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THE INFLUENCE OF THE ROTOR POLE SHAPE ON THE STATIC EFICIENCY OF THE SWITCHED RELUCTANCE MOTOR

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Abstract: *This paper presents results of reductor switched reluctance motor static simulations by means of Finite Element Method. The dependence between machine performances and its rotor pole shape and electrical load, is studied and the results are displayed as curves, which offer a clear images of optimum geometry in terms of connection modes of each phase.*
Key words: *reductor switched reluctance motor, finite element method, rotor geometry, connection modes of phase*

1. INTRODUCTION

The optimization in the electrical machines field is now a process developed under Finite element method (FEM) technologies. The easy way to accomplish the non linearity and the complicated structure of the materials, great accuracy of the simulation, reduced costs, speed of analysis permit to take into account a lot of models and choose the best fitting of a desired imputed condition.

Two aspects that influence the reductor switched reluctance motor (RSRM) static efficiency are the points of interest in this paper: the rotor pole shape, more specifically the slot width per tooth width ratio, β and the connection modes of each phase.

Identifying the values of β ratio, for all the connection modes of phase tucked into account, which realize the maximization of the specific torque, T_S maximum static torque per rotor volume unit, is an important step in RSRM design and optimization.

2. RSRM SPECIFIC TORQUE AS THE OPTIMIZATION FUNCTION

To serve as an optimization function the specific torque must be expressed in terms of the variables above. Taking into account the leakage function $k_d\ (i,\ \theta)$, with θ the geometric angle of rotor position versus stator, the flux linkage produced by N turns/phase can be written, pointed the magnetizing flux, ϕ_{fu}:

$$\Psi(i,\theta) = \frac{N \cdot \phi_{fu}(i,\theta)}{k_d(i,\theta)}, \tag{1}$$

Defining the corresponding magnetizing linkage permeance, $\Lambda(i,\theta)$ as a function:

$$\Lambda(i,\theta)=\frac{\phi_{fu}(i,\theta)}{Ni}, \tag{2}$$

the static torque, computed by virtual work method become:

$$T(\theta,i)=\frac{\partial W'(\theta,i)}{\partial\theta}=\frac{\partial}{\partial\theta}\sum_{1}^{k}\left(\int_0^i\Psi_k(\theta,i)di\right)=\frac{\partial}{\partial\theta}\int_0^i\frac{N^2\cdot i}{k_d(i,\theta)}\Lambda(\theta,i)di, \tag{3}$$

Two hypotheses must be introduced to offer the generalities:

- the permeance along the axial direction of the machine is equal in each transversal section, the end effect is neglected,
- the permeance is proportional with the number of teeth per stator pole,

Writing the following relation between geometrical parameters:

$$c=\frac{\pi D}{Z_R}\cdot\frac{\beta}{\beta+1}, \tag{4}$$

the permeance becomes:

$$\Lambda(\theta,\mathrm{NI},\mathrm{geometry})=Z_p\cdot l\cdot\Lambda'(\theta,\mathrm{NI},\frac{\mathrm{D}}{\delta},\beta,\frac{h}{\delta}), \tag{5}$$

Relation (3) leads to an expression for maximum static torque, impossible to handle in analytical mode, but very easy to solve by FEM:

$$T_{\max}=Z_p\cdot l\cdot\alpha(NI,\frac{D}{\delta},\beta,\frac{h}{\delta}), \tag{6}$$

The specific torque, maximum torque per volume unit, is:

$$T_s=\frac{T_{\max}}{Volume}=\frac{4Z_p}{\pi D^2}\cdot\alpha(NI,\frac{D}{\delta},\beta,\frac{h}{\delta}), \tag{7}$$

which is a function of motor geometry and ampere-turns, but compulsory to be maximized for all composing mode of the phase winding.

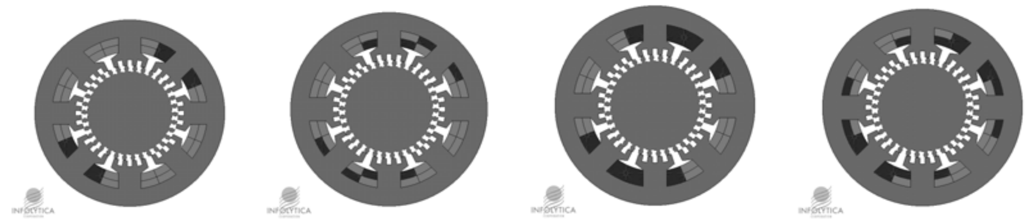
3. REDUCTOR SWITCHED RELUCTANCE MOTOR GEOMETRY AND CONNECTION MODES OF PHASE

First, a base model of RSRM is constructed, *fig.1*.

