Effects of Different Rotor and Stator Constructions on The Performance of Switched Reluctance Motors

CANER AKUNER
Electrical Department
Marmara University Technical Education faculty
Goztepe Campus, Kadikoy/Istanbul/Turkey

DURMUS UYGUN
Electricity Programme
Bozok University, Akdagmadeni Technical Vocational School of Higher Education
Akdagmadeni, 66300 Yozgat, TURKIYE.

Abstract: - This paper is carried out to develop a theoretical model for the simulation of 8/6-pole and 6/4-pole switched reluctance motors and describes the difference of these kinds of motors in dynamic characteristics such as magnetic field energy, magnetic field coenergy, magnitude of B_v, magnetization losses, steady-state weighted stress tensor torque, mutual inductance and so in performance. As known; finite element method (FEM) has been a powerful tool to solve many complex problems in electromagnetics. Thus; it has been possible to determine the effects of different rotor and stator constructions on the performance of motors. The comparison of the dynamic output performance for each motor provides the basis for the discussion on the relationship of output performance of switched reluctance motor to its physical size [2]. In this study; we are going to develop a model using Femm 4.0 software with respect to some main geometric and electromagnetic characteristics and we will try to explain the differences between the motors mentioned above.

Key-Words: - Finite Elements, Switched Reluctance, Magnetic Energy.

1 Introduction

The finite element method (FEM) has been widely used as an analysis and design tool in many engineering disciplines like structures and computational fluid mechanics. Though FEM has been applied to electromagnetic problems, it was mainly confined to electrical machines and magnetics [1]. In this paper, we are going to examine switched reluctance motors having different physical sizes. Three and four phased SR motors with different rotor and stator constructions are used for comparison. These are 8/6-pole (8 geared stator and 6 geared rotor) and 6/4-pole (6 geared stator and 4 geared rotor) SR motors. Many significant research in the development of more appropriate numerical algorithms for a FEM study of SR machines has been done in the past years [6]–[9].

The numerical non-linear iterative calculation of two dimensional magnetic field in the switched reluctance motor is performed by the package software named as Femm 4.0. The relationship of output performance of the switched reluctance motors with different rotor and stator constructions is investigated using an analytical method as used in [5].

2 Finite Element Analysis And Switched Reluctance Motor FEM Models

It is normally very difficult to get closed-form solution for all geometries, especially for complex ones such as motors. But that was carried out since finite element method had been developed.

The idea of finite elements is to break the problem down into a large number regions (as shown in fig. 1), each with a simple geometry such as triangles. If enough small regions are used, the approximate potential closely matches the exact solution. Specifically, FEMM discretizes the problem domain using triangular elements. Over each element, the solution is approximated by a linear interpolation of the values of potential at the three vertices of the triangle. The linear algebra problem is formed by minimizing a measure of the error between the exact differential equation and the approximate differential equation as written in terms of the linear trial functions [4].

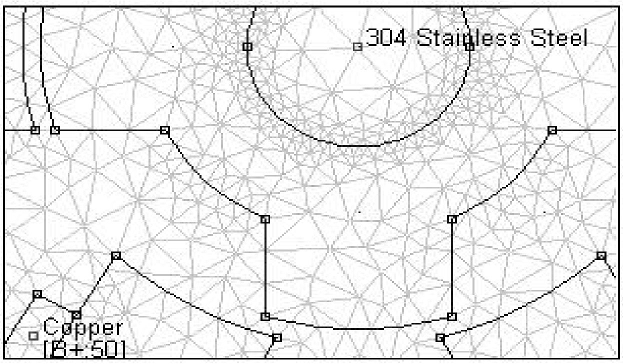


Fig. 1. Triangulation of the aimed system (Mesh mode)

2.1 The Types of SRM Analysed

The two different switched reluctance motors are used in this paper. One of them is three-phase SR motor having 6 geared stator and 4 geared rotor configuration and the other one is four-phase SR motor having 8 geared stator and 6 geared rotor configuration. A PC-based package software is used for the design of these two SR motors. The designs drawn are saved as *.dxf format in order to use them in Femm 4.0 package software.

