ANALYSIS OF MAGNETIC HYSTERESIS LOSSES UNDER ARBITRARY VOLTAGE WAVEFORMS

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***Abstract* – This paper analyzes and compares the evolution of magnetic hysteresis losses in iron steel sheets submitted to different supplies: sinusoidal, square, triangular, two and three-level PWM voltage waveforms. The influence of the magnetic induction amplitude, the triangular frequency 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 a flux density sensor.**

***Keywords* - Arbitrary Voltage Waveforms; Eddy current loss; Excess losses; Hysteresis Losses; Hysteresis Loops; PWM Voltage Waveforms.**

I. INTRODUCTION

The iron sheets present hysteresis, eddy current and anomalous losses [1]. With the advent of Power Electronics, the electromagnetic devices became frequently fed by static converters subjecting them to non-sinusoidal voltage waveforms. Some of these waveforms may increase the iron losses when compared to purely sinusoidal voltage [2]. This work complements the conclusions presented in [2].

Non-sinusoidal voltages cause non-sinusoidal magnetic inductions and these inductions lead to more dynamic losses (eddy current and anomalous losses) because they depend on the induction time derivative, as shown in (1).

$$W = W_h + W_d = W_h + \frac{\sigma d^2}{12}\int_0^T \left(\frac{dB}{dt}\right)^2 dt + \sqrt{\sigma GSVo}\int_0^T \left|\frac{dB}{dt}\right|^{3/2} dt \qquad (1)$$

Where W_h is the hysteresis losses and W_d is the dynamic losses (eddy current plus anomalous losses) [3].

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

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

Where:

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

Equation (2) shows that the hysteresis losses are depending on the peak value of the flux density and can be used only if the supply voltage does not produce minor loops in the complete hysteresis cycle. However, under some conditions, magnetic hysteresis losses can also increase. The hysteresis losses increase is associated to the minor loops inside the main hysteresis loop.

One of the aims of the work is to analyze the behavior of the losses under arbitrary voltage waveforms, as well as to investigate the increase in losses due to the minor hysteresis loops for two and three-level PWM voltage waveforms considering the influence of the magnetic induction amplitude, the triangular frequency and the modulation index here defined as

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

Where V_{sin} is the amplitude of the sinusoidal reference voltage and V_{triang} is the amplitude of the triangular carrier signal.

II. THE EXPERIMENTAL WORKBENCH

The experiments were performed in a test workbench developed for characterizing electrical steel sheets [4]. This workbench is basically constituted by a closed loop PWM inverter, an oscilloscope to measure primary current and secondary voltage waveforms, a computer for generating the signals of the arbitrary voltage waveforms reference, calculating the losses, and the Epstein frame (B-EP-25cm - Yokogawa Electric Works Ltd.) where the electrical steel samples are introduced. A feedback loop controls the PWM inverter in order to guarantee the desired voltage waveform on the secondary winding and the free current evolution in the primary winding of the Epstein transformer. Figure 1 presents the scheme of the experimental instrumentation used in this work.

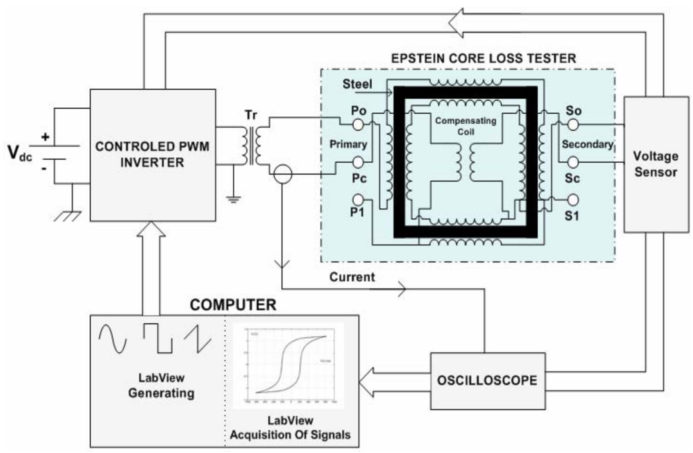


Fig. 1 The workbench used in the experimental investigation.

