THREE DIMENSIONAL MAGNETOSTATIC ANALYSIS OF A 3-PHASE, 12/8 POLE 250 W SWITCHED RELUCTANCE MOTOR USED IN A WASHING MACHINE DRIVE

Ahmet FENERCİOĞLU[1] Ünal KURT[2]

[1] Gaziosmanpaşa University, Turhal Higher Vocational School, 60300 Turhal ,Tokat, Turkey, af@gop.edu.tr
[2] Amasya University, Amasya Higher Vocational School, 05189 Amasya, Turkey, ukurt@omu.edu.tr

Key Words: SRM design, finite element analysis, SRM magnetic analysis.

ABSTRACT

In this study, physical sizes and geometry of a 3-phase, 12/8 pole, 250 watts switched reluctance motor (SRM) which is used in a washing machine drive have been determined and its one-to-one model has been developed. The model obtained has been analyzed through the 3 D magnetostatic analysis method and 3 D finite elements method. As a result of the analyze, phase inductance, torque ripple, average and instant torque, air – gap power and magnetic flux pattern values have been obtained. Besides, analytical approach values for these magnitudes have been calculated and simulated. The fact that the results of the analytical approaches and simulation results are close to the real size values proved that the applied simulation method was correct.

I. INTRODUCTION

The theory of motor with variable reluctance has been started to be used since 1980's for the variable or adjusted speed application and the use of these motors started to be very popular in engineering applications. The advantages brought by the cheap and powerful switching elements enabled the re-discovery of this motor. SRM is very simple in structure. However its control is complex. For instance, the process of excitation of the phase windings in appropriate order for torque generation requires the provision of the position information of the rotor.

Besides, SRM's have been enabled to compete with the other DA and AA motors by the possibility of obtaining low cost microprocessor and power electronic elements [1, 2].

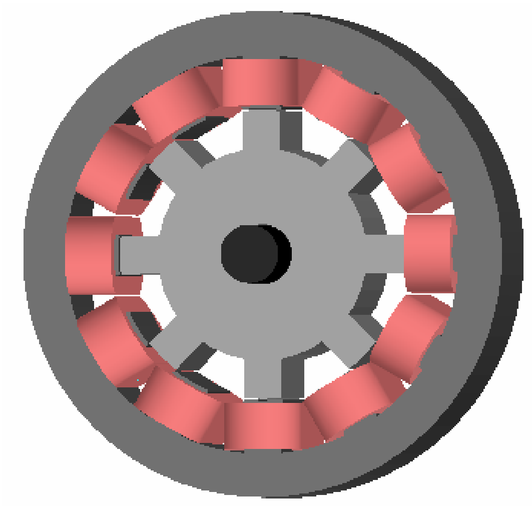
II. MATERIAL AND METHOD

In this study, magnetostatic analysis of a three-phase, 12/8 SRM used in the washing machine drive through the computer aided three dimensional finite elements method by determining its real sizes and geometry. As a result of the simulations, inductance, torque and power values have been estimated and compared with the analytic results [1–3].

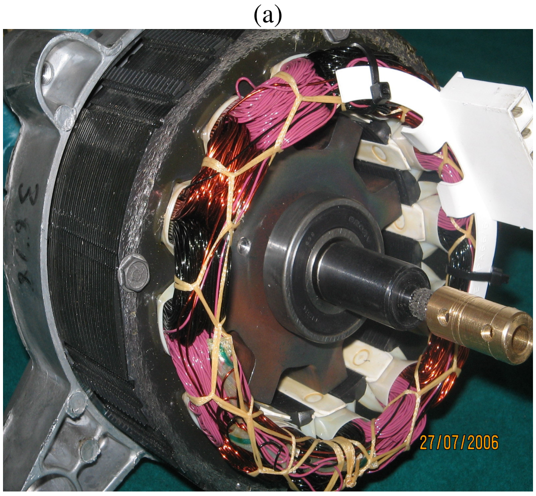
The values of physical changes of SRM with 12/8 pole [4] are seen the Table 1. The real picture, simulator cross section and size variables and values [4] are given in Figure 1.

