A New Construction of Switched Reluctance Motor Improving Magnetic Field Energy and Torque Production

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Abstract—This paper is performed to develop a new 8-6 pole switched reluctance motor (SRM) in order to improve the magnetic field energy and torque production; and describes the differences of standart 8/6-pole SRM and that newly developed SRM in dynamic characteristics such as magnetic field energy and torque production. Finite element analysis (FEA) was used to obtain the nonlinear magnetisation data for application to the modelling. As known; finite element method (FEM) has been a powerful tool to solve many complex problems in electromagnetics. For the optimum design of switched reluctance motors, this paper presents the methods and results, which are calculated by the finite element analysis. Thus; it has been possible to determine the effects of different construction methods and motor specifications on the performance. 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], construction and excitation method. In this paper; by using FEM, we are going to develop a model of SR motor that is different from the ones developed before, and try to explain the running discriminations between the developed and the known SRMs.

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

1 Introduction

The finite element method (FEM) has been widely used as an analysis and design tool in many engineering applicational fields like rotating machinery, computational fluid mechanics and so on. 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 [1], [6]–[9].

In many applications, switched reluctance motors have a number of advantages compared to rotating machineries such as induction machines and brush-less permanent magnet machines. This is because of the fact that they have good performances, which are high torque-weight ratio and high reliability.

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 SRMs with different rotor and stator constructions is investigated using an analytical method as used in [5].

2 Finite Element Method and SR Motor FEM Model

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.

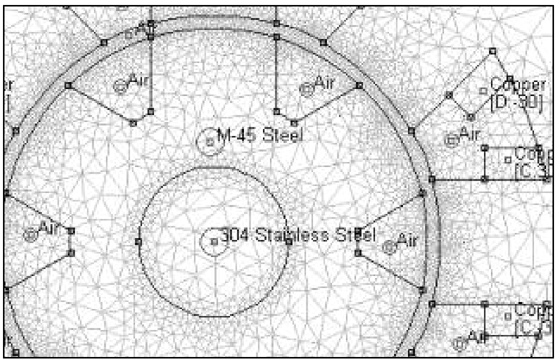


Fig. 1. Triangulation of the aimed system (Mesh mode).

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].

2.1 Basic Principles of SRM and SRM Design

The switched reluctance motor is a doubly-salient and singly-excited motor. The torque is produced by the tendency of its moveable part to move to the position where the inductance of the excited phase winding is minimised [10]. Recent advances in power electronics and microelectronics have demonstrated the huge potential of switched reluctance motor drives. The manufacturing and maintenance costs for switched reluctance motor drives will be much lower than alternatives such as the brushless DC motor, the induction motor and the AC motor [11].

Below, the dimensions of the SR motors taken into consideration are given.

Table 1 The main dimensions of SR motors (Unit: mm)

	Standard SRM	Developed SRM
Stator outer diameter	105,6	105,6
Stator inner diameter	57,92	57,92
Stator teeth lenght	14,61	14,61
Rotor outer diameter	54,15	54,15
Airgap	1,70	1,70
Number of turns perpole	50	50
stator foot lenght (a)	***-***	***1,05***
Rotor teeth lenght	9,55	9,55
Shaft diameter	19,52	19,52

As seen on the table; all dimensions of the motors are the same, except stator foot lenght of developed SRM indicated as "a" in Fig.3 which is the single and main difference. And FEM model of the standart SRM is given in Fig.2.

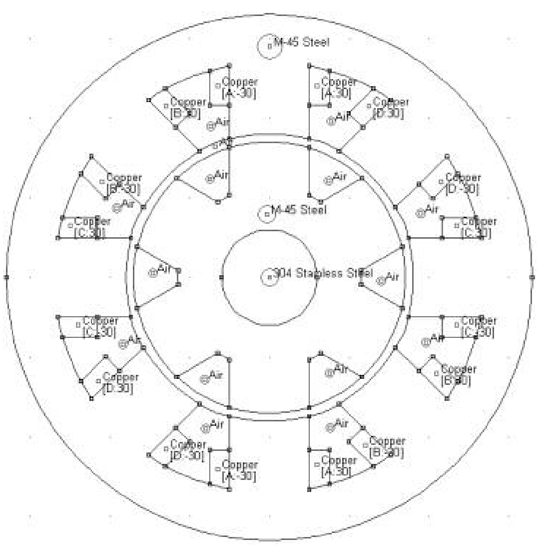


Fig. 2. Standart 8/6-pole SR motor

For developed SRM; teeth having a lenght of 1,05 mm (shown in Table 1) have been added to the both sides of stator salients.

