Erciyes Üniversitesi Fen Bilimleri Enstitüsü Dergisi **22**(1-2) 50-56 (2006)
http://fbe.erciyes.edu.tr/
ISSN 1012-2354

ANALYSIS OF A NEW DOUBLE-SIDED LINEAR SWITCHED RELUCTANCE MOTOR

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ABSTRACT

This paper presents the analysis of a linear switched reluctance motor (LSRM) which is a model increased power density structure. The new structure has double sided configuration and provides a high push/pull force for many applications with low cost. The characteristics of the LSRM are obtained by using finite element analysis (FEA) and analytical calculations to evaluate the model.

Keywords: Linear switched reluctance motor, Finite element analysis.

ÇİFT YANLI YENİ BİR LİNEER ANAHTARLAMALI RELÜKTANS MOTORUN ANALİZİ

ÖZET

Sunulan çalışma, lineer anahtarlamalı relüktans motorun (LARM) güç yoğunluğuna artırılmış modelinin analizini sunmaktadır. Yeni model, çift yanlı bir konfigürasyona sahip olup birçok uygulama için düşük maliyetle birlikte yüksek itme/çekme kuvveti sağlamaktadır. Modelin değerlendirilebilmesi için LARM karakteristikleri sonlu elemanlar analizi (SEA) ve analitiksel hesaplamalar ile elde edilmiştir.

Anahtar kelimeler: Lineer anahtarlamalı relüktans motor, Sonlu elemanlar analizi.

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1. INTRODUCTION

There has been widespread interest in the switched reluctance motor (SRM) drives in recent years. Although many articles have been published on modeling and analysis of the rotary switched reluctance motor (RSRM), there is a paucity of the literature on linear switched reluctance motors (LSRMs). LSRMs are the attractive alternative to other linear motors due to absence of windings on either the stator or rotor structure. Furthermore, the windings are concentrated rather than distributed, making them ideal for low cost manufacturing and maintenance [1-9].

The LSRM presented in this paper has double sided structure with three phases and windings are located on the translator (stator). Since the phase windings are located on the translator, the production cost of the LSRM system is much lower than the other motor structures for many applications.

This paper contains the illustration of the proposed motor analysis procedures. The analytical methods use simplified physical assumptions, but generally offer simple and analytical solutions that are well suited for an understanding of the physical phenomena and for computer-aided design (CAD) of the LSRMs. However, these analytical methods are not very accurate to calculate the magnetic characteristics of the LSRMs.

Most of the limitations of analytical techniques can be overcome by using the numerical methods. The numerical methods such as FEA [10-13] provide accurate results but usually require tremendous computational effort and numerical procedures. Therefore both of analytical method and FEA are used in the study.

The organization of the paper is as follows. Section 2 gives the analytical analysis of the motor. The topology of the proposed LSRM and its basic operation principles are described in detail in Section 3. Section 4 covers the analytical and FEA calculations of the characteristics of the motor. Section 5 presents the conclusions of this study and interpretations about the proposed double sided LSRM structure.

2. ANALYTICAL ANALYSIS

In general, precise calculations of the permeance for flux paths through air regions are very difficult since the flux distributions are three dimensional with geometries that do not lend themselves to simple mathematical description [2,4-7]. However, magnetic field analysis of the subject LSRM in the regions of air is based on well known permeance calculation methods outlined in [2]. The magneto motor force (MMF) applied to a phase winding at any position is given by

$$F = F_g + F_s + F_r \tag{1}$$

where F is the total MMF per phase applied and F_g, F_s, and F_r are the MMF drops in the air gap, stator iron core, and rotor iron core, respectively. Eq (1) can be written in terms of the magnetic field density and flux path as given,

$$F = T_{ph} i = \sum H_g l_g + \sum H_s l_s + \sum H_r l_r \tag{2}$$

where H_g, H_s, H_r, and l_g, l_s, l_r are magnetic field intensities and flux path lengths in the air gap, stator iron core and rotor iron core, respectively, and T_{ph} is the number of turns per phase.

