A NEW MODEL FOR AC PLUNGER-TYPE MAGNETS IN STEADY-STATE REGIME

Ioana-Gabriela SÎRBU[1], Mihai IORDACHE[2], Lucian MANDACHE[1]

[1]*University of Craiova, Electrical Engineering Faculty, Romania, osirbu@elth.ucv.ro*
[2]*University POLITEHNICA Bucharest, Electrical Engineering Faculty, Romania*

Abstract – **This paper proposes a new model for plunger-type magnets that could be used in SPICE simulations of some complex systems. The model uses a new advanced modeling technique of ferromagnetic cores that was developed in the last years in various technical papers. This technique is now adjusted to the AC plunger-type magnets that operate in the steady-state regime. The case that corresponds to the position "closed" of the electromagnet is analyzed. We considered a 230V/50Hz electromagnet as example to be studied. The constant parameters as well as the characteristic of the resistance forces and the hysteresis curve are obtained from the magnet design documents. A special attention was paid to the short-circuit ring, as position, dimensions and influence on the magnet operation. The simulation offered an image on the equipment behavior in the steady-state operation regime. Also comparisons and analysis can be made on the waveforms of the magnetic fluxes, currents or voltages and thus some important conclusions can be obtained. Magnetization cycle of the movable core, supply voltage waveform, coil current waveform, magnetic flux in the movable core, magnetic fluxes inside and outside the short-circuit ring as well as the current induced in the short-circuit ring are represented in a comparative manner in order to better analyze the results and to compare them with those presented in the technical literature. Finally some conclusions are depicted in order to improve the model and to generalize it for a class of electromagnets.**

Keywords: *AC electromagnet, simulation, steady-state regime.*

1. INTRODUCTION

A driving device represents an assembly of elements that realizes a mechanical operation. These devices are used for breaking commands, for the protection equipment tripping, to open or to close valves, for the switching device control, etc. For the electromagnetic switching devices the electromagnet represents the main component. In general long strokes of 1 to 4 cm are necessary. Also the resistance forces are almost constant during the operation. That is why AC or DC plunger-type magnets are used [1].

Even if (in some equipment) the electromagnets were replaced with some electronic devices, many of them are still in use or remained a piece of resistance in many electromechanical assemblies that are manufactured in the world. That is why the design and the optimization of the electromagnets are still of great importance in the electrical engineering conception.

In the last years the development of the dedicated software tools made possible the advanced analysis of these equipments and some phenomena that appears inside the device could be explained. Also a lot of electric or magnetic parameters could be calculated easier and with much accuracy [2]-[4].

This paper proposes to analyze AC the plunger-type magnets in the steady-state regime. For this reason a new advanced modeling technique of ferromagnetic cores is presented shortly [5]-[7]. After that the model for ferromagnetic cores is implemented in SPICE software in order to obtain an accurate model of the AC electromagnet [8]-[10]. A case study is analyzed corresponding to the minimum gap position of the movable core. The results are analyzed in order to explain the device operation. The waveforms of the supply voltage, of the currents in the coil and in the short-circuit ring and of the magnetic fluxes in several locations are represented graphically in a comparative manner. The results are compared with those presented in the technical literature [11]-[13]. Finally some important conclusions are depicted.

2. FERROMAGNETIC CORE MODEL

A new high precision model for nonlinear lossy ferromagnetic cores is used in order to be implemented in the SPICE model of the AC electromagnet [5], [6] (figure 1).

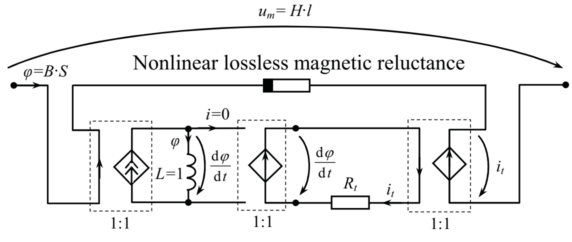

Figure 1: Model of a ferromagnetic section that consider the eddy current losses and the reaction magnetic field of eddy currents.

