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A simple and Efficient Tool for Design Analysis of Synchronous Reluctance Motor

T. Hamiti, T. Lubin, and A. Rezzoug

Abstract—This paper presents an efficient tool for design analysis of a Synchronous Reluctance Motor (SynRM). The Winding Function Analysis (WFA) is used instead of the Finite Element Analysis (FEA). With WFA approach, parameters sensitivity analysis and the impact on the machine design can be evaluated very rapidly (under linear condition). The effect of rotor skewing, stator winding chording, pole arc and interpolar air-gap length on average torque and torque ripple is investigated. The results obtained by WFA are compared with those obtained by two-dimensional FEA. It is shown that the two methods give approximately the same results but require different computation time.

NOMENCLATURE

R	.....	Rotor outer radius (m).
L	.....	Active axial length (m).
Ne	.....	Number of stator slots.
W	.....	Number of turns in series per phase.
α	.....	Angular position along the stator inner surface (rad).
θ	.....	Electrical angular position of the rotor (rad).
$e_s(\theta)$	.....	Rotor air-gap length function (m).
$e_r(\alpha - \theta)$	.....	Stator air-gap length function (m).
i_a, i_b, i_c	.....	Currents of phase a, b and c respectively (A).
L_a, L_b, L_c	.....	Self inductance of phase a, b and c (H).
L_{ab}, L_{bc}, L_{ca}	.....	Mutual inductances (H).
Γ	.....	Instantaneous torque (N.m).
Γ_{avg}	.....	Average torque (N.m).
$\Delta\Gamma$	.....	Torque ripple (%).
$e1$	.....	Air-gap length (mm).
$e2$	.....	Interpolar air-gap length (mm).
β	.....	Pole arc (degree).
δ	.....	Skewing angle (degree).
k	.....	Chording factor.

I. INTRODUCTION

SYNCHRONOUS reluctance motor is an interesting solution for variable frequency drives and servomechanisms [1], [2]. In its cut-outs rotor version, despite poor efficiency and power factor, its cost manufacturing, ruggedness and synchronism with power supply frequency can constitute a good challenge, while an optimal design for maximum torque and minimum torque ripple must be achieved. To maximise average torque and power factor of a line-start SynRM, an

analytical design model is proposed in [3]. However, it does not take into account torque ripple which is a serious drawback especially when position control is needed. Furthermore, the motor was designed for self starting operation, thus it contains a squirrel cage which adds an other constraint for the design task, and is subject to additional losses. Vector control permits synchronous self starting without damping bars.

X. Bomela and M.J. Maarten have done a consisting study on stator chording and rotor skewing effect on average torque, power factor and torque ripple [4]. This study has been evaluated with FEA which is, as known, very time consuming. Broadly, very much attention is given for high anisotropy normally or axially laminated flux barrier SynRM [5], [6]. With this type of structure, high performance drives can be achieved but the manufacturing simplicity is lost.

We have shown in [7] that accurate shapes of inductances and electromechanical torque can be obtained using the winding function theory. The computation quickness of this method constitutes its main advantage when several stator and rotor geometries are to be tested, also when a refined model of the machine must be inserted within a complex simulation control scheme.

This paper proposes a use of Winding Function Analysis to design an optimized SynRM in terms of average torque and torque ripple. The cross-section of the stator and the rotor structure of the studied SynRM is shown in Fig.1. The rotor presents a simple and robust structure without damper bars. The stator is the same as the one of an induction machine and has 3 phases distributed winding within 36 slots. The machine dimension details are given in table I.