The flux density $B_k(i,x)$ in path k for current i and position x given by,

$$B_k(i,x) = \frac{\phi_k(i,x)}{A_k} \tag{3}$$

where $\phi_k(i,x)$ is the magnetic flux, and A_k is the cross-sectional area determined by the geometry of LSRM. In the air gap, flux density can be represented in terms of the permeance equation as

$$B_{gk} = \frac{\phi_k(i,x)}{P_{gk}(x)} \frac{\mu_0}{l_{gk}} \tag{4}$$

where $P_{gk}(x)$ is the air gap permeance, and l_{gk} is the average air gap length of flux lines in path k. Due to magnetic flux is an unknown variable, iterative procedures such as a bi-section root finding algorithm is introduced by assuming an arbitrary initial value of magnetic flux. Flow chart for calculation of the phase inductance using bi-section root finding is shown in Figure 1.

The value of the flux density is obtained with the use of Eq (3) and is used in the $B-H$ characteristics of the core material to obtain the magnetic field intensity $H_k(i,x)$, except in the air gap region of linear space. The iterative solution gives the value of magnetic flux associated with path k. Finally, the inductance $L(i,x)$ for one phase with all magnetic flux path calculated by using Eq (5) [2].

$$L(i,x) = \sum_k L_k(i,x) = \frac{T_{ph}}{i} \sum_k \phi_k(i,x) \tag{5}$$

3. DESCRIPTION OF THE LSRM

Figure 1 shows a cross-sectional figure of the proposed double sided LSRM with three phases. Excitation windings are located on two outer stator laminated structures. The active translator is shown at the position of minimum reluctance in Figure 2. If phase B is excited, then the translator movement will be towards the right direction. Otherwise, phase C is energized.

Table 1. Mechanical and electrical parameters of the proposed LSRM.

Phase Number	**3**
Stator pole width	17 mm
Stator slot width	17 mm
Stator pole height	25 mm
Stator depth	50 mm
Rotor pole width	17.6 mm
Rotor depth	50 mm
Overall Length	204 mm
Overall Width	112 mm
Air gap width	1 mm
Steel type	M19

