ANALYSIS OF HYSTERESIS LOSSES IN IRON SHEETS UNDER ARBITRARY VOLTAGE WAVEFORMS

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Abstract – **This paper analyses and compares experimentally the magnetic hysteresis losses evolution in iron steel sheets submitted to different supplies: sinusoidal, square, triangular, two and three-level PWM voltage waveforms. The magnetic induction amplitude influence and the modulation index are investigated for Two and Three-level PWM voltage waveforms. The experimental investigation is performed using a workbench with a closed loop PWM inverter for imposing the induced voltage waveform on the secondary winding of an Epstein frame.**

Keywords - **Arbitrary Voltage Waveforms; Iron Losses; Hysteresis losses; Hysteresis Loops; PWM Voltage Waveforms.**

I. INTRODUCTION

Iron sheets present hysteresis, eddy current and anomalous losses [1,2]. With the advent of Power Electronics, electromagnetic devices became frequently fed by static converters imposing non-sinusoidal voltage waveforms. Some of these waveforms may increase the iron losses when compared to purely sinusoidal voltage [1,2]. This work presents some relevant technical aspects, complementing the conclusions already presented in [3].

Non-sinusoidal voltage waveforms cause non-sinusoidal magnetic inductions. The dynamic losses W_d depend on the induction derivative *dB/dt*. Equation (1) is the most accepted model [2] to evaluate the total iron losses *W* in iron sheets; k_f and k_e are constant coefficients. The dynamic losses (eddy current and anomalous losses) are modeled according the two last terms on the right side of (1). The focus of this work is on the results related to non-sinusoidal induction waveforms hysteresis losses W_h.

$$W = W_h + W_d = W_h + k_f \int_0^T \left(\frac{dB}{dt}\right)^2 dt + k_e \int_0^T \left|\frac{dB}{dt}\right|^{3/2} dt \qquad (1)$$

The contribution of the hysteresis losses can be evaluated by the following equation [3]:

$$W_h = k_h B_p^{\alpha} \qquad (2)$$

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Where:

- k_h - Constant coefficient;
- B_p - Peak value of the flux density;
- α - Steinmetz coefficient.

Equation (2) the hysteresis losses depend on the induction peak value B_p and it is validated only when the voltage fed waveform does not produce minor loops [4]. Nevertheless, magnetic hysteresis losses may increase under some conditions. The hysteresis losses rising are related to the minor loops appearing inside the main hysteresis loop.

One of the purposes of the work is to analyze how the losses behave under arbitrary voltage waveforms. Also, another goal here is to investigate the losses increasing due to the minor hysteresis loops appearing from PWM voltage waveforms. In these waveform types, the influence of the magnetic induction amplitude, the triangular frequency and the modulation index *m* will be investigated. The modulation index *m* is defined by (3), where V_{sin} is the voltage sinusoidal reference amplitude and V_{triang} the triangular carrier signal amplitude.

$$m = V_{\sin} / V_{triang} \qquad (3)$$

II. THE EXPERIMENTAL WORKBENCH

The experiments were performed in a test workbench developed for characterizing electrical steel sheets [5]. Figure 1 presents its scheme. This workbench consists basically in a closed loop PWM inverter, an oscilloscope to measure primary current and secondary voltage waveforms on Epstein frame (B-EP-25cm - Yokogawa Electric Works Ltd.). The electrical steel samples are introduced in the Epstein frame. A feedback loop controls the PWM inverter [6] in order to guarantee the desired voltage waveform on the secondary winding as well as the free current evolution in the primary winding of the Epstein transformer. A virtual instruments based on a computer generates the arbitrary voltage waveforms reference. To calculate the losses, another virtual instrument was developed using LabVIEW software [7]. The workbench uses a *2430 Tektronix* oscilloscope, a Hall effect *A6302 Tektronix* current sensor and its *TM502A Tektronix* amplifier.