Fig. 1. *RSRM base model*

The active materials used are cooled rolled 1010 steel and electro technical cooper. The main characteristics are: voltage, *U=220 V,* the step angle*,* $\theta_p=2.65\,^o$*,* number of phases*, m=4,* number of teets per rotor and stator pole, $Z_R=34$ and $Z_P=4$, yoke width, $h_{js}=17$ *mm*, stator pole height and width, $h_m=16$ *mm*, respectively $b_m=23$ *mm*, stator pole shoe height, $h_p=14$ *mm*, maximum torque, $T_{max}=44.855$ *Nm*, at *200 A turns*, in connection 2 (see next paragraph), tooth and slot width (considered the same for stator and rotor), *a=4.5 mm* and *c=4.5 mm,* air gap length*,* $\delta=0.28$ *mm,* tooth length*, h=6mm,* stack length*, l=175 mm*.

On each stator pole there are placed two, 50 turn-coils, allowing to create four connections, shown and named in *fig.2*, the energized coils being black filled.



connection 1 *connection 2* *connection 3* *connection 4*

Fig. 2. *Connection modes of phase*

Connections 1 and 2 generate 200 turns per phase and connections 3 and 4, 400 turns per phase.

4. FEM APPLIED TO RSRM MAGNETIC FIELD COMPUTATION

Magnetic field distribution inside the RSRM is given by the Maxwell equation, reduced to static regime and can be expressed by a vectorial Poisson equation:

$$\nabla \times \left(\frac{1}{\mu(B)} \nabla \times \overline{A} \right) = \overline{J} \,, \tag{8}$$

FEM solving of (8), trough its associated functional:

$$F(\overline{A}) = \frac{1}{2} \iiint_V \frac{1}{\mu_r} (\nabla \times \overline{A}) \cdot (\nabla \times \overline{A}) dV - \mu_0 \iiint_V \overline{J} \cdot \overline{A} dV \,, \tag{9}$$

allows calculating the torque by virtual work method, (3), or using Maxwell stress method, integrating the component of stress:

$$\overline{F} = \oint_S \left(\overline{H}\left(\overline{B}\overline{n}\right) - \frac{1}{2}\left(\overline{H}\,\overline{B}\right)\overline{n} \right) dS \,, \tag{10}$$

over a rotor enclosed surface, passing entirely trough air.

The ratio β was modified to cover the 0.5 to 2 interval for each connection modes of phase. Rotor diameter, air gap length and tooth length are invariable so from relations (6) and (7) it's easily seen that the evolution of specific torque in terms of ratio β and ampere turns per phase is the same as the maximum torque.

Nine rotor positions were analyzed for each model, the zero angle corresponding to the maximum torque and ± θ_p for the aligned and unaligned position.

All FEM analyses were made using Infolytica Magnet 6.11 software, [5].

In *fig.3* the final mesh and the magnetic field spectrum for connection 1, *I=10 A, β=1* in unaligned position are exemplified.

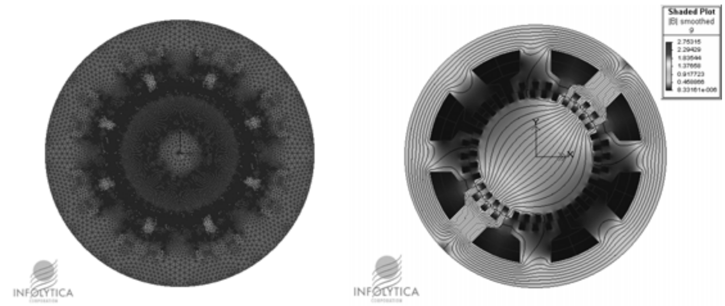


Fig. 3. *RSRM final mesh and magnetic field spectrum*

Before the FEM simulations the necessarily settings to be operate in Magnet 6.11, to keep a healthy balance between accuracy and computational costs were tested. These are referred to as “h-refinement”, sated to 60% of total elements, “p-refinement” to second order polynomial interpolation and the outer periphery of the stator treated as zero magnetic vector potential line.

5. RESULTS

The searched results of FEM analysis are the static torques for different rotor position, especially their maximum values. An example for the configuration mentioned above is shown in *fig. 4*.

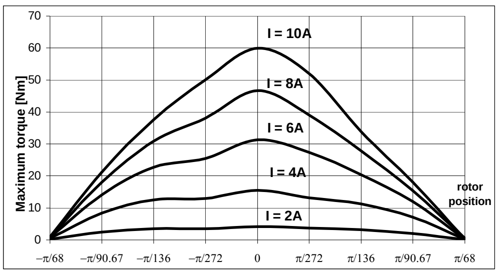
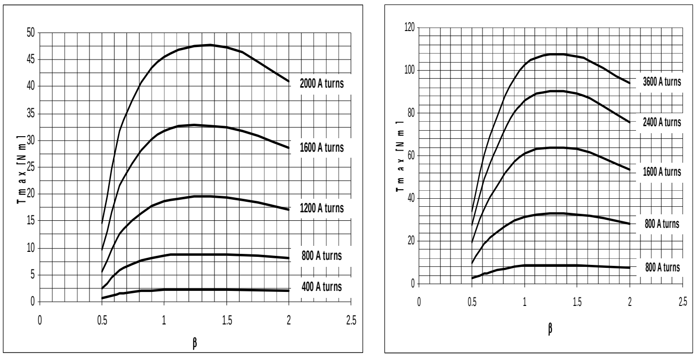