Table I
DIMENSIONS OF THE MACHINE

Symbol	Quantity	Value
p	Number of pole pairs	2
R	Rotor outer radius	0.045m
e1	Air-gap length	0.26mm
W	Number of turns in series per phase	29
Ne	Number of stator slots	36
L	Active axial length	0.155m
β	Pole arc	Variable
e2	Interpolar air-gap length	Variable
δ	Skewing angle	Variable
k	Chording factor	Variable

II. COMPUTATION PROCEDURE AND RESULTS

A. Winding Function Analysis (WFA)

Winding function theory [8], gives the self and mutual inductances expression as:

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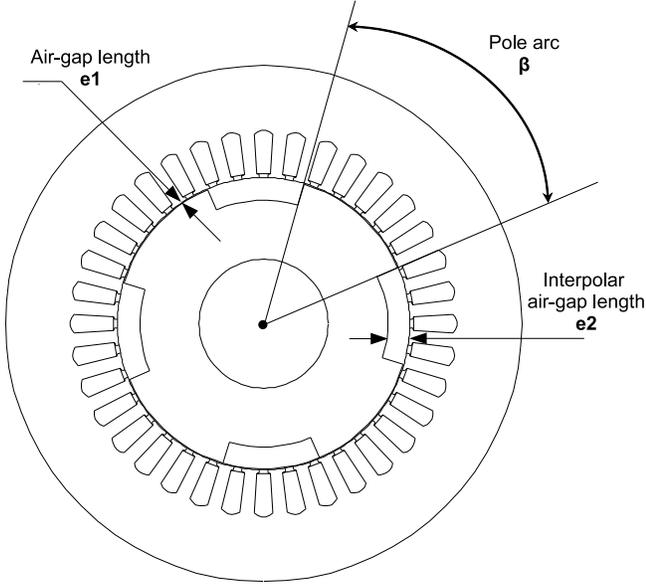


Fig. 1. Cross-section of the studied SynRM.

$$L_{ij} = \mu_0 R L \int_0^{2\pi} \frac{1}{e_s(\theta) + e_r(\alpha - \theta)} N_i(\alpha) N_j(\alpha) d\alpha. \quad (1)$$

In this expression, $N_i(\alpha)$ is called the winding function i and represents in fact the magnetomotive force distribution along the air-gap per unit current flowing in the stator winding i . The rotor and stator air-gap length functions $e_r(\alpha - \theta)$ and $e_s(\alpha)$ of the studied SynRM have been defined in [7].

The instantaneous torque computation is obtained by:

$$\Gamma = \frac{1}{2} [\mathbf{I}]^t \left[\frac{\partial \mathbf{L}}{\partial \theta} \right] [\mathbf{I}], \quad (2)$$

with:

$$[\mathbf{L}] = \begin{bmatrix} L_a(\theta) & L_{ab}(\theta) & L_{ac}(\theta) \\ L_{ab}(\theta) & L_b(\theta) & L_{bc}(\theta) \\ L_{ac}(\theta) & L_{bc}(\theta) & L_c(\theta) \end{bmatrix}, \quad (3)$$

and:

$$[\mathbf{I}] = \begin{bmatrix} i_a(\theta) \\ i_b(\theta) \\ i_c(\theta) \end{bmatrix}. \quad (4)$$

For a given structure of the machine, (1) is numerically integrated after the definition of winding and air-gap functions [7]. For each rotor position, (2) is computed with the following imposed currents:

$$\begin{aligned} i_a &= \sqrt{2} I_{rms} \cos(\theta + \phi); \\ i_b &= \sqrt{2} I_{rms} \cos\left(\theta - \frac{2\pi}{3} + \phi\right); \\ i_c &= \sqrt{2} I_{rms} \cos\left(\theta + \frac{2\pi}{3} + \phi\right). \end{aligned} \quad (5)$$

To avoid saturation I_{rms} is fixed to 2A and the electrical current phase ϕ is fixed to 45° in order to develop the maximum average torque.

B. study of parameters sensitivity

To minimize the ratio of the torque ripple $\Delta\Gamma$ to the average torque Γ_{avg} , the skewing angle δ , the chording factor k , the pole arc β and the interpolar air-gap length $e2$ have to be considered (Table I).

Every parameter influence is studied by calculating

$$\Gamma_{avg} = \frac{1}{N_p} \sum_{i=1}^{N_p} \Gamma(i); \quad (6)$$

$$\Delta\Gamma = \frac{\max(\Gamma) - \min(\Gamma)}{\Gamma_{avg}}, \quad (7)$$

N_p is the number of points over one computation period. 3600 points ensure a satisfying precision.