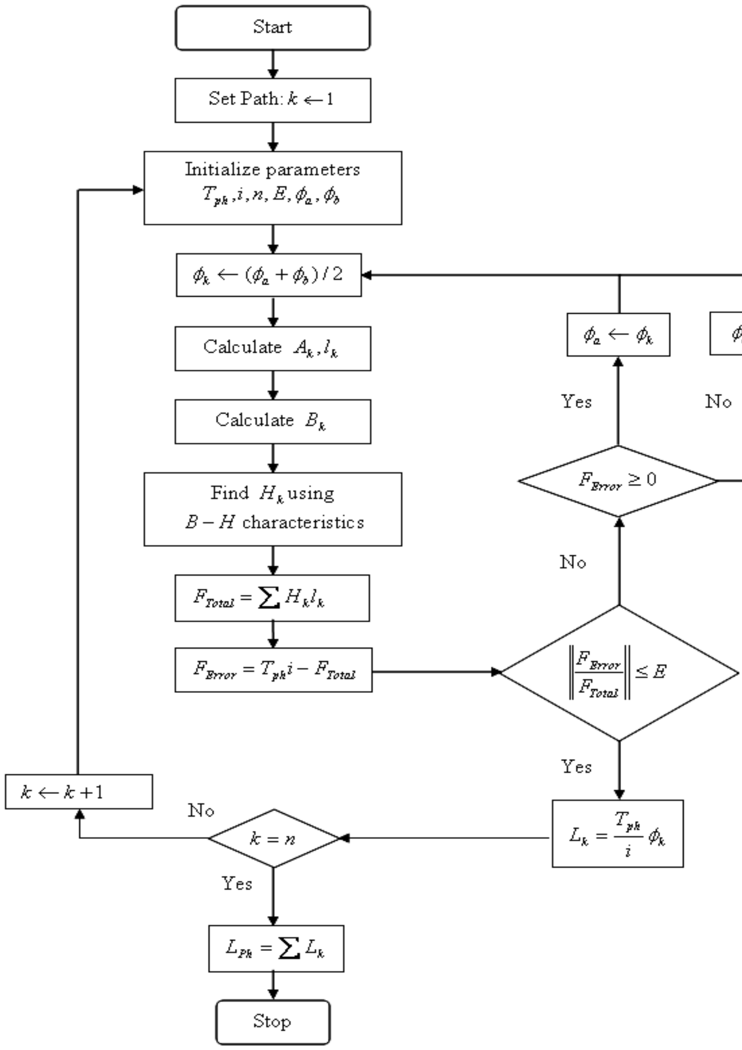

Figure 1. Flow chart for calculation of the phase winding using bi-section root finding.

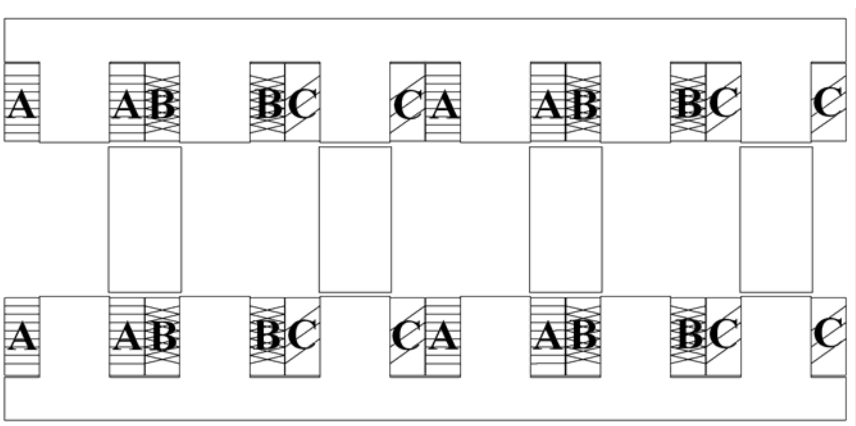

Figure 2. Cross-section of the proposed double sided LSRM.

The stator and rotor platforms of the LSRM are modeled with the use of M19 steel characteristics. The mechanical and electrical parameters of the proposed LSRM are summarized in Table 1.According to the specifications listed in Table 1, three-dimensional model of the LSRM is shown in Figure 3.

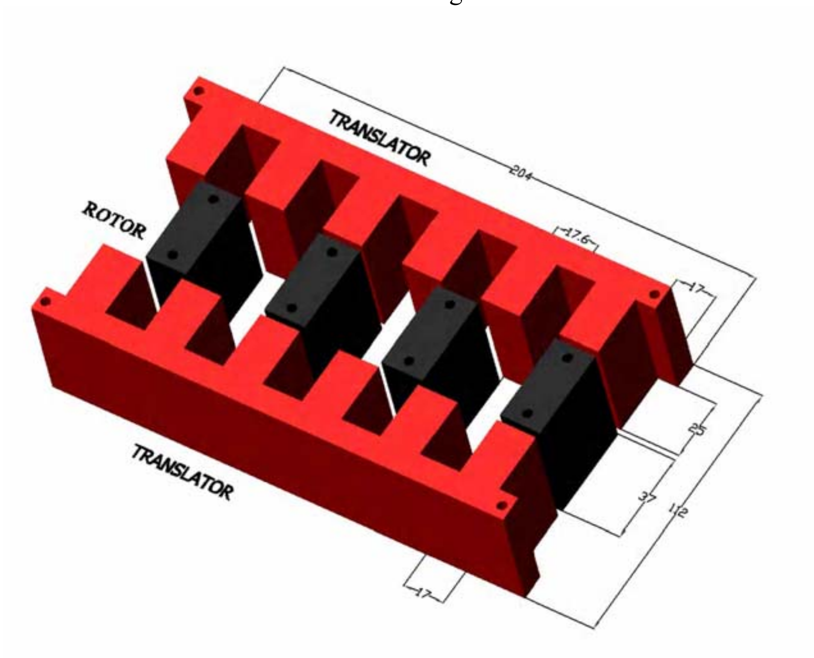

Figure 3. Three-dimensional model of the proposed LSRM.

