Static Simulation of a Linear Switched Reluctance Actuator with the Flux Tube Method

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Abstract—The linear counterpart of the rotational switched reluctance drive is receiving increasing attention from academic and industrial societies. The special characteristics of this driving technology, that normally works in a highly magnetic saturation regimen, make the development of efficient design methodologies more difficult. This paper proposes a new numerical model of a Linear Switched Reluctance Actuator based on the flux tube method. For validation purposes, simulation results obtained from the application of presented model are compared with the ones obtained from the application of a commercial finite element tool. The modulation technique proposed here makes possible, with minimal computational effort, the evaluation of the impact in actuator behaviour caused by the changes on the magnetic circuit geometries.

Index Terms—Electromagnetic Analysis, Linear Motors, Numerical Analysis, Reluctance Machines, Simulation

I. INTRODUCTION

Reluctance describes the resistance to the magnetic flux circulation in a magnetic circuit. If a mobile component is present, then the developed mechanical force will promote a geometric reconfiguration. The magnetic circuit will assume a new geometric configuration corresponding to the minimal reluctance or maximal inductance [1],[2].

The switched reluctance effect was used in the firsts attempts to build electromagnetic drives. We can mention, as an example, the experiments performed by Robert Davidson in 1842 [3]. At that time, the technology was abandoned, not only because of the total absence of electronic devices, required to build the power converter, but also, because of the lack of efficient design methods. In the seventies this technology started to be used again to develop new rotational drives. Several design methods have been proposed in literature [4]-[7]. This paper presents a new study approach of a Linear Switched Reluctance Actuator (LSRA) based in a flux tube method. The results obtained from a set of static simulations allow the construction of the device flux linkage map. The computation of the quantities as energy, co-energy, and traction force maps enables actuator characterization. The data requested to perform device characterization is obtained from the flux linkage map, using the theoretical bases introduced. Results are validated with a commercial finite element tool, allowing actuator model quality evaluation [8].

Beyond the rotational drives, this kind of technology is also being used more recently to build not only linear actuator, but also other actuators that can perform more complex displacements. This reappearing is associated with both characteristics and functional advantages that switched reluctance can provide: high performance; excellent force/weight ratio; simple and flexible control allowing different behaviours; simple economical and robust construction; and large velocity operational range are some of the advantages that it can offer. When compared with DC drives the absence of brushes is noticed, since they do not require an excitation field to work [9].

Binary ripple, amongst others, is one of the most related disadvantages; it occurs on account of the salient poles and produces annoying vibrations. However, a carefully designed control of the wave shape current in the coils of the phase will diminish the force ripple, reducing simultaneously the actuator vibration.

In the rotational configuration the actuator presents salient poles both in stator and rotor. On the contrary of the rotor, that has no coils, the stator lodges the coils of the phase. Currents are controlled turning on and off the power converter switches, obeying to the command logic imposed by the controller.

A rotational drive with 8 stator poles and 6 rotor poles is illustrated in Figure 1. Diametrically opposite poles share the same phase current and, as a consequence, the developed radial force is null.

The same working principle can be used to build a linear actuator. With the introduction of linear actuators, traditional conversion mechanisms from rotational to linear are avoided. System robustness and simplicity are improved, since the mechanical parts count is reduced. The mechanical force f_{mec} produced by the linear actuator can be vectorially decomposed in two orthogonal components. The longitudinal vector component, designated by traction force f_i , is responsible by the linear displacement. The normal vector component, denominated by attraction force f_a , must be minimized, since it does not contribute to the linear displacement and difficult the actuator mechanical design.



Figure 1. Structural representation of a 8/6 pole rotational drive.

The linear configuration can assume a longitudinal configuration being the magnetic flux parallel to the motion direction, a transversal configuration with magnetic flux perpendicular to the motion direction, or a radial configuration with symmetrical magnetic flux distributed around the symmetrical axis [10],[11]. A linear actuator with longitudinal magnetic flux is presented in Figure 2. A minimal number of three phases are needed to produce a bidirectional displacement. Each actuator primary phase owns two poles. The secondary exhibit a teeth sequence without coils. When a phase coil is powered, the mechanical force produced tends to displace the primary in order to align its poles with the nearest secondary teeth, achieving this way a geometric configuration with minimal reluctance. This displacement will put another phase in a position in which a traction force can be produced. This operating sequence causes a linear motion. The traction force produced by the actuator is not constant, but depends on phase currents and position. The mechanic and electromagnetic independence between phases brings several advantages. The robustness is improved, since one damaged phase can be removed from service, with minimal consequences in actuator performance. Also, the phase count can be changed after the design stage, adjusting the actuator performance to its real life duty. The physical dimensions of the actuator under study are listed in Table I.