1) Effect of rotor skewing (δ)

To reduce the ripple torque caused by the slots, the well known technique is the skewing.

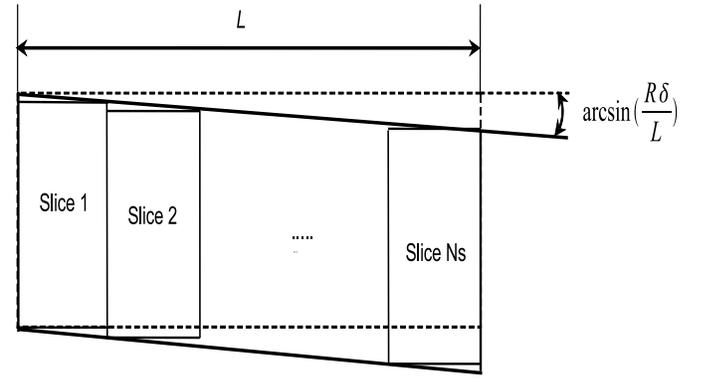


Fig. 2. Axial view of the skewed rotor.

To simulate the 3D effect generated by the skewing, multiple 2D unskewed submachines are considered as shown in Fig.2 [9]. With WFA, thanks to the refined path resolution ($N_p = 3600$), computing only the average value over N_s points of the unskewed inductances, we obtain the skewed inductances as:

$$L_{sk_i} = \frac{1}{N_s} \sum_{r=-\frac{N_s}{2}}^{-\frac{N_s}{2}+1} L_i(r), \quad (8)$$

$$M_{sk_{ij}} = \frac{1}{N_s} \sum_{r=-\frac{N_s}{2}}^{-\frac{N_s}{2}+1} M_i(r), \quad (9)$$

N_s is the integer number of the skewing angle/path resolution (0.1°) ratio. After computing (8) and (9), the torque is obtained by (2). With FEA software [10], because of the required time computation, the path angle resolution is 1° , we can't obtain the skewed torque by averaging. Hence, to compute correctly the skewed torque, 10 slices must be taken.

Figs 3 and 4 show the inductances and the instantaneous torque for unskewed and one slot pitch (10°) skewed rotor. Differently of flux barrier rotor SynRL [5], the salient poles SynRL becomes free of slots ripple torque with exactly a

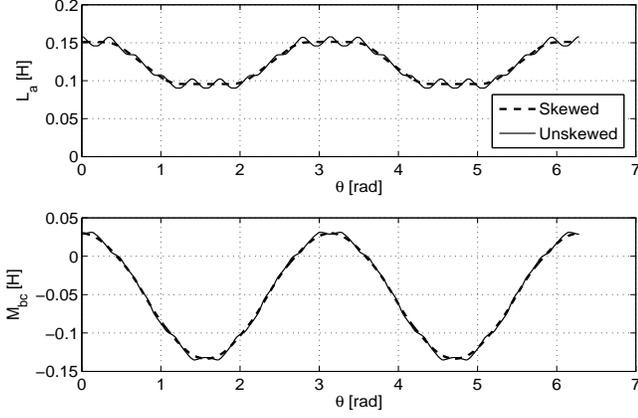


Fig. 3. Self- and mutual- skewed ($\delta = 10^\circ$) inductances, with $\beta = 0.5$, $e_2 = 10\text{mm}$, not chorded winding, skewed rotor.

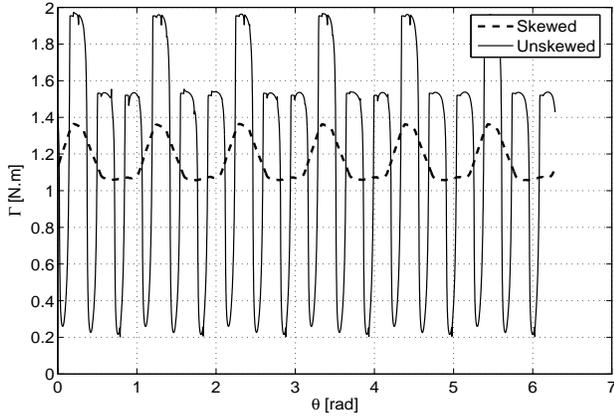


Fig. 4. Torque of skewed ($\delta = 10^\circ$) and unskewed machine.

full stator slot pitch. The residual torque ripple is due to the distributed winding and the rotor saliency.

