Research Article
A Novel Hysteresis Model of Magnetic Field Strength Determined by Magnetic Induction Intensity for Fe-3% Si Electrical Steel Applied in Cigarette Making Machines

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Hysteresis characteristics of grain-oriented electrical steel were studied through the hysteresis loop. Existing hysteresis fitting simulation methods were summarized, and new Fe-3% Si grain-oriented electrical steel hysteresis loop model was proposed. Undetermined coefficients of the magnetic field intensity and magnetic flux density were determined by both the fixed angle method and the least squares method, and the hysteresis loop model was validated with high fitting degree by experimental data.

1. Introduction

Fe-3% Si grain-oriented electrical steel is an important soft magnetic material, which is often used for cigarette machine sensor because of its high magnetic flux density and good magnetic performance [1–5]. Therefore, parameters such as iron loss, permeability, shielding efficiency, and Barkhausen noise of Fe-3% Si grain-oriented electrical steel have been studied extensively. When the magnetic flux is alternating, hysteresis and eddy current losses will be generated. Existence of hysteresis and eddy current losses will make the magnetic flux density lag behind the magnetic field intensity; after repeatedly magnetizing multiple cycles, the hysteresis loop forms [6, 7]. Applied sensors in cigarette making machines usually do not consider the complex effects of the hysteresis loop, inevitably leading to errors in the following simulation or performance prediction, which is an important reason why switch protection of cigarette making machine sensor is not accurate enough [8–10].

Hysteresis is a quite important magnetic property of Fe-3% Si grain-oriented electrical steel, since its hysteresis loops and magnetization curves reflect the significant characteristics of the material, which is also an important basis for the selection of cigarette machine sensor materials [11, 12]. Study on the material hysteresis loop model is helpful to better understand the hysteresis property of the material, which is significant to the design of materials and related components [13]. With the increasingly higher demand of equipment design accuracy in the actual operation, it is necessary to accurately determine the impact caused by hysteresis [14, 15]. In the characterization analysis of motors, transformers, and other electromagnetic equipment, it is the first step to obtain...
2. Experimental

Conventional grain-oriented (CGO) electrical steel sheets and high permeability grain-oriented (HGO) electrical steel sheets were the tested materials in this paper. CGO and HGO electrical steel were named CC1 and CH1, respectively, and the chemical composition is shown in Table 1.

The samples were manufactured as standard Epstein samples, and the sample size is 350 mm × 30 mm × 0.3 mm. Initial magnetic properties of CC1 and CH1 at 1.0 T are shown in Table 2.

A standard Epstein strip for testing is placed between the yokes, and a feedback control system implemented in LabVIEW was used to control the flux density to have repeatable and comparable measurements. The whole measurement was conducted in a magnetic shielding room and the computer was put in another room to avoid interference [2–5].

3. Formula Derivation and Modeling

Since the hysteresis loop is nearly symmetrical concerning the loop curve origin point, according to the Fourier series, the magnetic induction intensity and magnetic field strength could be expanded, respectively. Symmetry of the origin makes Fourier series contain only odd entries, and the expanded equations are as shown in

\[
H = H_4 \sin(\omega t + \varphi_4) + H_5 \sin(\omega t + \varphi_5)
+ H_3 \sin(\omega t + \varphi_3) + \cdots
\]

\[
B = B_4 \sin(\omega t + \varphi_4) + B_5 \sin(\omega t + \varphi_5)
+ B_3 \sin(\omega t + \varphi_3) + \cdots.
\]  

To simplify the calculation, magnetic induction intensity is taken as the first term, and the magnetic field strength is viewed as a function of magnetic induction intensity, and magnetic field strength should contain unlimited expansion terms. In the derivation and calculation of the model, only the first two terms were used, and the basic model of the hysteresis loop could be obtained. Hence,

\[
B = B_1 \sin(\omega t),
\]

\[
H = B_1 \left( \frac{1}{\mu_1} \sin(\omega t + \varphi_1) + \frac{1}{\mu_5} \sin(3\omega t + \varphi_3) \right).
\]

Equation (3) reflects the nonlinear relationship between the magnetic field strength and magnetic induction intensity, in which \( \varphi \) represents the impact hysteresis. Values of \( \varphi_1, \varphi_3, \mu_1, \) and \( \mu_5 \) are influenced by magnetic field strength, which are determined by hysteresis loop. Once values of \( \varphi_1, \varphi_3, \mu_1, \) and \( \mu_5 \) are determined, ideal hysteresis loop could be simulated. If the hysteresis loop is smooth, the fitting degree will be high.