2.2 Design of SR Motors

As shown below; the designed switched reluctance motors are drawn with the help of a CAD-based package programme. After they have been saved as *.dxf to be used in simulation software, each part of the motors and motor windings are named according to the metals they are constructed from such as M–45 steel, 304 stainless steel, copper, etc. It must not be forgotten to name air gap as "air".

We carry out the analysis on Femm 4.0 which is one of the general purpose circuit simulators.

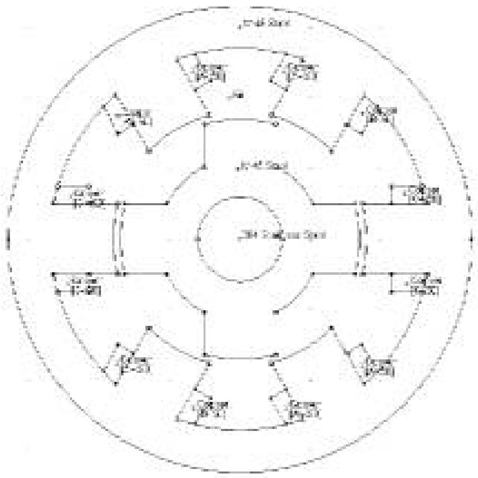


Fig. 2. Rotor and stator cross-section of 6/4 SR motor.

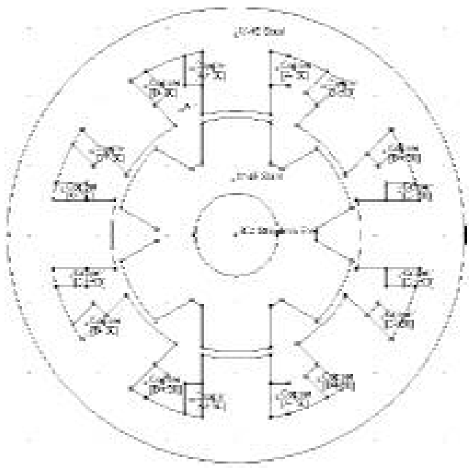


Fig. 3. Rotor and stator cross-section of 8/6 SR motor.

It must be emphasized that input and outputs of each phase must be shown as A+, B+, C-, C+, etc. and number of phase windings must be written such as 50, 100, etc.

2.3 The Magnetic Properties of SR Motors

Two-dimensional finite element method is used to analyze the magnetic characteristics of the motors. The solutions of the magnetic field energy, magnetic field coenergy, magnetization losses magnitude of B_y, steady-state weighted stress tensor torque, mutual inductance for each motor with different rotor and stator displacements are obtained.

The magnetization characteristics of switched reluctance motors are; the phase flux linkage $\psi(\theta,i)$, function of rotor position θ and phase current i. And these expressions are obtained by integrating the following equation [2];

$$\varphi(\theta,s) = \int_S \vec{B}.d\vec{S} = \int_S (\nabla x \vec{A}).d\vec{S} = \oint_I \vec{A}.d\vec{I} = L_{stk}\left[A(xj,yj) - A(xj,yj)\right] \quad (1)$$

From this equation;
L_{stk} = Stack lenght of the motor,
$\pm$ xj, yj = The points within the winding region.

When we consider the total winding turns as N_p, the first equation can be developed as;

$$\psi(\theta,i) = \frac{L_{stk}.N_p}{S_w}\left[\int_{S_{w1}} A(x,y).dS_{w1} - \int_{S_{w2}} A\right] \quad (2)$$

From this equation;
S_w = The winding crossing area,
S_{w1}/S_{w2}= The sides of the winding area.

