INVESTIGATION OF MAGNETIC CHARATERISTICS AND SIMULATION OF SWITCHED RELUCTANCE MOTOR USING FEM ANALYSIS

*Ediz GIZLIER *Sinan GÜNGÖR **Feriha ERFAN *A. Faik MERGEN
e-mail: ediz@elk.itu.edu.tr *e-mail:* gungor@elk.itu.edu.tr *e-mail:* erfan@kou.edu.tr *email:* mergen@elk.itu.edu.tr
**Istanbul Technical University, Faculty of Electric-Electronics Engineering, Department of Electrical Engineering, Electrical Machines Division,*
80626, Maslak/Istanbul/Turkey
*** Kocaeli University, Faculty of Engineering, Department of Electrical Engineering, Electrical Machines Division Izmit/Kocaeli/Turkey*

Key words: Switched reluctance motor, finite element method, static characteristics

ABSTRACT

In this study, performance analysis and simulation of 6/4-switched reluctance motor (SRM) is presented. Prediction of performance analysis of SRM is quite complex, because of its highly non-linear structure and the complex influences between the motor parameters and excitation. In this paper finite element method (FEM) analysis of 6/4 SRM is presented to calculate the static characteristic. On the basis of the FEM model, flux-current-position, torque-position curves are gathered which are the fundamental characteristics of SRM and have significant influences on motor performance. In addition calculated FEM results are used as look-up table for the simulation of SRM. Accurate results are achieved with the literature, for different firing excitation SRM performance can be analysed.

I. INTRODUCTION

The reluctance variable principle is known from the first electromagnetic experiments. The researches for electrical machines producing a continues rotation with the reluctance principle started at the nineteenth century and these machines are named as electromagnetic machines. At 1840 W.H.Taylor presented a electromagnetic machine which is the basis for today's SRM. After this study further approaches and studies are presented. Unfortunately, because of its highly inductive current, problems at designing a accumulators for power supply, high torque ripple, heat problems and commutation problem at supply current had made SRM unattractive for industrial applications and academic researches in these days.. Since 1960's this machines has reappeared with the development of semiconductor switches. With the availability of inexpensive fast electronic power switches and high performance digital controllers, SRM performance and control strategies are improved, leading to widespread application area in the industry.

Current interest on the subject is stimulated mainly by the contributions made by Lawrenson , in which they describe the fundamental design considerations of high efficiency SR motors such as the number of stator and rotor poles, the rotor pole pitches, suitable configuration and rating of drive circuits. Davis and Miller make other noticeable contributions, on different inverter circuits and microprocessor control strategies.

Earlier analyses of SRM performance were based on a linear or an idealised non-linear model of magnetic circuit. The linearity is made generally in the magnetic material, simplified magnetic structure and idealised current waveforms. Although such idealised approximations of the non-linear field condition may be convenient and useful for qualitative analysis of drive performance and estimating the design parameters and circuit ratings. But they lacked sufficient accuracy for further refining switch control or magnetic design. Because, SRM usually operates at magnetically saturated regions where as affecting the performance of the machine. In order to overcome these problems, finite element method is the ideally suited to handle the highly non-linear magnetic structure of SRM.

This paper deals with the detailed magnetic analyses of SRM and gathering its static characteristic. In addition the FEM analysis results are used as look-up table for the simulation with numerical solution of non-linear differential equations describing SRM.

II. BASICS OF OPERATION AND STRUCTURE

The SRM is a variable reluctance step motor that is designed for converting energy efficiently. The motor is doubly salient with different number of rotor and stator poles. Torque is produced with the attraction of rotor poles to the excited stator phase according to reluctance principle. Furthermore, the torque produced by the machine is independent of the polarity of the phase current. Then the structure of the converter can be simplified and eventually the number of power semiconductor switches can be reduced per phase (Fig 1, fig 2)

