Dynamic Hysteresis Behavior Modeling of Ferromagnetic Material Based on Jiles-Atherton Theory

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With the rapid development of power electronic technology, the non-sinusoidal power supply have already been applied in a variety of electrical machines. The voltage or current waveform of the power source contains many higher harmonic components, which leads to distorted magnetic flux density in the motor core. Consequently, the total iron loss may increase. In order to predict the iron loss accurately, one has to measure and model the magnetic properties of silicon steel sheets under non-sinusoidal exciting condition. Jiles-Atherton (JA) model is one of most popular physical background based hysteresis models and employed to describe the static hysteresis characteristics. To extend the scope of application, this article proposes a simple modeling algorithm to model the dynamic hysteresis behavior. Finally, the calculated hysteresis loops are compared with measured ones to validated the proposed method.

Index Terms—**Frequency-dependent, Jiles-Atherton model, Magnetic properties, Minor loops**

I. INTRODUCTION

IT is known that iron loss in the motor core is increased by the non-sinusoidal excitation, such as square and PWM waveform. These waveforms contain much higher harmonic components [1]. To predict the iron loss for electrical steel sheets (ESS) accurately, it is necessary to investigate the hysteresis behavior which can consider the minor loops. On the other hand, it is important that the magnetic property is influenced by frequency in the alternating magnetization process, the difference of hysteresis loops cannot be ignored.

JA hysteresis model simulates the magnetization process by introducing theory of domain wall motion with pinning effects, which can be expressed by a first-order ODE and merely five material related parameters. However, the original JA model can only describe static hysteresis loops. When non-sinsoidal excitation is applied, in this case, the B or H waveform will be arbitrary shape, therefore, a series of minor loops may appear in the major hysteresis loop and it could lead to increase the total iron loss[2].

Many factors can affect the magentic properties of ferromagnetic materials such as temperature, stress, and excitation condition. One of the significant factors is frequency. In the experimental process, we can find that the iron loss is increased with the ascend of frequency [3].

To extend the application scope of hysteresis model, the modified pinning factor k and reversible magnetization related parameter c are proposed to consider the minor loops. On the other hand, a novel dynamic term is introduced to consider the characteristecs of frequency on the base of static model. Finally, in the paper, a comprehensive dynamic hysteresis model is derived, which are capable of simulating both minor loops and frequency dependent hysteresis properties.

II. MODELING DYNAMIC HYSTERESIS LOOPS

A. Improved JA Hysteresis Model for Minor Loops

The original JA model is based on the theory of magnetic domain. The bulk magnetization M is the sum of the two components: reversible M_{rev} and irreversible M_{irr}. The final differential equation of JA model can be expressed:

$$\frac{dM}{dH}=\frac{\delta_m\left(M_{an}-M\right)+k\delta c\dfrac{dM_{an}}{dH_e}}{k\delta-\alpha\left[\delta_m\left(M_{an}-M\right)+k\delta c\dfrac{dM_{an}}{dH_e}\right]} \tag{1}$$

where M_{an} is the anhysteretic magnetization can be given by the modified Langevin equation.

$$M_{an}=M_s\left[\coth\left(\frac{H_e}{a}\right)-\frac{a}{H_e}\right] \tag{2}$$

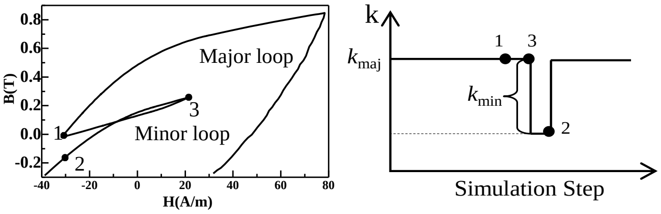
According to the above equation, the only five parameters: (M_s, a, k, c, α) are used to simulate the magnetic properties for ESS. The value of δ is a directional parameter, and if $dH/dt>0$, it is +1, if $dH/dt<0$, it is -1. δ_m is introduced to remove the negative susceptibilities at the tips of hysteresis loop, and if (M_{an}-M)<0, it is 0, in contrary, if is positive, it is 1 [4].

In the classical model, the five parameters to be identified are considered to be constant. For achieving the objective to accurate simulate the minor loops, according to the presented theory by D. C. Jiles in 1992, and combine the experimental observation and empirical considerations. This paper propose a modified method by changing parameters k and c in the interval of minor loop. The minor loops are generated by the non-sinusoidal alternating magnetization, as a result of, the component of reversible and irreversible could be changed. Therefore, the parameters k and c may be modified when the time interval of occurrence of minor loops.

$$\begin{cases} k=k_{\mathrm{maj}}+k_{\mathrm{min}} \\ c=c_{maj}+c_{\mathrm{min}} \end{cases} \tag{3}$$

In Eq. (3), k_{maj} and c_{maj} are the parameter value for JA model to simulate the major loop, however, during the minor loops, the parameter k is the sum of both k_{maj} and k_{min}. Another parameter c can be determined by the same way. In order to avoid unphysical phenomenon of Fig. 1(a), the two parameters may be controlled by the way of Fig. 1(b). In Fig. 1(a), the point 1 and 2 are the start and end location, respectively. The modified JA model parameter identification problem can be converted to global optimization problem which minimize the error between calculated and measured B. The single object particle swarm optimization algorithm is adopted in this paper to search the optimal parameter set.

