DYNAMIC EVALUATION OF FRINGING FLUX IN LINEAR ELECTROMECHANICAL DEVICES

Antonio GARCIA ESPINOSA, Jordi-Roger RIBA RUIZ, Jordi CUSIDÓ ROURA, Luis ROMERAL MARTINEZ, Juan A. ORTEGA REDONDO
Motion Control and Industrial Applications, Group MCIA, Technical University of Catalonia,
C/ Colom 1 Tr. 2-225. 08222 Terrassa, Catalonia. Spain, e-mail: garciae@ee.upc.edu

***Abstract**: Accurate dynamic models of electromechanical devices are essential in order to develop effective motion control strategies of such devices. The effects of fringing flux can not be ignored when dealing with electromagnetic devices that present air gaps. So far parametric models applied to compute the motion of electromechanical devices do not include accurate formulations to take into account this effect.*
This paper develops an experimental method to obtain a simple analytic formulation of such an effect that can be used to calculate the linear motion of the aforesaid devices in a proper and accurate way. These effects are introduced in a robust and low time-consuming parametric model and the results are shown. Measured data has been compared with data obtained from simulations thus validating the simplicity and effectiveness of the proposed methodology.

***Key words:** fringing flux, air gap, electromechanical device, contactor*

1. Introduction

Since the early 90's, many studies have been carried out to model the dynamics of electromagnetic actuators. The main purpose is to develop new control structures for improving the dynamic behaviour of such devices. Nowadays, in case of electromechanical contactors, new control strategies have been presented [1-7] in order to avoid the contact bounce phenomenon. The contact bounce is due to the fact that the contact is not made at first touch due to the excess of energy available during the closure process. Therefore, because of bouncing, the members make and break their contacts several times before they reach a permanent state of contact. It causes the apparition of the electric arc in each bounce, so the electrical life and reliability of the contacts, as well as the mechanical endurance of the contactor, are significantly reduced.

For the development of control structures it is indispensable to get an accurate dynamic model of the movement of such devices. So, dynamic simulation is a powerful tool that allows on one hand, a better understanding of the behaviour of the electromechanical devices, and on the other to build up electronic control units. Besides, it is an essential tool for design verification, device integrity and operational studies [8-9].

Contactors are highly non-linear devices; therefore the mathematical modelling of their motion is a challenging problem that is still being investigated [10-15], so much so that artificial intelligence techniques are being used in order to predict their performance characteristics [10]. In order to determine the forces that explain their dynamic response, it is necessary to solve coupled electromagnetic and mechanical equations, which make it a complex problem. It is in part due to the highly non-linear relationship between the magnetic force and the air gap length of the magnetic circuit, and to the complex characterization of the flux lines distribution in the polar area.

When a magnetic core has an air gap, the flux must jump across the gap to reach the opposite side. In most available parametric models of electromechanical actuators, it is commonly assumed that magnetic flux flows through the air gaps through a constant section, regardless of its position. But this is not so. A portion of the magnetic flux will go straight through the air gap, and the rest of the flux will be obliged to take a longer and partly curved path, this being fringing flux. The models presented in the literature do not accurately consider such an effect. When dealing with large enough air gaps, these models must have used some kind of

coefficient introduced for computing the inductance, any case, the models presented in the technical literature about electromechanical devices such as contactors, electrovalves, among others, do not specify the treatment of the fringing flux.
Thus, fringing flux is a matter that concerns the design and modelling of all electromagnetic devices in general and in particular the linear actuators [17-20].Many authors have dealt with this by means of FEM (Finite Element Method) based models [21-24], in order to compute the performance of the devices, but these methods have the drawbacks of being very time consuming as well as requiring specific and complex software.

However, when the mathematical modelling is based upon a network of reluctances/permeances and a source of magnetomotive force, the distribution of fringing flux near the air gap region is an important task, and different reluctances/permeances are added depending on the geometry of the actuator [25]. This is an approximate method since one has to imagine how the flux is spread; so that it leads to successive iterations until a good enough model is obtained.
Another way to take into account the fringing flux found in the literature is to increase the effective area of the air gap by a value that depends on the air gap length as well as on the geometry of the magnetic circuit. Mainly this can be found as used [26-27], and called fringing factor.

