Effect of Voltage Harmonics on Iron Losses in Magnetic Cores with Hysteresis

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Abstract— The effect of distorted voltage waveforms on the iron losses, considering the magnetic hysteresis, is quantitatively studied, using an accurate losses separation method and a time-integration for each component. The model parameters, including the Preisach hysteresis function, are identified by magnetic measurements. A case-study, implying measured electric power quality data in a metal processing and thermal treatment facility, is presented to outline the consequences of a non-sinusoidal regime on iron losses in high power low-voltage motors with rated power between 132 kW and 200 kW. Three sorts of standard FeSi non-oriented electrical sheets (M330-50A, M400-65A and M700-65A) were considered for the motor magnetic core. The iron losses, estimated both for non-saturated and saturated core regions, rise with 11-35 % for the measured non-sinusoidal voltage having 7.6% total harmonic distortion.

Index Terms — Iron losses, Magnetic cores, Power quality, Voltage harmonics, Preisach hysteresis model.

I. INTRODUCTION

The continuously spreading of nonlinear loads and the new regenerable energy plants, involving complex storage systems, generates new issues related to the power quality and its economic consequences. Indeed, the harmonics' presence in electrical networks influences all the connected consumers, rising the losses, changing the operating parameters and reducing life time expectation for devices, generally designed for a sinusoidal supply. The existing international standards [1] try to control the various power quality parameters which assure a normal functioning of devices, under their rated parameters values. Unfortunately, an accurate analysis must consider more parameters than the standardized ones. For example, the total harmonic distortion (THD) is computed as function of the harmonics amplitudes, ignoring their initial phases. Consequently, the distorted shapes of signals having the same THD are different, generating different results for time-integration methods [2].

The specific iron power losses (in W/kg), averaged for a period $T$, are estimated using the Bertotti’ theory [7]:

$$ P = P_h + P_c + P_e, $$

(1)

where the three components – hysteresis loss $P_h$, classical loss $P_c$, excess loss $P_e$ – are computed by time-integration [8]:

$$ P_h = \frac{1}{\rho T} \int_{0}^{T} H \cdot \frac{dB}{dt} dt $$

(2)

consumers [3], [4]. An optimal load could be decided using quantitatively simulations, a critical parameter being the losses [5], which could be estimated by Steinmetz theory [6].

Our study is focused on the accurate prediction of the iron losses in magnetic cores. The magnetic losses separation proposed by Bertotti [7] is used to compute the hysteresis loss, the classical (eddy currents) loss, and the excess loss for standard magnetic materials (FeSi non-oriented sheets) used for high power low-voltage motors, which are connected to a distorted voltage measured in an industrial plant. The losses are precisely computed using a time-integration technique [8] and models with parameters accurately identified [9]. The magnetic core behavior is obtained by an inverse Preisach hysteresis model, which was improved for a non-sinusoidal voltage (model input) [10]. The presented case-study starts from in-situ measurements of power quality data and from laboratory magnetic measurements on three sorts of FeSi electrical sheets. The results show the detailed loss rising for each loss component and for each magnetic material sort, under moderate distorted voltage (THD=7.6%). The influence of the harmonic initial phases is outlined, showing why THD is not sufficient for the accurate iron loss estimation.

II. NUMERICAL METHOD FOR ESTIMATING IRON LOSSES

A numerical simulation by commercial software packages can generate the value of the magnetic induction $B(t)$ in each device point, for every value of the applied voltage $u(t)$. The $B(t)$ series is treated as the input for an inverse Preisach hysteresis model, generating the corresponding values of the model output - the magnetic field strength $H(t)$.

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(1)

where the three components – hysteresis loss $P_h$, classical loss $P_c$, excess loss $P_e$ – are computed by time-integration [8]:

$$ P_h = \frac{1}{\rho T} \int_{0}^{T} H \cdot \frac{dB}{dt} dt $$

(2)
The accuracy of the proposed iron losses estimation is based on a proper parameters fitting, starting from an extended set of measured losses for sinusoidal regime (see Fig. 3 for M700-65A material) and using higher-order fitting polynomials [10].

\[
P_e = \frac{\sigma l^2}{8\rho T} \int_{0}^{T} \left[ B(t) \frac{dB}{dt} + \left( \frac{dB}{dt} \right)^2 \right] dt
\]

\[
P_e = \frac{1}{\rho T} \int_{0}^{T} H_e \frac{dB}{dt} dt
\]

