The nonlinear characteristics of transformer broadband

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Abstract. At present, the modeling of the transformer broadband nonlinear characters is based on the nonlinear features of 50Hz, so there are still some questions. In this paper, the magnetic hysteresis loop of the silicon steel in the range of 50Hz to 100kHz is measured by using a measuring system composed of a 25cm Epstein square coil and an amh-1m magnetometer. The J-A parameters of the silicon steel core in the frequency wide range of the range of the optimized by using the hybrid means on the oneran fish swarm and L-M. Then, the nonlinear core model of transformer based on J-A parameters is set in PSPICE. Based on the model, the transformer simulation circuit is built. By applying sinusoidal voltage signal of the specific frequency to the nonlinear transformer model with the specific frequency, the non-linear characters of the transformer in wide frequency range areed. It is found the nonlinear characters of the transformer core change dramatically with the change of the frequency. Therefore, in the broadband nonlinear modeling of the transformer, using the nonlinear characters at 50Hz to nonlinear the broadband model will lead to large error. In the follow-up modeling research, scholars should consider the nonlinear characters of the transformer to the set the model, and try to use the nonlinear characters of the transformer under the frequencies for the broadband linear modeling.

1. Introduction

Transformer, as a key equipment in power system, is of great significance to establish its broadband equivalent model. A large number of literature shows that because of the eddy current, saturation and hysteresis characteristics[1-3], so that transformers have both frequency-variable and nonlinear characteristics, so the establishment of an equivalent model that also considers the frequency-change characteristics and nonlinear characteristics of transformers, has been the weak point of electromagnetic transient simulation software, but also the focus and difficulty of research[4-8].

At present, the modeling methods that consider the nonlinear characteristics of transformer cores mainly include the modeling method of iron cores described by single straight curves, the modeling methods of iron cores described by magnetic hysteresis backlines, and the nonlinear modeling methods that consider the frequency changes of iron cores. The iron core model described by the single straight curve simplifies the complex hysteresis return line to a single straight curve, and in the literature[9], a nonlinear model with frequency variable characteristics is established using the iron core parameters described by the single straight curve of different frequencies, but the transformer core is described using a single straight curve, although the method is simple, but the use of the application is limited to the low accuracy requirements[10-13]. The modeling method of the magnetic hysteresis return wire core can more accurately describe the characteristics of the transformer iron core, and the paper[14]
deduces the iron core impedance equation through electromagnetic field theory, and then establishes the iron core equivalent circuit through the circuit synthesis, and represents the nonlinear characteristics of the iron core with the U-I characteristic curve of the transformer at 50Hz. The paper[15] establishes the transformer wide frequency nonlinear model by black box modeling, which is formed by two high frequency variable linear modules and the low frequency nonlinear module in tandem, but the model does not take into account the frequency-change characteristics of the equivalent magnetic conductivity of the iron core. Considering that the nonlinear modeling of iron core frequency change is the most accurate way to describe it, the paper[16] first establishes the linear model of transformer by means of scattering parameters, using vector matching method and circuit synthesis, and then uses the iron core frequency change resistance expression to consider the equivalent magnetic conductivity frequency change effect by solving Maxwell's equation system, and finally uses the U-I characteristic curve at 50Hz to establish the transformer frequency variable nonlinear model.

It can be found that, based on the iron core modeling method described with a single straight curve, the iron core modeling method using the magnetic hysteresis backline description, and the nonlinear modeling method of considering the frequency change of the core, only the saturation of the transformer at a single frequency of 50Hz is taken into account when nonlinearization is carried out. Characteristics, and the use of 50Hz transformer U-I curve for nonlinear processing, because the transformer has both frequency change and saturation and nonlinear characteristics, only the 50Hz saturation characteristic curve for nonlinear treatment, whether the method is accurate or not, it is necessary to explore. However, the measurement of the nonlinear characteristics of transformers is the nonlinear characteristics of using the signal generator to excite empty transformers, which makes it difficult to obtain the nonlinear characteristics of transformers at high frequencies by experimental method at wide frequencies, which is less studied at present. In this paper, the transformer core hysteresis model is established by Epstein square circle measurement at different frequencies, the transformer core hysteresis model is established by Jiles-Atherton theory, and the transformer model with iron core hysteresis is established in the simulation software, and the satiet and nonlinear characteristics of transformers at different frequencies are obtained, which provides a certain reference for subsequent modeling research.