The originality of the work presented here, is that it proposes a effective methodology for computing the specific fringing factor that appears in any type of linear electromechanical device. In this way, the electromagnetic circuit is thoroughly characterized, helping the researcher or designer to better understand the behavior as well as the kinematics of the magnetic circuit's movable parts.

Nowadays the new trend in electromagnetic devices is to be electronically controlled. In order to meet this objective it is necessary to obtain a detailed mathematical model of them. The mechanical and electric parameters can be obtained successfully to greater or lesser extent, but fringing flux corrections are very specific of each device, depending strongly on its geometry. Moreover, there is not a general and simple formulation to deal with fringing flux corrections. So, it makes necessary to obtain the specific factor for each geometry dealt with by means of the measurements detailed in this work. By this the magnetic force [16] or the air gap reluctances. In way, the proposed methodology is a very useful tool in order to determine this correction factor.
In order to demonstrate its validity it has been applied to a DC contactor shown in figure 1. In Section 3 the magnetic circuit is modelled in order to obtain the reluctances network. In Section 4, the magnetic core has been modelled by means of FEA (Finite Element Analysis) in order to show the flux paths and to emphasize the existence of fringing flux. After that the procedure to evaluate the fringing flux is thoroughly described. In Section 5, the experimental results are presented and compared with the results obtained from simulations by applying the proposed methodology. Finally, in Section 6 the conclusions are shown.

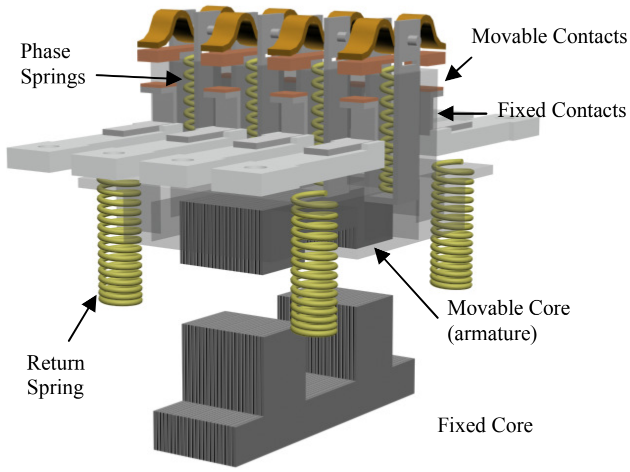

Fig. 1 Sketch of the electromechanical DC contactor

2. List of Symbols

$\Re_x$, x: reluctance and length of each air gap path
$\Re_f$, l_f: reluctance and length of the fixed core
$\Re_m$, l_m: reluctance and length of the movable core
$\Re_t$, l_t: reluctance and length of the PTFE sheet
u, i: voltage and current through the contactor coil
N, R: number of turns and electrical resistance of the coil
S: cross-sectional area of the magnetic core

3. Magnetic Circuit

First of all it is necessary to model the device's fixed and movable cores, air gap, coil, etc. in order to determine the electrical and magnetic equations that govern the dynamic behaviour.

Figure 2 shows a sketch of the magnetic circuit of the contactor and the theoretical model of the magnetic circuit.

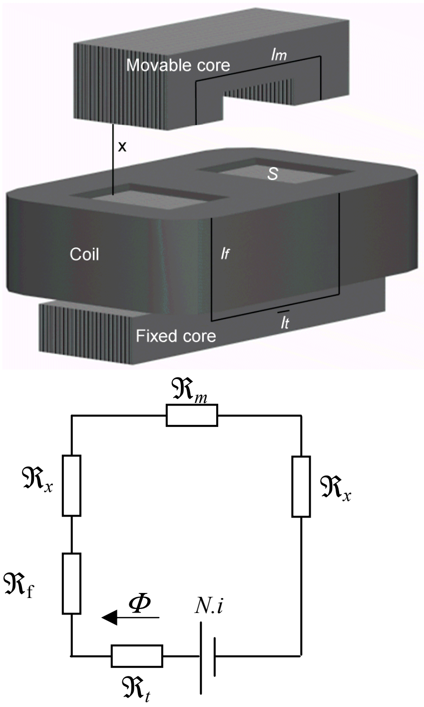

Fig. 2 (a) Sketch of the magnetic circuit of the DC contactor and (b) model of the magnetic circuit of the DC contactor which includes a PTFE sheet.

