Design and Analysis of Switched Reluctance Motors

İbrahim ŞENGÖR, Abdullah POLAT, and Lale T. ERGENE

Electrical and Electronic Faculty, İstanbul Technical University, 34469, Istanbul, TURKEY
sengoribrahim@gmail.com, polata@itu.edu.tr, ergenel@itu.edu.tr

Abstract

In this paper, the design and analysis of switched reluctance motors (SRM) are studied. SRMs gained more importance in recent years due to simple structural properties. Finite element method (FEM) is used for the analysis of SRM and the motor characteristics are investigated with simulation results. The changing of flux density, moment, current and inductance values are obtained. Besides, these characteristics are compared with different models that modified some of the parameters such as number of turns, winding resistance and material properties. The effects of these changes on the operation of the SRM are presented.

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1. Introduction

Variable reluctance motors has variable air gap and reluctance respect to the position. The motor has a stator with concentrated coils and a passive rotor with no brushes or windings. Since they need power electronic circuit to drive they are called switched reluctance motor (SRM) that is the simplest rotational electric motors. [1]. SRMs are suitable for the applications where high speed and high power are required. Each stator phase is supplied with dc voltage and developed torque tends to rotate the rotor aligned with the energized stator poles. This makes the inductance of the excited coils maximum. Torque production is not dependent of the current direction [2]. If this rotation tendency in the same direction is kept continuously rotational torque will be produced. A control scheme is required to observe the rotor position and switch the stator phases respect to these rotor positions by using the power electronic circuit.

There are many advantageous of SRMs over a conventional electric motors: Easy construction, less copper losses, higher efficiency compared to the motors in the same power ratings, tolerable phase faults, very high speed applications, high torque/İnertia ratio, etc. There are also some disadvantageous of SRMs: requirement of rotor position sensor or microcontroller for the sensorless control, complexity of the controller since the produced torque is also a function of the position beside the phase current, torque has strokes because of the switching, noise, torque pulsations.

2. Design of SRM

The priorities of any SRM design are the demanded power for the application and frame size. Starting point for the design is to determine the dimensions and calculate the inductance change due to rotor position. It is also very important to determine stator pole angle (β_s) and rotor pole angle ((β_r) for an efficient output. The steps for the design of a SRM can be listed as follows [2,3]:

- Motor specs: n (min^{-1}) speed, maximum permissible current I (A) ve AC Supply voltage V
- Output Torque: By using the output power and speed information SRM shaft torque can be calculated

$$T_{shaft} = \frac{P_{out}}{2\pi n / 60} \quad \text{[Nm]} \qquad (1)$$

- Dimensions: Frame size should determined due to outer radius of stator (D_{so})

$$D_{so} = (L_d - 3)*2 \quad \text{[mm]} \qquad (2)$$

  Stack length values (L_d) for SRM are already defined in IEC Standards [4].
- Defining the pole numbers: Stator (Ns) and rotor pole numbers (Nr) should be decided by the designer. They have various combinations.
- Determining the stator and rotor pole angles (β_s), (β_r): There are some constraints. Stator pole angle should be smaller than rotor pole angle. The angle between adjacent rotor poles should be bigger than stator pole angle. Effective torque region should be smaller than stator pole angle but bigger than the firing angle (ε)
- Determining the air gap length (g): The most effective energy conversion can be achieved with the smallest air gap possible.
- The stack length (L_d)/Rotor outer radius (D_{ro}) ratio is generally in between 0.4-3.0.
- Rotor outer radius (D_{ro})/Stator outer radius (D_{so}) ratio should be approximately 0.5-0.55.

3. Mathematical Model

The basic equivalent circuit of an SRM is given in Figure 1 with no mutual inductance. Rs is the phase winding resistance and L is the phase self inductance.

