EXAMINATION OF RADIAL FORCE WITH FINITE ELEMENT METHOD IN SWITCHED RELUCTANCE MOTOR

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Abstract

The aim of this study is computation of radial forces shown as one of the main and important reasons of noise in Switched Reluctance Motor (SRM). In this paper, radial forces in saturation and unsaturation regions of a standart submersible pump type 8/6-pole SRM have been calculated and their changes have been obtained. ANSYS 10.0 package program which makes a solution with Finite Element Method (FEM) has been used for computation of radial forces. After geometric shapes are given, radial forces have been calculated from unaligned position of rotor towards aligned position with angle of one degree according to different current values.

1. Introduction

SRM converts electrical energy into mechanical energy with the reluctance force. This force creates torque performing the movement of the rotation. Production of a constant torque depends on feeding of phase windings respectively according to being monitored rotor pole by the position of the stator pole. For this purpose, a power electronic circuit and control mechanism are also required.

There are two main problems in SRM. First of all is torque ripple and acoustic noise due to radial forces. Second one is detection of the motor position. The cause of the noise explaines that this is due to salient-pole rotor and stator of SRM. Once current is leaked from the windings on the stator pole, according to electromagnet principle, the stator pole pulls the rotor pole in itself. Gap between the rotor poles causes variable air gap distance between the stator and rotor.

For this reason, when rotor rotates, radial and axial forces which act on the rotor pole constantly change. The main magnetic reason caused the noise is radial forces acting on the rotor. The forces which occur in the direction of the radius and act on the rotor poles cause vibrations in bearings. These vibrations are perceived as acoustic noise in the stator and they may cause a fault in bearings [1]. It is possible to reduce these vibrations and the noise by innovations in the motor design and control systems.

It can be found in a lot of studies in literature to reduce the causes of this noise and explain the most important reason. One part of these studies has been carried out by Cameron and his team [2]. They have explained the reasons of the noise and examined what the reason of the noise is and how effective is. One of the reasons is that the acoustic noise increases in a situation which harmonics of the square of the current and harmonics of the stator resonance frequency are aligned. It has been stated that frequency of feeding current and pulse width ratio also affect acoustic noise. In another study, experimental results made by feeding only single phase when rotor is at aligned position and experimental results made while rotor is rotating have been compared and they have concluded that acoustic noise is higher at aligned position and consequently, it has been put forward that the most important reason of the noise is radial forces. The reasons such as torque ripple, forces came to stator winding and mechanical asymmetry due to production affect the noise. However, it has been proved by experimental results that these reasons affect less than radial forces [2,3].
In another study, a three-phase 12/8 pole SRM has been designed for increasing efficiency and reducing the noise. Magnetic analysis of SRM designed have been carried out by finite element and boundary element method taking into account non-linear structure. Radial forces acting on the poles have been obtained from different current values. Furthermore, the change of motor figures in different frequencies has been observed [4].
Pillay and his team have analyzed the situation in which stator surface is round and salient. It is concluded that salient pole stator has a higher vibration [5].

M. Sanada and his team have made a study on new rotor pole figures to reduce acoustic noise in SRM. Firstly, the effect of different stator and rotor pole ratio to acoustic noise has been examined and this examination has been made by radial forces in the study. As the number of the poles increases, acoustic noise also reduces by reduction of the radial force. Then, six type rotor pole has been defined and examined the radial forces in three-phase 6/4 SRM by using parameters such as height and width of rotor pole [6]. M. N. Anwar and H. Iqbal has presented an analytical method to determine the intensity of acoustic noise and calculate the radial force. The accuracy of the radial force calculated by an analytical model has been supported by the results calculated from FEM [7]. T.J.E. Miller has published a comprehensive study on an ideal SRM design. After general characteristics of SRM are mentioned, an analytical method has been presented for torque prediction in the paper. Torque and energy equitations have been defined by the results performed magnetic simulation with PC-SRD program. Finally, how the number of the phase and poles affects acoustic noise has been examined [8].

As seen from the base studies, radial forces caused acoustic noise for saturation and unsaturation condition have been calculated by FEM and the changes based on current and position have been revealed.

