Hysteresis Losses Evaluation in Electromagnetic Devices under Non Sinusoidal Induction Waveforms

D.C.S. do Prado, P. Kuo-Peng, N.sadowski and N.J. Batistela,
GRUCAD/EEL/CTC/Universidade Federal de Santa Catarina CP476 CEP 88040-970 Brazil
dcufsc@yahoo.com.br, patrick.kuo.peng@ufsc.br, nelson.sadowski@ufsc.br, jhoe.batistela@ufsc.br

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 with simplified methods. The needed parameters are extracted automatically from the original applied induction waveform using a cycle counting algorithm developed by the authors. Comparison between calculated and measured results shows the validity of the proposed method.

Index Terms—Cycle Counting algorithm, Hysteresis Loss, Non Sinusoidal Induction Waveform.

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. Iron losses can be expressed as the sum of hysteresis loss, dynamic or eddy current loss and anomalous or excess loss [3]-[4]. So, if the applied voltage is sinusoidal, there are no minor loops in the main cycle and the hysteresis losses can be determined from the Steinmetz equation given by:

\[ P = K_H \left(\frac{\Delta B}{2}\right)^\alpha \left[\frac{J}{K_g}\right] \]  (1)

Where \( \Delta B \) is the peak to peak induction amplitude, \( K_H \) and \( \alpha \) are parameters to be determined by curves fitting algorithm using measurements data. However, in most cases, electromagnetic devices are fed by non sinusoidal waveforms, where minor loops become significant. As the result, the classical hysteresis loss calculation method using (1) must be modified or adapted to take into account these minor loops as well as the influence of the DC bias [5]-[11]. For this purpose, in [12]-[13], the authors suggest a generalization of (1) which involves the sum of every parcel corresponding to major and minor loops in the cycle:

\[ P_{dc} = \sum_{i=1}^{N+1} K_H \left(\frac{\Delta B_i}{2}\right)^\alpha \left[1 + 0.65 B_{dc}^{2\alpha+1}\right]\left[\frac{J}{K_g}\right] \]  (2)

Where \( N \) is the number of harmonics, \( \Delta B \) is the peak to peak induction amplitude of each harmonic and \( B_{dc} \) is their DC induction level. Thus, this approach involves the Fourier transform of the applied
induction and as shown in [13], it leads to better results in comparison with results obtained using (1). Nevertheless, these results lack accuracy when compared with experimental data. So, in order to improve these results, the authors propose an algorithm to extract parameters $\Delta B_i$ and $B_{dc}$ of equation (2) directly from the applied induction waveforms without performing its Fourier transform. In this case, $N$ represents the number of induction reversals and $\Delta B_i$ is the peak to peak induction amplitude of major and minor loops. Recursive algorithms to identify major and minor loops have been proposed, for instance, in [8]. Nevertheless, the proposed core losses calculation does not consider the influence of the DC bias. In section II, by a simple example, it is demonstrated that applying Fourier Transform analysis to a non sinusoidal induction leads to overestimate or underestimate the hysteresis loss compared with measurements. In section III, the algorithm to identify major and minor loops as well as parameters $\Delta B_i$ and $B_{dc}$ of equation (2) is presented. Finally, section IV shows comparison between calculated and measured hysteresis losses to justify the proposed approach.

II. COMPARATIVE HYSTERESIS LOSSES EVALUATION

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 $\alpha$ of this electromagnetic device are respectively 0.015 and 1.617.

Fig. 1. Applied Induction Waveform.

Fig. 2. Fourier Transform of the applied Induction Waveform.

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

Parcel 1 – Referred to pure sine wave:

Parcel 2 – Referred to third harmonic components:

Resulting in:

On the other hand, analyzing Fig.1, we can intuitively deduce that the applied induction waveform results in a principal hysteresis loop and two reversals. $\Delta B$ of the principal hysteresis loop is 2.828 T and its DC level is null. The minor loops peak to peak induction are both equal to 0.414 T and their
DC level is 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:

\[ L = \frac{1}{2} B_{dc} \Delta B \int_{0}^{2\pi} (H - H_0) \, d\phi \]

The total hysteresis loss is:

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

III. MAJOR AND MINOR LOOPS IDENTIFICATION ALGORITHM

The major and minor loops, as well as parameters \( \Delta B_i \) and \( B_{dc} \) of equation (2) identifications are based on a cycle counting algorithm called Rainflow algorithm [14]. The Rainflow cycle counting algorithm is widely used in mechanical engineering to estimate fatigue life in structures. In this case, the input of the algorithm is the stress versus time curve, while in this study the input is the applied induction versus time waveform. Note that in electrical engineering, the applied induction waveforms are in most case periodic (Fig. 3). The voltage which generates this induction is also presented in Fig. 3.

