Hysteresis Losses Evaluation in Electromagnetic Devices under Non Sinusoidal Induction Waveforms

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Abstract — This paper deals with the evaluation of hysteresis losses in electromagnetic devices under non sinusoidal induction waveforms. The originality of this work lies on the fact that it is not necessary to perform Fourier Transform of the applied waveforms, as it is usually presented in the literature to calculate the hysteresis losses. The needed parameters are extracted automatically from the original applied induction waveform using an algorithm developed by the authors. Comparison between calculated and measured results shows the validity of the proposed method.

I. Introduction

All electromagnetic devices present an associated loss while operating [1], [2]. That generally results in the heating of their structure. There are basically three types of losses: copper losses, iron losses and mechanical losses due to, for example, friction and ventilation. One of the objectives of this work is to evaluate hysteresis losses in electromagnetic devices due to arbitrary voltage supply. So, if the applied voltage is sinusoidal, there are no minor loops in the main cycle and the hysteresis losses can be determined by the Steinmetz equation given by:

$$P = K_H f\left(\frac{\Delta B}{2}\right)^{\propto}\left[\frac{W}{kg}\right] \qquad (1)$$

Where ΔB is the peak to peak induction amplitude, f is the frequency and K_H and α are parameters to be determined by experiments. However, in cases where minor loops become significant, i.e. when the applied voltage is no more sinusoidal, the classical calculation method must be modified [3], [4]. The generalization of (1) involves the sum of every parcel corresponding to inner loops in the cycle and leads to (2) [5].

$$P_{dc} = \sum_{i=1}^{N+1} K_H\left(\frac{\Delta B_i}{2}\right)^{\propto} f[1 + 0.65B_{dc}^{2.1}]\left[\frac{W}{kg}\right] \qquad (2)$$

Where N is the number of harmonics and B_{dc} is their continuous induction value. Thus, this approach involves the Fourier transform of the applied induction and as shown in ([5], [6]), it leads to better results in comparison with results obtained using (1). Nevertheless, these results lack accuracy when compared to experimental data. So, in order to improve these results, the authors propose an algorithm to extract parameters ΔB, B_{dc} and f of (2) directly from the applied induction waveforms without performing its Fourier transform. In this case, N represents the number of induction reversals. To illustrate the two different approaches cited above, let's evaluate the hysteresis losses of an electromagnetic structure supplied by the induction waveform presented in Fig. 1. Parameters K_H and α of this electromagnetic device are respectively 0.015 and 1.617.

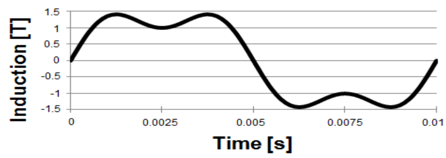

Fig. 1. Applied Induction Waveform

One can deduce that the Fourier transform of the induction waveform presented in Fig.1 results in a pure sine wave with ΔB = 3 T and its third harmonic component having ΔB = 1 T. Using these values in (2), hysteresis losses are obtained by the sum of each parcel:

Parcel 1 – Referred to pure sine wave:

$$P_{dc} = 0.015(3/2)^{1.617} = 28.895 \text{ [mJ/kg]}$$

Parcel 2 – Referred to third harmonic components:

$$P_{dc} = 3\text{x}0.015(1/2)^{1.617} = 14.670 \text{ [mJ/kg]}$$

Resulting in:

$$P_{dc}T = 28.895 + 14.670 = 43.565\ [mJ/kg]$$

One the other hand, analyzing Fig.1, we can intuitively deduce that the applied induction waveform results in a principal hysteresis loop and two reversals. ΔB of the principal hysteresis loop is 2,828 T and its dc level is null. The minor loops peak to peak induction is 0,414 T and its dc level equal to 1,207 T. Using these values in (2), hysteresis losses of the main hysteresis loop and the two minor loops are calculated as below:

$$\mathrm{P_{dc_1}} = [0.015(2.828/2)^{1.617}(1+0)] = 26.264 \text{ [mJ/kg]}$$

$$\mathrm{P_{dc_2}} = \mathrm{P_{dc_3}} = [0.015(0.414/2)^{1.617}(1 + +0.65(1.207)^{2.1}] = 2.309 \text{ [mJ/kg]}$$

The total hysteresis loss is:

$$P_{dc} = 26.264 + 2.309 + 2.309 = 30.882 \text{ [mJ/kg]}$$

As it can be notice, the results show non negligible difference between these two approaches and it will be shown at the next section by comparing with experimental results that the methodology where parameters ΔB, B_{dc} and f of (2) are directly obtained from the applied induction waveform is more reliable. The algorithm to obtain these parameters will be presented in the final version of the paper. Note that this algorithm is able to extract the parameters mentioned above from any waveforms, including from experimental one showing its robustness.

II. Results and Conclusion

In order to validate the proposed methodology, the electromagnetic device utilized in the section above is submitted to three different waveforms (Fig.2, Fig.4 and Fig.6) and its respective hysteresis losses are calculated using the two approaches presented in the section above. For clarity purpose, hysteresis loop associated to each waveform is respectively presented in Fig.3, Fig.5 and Fig.7. Nevertheless, it is important to notice that parameters ΔB, B_{dc} and f needed to evaluate hysteresis losses using (2) are determined from the induction waveform (Fig.2, Fig.4 and Fig.6) using an algorithm developed by the authors. The calculated hysteresis losses are then compared to experimental results (Table I). As it can be verified in this table, hysteresis losses obtained with the proposed approach is similar to the measured one.

