to the position in which the supplied winding inductance is maximum. The inductance variation is determined by the strong asymmetry of the magnetic circuit relatively to the coordinate to which the motion is made.
Because the torque that is developed by these motors in synchronous regime is proportional with the difference between the two-axes inductances, the rotor should have a strong magnetic asymmetry.

2. ELECTROMAGNETIC TORQUE

In order to finalize this study, first of all, the general equations of the synchronous machine will be established when considering all the losses.
In this purpose, in accordance with [2], in symmetrical sinusoidal steady state, the following equations system can be written:

$$\begin{aligned}
&\underline{U} = -\underline{Z}\,\underline{I} + \underline{U}_{eE}\\
&\underline{U}_{eE} = -\underline{Z}_{md}\,\underline{I}_o\\
&\underline{I}_o = \underline{I}_d + k_q \underline{I}_q + k_E \underline{I}_E\\
&\underline{I}_d = -\frac{I \sin\psi}{I_E}\underline{I}_E\\
&\underline{I}_q = -j\frac{I \cos\psi}{I_E}\underline{I}_E\\
&\underline{I} = \underline{I}_d + \underline{I}_q\\
&\underline{I}_E = j\frac{I_E}{U}\underline{U}\,e^{j\theta}
\end{aligned} \tag{1}$$

where the known notations have been used, notations detailed in the introductory part.
Further on there will be explicitate the components of the electromotive force $\underline{U}_{eE}$ determined by the excittaion winding field and by the armature field,

considered decomposed in its components on the two axes.
From the equations system (1) one can obtain:

$$\underline{U} = -\underline{Z}\,\underline{I} + \underline{U}_{ead} + \underline{U}_{eaq} + \underline{U}_{ep} \quad (2)$$

where:

$$\underline{U}_{ead} = -\underline{Z}_{md}\underline{I}_d$$
$$\underline{U}_{eaq} = -\underline{Z}_{mq}\underline{I}_q$$
$$\underline{U}_{ep} = -\underline{Z}_{mE}\,\underline{I}_E \quad (3)$$
$$\underline{Z}_{mq} = k_q\underline{Z}_{md}$$
$$\underline{Z}_{mE} = k_E\underline{Z}_{md}$$

The equation (2) can be also written in the form:

$$\underline{U} = \underline{U}_{ep} - \underline{Z}_d\underline{I}_d - \underline{Z}_q\underline{I}_q \quad (4)$$

where the expressions of the longitudinal and transversal impedances have the folowing forms:

$$\underline{Z}_d = \underline{Z} + \underline{Z}_{md} = (R_s + R_{md}) + j(X_{s\sigma} + X_{md}) = $$
$$= R_d + jX_d = jZ_d e^{-j\gamma_d}$$
$$(5)$$
$$\underline{Z}_q = \underline{Z} + \underline{Z}_{mq} = (R_s + R_{mq}) + j(X_{s\sigma} + X_{mq}) = $$
$$= R_q + jX_q = jZ_q e^{-j\gamma_q}$$

To obtain the current expression, the equations system (1) is solved relatively to I, by taking (4) and (5) into account. Thus, one can obtain:

$$I = j\frac{U}{Z_d}e^{j\gamma_d} + [\frac{Z_{md}(1-K_q)}{Z_d}\cdot$$
$$\cdot\frac{U_{ep}\sin(\gamma_d-\beta)+U\sin(\vartheta-\gamma_d)}{Z_q\cos(\gamma_d-\gamma_q)} - \quad (6)$$
$$-j\frac{U_{ep}}{Z_d}]\cdot e^{j(\vartheta+\gamma_d-\beta)}$$

In the obtained expression the phasor $\underline{U}$ has been considered in the real axis, that is $\underline{U} = U$. The relation (6) determines the salient pole synchronous machine current when all the losses are considered function of the active load of the machine (the internal angle) and of the excitation.
The electromagnetic power is obtained with the help of the energetic balance.
In the case of a generator, it is given by the sum between the delivered active power, the windings losses and the iron losses.