In this model a ferromagnetic section of constant cross section S and length l was considered. This section is flown by a magnetic flux $\varphi = B \cdot S$. The corresponding magnetic force is $u_m = H \cdot l$. The dependency between the magnetic flux and magnetic force $\varphi(u_m)$ is imposed by the magnetization curve of the material. Thus the resistance used in the modeling is a voltage commanded nonlinear resistance.

The model must not neglect the eddy currents. They exist and the losses that they produce lead to Joule effects and reaction magnetic fluxes that modify the magnetization curve in dynamic regimes.

By considering an equivalent eddy current i_t that has the same effect as the real current through the section, its equation could be written as

$$\frac{\mathrm{d}\varphi(t)}{\mathrm{d}t} = R_t \cdot i_t \tag{1}$$

where R_t is an equivalent resistance passed by the current i_t and it depends of the shape and the dimensions of the magnetic core and also of the electrical resistivity of the material [5]. This current produces a magnetic force that is opposite to the initial magnetic force.

The equivalent resistance R_t depends on the specific power losses included in the data sheet of the material (p_{Fe} [W/kg]) - that correspond to a certain frequency of the magnetic field f_0 (usually for steady state harmonic regime) and a certain peak value of the magnetic flux density B_0, on the geometrical dimensions of the magnetic section (l and S) and on the material density γ [kg/m^3]:

$$R_t = K \cdot \frac{f_0^2 B_0^2 S}{\gamma \, p_{Fe} \, l} \tag{2}$$

The constant K depends on the cross section shape of the core. The value $K = \pi^3 / \sqrt{2}$ could be considered for the square shape section [6].

The resulted diagram (figure 1) contains the nonlinear lossless reluctance and an auxiliary circuit that correspond to the eddy currents and their effects. Thus the reluctance with losses takes the form of an electric circuit.

3. PLUNGER-TYPE MAGNET ANALYSIS

The purpose of this work is to realize a model of the AC plunger-type magnet based on the precision model of the ferromagnetic core presented in the above section. This model will be implemented in a SPICE program and the results will be compared with those presented in the technical literature.

3.1. The structure of the plunger-type magnet

The main structure of a plunger-type magnet is presented in figure 2. It consists in a movable core with a rectangular cross section (plunger), a fixed core, a coil supplied with an AC voltage and a short-circuit ring. The short-circuit ring has the role of improving the electromagnet operation by ensuring a non-zero magnetic flux in the central gap zone during its entire oscillation period.

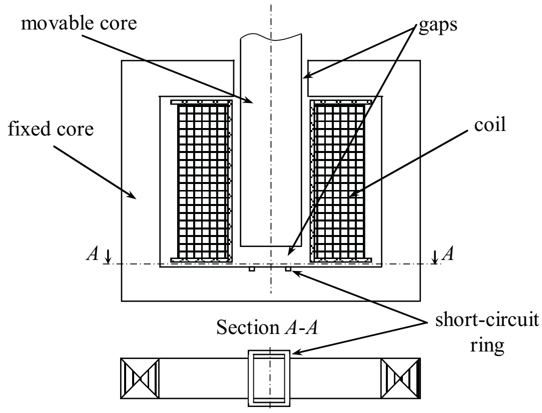

Figure 2: Plunger-type magnet.

In general the plunger-type magnet can be or can be not endow with a stop element. In our analysis we considered an AC electromagnet without stop element.

3.2. The SPICE model of the plunger-type magnet

We considered in our analysis an AC electromagnet that could be used in the AC contactors' construction. The main parameters of the plunger-type magnet to be analyzed are:

- Rms supply voltage: U=230V;
- Frequency of the voltage: f =50Hz;
- Relative connection time: CT=60%;
- Connection frequency: f_c=800 connections/h;
- Maximum stroke: δ_{max} =8mm.