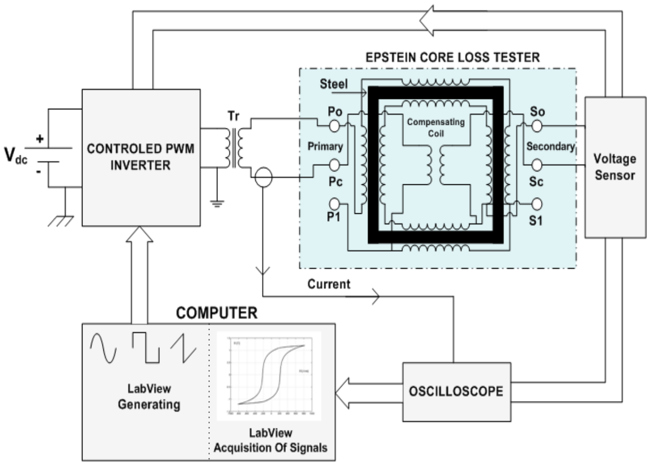


Fig. 1. The workbench used in the experimental investigation.

In order to perform the experimental investigation, twenty eight non-oriented silicon-steel sheet samples were employed in a Epstein frame. They are cut according to the rolling and transversal lamination directions. Table I presents their main characteristics.

TABLE I
Data of the blades

Used sample in the Epstein frame	
Number of sheets in each arm	7
Width of the sheet [cm]	3
Average length of the sheet [cm]	28
Thickness of the sheet [*mm*]	0.5
Average mass of each sheet [*g*]	32

III. EXPERIMENTAL RESULTS

The experimental results were obtained adopting a 1 Hz fundamental voltage waveform for neglecting the magnetic dynamic losses (W_d). In this investigation, the maximum value of magnetic induction is fixed on 1.2 T. To generate PWM pulses, the amplitudes of the triangular and the fundamental as well as triangular frequency were applied on the experiments. In this way the modulation index and the switching frequency can be modified.

A. Sinusoidal, Square and Triangular voltage waveforms

Figure 2(a) shows results obtained for square voltage waveform, where *v(t)* is the voltage on the secondary winding. *B(t)* and *H(t)* are the measured magnetic induction and the magnetic field, respectively. Fig. 2(b) shows the corresponding hysteresis loops (*B(t) vs. H(t)*). On the same figure, a hysteresis loop obtained at purely sinusoidal induction waveform is also presented. Both hysteresis loops are very close, since they depend only on the induction peak and magnetization procedure [2 - 5].

Figure 3 compares the sinusoidal and triangular voltage induced waveforms on the Epstein secondary winding. It is observed in Figure 2(b) and Figure 3(b) that the losses (or internal areas of loops) are the same for sinusoidal, triangular and square voltage waveforms.

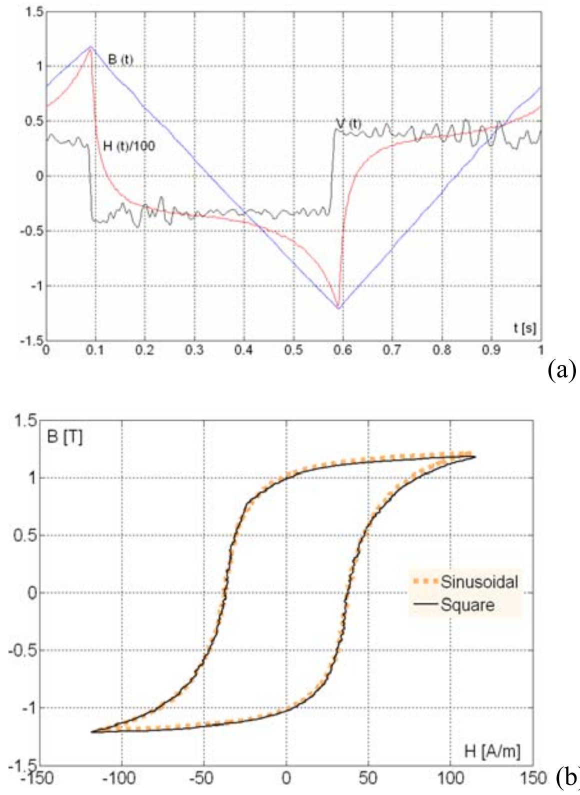


Fig. 2. Results for sinusoidal and square voltage waveforms: (a) Voltage *v(t)*, induction *B(t)* and magnetic field *H(t)* waveforms; (b) hysteresis loops.

