Influence of the cut angle and grain size on the behavior of non-oriented magnetic steels

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This paper shows the use of the Modified Scalar Preisach Model (MSPM) in order to describe static hysteresis losses of non-oriented magnetic steels for different grains size and cut angles with respect to the easy axis. A main result of this research shows that the Lorentzian used as approximation of Preisach function in the MSPM, yields good quantitative agreement with numerical Preisach function computed by means of the experimental magnetization symmetric loops in a set of non-oriented magnetic steels. Finally, theoretical static losses computed will be presented.

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1 Introduction

The design of the modern electric power devices requires increasing attention to their efficiency. Motors, transformers, and other transducers using magnetic materials, have two kinds of magnetic power losses: hysteresis and eddy currents [1]. Referring to the design of rotating machines the knowledge of the behavior of non-oriented magnetic steels (used as core materials) is important in order to determine the static hysteresis losses. A general theory that describes in complete way this behavior is very complex because it depends by grains size and cut angle with respect to the easy axis [2–4]. In this paper, we discuss about the static losses computation on the magnetic materials with several grains size and cut angles, using as tool the Modified Scalar Preisach Model (MSPM) in order to describe the hysteresis behavior. An advantage of this model is the possibility to treat the independence of the switching probability. Preliminary considerations, from the measurements of a few non-oriented soft steel samples, seems to indicate that the shape of the Lorentzian function, and in particular, the slope of its ascending and descending parts satisfactory fit the experimental behavior [5, 6]. In the next section, we present a brief description of the mathematical formulation of the MSPM and its identification. Next, we will show that the results obtained are in good agreement with the experimental data measured on non-oriented soft steels for different both grains size and cut angles. Lastly, using the MSPM, the static losses will be computed for fixed maximum applied field and for fixed maximum magnetization, on two different non-oriented magnetic steels.

2 Theory

From the physical viewpoint, irreversible and reversible magnetization have clearly distinct connotations: irreversible processes, responsible for the energy losses, are associated with the domain instabili-
ties. On the other side, reversible processes are associated with the energy stored and released, but not dissipated by the system during the magnetization process. This physical picture does not find a natural and sufficiently general description in the Preisach Model frame, where the development of tools for the separate treatment of the total magnetization leads to non-trivial complications. This problem is over passed by using the MSPM, where the irreversible part of the magnetization is independent from the reversible one. The MSPM is a differential magnetization dependent model of the scalar hysteresis and its mathematical formulation for increasing applied field is:

$$\frac{dM}{dH} = K(M) \left\{ W(H) + 2P_s(H) \int_{H_0}^H P_s(-H)dV \right\}$$ \hspace{1cm} (1)$$

where $H_0$ is the starting point of the applied field, $W(H)$ is an additional reversible component of the magnetization, and $K(M)$ is needed to overpass the congruency property of the minor loops. The expression of $K(M)$ and of the Lorentzian are reported in the Eqs. (2) and (3):

$$K(M) = 1 - \left( \frac{M}{M_s} \right)^2$$ \hspace{1cm} (2)$$

$$P_s(H) = \frac{A}{1 + \left( \frac{H - H_c}{H_s} \right)^2}$$ \hspace{1cm} (3)$$

where $\sigma$ and $H_c$ are the Lorentzian characteristic parameters ($\sigma$ generally no physical meaning, $H_c$ very close to the coercitivity), and $A$ is a normalizing factor for taking into account the magnetization at the saturation state ($M_s$) [6, 7]. Following this formulation, the equation (1) becomes:

$$\frac{dM}{K(M)dH} = W(H) + \frac{2A^2}{\sigma^2} \frac{H_s}{H_c} \left[ \tan^{-1} \left( \frac{H + H_c}{H_s} \sigma \right) - \tan^{-1} \left( -\frac{H - H_c}{H_s} \sigma \right) \right]$$ \hspace{1cm} (4)$$

it is important to note that the reversible part of the magnetization is independent from the irreversible one. This permits to deal the MSPM is an intrinsically State Independent Model with respect to the reversible magnetization. From this point of view a simple identification procedure can be applied [7].