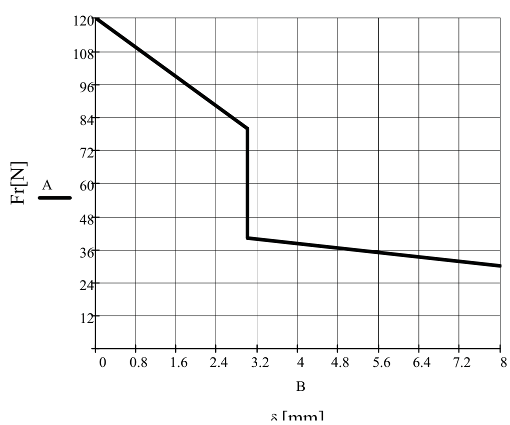

Figure 3: Characteristic of the resistance forces.

The characteristic of the resistance forces (total resistive force as a function of the gap length) is presented in figure 3.
The magnetization curve corresponds to the steel sheets of 0.35 mm.
Starting from the initial data the constructive parameters can be calculated, based on the algorithms presented in the technical literature (e.g. in [1]), or can be taken from the technical documentation of an existing equipment.
The main parameters that are necessary to our model refer to the electrical resistance of the coil, the number of the coil turns and the dimensions and the material properties of the magnetic cores.

The reluctances, both for magnetic cores and for gaps, are calculated using the general formula:

$$R_m = \frac{l}{\mu \cdot S} \quad (3)$$

where l and S are the length and respectively the cross section of the magnetic core, and μ is the magnetic permeability of the material and has a non-constant value.
For the gaps reluctance calculation the same formula (3) has been used, where μ has a constant value (in air, $\mu = \mu_0$).