Being,

$$\left.\begin{aligned} \Re_x &= \frac{x}{\mu_0 S} \\ \Re_t &= \frac{l_t}{\mu_0 S} \\ \Re_f &= \frac{l_f}{\mu_0 \mu_r S} \\ \Re_m &= \frac{l_m}{\mu_0 \mu_r S} \end{aligned}\right\} \qquad (1)$$

From figure 2b, and by applying equations (1), the analytical magnetizing reluctance of the equivalent magnetic circuit can be expressed as follows:

$$\Re_{magnetizing} = \frac{l_m + l_f + \mu_r l_t}{\mu_0 \mu_r S} + \frac{2x}{\mu_0 S} \qquad (2)$$

4. Fringing Flux Corrections

The fringing flux describes the dispersion of the flux lines in an air gap, from the shortest path between poles in a magnetic circuit. This effect increases the effective cross-section of the air gap. It also decreases its reluctance and the attractive magnetic force exerted by the magnetic field on the movable core of the contactor. The effects of flux fringing become more evident as the air gap becomes larger.

Figure 3 shows the fringing flux effects in the immediate vicinity of the pole faces. It clearly shows that the effective area of the air gap is increased.

In order to consider the effects of flux fringing, the area of the cross-section of the air gap should be multiplied by a correction factor $F(x) \geq 1$. Different

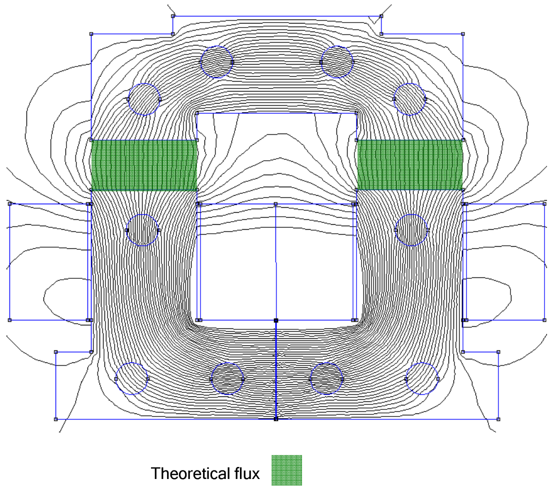

Fig. 3 FEA visualization of the flux fringing paths in a DC core

approximations for computing the flux fringing factor $F(x)$ can be utilized. A common and well known expression of the spreading of the air gap effective area due to the fringing paths can be expressed as:

$$F(x) = \frac{S_{air\ gap}}{S_{pole}} = \frac{(x+A)(x+B)}{S} = 1 + \frac{A+B}{S}x + \frac{1}{S}x^2 \qquad (3)$$

where x is the air gap length, S is the cross-sectional area and A and B are, respectively, the dimensions of the rectangular section of the magnetic pole. This expression is known to be applicable only for small air gaps. Other authors [24-25] approximate the fringing factor by means of the following equation (4).

$$F(x) = 1 + \frac{x}{S^{1/2}} \ln\left(\frac{2G}{x}\right) \qquad (4)$$

where G is the winding length. Equation (4) is commonly applied when dealing with gapped inductances with EE or UU cores.

Note that the two aforementioned expressions of flux fringing are empirically deduced, although the best expression for the fringing factor is not closed subject. Furthermore, the abovementioned expressions suppose static cores, it means cores with constant air gap lengths. When dealing with electromechanical devices such as contactors, the air gap length is time-dependent because it decreases sharply during closure. So far this question has not been studied by the parametric models of DC contactors available in the technical literature, except in one reference [6]. In this reference the fringing flux effects are approximated to in a simple way. A simplified expression of the magnetizing inductance that takes into account fringing flux effects is obtained by adding a constant value in the expression of inductance. This method obtains good enough results but has the drawback of lacking in theoretical fundamentals.

The work presented here attempts to be rigorous with the corrections necessary to model the fringing flux effects. Note that these corrections have been established from their measured effects.