2. Silicon steel sheet wideband hysteresis backline measurement
The magnetic properties of the transformer's core silicon steel sheet are generally measured using the 25cm Epstein square ring[17], as shown in Figure 1.

![Figure 1. 25 cm Epstein square circle](image)

The square ring structure consists of an iron core made of a side, a secondary side winding and a sample of silicon steel sheet to be measured. The iron cores made from the samples of the silicon steel sheet to be tested must be assembled using the double joints shown in Figure 2 in accordance with the specified size, quantity and quality.
During the measurement, the excitation signal of the characteristic frequency is applied to the one-sided winding of Epstein's square circle, and then the first and second side measurement results are calculated and converted to obtain the magnetic hysteresis characteristics of the silicon sheet to be measured. In the literature, I designed a measurement system consisting of the Epstein frame and the AMH-1M magnetic conduction instrument[18], which provides the voltage waveforms needed to measure any function generator through software feedback control.

2.1. Wide-band hysteresis backline measurement results
Using the magnetic characteristic measurement system designed above, the dynamic magnetic characteristics of the silicon steel sheet B27RK100 sample (B27RK100 silicon steel sheet samples are commonly used in the manufacture of large transformer cores) are measured, as shown in Figure 3, 4 below.

The relative magnetic conductivity of the sample to be tested is exported as shown in Figure 5. The relative magnetic conductivity of the silicon steel sheet B27RK100 sample can be found to decrease sharply with the increase in frequency, due to the skin-collecting effect.

3. J-A hysteresis model parameter recognition
The magnetic hysteresis backline of the silicon steel sheet from 50Hz to 100kHz was measured using the magnetic characteristic measurement system in the upper section, but a mathematical model must
be established to study the properties of ferromagnetic materials using the magnetic hysteresis return line. Currently, commonly used mathematical models are Preisach Theory, Globus Theory, Stoner-Wohlfarth Theory [19-21], and Jiles-Atherton Theory Models, which have simple parameters and clear physical significance, so this paper attempts to use J-A [22-23]. The parameters establish a model of the iron core of the silicon steel sheet.

### 3.1. J-A hysteresis model

The J-A hysteresis model uses the pattern of magnetic wall movement under the nailing effect to build a model with clear physical significance to represent the relationship between magnetic field strength $H$ and magnetization strength $M$ [24-25]. The conversion relationship between magnetic induction strength $B$ and magnetic field strength is obtained using formulas such as Type 1.

$$ B = \mu_0 (H + M) \quad \text{(1)} $$

$\mu_0$ is the vacuum magnetic conductivity.

Magnetized strength $M$ consists of reversible component $M_{\text{rev}}$ and non-reversible component $M_{\text{irr}}$.

$$ M = M_{\text{rev}} + M_{\text{irr}} \quad \text{(2)} $$

$M_{\text{rev}}$ represents the magnetization intensity caused by elastic deformation, and $M_{\text{irr}}$ indicates the magnetization intensity due to the insesis of the magnetic field, and their relationship can be expressed as:

$$ M_{\text{an}} = \frac{M_{\text{rev}}}{c} + M_{\text{irr}} \quad \text{(3)} $$

$M_{\text{an}}$ is non-magnetic hysteresis strength and $c$ is a reversible coefficient.

Described using the improved Langevin method, the non-magnetically magnetized intensity Man expression is:

$$ M_{\text{an}} = M_y (\coth(H_c / \alpha) - \alpha / H_c) \quad \text{(4)} $$

where $\alpha$ is the shape parameter and $H_c$ is the effective magnetic field strength.

The effective magnetic field strength is $H_e = H + \alpha M$, $\alpha$ is the average field parameter.