And also, if the magnetic properties of switched reluctance motors are entirely wanted to be determined, the torque and energy conversations must be obtained. Within SR motors; the energy conversations are determined according to the graphic given below (mmc=magneto motor force):

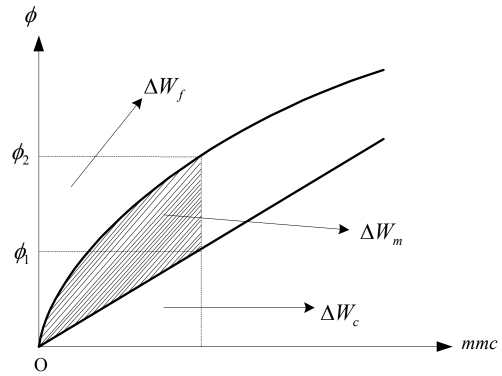


Fig. 4. The mechanical energy increasing.

From the graphic given above;
ΔW_f = The variation of field energy,
ΔW_m = The variation of mechanical energy,
ΔW_c = The variation of coenergy.

The variation of mechanical energy in SRM is determined by electromegnetic moment and the function of rotor position. And so we can configure this relation as;

$$\Delta W_m = T_e.\Delta\theta \quad (3)$$

Where;

ΔW_m = The variation of mechanical energy,
T_e = Electromegntic moment (Nm),
θ = Rotor position (degree).

In case of stable excitation (mmc is constant); the remaining work done is equal to the variation ratio in coenergy. In fact, there is not any coenergy. It is only complementary function of field energy. That is why, the remaining work done;

$$\Delta W_m = \Delta W_c \tag{4}$$

And so;

$$W_c = \int L(\theta, i) i.di \tag{5}$$

If "*i*" is constant, the equation is;

$$W(i,\theta) = \int_0^i \psi(i,\theta).di \tag{6}$$

2.4 FEM Discretization and Block Integrals

The geometry section of the SR machine designed in AUTOCAD can be automatically discretized by adjusting the dimensions of the finite elements through a smart size option (according to the local machine geometry). The mesh grid size around the air gap must be smaller than the other adjacent regions, which allows greater mesh refinement, where one expects a higher degree of changing the magnetic quantities. The next step consists of specifying the phase current for which a solution is to be obtained. This is done by applying a current density on the elements that correspond to the windings of a certain phase. The value of the current density to apply is given by the quotient between the excitation current and the section area of one wire of the winding [3]. After the SR motors have been designed, the procedure of computing the values of magnetic field energy, magnetic field coenergy, block volume, magnitudes of B_x and B_y, moment of inertia, magnetization losses, steady-state weighted stress tensor torque and mutual inductance are illustrated by the block integrals given by Femm 4.0. And all these values are determined by using that short software written in lua language (a kind of language developed by and used by Femm 4.0 package programme) given below:

```
“open("Reluktans motor.fem")
mi_saveas("temp.fem")
pi = 3.141592
step = 5
for deg=0, 360, step do
        mi_seteditmode("group")
        mi_selectgroup(1)
        mi_moverotate(0,0,step)
        mi_analyze()
        mi_loadsolution()
        mo_groupselectblock(1)
        cog=mo_blockintegral(2)
        mo_clearblock(1)
        handle = openfile("cog.dat","a")
        write(handle, deg,"    ",cog,"    ","\n")
        closefile(handle)
        mo_close()
end”
```

By using this algorithm and changing the value of block integral within numbers from 1 to 24, different operation values for two SR motors can be obtained. In this paper, we only compare the results of magnetic field energy, magnetic field coenergy, magnitudes of B_y, magnetization losses, steady-state weighted stress tensor torque and mutual inductance.

