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POWER LOSSES ESTIMATION FOR FESI SHEETS USING ALGEBRAIC MODELS

LUCIAN PETRESCU[1], VALENTIN IONIȚĂ[1], EMIL CAZACU[1], MARIA-CĂTĂLINA PETRESCU[1]

Key words: Soft magnetic materials, Hysteresis parameter modelling, Algebraic models.

Nowadays, the electrical machines are designed to operate at high frequencies (up to kHz). Therefore, is important for manufacturers to predict the power losses of these equipments using simple tools. Thus, this paper suggests a solution considering two algebraic models with hysteresis parameters for estimating the specific power losses of FeSi sheets. The models use fitting values of coercivity force and remanence points necessary in representing the hysteresis loop for higher frequency values. Two sorts of non-oriented grain (N.O.) electrical sheets are selected for determining the fitting parameters considering the experimental data provided by a Single Sheet Tester (SST). The measurements are limited to 200 Hz, but the models could also manage to estimate the parameters and the specific power losses for higher frequencies up to 1 kHz.

1. INTRODUCTION

Electrical machines and transformers cannot work without soft magnetic materials. The magnetic cores of these devices are designed using especially electrical sheets. The grain oriented (G.O) sorts are adopted for transformers due to their substantial anisotropy while the non-oriented (N.O.) sorts are selected for electrical rotative machines [1–3]. In order to improve the mechanical and electrical properties, beside Fe and Si other materials (Al, Mn, P) are be found in N.O. sheets composition (in less than 1% proportion). The manufacturing processes of these sheets respect the international standards [4–6] and the commercialized sorts have the typical thickness of 0.35, 0.5, 0.65 and 1.00 mm, respectively [5].

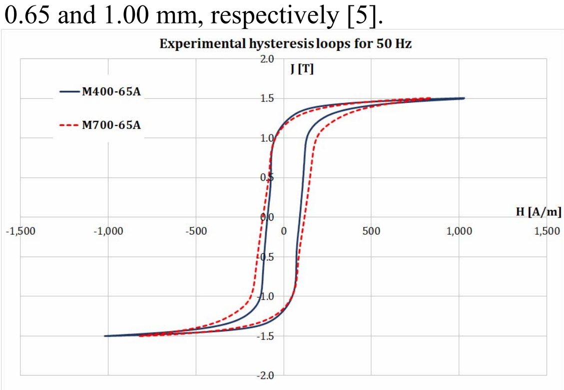

Fig. 1 – Experimental hysteresis loops for M400-65A and M700-65A, respectively, obtained for 50 Hz, using SST.

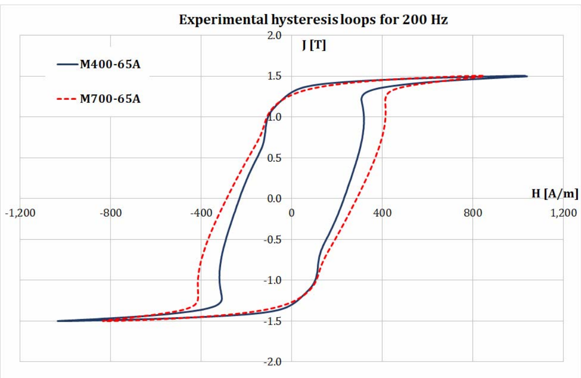

Fig. 2 – Experimental hysteresis loops for M400-65A and M700-65A, respectively, obtained for 200 Hz, using SST.

For this study, two different sorts of N.O. sheets (M400 and M700, respectively) with the thickness of 0.65 mm were used. The identification of these materials is indicated according to the International Standard SR EN 10106:2009 [6]. This denotes with M magnetic the alloys steels and also states that their specific magnetic losses (multiplied with 100 at 1.5 T and 50 Hz) cannot exceed 4 and 7 W/kg, respectively. A full characterization of these sheets was previously presented [4] and here there only the major loops are illustrated. They are experimentally obtained (using single sheet tester - SST [7]) for 50 Hz -Fig. 1, and 200 Hz -Fig. 2, respectively.