To determine the experimental profile of the fringing factor *F(x)* the position of the movable core *x*, the voltage *u* and the current *i* through the coil have been measured during a contactor closure. To validate the model presented in this work it is necessary to measure the extent to which the movable core travels. This has been measured by using a laser Doppler vibrometer Polytec OFV-3000/OFV-502 which is a non-invasive measurement system and does not modify the kinematics of the movable parts. The laser vibrometer measures the acceleration of the movable core, which is integrated to obtain the velocity and the position.

The effects of the analytical magnetizing reluctance of the contactor –which takes into account the magnetic circuit and the air gap without considering the flux fringing –given in equation (2), can be expressed as,

$$\Re_a = \frac{l_m + l_f + \mu_r l_t}{\mu_0 \mu_r S} + \frac{2x}{\mu_0 S} = a + bx \tag{5}$$

where,

$$a = \frac{l_m + l_f + \mu_r l_t}{\mu_0 \mu_r S} \qquad b = \frac{2}{\mu_0 S} \tag{6}$$

The experimentally measured magnetizing reluctance – which contains the fringing flux effects– has been measured as follows,

$$\Re_{\exp} = \frac{N i_{\exp}}{\Phi_{\exp}} = \frac{N i_{\exp}}{\frac{1}{N}\int_0^t (u_{\exp} - i_{\exp} R)\, dt} \tag{7}$$

where the subscript *exp* denotes that the magnitudes have been measured experimentally. Note that the magnetic flux through the magnetic core has not been measured directly but it has been deduced from the acquisitions u_{exp} and i_{exp}, according to the denominator of equation (7).

The experimentally measured reluctance can be rewritten as,

$$\Re_{\exp} = \frac{l_m + l_f + \mu_r l_t}{\mu_0 \mu_r S} + \frac{2x_{\exp}}{\mu_0 S F(x)} = a + \frac{b x_{\exp}}{F(x)} \tag{8}$$

Note that position x_{exp}, current i_{exp} and voltage u_{exp} have been measured during a closure of the contactor. From equations (5) and (8), and taking into account the experimental measured air gap length, it results,

$$\frac{\Re_a}{\Re_{\exp}}(x) = \frac{a + b x_{\exp}}{a + \frac{b x_{\exp}}{F(x)}} \tag{9}$$

Equation (9) leads to,

$$F(x) = \frac{b x_{\exp} \frac{\Re_a}{\Re_{\exp}}(x)}{a\left[1 - \frac{\Re_a}{\Re_{\exp}}(x)\right] + b x_{\exp}} \tag{10}$$

Equation (10) is evaluated at each acquired air gap position x_{exp} during the closure of the contactor, in such a way that figure 3 plots the evolution of the fringing factor *F(x)*. Afterwards it is adjusted by means of the function shown in equation (11),

$$F(x) = \frac{1 + c_1 x}{c_2 + c_3 x} \tag{11}$$

The least squares regression of equation (11) leads to the following values for the coefficients: c_1 = 0.293 mm^{-1}, c_2 = 0.995, c_3 = 0.040 mm^{-1} and a correlation coefficient R = 0.9987.

Figure 4 shows the performance of the commonly applied fringing flux corrections derived from equations (3) and (4) as well as the one obtained by means of the proposed measurements, which is given in expression (10). As observed, equations (3) and (4) lead to an underestimation of the fringing flux factor.

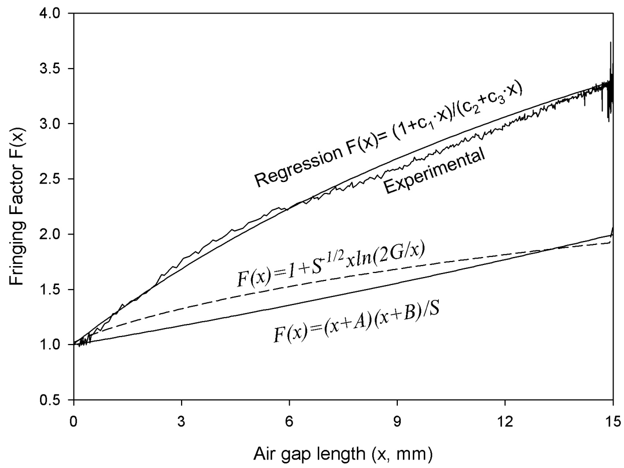

Fig. 4 Different profiles of the fringing flux factor as a function of the air gap length

Note that the DC powered contactor by GE Systems type CK10CE411, has been studied. Complete data for this contactor is available from the authors.