All these operating values are calculated by the programme according to the different equations. These are given below:

- **Mutual Inductance:** This integral is used to evaluate mutual inductances between coils and calculated as;

$$L_{mutual} = \frac{\int A_1.J_2.dV_2}{i_1.i_2} \tag{7}$$

Where;
L_{mutual} = Mutual inductance (Nm/A^2),
A_1 = The term of vector potential,
J_2 = The current density (A/m^2)
dV_2 = Meant to denote that integral is taken over the volume of second coil,
i_1 = The current of first coil (A),
i_2 = The current of first coil (A).

- **Magnetic Field Energy:** This integral is used to determine total magnetic field energy and calculated as:

$$W_f = \int (\int_0^B H(B').dB').dV \tag{8}$$

Where;
W_f= Magnetic field energy (J)
H = Magnetic field force (A/m)
B = Flux density (T)

- **Magnetic Field Coenergy:** This integral is used to determine magnetic field coenergy and calculated according the equation (5).
- **Magnetization Losses:** This expression is the difference between magnetic field energy and magnetic field coenergy and so it is is expressed by the following equation:

$$W_{ml} = W_f - W_c \tag{9}$$

Where;
W_{ml} = Magnetization losses (J),
W_f = Magnetic field energy (J),
W_c = Magnetic field coenergy (J).

2.5 Comparison of B-H Curves of SR Motors Taken into Consideration

In many papers, the Ψ~i trajectory is often used to describe the difference between the motors used. A hybrid method combining dynamic time integration on the output voltage equation with field solutions was used in ref [2] to obtain the energy conversion loops for the motors taken into consideration.

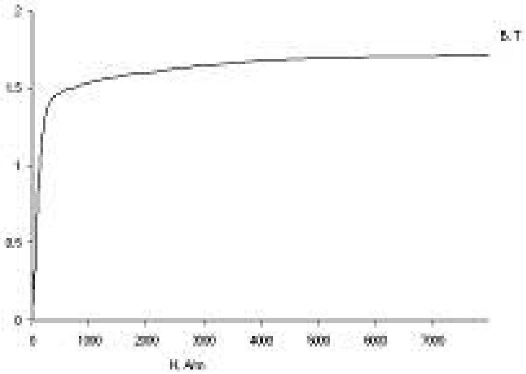


Fig. 5. B-H curve of 6/4 pole SR Motor.

But in our paper, B-H curves have been used as basic comparison method. Because; when the trajectory of B-H curves or the magnetic flux density related to magnetic field force change, that means the characteristics or the dimensions of the motors have been changed.

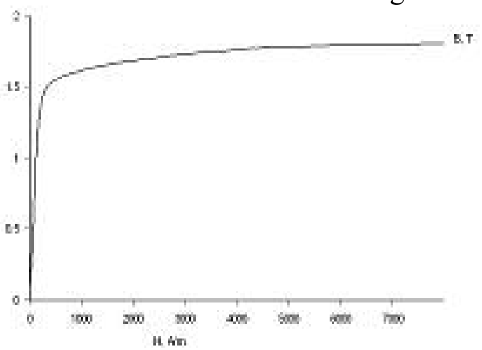
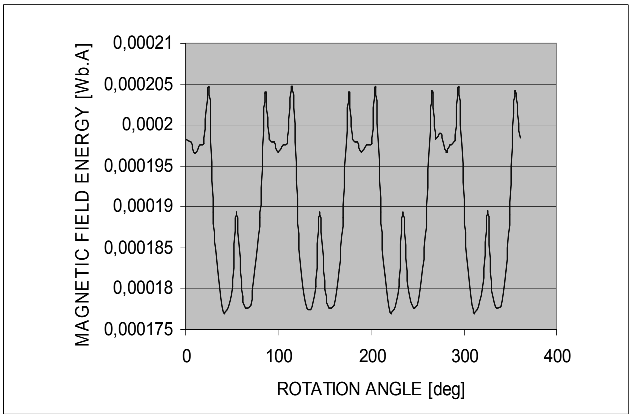


Fig. 6. B-H curve of 8/6 SR Motor.