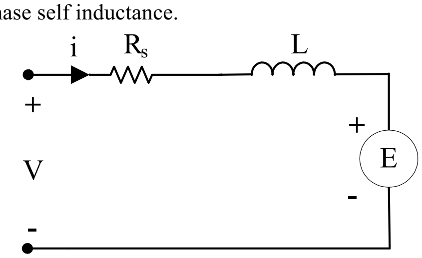

Fig.1. Basic equivalent circuit of SRM

Phase voltage equation;

$$v(t) = R_s . i(t) + \left(\frac{d\lambda(t)}{dt}\right) \qquad (3)$$

$$v(t) = R_s . i(t) + \frac{dL(t).i(t)}{dt} = R_s . i(t) + L(t)\frac{di(t)}{dt} + i(t)\frac{d\theta}{dt}\frac{dL(t)}{d\theta} \qquad (4)$$

4. Methodology

The motor geometrical parameters are determined and applied to the Finite Element Method Software. The designed motor will have 6/4 pole numbers, 3 phase, 0.5 mm aligned position airgap, 80 mm stator outer radius and 45 mm rotor outer radius, 30° stator pole angle. The basic 6/4 SRM is shown in Fig.1.

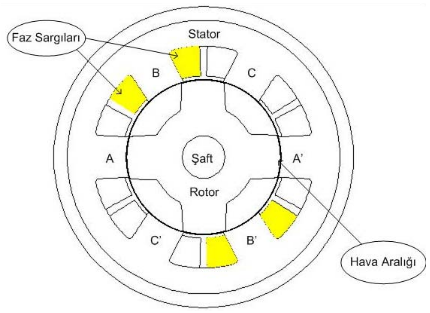

Fig.1. 6/4 SRM layout

The stator and rotor materials choice are also very important. M800-65 A is chosen at the beginning of the design as a standard material. B-H characteristic of the material is given in Fig.2.

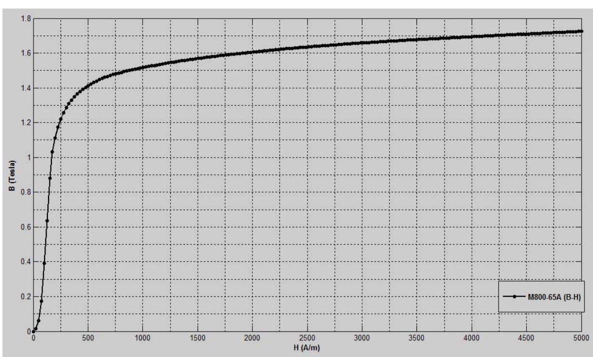

Fig.2. Stator and Rotor Material (M800)

4. Finite Element Model

Finite Element Method (FEM) is the most common numerical method for machine design. The method can give static, AC steady state or transient solutions for thermal, electric and magnetic problems of the complex electromechanical geometries in two or three dimensions with nonlinear materials. The boundary conditions and constraints (such as Coulomb's Gauge) should be applied properly to get a unique solution.

According to Maxwell equations, magnetic vector potential equation is derived as in (1) with Cartesian Coordinates:

$$\frac{\partial}{\partial x}\left(\frac{1}{\mu}\frac{\partial \mathbf{A}}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{1}{\mu}\frac{\partial \mathbf{A}}{\partial y}\right)=-\mathbf{J}_s \qquad (5)$$

where **A** is the magnetic vector potential, μ is the permeability of the material, and $\mathbf{J}_s$ is the source current density. In the two dimensional model finite length, rotation of the magnetic field is assumed only in z axis and the magnetic vector potential has A_z component which is **A**= (0,0,A). Unknown quantities with finite number are obtained by using known quantities of system.

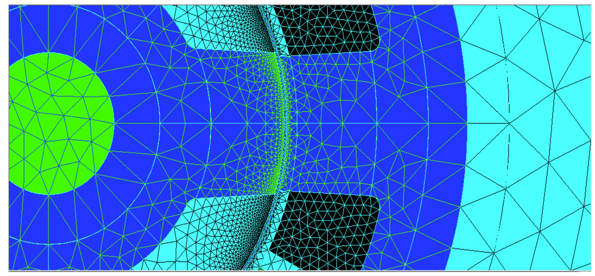

Fig.3. Finite element Mesh for 6/4 SRM (aligned)

The FEM consists of certain algorithm steps. These are decomposing of problem into finite regions, deriving basic equation for each node, combining finite elements of the problem, solution of the equation system and post processing steps. The outer boundary of stator is defined as Dirichlet condition setting to zero. Mesh distribution over the geometry affects to the accuracy. Therefore fine mesh elements should be preferred especially where the flux changes rapidly. Fig.3. shows the mesh distribution. Around the air gap finer mesh has been used.