The parameters involved in (2) - (4) are: mass density \( \rho \), electrical conductivity \( \sigma \), the maximum value of \( B(t) \) during a period \( B_{\text{max}} \), the FeSi sheet thickness \( d \), and the excess field \( H_e \) computed by:

\[
H_e = \frac{n_0 V_0}{2} \left( \frac{1}{\sqrt{1 + \frac{4\sigma Gdl}{n_0^2 V_0^2} \frac{dB}{dt}}} - 1 \right),
\]

where \( G=0.1356 \) is a microscopic geometrical parameter [7], \( l \) is the sheet width, and the parameters \( n_0 \) and \( V_0 \) are identified [10] starting from the measured losses for sinusoidal waveforms at various frequencies \( f \) and amplitudes \( B_{\text{max}} \).

The experimental data used to identify the above parameters, including the Preisach hysteresis function, are obtained by standardized measurements using an industrial single sheet tester (SST). For example, the major hysteresis loops for the used FeSi non-oriented sheets are presented in Fig. 1, while Fig. 2 shows a family of symmetrical hysteresis cycles measured at \( f=50 \) Hz for M700-65A material.

III. IRON LOSSES COMPUTATION FOR MOTORS UNDER NON-SINUSOIDAL VOLTAGES – CASE STUDY

To exemplify the suggested method for the computation of additional losses in magnetic materials caused by the voltage high order harmonics, a heavy industrial electric installation that operates under non-sinusoidal voltage and current conditions was selected (a metal processing and thermal treatment facility). This mainly comprises high power low-voltage AC and DC drive motors with rated power between 132 kW and 200 kW and a DC welding machinery of 250 kW. These loads are either nonlinear being controlled by different rectifiers and adjustable speed drives or simple linear when only start-up voltage changers are used (autotransformers). These loads are being supplied by a dry-type distribution transformer of 1600 kVA, as it is presented in Fig. 4.
The main electric power quality data were measured with a high precision analyzer (Fluke 435 [11]) connected at the point of common coupling of the electric panel that supplies both linear and nonlinear loads. The measured phase voltages and currents waveforms along with the corresponding harmonic spectrum histograms are presented in Figs. 5-8. Figure 9 depicts the measured absorbed active, reactive and apparent power with the associated power factors.

Each voltage harmonic could have another initial phase and the same THD value will correspond to various distorted waveforms. For example, if one considers a maximal value of 1 T for the maximum applied sinusoidal voltage, three non-sinusoidal waveforms having THD=7.6% could be observed in Fig. 10, keeping the same amplitude (1T) for the fundamental harmonic. The symmetrical and the asymmetrical curves are generated using the same harmonics as the measured distorted voltage, but the initial phases are identical for all the harmonics (π/2), or changed (-π/10) for 5th and 7th harmonics, respectively. The local peaks will generate minor hysteresis loops, as for the asymmetrical distorted waveform – see Fig. 11 for M700-65A material – and the iron losses will be changed, as one presents in Section IV.
The numerical tests consider both non-saturated and saturated zones of the motor magnetic core. Consequently, the losses estimation uses two values for the amplitude of the fundamental harmonic: $B_{\text{max}} = 1\, \text{T}$, and $B_{\text{max}} = 1.5\, \text{T}$, respectively. The model parameters are identified for three sorts of standard FeSi non-oriented electrical sheets: M330-50A, M400-65A and M700-65A. All the experimental data were obtained in our Laboratory of Technical Magnetism, using an industrial single sheet tester (SST Brockhaus®).

The proposed estimation method was verified for sinusoidal voltages, comparing the computed and the measured iron losses for a single sheet sample. The computed losses are presented in Figs. 12-14, the components structure (hysteresis / classical / excess losses) being able to help us to understand the various mechanisms and correlations in the additional losses generation, if the applied voltage is distorted.

The results show an increasing of the total iron losses under non-sinusoidal voltages by 32-35% for $B_{\text{max}}=1\, \text{T}$, and 10-13% for $B_{\text{max}}=1.5\, \text{T}$, respectively, reported to the standard sinusoidal regime. The details are presented in Table I for the relative losses increasing $\Delta P_h$ (hysteresis loss), $\Delta P_c$ (classical loss), $\Delta P_e$ (excess loss), and $\Delta P$ (total loss).