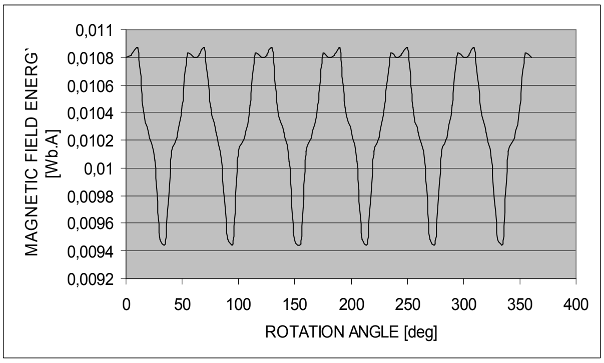
The silicon–iron magnetization curve (B-H curve) was first computed using the results of the FEM model as shown in Fig.5 and 6. The results were then compared. These results indicate that this approximation bears acceptable differences. We think that this acceptable differences resulted from different sizes and different excitation times. Because for 6/4 SR motors; excitation occurs shorter than 8/6 SR motors. That is because of the fact that 8/6 SR motors have one more phase.

3 Comparison Of Fem Results Of SR Motors

There are twelve different graphics obtained by using Femm 4.0 simulator. They are given below:

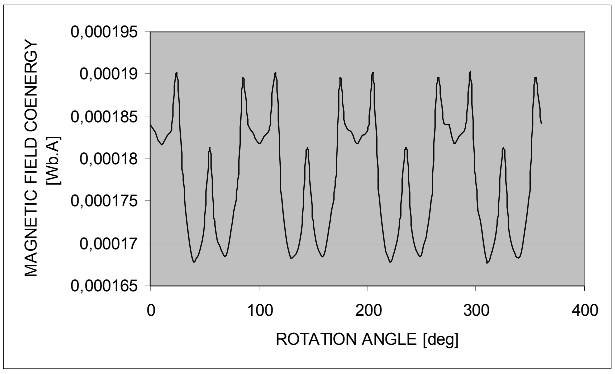


(a)

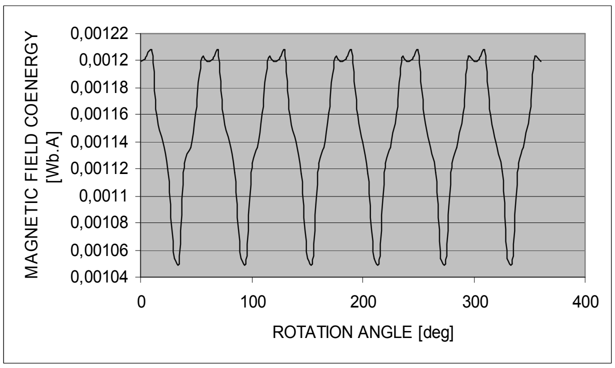


(b)

Fig.7. Comparison of the variation of magnetic field energy, (a) Magnetic field energy for 6/4 pole SR motor, (b) Magnetic field energy for 8/6 pole SR motor.



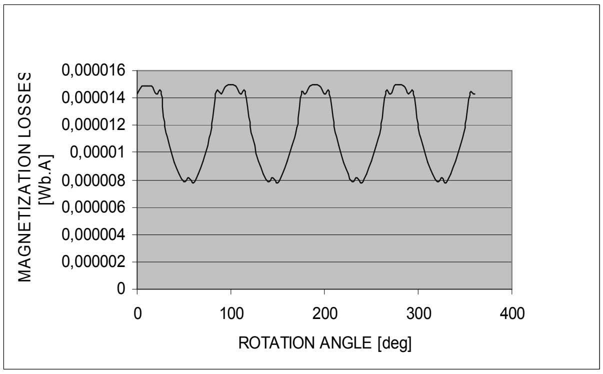
(a)