$$P_M = UI\cos\varphi + R_s I^2 + R_{md} I_o^2 \quad (7)$$

By expressing I, $\underline{I}_o$ and φ, relatively to the polar electromotive force U_{ep} and to the internal angle ϑ, one obtains as in the current case:

$$P_M = \frac{1}{\cos(\gamma_d - \gamma_q)}\cdot$$
$$\cdot\{\, UU_{ep}[\frac{\cos(\gamma_q-\beta)}{Z_d}\sin\vartheta + \frac{\sin(\gamma_d-\beta)}{Z_q}\cos\vartheta -$$
$$-2[\frac{R_d\cos(\gamma_q-\beta)}{Z_d^2\cos(\gamma_d-\gamma_q)} - \frac{\sin\beta}{Z_d}]\cos(\vartheta-\gamma_q) +$$
$$+2\frac{(R_s+k_qR_{mq})\sin(\gamma_d-\beta)}{Z_q^2\cos(\gamma_d-\gamma_q)}\cdot\sin(\vartheta-\gamma_d)] +$$
$$+U^2[\frac{1}{Z_q}\sin(\vartheta-\gamma_d)\cos\vartheta - \frac{1}{Z_d}\cos(\vartheta-\gamma_q)\sin\vartheta +$$
$$+\frac{R_d\cos^2(\vartheta-\gamma_q)}{Z_d^2\cos(\gamma_d-\gamma_q)} + \frac{(R_s+k_qR_{mq})\sin^2(\vartheta-\gamma_d)}{Z_q^2\cos(\gamma_d-\gamma_q)}] +$$
$$+U_{ep}^2[\frac{R_d\cos^2(\gamma_q-\beta)}{Z_d^2\cos(\gamma_d-\gamma_q)} + \frac{(R_s+k_qR_{mq})\sin^2(\gamma_d-\beta)}{Z_q^2\cos(\gamma_d-\gamma_q)} +$$
$$+\frac{\sin\beta\cos(\gamma_d-\gamma_q)}{Z_{md}} - \frac{2\sin\beta\cos((\gamma_q-\beta)}{Z_d}]\,\}$$
$$(8)$$

With $M = \frac{1}{\Omega_1}P_M$ and with the notations

$$k_x = \frac{X_q}{X_d};\quad k_r = \frac{R}{X_d}, \quad (9)$$

the *reactive electromagnetic torque (the reluctance torque)* is obtained

$$M_{dq} = \frac{mU^2}{2X_d\Omega_1}\cdot\frac{1-k_x}{(k_x+k_r^2)^2}[(k_x-k_r^2)\sin 2\theta +$$
$$+k_r(1+k_x)\cos 2\theta - k_r(1-k_x)] \quad (10)$$

This torque can be expressed as a sum between two components:

$$M_{dq} = M_{dqa} + M_{dqf} \quad ,(11)$$

where M_{dqa} is the *active reluctance torque*, depending on the internal angle and M_{dqf} is the *breaking torque,* determined by the magnetic asymmetry and by the stator winding resistance.

The following expression can be written for M_{dqa}:

$$M_{dqa} = M_{dqa\,\max} \sin 2(\theta + \alpha_{dq}) + M_{dqf} \,, \quad (12)$$

with

$$M_{dqa\max} = \frac{mU^2}{2\Omega_1} \cdot \frac{1 - k_x}{X_d (k_x + k_r^2)^2} \cdot \sqrt{(k_x - k_r^2)^2 + k_r^2 (1 + k_x)^2} \quad (13)$$

and

$$\alpha_{dq} = \frac{1}{2} arctg \left[\frac{k_r (1 + k_x)}{k_x - k_r^2} \right]. \quad (14)$$

The following expression can be written for M_{dqf}:

$$M_{dqf} = -\frac{mU^2}{2\Omega_1} \cdot \frac{k_r (1 - k_x)^2}{X_d (k_x + k_r^2)^2}. \quad (15)$$

The maximum value of the reactive synchronous torque is obtained for the internal angle $\theta_{kdq} = 45^0 - \alpha_{dq}$ and is computed with the relation

$$M_{kdq} = \frac{mU^2}{2\Omega_1} \cdot \frac{1 - k_x}{X_d (k_x + k_r^2)^2} \cdot \quad (16)$$

$$\cdot [\sqrt{(k_x - k_r^2)^2 + k_r^2 (1 + k_x)^2} - k_r (1 - k_x)]$$

In order to extend the possibilities for the comparison of the different motors performances per unit quantities are used,

$$M^* = \frac{M}{M_b}, \text{ respectively } M_k^* = \frac{M_k}{M_b}, \quad (17)$$

where the basic torque is

$$M_b = p \frac{3 U_N I_N}{2\pi f_1}. \quad (18)$$

3. 3. PARAMETERS INFLUENCE ON THE TORQUE

In order to emphasize the armature winding parameters influence, some MATLAB programs have been achieved and with their help there have been plotted the dependences of the maximum reluctance torque (fig. 1) and of the internal angle for which this one is obtained (fig. 2) versus the factors k_x and k_r; the angular characteristics for a few particular cases have also been plotted (fig. 3 ÷ fig. 7).