The SRM has rather simple construction; the stator consists of salient poles which carries the excitation windings wounded across the poles. Each opposite pole is connected in series to generate N-S poles. Its rotor has no winding, brush or magnet. Both stator and rotor is made of laminated steel for to decrease core losses. Its simple and robust structure makes it attractive for variable speed applications. For motoring operation a stator phase is excited when a pair of rotor poles is approaching and it must be turned off before rotor and stator poles actually come into alignment. For continuous rotation a position feedback is required. The SR driver has additional advantages compared with the conventional adjustable ac or brushless dc drives (including permanent magnet motor drives). Beside these advantages, there are some important disadvantages of SRM. Torque produced in SRM is naturally pulsed, because of its operation principle and magnetic structure. These torque ripples contribute to mechanical wear and acoustic noise especially at high speeds. The ripples can be reduced, and performance of the SRM can be improved initially through modifying geometric parameters using FEM analysis. Further reduction can be accomplished by using appropriate control with the SRM.

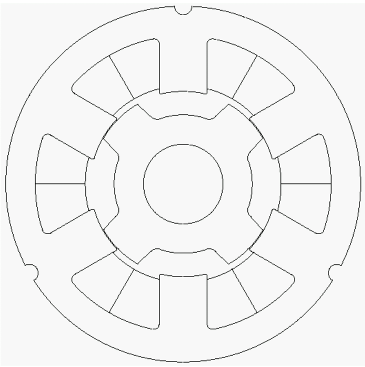

Fig1 6/4 Switched Reluctance Motor Geometry

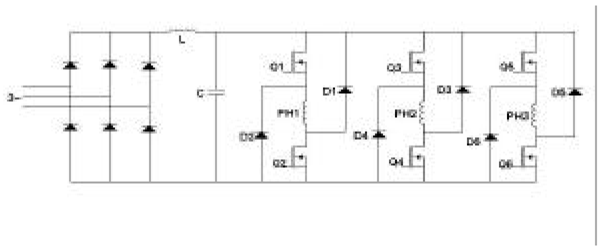

Fig2 SRM Classical Inverter Circuit

When it comes modelling of the SRM, the outward simplicity of its construction is deceiving because the magnetic structure is naturally non-linear. For improved energy conversion, the motor is operated in saturated region by making airgap narrower. Furthermore static characteristics such as static torque, flux linkages, inductances are functions of both rotor position and excitation current. In a fixed voltage both current and torque are affected by switching angles. The shape of the resultant current is dependent on the conduction interval and the stator phase inductance waveform or rotor position. Also average torque is a function of iron geometry, current pulse and level.

III. FEM ANALYSIS

The early analyses of SRM performance were based on a linear or an idealised non-linear model of the magnetic circuit. Although these approximations are useful for certain analyses of drive performance and estimating parameters. But they lack of giving information in switching control strategy or magnetic circuit design. Because SRM usually operates at saturated region, which increase the efficiency and torque.

The accurate characterisation of SRMs is difficult because of the large change in inductance between unaligned and aligned positions and the high level of magnetic saturation. In order to characterise the machine experimental and theoretical studies are performed in the literature. In experimental studies basically two ways are mostly used.

i) Applying a sinusoidal voltage of known rms value and frequency and measuring the resulting rms current. Knowing the winding resistance, the flux linkage can be calculated.

ii) Using $V = L\dfrac{di}{dt}$ with a constant voltage applied and measuring the rate of rise current. From this, flux-linkage can be calculated.

In both of this measurement techniques absolute accuracy is quite good. However distortion of applied voltage and distortion of resultant current makes this methods unsuitable at saturating regions. In this study we prefer to analyse the SRM using FEM.

Finite element methods are widely used in the design and analysis of electrical machines, which saves costs and time in the design and practical application procedure. In our FEM program two-dimensional analyse is made for 6/4 1kW SRM (fig1). The magnetic flux in the SRM is determined by computing the magnetic vector potential A, using the non-linear Poisson’s equation

$$\frac{d}{dx}\left(\nu\frac{dA}{dx}\right)+\frac{d}{dy}\left(\nu\frac{dA}{dy}\right)=-J \qquad (1)$$

Where ν is the magnetic reluctivity (which is a function of both position and the magnetic flux density) and J is the current density.