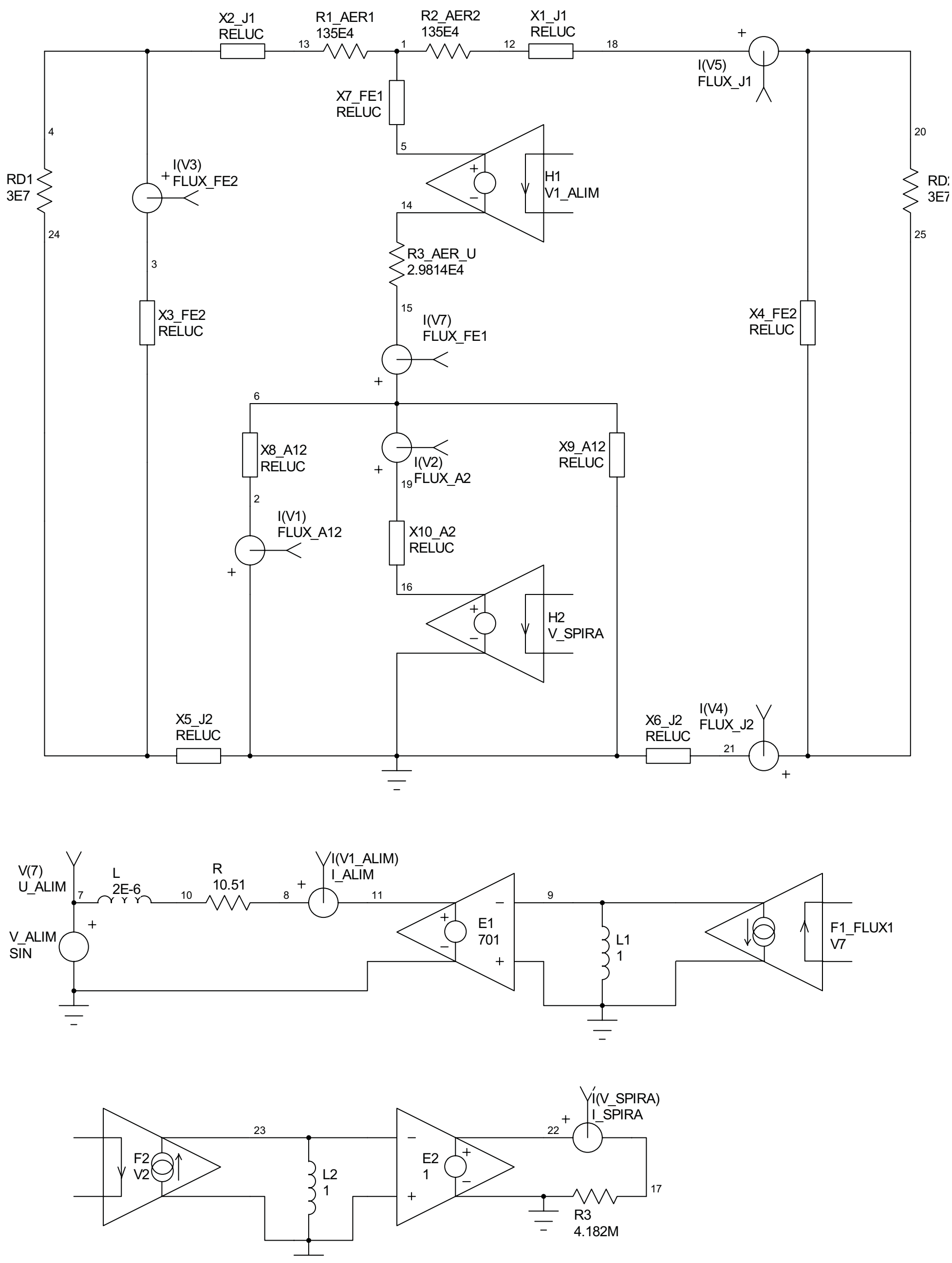

Figure 4: SPICE model of the analyzed plunger-type magnet in steady-state regime

The SPICE model of the analyzed plunger-type magnet in steady-state regime is presented in figure 4.

The upper figure represents the equivalent magnet circuit. The X elements represent the equivalent subcircuits corresponding to the ferromagnetic cores reluctances. The resistances correspond to the constant gap reluctances. H1 element models the coil's influence while the H2 element corresponds to the short-circuit ring. Using this circuit various magnetic fluxes can be depicted and analyzed.

The middle figure is due to the supply electric circuit. Here the supply voltage and the winding parameters are considered as well as the influence of the magnetic circuit.

The lower circuit corresponds to the electric circuit of the short-circuit ring. It is here where the induced current appears. Its value is considered in the equivalent magnetic circuit.

The magnetization curve of the magnetic cores is introduced by means of a PWL model as is shown in figure 5.

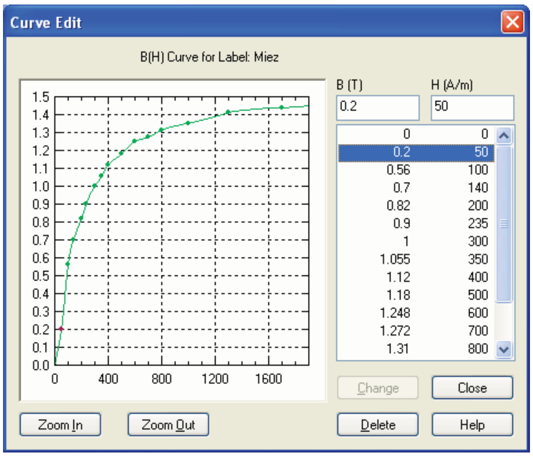

Figure 5: Hysteresis curve as it is introduced in SPICE

The magnetization curve and the equivalent electric circuit corresponding to the ferromagnetic core are introduced in a SPICE subcircuit, in the Edit Controls section of the SPICE program. Here the analysis type (a time-domain analysis) is chosen and some options are imposed in order to optimize the analysis and to improve the simulation process [14].