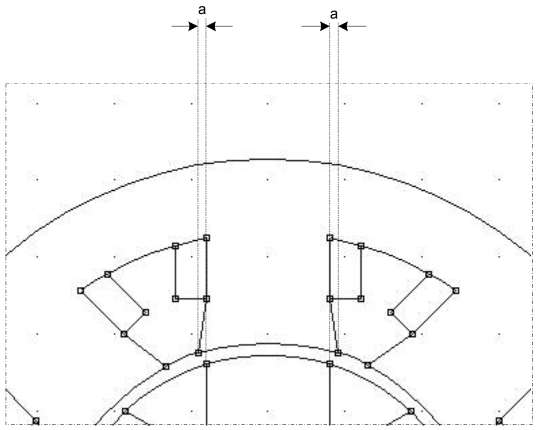


Fig. 3. Notation of stator foot lenght of developed SRM

Here, there are a few important notes to be referred to while computing and performing the processes in the program used to discretize the problem. The designed switched reluctance motors are drawn with the help of a CAD-based software. Each part of the motor are named according to the metals they are constructed from such as M–45 steel, 304 stainless steel, etc. and the motor windings must be marked as "copper" since the drawings have been saved as *.dxf to be used in simulation software. Nevertheless, it must not be forgotten to name air gap as "air". And also 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.

2.2 The Electromagnetic and Electrical Equations of SRMs

The magnetization characteristics and parameters [3] of switched reluctance motors are; the phase flux linkage, function of rotor position and phase current. And so; the flux linkage equation;

$$\lambda = \int (v - Ri)dt \tag{1}$$

where λ is the phase flux linkage as Wb, v is the phase voltage of the motor as V, R is the phase resistance as Ω and the i is the phase current as A.

And also these magnetization characteristics can be obtained by integrating this equation [2];

$$\varphi(\theta, s) = \int_S \vec{B}.d\vec{S} = \int_S (\nabla x \vec{A}).d\vec{S} = \oint_l \vec{A}.d\vec{l} \tag{2}$$
$$= L_{stk}\left[A(xj, yj) - A(xj, yj)\right]$$

where L_{stk} is the stack lenght of the motor and "± xj, yj" are the points within the winding region.

The instantaneous voltage across the terminals of a phase of an SR motor winding is related to the flux linkage in the winding by Faraday's law as;

$$V = R.I + \frac{d\lambda}{dt} \tag{3}$$

where V is the terminal voltage, I is the phase current, R is the phase resistance, and λ is the flux linked by the winding. Because of the double salience construction of the SR motor and the magnetic saturation effects [13], the flux linked in an SRM phase varies as a function of rotor position and the phase current. And so; equation (3) can be expanded to;

$$V = R.I + \frac{\partial\lambda}{\partial I}.\frac{dI}{dt} + \frac{\partial\lambda}{\partial\theta}.\frac{d\theta}{dt} \tag{4}$$

where $\partial\lambda/\partial I$ is defined as the instantaneous inductance, and term ($\partial\lambda/\partial\theta$).(d /dt) is the instantaneous back e.m.f.

And the electromagnetic torque of four phase SRM can be calculated by using the following equation [12], applying partial derivative of the conjugate magnetic energy with respect to rotor displacement under constant current;

$$W_{ce} = \int \lambda(\theta, i)di \tag{5}$$

$$T_e = 4\frac{\left.\int_{\theta_1}^{\theta_2} \frac{\Delta W_{ce}(i,\theta)}{\Delta\theta}.d\theta\right|_{i=const}}{\theta_r} \tag{6}$$

where W_{ce} is conjugate energy (J), T_e is electromagnetic torque (Nm), θ is the rotor position (deg), θ_1 is the rotor position that the phase windings of the machine are started to supply (deg), θ_2 is the rotor position that the supply of the phase windings are end (deg), λ is flux linkage (Wb), i is the stator current (A) of each phase.

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;

$$\Delta W_m = T_e.\Delta\theta \tag{7}$$

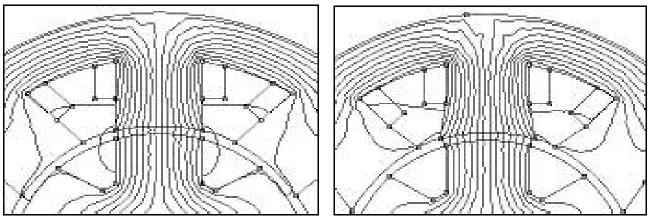
where ΔW_m is the variation of mechanical energy, T_e is the electromegntic moment (Nm), θ is the rotor position (deg).