As it is seen in Eq.3, electric and magnetic quantities are coupled and solved simultaneously. There is also an electrical circuit coupled to the magnetic circuit. The supplying circuit of an SRM has some advantageous over the circuits used in permanent magnet motors. There is no short circuit possibility in SRM circuit since each phase is connected to the main switch in series. Another advantage is the phase independence. Asymmetric bridge rectifier, bifiliar rectifier, R-dump rectifier, C-Dump rectifier can be given as examples for the SRM drive circuits. This circuit used in the paper is shown in Fig. 4.

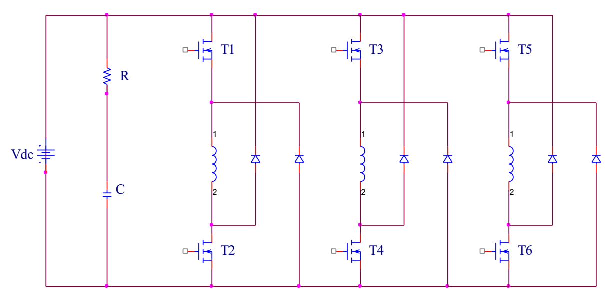

Fig.4. Electrical Circuit

There are six switching elements and two for each phase. These switching elements defines which phase winding will be energized and makes the rotor rotates continuously. Switching angles for each element is given in Table. The supply voltage is 300 V. Number of turns for each phase is 300.

Table 1. Switching Angles

	On State	Off State	Duty Period
T1, T2	60°	90°	90°
T3, T4	30°	60°	90°
T5, T6	0	30°	90°

5. Results

The equi flux lines of 6/4 SRM with two poles are shown in Fig.5

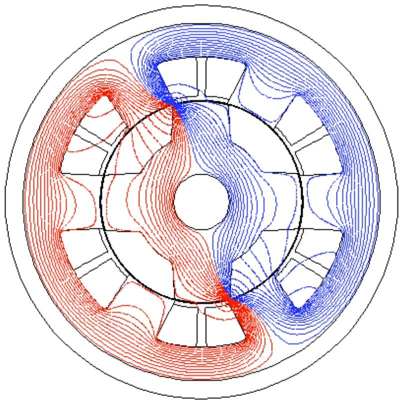

Fig.5. Equi flux lines

When the rotor pole is aligned with the stator one the flux lines will be more distinctive. Then the switches for this phase will be off state and the next phase winding will be energized. This switching process for consecutive two phases is given in Fig. 6.

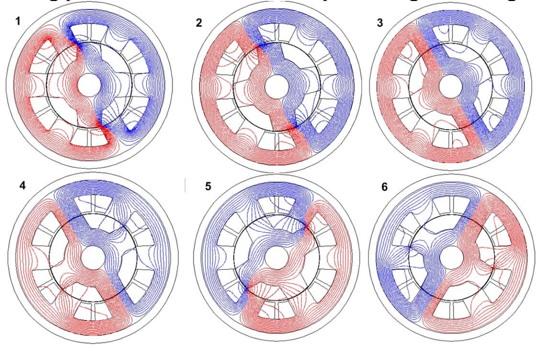

Fig.6. The equi flux lines during the phase changes.

The flux density color shade and the scaling in Tesla are given in Fig. 7 for the aligned position. Fig. 8 shows the flux density change in the air gap region for the energized phase. The material will be affecting the magnetic flux density values respect to its B-H characteristics. Eventually the flux created and the torque produced in the machine is also dependent to the material.

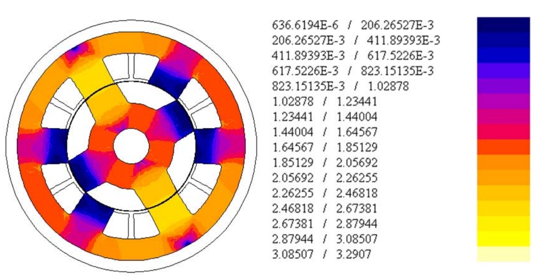

Fig.7. Flux density for aligned position.