The new proposed motor structure reduces the mass production cost because its windings are located on the translator. In addition, the rail parts of the road do not need to be continuous because of the flux distribution of the model. However, the parts of rail have to be continuous for the flux flow and force production of the motor when the single sided LSRM structure is used.Operation principle of the proposed LSRM is based on forward force generation. Because of the double sided LSRM structure, the produced lateral forces by two sides of the motor are eliminated by each other. This elimination is also very important for the reduction of the acoustic noise of the LSRM in the operation.

4. FEA AND ANALYTICAL CALCULATIONS

Analytical calculations and FEA are used to evaluate the LSRM. The translator of the LSRM is moved from the unaligned position with respect to the rotor to the aligned position for different excitation currents. Therefore, static force and inductance profiles are obtained as a function of position and current. The solution positions are chosen from complete unaligned position to complete aligned position in small increments. The excitation levels are chosen to be in steps of 5 A from 5 A to 45 A. When the analytical calculation and FEA results are compared with each other, it is observed that there are only very minor differences between the values.Flux distribution of the LSRM obtained from FEA for the aligned position is shown in Figure 4.

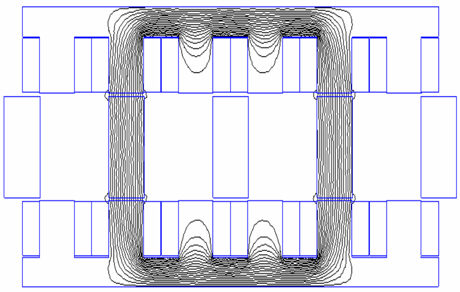

Figure 4. Flux distribution of the proposed LSRM in aligned position.

Figure 5 and 6 show the inductance and force profiles of the proposed LSRM at different currents for various positions, respectively.

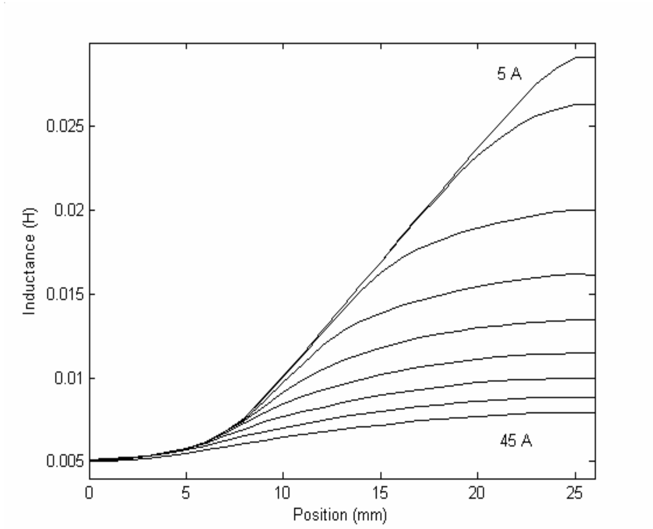

Figure 5. Inductance profile of the proposed LSRM for various excitation currents and translator positions.

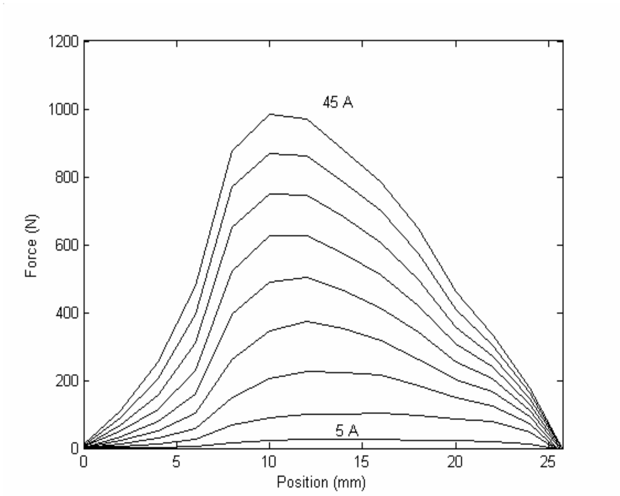

Figure 6. Force profile of the proposed LSRM for various excitation currents and translator positions.