2. Finite Element Method

Finite element method (FEM) is a method which is used in a solution of Laplace (Equation 1) and Poission (Equation 2) partial differential equations. In this method, an interrupt fault occurs due to not having infinite terms in potential function defined in elements. Potential solution minimizing the energy equation is found instead of direct solution of Laplace equation. Potential solution minimizing energy in region is a solution of Laplace equation at the same time. FEM is easy to keep up with curvilinear boundaries. In desired part of the solution region, we can increase the number of element using advanced algorithms [9].

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} = 0 \tag{1}$$

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} = f(x, y) \tag{2}$$

In this method, four main method is used for search of trial function. These are as follows:

1. Rayleigh–Ritz method
2. Galerkin method
3. Least squares method
4. Weighted residual method

The most common methods used are Rayleigh–Ritz and Galerkin.

ANSYS Package Programme

ANSYS is an analysis and design programme used FEM. ANSYS is a general package programme and it can be found what kind of reactons are given by model obtained under work conditions. Programme window of ANSYS 10.0 has been shown in Fig. 1.

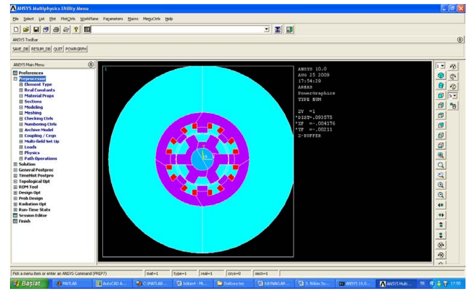

Fig. 1. Programme window of ANSYS 10.0

Before this programme, it must be made necessary selections about which type is to be used to solve a problem. The solution of the problem with ANSYS is carried out in four stages. These are as follows:

- According to the discipline, the selection of which FEM solution is made from 'Preferences'.
- The second stage is to transfer to ANSYS, definition in a model of characteristics of the materials constituting geometry and division. In this stage, element type, material type are defined and if it has material constants and non-linear construction (such as B-H curve), they are given.
- The third stage is identifying an analysis type and 'solution' part in which are given loads.
- Calculation of some informations such as being shown field distribution, electromagnetic torque, magnetic force, flux, inductance and energy is made from “General Postproc >”menu and this is final pure stage.

Except for these menus, there is “File”menu. File operations such as saving the study or display of the saved work again are implemented. Node, line, field and divisions of geometric figure are provided to show on the display from “Plot” menu. The numbers of the node, line, field and divisions can be displayed on “PlotCtrls”. Moreover, processings as enlarging or reducing the appearance of a shape, shifting right or left are perfomed. “WorkPlane” menu provides selecting one of the cartesian or cylindrical coordinate systems and axis shift. It is possible to take any kind of information with examples about theory and use of ANSYS programme with “Help” menu.

In this study, the selection of “Emag 2D” which is two-dimensional field solution has been made because of being made the solution of a two-dimensional electromagnetic problem. Element type is PLANE53. This element has eight nodes used for two-dimensional magnetic analysis. Variety degrees of freedom are defined for nodes. Besides, magnetization curve of sheet material created rotor and stator has also been applied to the motor.

Newton Raphson Method has been used for numerical solution of non-linear mathematical equations occured in FEM and Maxwell Stress Tensor Method has been used for the calculation of force and torques. Homogeneous Dirichlet boundary condition has been taken as boundary conditions.

3. Calculation of Radial Forces in SRM

Magnetic analysis of SRM have been examined and radial forces of SRM have been calculated according to the Maxwell Stress Tensor Method.

3.1. Maxwell Stress Tensor Method

Maxwell Stress Tensor Method is one of the methods used for calculation of magnetic forces or torque in moving sections. A closed line should be defined in model for calculations. A selection of the closed line quite affects the accuracy of the results. Defined closed line should plug into the air gap region and it should be as far as possible from magnetic vehicles. The selection of the closed line has been illustrated at Fig. 2.