The content of the Edit Control section is presented below:

```
.SUBCKT RELUC 6 20
.MODEL PWL_001 PWL(XY_ARRAY=[-1.7K
+ -1.44 -1.3K -1.4 -1K -1.35 -800 -1.31 -700 -1.272
+ -600 -1.248 -500 -1.18 -400 -1.12 -350 -1.055
+ -300 -1 -235 -0.9 -200 -0.82 -140 -0.7 -100 -0.56
+  -50 -0.2 50 0.2 100 0.56 140 0.7 200 0.82 235 0.9
+ 300 1 350 1.055 400 1.12 500 1.18 600 1.248
+ 700 1.272 800 1.31 1K 1.35 1.3K 1.4 1.7K 1.44]
+ INPUT_DOMAIN=10.0M FRACTION=TRUE)
*INCLUDE CM1.LIB
*ALIAS  I(V2)=FLUX
*ALIAS  V(5)=B
*ALIAS  V(4)=H
*ALIAS  I(V3)=IT
*ALIAS  V(6)=UM
B1 2 3 I={SFE}*V(5)
V2 3 20
E1 4 0 2 3 {1/LFE}
H1 6 2 V3 1
F1 0 7 V2 1
L1 7 0 1
E2 0 11 7 0 1
*RT 0 10
+ (4.935*1^2*50^2*{SFE})/(7650*1.3*{LFE})
RT 0 10 0.1654
V3 10 11
A2 4 5 PWL_001
.ENDS
.TRAN 1E-5 1.6 1.5 1E-5 UIC
*.OPTIONS METHOD=GEAR MAXORD=2
*.OPTIONS RELTOL=1E-1
*.OPTIONS ITL4=200
.PRINT TRAN V(5,1)
```

3.3. Results

By means of the SPICE software and by using the proposed model of the AC electromagnet, the waveforms of several electromagnetic quantities were obtained.

Figure 6 depicts the dependence of magnetic flux on the magnetic force (the magnetization cycle). It was obtained in the dynamic regime operating conditions corresponding to the movable magnetic core. This characteristic is specific to this material and to a frequency of 50 Hz. The area delimited by the curve corresponds to the eddy current losses. For an operating frequency of a bigger value this curve will be more flat because the losses grow. These are in good agreement with the electromagnetic theory [11].

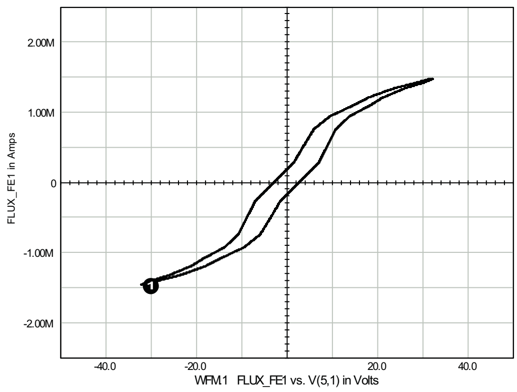

Figure 6: Magnetization cycle of the movable core (magnetic flux versus magnetic force)

Figure 7 presents in a comparative manner the supply voltage waveform and the coil current waveform corresponding to the supply electric circuit. Here the influence of the magnetic core nonlinearity is noticed in the waveform of the current, while the supply voltage is sinusoidal.

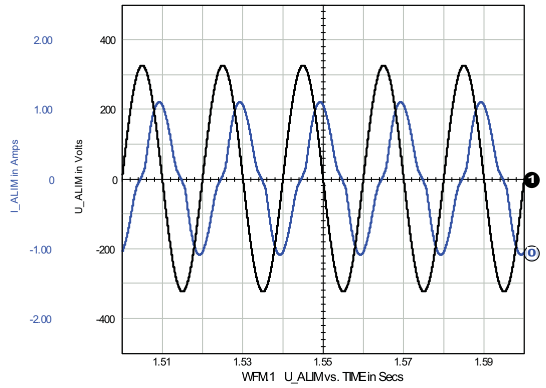

Figure 7: Supply voltage waveform (curve 1 - black) and coil current waveform (curve 0 - blue)

In some practical applications the distorted form of the current in an inductive circuit produces a distortion of the voltage. This effect will never be able to be put into evidence in a simulation program because the supply voltage is imposed by the user and thus it remains sinusoidal.