The inductance value for the aligned position obtained by using analytical method is 27.90 mH and the FEA predicts this value as 26.27 mH. It is seen that there are only very small differences between these values and they are in very good agreement with each other. Accurate prediction of the unaligned inductance values are very difficult and we obtained values of 6.82 mH from the analytical calculation and 5.12 mH from the FEA (%11). In the aligned translator position, both the analytical and finite element results are very close with less than 6 % error. On the other hand, in the unaligned translator position, there is an error with 11% between the analytical and finite element results. The error is the attributable to the end effects and, to a smaller degree, to distortion of the magnetic properties of the core material due to punching stresses, inexact B-H characteristics provided by the steel manufacturers and no uniformity of the air gap. End leakage effects are severe in the fully aligned position because the reluctance of the end paths becomes comparable to that of the air gap paths.

5. CONCLUSIONS

In this study, the analysis of a new double sided LSRM structure is discussed. Analytical predictions of aligned and unaligned inductances with the use of magnetic circuit analysis are realized and verified with FEA. In addition, force profile of the motor has been obtained by using FEA to show effectiveness of the LSRM.

REFERENCES

1. Miller, T.J.E., Switched Reluctance Motors and Their Control, Oxford University Press, Oxford, 1993.
2. Krishnan, R., Switched Reluctance Motor Drives Modeling, Simulation, Analysis, Design and Applications, CRC Press, London, 2001.
3. Corda, J., Stephenson, J.M., Analytical Estimation of the Minimum and Maximum Inductances of a Double-Salient Motor, Proc. Int. Conf. on Stepping Motors and Systems, pp. 50-59, 1979.
4. Deshpande, U., Cathey, J.J., Richter, E., High Force Density Linear Switched Reluctance Machine, IEEE Transactions on Industry Applications, 31, 2, 345-352, 1995.
5. Deshpande, U., Two-Dimensional Finite-Element Analysis of a High-Force-Density Linear Switched Reluctance Machine Including Three Dimensional-Effects, IEEE Transactions on Industry Applications, 36, 4, 1047-1052, 2000.
6. Bae, H.K., Lee, B.S., Vijayraghavan, P., Krishnan, R., A Linear Switched Reluctance Motor: Converter and Control, IEEE Transactions on Industry Applications, 36, 5, 1351-1359, 2000.
7. Lee, B.S., Bae, H.K., Vijayraghavan, P., Krishnan, R., Design of a Linear Switched Reluctance Machine, IEEE Transactions on Industry Applications, 36, 6, 1571-1580, 2000.
8. Gan, W.C., Cheung, N.C., Qiu, L., Position Control of Linear Switched Reluctance Motors for High-Precision Applications, IEEE Transactions on Industry Applications, 39, 5, 1350-1362, 2003.
9. Stumberger,G., Stumberger, B., Dolinar, D., Identification of Linear Synchronous Reluctance Motor Parameters, IEEE Transactions on Industry Applications, 40, 5, 1317-1324, 2004.
10. Lindsay, J.F., Arumugam, R., Krishnan, R., Magnetic Field Analysis of a Switched Reluctance Motor with Multitooth per Stator Pole, Proc. Inst. Elect. Eng., 133, 6, 347-353, 1986.
11. Fulton, N.N., The Application of CAD to Switched Reluctance Drives, Electric Machines and Drives Conf. 275-279, 1987.
12. Radun, A.V., Design Considerations for the Switched Reluctance Motor, IEEE Transactions on Industry Applications, 31, 5, 1079-1087, 1995.
13. Omekanda, A.M., Broche, C., Renglet, M., Calculation of the Electromagnetic Parameters of a Switched Reluctance Motor Using an Improved FEM-BIEM Application to Different Models for the Torque Calculation, IEEE Transactions on Industry Applications, 33, 4, 914-918, 1997.