In the case studied here, values of $F(x)$ range from 1 ($x = 0$) to 3.4 ($x = x_{max}$). This means that the fringing flux must be considered, as previously mentioned, because their effects can considerably modify the dynamic behaviour of the electromechanical device.

A complete flow chart of the methodology proposed in this work is shown in figure 5.

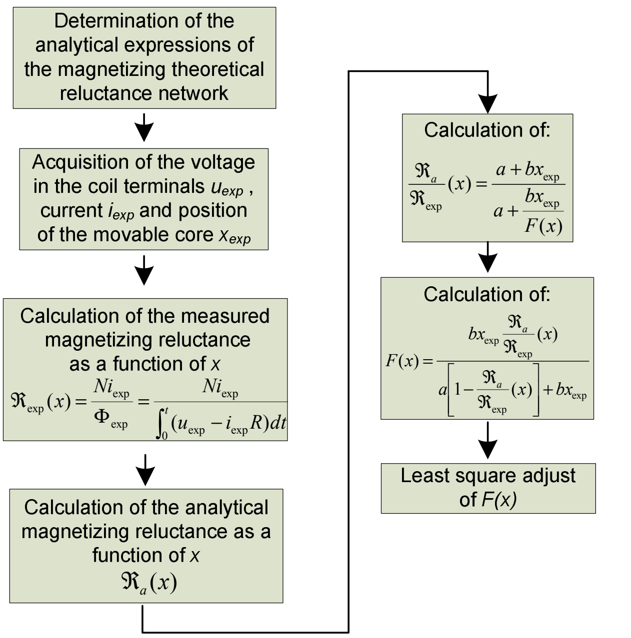

Fig. 5 Flow chart for obtaining the fringing flux corrections

5. Experimental Results and Simulations

In this work, the contactor manufactured by GE Systems type CK10CE411 was used. A comparison between experimental data and results from simulations during a closure manoeuvre was carried out. This contactor incorporates an electronic module that acts as a current limiter. Figure 6 plots the voltage applied to the coil during a closing action where the effects of the current limiter module can be clearly appreciated.

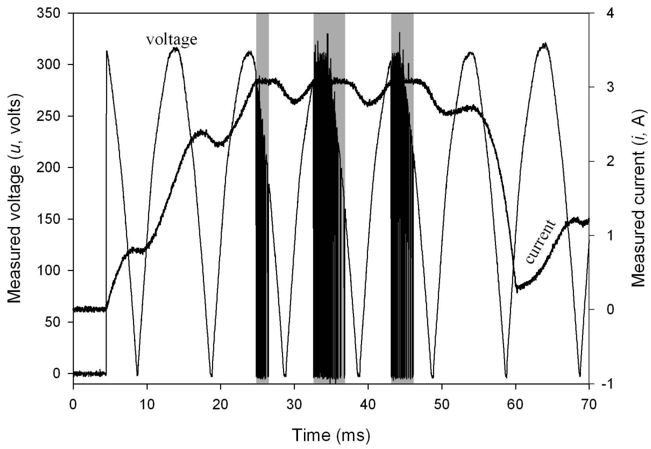

Fig. 6 Measured voltage and current through the coil of the contactor

The limitation of the current flowing through the coil of the contactor is due to the performance of the current limiter module of the contactor which is detailed in figure 7. This electronic module limits the current of the contactor coil to 3 A. When the current reaches this value the voltage is chopped as indicated in the grey interval in figure 6.