3 Analysis and Comparison of FEM Results of SR Motors

For the analysis and investigation; a time-stepping 2D finite element method magnetics program (FEMM) was adopted [4].

Firstly, the flux linkages of all phases related to turning angle of the motor over 0–65º were computed as a circuit property for aech motor. And then energy and conjugate energy values of a rotation between -30 º and -30 º are computed by using a exceptional script of FEMM. At the end; torque computation is achieved by using FEMM's weighted stress tensor integral. This block integral computes a weighting function over the finite element mesh that allows all possible air elements to contribute to the stress tensor integration [14]. This means that time-stepping simulation have solved the flux linkages in each time step, the current and the torque in the time step are then obtained by interpolating the static flux-linkage and torque data precomputed by finite element respectively. Since these values have been obtained, they are prepared for the comparisons.

Before evaluating the results obtained; it will be useful to examine flux distribution of standart and developed SRMs.



(a) (b)

Fig.4 (a) magnetic flux paths for standart 8/6-pole SRM (b) magnetic flux paths for designed 8/6-pole SRM

At first glance; it may be seen like that there isn't any difference between flux distributions of the motors taken into consideration. But for Fig.4(b); the flux distribution is smoother, and stronger over stator-rotor interaction path. That provides a better current-flux curve and make the system increase torque production almost in many turning angles of the developed switched reluctance motor even though it is not effective in all turning conditions.

Below, five kinds of graphs have been obtained using simulation results performed by finite element analysis to compare standard and develeoped switched reluctance motors in performance such as magnetic flux linkages and so magnetic field energy; torque production. And thus, it will be possible to select and use the best model.