The study has been made for a three-phase reluctance synchronous motor rated at: P_N=1,5 kW, U_{Nf} = 220 V, I_{Nf} = 3,8 A, m = 3, f_1 = 50 Hz, n_1=1500 r.p.m.

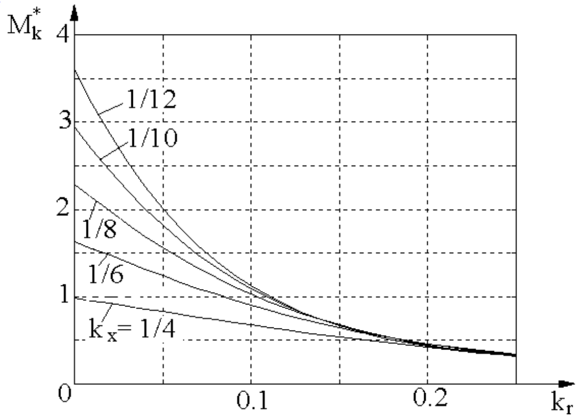

Fig. 1 - Characteristics $M_k^* = f(k_r)$

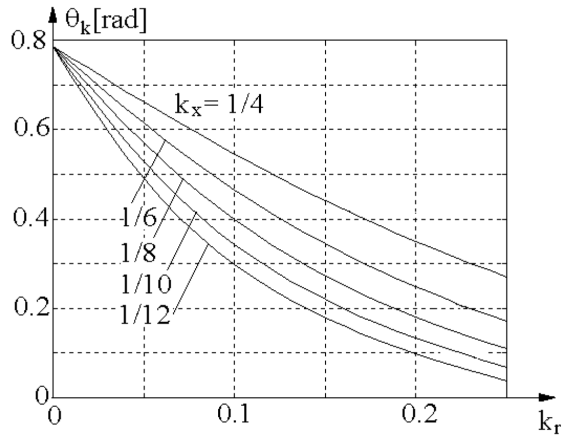

Fig. 2 - Characteristics $\theta_k = f(k_r)$

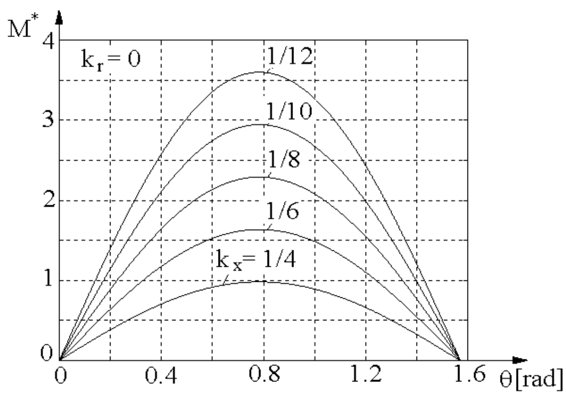

Fig. 3 - Characteristics $M^* = f(\theta)$, for $k_r = 0$

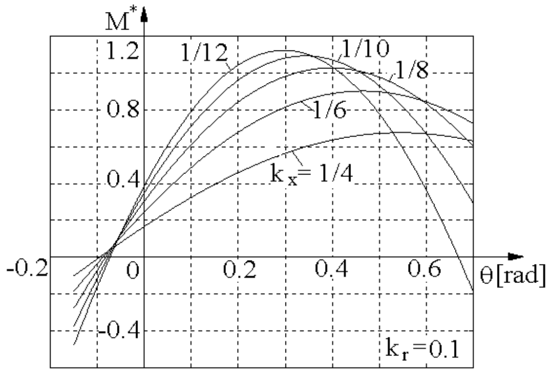

Fig. 4 - Characteristics $M^{*} = f(\theta)$, for $k_r = 0.1$

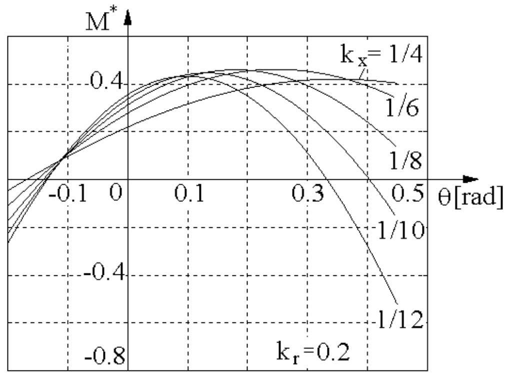

Fig. 5 - Characteristics $M^{*} = f(\theta)$, for $k_r = 0.2$

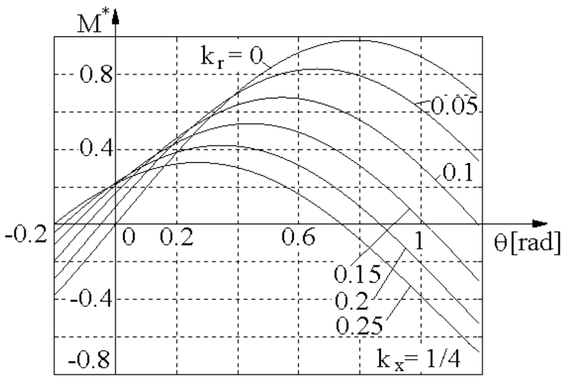

Fig. 6 - Characteristics $M^{*} = f(\theta)$, for $k_x = 1/4$

4. EXPERIMENTAL DETERMINATIONS

A few experimental results will be presented further on; they justify the conclusions obtained in the previous chapter. Thus, in order to catch experimentally the influence of the *armature resistance influence on the maximum torque* developed by the motor, the scheme depicted in the following figure has been used.
