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Finite Elements Method in Electromagnetism for Actuator Design And Dynamic Behavior Prediction

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Summary

This paper presents the analysis, based on Finite Elements Method, of a Linear Switched Reluctance Actuator (LSRA), with 6 primary poles and 4 secondary poles. The numerical analysis makes possible the optimization design of this kind of electrical machines, being defined both dimensional parameters and excitation current levels, as well proper instants for excitation feeding. On another hand, after dimensional and physical parameters set, it is possible to predict the actuator electrodynamics' performance, in terms of thrust force, attraction force and velocity.

Introduction

The electric machine analysed in this paper is a non-conventional machine, sending the designer for a field out of the classical design methodology. In fact, the usually applied empirical factors, in both direct and alternating current machine designs, as well as the magnetic flux density distributions, are unknown.

The LSRA is an actuator with simple constructive structure, but with sever transitory regimes, where the operating points are of temporary equilibrium, with extremely located saturation, demanding complex feeding system, and most of all, are machines with different geometries during movement. Both the local and global saturation, for variable machine geometries, from the magnetic circuit point of view, send the machine analysis for the numerical analysis domain, with strong relation with analytical analysis methods [1, 4, 5].

From the previous mentioned connection between analytical and numerical analysis, it is possible to establish optimized designs for this and another electrical machines. In this case the numerical analysis was carried out trough the utilization of specific software tools based on Finite Elements Method [2, 3], being the dimensional and physical first parameters statement done using an original analytical method developed by the authors [5].

The Linear Switched Reluctance Actuator

The Linear Switched Reluctance Actuator is an electric machine able to produce traction forces, without any kind of mechanical connection, being the linear movement

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Advances in Computational & Experimental Engineering & Science

due to the tendency of the secondary part to occupy positions where the primary part magnetic circuit reluctance is minimum, and the magnetic inductance is maximum. According to this, the LSRA is a polyphase machine, with phases being excited one by one, in such a proper time instants that the developed traction force is the highest possible. Figure 1 shows the LSRA prototype build in the Department of Electromechanical Engineering of the University of Beira Interior, designed according to the already mentioned analytical method for optimised design, and was refined using numerical analysis [1, 2, 5].

Figure 1 LSRA prototype mounted on a test branch

Numerical Analysis

The Finite Element Method (FEM) is now a popular method and are commonly used in Electrical Engineering, namely for the analysis of electromagnetic phenomenon's. This method, and the corresponding existing software packages based on it, provides a number of benefits, as are the performance optimisation of electromagnetic devices and the reduced investment, in both better performance/material ratio and decreasing on build prototypes. In addition, and concerning this particular actuator, after prototype construction, the FEM is a major method for performance analysis, with the possibilities of change excitation positions and current levels.

The governing electrostatic expressions, the Maxwell equations, are field equations and allow a number of mathematical manipulations, as the local approach problem. Being the analysed actuator of irregular geometry and physically heterogeneous, the FEM is a very good tool to evaluate fields and magnetic flux distribution in the machine.

The FEM application is based on three steps, that are:

definition of machine geometry (done by analytical design);

numerical integration of Poisson equation; it is possible to evaluate the potential vector in each mesh element and the magnetic flux density;

characterization of magnetic parameters and machine performance prediction.

Advances in Computational & Experimental Engineering & Science

In all this described process it is possible to considerer different dimensional parameters, as the airgap length or the pole tooth width, and investigate their influence on magnetic airgap flux, or in the traction force. It is even possible to recognize construction difficulties and calculate necessary material costs. Behind these optimisation philosophies, one can considerer the performance evaluation, allowing the knowledge of proper currents and positions, and by this way direct interfere in control approaches.

The electromagnetic field can be expressed by a set of equations, the Maxwell equations, in differential form, with five vectors and one scalar variable:

$$\nabla \times E = -\frac{\partial B}{\partial t}; \quad \nabla . B = 0 \tag{1}$$

$$\nabla \times H = J + \frac{\partial D}{\partial t}; \nabla . D = \rho \tag{2}$$

and, the constitutive relations are:

$$D = \varepsilon E \ ; B = \mu H \ ; J = \sigma E \tag{3}$$

being E the electric field intensity, H the magnetic field intensity, B the magnetic flux density, D the electric flux density, J the electric current density, ρ the electric charge density, ε the permitivity, μ the permeability and σ the conductivity. The constitutive equations describe the macroscopic properties of medium, and the coefficients ε , μ e σ may not be constants, and for anisotropic materials, with flux densities differing in direction from their corresponding field intensities, they are tensors. For regions free of current:

$$J + \frac{\partial D}{\partial t} = 0 \tag{4}$$

and the equation (2) becomes:

$$\nabla \times H = 0 \tag{5}$$

The magnetic field intensity can be expressed in terms of the potential scalar P as:

$$H = -\nabla P \tag{6}$$

One can now considerer the potential vector A , defined as:

$$B = \nabla \times A \tag{7}$$

For stationary currents, the obtained equation, with υ the magnetic reluctivity, is:

Advances in Computational & Experimental Engineering & Science

$$\nabla \times \left(\upsilon \nabla \times A \right) = J \tag{8}$$

For simplification, in terms of computation time and visualization results, it is usual to manipulate the equations in order to only considerer two dimensions. The initially three--dimensional problem is simplified into a two-dimensional problem, and for the analysed machine the obtained equation is still valid:

$$\frac{\partial}{\partial x}\left(\upsilon \frac{\partial \mathrm{A}}{\partial x} \right) + \frac{\partial}{\partial y}\left(\upsilon \frac{\partial \mathrm{A}}{\partial y} \right) = -\mathrm{J} \tag{9}$$

The previous equation is non-linear, similar to the Poisson equation, and the reluctivity is field dependent. For FEM consideration, an equivalent equation is stated [7]:

$$F\left(U\right) = \int_{\Omega} \frac{BH}{2} d\Omega - \int_{\Omega} JU d\Omega \tag{10}$$

with U the solution for A in the region Ω, for the minimum energy condition. The potential U is obtained trough an iterative method, stating an initial value, for each mesh element, as below:

$$U^{(k+1)} = U^{(k)} - \left(P^{(k)} \right)^{-1} V^{(k)} \tag{11}$$

with k the iteration number, P the Jacobian of Newton iteration and V the function $F(U)$ gradient for point U. Figure 2 shows one example mesh used for the machine numerical analysis, for primary-secondary aligned position. Based on FEM analysis, it was possible to obtain the airgap magnetic co-energy, for different actuator relative positions, and for different excitation currents. The traction force F, the most important parameter for these actuators can be calculated knowing the co-energy W' variation, depending of dimensional coordinate x, the relative position, as follows:

$$F\left(i, x\right) = \frac{\partial W'\left(i, x\right)}{\partial x} \tag{12}$$

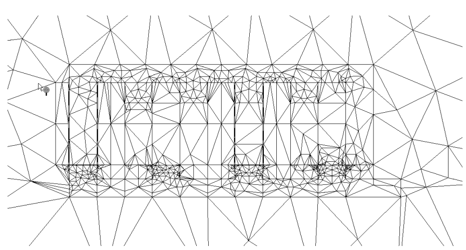

Figure 2 Solution mesh example

Advances in Computational & Experimental Engineering & Science

Figure 3 shows the 3D graphic with this three variables, considering the airgap length g=0.5 mm. Based on (12) the theoretical traction force was obtained and compared with that obtained by experimental tests on the build prototype (the secondary machine part was locked for each position, and a load cell with digital acquisition data system gave the corresponding forces). These forces are shown in Figure 4, and one can see that the results are well fitting. Due to mechanical limitations, as the attraction force is considerable, not all currents level considered in theoretical forces, were considered in experimental tests.

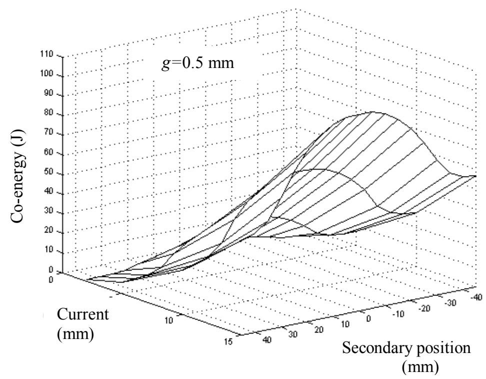

Figure 3 Co-energy versus current for different relative positions

Concerning the machine performance, it is possible to choose the proper current and position for coil feeding, in order to obtain the maximum traction force, or with another quite different propose, the smoothest displacement. These different looks on the actuator define the kind of control to be applied on complete drive.

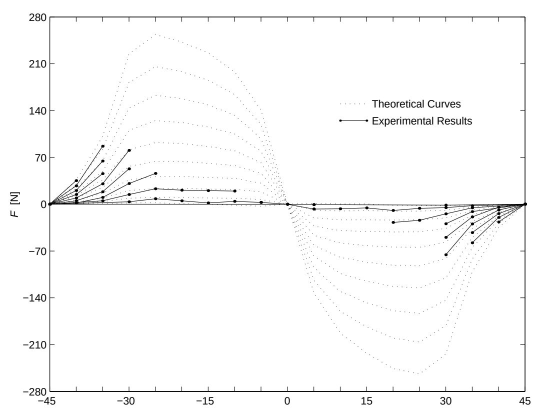

Figure 4 Traction forces versus relative position, for different currents

Advances in Computational & Experimental Engineering & Science

Conclusion

The FEM is a good tool for both design optimisation and performance prediction of this kind of electric machine. Being the LSRA a very complex actuator in terms of its electromagnetic analysis, the good connection between the developed analytical design and the numerical analysis is the adequate methodology for evaluate the influence of different parameters on machine traction force. And, once the machine is build, the same analysis makes possible the performance prediction, defining electric and dimensional parameters for suitable control development.

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