Although this kind of actuator owns a simple working principle, its development and design are very challenging tasks. Several design procedures can be found in literature, but none of them is accepted as a standard, and mainly are developed and proposed for the rotational configuration [12]-[16].

One important aspect, which turns difficult the design of a switched reluctance actuator, is its nonlinearity [17]. The finite element method is one of the most efficient techniques to study this kind of systems [18],[19]. However, the computational effort demanded by this kind of analysis tool makes very difficult to rapidly re-evaluate geometrical changes. Another solution appeals to the equivalent magnetic circuits device representation [20].



Figure 2. Linear switched reluctance drive

TABLE I. LSRA PHYSICAL DIMENSIONS [mm]

	L J
Yoke pole width (<i>a</i>)	10
Coil length (b)	50
Space between phases (c)	10
Yoke Thickness (d)	10
Yoke pole depth (e)	30
Air gap length (f)	0.66
Stator pole width (g)	10
Stator slot width (h)	20
LSRA length (i)	2000
LSRA stack width (j)	50

This technique is computationally efficient, allowing the quick evaluation of different geometrical configuration. Obviously, a special care must be observed in the modulation of magnetic saturated regions.

II. SWITCHED RELUCTANCE ACTUATOR

The working principle of a reluctance actuator can be explained through the energy exchanges between the systems embraced in the energy conversion procedure [21]. The electrical system supplies energy to the electromagnetic coupling system that deliveries it to the mechanical system. The illustration of the different stages associated with the energy conversion procedure is made in Figure 3, where a very fast movement from position x to position x + dx occurs. Throughout rapid movement it is assumed that the flux linkage does not change.



Figure 3. Quasi-instantaneous movement from position x to position x + dx. a) initial system condition, b) actuator movement, c) restoring energy.

At the beginning, the system energy W_{fe} is given by the area defined in Figure 3a) as

$$W_{fe}(a') = \operatorname{area}\{o, a', c', o\}$$
 (1)

.

With actuator fast displacement from position x to position x + dx, represented in Figure 3b), some energy dW_{fe} stored in the magnetic coupling field is converted into mechanical work. This amount of energy is equivalent to the area given by

$$dW_{fe} = \operatorname{area}\left\{o, a', P_1', o\right\}.$$
(2)

It can be observed that the energy stored in the coupling field decreases. Simultaneously, current also decreases. If voltage from the supply source is constant, the current value will return to its initial value i_0 , through the path represented in Figure 3c), restoring by this way the energy taken from the magnetic coupling field during the fast movement.

Since flux linkage does not change during this rapid movement, there is no induced voltage, and therefore, the magnetic coupling field does not receive energy from the voltage source.

The energy used to move the actuator, which is taken from the magnetic coupling field, can be expressed by

$$dW_{em} = -dW_{fe} \Longrightarrow f_{em} = -\frac{dW_{fe}}{dx}\Big|_{\lambda = \text{constante}}.$$
(3)

The variation of the energy in the coupling field is the same, but with opposite signal, to the mechanical energy used to move the actuator. The mechanical force can be represented by

$$W_{fe} = \frac{1}{2} \frac{\lambda^2}{L} \Longrightarrow f_{em} = \frac{\lambda^2}{2L^2} \frac{dL}{dx} = \frac{i^2 dL}{2dx} .$$
(4)

Since i^2 is always positive, the force applied to the actuator, in the direction x, is also positive as long as the inductance L increases in the direction x. So, the mechanical force acts in the direction that also increases the magnetic circuit inductance.

The mechanical force can also be calculated from the change of the magnetic circuit reluctance with position. If the flux linkage λ is constant, then the magnetic flux φ in the magnetic circuit is also constant and, therefore, the mechanical force is given by

$$W_{fe} = \frac{\Re \varphi^2}{2} \Longrightarrow f_{em} = -\frac{\varphi^2}{2} \frac{d\Re}{dx}.$$
 (5)

The mechanical force acts in the direction that puts the actuator in a geometric configuration that corresponds to the path with the lower reluctance to the magnetic flux. Switched reluctance actuators base their working on this basic principle.