<table>
<thead>
<tr>
<th>Material</th>
<th>$B_{\text{max}} = 1, \text{T}$</th>
<th>$B_{\text{max}} = 1.5, \text{T}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\Delta P_h$ [%]</td>
<td>$\Delta P_c$ [%]</td>
</tr>
<tr>
<td>M330-50A</td>
<td>22.6</td>
<td>48.6</td>
</tr>
<tr>
<td>M400-65A</td>
<td>21.8</td>
<td>48.6</td>
</tr>
<tr>
<td>M700-65A</td>
<td>22.5</td>
<td>48.6</td>
</tr>
</tbody>
</table>

The most part of the difference in additional losses for non-sinusoidal voltage, between various magnetic materials, comes from the excess losses, which depend on the material microstructure.

**IV. INFLUENCE OF THE HARMONICS’ INITIAL PHASES ON IRON LOSSES**

The standardized parameter THD is not sufficient for estimating the additional iron losses for non-sinusoidal voltages. Indeed, similar distorted waveforms, having the same THD=7.6% and presented in Fig. 10, generate various iron losses in the tested soft magnetic materials. The results presented in Fig. 15 for non-saturated magnetic cores ($B_{\text{max}}=1\, \text{T}$) show differences between the losses produced by symmetrically and asymmetrically distorted waveforms. The empiric estimation of the additional hysteresis losses by the amplitude of the minor loops [12] fails: only the symmetrical non-sinusoidal waveform produces minor hysteresis loops, but the losses are smaller than the other two distorted voltages.
The detailed structure of the computed losses is presented in Table II, allowing a proper device derating for non-sinusoidal voltages. A proper design or acquisition are also facilitated, the user choosing the FeSi sheet sort which is adequate (from losses point of view) to the power quality characteristics of the local electric network.

<table>
<thead>
<tr>
<th>Material:</th>
<th>Components of Iron Losses (in [W/kg]) for Sinusoidal and Non-sinusoidal Voltages</th>
</tr>
</thead>
<tbody>
<tr>
<td>M330-50A</td>
<td></td>
</tr>
<tr>
<td>Waveform</td>
<td>$B_{\text{max}}=1 \ T$</td>
</tr>
<tr>
<td>Sinusoidal</td>
<td>$P_P$</td>
</tr>
<tr>
<td>Non-sinusoidal, measured</td>
<td>0.75</td>
</tr>
<tr>
<td>Non-sinusoidal, symmetrical</td>
<td>0.92</td>
</tr>
<tr>
<td>Non-sinusoidal, asymmetrical</td>
<td>0.98</td>
</tr>
<tr>
<td>Sinusoidal</td>
<td>0.81</td>
</tr>
<tr>
<td>M400-65A</td>
<td></td>
</tr>
<tr>
<td>Sinusoidal</td>
<td>0.94</td>
</tr>
<tr>
<td>Non-sinusoidal, measured</td>
<td>1.14</td>
</tr>
<tr>
<td>Non-sinusoidal, symmetrical</td>
<td>1.21</td>
</tr>
<tr>
<td>Non-sinusoidal, asymmetrical</td>
<td>1.02</td>
</tr>
<tr>
<td>M700-65A</td>
<td></td>
</tr>
<tr>
<td>Sinusoidal</td>
<td>1.24</td>
</tr>
<tr>
<td>Non-sinusoidal, measured</td>
<td>1.52</td>
</tr>
<tr>
<td>Non-sinusoidal, symmetrical</td>
<td>1.60</td>
</tr>
<tr>
<td>Non-sinusoidal, asymmetrical</td>
<td>1.36</td>
</tr>
</tbody>
</table>

Figure 15. Computed iron losses for $B_{\text{max}}=1 \ T$.

V. Conclusions

The presented results show the importance of an accurate computation of each component of the iron losses, by time-integration methods, especially for distorted waveforms. The proposed procedure for the iron losses estimation uses an efficient inverse hysteresis Preisach model and a losses separation based on high-order fitting polynomials for the model parameter identification. The accurate computing method allows a better estimation of iron losses in magnetic cores for non-sinusoidal working conditions. An advantage is the use of the voltage, related to the magnetic induction, as the model input, which is compatible with any electromagnetic analysis software working in vector magnetic potential. An extension to grain-oriented soft magnetic cores, as in transformers, involves a vector hysteresis model, but a primary estimation of iron losses could use the presented method.

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