Figure 8 depicts the coil current waveform and the magnetic flux waveform in the movable core. One can notice, as we expected, that the two quantities have the same phase. This fact is explained by the electromagnetic theory (Ampere's law). Moreover the waveforms of the two quantities have the same shape.

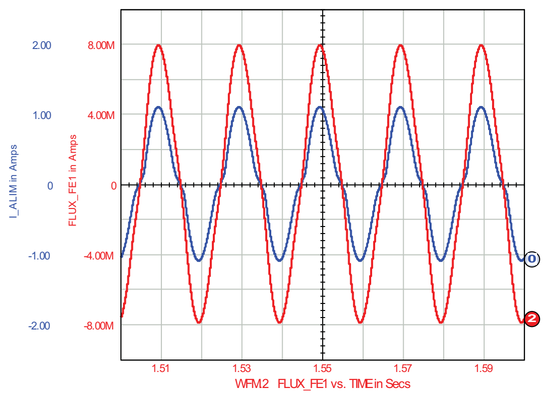

Figure 8: Coil current waveform (curve 0 - blue) and magnetic flux waveform in the movable core (curve 2 - red).

Figure 9 presents in a comparative manner the magnetic flux waveform inside the short-circuit ring and the waveform of the current induced in the short-circuit ring. One can notice a phase displacement of around 90 degrees between them that is explained by Faraday's law. The both waveforms are distorted, but of different shapes. This is due to the electric parameters of the short-circuit ring and it depends on the saturation level of the magnetic core.

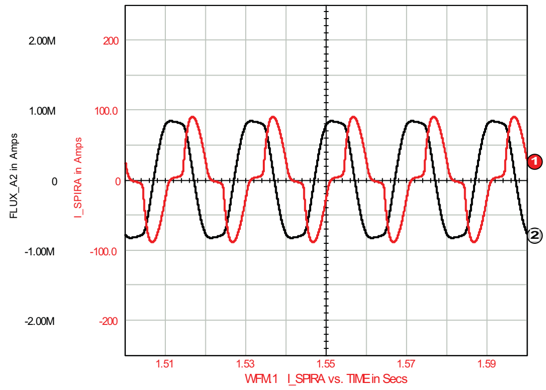

Figure 9: Magnetic flux waveform inside the short-circuit ring (curve 2 - black) and the waveform of the current induced in the short-circuit ring (curve 1 - red).

Figure 10 depicts the waveforms of the magnetic flux inside the short-circuit ring, of the magnetic flux outside the short-circuit ring and of the total magnetic flux in the movable core. Thus the role of the short-circuit ring is underlined, i.e. its role in the phase displacement between the magnetic fluxes waveforms inside and outside of the ring. This phenomenon improves the operation of the AC electromagnet and it is in agreement with the considerations presented in the technical papers [1]-[4].

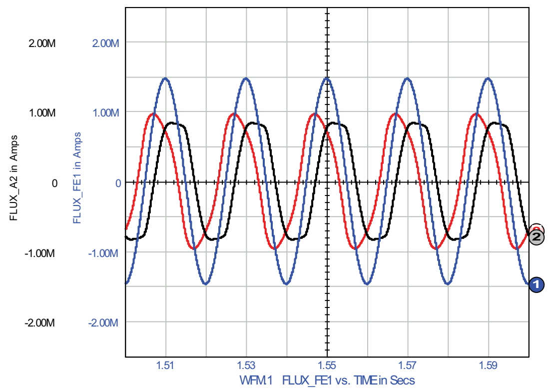

Figure 10: Magnetic flux inside the short-circuit ring (curve 2 - black), magnetic flux outside the short-circuit ring (curve 3 - red) and total magnetic flux in the movable core (curve 1 - blue).