The influence of the skewing angle on both average and ripple torque is shown in Fig.5. It illustrates the optimum skewing angle ($\delta = 10^\circ$) that is pointed on above. In this case we denote a reduction of torque ripple from 130% up to 26% and a decrease of average torque by only 3%.

2) Effect of stator winding chording (k)

The effect of stator winding chording on the torque ripple and average torque is investigated by varying the fractional pitch windings. Fig.6 represents the winding functions of the phase "a" in the cases of full pitch winding and $\frac{7}{9}$ chorded winding. It has been shown in [4] that chording the stator of a flux barrier SynRL has a very little effect on the torque ripple. That is false in our case. Indeed, Fig.7 shows an important reduction of torque ripple without a sensitive drop on the average torque for a chording factor of $\frac{8}{9}$ whatever β .

3) Effect of the pole arc (β)

The saliency angle is a deterministic parameter for a cut-outs rotor SynRM. In [3], an optimum angle of 45° was found.

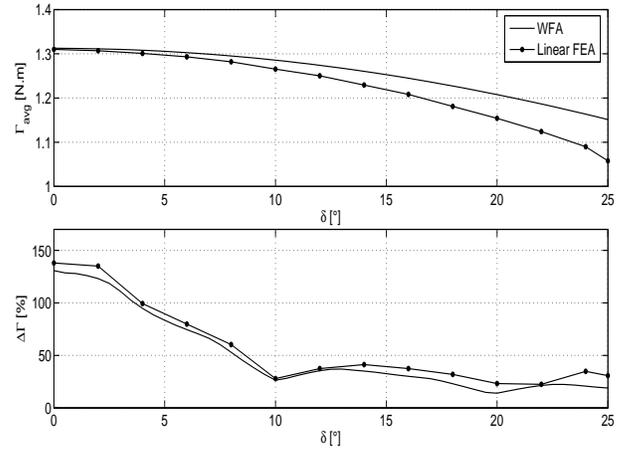


Fig. 5. Average torque and torque ripple vs skewing angle.

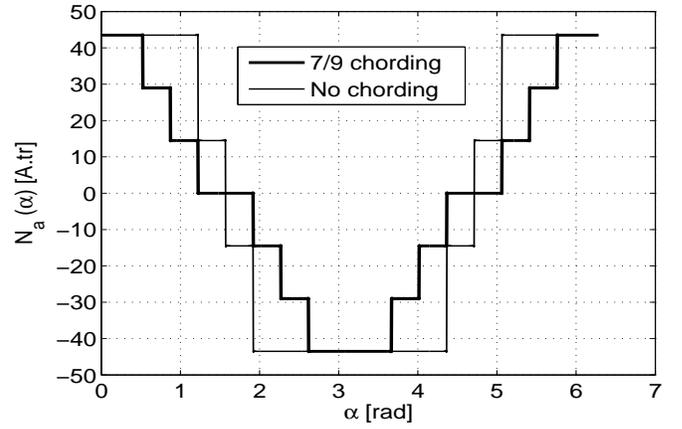


Fig. 6. No chording and $\frac{7}{9}$ chording winding function of the phase "a".

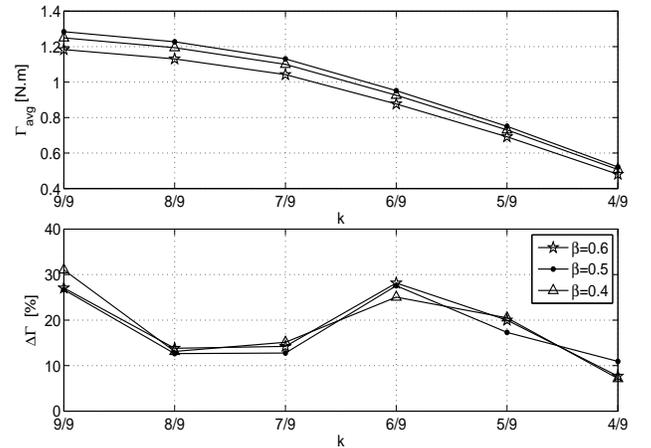


Fig. 7. Average torque and torque ripple vs chording factor of the skewed ($\delta = 10^\circ$) machine.