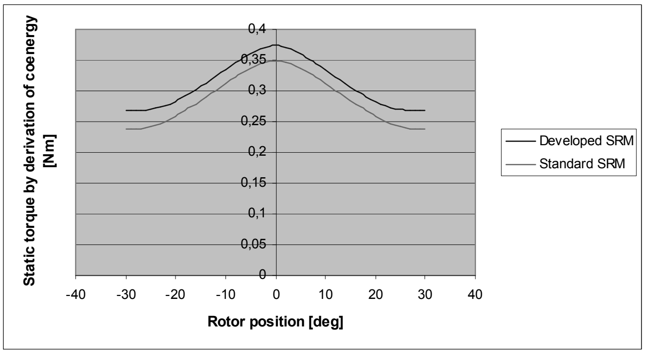


Fig.5 Static torque by derivation of coenergy relating to rotor position

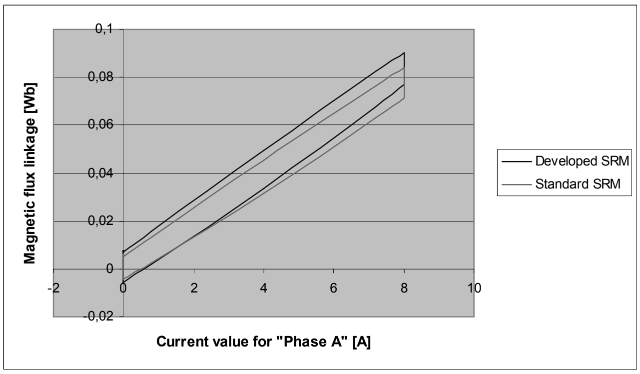


Fig.6 Variation of magnetic flux linkage relating to one phase current

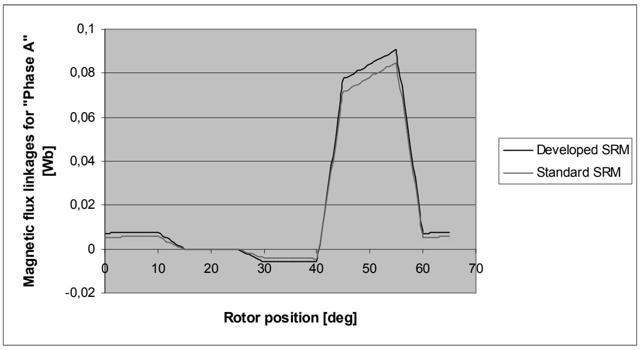


Fig.7 Magnetic flux linkage relating to rotor position

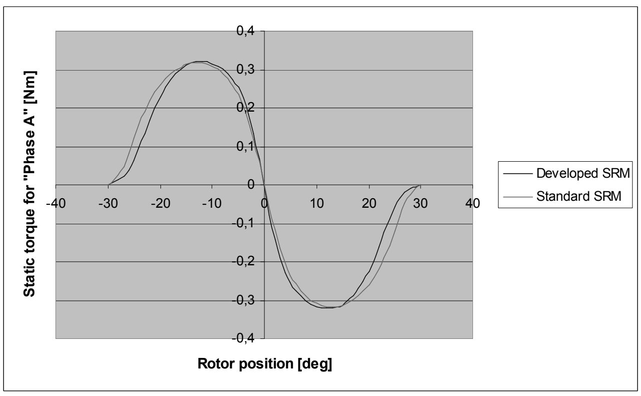


Fig.8 Static torque for one phase over a rotation of 60º

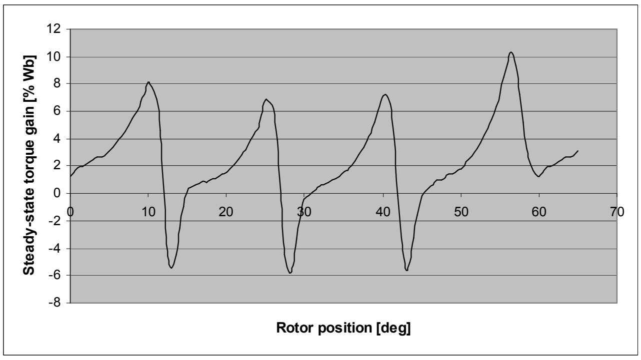


Fig.9 Steady state torque gain (%) acceptable for one phase over a rotation of 65 º

4 Discussion and Conclusion

The comparison of the two types of the machines is made at the condition of the same stator outer diameter, the same stator bore diameter, the same rotor bore diameter, the same rotor outer diameter, the same lenght of air gap, the same shaft diameter, and the same type of winding and number of windings. The main difference between the developed and Standard SRM is that the developed SRM has a stator foot lenght of 1,05 mm as shown in Fig.3.

Under these conditions; the analysis have been performed and the following results obtained from the graphs given in previous section have been found to discuss:

- In Fig.5; for the motors examined, the static torque by the derivation of conjugate energy relating to rotor position is compared. As seen on the graph; the amount of co-energy gained from that newly developed SRM is greater from the standart one. The more magnetic or conjugate energy produced by the stator poles, the more energy converted into mechanical energy and the greater output torque produced. The average gain found from the values obtained by the finite element analysis is 8.16%. That important energy evolvement achieved by the new construction increase the output capacity of the machine.
- Connected with the previous graph; the curves in Fig.6 show the relation of magnetic flux linkage with the phase current (only for phase "A") for each motor. When the amount of current flowing through motor windings is increased, the ratio of magnetic flux linkage increment get better for developed SRM. That means the new structural machine produces better magnetic flux than the standart one at the same current or current density.
- If the same situation is examined for magnetic flux linkage relating to rotor position for "phase A" in Fig.7, it can be seen that the amount of magnetic flux produced by developed SRM is greater than the standard one in

many positions, but not in all.

- The static torque variation of "phase A" relating to rotor position for a rotation of 60º is almost seen as same for each motor in Fig.8. But if the curves examined carefully, the static torque produced by "phase A" winding for developed SRM is less dispersed than the standard one. This advantage means "steady torque" curve and provides more accurate output capacity. Furthermore, if the curve given in Fig.9 is investigated, the steady-state torque gain as a percentage goes up to 10% in some rotor positions. On contrary; for a few certain rotor positions, the torque gain can be said "failed". But as a whole, the output torque gain is better for developed SRM compared to standard one.

As a result; the study using finite element analysis on the design gives the followings:

(i) By the method of constructing a new better pole shape, the magnetic field energy can be increased. The gain is approximately about 8%.

(ii) By the method of increased magnetic field energy and magnetic flux, the torque producing can be said to be increase for some positions of rotor, but not for all positions.

(iii) As a general; the output performance of the 8/6-pole developed SRM is better than the 8/6-pole Standard SRM if the machines are operated at the same conditions and it is more favorable to develop and apply four phase 8/6-pole newly developed SRM instead of the standard one.

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