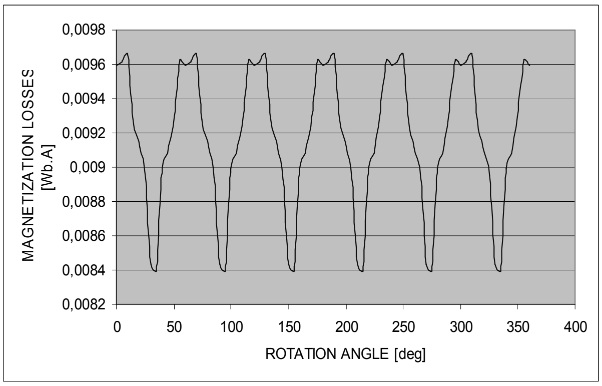
(b)

Fig.8. Comparison of the variation of magnetic field coenergy, (a) Magnetic field coenergy for 6/4 pole SR motor,

(b) Magnetic field coenergy for 8/6 pole SR motor.

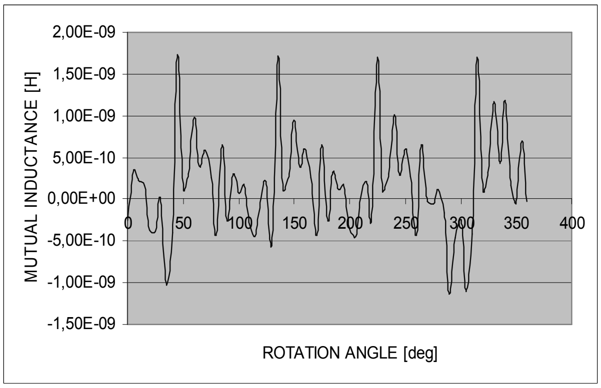


(a)

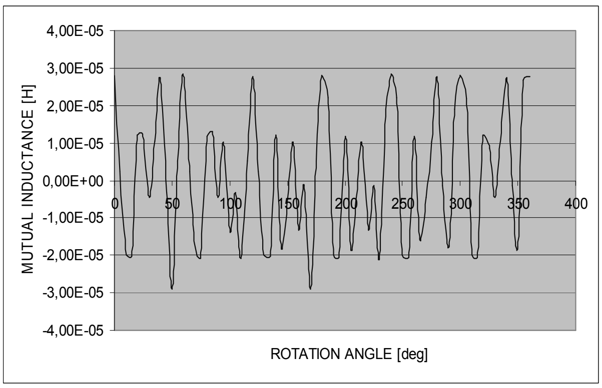


(b)

Fig.9. Comparison of the variation of magnetization losses, (a) Magnetization losses for 6/4 pole SR motor, (b) Magnetization losses for 8/6 pole SR motor.

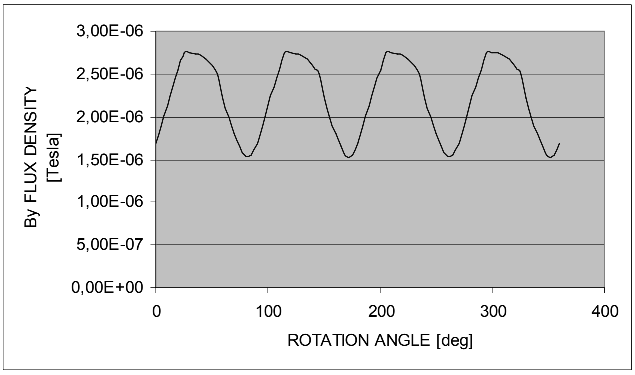


(a)