- Oscilloscope (*2430 Tektronix* ; 150MHz);
- Hall effect current sensor (*A6302 Tektronix* 50MHz and an amplifier *TM502A Tektronix*);
- LabView Virtual Instrument [5].

Twenty eight samples of a non-oriented silicon-steel cut according to the rolling and transversal lamination directions were employed. Table I presents their main characteristics.

TABLE I
Data of the blades

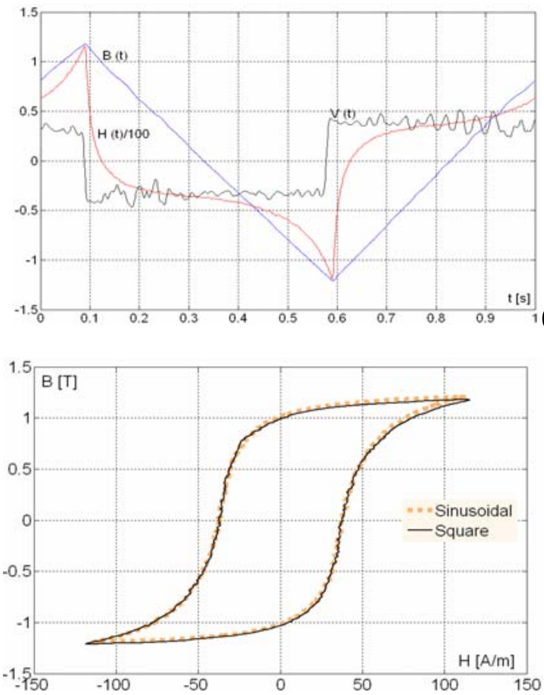
Blades used in the Epstein frame	
Number of sheets in each arm N_l	7
Width of the sheet l_l [cm]	3
Average length of the sheet C_l [cm]	28
Thickness of the sheet d [*mm*]	0,5
Average mass of each sheet [*g*]	32

III. EXPERIMENTAL RESULTS

The experimental results were obtained adopting a 1 Hz fundamental voltage waveform in order to neglect the magnetic dynamic losses (W_d). In this investigation, the maximum value of magnetic induction is 1,2 T. The triangular frequency and the amplitude of the fundamental voltage vary in the experiment. In this way the modulation index and the switching frequency can be modified.

A. Sinusoidal, Square and Triangular voltage waveforms

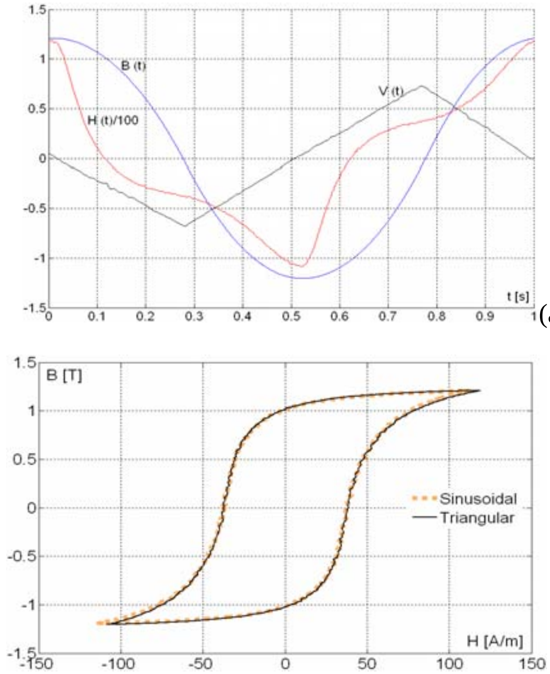
Figure 2(a) shows a result obtained for square voltage waveform, where *v(t)* is the voltage on the secondary winding and *B(t)* and *H(t)* are, respectively, the measured magnetic induction and the magnetic field. Fig. 2(b) gives the corresponding hysteresis loops (*B(t) vs. H(t)*). In this same figure, the hysteresis loop from a purely sinusoidal induction waveform with the same amplitude of the *B(t)* shown in Figure 2(a) is also presented.



(a)
(b)

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

Figure 3 compares the results between sinusoidal and triangular voltage waveforms. It is observed in Figure 2(b) and Figure 3(b) that the losses are the same for triangular and square voltages.