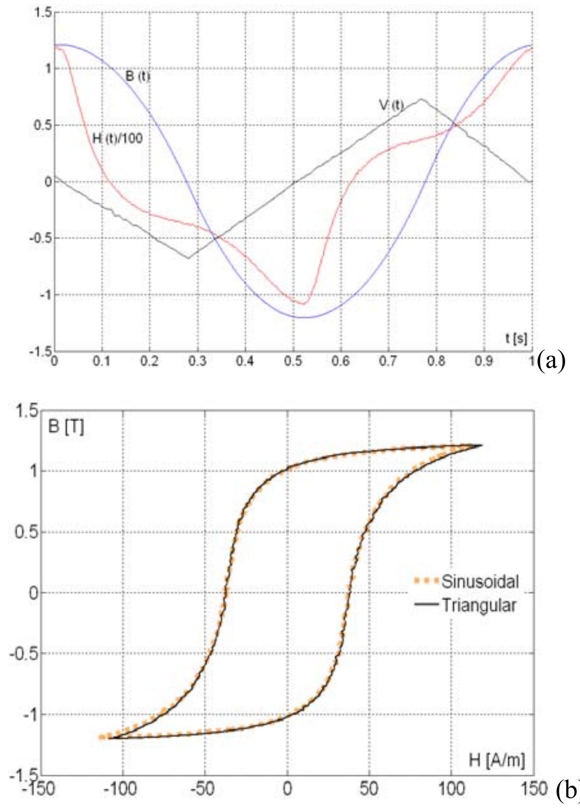


Fig. 3. Results for sinusoidal and triangular voltage waveforms: (a) Voltage *v(t),* induction *B(t)* and magnetic field *H(t)* waveforms; (b) hysteresis loops.

B. Sinusoidal and three-level PWM voltage waveforms

Figure 4 presents results for a triangular frequency of 11 Hz and modulation index *m* equal to 0.80. Figure 5 shows experimental data when the frequency is fixed to 31 Hz with a 0.95 modulation index. Figures 4(b) and 5(b) show comparisons of hysteresis loops obtained between the three-level PWM and the purely sinusoidal voltage waveforms. It can be observed that the three-level PWM operation does not generate minor loops for the whole hysteresis cycle.

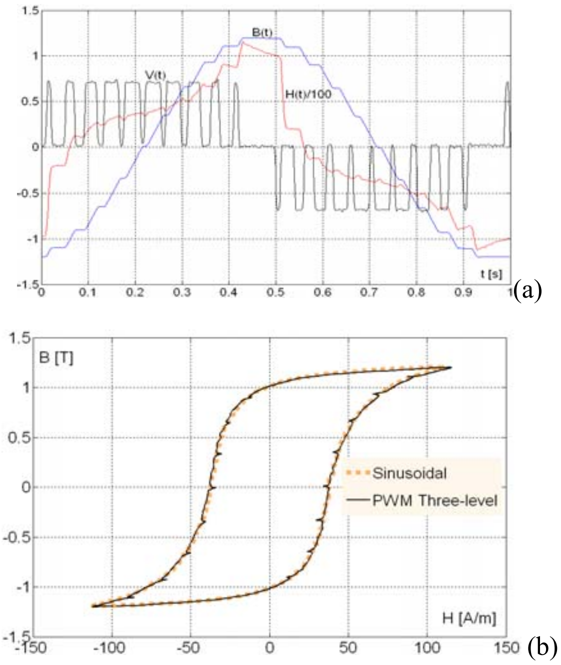


Fig. 4. Results for triangular frequency of 11 Hz and *m*=0.80:
(a) Voltage *v(t),* induction *B(t)* and magnetic field *H(t)* waveforms;
(b) hysteresis loops.