Undetermined parameters could be determined by the fixed angle method. In (2) and (3), \( H_1 \) represents magnetic field strength \( H \) amplitude in the hysteresis loop. Making \( \omega t \) take different angles, respectively, in this paper, we chose 0, \( \pi/3, \pi/2, \) and \( 2\pi/3; \) the corresponding \( H_1, H_2, H_3, \) and \( H_4 \) could be found; taking \( H_4 \) back to the equation of magnetic field strength, the following equations could be obtained:

\[
H_1 = B_1 \left( \frac{1}{\mu_1} \sin \varphi_1 + \frac{1}{\mu_5} \sin \varphi_3 \right),
\]

\[
H_2 = B_1 \left( \frac{1}{\mu_1} \sin \left( \frac{\pi}{3} + \varphi_1 \right) + \frac{1}{\mu_5} \sin \left( \pi + \varphi_3 \right) \right)
= B_1 \left( \frac{1}{2\mu_1} \sin \varphi_1 + \frac{\sqrt{3}}{2\mu_1} \cos \varphi_1 - \frac{1}{\mu_5} \cos \varphi_3 \right),
\]

\[
H_3 = B_1 \left( \frac{1}{\mu_1} \sin \left( \frac{\pi}{2} + \varphi_1 \right) + \frac{1}{\mu_5} \sin \left( \frac{3\pi}{2} + \varphi_3 \right) \right)
= B_1 \left( \frac{1}{\mu_1} \cos \varphi_1 - \frac{1}{\mu_5} \cos \varphi_3 \right),
\]

\[
H_4 = B_1 \left( \frac{1}{\mu_1} \sin \left( \frac{2\pi}{3} + \varphi_1 \right) + \frac{1}{\mu_5} \sin \left( 2\pi + \varphi_3 \right) \right)
= B_1 \left( \frac{\sqrt{3}}{2\mu_1} \cos \varphi_1 - \frac{1}{2\mu_1} \sin \varphi_1 + \frac{1}{\mu_5} \sin \varphi_3 \right).
\]

Adding \( H_2 \) and \( H_4 \), the following calculation could be obtained:

\[
H_2 + H_4 = B_1 \frac{\sqrt{3}}{\mu_1} \cos \varphi_1.
\]

After transformation, \( \varphi_3 \) could be deleted; hence,

\[
H_1 + H_2 = B_1 \left( \frac{3}{2\mu_1} \sin \varphi_1 + \frac{\sqrt{3}}{2\mu_1} \cos \varphi_1 \right).
\]
Table 2: Initial magnetic properties of CCI and CH1 steel at 1.0 T.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Iron loss (W/kg)</th>
<th>Coercive force (A/m)</th>
<th>Relative permeability</th>
<th>MBNrms (mV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCI</td>
<td>0.711</td>
<td>282.9</td>
<td>799.4</td>
<td>0.391</td>
</tr>
<tr>
<td>CH1</td>
<td>0.668</td>
<td>287.6</td>
<td>2473.7</td>
<td>0.447</td>
</tr>
</tbody>
</table>

To delete $\mu_1$, sine expression concerning $\varphi_1$ could be obtained through calculation; hence,

$$
2H_1 + H_2 - H_4 = B_1 \left( \frac{3}{\mu_1} \sin \varphi_1 \right).
$$

(7)

Delete $\mu_1$, and the expression concerning $\varphi_1$ could be obtained as

$$
\frac{2H_1 + H_2 - H_4}{H_2 + H_4} = \sqrt{3} \tan \varphi_1,
$$

$$
\varphi_1 = \arctan \left( \frac{2H_1 + H_2 - H_4}{\sqrt{3}(H_2 + H_4)} \right).
$$

(8)

Value of $\mu_1$ could be calculated as

$$
\mu_1 = \frac{3B_1}{2H_1 + H_2 - H_4} \sin \varphi_1
$$

or

$$
\mu_1 = \frac{\sqrt{3}B_1}{H_2 + H_4} \cos \varphi_1.
$$

(10)

Through a similar method, sine and cosine expression concerning $\varphi_3$ could be calculated as

$$
H_1 - H_2 + H_4 = \frac{3B_1}{\mu_3} \sin \varphi_3,
$$

$$
H_2 + H_4 - \sqrt{3}H_3 = \frac{\sqrt{3}B_1}{\mu_3} \cos \varphi_3.
$$

(11)

To calculate $\varphi_3$, it is necessary to delete $\mu_3$ first, and the following transformation could be made:

$$
\tan \varphi_3 = \frac{H_1 - H_2 + H_4}{\sqrt{3}(H_2 + H_4) - 3H_3}.
$$

(12)

The value of $\varphi_3$ could be calculated as

$$
\varphi_3 = \arctan \left( \frac{H_1 - H_2 + H_4}{\sqrt{3}(H_2 + H_4) - 3H_3} \right).
$$

(13)

$\mu_3$ could be calculated when taking it back; hence,

$$
\mu_3 = \frac{3B_1 \sin \varphi_3}{H_1 - H_2 + H_4}
$$

or

$$
\mu_3 = \frac{3B_1 \cos \varphi_3}{\sqrt{3}(H_2 + H_4) - 3H_3}.
$$

(15)

After the hysteresis loop was obtained after experiment, other hysteresis loop parameters could be determined by linear interpolation.

For given $B_k$ ($B_j < B_k < B_{j+1}$), linear interpolation could be applied to calculate model parameters $\varphi_1, \mu_3, \mu_1$, and $\mu_3$.