Table 1. Sizes of the SR Motor studied

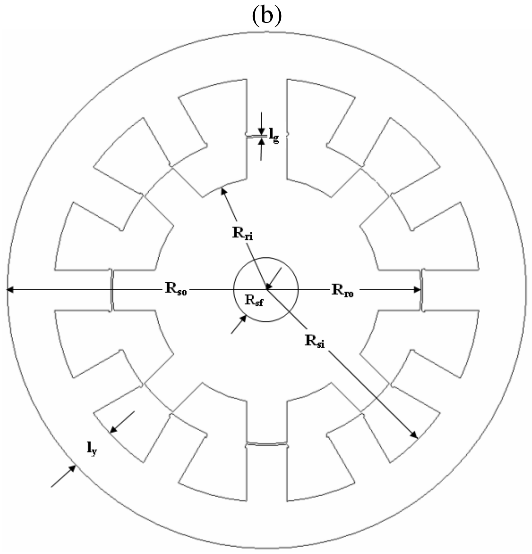
Symbol	Meaning and Unit	Value
R_{so}	Stator outer diameter (m)	0,06975
R_{si}	Stator inner diameter (m)	0,05725
R_{ro}	Rotor outer diameter (m)	0,04144
R_{ri}	Rotor outer diameter (m)	0,03050
R_{sf}	Shaft diameter (m)	0,00842
l_y	Stator yoke (m)	0,01250
l_g	Air gap (m)	0,00046
L_{stk}	Stack length (m)	0,04630
β_s	Stator pole angle (rad)	0,2616
β_r	Rotor pole string angle (rad)	0,2704
n_s	Stator pole number	12
n_r	Rotor pole number	8
q	Number of phase	3
N	Number of winding for a pole	200



(a)



(b)



(c)

Figure 1. Model of the 12/8 SR Motor which is studied. a) Simulator model, b) Real model c) Size variables.

EQUIVALENT CIRCUIT OF SRM

Motor phase inductance in SRMs varies according to rotor position and the current passing through the winding. General circuit equation of SRM is given in Eq. (1). In Figure 2 the equivalent value for one phase of SRM is shown [3,5].

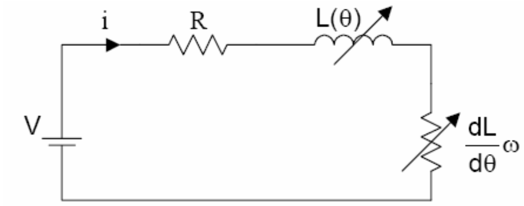


Figure 2. Equivalent circuit for one phase of SRM

It is expressed as follows:

$$V = Ri + \frac{d\psi(\theta,i)}{dt} - M(\theta)\frac{di'}{dt} \qquad (1)$$

Here the V is the supply voltage, R is the winding resistance, ψ is the magnetic flux, i is the phase winding current, $M(\theta)$ is the mutual inductance, θ is the rotor position angle, i' is the winding current excited before the relevant phase. When saturation is neglected magnetic flux is $\psi = L(\theta, i)$ and there for Eq. (1) is re arranged as follows:

$$V = Ri + \frac{dL(\theta)}{dt} - M(\theta)\frac{di'}{dt} \qquad (2)$$

Here $L(\theta, i)$ shows the phase inductance. When the differential expression in Eq. (2) is divided into pieces, it becomes as follows by neglecting the mutual inductance;

$$V = Ri + L(\theta)\frac{di}{dt} + i\frac{dL(\theta)}{dt} \qquad (3)$$

When the mutual inductance value is neglected it becomes as Eq. (3) and Eq. (4) [3,5].

$$\frac{dL(\theta,i)}{dt} = \frac{dL(\theta,i)}{d\theta}\omega \qquad (4)$$

Here we obtain:

$$\frac{di}{dt} = \frac{di}{d\theta}\omega, \quad V = Ri + L(\theta)\frac{di}{d\theta}\omega + i\frac{dL(\theta)}{d\theta}\omega \qquad (5)$$

Here ω is the angular velocity. [3,5]

In order to find the phase inductance in the intermediary rotor positions of a SRM, cosine correlations are given in Eq. 6 as a Fourier Series by using the maximum and minimum inductance values.

$$L(\theta,i) = \sum_{k=0}^{m} L_k(i)\cos(kn_R\theta) \qquad (6)$$

Here L indicates the phase inductance (H), θ indicates the rotor position in degrees, n_r indicates the pole number.