![Fig. 3. Example of applied voltage on an electromagnetic device and its corresponding induction waveform.](image)

A. Concept of the Rainflow method

The Rainflow cycle counting method is illustrated in Fig.4 where the induction waveform of Fig. 3 is rotated 90 degrees clockwise. Therefore, one can imagine that the induction peaks represent the edges of a pagoda roof where the rain can drip down. Rainflows start at each valley (points A, C, E, G, I, K, M and O) and at each peak (points B, D, F, H, J, L and N) complying to the following rules...
[16]:

- The Rainflow initiating at each valley must stop when it reaches a valley that is less or equal to from which it initiated. For example, Rainflow starting at valley I must stop at valley K. However, Rainflow beginning at valley A continue to drip down until valley I.

- Similarly, the Rainflow initiating at each peak must stop when it reaches a peak that is higher or equal to from which it initiated. For example, Rainflow starting from peak B must stop at peak D.

- A Rainflow must also stop when it meets another flow from above and in this case a reversal or a minor loop is detected. This is the case of Rainflows starting at valley C or peak H.

The hysteresis major and minor loops associated to waveform of Fig.4 are presented at Fig.5.

Fig. 4. Rainflow cycle counting method applied to a periodic induction waveform

Fig. 5. Hysteresis major and minor loops related to induction waveform of Fig.4

The original Rainflow algorithm has been used by the authors to evaluate and to analyze iron losses in electrical machines [16]. However, it is necessary to point out that the computational implementation of the original algorithm is not an easy task. Therefore, based on the original Rainflow method, a simpler algorithm which is well adapted to periodic waveforms (as is the case of waveforms applied to most of electromagnetic devices) is proposed and detailed as follow.

B. The developed algorithm

The developed program starts by reading an induction versus time curve and all the original data are adjusted in order to fit the first induction point at zero value. This is only to ease the detection of the waveform period since the developed algorithm assumes that the zero crossing of the waveform is likely the end of a cycle. Obviously, the original value of the induction is used to calculate the needed parameters of (2). Thus, to identify a period, at each zero crossing of the signal, variation of maximum and minimum induction in the interval between the first point and that zero crossing point ($\Delta B_0$) is calculated. $\Delta B_0$ is then compared to the variation of the global maximum and minimum induction ($\Delta B_T$) of the waveform. If $\Delta B_0$ is close to $\Delta B_T$, that zero crossing point is considered the end of a
cycle and a major loop is detected. Then the program identifies all peaks and valleys of the waveform. As the waveform is periodic, the minor loops or the reversals are identified only in one period and it is performed as follow:

For each peak \((B_p, t_p)\) the algorithm checks if at \(t < t_p\) (left side of \(B_p\)) and at \(t > t_p\) (right side of \(B_p\)) there is any inductions \((B_{pc})\) which value is greater or equal to \(B_p\). If these points \((B_{pc})\) exist then:

a) if the valley at the right side of the considered peak \((B_p)\) is less than the valley at its left side, then the minor loop closes at the induction \((B_{pc})\) at the left side of \(B_p\). If there is no \(B_{pc}\) at the left side then the minor loop closes at the right side of \(B_p\).

b) If the valley at the right side of the considered peak \((B_p)\) is greater or equal to the valley at its left side, then the minor loop closes at the induction \((B_{pc})\) at the right side of \(B_p\). If there is no \(B_{pc}\) at the right side then the minor loop closes at the left side of \(B_p\).

c) If that induction \((B_{pc})\) have been already taken into account, then the closing cycle is chosen at the next non considered \(B_{pc}\) at the same side.

On the other hand, if any inductions \(B_{pc}\) are found either at the right and left side of \(B_p\), then no closed loop is detected from that peak.

For illustration purpose, let’s apply these rules to the waveforms presented in Fig.4 and Fig.6 to show how the minor loops or reversals are detected.

Fig. 6. Hypothetic periodic induction waveform

In Fig.4, starting from peak B, according to rule b), a reversal \((BCB'B)\) is found at the right side of peak B. \(\Delta B\) of this reversal is identified as the difference between peak B and valley C. For peak D, as for peak B, a reversal \((DEFD)\) is found at its right side. For peak F, according to rule a), a minor loop should close at its left side (at peak D). However, this minor loop has been already considered. So according to rule c), the program searches for the next \(B_{pc}\) in the same direction (in this case at the left side). As such point does not exist, so no minor loop is computed from peak F. For peak H, according to rule a), the minor loop \(HG'GH\) can be identified. Applying the same rules for the negative half period of the induction waveform presented in Fig.4, it can be easily verified that the proposed algorithm found all minor loops and their corresponding \(\Delta B\) and \(B_{dc}\) identified by the Rainflow
method. Unlike the Rainflow method, the developed counting cycle algorithm identifies minor loops only from the peaks simplifying its programming.