The J-A model divides the core magnetization process into reversible and irreversible magnetization processes, the energy consumed during the magnetization process can be expressed as the next type 5:

$$ E_{\text{irr}} = \mu_0 \int_0^{M_{\text{irr}}} dM_{\text{irr}} \quad \text{(5)} $$

The joint is available.

$$ M_{\text{irr}} = M_{\text{an}} - k \delta \frac{dM_{\text{irr}}}{dH_c} \quad \text{(6)} $$

Where $\delta$ is the direction coefficient and $k$ is the hysteresis coupling parameter.

The final J-A model differentiation equation is solved as follows:

$$ \frac{dM}{dB} = \mu_0 ((1 - \alpha) \delta (M - M_{\text{an}}) - k \delta c M_{\text{an}} / dH_c - k \delta) \quad \text{(7)} $$

The resulting hysteresis model J-A hysteresis model can be determined by a joint set of 5 coefficients in the expression. Therefore, in the actual research process, as long as we calculate the five coefficients of the iron core element, we can get the standard J-A model of the iron core element.

### 3.2. J-A model parameter calculation

In the current research, scholars for the iron core J-A model parameter algorithm mainly have particle groups and neural networks, but these calculation methods not only iterate a lot, but also the solution results easily offset to local optimal, this paper uses the literature [26] based on artificial fish and L-M mixing algorithm to achieve accurate identification of J-A parameters.

Artificial fish algorithm is a biological intelligent bionics algorithm, which achieves region-wide excellence by utilizing biome bionic characteristics. Although the artificial fish algorithm can quickly find the global optimal solution feasible domain from within the domain to be sought, the process of solving the optimal solution accurately requires many iterations, so the L-M algorithm can be used to solve it quickly and accurately. L-M algorithm is a deterministic optimization algorithm combining Gauss
Newton and gradient drop methods, and L-M can make rapid iterations by fixing the gradient direction to achieve high-precision and fast solution. In this paper, the global optimal feasible domain is obtained by using artificial fish algorithm, and L-M is used to solve it quickly.

To verify the feasibility of the algorithm, a set of known hysteresis curves of the J-A parameters are imported and the J-A parameters are calculated using artificial fish and L-M mixing algorithms, as shown in Table 1 below.

**Table 1. Verification results of parameter calculation**

| Parameter | Exact value | Calculated value |
|-----------|-------------|------------------|
| $M_s$ (A/m) | $1.80 \times 10^6$ | $1.81 \times 10^6$ |
| $\alpha$ | 0.00085 | 0.001 |
| $a$ (A/m) | 2.81 | 3.03 |
| $k$ | 38.93 | 40.25 |
| $c$ | 0.0198 | 0.0201 |

By comparing the results with the known parameters, the above algorithm can be used to calculate the iron core hysteresis parameters accurately.

The magnetic hysteresis return lines in the 50Hz to 100kHz range of the silicon steel sheet B27RK100 sample measured using magnetic characteristic measurements in the previous section solve the J-A parameters of each magnetic hysteresis backline using the above-mentioned artificial fish and L-M mixing algorithm, as shown in Table 2 below.

**Table 2. Broadband J-A parameters of silicon steel sheet**

| Frequency (Hz) | $M_s$ (A/m) | $\alpha$ | $a$ (A/m) | $k$ | $c$ |
|----------------|-------------|----------|-----------|-----|-----|
| 50Hz           | $1.85 \times 10^6$ | $1.2 \times 10^{-4}$ | 2.83 | 42.12 | 0.0198 |
| 100Hz          | $1.81 \times 10^6$ | $1.0 \times 10^{-4}$ | 3.41 | 72.31 | 0.0197 |
| 200Hz          | $1.60 \times 10^6$ | $1.1 \times 10^{-4}$ | 4.53 | 53.14 | 0.0198 |
| 500Hz          | $1.50 \times 10^6$ | $0.83 \times 10^{-4}$ | 8.31 | 98.12 | 0.0212 |
| 1kHz           | $0.20 \times 10^6$ | $1.1 \times 10^{-4}$ | 3.55 | 43.32 | 0.0201 |
| 5kHz           | $0.19 \times 10^6$ | $0.52 \times 10^{-4}$ | 30.23 | 62.34 | 0.0231 |
| 10kHz          | $0.165 \times 10^6$ | $0.41 \times 10^{-4}$ | 41.54 | 77.23 | 0.0243 |
| 100kHz         | $0.05 \times 10^6$ | $0.35 \times 10^{-4}$ | 80.32 | 100.42 | 0.0251 |

