A PROCEDURE FOR SPECIFIC MAGNETIC LOSSES CALCULATION IN FeSi ELECTRICAL SHEETS

Marius-Daniel CALIN, Carmen LUNGOCI, Elena HELEREA

„Transilvania” University of Brasov /Department of Electrotechnics, Romania
marius.calin@unitbv.ro, Helerea@unitbv.ro

Abstract – **The losses in the magnetic circuit of electrical machines produce machine heating and reduce efficiency with implications in lifetime and energy save. The factors that affect the losses in magnetic circuits of electrical machines are: material performances, geometry of magnetic circuit, load characteristics and working frequency. Taking into account all these factors, the paper analyzes the magnetic losses in the FeSi electrical sheets used in magnetic circuit of electrical machines construction and proposes a new and fast mathematical model for specific magnetic losses calculation in a specific range of magnetization. A procedure of losses division for hysteresis losses, eddy currents losses and additional magnetic losses is proposed, resorting to a minimum of experimental data. The proposed model has as advantage rapidity of magnetic losses determination due to the use of variable coefficients involved in hysteresis losses determination, reported to magnetization frequency and magnetic induction. Validation model was made over a frequency range of 10 Hz to 200 Hz and magnetic induction from 0.1 T to 1.5 T, with errors compared with those of classical model.**

Keywords: *magnetic materials, specific losses, hysteresis losses, FeSi electrical sheets*

1. INTRODUCTION

Nowadays, efficient use of energy is an important issue in the electrical engineering. Requirements referring to high efficiency electromechanical energy conversion under security conditions and low functioning temperatures should be ensured at any time of operation regime [1].
From this point of view, the losses in the magnetic circuit of electrical machines produce machine heating and reduce efficiency, with implications in lifetime and energy saving. The main factors that affect the losses in magnetic circuits of electrical machines are: material performances, geometry of magnetic circuit, load characteristics and working frequency. The minimization of losses in electrical machines, which mainly are determined by the losses in the stator magnetic core realized usually of Fe-Si electrical sheets [2], [3], is taken into account through an optimal design and manufacturing, and, especially through using the improved magnetic materials.

Recent models developed for describing the magnetic hysteresis phenomenon - Stoner–Wohlfarth model as a physical-empirical model, Jiles–Atherton model, isotropic and anisotropic Preisach models, and analytic-geometrical models permit the representation of the major hysteresis loop and different minor loops with relatively simple computations. New approaches have in view the fuzzy and neural network methods. Because of the complexity of the phenomena, many difficulties appear to find a mathematical model of losses that perfectly describes the losses curves obtained experimentally.
The model of magnetic losses separation in components is suitable due to multiple reasons: from the phenomenological point of view regarding displacement of magnetic domains and other microscopic processes [4] - [6], for improvement of magnetic materials performances [7] - [9].
In present paper, the overall magnetic losses curves and their components at the frequency range of 10-200 Hz are obtained for samples of FeSi electrical sheets with 3.5 Si %, and the influence of rolling direction on the magnetic losses components is investigated. The method of magnetic losses separation is applied and a procedure for specific magnetic losses calculation, with minimum requirements of experimental data and low errors, is proposed.

2. MATERIAL, METHOD AND MEASUREMENT SYSTEM

The investigated magnetic materials have been two non-oriented FeSi electrical sheets with 3.5 % Si (ER and KO samples). The characteristics are shown in Table 1.

Sample	Sample length [mm]	Sample width [mm]	Thickness [μm]	Weight [g]	Number of samples / package	Magnetization & Rolling direction
ER-L	305	30	650	1080	24	parallel
ER-T	305	30	650	1087	24	perpendicular
KO-L	280	30	650	1010	24	parallel

Table 1: FeSi investigated samples characteristics.

The measurement system used for experimental determination of magnetic characteristics of specimens is DEM 25 type (Brockhaus Messtechnik-Germany), provided with an Epstein frame, 100 primary and secondary windings, according to IEC 404-10 Standard, which allows measurements in the frequency range of 10 – 1000 Hz (Figure 1).

Figure 1: Epstein frame measurement system.

Testing was performed through a magnetizing frequency range of 10 - 200 Hz and magnetic inductions from 0.1 to 1.5 T.

3. EXPERIMENTAL DATA

The experimental data of overall specific magnetic losses for longitudinal (L) and transversal (T) rolling samples of two types of FeSi sheets (ER and KO) are obtained. In Table 2 and 3, the overall specific losses are shown for three values of magnetic induction: 0.5, 1.1 and 1.5 T.