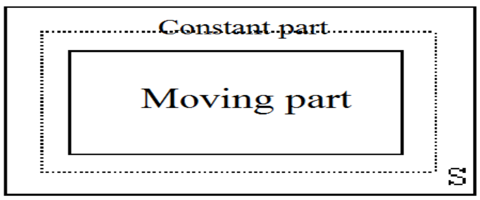

Fig. 2. A selection of the closed line in Maxwell Stress Tensor Method.

Local stress in Maxwell Stress Method is calculated in all boundary points and surface integral is applied to find total normal and tangential force components (or two-dimensional linear integral) [10].

Maxwell Stress Method is preferred in the calculation of the magnetic force components and torque in FEM due to a field solution requirement. In two-dimensional problems with Maxwell Stress Method, normal and tangential components of the flux intensity values must be known in all points along the closed line [11]. Magnetic field B, local stress t and other components have been showed in Fig. 3. The components of stress are based on field components. Normal and tangential force values can be calculated from equation 3,4,5 along the line [12,13].

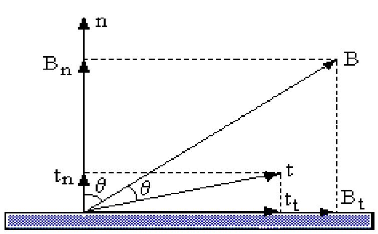

Fig. 3. Magnetic field diagram, local stress and other components.

$$F_n = \frac{1}{2\pi \mu_0} \int_s \left(B_n^2 - B_t^2\right) ds \tag{3}$$

$$F_t = \frac{1}{\mu_0} \int_s B_n B_t ds \tag{4}$$

$$T = \int_s [\frac{1}{\mu_0}(r \times B)(B.n) - \frac{1}{2\mu_0} B^2 (r \times n)] ds \tag{5}$$

Magnetic permeability is μ_0, r is displacement distance, B_n is the normal component of magnetic field, B_t is tangential component of magnetic field, n is force component in normal direction, F_t is tangential force component and T is total torque produced [14,15,16].

3.2. The Creation of the Model and Calculation of Radial Force

8/6 pole sizes and electrical properties of SRM have been given in Table 1 and drawing of SRM according to the given measurements has been shown in Fig. 4. Three dimensional view has been given from different directions in Fig. 5.

Table 1. Submersible pump type 8/6 pole dimensions and electrical properties of SRM

Number of stator poles (N_s)	8
Number of rotor poles (N_r)	6
Stator pole arc length (β_s)	22^0
Rotor pole arc length (β_r)	24^0
The width of stator pole	9.98 mm
The width of rotor pole	10.9mm
Step of stator pole (α_s)	45^0
Step of rotor pole (α_r)	60^0
Air gap	0.5 mm
Outer diameter of stator	92.2 mm
Inside diameter of rotor	52 mm
Package length of stator	180 mm
Shaft diameter	22 mm
Outer diameter of rotor	51 mm
The length of stator pole	10.1 mm
The length of rotor pole	7.9 mm
Number of turns in a phase	108
Conductor diameter	0.75 mm
Rated current	12 A

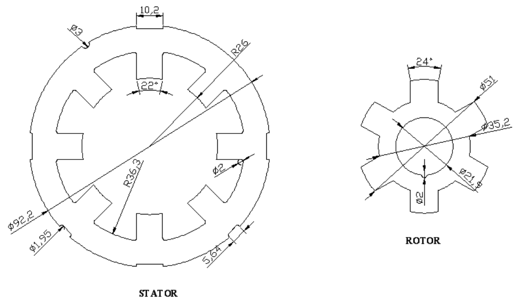

Fig. 4. Front view of 8/6 pole SRM (Dimensions are mm)

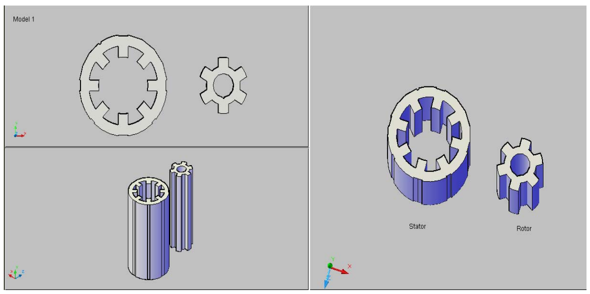

Fig. 5. Three-dimensional view from various directions of 8/6 pole SRM

According to the rotor angle, the change of radial force which is shown the biggest impact on acoustic noise obtained from ANSYS 10.0 package programme based on the rated current requirement has been given in Fig. 6. To create this curve, rotor has been moved from unaligned position towards aligned position with angle of one degree. As seen that the highest radial force occurs in aligned position and its value is 1550 Nt.