However, no attention has been given to the influence of this parameter on torque ripple. Fig.8 shows the effect of the pole arc (β) on both the average and ripple torque. The optimum β for maximum average torque is 43° and for minimum torque ripple is 44° . With FEA, the optimum angle is 40° for both

ripple and average torque. However, we can observe that the curves are relatively flat in the interval $[40^\circ, 45^\circ]$, we can thus choose an angle within this interval. It is important to note that even not 1 minute is required to compute the whole skewed torque with WFA against more than 2 hours with FEA.

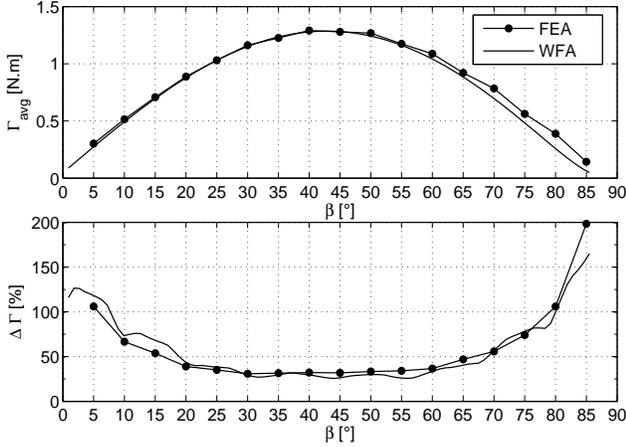


Fig. 8. Average torque and torque ripple vs β of the skewed ($\delta = 10^\circ$) machine.

4) Effect of the interpolar gap length (e_2)

The interpolar gap length has been defined in Fig.1. Its influence is also studied and the results are shown in Fig.9. We can observe that beyond the value of approximately 20 for the ratio $\frac{e_2}{e_1}$ the average and ripple torque are not subject to sensitive variation. Moreover, this low value is beneficial for mechanical ruggedness and for a judicious choice of rotor yoke length to avoid flux path undersizing.

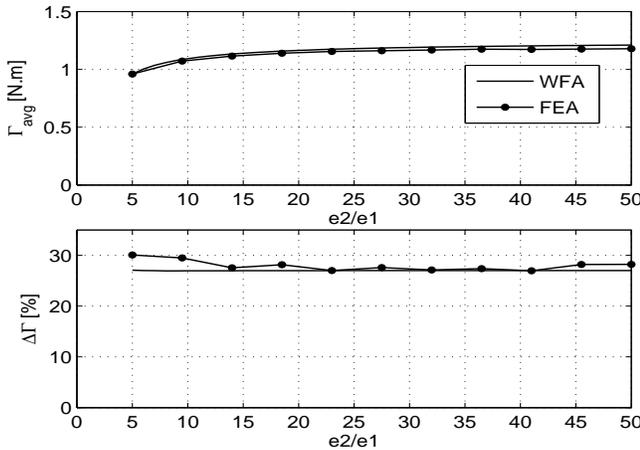


Fig. 9. Average torque and torque ripple vs interpolar gap length e_2 to air-gap length e_1 ratio of the skewed ($\delta = 10^\circ$) machine.

III. EFFECT OF THE MAGNETIC SATURATION

In order to check if the magnetic saturation have an influence on the optimized parameters obtained by WFA, FEA is used by considering a nonlinear magnetic $B(H)$ characteristic and an I_{rms} value of 6A. Fig.10 shows the superposed results of the two methods and leads to the following observations.

Firstly, the optimum pole arc stay the same for both linear and nonlinear cases. Secondly, as commonly known, the average produced torque is strongly decreased by the saturation.