The energy conversion procedure performed by the actuator is represented in Figure 4. If initially the phase is at position x_{on} , in the vicinity of the unaligned position, and the power source is turned on, the current will linearly increase, since the inductance value in this region is low and almost constant. At position x_{off} , the voltage source is removed. The current path is now made by the free-wheel diodes, resulting a negative voltage applied to the phase.

The energy supplied by the power source, during the displacement from position x_{on} to position x_{off} , is equal to the area corresponding to the sum of partial areas W_{mf} , W_{mf} and W_d . While the energy quantity W_d is returned to the power source, the energy quantities W_{mf} and W_{md} are converted into mechanical energy. The energy conversion procedure efficiency is expressed by the conversion ratio established by the following relation

$$E = \frac{W_{mf} + W_{md}}{W_{mf} + W_{md} + W_d} \,. \tag{6}$$

Energy is a state function on a conservative system. If losses are ignored, balance energy can be written as in (7), where W_e is the system input energy, W_{fe} the field storage, and f_{em} the mechanical force that produces mechanical work dW_{em} , when differential displacement dx occurs. Expression (7) also shows that system energy, in a lossless device, depends on λ and x.

$$dW_e = dW_{fe} + f_{em} dx \Leftrightarrow dW_{fe}(\lambda, x) = id\lambda - f_{em} dx . \tag{7}$$



Figure 4. Electromagnetic energy conversion

A different energy entity, defined as co-energy W_{fe} , without physical meaning, can be expressed by

$$W_{fe}'(i,x) = i\lambda - W_{fe}$$
. (8)

After mathematical manipulation of (8), considering (7), (9) is obtained. This expression shows that co-energy W_{fe} depends on current *i* and position *x*.

$$dW_{fe}'(i,x) = \frac{\partial W_{fe}'(i,x)}{\partial i} di + \frac{\partial W_{fe}'(i,x)}{\partial x} dx .$$
(9)

Because i and x are independent variables, the coefficients of the equations (9) are defined by (10) and (11).

$$\lambda = \frac{\partial W_{fe}'(i,x)}{\partial i} \,. \tag{10}$$

$$f = \frac{\partial W_{fe}'(i,x)}{\partial x}.$$
(11)

The actuator inductance is obtained applying

$$L = \frac{\lambda}{i} \,. \tag{12}$$

For the number of actuator phases $n = \{1,2,3\}$, expression (13) describes electromagnetic behaviour, where R_n is coil's resistance and v_n the supplied voltage.

$$v_n = R_n i_n(t) + \frac{dL(i_n, x)i_n(t)}{dt}$$

$$= \frac{di_n}{dt} \left[L(i_n, x) + i_n(t) \frac{\partial L(i_n, x)}{\partial i} \right] +$$

$$+ \frac{dx}{dt} \left[i_n(t) \frac{\partial L(i_n, x)}{\partial x} \right] +$$

$$+ R_n i_n(t)$$
(13)

Mathematical expression (14) describes actuator mechanical behaviour where *a* is the device acceleration, *M* the mass and f_t the total traction force produced by all phases,

$$a = \frac{1}{M} f_t \,. \tag{14}$$

To solve it numerically some changes must be introduced. Formulation represented by the system equations (15) can iteratively be solved.

$$\begin{cases} \frac{dx}{dt} = y \\ \frac{dy}{dt} = \frac{1}{M} f_t \\ \frac{di_n}{dt} = \frac{y\beta_n + R_n i_n - v_n}{\alpha_n} \end{cases}$$
(15)

where α_n and β_n stands for:

$$\begin{cases} \alpha_n = L(i_n, x) + i_n \frac{\partial L(i_n, x)}{\partial i} \\ \beta_n = i_n \frac{\partial L(i_n, x)}{\partial x} \end{cases}$$
(16)

This formulation demands for actuator characterization maps. Actuator non-linearity can be observed from the inductance map L(i,x) and the traction force map F(i,x). If

these maps are used for device modelling, then the dynamic simulation will take into account actuator nonlinearities. The method presented next can be used to quickly obtain the requested information.

III. LSRA AIRGAP MODELATION

The concept of flux tube can be used to calculate the magnetic reluctance of a specific material [22]-[24]. When the flux tube is within a quasi-stationary magnetic field, as the one represented in Figure 5, where the magnetic flux lines are always perpendicular to the tube bases, never crossing the side walls, one can define the equipotential planes S_1 and S_2 .



Figure 5. Typical flux tube.

