

Identification of A Hysteresis Model Parameters Using the Differential Evolution Algorithm

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Abstract. Establishing the accurate mathematical and simulation model of transformer is the basis of the power system steady state and transient state analysis, but the nonlinear of the transformer main magnetic circuit makes it difficult to accurate analysis of the transformer and its system. Jiles-Atherton hysteresis model as one of the classical model of ferromagnetic materials, is a physical basis of phenomenological model. It enables the mathematical description of hysteresis curves using five parameters that depend on the magnetic material characteristics. This paper introduces a modified Jiles-Atherton static hysteresis model, and the inverse model was deducted. And then this paper identifies of a hysteresis model parameters using the differential evolution algorithm, and the calculated results are well agreed with the date.

1. Introduction

As one of the most important electrical equipment in power system, the safe operation of transformer is directly related to the stable and continuous work of the power system. At present, with the expansion of the scale about the power system, more and larger capacity transformers are put into the power grid, and the number of accidents increases. The magnetic circuit of the transformer is mainly composed of ferromagnetic material. At present most of transformer designs don't considering the complex influence of hysteresis loop, or simulate based on the basic magnetization curve to simplify the characteristics of the material' magnetization. These questions can cause inevitable simulation error on the excitation current and fault current. This is one of the important reasons for the low accuracy of relay protection [1].

At the same time the transformer DC bias phenomenon caused by the DC magnetic potential and the corresponding DC magnetic flux in the transformer electromagnetic field. In the condition of DC bias, the winding current of power transformer will be seriously distorted, which contains abundant even and odd harmonics. In the power transformer, a large number of magnetic flux in the supersaturation of the iron core closed, the transformer itself will be increased vibration, noise, local overheating, and even insulation damage. Establishing the correct the mathematical model of transformer under DC bias is an important way to solve the problem [2].

Jiles-Atherton hysteresis model [3-5] is a classical mathematical model which is the most commonly used to accurately describe the hysteresis characteristics of ferromagnetic materials. The physical meaning of the Jiles-Atherton model is easy to understand, and it can describe the nonlinear relationship between B and H accurately. By solving the model equation can obtain the accurate B-H



magnetic hysteresis, the key of the problem is identifying the model's parameters. Based on the situation, this paper attempts to use the differential evolution algorithm to solve this problem.

2. Jiles-Atherton model

According to J-A model, we can divide the magnetization M into reversible magnetization M_{rev} and irreversible magnetization M_{irr} , the equation of the whole model is as follows.

$$M = M_{irr} + M_{rev} \quad (1)$$

This model include five parameters, and can be described by a set of differential equations contain the five parameters. The five parameters of the Jiles-Atherton model k , c , a , α , M_s can be described as:

$$H_e = H + \alpha \cdot M \quad (2)$$

$$M_{an} = M_s \cdot \left(\coth\left(\frac{H_e}{a}\right) - \frac{a}{H_e} \right) \quad (3)$$

$$\frac{dM}{dH} = \frac{c \cdot \frac{dM_{an}}{dH_e} + \frac{M_{an} - M}{\delta \cdot k - \frac{\alpha \cdot (M_{an} - M)}{1 - c}}}{1 - c \cdot \alpha \cdot \frac{dM_{an}}{dH_e}} \quad (4)$$

Where H_e means the effective magnetic-field strength, δ is the parameter that is represent the increase/decrease of magnetic-field. For the 5 model parameters, a is the shape parameter of hysteresis parameters, α is the even field parameter of magnetic domain wall bending constant, k is the parameter about hysteresis loss and M_s is the saturation magnetization. M_s determine the maximum magnetization.

Jiles-Atherton model includes the original model and the inverse model. The original model regards H as independent; the inverse model regards B as independent. When describing the characteristics of transformer core due to experimental data, the voltage of the primary side of the transformer can be measured, so the inverse model is used more, this paper uses the inverse model.

From equation above, we can get the inverse model:

$$\frac{dM}{dB} = \frac{(1 - c) \frac{M_{an} - M_{irr}}{\mu_0 k \delta} + \frac{c dM_{an}}{\mu_0 dH_e}}{1 + (1 - c) (1 - \alpha) \frac{M_{an} - M_{irr}}{k \delta} + c(1 - \alpha) \frac{dM_{an}}{dH_e}} \quad (5)$$

$$H = \frac{B}{\mu} - M \quad (6)$$

The paper [5] modified the Jiles-Atherton model, using equation 7 instead of equation 8

$$\frac{dM_{irr}}{dH_e} = \frac{M_{an} - M}{\delta k} \quad (7)$$

$$\frac{dM_{irr}}{dH_e} = \frac{M_{an} - M_{irr}}{\delta k} \quad (8)$$

So, the inverse model becomes:

$$\frac{dM}{dB} = \frac{(1 - c) \frac{M_{an} - M}{\mu_0 k \delta} + \frac{c dM_{an}}{\mu_0 dH_e}}{1 + (1 - c) (1 - \alpha) \frac{M_{an} - M}{k \delta} + c(1 - \alpha) \frac{dM_{an}}{dH_e}} \quad (9)$$

As the paper mentioned, this modification makes the model had more scope application, even the parameter c is small [6]. So to improve the accuracy and application scope of the model, this paper adopt this modification.