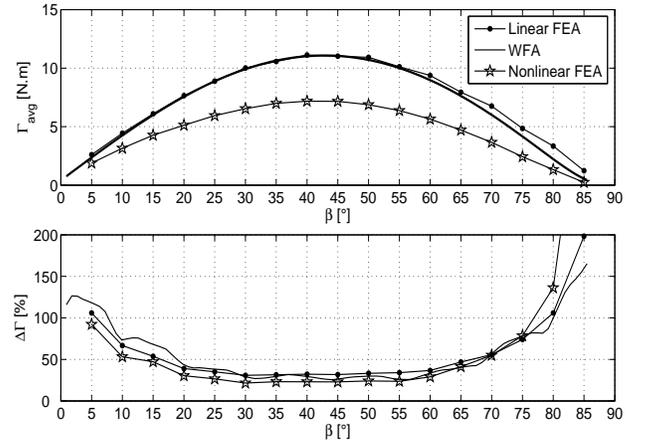


Fig. 10. Average torque and torque ripple vs β of the skewed ($\delta = 10^\circ$) machine.

IV. PROTOTYPE REALIZATION

The prototype reluctance motor is designed on the basis of a standard 4-pole, 3kW squirrel cage induction motor. The stator of the considered motor contains 36 slots with three phase full pitch winding ($k = \frac{9}{9}$). The skewing angle of the rotor bars being equal to 13° determines the direction of milling to obtain the rotor salient poles. The manufactured rotor is shown in Fig.11. It has the following parameters : $\beta = 45^\circ$, $e_2 = 10mm$ and $\delta = 13^\circ$. To avoid damping effect, the rotor end-rings are cut-off. As demonstrated previously, the best values of the chording factor k and skewing angle δ are respectively $\frac{8}{9}$ and 10° . One can observe in Fig.5 that the curve representing the torque ripple versus δ is relatively flat between $\delta = 10^\circ$ and $\delta = 15^\circ$, so the chosen skewing angle is suitable to verify the theory. To investigate the chording effects on the torque ripple, in addition to the original stator with $k = \frac{9}{9}$, another one having $k = \frac{8}{9}$ is currently under construction. Experimental tests will be done in futur work in order to validate the theoretical results.

V. CONCLUSION

An entire study of a four pole, 36 slots and three phases SynRM is done with a simple and fast computation method based on Winding Function Theory. The improvement of the method is verified with Finite-Element Analysis. It is shown that to obtain minimum torque ripple and maximum average torque, the rotor must be skewed by a stator slot pitch, a chording factor of $\frac{8}{9}$ ensure a good compromise, no necessity to have a very large interpolar air-gap length (a value of 20 times e_1 is sufficient) and the optimal pole arc is around 45° . An optimized rotor prototype has been manufactured by milling the one of an existing induction machine. Futur work consists on experimental validation of the theoretical results.

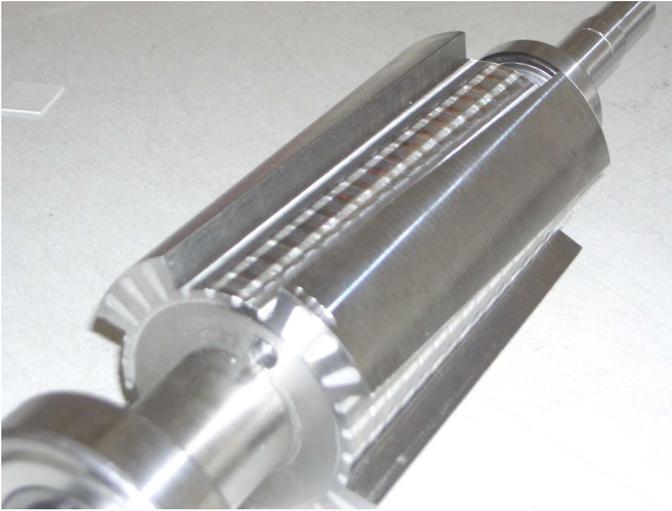


Fig. 11. Photography of the prototype rotor.

Furthermore, as the proposed method is not time consuming, it can be easily used within a global design optimization task. For that, one can use for example genetic algorithms or sequential quadratic programming.

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