ER-L					
B[T]	40Hz	50Hz	60Hz	100Hz	200Hz
0.5	0.4759	0.6468	0.8370	1.7526	4.9775
1.1	1.8846	2.5984	3.4066	7.5705	23.908
1.5	3.3983	4.664	6.1007	13.482	42.999
ER-T					
0.5	0.5135	0.6890	0.8809	1.8020	5.0166
1.1	1.9554	2.6566	3.4345	7.3604	22.503
1.5	3.5365	4.8122	6.2406	13.456	41.755

Table 2: Overall magnetic losses in ER samples, in W/kg.

KO-L					
B[T]	40Hz	50Hz	60Hz	100Hz	200Hz
0.5	0.6081	0.8069	1.0210	2.0220	5.3651
1.1	2.289	3.0847	3.9697	8.3445	24.312
1.5	4.1886	5.6393	7.2580	15.300	46.325
KO-T					
0.5	0.6920	0.9070	1.1362	2.1980	5.7009
1.1	2.5130	3.3443	4.2532	8.6481	24.766
1.5	4.6580	6.2061	7.9126	16.228	48.000

Table 3: Overall magnetic losses in KO samples, in W/kg.

Using MatLab software, for each sample, the 3D cartographies are obtained. In Figure 2, the dependence of magnetic specific losses on frequency and magnetic induction is shown.

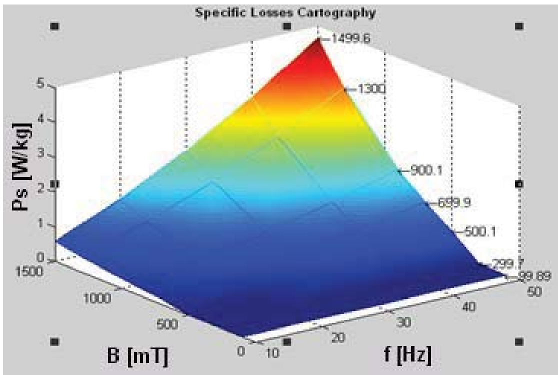

Figure 2: 3D magnetic losses cartography for ER-L sample.

The experimental data indicate higher values for magnetic losses in transversal samples (ER-T and KO-T) compared to longitudinal rolling samples (ER-L and KO-L). The explanation is in connection with difficulties in orientation of magnetic domains in the case of perpendicular magnetization of transversal rolling samples.

4. MATHEMATICAL MODEL FOR MAGNETIC LOSSES

In literature traditional formulation for overall specific magnetic losses is:

$$p_{Fe} = p_H + p_F + p_{Ex}\,, \qquad (1)$$

where the magnetic losses p_{Fe} are separated in hysteresis losses p_H, eddy current losses p_F and additional magnetic losses p_{Ex}.

Initially, additional magnetic losses p_{Ex} are included in eddy current losses, usually having a reduced weight in total magnetic losses. Having in view the classical dependence on frequency and magnetic induction, then relation (1) becomes [10]:

$$p_{Fe} = C_H \cdot f \cdot B^n + C_F \cdot f^2 B^2\,, \qquad (2)$$

where C_H, n represent coefficients of hysteresis specific losses and C_F is coefficient of eddy currents specific losses.

Dividing relation (2) to magnetization frequency, the following relation is achieved:

$$\frac{p_{Fe}}{f} = C_H \cdot B^n + C_F \cdot f \;\; B^2 \qquad (3)$$

From relation (3) that graphically represents the straight lines in coordinates (p_{Fe}/f, f), the coefficients C_H and n result from linear interpolation of experimental data (Figure 3).