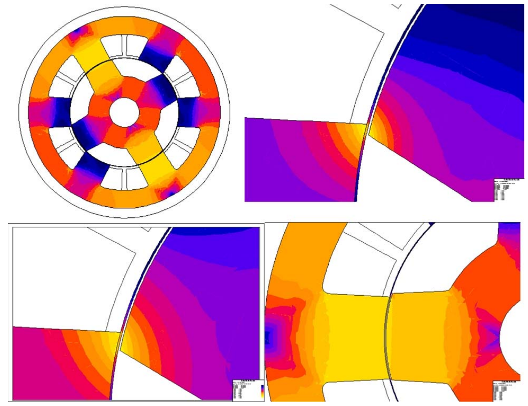

Fig.8. The change in flux density

The shaft torque vs. time variation is computed and given in Fig.9. The maximum torque value is 76.42 Nm.

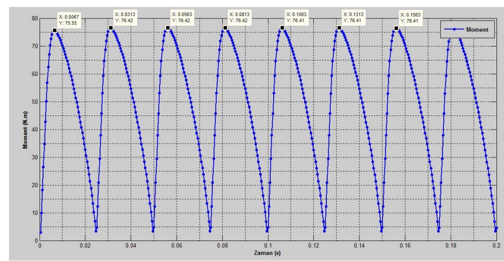

Fig.9. Torque vs. Time

The phase currents vs. time variation is presented in Fig.10. The maximum phase current is 115 A. The computed value is coherent with the analytical result within 1%.

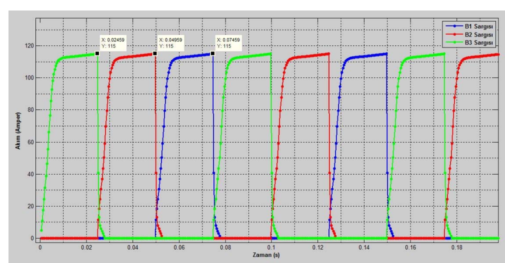

Fig.10. Phase currents vs. Time

Fig.11 gives the inductance variation while the rotor poles gets align position.

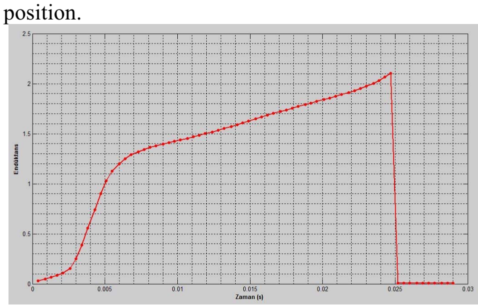

Fig.11 : Inductance change

Inductance is inverse proportional to the reluctance so the inductance is increasing while the reluctance decreasing. Inductance will be maximum and reluctance will be minimum for the aligned position. Since the switches for each phase will be across to the same voltage, only one switch voltage is shown for each phase in Fig. 12.

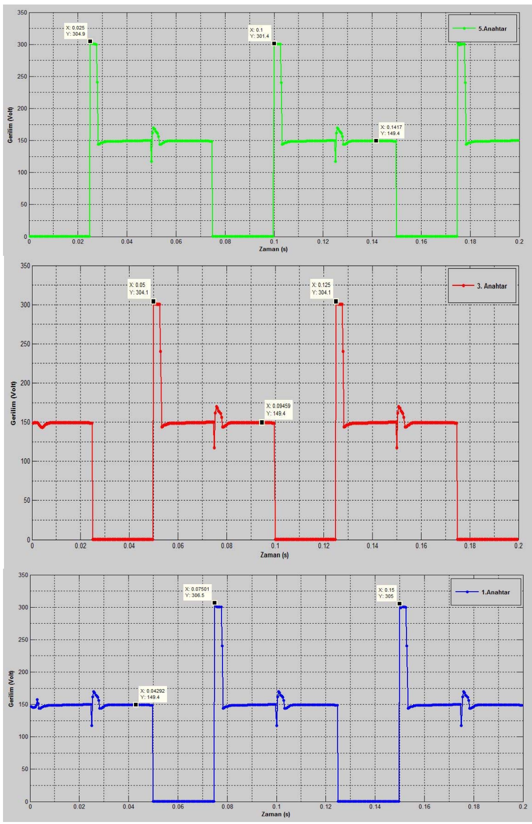

Fig.12 : Voltages across the switches

After completing the basic design, some parametric studies are carried on to observe how the machine operation will be affected by changing number of turns of phase windings, resistance of phase windings and materials. Torque vs. time variation for different number of the turns of phase windings is presented in Fig.13. Since the magnetic field intensity **H** is proportional to the number of the turns, decreasing the number of the turns result decreasing torque values.