MAGNETIC FLUX DISTRIBUTION

An accurate prediction of the parameters and the static characteristics of an SRM using FE method is also difficult because the field distribution in the SRM is highly non-uniform. The flux distribution is gathered for all rotor positions while excitation current is increased from zero up to high level of saturation to include its effects. The two dimensional finite element method includes the following assumptions

i) A is axial with A_x and A_y components equal to zero, thus the magnetic field has two components B_x and B_y

ii) The current density within any conductor is uniform.

iii) Hysteresis effects are neglected.

iv) The induced conduction current in iron is neglected because of the relatively high resistance offered by steel laminations for eddy currents in the axial direction

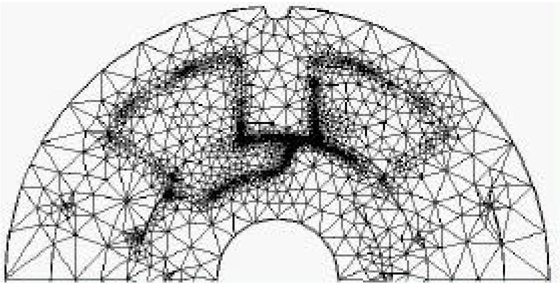

Fig 3 Meshed Diagram of SRM

In the above figure 3 problem region is subdivided into triangles taking care to see that the sides of the triangles coincide with material boundaries. The remedy of increasing the mesh resolution is done with optimisation and using low aspect ratio.

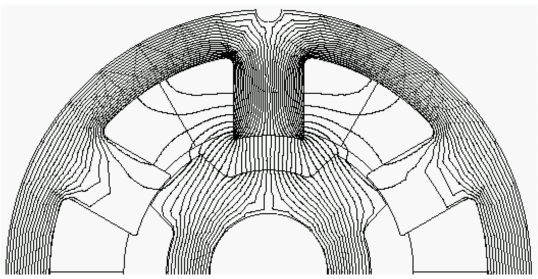

Fig 4 Flux Distribution of SRM for $\theta=32^0$

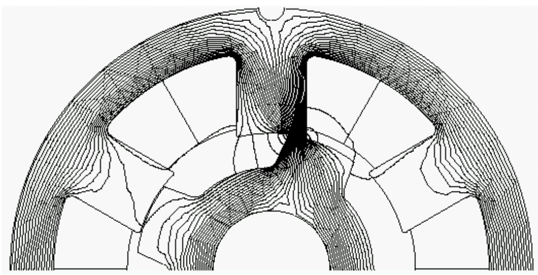

Fig 5 Flux Distribution of SRM for $\theta=12^0$

In the above figures (fig 4 and fig 5) the flux distribution is shown for two different rotor position. In figure 5 overlapping pole corners show the effect of local saturation. The results from our study shows that most of the field energy is concentrated in the narrow air gap region between overlapped poles of the rotor and stator where local saturation occurs and fringing flux lines curve sharply. In adequate modelling of this region will affect thoroughly in all characteristic curves.

The numerical solutions obtained from the finite element field analysis are stored as data file to be used in Matlab. The corresponding flux-current-position curve is shown in the below figure 6