ARM has low energy ratio. To express this, an energy conversion cycle has been calculated magnetically. SRM is a linear model in the first harmonic of the Fourier Series of the inductance according to the SRM rotor position. Here the inductance value is given in Eq. 7, flux linkage is given in Eq. 8 [3, 6].

$$L(\theta,i) = [(a_0 - a_1 \cos(n_R\theta)] \tag{7}$$

$$\lambda(\theta,i) = [(a_0 - a_1 \cos(n_R\theta)]i \tag{8}$$

Here λ is the flux linkage (wb), i is the phase current. The a_0 and a_1 coefficients in Eq. 3 can be obtained from Eq. 9 [5].

$$a_0 = \frac{1}{2}(L_a + L_u) \;,\; a_1 = \frac{1}{2}(L_a - L_u) \tag{9}$$

Here n_R is the number of rotor, for one phase, L_a is the maximum inductance, L_u is the minimum inductance.

In the application, this motor is not run in the unaligned position. The operation area of the motor is between the overlap position and the aligned position of the rotor and stator pole. After this position the same region is valid for the 2nd phase and the excitation is cut and the 2nd phase is excited when the 1st phase overlaps.

When there is a current pass a phase, the torque tends to rotate the rotor in a direction to increase the inductance. The direction of the torque is always towards the closest overlapping position. Therefore positive torque (for instance motor operation torque) can be generated only if the rotor is between the non-overlapping forward position and the next overlapping position. The most general expression of the instantaneous torque caused by a phase in each rotor position is given in Eq. 10 [3,4,6,7].

$$T = \left[\frac{\partial}{\partial\theta}\int_0^i \lambda(\theta,i)di\right] = \left[\frac{\partial W'}{\partial\theta}\right]_{i=sabit} \tag{10}$$

Here T is the instantaneous torque (Nm), W is the co-energy (J). Since the instantaneous torque changes according to the rotor position, mean torque is a more appropriate term to express the torque of a motor. Considering the linear magnetic characteristic of SRM, mean torque or electromagnetic torque is given in Eq. 11.

$$T_e = \frac{1}{2}i^2\frac{dL}{d\theta} = \frac{1}{2}i^2\frac{L_a - L_u}{\beta_s} = \frac{1}{2}i^2\frac{L_a}{\beta_s}\left(1 - \frac{L_u}{L_a}\right) \tag{11}$$

Here β_s is the angle of stator pole angle in degrees

III. RESULTS AND DISCUSSION

Magnetic devices are traditionally designed by combining the simplified circuit models and rules based on experimental evidence. However, since the devices are increasingly variant and complex and the rules are not sufficient, electromagnetic field problems have been started to be solved according to the analysis and design based on logical, detailed solution [1,3].

Phase inductances and instantaneous torque values of the SRM model developed are estimated according to the position change for each 2.5 degree of the rotor after the magnetostatic analysis is made with the 3-dimensional simulator. Besides these results are also obtained analytically and compared in the graphic in Figure 3. Here the rotor position is given between 0-45º. 0º-22,5º indicates the generator operation region and 22,5º-45º indicates the motor operation region. In both areas, the concerned phase is not operated between 15º-30º which is the unaligned region. In this region other phase is excited.

When the align of the stator pole of the phase with the rotor pole finishes, the excitation of that phase is stopped and the energy is supplied to the other phase. That is, when the rotor pole starts overlapping with the stator, phase excitation is started.