4. Research on the nonlinear characteristics of transformer broadband

Using the J-A model parameters in the wide range of silicon steel sheets found above, the model editor of PSPICE is used to establish core models for each frequency, and the parameters of the nonlinear core model of PSPICE are required to be the initial relative magnetic conductivity, dimensional parameters, saturation magnetization strength $M_s$, shape coefficient $a$, average field coefficient $\alpha$, coupling coefficient $k$ and reversible coefficient $c$.

Select an iron core with an inner diameter of 60mm, an outer diameter of 90mm, a height of 40mm, set the original edge 100, the side 2, and establish a nonlinear transformer model as shown in Figure 6 below, where $R$ is the stray resistance parameter.

Figure 6. PSPICE nonlinear core transformer model

The core transformer model based on a specific frequency will be connected to the original sine AC power supply at a specific frequency. The nonlinear properties of the transformer model are stimulated by adjusting the voltage amplitude of the sine AC power supply output.

In the case of 50Hz, the corresponding nonlinear core model is first established in PSPICE using the J-A model parameters at 50Hz, and the nonlinear transformer model at 50Hz is established based
on the core model. The model's side is then empty, the original side is applied a sine AC voltage of 50Hz frequency, gradually increasing the applied voltage amplitude, and records the transformer's empty U-I characteristics until the transformer is saturated.

Record the empty U-I characteristics of the transformer at each frequency, as shown in Figure 7 below.

![Graph of nonlinear characters of transformer under wide frequency and no load](image)

**Figure 7. nonlinear characters of transformer underlying wide frequency and no load**

It can be found that the saturation and nonlinear characteristics of the transformer vary dramatically with frequency, except for 1kHz, the transformer airborne saturation voltage amplitude increases with the increase of frequency, mainly due to the change of the saturation magnetic field strength and relative magnetic conductivity of the silicon steel core with frequency. The transformer's empty load saturation voltage amplitude at 100Hz nearly doubles from 50Hz, and with the increase in frequency, it is almost linear, so in the nonlinear modeling of transformer broadband, the nonlinear characteristics at 50Hz will be used to delinearize the broadband model will have a large error. In the subsequent study of transformer broadband modeling method, we can try to establish a more accurate transformer frequency nonlinear equivalent model by utilizing the nonlinear characteristics of transformers at multiple frequencies (under wide frequency range).

5. Conclusions

This paper focuses on the nonlinear characteristics of transformer wide frequency, first of all, using the 25cm Epstein ring frame and AMH-1M magnetic guide measurement system to measure the silicon steel sheet B27KR100 samples in the range of 50Hz to 100kHz magnetic hysteresis backline, and using artificial fish and L-M mixing algorithm, optimized the wide frequency range transformer silicon core J-A parameters. Then, using this parameter, a nonlinear model of the iron core of silicon steel sheet is established in PSPICE, and a transformer model is built based on this model. By applying the sine voltage signal of a specific frequency to the nonlinear transformer model of a specific frequency, the nonlinear characteristics of transformers in the wide frequency range are obtained, and the nonlinear characteristics of transformer cores are found to change dramatically with frequency. Linear modeling of transformer broadband, there will be a large error in the nonlinearization of the broadband model by using the nonlinear characteristics at 50Hz, and the subsequent modeling research should consider the frequency-variable nonlinear characteristics of the transformer for modeling, and try to use the nonlinear characteristics of transformers at multiple frequencies to model the broadband nonlinear.

Acknowledgement

This work is supported by Science and Technology Project of State Grid Corporation of China (SGTYHT/17-JS-199);

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