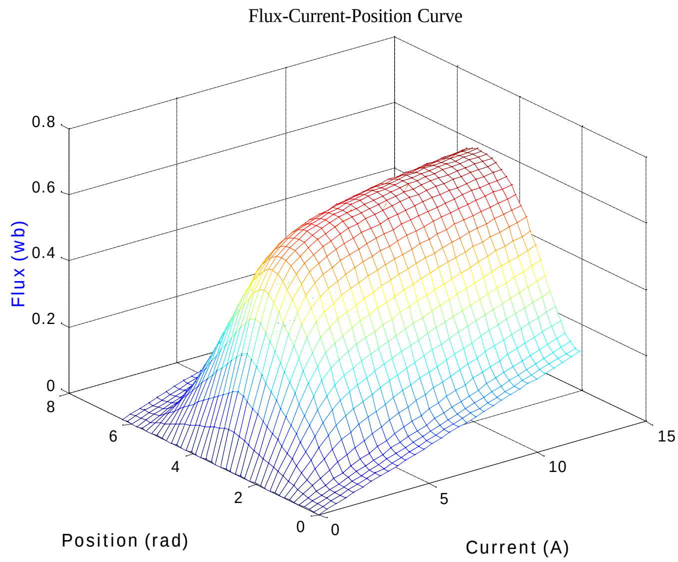

Fig 6 Flux-Current-Position Curve

IV. CHARACTERISTIC CURVES OF SRM

The flux-linkage in a two dimensional region with area S containing non-linear material can be derived from the Maxwell equation with no displacement current.

$$l = Nd\left(\frac{\int_S AJds}{\int_S Jds}\right) \qquad (2)$$

Where λ is the flux linkage of one slot, N is the number of conductors in each stator slot, J is the current density in the slot, A is the magnetic vector potential, S is the surface area and d is the depth of the region.

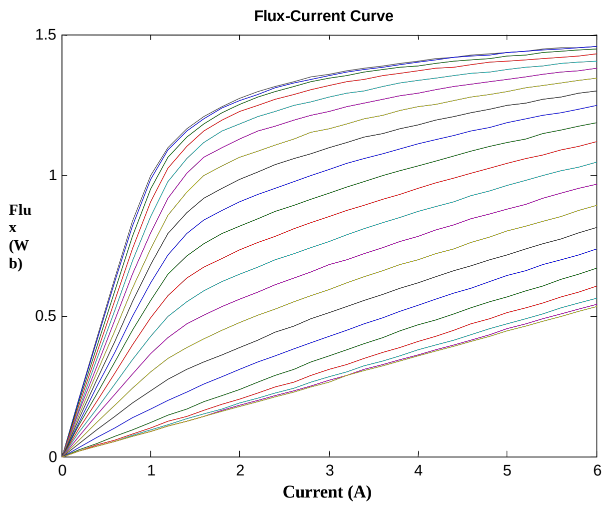

Fig 7 Flux-Current Curve

Flux-Current curve is shown for different rotor position in figure 7. In unaligned rotor position, the flux current diagram is approximately linear as expected. In addition when rotor is approaching the excited stator pole, the overlapping pole corner indicates the effect of saturation for high level current. SRM is usually operated in the region of saturation. The figure clearly indicates the region where;

$$T = \frac{\partial W^{'}}{\partial q} \qquad (3)$$

T is torque, $W^{'}$ is the coenergy, which can be evaluated by the region below the flux-current curve.

The next characteristic, which will be gathered, is inductance curve with respect to rotor position. The winding inductance is also an important parameter that has considerable effect on the motor operation and also the key parameter for simulation. The inductance L can be found from the flux linkages λ by using definition;