The SST limits the measurements investigation to 200 Hz, but some industrial applications require higher value of the operating frequency (up to 1 kHz). In this paper, two simplified and robust models for the losses estimation over the devices restrains are suggested.

2. ALGEBRAIC MODELS

Estimation of the specific power losses is a topic that was discussed and analyzed over the years [8–11]. That was performed by using models with more or less complexity, which requires different amount of experimental data [12, 13]. Starting from [14], two sigmoid-algebraic models that demand only a few experimental data results were adopted:

- Algebraic sigmoid function:

$$f_1(H) = \frac{a(H+c)}{\sqrt{d+[b(H+c)]^2}}. \quad (1)$$

- Elliot transfer function:

$$f_2(H) = \frac{a(H+c)}{d+b|H+c|}, \quad (2)$$

where H is the magnetic field strength, a, b, c, d are coefficients defined below. The sigmoid functions have the advantage of converging to a specific value (parameter "a") and they are commonly used in different domains [15–17].

Parameters "b" and "c" determinate the functions slope and their horizontal translation (corresponding to the coercivity point). These functions also offer the possibility of fitting the hysteresis cycles through the remanence point (J_r) using the fourth parameter d:

[1] University "POLITEHNICA" of Bucharest, Faculty of Electrical Engineering, Department of Electrical Engineering, 313 Splaiul Independentei, 060042 Bucharest, Romania, E-mail: lucian.petrescu@upb.ro

$$f_1(0) = J_r \Rightarrow d = \left(\frac{ac}{J_r}\right)^2 - (bc)^2 . \qquad (3)$$

$$f_2(0) = J_r \Rightarrow d = \frac{ac}{J_r} - b|c| . \qquad (4)$$

The selected experimental data are the maximum value of the polarization (J_m), the maximum point of the magnetic field strength (H_m), the coercivity field (H_c) and the remanence point (J_r), respectively.

3. MODEL PARAMETERS FITTING

Using the measurements obtained with the SST for two sorts of materials, a Matlab© [18] fitting procedure for J_r and H_c, respectively was performed. The objective of the procedure was to determine a function with the minimum number of parameters that uses the experimental data [19].

As it can be observed in Fig. 3, the variation of the coercivity value with the frequency is close to a straight line (the square for M400-65A and the triangle for the M700-65A). For this parameter, the used fitting function (5) has the corresponding fitting coefficients indicated in Table 1.

$$H_c(f) = p_1 f + p_2 . \qquad (5)$$

Table 1

Fitting coefficients for H_c

Material	p_1	p_2
M400-65A	0.9512	43.93
M700-65A	1.162	58.28

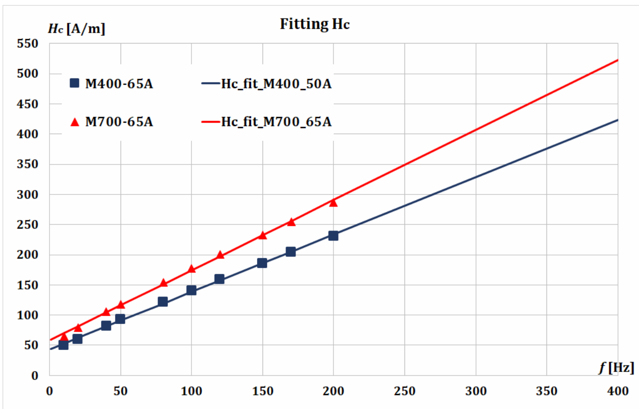

Fig. 3 – Fitting parameter H_c for both materials.

The best fitting for parameter J_r is an exponential function:

$$J_r(f) = a_1 \exp(b_1 f) + c_1 \exp(d_1 f) , \qquad (6)$$

with the parameter's values represented in Table 2:

Table 2

Initial fitting coefficients for J_r

Material	a_1	b_1	c_1	d_1
M400-65A	1.161	0.000556	-0.07489	-0.03254
M700-65A	1.173	0.000386	-0.1386	-0.02171

This function offers very good results – Fig. 4, but for higher values of the frequency (up to 1 kHz) the calculated remanence point of the magnetic polarization exceeds the maximum measured values (over 1.5T) – Fig. 5. In order to overcome this detriment, another fitting function was proposed. This one does not provide the same precision, but offers acceptable results for higher frequencies f (in a range of kHz):

$$J_r(f) = 0.1 \ln\left(\frac{f}{\alpha} + 1\right) + \beta, \qquad (7)$$

with α and β are two fitting coefficients presented for the studied materials in Table 3.