The hysteresis loop for sinusoidal magnetic field intensity adds merely the third harmonic is to evidence the feasible approach. The parameters of improving JA model is: M_s=1.85 × 10^6A/m, a=95.3, k_{maj}=62.5, c_{maj}=0.416, α=0.0001098, k_{min}=−11.5, c_{min}=−0.26. The major and minor loops have a good agreement with the measured loop shown in Fig. 2.



(a). Non-closure minor loop (b). Variety process for k

Fig. 1. The sketch of variable parameters determination.

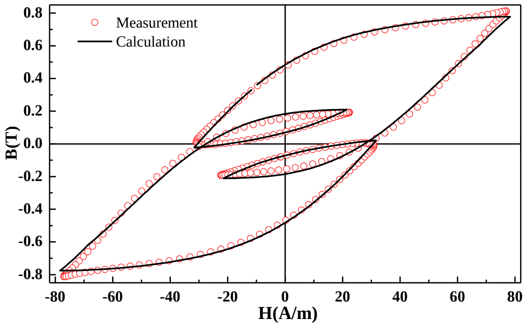


Fig. 2. A comparison between measured and calculated curves include the third harmonic.

B. Frequency-Dependent Hysteresis Model

Under the condition of quasi-static state, the loss is mainly comprised with magnetic hysteresis loss. With the increase of excitation frequency, the eddy current loss and excess loss are more and more remarkable. Because of the reason, the shape of hysteresis loops is more and more close to the ellipse [5]. A accurate hysteresis model which can consider the effect of frequency, up to now, has not been proposed.

For some materials, the iron loss can be predicted by an accurate static hysteresis model, but if the frequency of applied magnetic field is increased, the total iron loss is, in general, underestimated because of missing the eddy loss and excess loss. In order to precisely predict the total loss, the articles proposes a dynamic hysteresis model. An additional item can consider the frequency factor is introduced on the base of the static JA hysteresis model.

The equation of dynamic hysteresis model is expressed below:

$$B(H) = B_{\mathrm{st}}(H) + \mathrm{sign}\left[f - f_0\right]\left|B_{\mathrm{f}_1}(H) - B_{\mathrm{f}_0}(H)\right|^{\gamma(f)} \quad (4)$$

where $B(H)$ is the total magnetic flux density, the first term of Eq. (4). is the static component determined from original JA model, and the second term is the dynamic component. The f_0 and f_1 are the boundary frequencies according to the specific case. The value of γ is a function which is related to frequency, the function is follows:

$$\gamma(f) = (f - f_0)/g(f) \quad (5)$$

where the $g(f)$ is a polynomial function. and the least square method is used to identify the coefficients.

A series of hysteresis loops are measured under different frequencies of 50Hz, 100Hz, 150Hz, 250Hz and 400Hz, respectively. Then, f_0=50Hz and f_1=400Hz are chosen to model the frequency-dependent JA model and $B_{f0}(H)$ and $B_{f1}(H)$ are magnetic flux density data at f_0 and f_1, respectively. The coefficients of formula g(f) in Eq. (5) are determined by several measurement loops under the different frequencies (f=100Hz, 400Hz). Fig. 3 shows the comparison between measurement and calculated hysteresis loops under the frequency of f=150Hz, 250Hz at B=0.8T. In this example, the order of polynomial function $g(f)$ is merely first order that can satisfy the demand for the frequency range, and coefficients are 0.888 and 7.8, respectively. The results can validate the proposed algorithm.

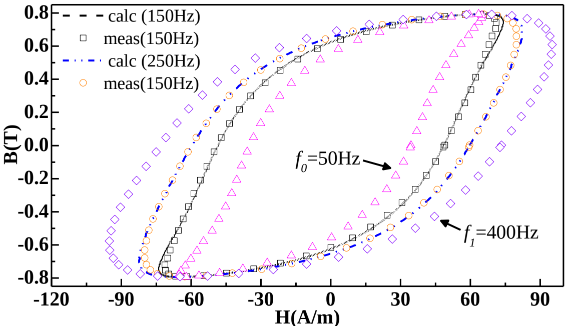


Fig. 3. A comparison between measured and calculated curves under 150Hz and 250Hz

In order to extend the representation of minor loops and frequency-dependent by JA hysteresis model, Fig. 2 and 3 verify the validity of the proposed method, respectively, when the magnetic field intensity only contains the third harmonic with different frequencies.

In the full version of paper, we are going to make JA model implement simulate the hysteresis loops contain more higher harmonic under PWM supply and different fundamental frequencies.

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