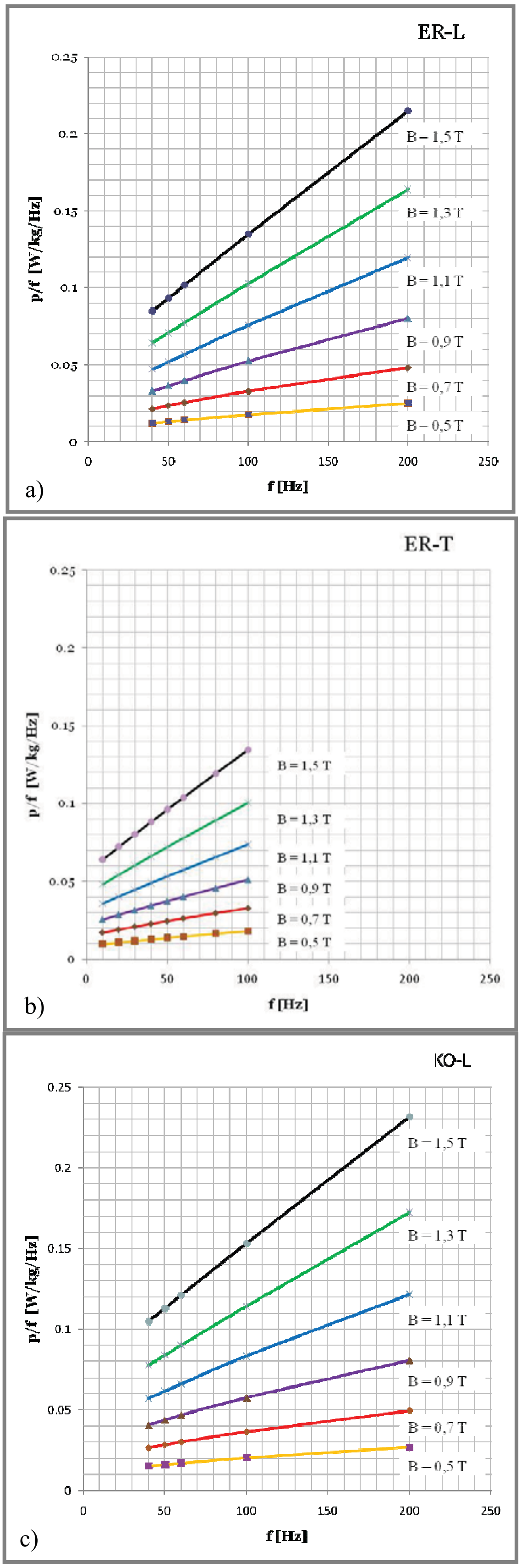

Figure 3: Dependence of p_{Fe}/f in function of frequency for samples: a) ER-L; b) ER-T; c) KO-L.

From the straight lines of magnetic losses at specific magnetizing frequencies are obtained the variable coefficients for hysteresis losses C_H and n. To improve the stability of hysteresis losses coefficients determination, five measurement points were taken at the same induction. In Table 4 the coefficients C_H and n are shown for ER-L sample, for two domains of magnetic inductions, respectively 0 - 1 T and 1 - 1.5 T.

B [T]	C_H	n
0 - 1	0.0259	1.5164
1 - 1.5	0.00246	1.8693
0 - 1.5	0.0265	1.5825

Table 4: Variable coefficients of hysteresis losses obtained for ER-1-L sample.

The classical eddy current losses are introduced, in which the coefficient C_F is analytically determinate with relation [11]:

$$C_F = \frac{\pi^2}{6} \cdot \frac{\Delta^2}{\rho \cdot d_v} \tag{3}$$

where Δ is sample thickness, ρ is material resistivity and d_v is the volumetric mass density.

With data for FeSi samples considered (Δ=650μm, $\rho=0.4\cdot10^{-6}\Omega$m, d_v=7.55g/cm^3) the value obtained for the eddy current coefficient C_F is $2.3\cdot10^{-4}$.

From this point, the additional magnetic losses p_{Ex} are obtained by total magnetic losses experimentally achieved and hysteresis and eddy currents losses difference. Based on typical values obtained for hysteresis and eddy currents coefficients, the curves of magnetic losses are raised (Figure 4).

The calculation algorithm of specific losses in FeSi electrical sheets used in magnetic circuit construction of electrical machines has the follow logic diagram shown in fig. 5.

According to data obtained by proposed analytical model, an estimation of specific eddy currents and hysteresis losses is revealed for ER-L and ER-T specimen samples (Table 5).

B [T]	p_F/p_H [%]							
	f=10Hz		f=60Hz		f=100Hz		f=200Hz	
	ER-L	ER-T	ER-L	ER-T	ER-L	ER-T	ER-L	ER-T
0.3	5.1	5.1	31.0	31.0	51.7	51.7	103.5	103
0.5	6.3	6.3	38.3	37.9	63.8	63.1	127.7	126
0.7	7.3	7.2	44.2	43.6	73.6	72.7	147.3	145
0.9	8.5	8.1	51.0	48.6	85.0	81.0	170.1	162
1.1	9.4	8.7	56.4	52.3	94.0	87.2	188.0	174
1.3	9.7	9.1	58.6	54.7	97.6	91.2	195.3	182
1.5	9.7	9.1	58.7	54.6	97.8	91.1	195.6	182

Table 5: Eddy current losses compared with hysteresis losses for ER-L and ER-T specimen samples [%].