$$L = \frac{\partial l}{\partial i} \qquad (4)$$

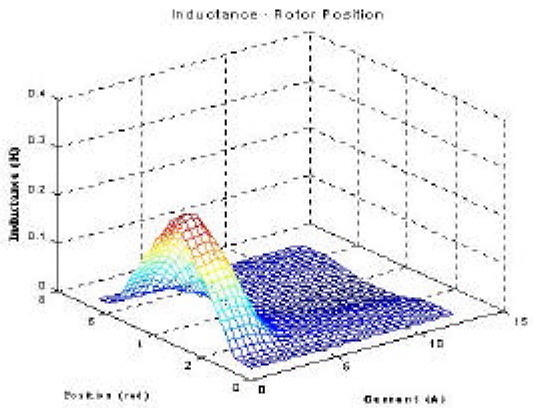

Fig 8 Inductance Curve – Rotor Position

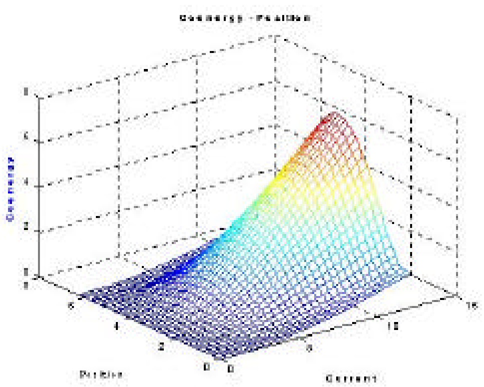

Fig 9- Coenergy Profile of SRM

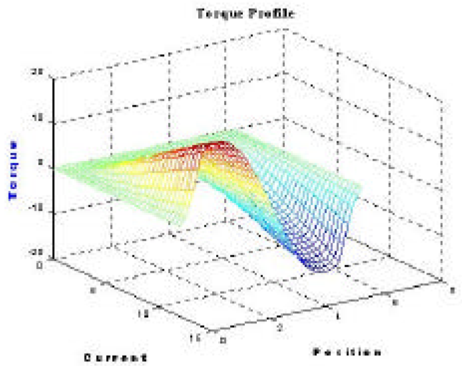

Fig 10- Torque Profile of SRM

It is important to calculate the electromagnetic energy stored in the field accurately because the energy stored is often used as a convergence criterion for finite element solutions.

V. SIMULATION OF SRM USÝNG FEM RESULTS

In simulation of electrical machines, the differential equations containing the system parameters are used. These parameters can be determined by experimentally or analytically. In the case of conventional type of electrical machines, system parameters do not change with rotor position. However in SRM, is varying with rotor position due to its operating principle. This inductance variation can be gathered experimentally, but the accuracy is not enough for dynamic simulations. In this study FEM analysis results will be used to obtain a model of SRM. The differential equation defining the system is;

$$V = R.i + \frac{dl}{dt} \qquad (5)$$

$$V = R.i + \frac{\partial L(q,i)}{\partial q}.\frac{dq}{dt}.i + \frac{\partial L(q,i)}{\partial i}\frac{di}{dt}i + L(q,i)\frac{di}{dt} \qquad (6)$$

$$V = R.i + l(q,i).\frac{di}{dt} + E_B(q,i) \qquad (7)$$

In the last equation the term $l(q,i)$ indicates the incremental inductance and $E_B(q,i)$ indicates the induced voltage due to the speed of the system. The simulation of the SRM is made in simulink. The simulink model is obtained by using FEM results