### 3 Results and conclusions

Figures 1 and 2 show a comparison between experimental and computed minor loops data. The identification parameters are reported in the Table 1; they have been computed by the knowledge of the experimental major loop data only (saturation field is 1000 A/m). Experimental data showed in the figures come from measures on non-oriented soft magnetic steels (Si-Fe 3.2% in weight) for different average grains size, 46 µm (C1) and 174 µm (C6). The samples were cut along different directions, from 0° to 90° with respect to the lamination direction. The compared loops have a maximum applied field of 20 and 60 A/m. The obtained results are in a good agreement with the experimental data and clearly confirm the validity of the approach proposed and demonstrate that the MSPM is a powerful tool for the characterization of few non-oriented soft magnetic steels, therefore the proposed approach can be used to model the static hysteresis losses in converter transformer [8]. The static energy losses in a closed magnetization cycle is proportional to the area enclosed by the M-H loop. The area of the loop is computed in this way:

$$W = \int_{\text{Loop}} HdM$$ \hspace{1cm} (5)$$
In this paper, the static losses are computed as the difference between the area subtended by the increasing and decreasing positive branch of a symmetric loop, as reported in equation 6:

\[ W = 2 \left( \sum_{i=1}^{m} M(i) \Delta H_i - \sum_{j=1}^{n} M(j) \Delta H_j \right) \]  

where \( m \) and \( n \) are the vector size of the increasing and decreasing branch of the magnetization of a symmetric loop respectively.

**Table 1** Identification parameters of the Lorentzian function.

<table>
<thead>
<tr>
<th>Size</th>
<th>Cut angle</th>
<th>( \sigma )</th>
<th>( H_c ) [A/m]</th>
<th>( M_s ) [T]</th>
<th>Size</th>
<th>Cut angle</th>
<th>( \sigma )</th>
<th>( H_c ) [A/m]</th>
<th>( M_s ) [T]</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>0°</td>
<td>6.24</td>
<td>23.8</td>
<td>1.532</td>
<td>C6</td>
<td>0°</td>
<td>2.88</td>
<td>11.3</td>
<td>1.513</td>
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<td>30.26</td>
<td>1.37</td>
<td>C6</td>
<td>25°</td>
<td>2.18</td>
<td>14.97</td>
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</tr>
<tr>
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<td>1.84</td>
<td>32.8</td>
<td>1.242</td>
<td>C6</td>
<td>45°</td>
<td>1.62</td>
<td>17.9</td>
<td>1.38</td>
</tr>
<tr>
<td>C1</td>
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<td>1.26</td>
<td>34.16</td>
<td>1.374</td>
<td>C6</td>
<td>75°</td>
<td>1.04</td>
<td>21.7</td>
<td>1.41</td>
</tr>
<tr>
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<td>1.1</td>
<td>34.5</td>
<td>1.44</td>
<td>C6</td>
<td>90°</td>
<td>0.75</td>
<td>23.6</td>
<td>1.426</td>
</tr>
</tbody>
</table>

**Fig. 1** Comparison between experimental and computed symmetric loops data. The maximum applied fields are 20 and 60 A/m. The laminated magnetic steel has a size of C6 and a cut angle of 45°.

**Fig. 2** Comparison between experimental and computed symmetric loops data. The maximum applied fields are 20 and 60 A/m. The laminated magnetic steel has a size of C1 and a cut angle of 45°.

**Fig. 3** Plot of the static losses (J/m³) with respect to the cut angle (degree) in grain C1 for different loops.

**Fig. 4** Plot of the static losses (J/m³) with respect to the cut angle (degree) in grain C6 for different loops.
Figures 3 and 4 show the static losses computed using the MSPM for fixed maximum applied field (\(H_A\)) with respect to the cut angle. If \(H_A >> H_c\), the losses increase with the cut angle in agreement with the fact that when the cut direction is the easy axis, they are smaller. When \(H_A \approx H_c\), the losses behavior depends on the grain size. Lastly, when \(H_A << H_c\), the losses are practically independent of the cut angle and the grain size. Similar remarks seem by the results obtained by the plot of the losses for fixed magnetization, as shown in the Figs. 5 and 6.

The MSPM and the Lorentzian function have been used to model non-oriented magnetic steels behavior for different grains size and cut angles with respect to the easy axis. It reproduces minor symmetric loops in good agreement with the experimental data measured at 0.1 Hz. Therefore, using this model, theoretical static losses computed would have to be very close to the experimental one. An advantage of this approach is the possibility to deal the model in semi-analytical way (computational time less than complete numerical way) and to solve the identification problem using a reduced set of experimental data, the major loop and the virgin curve. The theoretical results obtained show how the static losses behavior depends on the grains size when the maximum applied field of the symmetric minor loop is very close to the coercitivity. Furthermore, they show that for fixed grains size the losses increase with the cut angle.

References