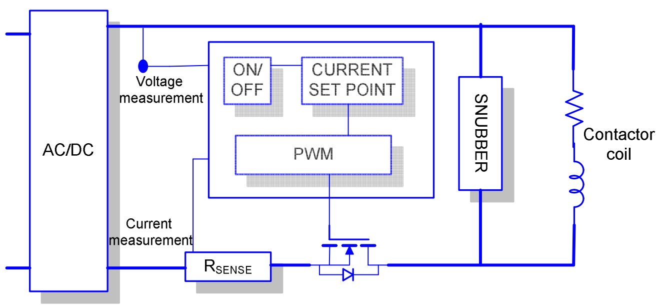

Fig. 7 Diagram of the electronic module attached to the contactor

Figure 8 shows the acquired position $x(t)$ of the armature and the results of simulations under different fringing flux corrections. As displayed in figure 8, if the fringing flux effects are not taken into account, the values of $x(t)$ obtained from simulations indicate that the closure is much faster than in reality. This is so because fringing flux reduces the attractive magnetic force, as explained in Section 4. When the fringing factor derived in this work is introduced in the parametric model, there is a very close similarity between the acquired profile of *x(t)* and the simulated one.

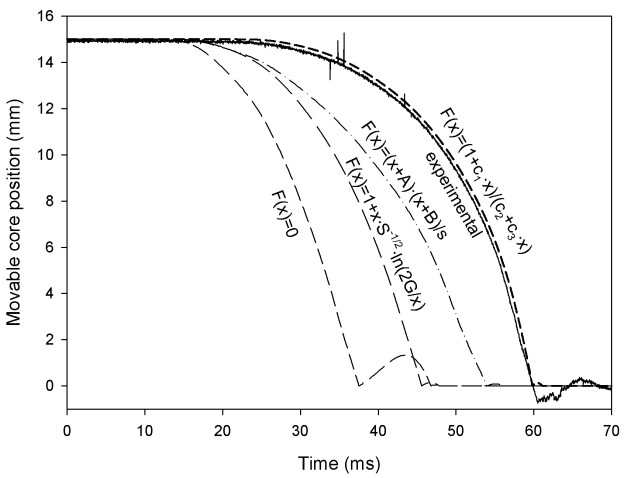

Fig. 8 Measured and simulated position –with different fringing factors- of the movable core position

Figure 9 shows during a closure of the contactor, the calculated flux through the magnetic core by means of the acquisition of the current and voltage through the magnetizing coil, and the flux calculated by means of introducing the proposed fringing flux factor in the analytical expression of the reluctance, which is shown in equation (12) for more clarity.

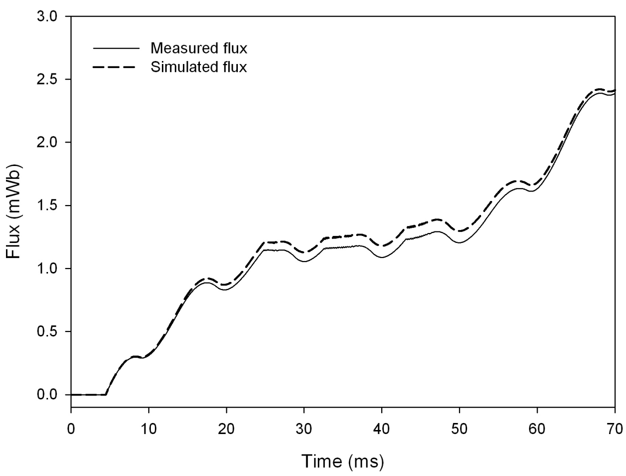

Fig. 9 Measured and simulated flux through the coil of the contactor

$$\Re = \frac{l_m + l_f + \mu_r l_t}{\mu_0 \mu_r S} + \frac{2x_{\exp}}{\mu_0 S F(x)} = a + \frac{b x_{\exp}}{F(x)} \qquad (12)$$

Figure 10 shows the measured and simulated profiles of the current through the coil of the contactor, during a closure of the contactor.