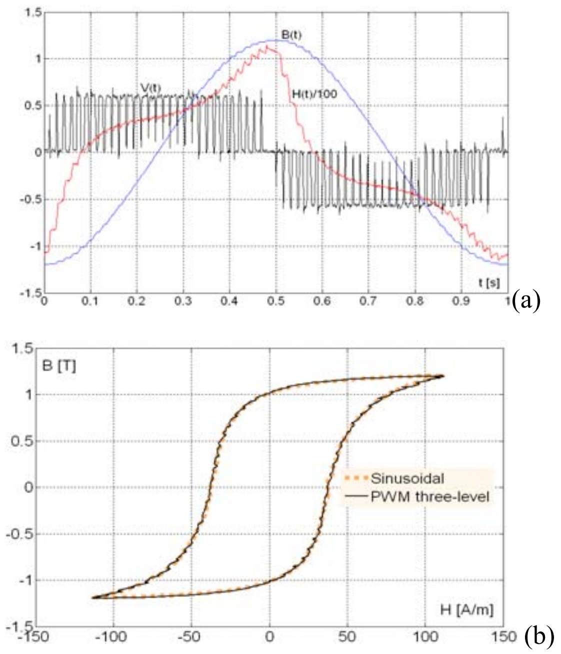


Fig. 5. Results for triangular frequency of 31 Hz and *m*=0.95:
(a) Voltage *v(t)*, induction *B(t)* and magnetic field *H(t)* waveforms*;*
(b) hysteresis loops.

C. Sinusoidal and two-level PWM voltage waveforms

The same variations in triangular frequency and modulation index were performed with a two-level PWM induced voltage waveform imposed on the Epstein frame secondary winding. Figures 6 and 7 show results for triangular frequency of 11 Hz and for modulation indexes of 0.80 and 0.50, respectively. Contrarily to the results obtained for three-level PWM waveforms, here minor closed loops appear on the *B(t)* vs. *H(t)* locii. Comparing to the hysteresis curve obtained with sinusoidal voltages, additional losses due to minor loops are here generated.

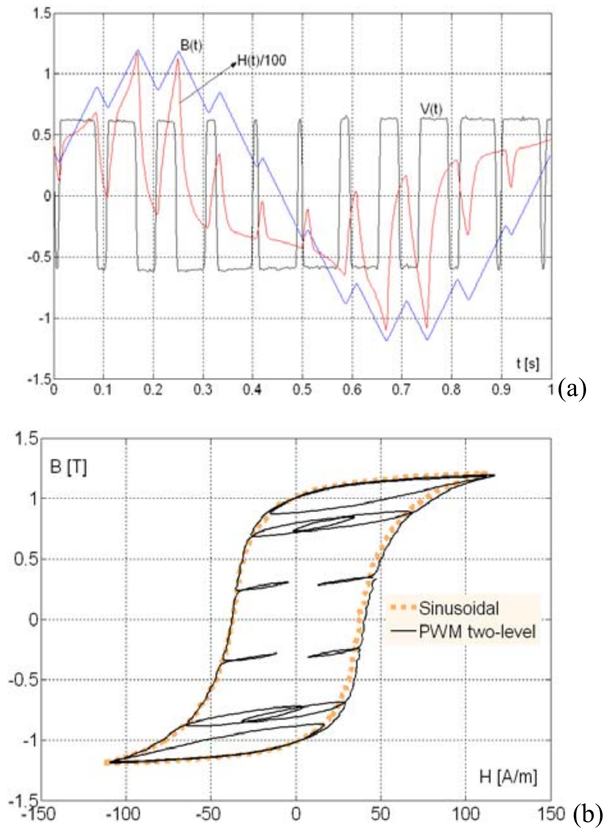
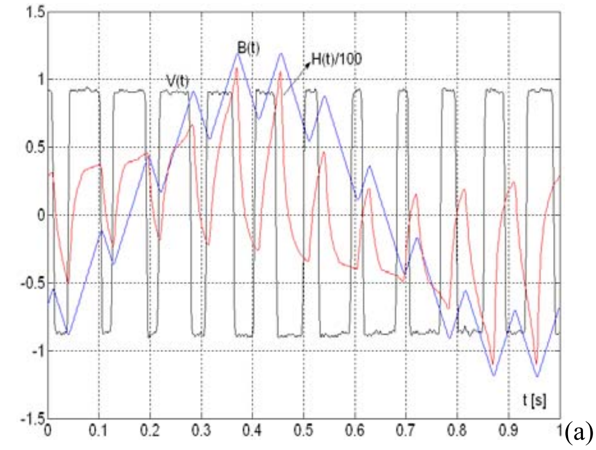
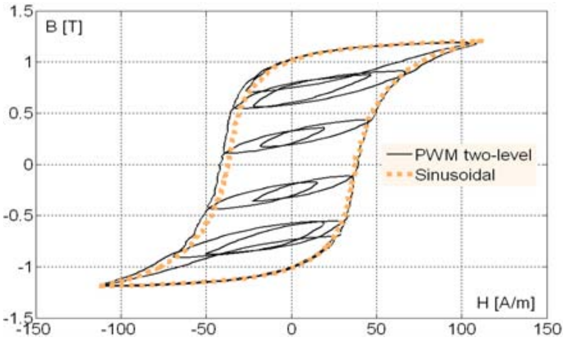