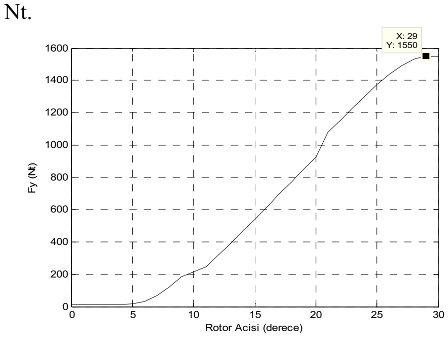

Fig. 6. Radial force-rotor angle curve of 8/6 SRM

3.3. Radial Forces in Unsaturation

Linear part of magnetization curve of SRM is used for unsaturation work. For this reason, motor is operated under the rated current values. In follow results, rotor has been moved from unaligned position towards aligned position with angle of one degree under constant current excitation. Current values of unaligned position have been taken as 3, 6 and 9A.

The changes of radial forces according to the currents and rotor position in unsaturation have been shown in Fig. 7. It is proved that the change of radial force in unsaturated is approximately proportional to the square of the current.

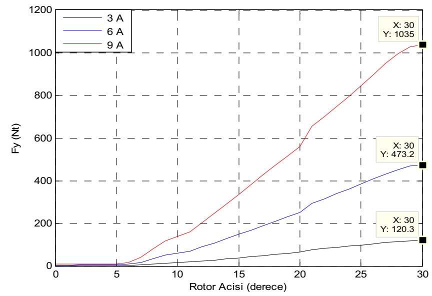

Fig. 7. Radial force-rotor angle curves of 8/6 SRM in unsaturation

3.4. Radial Forces in Saturation

By operating SRM in the rated current and higher values, it has been passed to the saturation region to perform the operation in saturation which is one of the aims of this study. Like in unsaturation region, rotor has been moved from unaligned position towards aligned position with angle of one degree under constant current excitation. Current values above the rated currents have been taken as 12, 15 and 18A.

The changes of radial force in saturation are shown in Fig. 8. Although it has been proved that the change of radial force is approximately proportional to the square of current, it has been seen that this change doesn't exist. It can be said that the change in here is not too much as unsaturation region.

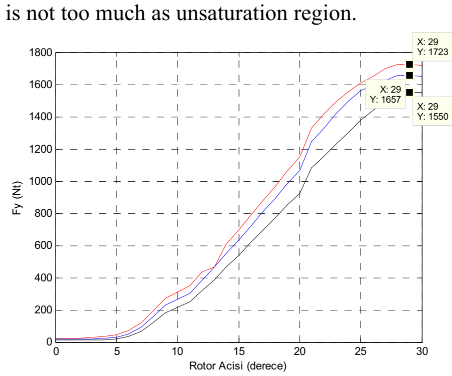

Fig. 8. Radial force-rotor angle curves of 8/6 SRM in saturation

4. Conclusion

This study has been made on the radial forces which is shown as the main reason of acoustic noise. For this reason, ANSYS 10.0 package programme has been used. As a result of the study, radial force changes in saturation and unsaturation of 8/6-pole SRM which is a submersible pump type have been obtained. As we look at the changes of the radial forces, it has been observed that different characteristics show in saturation and unsaturation region. It has been seen that radial force almost changes the proportional to the square of the current in unsaturation. However, this property is not valid for saturation region. The examination of these changes in design is important for taking some precautions in order to reduce acoustic noise. For instance, if radial forces are greater than desired, this is reduced by being made some changes in the geometry of SRM and using different methods. Hence, one of the major problems of SRM has been solved in design stage.

5. References

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