Table 3

Fitting coefficients for J_r

Material	α	β
M400-65A	30	1.089
M700-65A	24	1.037

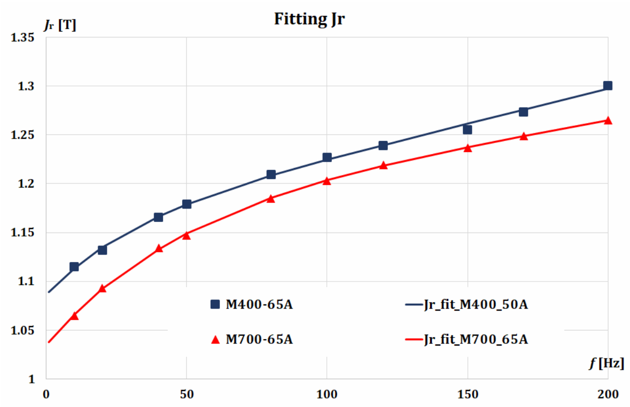

Fig. 4 – Fitting curves for parameter J_r.

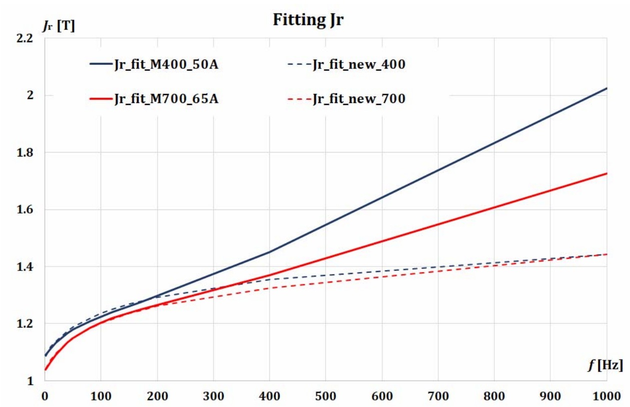

Fig. 5 – New solution for fitting parameter J_r in comparison with the initial solution.

For the coefficient β value $J_r(0)$ is to be considered, which represents the interpolated magnetic polarization to lower values of the frequency, close to dc, by using (6).

Adopting these parameters fitting functions, the hysteresis loops were modeled for different frequencies and the results were compared with the measured values. In Figs. 6–8 are presented these comparisons for both materials at 20, 50 and 150 Hz, respectively. The relative differences err(1-2) and err(1-3), between the curves (1), (2) and (3) are also indicated.

$$err(1-2)=\left|\frac{\text{Area}_{\text{exp}}-\text{Area}_{Alg}}{\text{Area}_{\text{exp}}}\right|, \tag{8}$$

$$err(1-3)=\left|\frac{\text{Area}_{\text{exp}}-\text{Area}_{\text{Elliot}}}{\text{Area}_{\text{exp}}}\right|. \tag{9}$$

where Area_{exp}, Area_{Alg} and $\text{Area}_{\text{Elliot}}$ represent the area of the experimental cycle and the area of modeled cycles using the proposed fitting functions.