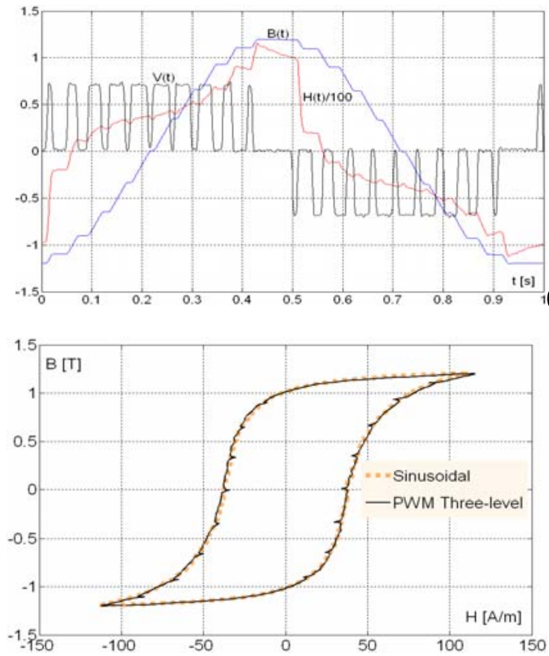


(a)
(b)

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

B. Sinusoidal and three-level PWM voltage waveforms

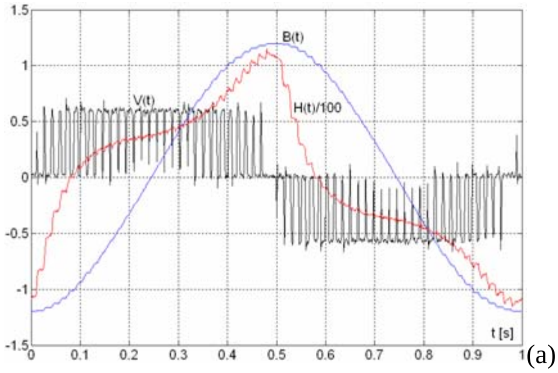
Figures 4-6 show some comparisons obtained between the three-level PWM and a purely sinusoidal voltage waveforms. Figs. 4 and 5 present results for a 11 Hz triangular and modulation index *m*=0.80.



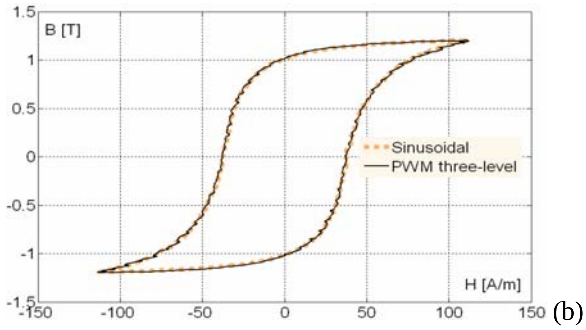
(a)
(b)

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

Figure 5 shows the experimental data when the triangular frequency is changed to 31 Hz and the modulation index to *m*=0.95.



(a)



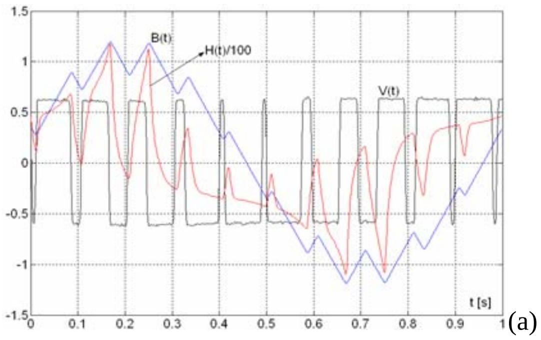
(b)

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

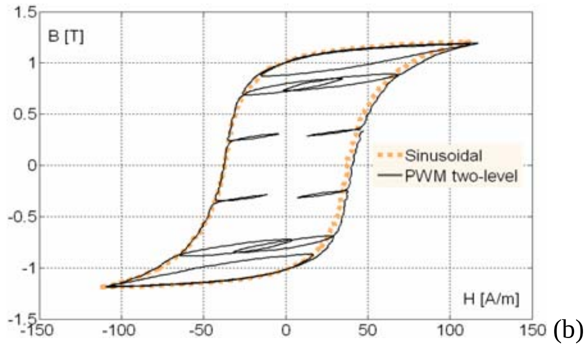
One observes that the three-level PWM operation does not generate minor loops in the complete hysteresis cycle.