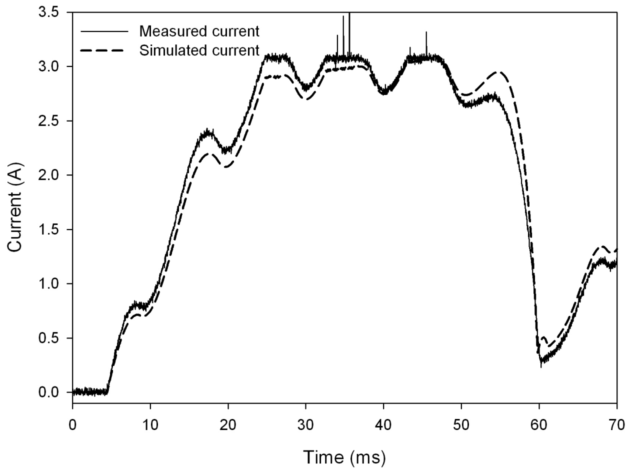

Fig. 10 Measured and simulated current absorbed by the coil of the contactor

Both figures 9 and 10 show a close correlation between measured data and results from simulations when the proposed fringing flux factor has been taken into account.

6. Conclusions

This paper proposes a methodology for obtaining the effects of the fringing flux that provides the fringing factor as a function of the air gap length.

The proposed methodology is very useful in order to improve the existing parametric model of an electromagnetic device. Thus, the dynamics of the system can be reproduced accurately enough in order to carry out simulations of control strategies for improving the dynamic behaviour of the device. Once the control has been studied and optimized, it can be implemented and attached to the electromagnetic device.

From the experimental results, an adjusted function of the fringing factor with respect to the air gap length has been obtained. The obtained fringing factor has been incorporated in the parametric model of the DC contactor. The comparison between measured values of different mechanical, electrical and magnetic variables of the contactor and the results from simulations show a very close similarity. This is an experimental validation of the effectiveness of the proposed methodology for computing the fringing factor, showing proper performance when it is introduced in the parametric model of the device.

This methodology has been applied in a DC powered contactor in order to demonstrate its feasibility and reliability, but it should be noted that can be extended to other linear electromagnetic actuators such as AC contactors, and electromechanical valves, among others. This subject is object of author's future work.