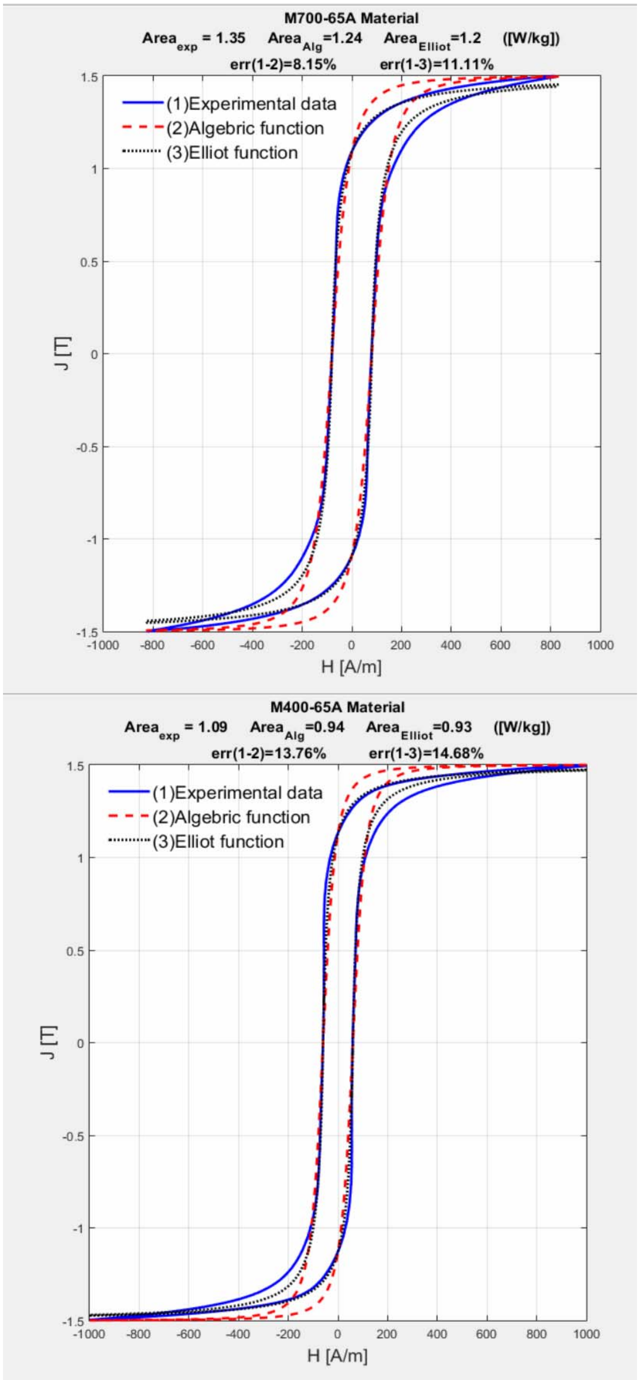

Fig. 6 – Comparison between the measured and modelled hysteresis loop (using both algebraic models), for both materials at 20 Hz.

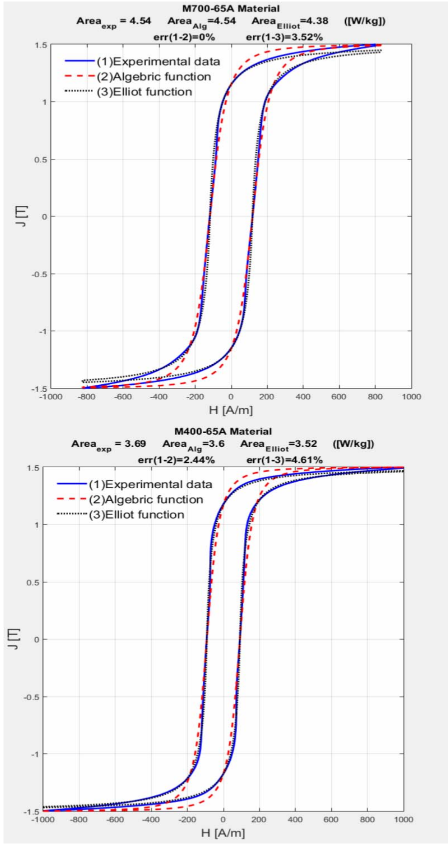

Fig. 7 – Comparison between the measured and modelled hysteresis loop (using both algebraic models), for both materials at 50 Hz.