Fig. 6. Results for triangular frequency of 11 Hz and *m*=0.80.
(a) Voltage *v(t),* induction *B(t)* and magnetic field *H(t)* waveforms*;*
(b) hysteresis loops.

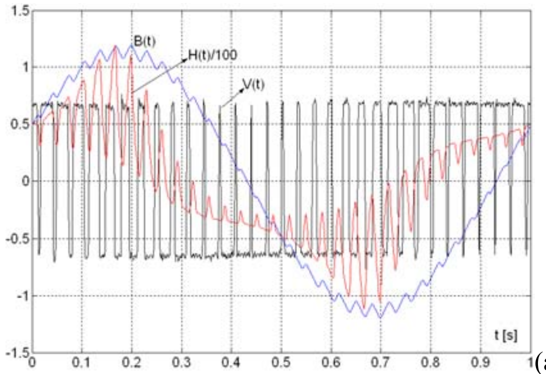




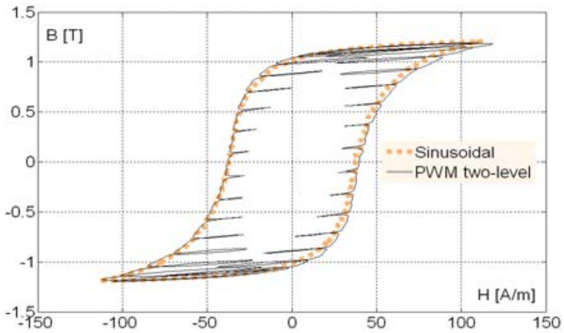
(b)

Fig. 7. Results for triangular frequency of 11 Hz and m=0.50: (a) Voltage $v(t)$, induction $B(t)$ and magnetic field $H(t)$ waveforms; (b) hysteresis loops.

Figure 8 shows the results for a triangular frequency of 31 Hz with a modulation index m equal to 0.80. In Figure 8(b) the hysteresis loops are close for both fed voltage waveforms, but the minor loops are smaller than those presented on Figures 6(b) and 7(b).



(a)



(b)

Fig. 8. Results for triangular frequency of 31 Hz and m=0.80: (a) voltage $v(t)$, induction $B(t)$ and magnetic field $H(t)$ waveforms; (b) hysteresis loops.

One observes that the main (outer) hysteresis loops depend only on the induction peak values and they are not affected by the voltage waveform. In the other hand, the minor loops depend on the voltage waveforms. As a matter of fact, they are closely related to the switching frequency and the modulation index. When the triangular and the sinusoidal reference voltages are synchronized (as in the case of the workbench used in this work) the number of minor loops n can be calculated as function of the triangular frequency (f_{triang}) by the reference frequency (f_{sin}), as

$$n = \left(f_{triang} / f_{\sin} \right) - 1 \qquad (4)$$

D. Losses for sinusoidal and PWM voltages

Figure 9 presents the hysteresis losses as function of the magnetic induction amplitude for sinusoidal, square, triangular and PWM voltage waveforms. The fundamental voltage frequencies were kept at 1 Hz. For PWM voltage waveforms the modulation index is equal to 0.80 and the triangular frequency is 3 Hz. The hysteresis losses to two-level PWM voltage waveform are larger compared to the other waveforms, which is due to the minor loops.