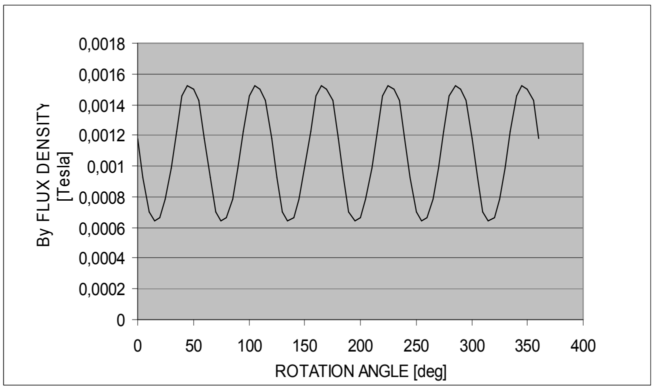


(b)

Fig.10. Comparison of the variation of mutual inductance, (a) Mutual inductance for 6/4 pole SR motor, (b) Mutual inductance for 8/6 pole SR motor.

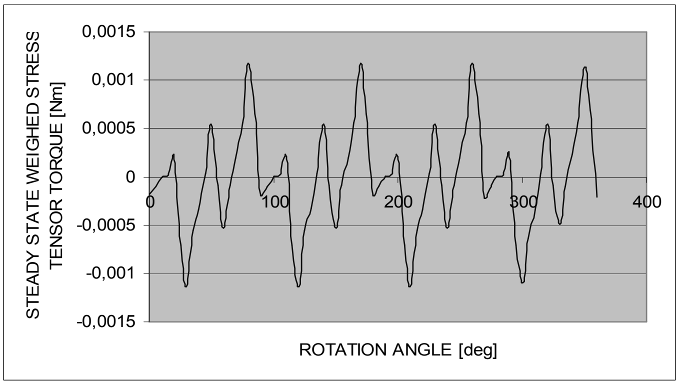


(a)

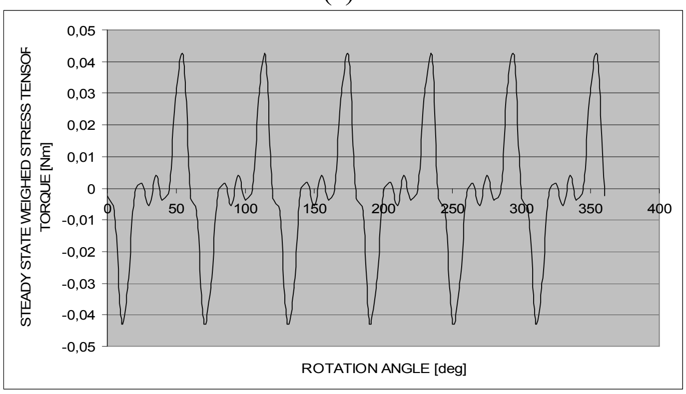


(b)

Fig.11. Comparison of the variation of flux density, (a) Flux density for 6/4 pole SR motor, (b) Flux density for 8/6 pole SR motor.



(a)



(b)

Fig.12. Comparison of the variation of steady state weighed stres tensor torque, (a) Tensor torque variation for 6/4 pole SR motor, (b) Tensor torque variation for 8/6 pole SR motor.

Results: The values obtained in the graphics are determined for a rotation of 360º (one complete rotation) and every value has been derived in every 5º.

In fig. 7(a)-(b), the magnetic field energies obtained from both those 6/4 pole and 8/6 SR motors are compared. As can be seen, the results shown have significant differences. These differences resulted from that (as can be seen from B-H curve of 8/6 pole SR motor) the 8/6 pole SR motor has always more magnetic flux density over rotor and stator gears. That is why, the magnetic field energy obtained from 8/6 pole SR motor are greater than that obtained from 6/4 pole SR motor.

This rule is the same while comparing magnetic field coenergies obtained for 6/4 pole and 8/6 SR motors. Because coenergy is the complementary function of field energy. Fig. 8(a)-(b) shows the difference between magnetic field coenergies.

And also we can obtain magnetization losses by extracting value of magnetic field coenergy from magnetic field energy (see equation 9). Fig. 9(a)-(b) show those differences.