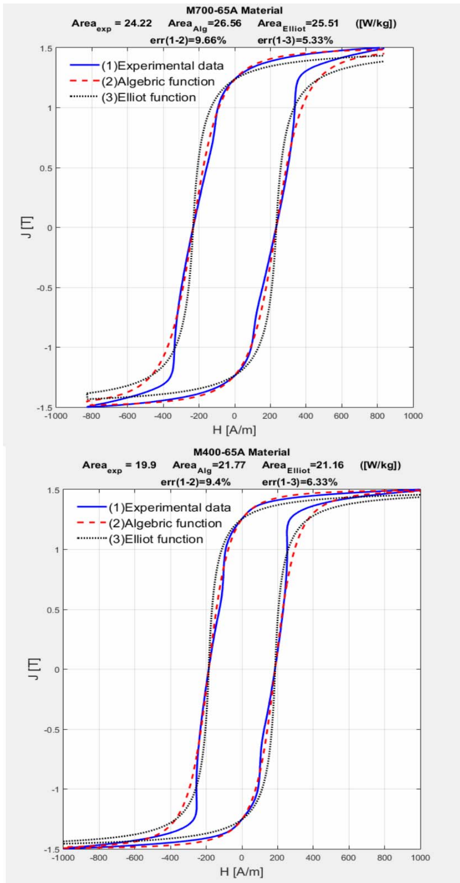

Fig. 8 – Comparison between the measured and modelled hysteresis loop (using both algebraic models), for both materials at 150 Hz.

4. ESTIMATION OF SPECIFIC POWER LOSSES

An estimation of total specific power losses was also performed for both materials at frequencies that exceeded the SST limitation (200 Hz). Using a similar fitting procedure, the power losses were evaluated considering a second-degree function:

$$P(f) = mf^2 + nf + q . \qquad (10)$$

The fitted values of coefficients m, n and q, respectively are indicated in Table 4.

Table 4

Fitting coefficients for P

Material	m	n	q
M400-65A	5.89E-04	0.04461	-0.02335
M700-65A	6.99E-04	0.05719	-0.3678

This fitting function offers very similar results with those obtained by measurement procedure in the range of 0–200 Hz. In Figs. 9 and 10 are presented the estimated power losses considering the fitted values of the coercivity force and the remanent polarization for M400-65A and M700-65A, respectively. A comparison between the results of the two models and the measured values can be notice for frequencies lower than 200 Hz.

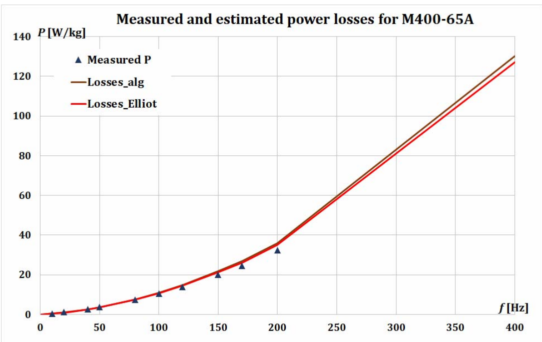

Fig. 9 – Measured and estimated specific power losses for M400-65A, using both algebraic models.

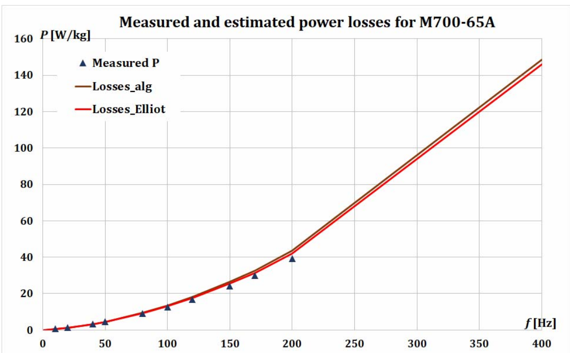

Fig. 10 – Measured and estimated specific power losses for M700-65A, using both algebraic models.

5. CONCLUSIONS AND REMARKS

In this paper, the hysteresis parameters modeling were estimated for two soft magnetic materials used for common electromagnetic devices. Two sorts were considered (M400-65A and M700-65A) and the coercivity field and the remanent magnetic polarization were fitted using functions with a few parameters. The aim of this procedure was to model the major hysteresis loops for higher values of the frequency (up to kHz) where the SST is unable to perform measurements.

Also, the fitting procedures follow the simplicity of the chosen function with a reduce number of coefficients. Linear equation for coercivity field value fitting (two coefficients) and a logarithmic function with two parameters for the remanence polarization value were found. Using these functions, we were able to obtain the major hysteresis loops for 400 Hz and 1 kHz, respectively. The estimated specific power losses were also determined from the loops. The results could be used by the electrical machines manufacturers to estimate the specific power losses for frequency up to kHz. Additionally, the models are very simple and require few measured parameters. Further work will follow by estimation of the specific power losses for other sorts of non-oriented sheets.