The notations used in the previous figure are as follow:
RSM – reluctance synchronous motor;

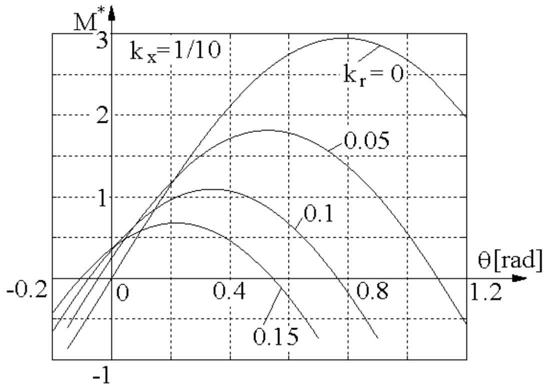

Fig. 7 - Characteristics $M^{*} = f(\theta)$, for $k_x = 1/10$

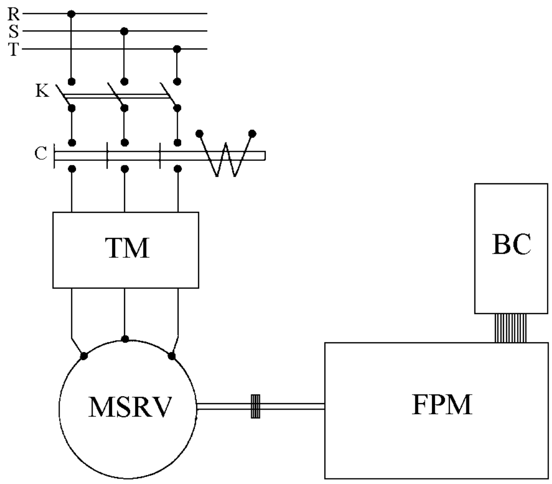

Fig. 8 - Scheme for determination of the maximum torque

TM – three phase measurement system;
FPM – magnetic powder breaking device;
BC – command block of the breaking device.

The maximum torque has been determined experimentally in three situations, the obtained results being filled in the following table.

Table 1

Total resistance of the armature circuit [Ω]	I [A]	$M_{k\ measured}$ [Nm]	$M_{k\ simulated}$ [Nm]
5,2	7	10	9,7
6,7	6	8,75	9
10,2	5,6	7,5	8

The simulations results obtained for the cases corresponding to the three situations are depicted in the following figures.