In the paper [7], the parameter k is modified as [7]

$$k = k_0 e^{-\left(\frac{H^2}{2\sigma^2}\right)} \quad (10)$$

Where the k_0 is the original constant parameter, σ means the Gaussian function's standard deviation.

In the paper [8], the parameter k is modified as [8]

$$k = k_0 \left[1 - 0.96 \left(\frac{M}{M_s} \right)^2 \right] \quad (11)$$

In consideration of the inverse model the paper used, I chose the last one. The expression of the model is relatively complex, there are five parameters, M_s , k , c , a , α . M_s can be given by the manufacturer specific material, the others can be get according to differential rate of the measured hysteresis loop at a particular point, but the requirement of the accuracy of experimental data is very high. In practice, it is very difficult to achieve such precision, so the fitting method is often used to get the parameters.

3. Parameter identification method based on the DE algorithm

This years, differential evolution algorithm (DE) was paid more and more attention in the field of evolutionary computation, and its application field has become more and more wide. Compared with genetic algorithm, the most important characteristic of DE in every new generation process of the individual uses the linear combination of multiple individuals instead of the traditional parent's chromosome crossing technique. So DE can be a good expansion of search space while ensuring the convergence of the algorithm.

The algorithm of DE can quickly and efficiently solve the minimum of the objective function of the differential equations. This paper writes the transformer model function and difference evolution algorithm, by combining with the objective function, and identifies the model parameters, as shown in Fig. 1.

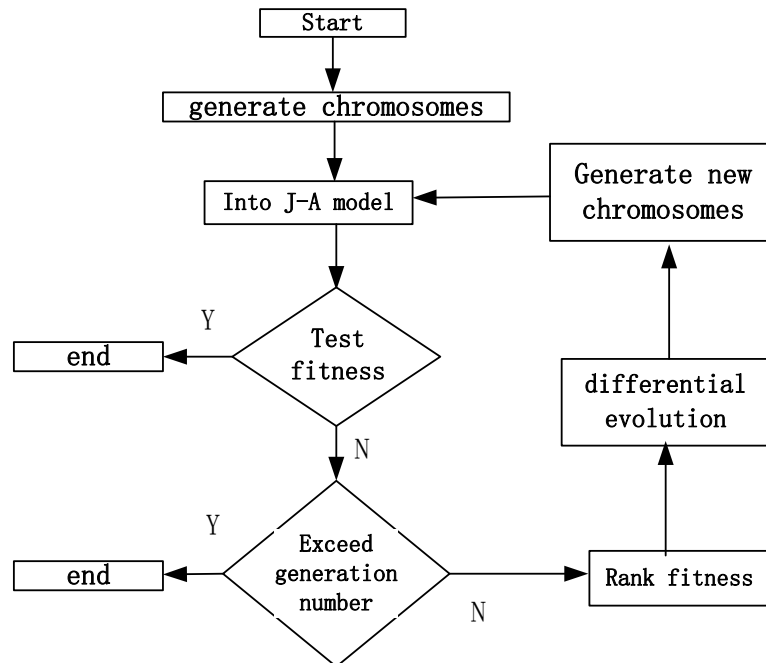


Figure 1. Figure about the differential evolution algorithm.

The Jiles-Atherton model's equations were using the 4th order Runge-Kutta method for diminishing integration errors.

The fitness function is the squared error between the measured value and the calculated ones.

$$\text{fitness} = \frac{1}{N} \sqrt{\sum_{i=1}^N (H_{\text{exp}}(B) - H_e(B))^2} \quad (12)$$

Where N is the number of dates, H_{exp} represents the calculated date values, and H_e means the measured dates.

In order to check the effectiveness of the method of this paper, a hysteresis loop is generated by using the parameters:

$$M_s = 1.7 \times 10^6 \text{ A/m}, k = 500 \text{ A/m}, c = 0.1, a = 1000 \text{ A/m}, \alpha = 0.001$$

And then the parameters are identified. The identification results are shown in Tab. 1, Fig. 2.