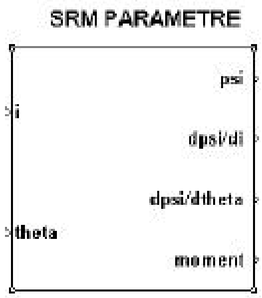

Fig 11 Simulink model of SRM

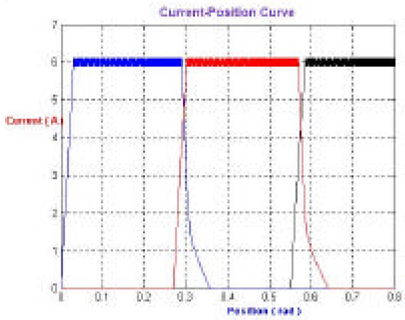

Fig 12- Current waveform for 600rpm

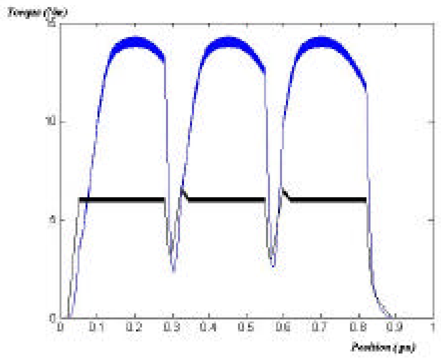

Fig 13- Total Torque&Current Waveform for 600 rpm

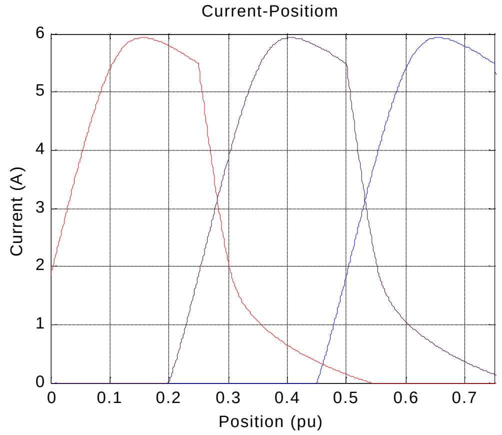

Fig 14- Current Waveform for 2000 rpm

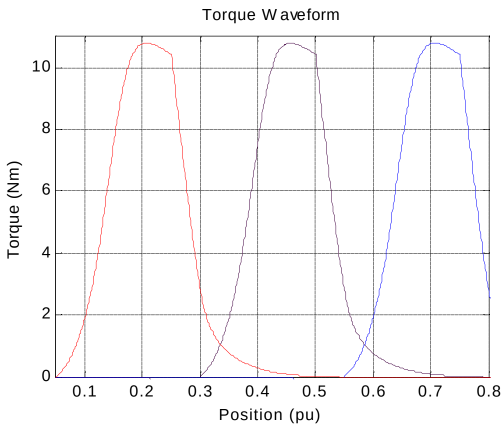

Fig 14- Torque Waveform for 2000 rpm

In high speeds advanced angle control is required for optimum torque control as shown in the above figures.However there are still torque pulsation due to the operational principle of SRM.

VI. CONCLUSION

In this paper two-dimensional magnetic analysis of a switched reluctance motor is given. The flux distribution is gathered for different rotor positions and currents in order to account the saturation effect. The FEM results are indicates the accurate flux distribution of the motor, which are given in the section ýv. The simulation of the reluctance motor differs from the classical machines because of the inductance variation. FEM results are used as look up table in the simulation for getting accurate results. The simulation is performed for different speeds. Current chopping is performed for low speed applications and at high speeds advanced torque control is performed.

VII. REFERENCES

1. P. J. Lawrenson, S . R. Vamaraju, “ New 4/6 pole reluctance motor, “ Electric Machines and Electromechanics, pp. 311-323 1978
2. M. R. Harris, A. Hughes and P. J. Lawrenson, “ Static torque production in saturated doubly salient machines,” in Proc. Inst.Elec.Eng. (England), vol 122, no. 10, pp. 1121-1126, Oct. 1975.
3. L. E. Unnewehr and W. H. Koch, “ An axial air-gap reluctance motor for variable speed application, “ IEEE Trans. Power Appl. Syst., vol PAS-93, no.1, pp 367-376, Jan./Feb. 1974
4. R. Arumugam, D. A. Lowther, R. Krishnan, J. F. Lindsay “ Magnetic Field Analysis of a Switched Reluctance Motor Using aTwo Dimensional Finite Element Model “ IEEE Transactions On Magnetics Vol MAG-21 no. 5, September 1985
5. J. F. Linsday, R. Arumugam, R. Krishnan, “Finite Element Analysis Characterisation of a Switched Reluctance Motor with Multitooth per Stator Pole“ IEE Poceedings Vol. 133 pt. B. no.6 November 1986
6. S. Bolognani, G. Buja, M. I. Valla. “Switched Reluctance Motor Performance Analysis Based On an Improved Modelling Of its Magnetic Charateristics” Electrical Machines And Power Systems. 1991
7. M. Moallem. C. M. Ong, “ Predicting the Steady-State Performance of a Switched Reluctance Machine” IEEE Transactions on Industry Applications Vol. 27, no. 6 November/December 1991
8. W. Cai, P. Pillay, A. Omekanda, “Analytical Formula for Calculating SRM Model Frequencies for Reduced Vibration and Acoustic Noise Design. IEEE International Electric Machines and Drives Conference. June 2001