The relation between the magnetic potential at the flux tube extremities and the magnetic flux that crosses it depends on the flux tube geometry, as well as on the magnetic characteristics of the material. The magnetic tube reluctance can be defined by

$$\Re = \int_{0}^{l} \frac{dx}{\mu(x)A(x)},\tag{17}$$

where *l* is the flux tube length with a transversal section A(x), and $\mu(x)$ is the function of the properties of the material. Observing the equation is possible to see that the magnetic reluctance depends on the geometric shape, being

constant or time dependent, and on the permeability of the material. The last characteristic can be linear or nonlinear.

The magnetic flux distribution in the actuator airgap can be approximately modelled using the simple elements with shapes drawn in Figure 6. All elements have the same deep *l*. The arrow inside each element represents the magnetic flux direction.

The magnetic field is considered to be quasi-stationary, and all lines of magnetic flux are perpendicular to the flux tube bases, without any flux lines cutting their sides. The magnetic reluctances of these elements depend on physical dimensions and are listed in Table II.



Figure 6. Simple flux tube elements.

 TABLE II
 - Flux tube elements reluctances

Tube	Reluctance	Tube	Reluctance
А	$\Re = \frac{1}{\mu_0} \frac{a_2}{la_1}$	D	$\frac{1}{\Re} = \frac{2\mu_0 l}{\pi} \ln\left(1 + \frac{d_2}{d_1}\right)$
В	$\Re = \frac{1}{\mu_0 l} \frac{b_1}{b_2 - b_3} \ln \frac{b_2}{b_3}$	Е	$\frac{1}{\Re} = 0.52 \mu_0 l$
С	$\Re = \frac{1}{\mu_0} \frac{c_2}{lc_1}$	F	$\mathfrak{R}=rac{1}{\mu_{_{0}}}rac{l_{_{Fm}}}{S_{_{Fm}}}$



Figure 7. Flux tube arrangements for specific positions: a) aligned position (0 mm); b) beginning of alignment (10 mm); and c) unaligned position (15 mm).

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Figure 8. Flux tube arrangements for intermediary positions: a) positions between 0 mm and 10 mm; positions between 10 mm and 15 mm.

The magnetic flux distributions in the polar region are presented in Figure 7, for three specific actuator primary positions. The aligned position is drawn in Figure 7a); in this situation the majority of flux passes through a flux tube class A, while the fringing flux is modelled using an association of flux tubes class D and E.

Another special position is the one corresponding to the yoke poles reaching the stator tooth, as it is represented in Figure 7b); this is a more complex condition, but it is still possible its modulation through flux tube elements Finally, the unaligned position is represented at Figure 7c); in this position, the magnetic flux distribution is symmetric around the polar region. Magnetic flux distribution results obtained with Flux2D are also presented, for comparison purposes, with the three situations previously described.

Magnetic flux distributions for intermediary positions are modelled using the same basic flux tube elements. Now, flux tube dimensions depends on position x. Obviously, the accuracy of the model is not the same for all range of positions where the model is valid. Figure 8a) shows the flux tube association used to represent magnetic flux distribution in the positions range]0,10[mm. For the range of positions that belong to]10,15] mm the model used is the one represented in Figure 8b).

For each magnetic flux distribution, previously represented, an equivalent magnetic circuit is constructed. These magnetic circuits are built through the parallel and series association of simple flux tube elements. The magnetic circuit associate with the unaligned limit position is represented in Figure 9. Since each actuator phase has two polar regions, the equivalent magnetic circuit takes it into consideration.



Figure 9. Equivalent magnetic circuit representing flux distribution for the unaligned position.

IV. PROBLEM FORMULATION

The flux density B_k in the ferromagnetic circuit segment k, with length l_k and area A_k , when flux ϕ is present is given by

$$B_k = \frac{\phi}{A_k} \,. \tag{18}$$

Considering a magnetization curve B(H) (Figure 10) it is possible to obtain, through spline interpolation, the magnetic field H_k in segment k.



Figure 10. Magnetization curve.

The magnetomotive force drop MMF_k (Ampère's Law) in segment k is given by

$$MMF_k = H_k l_k \,. \tag{19}$$

An estimation of the flux $\phi_{estimation}$ is assumed, and the total value of MMF needed to produce it is calculated using (20).

$$MMF_{estimation} = 2\Re_{airgap}\phi_{estimation} + \sum_{k} H_{k}l_{k} .$$
⁽²⁰⁾

The difference between the real MMF, given by NI, and the estimated $MMF_{estimation}$ is used to choose new magnetic flux estimation. This iterative process is repeated until the MMF_error value error is under the initially established value E. This problem approach takes into account the saturation effects. The problem is solved by numerical software as described in Figure 11.