7. References

1. Pourmohamadiyan P, Niayesh K, Conceptual design of a novel arcless controlled switch, *Electrical Engineering*, vol. 90, Issue 8, pp. 529-538, 2009
2. Wada M., Yoshimoto H., Kitaide Y., Dynamic Analysis and Simulation of Electromagnetic Contactors with AC Solenoids, In: Proceedings of the IEEE International Symposium on Industrial Electronics Conference ISIE02, vol. 4, 2002, pp. 2745–2751
3. Alexandru Forrai, Takaharu Ueda, and Takashi Yumura, Electromagnetic Actuator Control: A Linear Paramenter-Varying (LPV) Approach, *IEEE Trans. on Ind. Electron.*, vol. 54, no. 3, pp. 1430 – 1441, 2007
4. Brian Carse, Neil Larsen, Hassan Nouri and Terry Davies. An Approach To The Reduction Of Contact Bounce Using Fuzzy Control, *In Proceedings of the IEEE Int. Symposium on Industrial Electronics ISIE99*, vol. 3, pp. 1025-1029
5. Dos Santos Dias de Moraes, P.M.; Perin, A.J. An Electronic Control Unit for Reducing Contact Bounce in Electromagnetic Contactors. , *IEEE Trans. on Ind. Electron.*, vol.55, no. 2, pp. 861 – 870, 2008
6. Garcia Espinosa, A., Riba Ruiz, J. R., Cusidó, J., and Alabern Morera, X.: Sensorless control and fault diagnosis of electromechanical contactors , *IEEE Trans. on Ind. Electron*, vol. 55, (10), pp. 3742 – 3750, 2008.
7. Garcia Espinosa, A., Riba Ruiz, and J. R., Alabern Morera, X.: A sensorless method for controlling the closure of a contactor, *IEEE Trans. Magn*., 43, (10), pp. 3896 – 3903, 2007
8. Wróblewski Z. A method of gamma-beta durability determination for reliability tests of brand-new AC electromagnetic contactors. *European Transactions on Electrical Power*; 10:219–224, 2000.
9. Wróblewski Z. Digital simulation of reliability of contacts used in AC electromagnetic contactors. *European Transactions on Electrical Power*; 8:201 – 206, 1998
10. Arkadan, A. A., Mneimneh, M. A., and Al Aawar, N.: Electromagnetic Fuzzy Logic Scheme for the Characterization of ac Actuators, IEEE Trans. Magn., 41, (10), pp. 3985 – 3987, 2005
11. Bottauscio, O., Chiampi, M., and Manzin, A.: Advanced model for dynamic analysis of electromechanical device, *IEEE Trans. Magn.*, 41, (1), pp. 36 – 46, 2005
12. Garcia Espinosa, A., Riba Ruiz, and J. R., Alabern Morera, X.: A Sensorless method for controlling the closure of a contactor, *IEEE Trans. Magn*., 43, (10), pp. 3896 – 3903, 2007
13. Lu, H., Zhu, J., Lin, Z., and Guo, Y.: A miniature Short Stroke Linear Actuator-Design and Analysis*, IEEE Trans. Magn*., 44, (4), pp. 497 – 504, 2008
14. Riba Ruiz, J. R., and Garcia Espinosa, A.: Design of an Estimator of the Kinematics of AC Contactors, *European Transactions on Electrical Power,* 2008
15. Riba Ruiz, J. R., and Garcia Espinosa, A.: A Novel Parametric Model for AC Contactors, *IEEE Trans. Magn*., 44, (9), pp. 2215-2218, 2008
16. Forrai, A., Ueda, T., and Yumura, T.: Electromagnetic Actuator Control: A Linear Paramenter-Varying (LPV) Approach, *IEEE Trans. on Ind. Electron*. , 54, (3), pp. 1430 – 1441, 2007
17. Nogawa, S., Kuwata, M.; Miyagi, D., Hayashi, T., Tounai, H., Nakau, T., and Takahashi, N.: Study of Eddy-Current Loss Reduction by Slit in Reactor Core, *IEEE Trans. Magn*., 41, (5), pp. 2024 – 2027, 2005
18. Fletcher, J., Williams, B., and Mahmoud, M.: Airgap fringing flux reduction in inductors using open-circuit copper screens, In IEE Proc. Electr. Appl., 152, (4), pp. 990 – 996, 2005,
19. Roshen, W.A.: Fringing Field Formulas and Winding Loss Due to an Air Gap, IEEE Trans. Magn. , 43, (8), pp. 3387 – 3394, 2007.
20. Jiabin Wang, Howe, D., and Jewell, G.W., Fringing in Tubular Permanent-Magnet Machines: Part I. Magnetic Field Distribution, Flux Linkage, and Thrust Force, *IEEE Trans. Magn.*, 39, (6), pp. 3507 – 3516, 2003
21. Khan, S. H., Cai, M.; Grattan, K. T. V., Kajan, K., Honeywood, M., and Mills, S.: Computation of 3-D Magnetic Field Distribution in Long-Lifetime Electromagnetic Actuators, *IEEE Trans. Magn.*, 43, (4), pp.1161-1164, 2007
22. Kim, J., and Chang, J.: 'A New Electromagnetic Linear Actuator for Quick Latching', *IEEE Trans. Magn*., 43, (4), pp. 1849-1852, 2007

23. Ping Fang, Fan Ding, and Qipeng Li: 'Novel high-response electromagnetic actuator for electronic engraving system', *IEEE Trans. Magn.* , 42, (3), pp. 460 – 464, 2006
24. Clark, R.E., Jewell, G.W., Forrest, S.J., Rens, J., and Maerky, C.: 'Design features for enhancing the performance of electromagnetic valve actuation systems', *IEEE Trans. Magn*., 41, (3), pp. 1163 – 1168, 2005
25. Se-Hyun Rhyu, In-Soung Jung, and Byung-Il Kwon: '2-D Modeling and Characteristic Analysis of a Magnetic Sensor', *IEEE Trans. Magn.,* 41, (5), pp. 1828 – 1831, 2005
26. Dezuari, O., Gilbert, S. E., Belloy, E., and Gijs, M. A. M.: 'Development of a novel printed circuit board technology for inductive device applications', *Sensors and Actuators*, 76, pp. 349 – 355, 1999
27. Van den Bossche, A., Valchev, V., and Filchev, T.: 'Improved approximation for fringing permeances in gapped inductors', *In Proceedings of the IEEE Industry Applications Conference*, vol. 2, pp. 932 – 938, 2002