Now, let’s determine the minor loops of the waveform presented at Fig.6. For peak B, according to rule b), a minor loop is found closing at peak F. The corresponding $\Delta B$ is the difference between peak B and valley C. As for peak B and according to rule b), the minor loops identified from peak D and F close respectively at D’ and peak J and their corresponding $\Delta B$ are respectively the difference between peak D and valley E and the difference between peak F and valley I. For peak H, following rule a), a minor loop is found closing at H’ and its corresponding $\Delta B$ is the difference between peak H and valley G. From peak J, using rule b), a reversal is found closing at J’ and its corresponding $\Delta B$ is the difference between peak J and valley K. For peak L, according to rule a), the minor loop should close at the left side of peak L. As there is no induction greater or equal of the induction of peak L at this side, the minor loop closes at the right side at peak N. For this minor loop the $\Delta B$ is identified as the difference between peak L and valley M. At peak N, according to rule b), the reversal should close at its right side. Nevertheless there is no induction greater than peak N induction at this side. Thus the algorithm checks at the left side of peak N and theoretically a minor loop can close at peak L. But as this minor loop have been already taken into account, according to rule c) the algorithm must search for another next point at the left side of peak N. As there is no such point, no minor loop is computed from peak N. For peak P, following rule b) a reversal is found closing at peak R and the corresponding $\Delta B$ is the difference between peak P and valley Q. Finally for peak R, according to rule a), a minor loop should close at peak P. As this minor loop has been already considered, the algorithm searches for another closing point at the same direction. This, results to consider point P’ as the closing point of the reversal found from peak R. In this case, the $\Delta B$ is the difference between peak R and valley O. Again, all minor loops and their corresponding $\Delta B$ and $B_{dc}$ identified are the same as those identified by the Rainflow method.

The flowchart of the developed counting cycle algorithm is presented in Fig.7.
IV. RESULTS

In order to validate the proposed methodology, non oriented electrical steel sheets are submitted to three different waveforms (Fig.8, Fig.10 and Fig.12) and its respective hysteresis losses are calculated using the two approaches presented in the section above. For clarity purpose, experimental hysteresis loop associated to each waveform is respectively presented in Fig.9, Fig.11 and Fig.13. However, it is important to notice that parameters $\Delta B$ and $B_{dc}$ needed to evaluate hysteresis losses with (2) are determined from the induction waveform (Fig.8, Fig.10 and Fig.12) using the algorithm presented above. 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. Note that for the studied steel sheets, parameters $K_H$ and $\alpha$ of (2) are respectively 0.015 and 1.617. The measured hysteresis losses are determined by a dedicated workbench described in the appendix [15].

Table I shows that for all waveforms, results obtained by the proposed methodology are closer to the experimental ones than using Fourier decomposition method.

For waveform III, the difference between computed and measured results is significantly higher because for this case, its harmonic content is higher and, despite of its fairly low fundamental frequency, higher harmonics originate dynamic losses detected in the experimental measurements which are not considered in the modeling that only takes into account the static hysteresis power dissipation. To consider this losses increasing, eddy current losses should be incorporated in the modeling [17].
V. CONCLUSION

In this paper, the authors propose a more accurate technique to evaluate hysteresis losses in electromagnetic devices under DC biased condition or fed by non sinusoidal induction waveform. Unlike classical method where the Fourier decomposition is applied to the feeding waveform to extract the needed parameters, the proposed methodology identifies these parameters directly from the induction waveform. For that purpose, a counting cycle algorithm is developed. This is the main contribution of this work besides the fact that the losses evaluation procedure remains simple when compared to other ones with higher accuracy but requiring the description of the B(H) cycle as, for instance, the Jiles-Atherton or the Preisach’s models. Observe that it can also easily be incorporated in a posteriori losses calculation by FE methods. Finally, comparisons between hysteresis losses obtained by the proposed technique with those calculated with classical method (Fourier decomposition) and measurements show the validity of the work as presented in Table I.

APPENDIX

The experimental workbench (Fig. A and Fig. B) consists in a PWM voltage inverter, filters to reduce harmonic contents caused by the PWM control, oscilloscope to measure voltage and current waveforms, a computer to generate reference signals, a computer for data acquisition and an Epstein frame (B-EP-25cm - Yokogawa Electric Works Ltda.) where the studied steel sheets are introduced. The converter allows imposing instantaneously the desired voltage waveform on the secondary winding of the Epstein frame. In this way, the current in the primary winding can freely evolve.

<table>
<thead>
<tr>
<th>Waveform</th>
<th>Losses [mJ/kg]</th>
<th>Difference between measured and calculated values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waveform I</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measured</td>
<td>21,177</td>
<td>-</td>
</tr>
<tr>
<td>Proposed Methodology</td>
<td>21,273</td>
<td>0.45%</td>
</tr>
<tr>
<td>Fourier Decomposition</td>
<td>21,805</td>
<td>2.97%</td>
</tr>
<tr>
<td>Waveform II</td>
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<td></td>
</tr>
<tr>
<td>Measured</td>
<td>28,234</td>
<td>-</td>
</tr>
<tr>
<td>Proposed Methodology</td>
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<td>-3.39%</td>
</tr>
<tr>
<td>Fourier Decomposition</td>
<td>33,728</td>
<td>19.46%</td>
</tr>
<tr>
<td>Waveform III</td>
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<td></td>
</tr>
<tr>
<td>Measured</td>
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<td>-</td>
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<td>Proposed Methodology</td>
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<td>Fourier Decomposition</td>
<td>21,613</td>
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Fig. A. Experimental workbench: schematic diagram.

Fig. B. Experimental workbench: photography
REFERENCES