Figure 11. Problem solver flowchart.

The software starts loading the B(H) data of the ferromagnetic material. Also, parameters like MMF admitted error *E*, maximum number of iterations *it*, flux linkage guess *FI* (maximum *FI_a* and minimum *FI b*) are

initially defined. The ferromagnetic circuit is sectioned in k segments; for each one, the flux density B_k and magnetic intensity H_k are iteratively computed. While the computed MMF *F_error*, for each iteration, is higher than the admitted value *E* and the number of iterations *control_it* is lower than *it*, the iterative process continues.

Through the proposed models it is possible to compute the LSRA inductance and polar airgap reluctance, depending on yoke position. The results are represented in Figure 12. Analyzing the results, it is possible to confirm that the maximum reluctance is achieved at unaligned positions, while minimal reluctance is obtained with primary poles aligned with the secondary tooth.

This information is used to compute the device flux linkage at different actuator primary positions and coil phase currents. The inductance not only changes with position, being maximum at the aligned position and minimum at the unaligned positions, but also changes with current.



Figure 12. LSRA inductance and polar airgap reluctance.

V. PROBLEM SOLUTION RESULTS

A finite element actuator model, with approximately 18 thousand elements, was constructed with a commercial tool (Flux2D). For a set of positions evenly spaced by 2.5 mm and located between the two unaligned positions, with the aligned position at the origin (0 mm), several static simulations were performed displacing successively the actuator primary. This task was accomplished by a software functionality that automatically adjust the element mesh. Simulations were performed at each actuator primary phase position for a set of coil current values starting from 0.5 until 4.0 A, with increments of 0.5. A total of sixty static simulations were performed. The results were saved for comparison purposes with the ones returned from solving the actuator flux tube model.

From the obtained results it is possible to conclude that both models give very similar solutions. However, at locations around the aligned position, for higher current values, the differences between the results provided by the two models are higher, since the influence of saturation in actuator magnetic circuit also increases at these locations. The results are drawn in the following Figures.

The flux linkage for a set of actuator positions with different currents is obtained using two different analysis tools: flux tube model and Flux2D. The results are represented in Figure. 13, and it can be observed that both approaches give very similar results.

The actuator energy map (Figure 14) and the co-energy map (Figure 15) are numerically derived from the flux

linkage map, returned by the actuator flux tube model. The saturation effects are clearly observed at the aligned position for higher current values.

The traction force map is obtained from the co-energy map and the results are exhibit in Figure 16. As it can be seen, the traction force is null for the unaligned and aligned positions. A symmetrical behaviour around the aligned position can also be observed.



Figure 13. Flux linkage obtained with Flux2D (--) and flux tube (-).



Figure 14. Energy map obtained with Flux2D (--) and flux tube (-).



Figure 15. Co-energy map obtained with Flux2D (--) and flux tube (-).



Figure 16. Traction force obtained with Flux2D (--) and flux tube (-).

VI. CONCLUSION

The undertaken study revealed the attractiveness of the proposed method to optimise the actuator dimensions, since the reluctance of the flux tube elements depends on its physical dimensions. Based on the actuator flux linkage map other relevant information was obtained: maps of energy, co-energy and traction force. A switched reluctance linear actuator airgap was modelled using the flux tube concept. Also the airgap reluctance was calculated for different primary positions. More, a magnetization curve B(H), used in the iterative process, introduces the magnetic saturation effect.

Taking into consideration that at the polar region does not exist magnetic flux in the plane perpendicular to the paper plane, only a bidimensional magnetic flux distribution was considered. This consideration could penalize the reliability of the method. But, for the LSRA, in which the stack width is much bigger than the airgap length, this approach can be adopted without loss of accuracy. Nevertheless, it is possible to take this flux into account by adding an extra flux tube to the model.

The application of the proposed method requires a special knowledge about the flux distribution in the airgap region. This information can be obtained with the application of a finite elements tool, or through experimental tests performed in the laboratory. Also, it is a valid and useful method to be used during design procedures, allowing the optimisation of topologies. Since flux tubes are described by a set of geometric parameters, small changes in the actuator geometry can be introduced using the same model. Obviously, the proposed method does not intent to challenge with the application of the finite elements tools. This is a computational analytical method that can be used as a powerful tool, with described advantages, in the early stages of the actuator design.

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