The entire behavior of the plunger-type magnet as it results from our simulation proved to be in a good agreement with other researchers' results that used different strategies in order to obtain a realistic behavior of the magnets [1-4], [9], [12], [13]. This think demonstrates that our model is a valid one.

4. CONCLUSIONS

The paper proposed a new model for plunger-type magnets. It has the advantages of being easy to be implemented in dedicated softwares, specific to the electric circuits (e.g. SPICE), and of considering some electromagnetic phenomena that occur in the magnetic cores of the device.

The comparisons made between our results, the electromagnetic theory and some experimental determinations presented in technical papers revealed a good agreement between the estimated behavior of the magnet and the real one. The proposed model could be improved in order to be used to a class of plunger-type magnets.

References

[1] Gh. Hortopan, Gh. Cosmin, M. Huhulescu, V. Panaite, D. Simulescu, R. Tomoioagă, *Aparate electrice de joasă tensiune* (in Romanian), Ed. Tehnică, Bucureşti, 1969.

[2] J. R. Riba Ruiz, A. Garcia Espinosa, *A Novel Parametric Model for AC Contactors*, IEEE Trans. On Magnetics, vol. 44, no. 9, 2008, pp. 2215-2218.

[3] G. A. Cividjian, N. G. Silvis-Cividjian, A.G. Cividjian, *Inductance of a Plunger-Type Magnet*, IEEE Trans. On Magnetics, vol. 34, no. 5, 1998, pp. 3685-3688.

[4] R. Gollee, G. Gerlach, *An FEM-Based Method for Analysis of the Dynamic Behavior of AC Contactors*, IEEE Trans. On Magnetics, vol. 36, no. 4, July 2000, pp. 1337-1340.

[5] L. Mandache, D. Topan, K. Al-Haddad, *Modeling of Nonlinear Ferromagnetic Cores*, Rev. Roum. Sci. Techn – Electrotechn. Et Energ., vol.53, no.4, 2008, pp. 403-412.

[6] L. Mandache, K. Al-Haddad, *High Precision Modeling of Nonlinear Lossy Magnetic Devices*, IEEE International Symposium on Industrial Electronics – ISIE 2006, 9-13 July 2006, Montreal, pp. 2671-2676.

[7] M. Iordache, L. Mandache, *Analiza asistată de calculator a circuitelor analogice neliniare* (in Romanian), Ed. Politehnica Press, Bucharest, 2004.

[8] H. G. Brachtendorf, C. Eck, R. Laur, *Macromodeling of Hysteresis Phenomena with SPICE*, IEEE Trans. On Circuits and Systems - II: Analog and Digital Signal Processing, vol. 44, no. 5, 1997, pp. 378-388.

[9] M. Iordache, L. Dumitriu, *Simularea asistată de calculator a circuitelor analogice* (in Romanian), Ed. Politehnica Press, Bucharest, 2002.

[10] ***, *IsSpice4 User's Guide*, Intusoft co., San Pedro, Ca., 1995.

[11] C. I. Mocanu, *Teoria circuitelor electrice* (in Romanian), Ed. Didactică şi Pedagogică, Bucureşti, 1979.

[12] B. Lequesne, *Dynamic Model of Solenoids under Impact Excitation, Including Motion and Eddy Currents*, IEEE Trans. On Magnetics, vol. 26, no. 2, 1990, pp. 1107-1116.

[13] K. Preis, O. Bíró, I. Ticar, *FEM Analysis of Eddy Current Losses in Nonlinear Laminated Iron Cores*, IEEE Trans. on Magnetics, Vol. 41, No. 5, 2005, pp. 1412-1415.

[14] D. Topan, L. Mandache, *Metode de analiză în circuite electrice complexe* (in Romanian), Ed. Universitaria, Craiova, 2002.