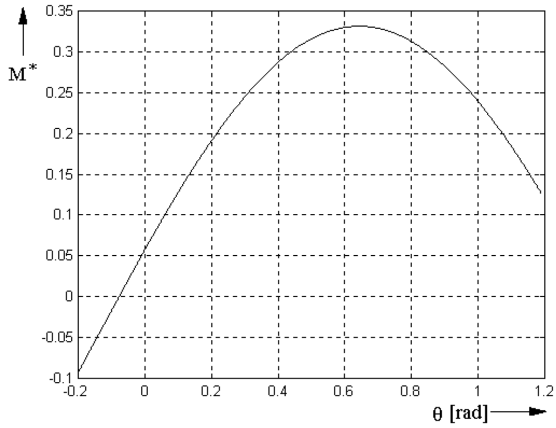

Fig. 9 - Static angular characteristic corresponding to the case 5.2 Ω

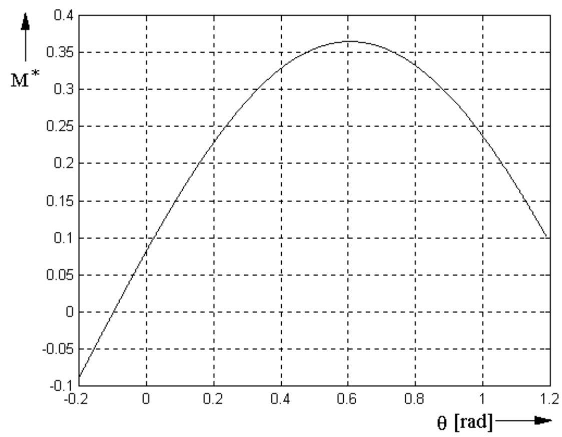

Fig. 10 - Static angular characteristic corresponding to the case 6.7 Ω

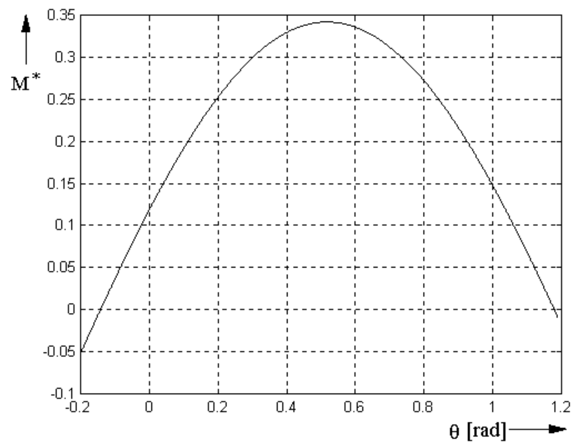

Fig. 11 - Static angular characteristic corresponding to the case 10.2 Ω

In the first case (fig. 9), in accordance with [5], the base torque M_b, which is related to, is:

$$M_b = p\frac{3\cdot U\cdot I}{2\cdot\pi\cdot f} = 2\frac{3\cdot 220\cdot 7}{2\cdot\pi\cdot 50} = 29{,}4 \text{ Nm.} \quad (19)$$

So, the maximum torque obtained by graphic will be:

$$M_{k_{simulated}} = 0{,}3313\cdot 29{,}4 = 9{,}7 \text{ Nm.} \quad (20)$$

In the second case (fig. 10), by doing as in the previous case, the torque M_b, which is related to, is:

$$M_b = 25{,}2 \text{ Nm.} \quad (21)$$

The maximum torque, obtained by graphic, has the value:

$$M_{k_{simulated}} = 0{,}3646\cdot 25{,}2 = 9{,}0 \text{ Nm.} \quad (22)$$

In the third case (fig. 11), the torque M_b, which is related to, is:

$$M_b = 23{,}5 \text{ Nm.} \quad (23)$$

The maximum torque, obtained by graphic, has the value:

$$M_{k_{simulated}} = 0{,}3418\cdot 23{,}5 = 8{,}0 \text{ Nm.} \quad (24)$$

It is noticed that the experimentally obtained results confirm in qualitative and quantitative manner the conclusion regarding the interdependence between the maximum torque and the total value of the resistance of the armature circuit.

5. CONCLUSIONS

The following conclusions, resulting from the ones presented before, can be emphasized:

- the greater the magnetic asymmetry degree is, the best the RSM technical performances (over-loading capacity and power factor) are (fig. 1, 3, 4). This thing justifies the preoccupation for the development of the rotor constructive solutions with distributed anisotropy;

- the armature winding resistance value cannot be neglected anymore and it must be taken into account in the case of the low power reluctance synchronous motors;

- it is noticed that this parameter has a negative influence, materialized in decreasing the zone of stable operation ($\theta_{kdq} < \pi/4$) and in decreasing the maximum torque (fig. 1, 2, 6, 7). It is mentioned that for relatively increased values of the winding resistance ($k_r > 0{,}15$), the advantages obtained by increasing the magnetic asymmetry degree become unessential (fig. 1, 5);

- when designing the reluctance synchronous motors it is recommendable that, at the same time with the rated power decrease, the supply voltage to be also decreased; in this way the winding resistance value is kept under a certain limit. It is also aimed to obtain an as great as possible value for X_d, by adopting a small air-gap, the both solutions leading to the decrease of the ratio k_r.

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