If $\varphi_j, \varphi_{j+1}, B_j, B_k$, and $B_{j+1}$ are given, calculations could be made as follows:

$$
\varphi_k = \varphi_j + \frac{\varphi_{j+1} - \varphi_j}{B_{j+1} - B_j} (B_k - B_j).
$$

(16)

When $k = 1, 3$, $\varphi_1$ and $\varphi_3$ could be calculated, respectively, as

$$
B = B_1 \sin (\omega t + \varphi_1) + B_3 \sin (\omega t + \varphi_3)
$$

$$
= H_1 (\mu_1 \sin (\omega t + \varphi_1) + \mu_3 \sin (3\omega t + \varphi_3)).
$$

(17)

$\mu_1 H_k$ and $\mu_3 H_k$ could be calculated by linear interpolation.

If $\mu_1, \mu_{1j+1}, H_{1j}, H_{1j+1}$, and $H_k$ were given, the following calculations could be made:

$$
L_1 (x) = \frac{x_{k+1} - x}{x_{k+1} - x_k} y_{k+1} + \frac{x - x_k}{x_{k+1} - x_k} y_{k+1},
$$

$$
\mu_1 H_k = \frac{H_{1j+1} - H_k}{H_{1j+1} - H_{1j}} \cdot \mu_1 H_{1j} + \frac{H_k - H_{1j}}{H_{1j+1} - H_{1j}} \cdot \mu_{1j+1} H_{1j+1}.
$$

(18)

The two-point linear interpolation could be expressed as

$$
\mu_1 = \frac{\mu_{1j} (H_{1j+1} - H_{1j}) H_{1j} + \mu_{1j+1} (H_k - H_{1j}) H_{1j+1}}{(H_{1j+1} - H_{1j}) H_k}.
$$

(19)

Similarly, if $\mu_1, \mu_{1j+1}, H_{1j}, H_{1j+1}$, and $H_k$ were given, $\mu_3$ could be calculated as

$$
\mu_3 = \frac{\mu_{3j} (H_{3j+1} - H_{3j}) H_{3j} + \mu_{3j+1} (H_k - H_{3j}) H_{3j+1}}{(H_{3j+1} - H_{3j}) H_k}.
$$

(20)

New models of hysteresis loop were derived above, and the calculation of undetermined coefficient method was given utilizing interpolation step, and the model is simple and convenient.

Least squares curve fitting method is a common fitting method. When using such method to make calculation of undetermined coefficients, since the basic relationship equations of the magnetic induction density and magnetic...
field strength have been given, undetermined parameters of the model can be determined by magnetic field strength and magnetic induction density values of a set of experimental measurements. Assuming \((H_1, B_1), (H_2, B_2), (H_3, B_3), \ldots\) are known and \(H\) is the measured magnetic induction intensity and \(H'\) is the calculated magnetic induction intensity, then undetermined coefficients \(\varphi_1, \varphi_3, \mu_1,\) and \(\mu_3\) could be determined by residual square difference minimization of the measured and calculated values. Hence,

\[
Q = \sum_{k=1}^{n} e_k^2 = \sum_{k=1}^{n} \left[ B_k - f(B_k, \mu_1, \mu_3, \varphi_1, \varphi_3) \right]^2 .
\]  \hspace{1cm} (21)

Undetermined coefficients of \(B-H\) loop model can be calculated while \(Q\) takes the minimum value in (21). Hence,

\[
\frac{\partial Q}{\partial \mu_1} = 0, \hspace{1cm} \frac{\partial Q}{\partial \mu_3} = 0, \hspace{1cm} \frac{\partial Q}{\partial \varphi_1} = 0, \hspace{1cm} \frac{\partial Q}{\partial \varphi_3} = 0.
\]  \hspace{1cm} (22)

The equations consist of the above four equations; the undetermined coefficients could be obtained, which could be back to the original hysteresis models. The relationship between the magnetic induction intensity and magnetic field strength can be obtained, illustrating the hysteresis loop model.

4. Model Application

The proposed model was applied for \(B-H\) curve fitting, as shown in Figure 1. The error of the single data point is controlled within 5%, achieving fine fitting effect.
Figure 1 simulation results show fine fitting result, and it is suitable for the working condition of silicon steel applied in the cigarette sensor machines, which is the possible complex magnetization condition in normal working conditions.

5. Conclusions

Expansion of the magnetic induction intensity and magnetic field strength was made according to the Fourier series, respectively. The magnetic field strength was determined by the magnetic induction intensity, and the undetermined parameters of angles, magnetic induction intensity, and the magnetic field strength could be determined by fixed angle method and the least squares method. General application steps of the model were given. The proposed model was applied for \( B-H \) curve fitting, and the error of the single data point is controlled within 5\%, achieving fine fitting effect.

Competing Interests

No potential conflict of interests was reported by the authors.

Authors’ Contributions

Hao Wang, Jianbo Zhan, and Zhenhua Yu contributed equally to the paper.

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