Fig. 10(a)-(b) show FEM model curves of mutual inductance. One can observe that although the results of both models evolve similarly, the variation of mutual inductance for 8/6 pole is greater and more. Because the 8/6 pole SR motor has many stator and rotor gears and so, it can produce more variated inductances.

Fig. 11(a)-(b) show magnetic flux density curves over "y" coordinate. From the graphics; it can be said that the magnitude of B for 8/6 pole SR motor is greater than the other one. Because 8/6 SR motor has one more phase and can produce greater and more magnetic flux density compared with that 6/4 pole SR motor.

4 Conclusion

This paper has described the electromagnetic characterization and the difference of a 8/6 pole switched reluctance machine (SRM) and 6/4 pole SR motor in dynamic characteristics such as magnetic field energy, magnetic field coenergy, magnitude of B_y, magnetization losses, steady-state weighted stress tensor torque, mutual inductance and so in performance. The package programme named as Femm 4.0 using two-dimensional (2-D) finite-element method (FEM) has been used to analyze and determine the dynamic characteristics given above.

It is important to note that 2-D magnetostatic FEM analysis is limited, not accounting for HF losses, nonsinusoidal current-related winding losses, or torque harmonics.

As can be seen from established B-H curves of the motors compared; the main difference is on these curves. And this was resulted from the construction and so the number of phases excited. A step-by-step procedure was then described and the differences between 6/4 pole and 8/6 SR motors have been introduced by discussing and pointing out important details. And in this way; effects of different rotor and stator constructions on the performance of motor concerning magnetic field energy, magnetic field coenergy, magnitude of B_y, magnetization losses, steady-state weighted stress tensor torque, mutual inductance have been determined.

References

[1] Silvester, P. P.; and Ferrari, R. L.: Finite Elements for Electrical Engineers. Second ed., Cambridge Univ. Press, 1990.

[2] Low, T. S.; Lin H.; Chen, S. X.: "Analysis and Comparison of Switched Reluctance Motors With Different Physical Sizes Using A 2D Finite Element Method", Magnetics Technology Centre, National University of Singapore, Singapore 0511, IEEE Trans. On Magnetics, vol. 31, no. 6, Nov. 1995.

[3] Parreira, B.; Rafael, S.; Pires A.J.; Costa Branco, P.J.: " Obtaining the magnetic characteristics of an 8/6 switched reluctance machine: from FEM analysis to the experimental tests", *IEEE Trans. On Ind. Electronics*, vol. 52, no. 6, Dec. 2005.

[4] Meeker, D.: "Finite Element Method Magnetics Version 4.0 User's Manual", February 13, 2004.

[5] W. Wu, J. B. Dunlop, S. J. Collocott and B. **A.** Kalati, "Design optimization of a switched reluctance motor by electromagnetic and thermal finite element analysis," *IEEE Transactions on Magnetics,* Boston, USA, March 30 - April 3, 2003.

[6] G. E. Dawson, A. R. Eastham, and J. Mizia, "Switched reluctance motor torque characteristics: Finite element analysis and test results," *IEEE Trans. Ind. Appl.*, vol. IA- 23, no. 3, pp. 864–869, May/Jun. 1987.

[7] H. Lin, T. S. Low, and S. X. Chen, "Investigation on magnetic saturation in switched reluctance motor using 2D hybrid finite element method," *IEEE Trans. Magn.*, vol. 32, no. 5, pp. 4317–4319, Sep. 1996.

[8] M. B. Fauchez, "Magnetic analysis of a switched reluctance motor using a boundary element-finite element coupling method," *IEEE Trans. Magn.*, vol. 24, no. 1, pp. 475–478, Jan. 1988.

[9] A. M. Omekanda, C. Broche, and M. Renglet, "Calculation of the electromagnetic parameters of a switched reluctance motor using an improved FEM-BIEM-application to different models for the torque calculation," *IEEE Trans. Ind. Appl.*, vol. 33, no. 4, pp. 914–918, Jul./Aug. 1997.