C. Sinusoidal and two-level PWM voltage waveforms

The same variations in triangular frequency and modulation index were performed with a two-level PWM waveform imposed on the secondary winding of the Epstein frame. Figs. 6 and 7 correspond to a triangular frequency of 11 Hz and modulation indexes of 0.80 and 0.50 respectively. Contrarily to the results obtained in the previous section, here minor closed loops are presented in the *B(t) vs. H(t)* locii. Comparing to the hysteresis curve obtained with sinusoidal voltages, additional losses were generated in this case.

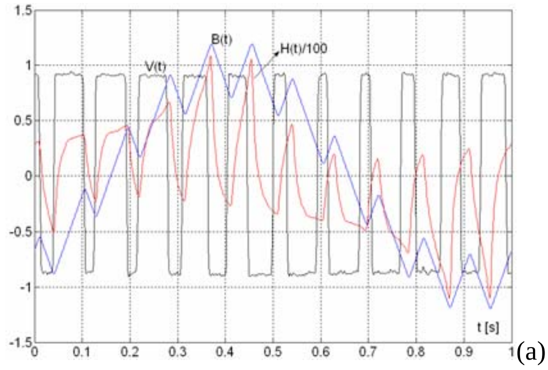


(a)

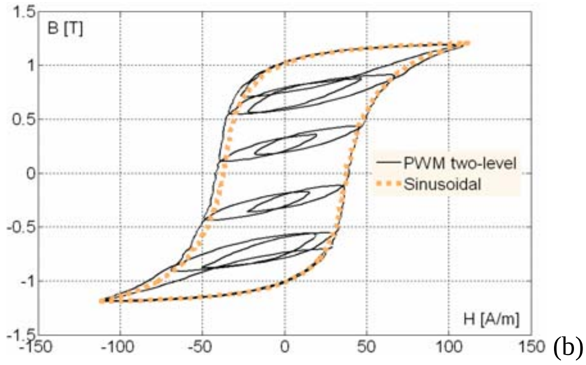


(b)

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



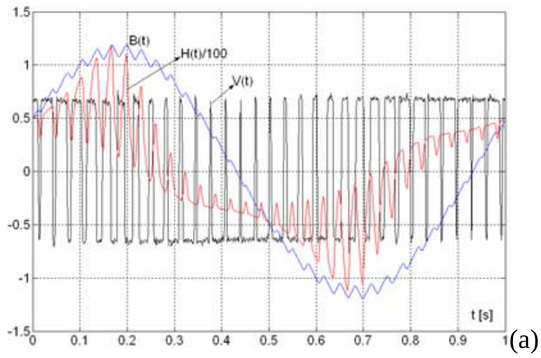
(a)



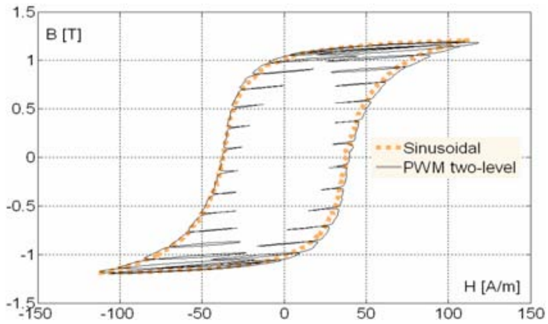
(b)

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

With the frequency equal to 31 Hz and the modulation index *m*=0.80, the voltage, the corresponding obtained induction and field waveforms are shown in Figure 8.