Fig. 4. *RSRM static torques for different rotor position*

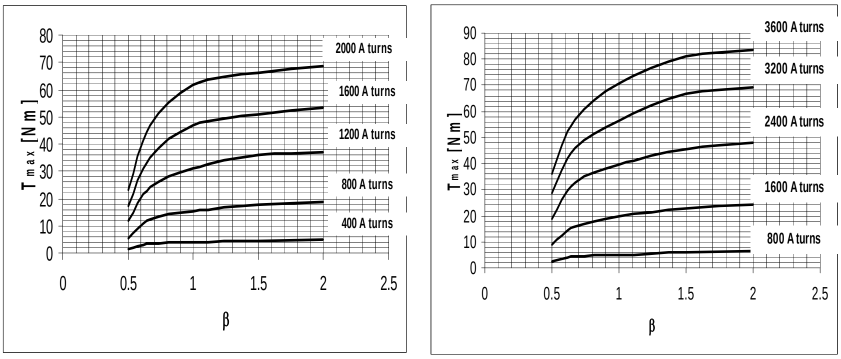
The most representative way to interpret such a huge volume of discrete data is based on polynomial interpolation, done by MathCAD 7.0 software.

Representing the variations of maximum specific torque in terms of slot width per tooth width ratio with ampere turns per phase as a parameter, for connection modes of phase 2 and 3, *fig. 5*, respectively 1 and 4, *fig.6*, the optimum configuration of RSRM can be select.



connection 2 *connection 3*

Fig. 5. *RSRM maximum* s*tatic torques for different* β *ratio*



connection 1 *connection 4*

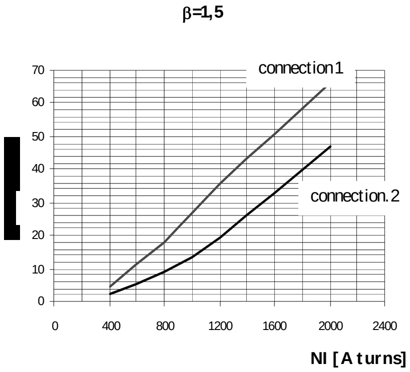
Fig. 6. *RSRM maximum* s*tatic torques for different* β ratio

Comparing the results by means of connection modes of phase it's clearly outlining the different comportment of maximum torque when the energized coils are placed on two opposite poles per phase (connection 1) or on six poles per phase (connection 4) instead on four poles per phase placement.

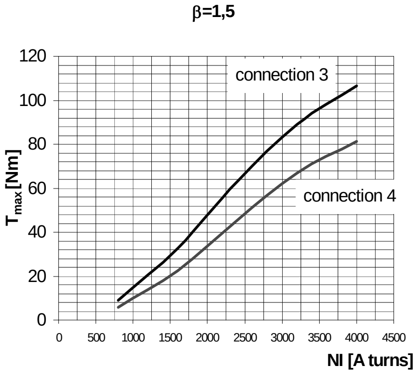
In second case the optimum values of β ratio vary between 1.2 and 1.4. The variation of maximum torque, identically with the specific torque is bigger than 200%, between $\beta=0.5$ and $\beta=1.3$.

For connections 3 and 4, β must be as close to 2 as it's possible by means of magnetic material saturation. For analyzed base model the raising values of β goes to raising values for torque but the saturation make the effect less important for β closed to 2.

To analyses the connection modes of the phase, those with the same number of turns, were compared, namely connection 1 and 2, respectively 3 and 4, exemplified in *fig. 7*, both for $\beta=1.5$.



connections 1 and 2



connections 3 and 4

Fig. 7. *RSRM maximum* s*tatic torques for different connection modes of phases*

The conclusions resulted, impose connection 1 in the detriment of connection 2 up to the electrical loading of 8000 A/m and show the better efficiency of connection 3, for any electrical loading, as compared to connection 4. Some values of extra torque produced by connection 1 versus connection 2 are summarized: 88.07% at 1300 A/m, 35% at 6500 A/m for $\beta = 1$; 111.4% at 1300 A/m, 39.78% at 6500 A/m for $\beta = 1,5$; 143.69% at 1300 A/m, 67.56% at 6500 A/m for $\beta = 2$.

6. CONCLUSIONS

This paper has developed a strategy to deal with reductor switched motor specific torque as an optimization function, ready to be maximized using Finite Element Method static simulations. It was kept as variables in the process only the slot width per tooth width ratio but covering four different connection modes of phase.

The results are presented in a very suggestive form by combining the FEM analysis with polynomial interpolation.

For each type of connection modes of phase, using one or both coils from a stator poles and two up to six poles per phase, the optimum values of β is outlined.

Also a discussion of the comparative eficiency of those connections is made.

Of course a complete RSRM static efficiency can be carried out tacking into account all the variables involved in relation (7).

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