Table 1. The results of identifying given parameters

parameters	M_s (A/m)	k (A/m)	c	a (A/m)	α
Original value	1.7×10^6	500	0.1	1000	0.001
Identification value	1.689×10^6	512.2	0.098	1013.9	0.00115
Error /%	0.6	2.44	2.2	1.39	15

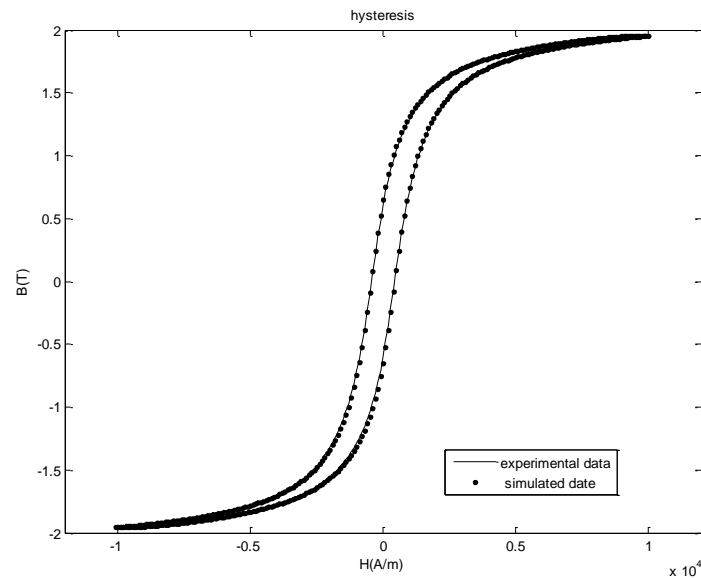


Figure 2. The results of identifying given parameters.

The identification results show that the parameters of identification values are close to the original values, and the hysteresis loop pattern is consistent. So the article's parameters identification method is effective.

4. Verified the algorithm

4.1. Verified the algorithm by the hysteresis measured from electrical steel sheet

In this paper, 30RGH20 electrical steel sheet is selected for simulation calculation, and the differential algorithm is used to optimize, and the calculated values of each parameter are obtained. J-A model simulation parameters are:

$$M_s = 1.207 \times 10^6 \text{ A/M}, k = 87.402 \text{ A/m}, c = 0.00462, a = 41.418 \text{ A/m}, \alpha = 0.9755 \times 10^{-6}$$

And the simulation identification results shown in Fig. 3.

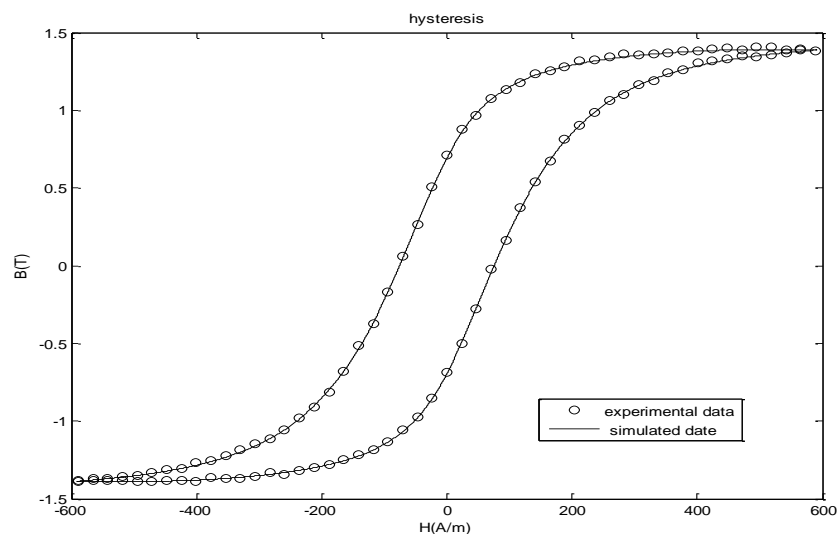


Figure 3. Hysteresis loop identification results.

From the results, simulation loop and the measured line is quite consistent.

4.2. Verified the algorithm by simulation

Using PSCAD to build the simulation system is shown in Figure 4. The system is used to simulate the single-phase transformer no-load closing. The ratio of the transformer is 230 KV: 110 KV. The capacity is 100 MVA. Copper losses is 0.15 per unit value, leakage reactance is 0.1 per unit value. So the leakage resistance of primary side R_p is 39.67Ω , the leakage inductance of primary side L_p is 0.08 H.

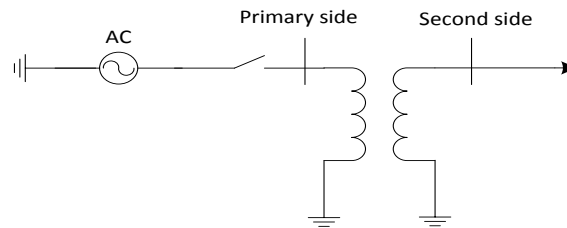


Figure 4. Single-phase transformer no-load closing.