(a)



(b)

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

One observes that the main (outer) hysteresis loop depends only on the peak values of the induction and it is not affected by the voltage waveform. In the other hand, when the triangular and the sinusoidal reference voltages are synchronized (as in the case in the workbench used in this work) the number of minor loops n can be calculated as function of the triangular frequency (f_{triang}) and the reference frequency (f_{sin}) by

$$n = (f_{triang} \ / \ f_{\sin}) - 1 \tag{4}$$

D. Losses for sinusoidal and PWM voltages

The variation of the hysteresis losses as function of the magnetic induction amplitude for sinusoidal, square, triangular and PWM voltages waveforms are shown in Figure 9. In these results, the fundamental of the PWM voltages frequency is 1 Hz. For PWM voltage the modulation index is 0.80 and the triangular frequency is chosen as 3 Hz.

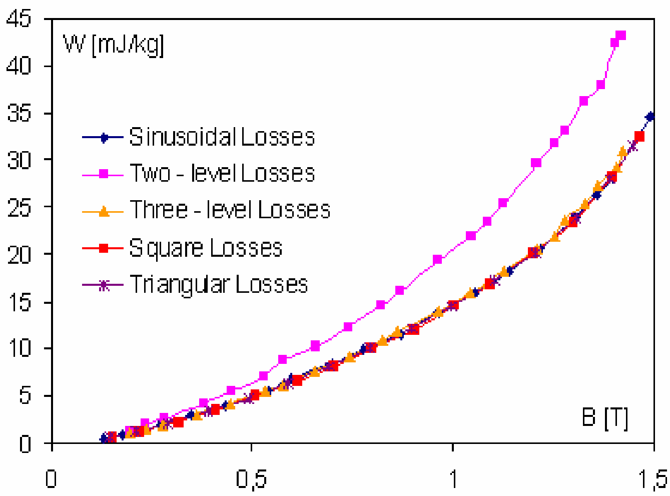


Fig. 9 Comparison between losses for sinusoidal, square, triangular and two and three-level PWM voltage waveforms.

As presented in [6], the hysteresis losses as function of the modulation index m for two-level and three-level PWM voltage are shown in Figure 10.

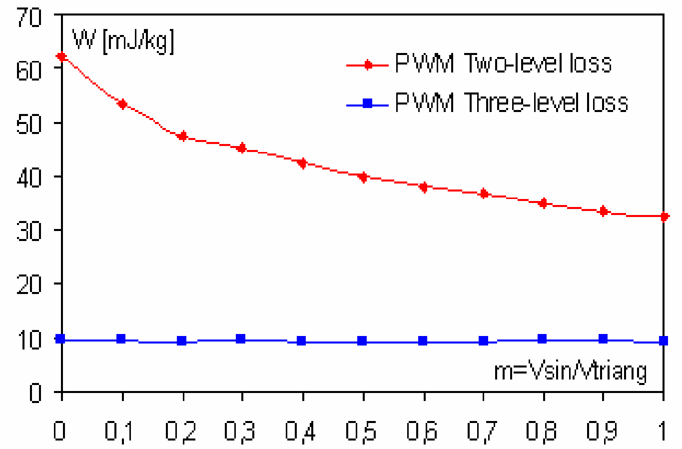


Fig. 10 Hysteresis losses as function of the modulation index m for two-level and three-level PWM voltage.

IV. CONCLUSION

Square, triangular and three-level PWM voltage waveforms (Figures 2-5) present, approximately, the same hysteresis losses and they are similar to those related to a purely sinusoidal voltage. It was observed that histeresis losses versus modulation index m are constant for three-level PWM voltage (the absence of minor loops). However, for two-level PWM voltages (see Figures 6-8) minor loops appear, although the main hysteresis loops are similar to those of sinusoidal case. It can be seen that the hysteresis magnetic losses for the two-level PWM vary with changes in the modulation index m. This is due to the area variation of the minor loops. The measured losses increase as the modulation index decrease (Figure 10) because larger minor loops appear.

The increase of hysteresis losses (compared to that resulting from sinusoidal voltages) occurs only for two-level PWM waveforms. The hysteresis losses under square, triangular and three-level PWM operation are identical to sinusoidal hysteresis losses. Experimental results show that the main hysteresis loop does not depend on the applied voltage waveform, i.e., similar main hysteresis loops are obtained with arbitrary or a purely sinusoidal voltage waveform. Finally, let us point out that the hysteresis losses depend obviously on the used material, but the conclusions can be applied for other materials, for example, ferrites.

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