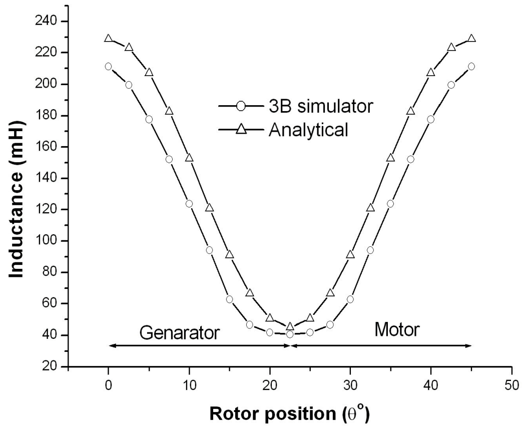
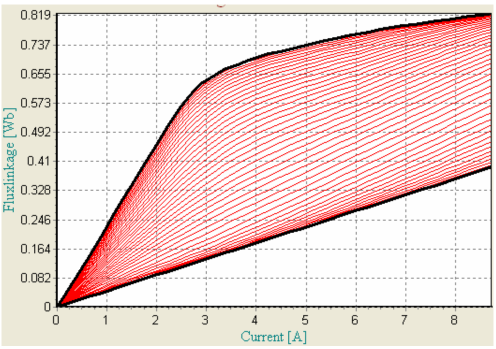
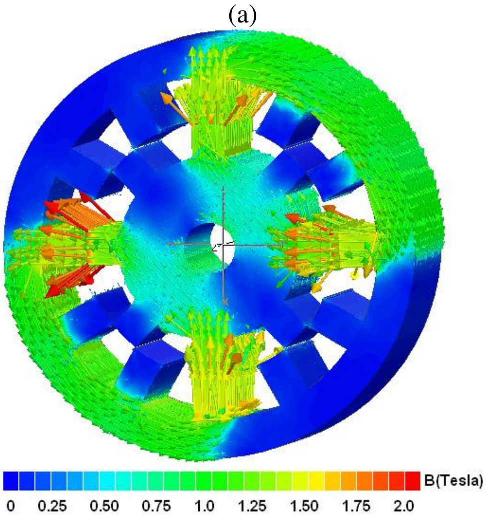


Figure 3. Change of phase inductance according to the rotor position

The characteristic of the flux linkage between the aligned and unaligned positions is given in Figure 4 (a) [3,4,7].



(a)



(b)

Figure 4. a) Flux Linkage characteristics of SRM
b) flux distribution of aligned position

Figure 4 (b) shows the flux distribution of SRM in aligned position as vectorial and magnitude values. In the aligned position the local saturation in the pole corners is at the minimum levels according to the flux distribution. In positions where the rotor pole overlaps less with the stator pole, this saturation effect is more. The material used in the simulator model is the one called steel 1010 and the BH characteristics are given in figure 5. The knee point of this material is around 1.9 T and saturation starts after this value.

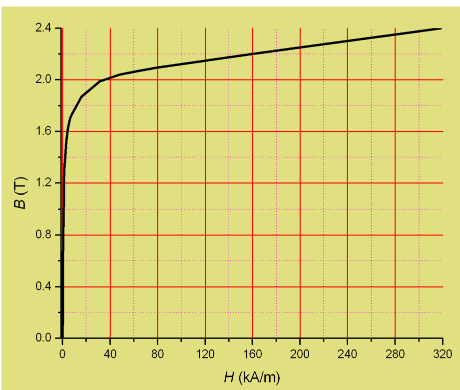
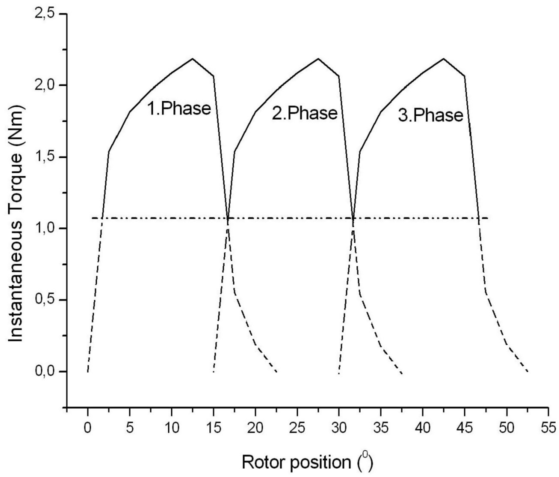


Figure 5. *B-H* curve of the material (steel 1010) used as rotor and stator core

In figure 6, torque ripple of SRM motor is shown. Here, torque ripple caused by the 45° movement of the rotor as a result of consecutive triggering of 3 phases. But the speed and inertia of the rotor has not been taken into consideration, and only the static conditions are considered. The speed, mass and inertia of the motor and the control strategy of its drive circuit will further reduce the torque ripple [8]. In figure 6, torque ripple is given for the 1/8 lap of the rotor according to the magnetostatic simulation results.



(b)

Figure 6. Torque ripple of SRM

In this case, the analytically estimated torque expression and the values obtained by the 3 dimensional simulators are given in Table 2 in comparison.