Due to no-load excitation, the current of primary side i_p is the same as inrush current. So the following equations were obtained. [9]

$$V_t(t) = V_p(t) - R_p i_p(t) - L_p \frac{di_p}{dt} \quad (13)$$

$$V_t = AN_p \frac{dB}{dt} = \frac{AN_p^2}{l_m} \frac{dB}{dH} \frac{di_t}{dt} \quad (14)$$

Where i_t is the excitation current, V_t is the excitation voltage.

The experimental and simulated values of the transformer inrush current is shown in Fig. 5.

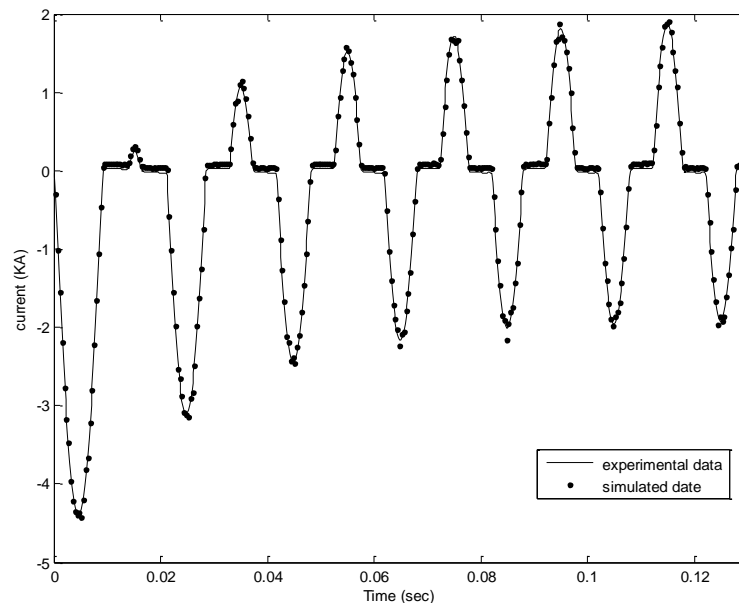


Figure 5. The simulation of the transformer inrush current.

From the result, the method can work well to simulate the inrush current. So the method identifying of the hysteresis model parameters using the differential evolution algorithm is effective.

Conclusion

In this paper, the Jiles-Atherton hysteresis model is used to describe the excitation branch of transformer, and the model parameters are optimized by differential evolution algorithm. The method can simulate the hysteresis loop and magnetizing inrush effective. It will be helpful to analyse the transient process of the transformer in the power system.

The next step is to analyse the dynamic Jiles-Atherton model and identify the parameters to raise the accuracy.

References

- [1] [Li, Huiqi, Qingfeng Li, and Junjie Zhang. (2009). Calculation of Jiles-Atherton hysteresis model's parameters using mix of chaos optimization algorithm and simulated annealing algorithm. *Microwave Technology and Computational Electromagnetics, 2009. ICMTCE. International Conference on. IET*
- [2] Li, Xiao-Ping, et al. (No. 9. 2007). "Test and simulation for single-phase transformer under DC bias." *Zhongguo Dianji Gongcheng Xuebao(Proceedings of the Chinese Society of Electrical Engineering)*. Vol. 27.
- [3] Jiles, David C, J. B. Thoeke, and M. K. Devine. (1992). Numerical determination of hysteresis parameters for the modeling of magnetic properties using the theory of ferromagnetic hysteresis. *IEEE Transactions on Magnetics* 28.1:27-35
- [4] Jiles, D. C., and D. L. Atherton. (1984). Theory of ferromagnetic hysteresis. *Journal of applied physics* 55.6: 2115-2120
- [5] Jiles, D. C., and D. L. Atherton. (1986). Theory of ferromagnetic hysteresis. *Journal of magnetism and magnetic materials* 61.1-2: 48-60
- [6] LI, Zhen, et al. (2011). Queries on the JA Modeling Theory of the Magnetization Process in Ferromagnets and Proposed Correction Method. *Proceedings of the CSEE* 3: 021
- [7] Wilson, P. R., Ross, J. N., & Brown, A. D. (2001). Optimizing the Jiles-Atherton model of hysteresis by a genetic algorithm. *IEEE Transactions on Magnetics*, 37(2), 989-993
- [8] Annakkage, U. D., McLaren, P. G., Dirks, E., Jayasinghe, R. P., & Parker, A. D. (2000). A current transformer model based on the Jiles-Atherton theory of ferromagnetic hysteresis. *IEEE Transactions on Power Delivery*, 15(1), 57-61
- [9] Huang, S. R., Chen, H. T., Wu, C. C., Guan, C. Y., & Cheng, C. (2012). Distinguishing internal winding faults from inrush currents in power transformers using Jiles-Atherton model parameters based on correlation coefficient. *IEEE Transactions on Power Delivery*, 27(2), 548-553