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REFERENCES

1. F. Fiorillo, *Measurement and characterization of magnetic materials,* Elsevier Academic Press, 2004.
2. H. Gavrila, H. Chiriac, P. Ciureanu, V. Ionita, A. Yelon, *Magnetism tehnic şi aplicat (Technical and Applied Magnetism)*, Editura Academiei, Bucureşti, 2000.
3. G.E. Fish, *Soft magnetic materials*, Proceeding of the IEEE, **78,** *6*, 1990, 947 – 972.
4. L. Petrescu, E. Cazacu, V. Ioniţă, C. Petrescu, *Comparison Between Non-Oriented Silicon Iron Sheets used for Electrical Machines*, Proceeding of the 10th ATEE Conference, 23-25 May 2017, Bucharest, pp. 524-528, DOI: 10.1109/ATEE.2017.7905174.
5. D.S. Petrovic, *Non-oriented electrical steel sheets*, Materials and technology **44** (2010) *6*, 317–325.
6. *Magnetic Materials—Part 8–4: Specifications for Individual Materials—Cold-Rolled Non-Oriented Electrical Steel Sheet and Strip Delivered in the Fully Processed State*, IEC Standard Publication 60404–8–4, 2005.
7. *** SST Brockhaus, https://brockhaus.com/.
8. L. Petrescu, V. Ionita, E. Cazacu, Catalina Petrescu, *Steinmetz' parameters fitting procedure for the power losses estimation in soft magnetic materials*, OPTIM & ACEMP 2017, May 2017, pp. 208- 213, DOI: 10.1109/OPTIM.2017.7974972.
9. G. Bertotti, *Hysteresis in Magnetism: For Physicists, Materials Scientists, and Engineers*, Academic Press, 1998.
10. V. Ioniţă, L. Petrescu, E. Cazacu, E.-A. Pătroi, E. Manta, *Improved prediction of hysteresis losses in electrical machine cores*, 2017 MPS, Cluj-Napoca, pp. 1-4, (2017).
11. L. Petrescu, H. Gavrilă, *Modeling the soft magnetic materials with high permeability in a large range of frequencies*, U.P.B. Sci. Bull., Series C, **72**, *2*, 2010, pp. 189-196.
12. A. Nicolaide, *An approach to the mathematical modelling of the hysteresis curves of magnetic materials: The minor curves*, Rev. Roum. Sci. Techn. – Électrotechn. et Énerg., **52**, *3*, pp. 301–310 (2007).
13. L. Petrescu, *Comparison between frequently used hysteresis models*, Rev. Roum. Sci. Techn. – Électrotechn. et Énerg., **52**, 3, pp. 311–320 (2007).
14. L. Petrescu, E. Cazacu, Catalina Petrescu, *Sigmoid functions used in hysteresis phenomenon modeling*, Proceeding of the 9th ATEE Conference, 7-9 May 2015, Bucharest, pp. 521-524, DOI: 10.1109/ATEE.2015.7133863.
15. N Bacaër, *Verhulst and the logistic equation* (1838), in N Bacaër, *A short history of mathematical population dynamics* (Springer-Verlag London, Ltd., London, 2011), 35-39.
16. X. Yin, J. Goudriaan, E. Latinga, J. Vos, H. Spiertz, "*A flexible Sigmoid Function of Determinate Growth*, Annals of Botany., **91**, pp. 361–371, 2003.
17. M.N. Gibbs, D.J.C. MacKay, *Variational Gaussian Process Classifiers* IEEE Trans. on Neural Networks.,**11**., *6*, pp. 1458-14645, 2000.
18. https://uk.mathworks.com/products/matlab.html.
19. C. Ghiţă, I.D. Deaconu, A.I. Chirilă, V. Năvrăpescu, I.D. Ilina, *2D analysis of electrical transformer's magnetic field due to the magnetizing magnetomotive force*, Rev. Roum. Sci. Techn. – Électrotechn. et Énerg., **54**, *3*, pp. 233–242 (2009).