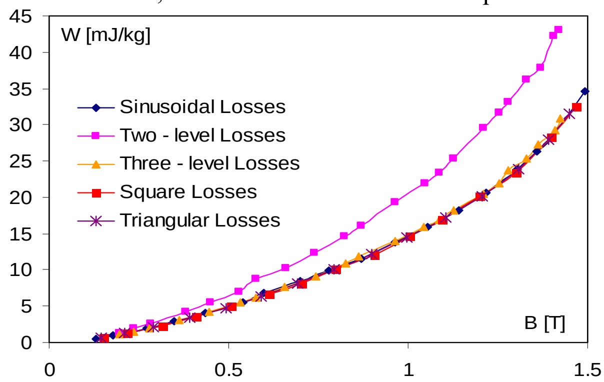


Fig. 9. Hysteresis losses comparison for sinusoidal, square, triangular and two and three-level PWM voltage waveforms.

Figure 10 presents the hysteresis losses as function of the modulation index m for two-level and three-level PWM voltage waveforms. As minor loops do not appear on the three-level PWM voltage waveforms, the hysteresis losses do not depend on the modulation index. Thus, on the two-level PWM voltage waveforms, where there are minor loops, the losses increase with the reduction of the modulation index values. Indeed, the inner loop areas decrease with the rising of modulation index values.

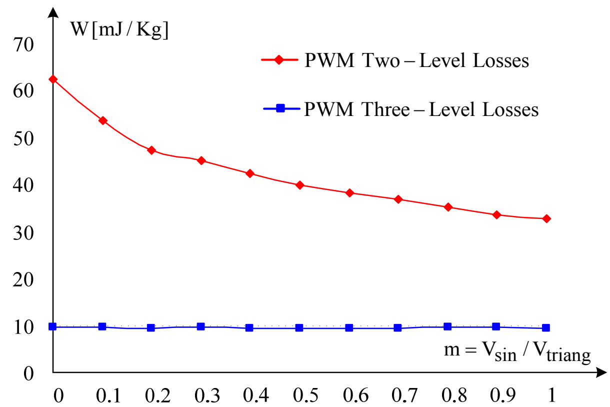


Fig. 10. Hysteresis losses as function of the modulation index m for two-level and three-level PWM voltage waveforms.

IV. CONCLUSION

Square, triangular and three-level PWM voltage waveforms present approximately the same hysteresis losses and they behave similarly to purely sinusoidal voltages. In these waveform types, hysteresis minor loops do not appear. It was observed that hysteresis losses versus modulation index m are constant for three-level PWM voltage (minor loops absence). However, for two-level PWM voltages, hysteresis minor loops occur, while the main hysteresis loops are similar to sinusoidal losses. Experimental results show that the main hysteresis loop does not depend on the shape of applied voltage waveform. Similar main hysteresis loops are obtained with arbitrary or with purely sinusoidal voltage waveforms. For the two-level PWM the hysteresis magnetic losses vary with the modulation index *m,* since the areas of minor loops vary. Also, measured losses increase as the modulation index decreases since larger minor loops appear.

The hysteresis losses depend obviously on the material itself. Nevertheless, the main conclusions here presented can be applied for different materials as, for instance, ferrites.

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BIOGRAPHIES

Claudenei Simão was born in Santa Catarina (09/05/1973), Brazil. He became Electrical Engineer by the Universidade Federal de Santa Catarina (UFSC) in 1999/2. His M. Sc. degree in Electrical Engineering was received from the same university in 2001 (INEP group). In 2008 he concluded his Doctoral Thesis at this institution (GRUCAD group). His interests include magnetic materials, iron losses, hysteresis models, power electronics and electromagnetic experimentation.

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João Pedro Assumpção Bastos was born in Porto Alegre (29/02/1952), Brazil. He became Electrical Engineer by the Universidade Federal do Rio Grande do Sul in 1975. His Docteur d'Etat thesis was obtained in 1984 at the Université Pierre et Marie Curie, Paris VI, France. He started working at the Univ. Fed. De Santa Catarina in 1984 and he is now Full Professor at this university. He was the first president of the SBMAG (Sociedade Brasileira de Eletromagnetismo) and is now its Emerit President. He has published four books on Electromagnetics and Calculations of Fields (2 in Portuguese and 2 in English) and is author of about 250 journal articles and conference proceedings. He has been active as reviewer for the most important journals and conferences in its area. His research specializes mainly on numerical methods and applied Electromagnetics and he has been coordinating relevant projects with research groups in Brazil and abroad.