Table 2. Mean torque and power values

Solution method	Mean torque (Nm)	Power (W) (for 1000 d/d)	Motor Power (W) (Label Value)
3B simulator	2,377	248,78	250
Analytic	2,558	267,78	250

Simulator results in Table 2 are predicted after the 3 dimensional magnetostatic analysis. The dynamic operating conditions of the motor, its control strategy and the effects of the drive circuit have not been taken into consideration. Stator and rotor have been taken as a whole in the motor design, and no lamination has been made. Windings have been drawn as single-coiled and each winding has been excited with 500 amper-tur mmk. It is assumed that 2,5 A flow passes through a coil with 200 number of windings. The magnetic material used in the simulation is not the same with the laminated material in the real motor. BH curve is the material called steel 1010 in the 3D FEA simulator software library which is a suitable material for SRM given in Figure 5.

The analytic results have been calculated according to the equations given in the material and method section according to the linear operating conditions. The torque estimated through simulation and analytic method is the electromagnetic torque as it is calculated according to the co-energy. Therefore the power values estimated in Table 2 are the air gap power and the losses have been neglected.

IV. CONCLUSION

It is more difficult to estimate the electrical and magnetic characteristics of SRM than the other methods. Because, inductance, power and energy amounts vary according to the rotor position in SRM. SRM doesn't have the stable condition where all state variables are fixed. The parameters changing according to the rotor position, local magnetic saturation effects and variant magnetic permeability affect the characteristics of SRM and therefore the behaviour of SRM is attempted to be increased through the simulation works rather than the analytical methods.

The basic electrical parameters of the 3 phase, 12/8 pole SRM which is examined in this study have been predicted by making magnetostatic analysis through the three dimensional finite elements method as well as the analytic solutions. The results obtained are the analytic estimates, simulation results and motor label values and it is seen that these values are close when compared to each other. In this case, the results provided by the study proves the correctness of the simulation method, because in order to conclude a correct design and analysis it is necessary that the computer based simulation methods for everything except basic sizing calculations are a part of the design process. In particular, it is strongly recommended to use the three dimensional simulators in magnetic system design as the machine geometry cannot be fully defined in two dimensional simulators and effects like coil end-fields, axial flux, fringing flux and skewing cannot be taken into account [3,9].

REFERENCES

1. Gürdal, O., "Elektrik Makinalarının Tasarımı", ***Atlas Yayın Dağıtım,*** İstanbul, 201-240, 2001.
2. Krishnan, R., "Switched Reluctance Motor Drives", ***CRC Press***, Florida, 1-169, 2001.
3. Fenercioğlu, A., "Anahtarlamalı Relüktans Motorun (HY-ARM) Tasarımı ve Analizi", Doktora Tezi, ***Gazi Üniversitesi Fen Bilimleri Enstitüsü***, Ankara 2006.
4. Tarımer, İ., "Redüktörsüz Mekanik Sistemler İçin Düşük Devirli Ve Yüksek Torklu Elektrik Motor Tasarımları", Doktora Tezi, ***Gazi Üniversitesi Fen Bilimleri Enstitüsü***, Ankara 2003.
5. Dursun, M., Saygın, A., "Güneş Enerjisi İle Çalışan Bir Sulama Sistemi İçin Boost Konvertörlü Anahtarlamalı Relüktans Motor Sürücüsü", ***Erciyes Üniversitesi Fen Bilimleri Ens. Dergisi,*** 22(1-2) 57-65, 2006.
6. Gürdal,O., Fenercioglu, A., "Computer Aided Three Dimensional Magnetostatic Analysis of Helically Structured Switched Reluctance Motor (HS-SRM)", ***Journal of The Faculty of Engineering and Architecture of Gazi University***, 2007.
7. Omaç, Z., Kürüm, H., "Anahtarlamalı Reluktans Motorun TMS320LF2407A Sayısal Sinyal İşlemcisi ile PWM Akım Kontrolü", ***Elektrik-Elektronik ve Bilgisayar Mühendisliği Sempozyumu,*** Bursa 111-116, 2004.
8. Şahin, F., Ertan, H.B., Leblebicioğlu, K., "Optimum Geometry for Torque Ripple Minimization of Switched Reluctance Motors", ***IEEE Transactions on Energy Conversion***, 15(1):30-39, 2000.
9. Fenercioglu, A., Tarımer, "Anahtarlamalı Relüktans Motorlarda Faz Endüktansına Etki Eden Faktörlerin İncelenmesi", ***Pamukkale Üniversitesi, Mühendislik Bilimleri Dergisi***, *13.cilt, 2.sayı,* 2007.