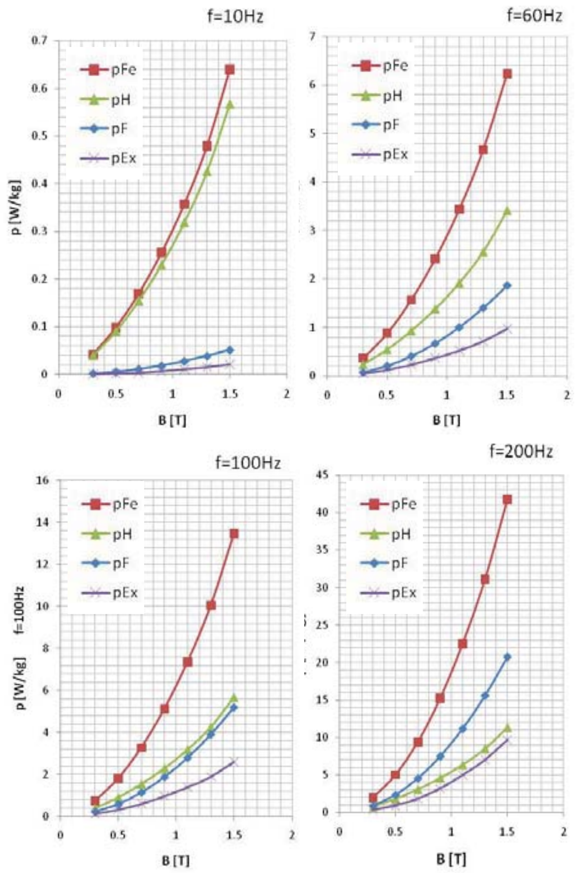

Figure 4: Raised curves of separated magnetic losses for ER-T sample.

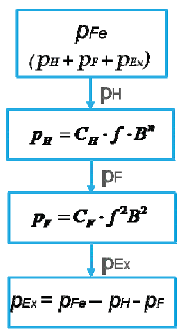

Fig. 5: Logic diagram of specific losses calculation.

The eddy currents losses compared with hysteresis losses reveal small proportion of eddy currents losses at low frequencies (10 - 60 Hz), high proportion at higher frequencies (more than 150 Hz) and about the same proportion near 100 Hz frequency.

5. CONCLUSION

The mathematical model based on separation of specific magnetic losses in the FeSi electrical sheets used for magnetic circuit of electrical machines construction, for a specific frequency and magnetization range has accuracy and rapidity advantages of losses determination due to the use of variable coefficients for hysteresis losses determination, reported to the magnetization frequency. A systematic procedure of losses separation for hysteresis losses, eddy currents losses and additional magnetic losses is proposed, resorting to a minimum of experimental data.
Validation model is successfully achieved for non-oriented FeSi electrical sheets of FeSi samples with longitudinal and transversal rolling direction, with lower errors than conventional model with constant coefficients.

Acknowledgments

This paper is partially supported by the Sectoral Operational Programme Human Resources Development financed from the European Social Fund under the contract number POSDRU/6/1.5/S/6.

References

[1] B. Mecrow, A. Jack, *Efficiency trends in electric machines and drives*, Energy Policy vol. 36, 2008, pp. 4336–4341.
[2] G.K. Kalokiris A.G. Kladas, I.K. Hatzilau, S. Cofinas, I.K. Gyparis, *Advances in magnetic materials and their impact on electric machine design*, Journal of Materials Processing Technology, vol. 181, 2007, pp. 148–152.
[3] P. Rovolis, A. Kladas, J. Tegopoulos, *Laminated iron core losses evaluation and measurements*, Journal of Materials Processing Technology, vol. 181, 2007, pp. 182–185.
[4] Z. Lin, J. Zhu, *Three-dimensional magnetic properties of soft magnetic composite materials*, Journal of Magnetism and Magnetic Materials, vol. 312, 2007, pp. 158–163.
[5] H. Yamaguchi, H. Pfüzner, A. Hasenzagl, *Magnetostriction measurements on the multidirectional magnetization performance of SiFe steel*, Journal of Magnetism and Magnetic Materials, vol. 320, 2008, pp. 618-622.
[6] H. Zhou, Y. Zhou, X. Zheng, Q. Ye, J. Wei, *A general 3-D nonlinear magnetostrictive constitutive model for soft ferromagnetic materials*, Journal of Magnetism and Magnetic Materials, vol. 321, 2009, pp. 281–290.
[7] K. Fonteyn, A. Belahcen, A. Arkkio, *Properties of electrical steel sheets under strong mechanical stress*, Pollack Periodica, vol. 1, 2006, pp. 93-104.
[8] A. Pulnikov et al., *The relation between the magnetostriction and the hysteresis losses in the non-oriented electrical steels*, Journal of Magnetism and Magnetic Materials, vol. 290–291, 2005, pp. 1454–1456.

[9] E. Burzo, M.M. Codescu, W. Kappel, E. Helerea, *Magnetic materials for technical application*, Journal of Optoelectronics and Advanced Materials, vol. 11, no. 3, 2009, pp. 229 - 237.
[10] A. Nicolaide, *Masini electrice. Teorie si proiectare, vol. I*, Scrisul Romanesc press, Craiova, 1975.
[11] M. Popescu, D. Ionel, *A Best-Fit Model of Power Losses in Cold Rolled-Motor Lamination Steel Operating in a Wide Range of Frequency and Magnetization*, IEEE Transactions On Magnetics, vol. 43, Issue 4, 2007, pp. 1753-1756.