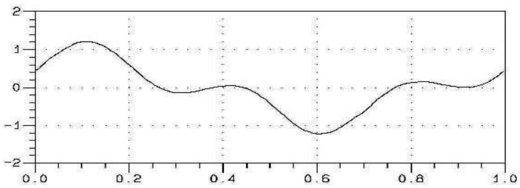

Fig. 2. Applied induction waveform I

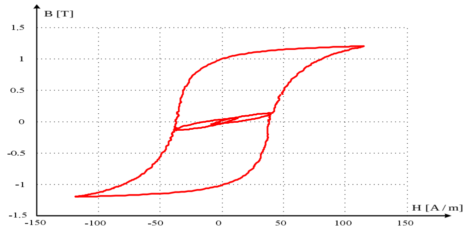

Fig. 3. Experimental hysteresis loop associated to waveform I

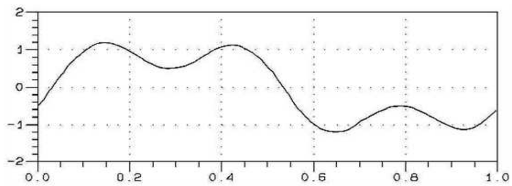

Fig. 4. Applied induction waveform II

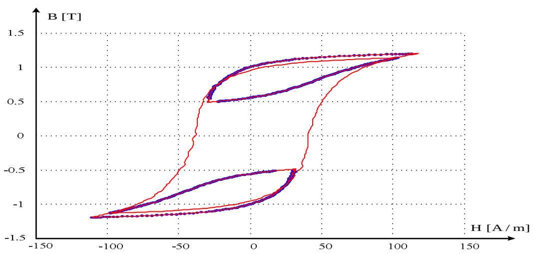

Fig. 5. Experimental hysteresis loop associated to waveform II

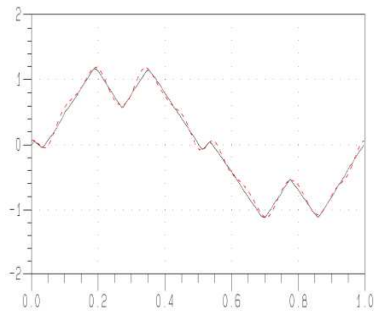

Fig. 6. Applied induction waveform III

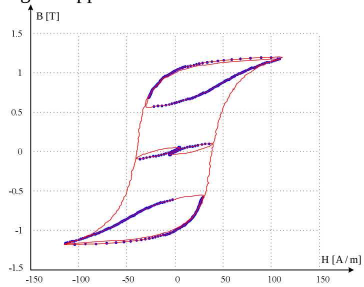

Fig. 7. Experimental hysteresis loop associated to waveform III

Table I : Comparison of hysteresis losses

		Losses [mJ/kg]	Difference between measured and calculated values
Waveform 1	Measured	21.177	-
	Proposed Methodology	21.273	0.45%
	Fourier Decomposition	21.805	2.97%
Waveform 2	Measured	28.234	-
	Proposed Methodology	27.278	-3.39%
	Fourier Decomposition	33.728	19.46%
Waveform 3	Measured	29.06	-
	Proposed Methodology	25.005	-13.95%
	Fourier Decomposition	21.613	-25.63%

III. References

[1] S. E. Zirka, Y. I. Moroz, P. Marketos, A. J. Moses, D. C. Jiles, T. Matsuo, "Generalization of the Classical Method for Calculating Dynamic Hysteresis Loops in Grain-Oriented Electrical Steels", *IEEE Trans. on Magn.*, Vol. 44, N. 9, September 2008, pp. 2113-2126.

[2] N. Kunihiro, T. Todaka, M. Enokizono, "Loss Evaluationof an Induction Motor Model Core by Vector Magnetic Characteristic Analysis", *IEEE Trans. on Magn.*, Vol. 47, N. 5, May 2011, pp. 1098-1101.

[3] J. G. Zhu, V. S. Ramsden, "Improved Formulations for Rotational Core Losses in Rotating Electrical Machines", *IEEE Trans. on Magn.*, Vol. 34, N. 4, July 1998, pp. 2234-2242.

[4] H. Nam, K. Ha, J. Lee, J. Hong, G. Kang, "A Study on Iron Loss Analysis Method Considering the Harmonics of the Flux Density Waveform Using Iron Loss Curves Tested on Epstein Samples", *IEEE Trans. on Magn.*, Vol. 39. N. 3, May 2003, pp. 1472-1475.

[5] C. Simão, N. Sadowski, N. J. Batistela, and P. Kuo-Peng, "Simplified Models for Magnetic Hysteresis Losses Evaluation in Eletromagnetic Devices", *Electric Machines and Drives Conference Proceedings*, 3-6 May 2009., Miami, pp. 876-880.

[6] J. P. Schlegel, N.Sadowski, N. J. Batistela, B. A. T. Iamamura, J.P.A.Bastos, A. A. Espíndola, "Core Tester Iron Losses Segregation by Finite Element Modeling, *IEEE Trans. on Magn.*, Vol. 48, N. 2, February 2012, pp. 715-718.