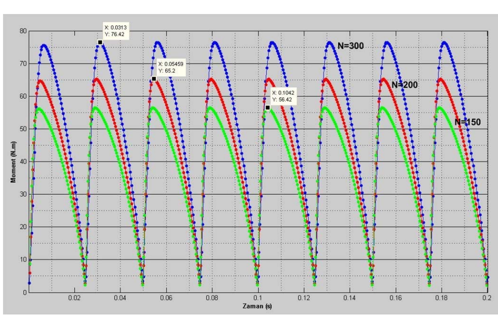

Fig.13. Torque change for different number of turns

Three different materials are used for the material analysis instead of M800-65A. These are silicon iron (1%), cast steel and cast iron. Their B-H characteristics are given in Fig. 14.

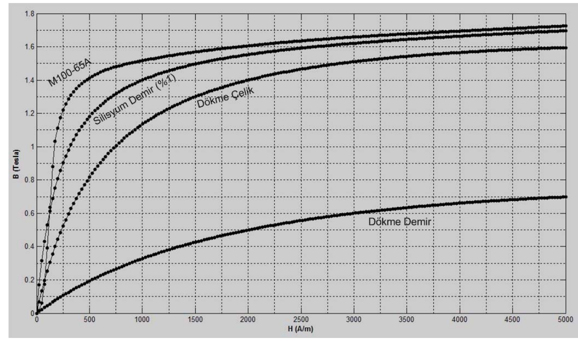

Fig. 14. B-H characteristics of different ferromagnetic material

The torque vs. time variation for different materials is given in Fig. 15. The worst solution is obtained with cast iron. The material has very low saturation value and high eddy current loss. The best solution in material sense is obtained with M800. This material is the steepest one compared to the others. It has high saturation value.

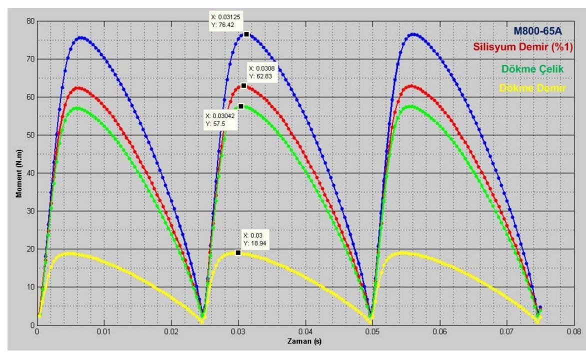

Fig.15. Torque change for different material

Finally different phase currents' effect on inductance value is searched. Inductance vs. Time variation for different phase currents is presented in Fig.16.

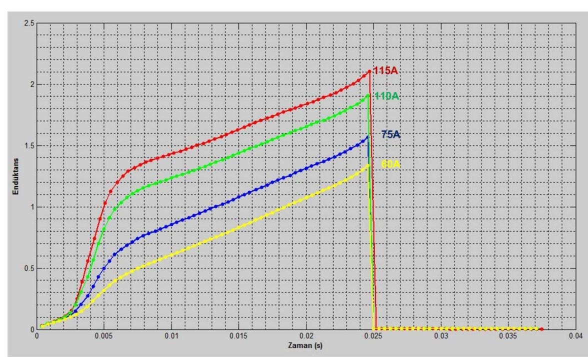

Fig.16. Inductance change at different phase currents

6. Conclusion

The trend in the motor and motor control is to design energy efficient and low cost systems. Improvements in the converter technologies will make SRM more prominent in applications in terms of energy efficiency. In this paper the design topology of an SRM is reviewed. With a new 6/4 SRM design is completed with Finite Element Analysis. Different parameters are investigated to observe machine performance in terms of output torque. The driving circuit scheme is kept the same while changing some parameters.

7. References

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