

## Research on Real Time Simulation and Protection Test of Power Transformer Inrush Current

Jun Liu<sup>1, a</sup>, Shiwu Xiao<sup>1, b</sup>, Xiaojiao Liang<sup>2, c</sup>, Huanju Liu<sup>2, d</sup> and Hao Zou<sup>2, e</sup>

<sup>1</sup>School of Electrical & Electronic Engineering, North China Electrical Power University, Changpin, Beijing, China

<sup>2</sup>State Grid Shandong Electric Power Company Tai'an Power Supply Company, Tai'an, Shandong, China

<sup>a</sup>ljncepu@163.com, <sup>b</sup>xiaoshiwu@263.net

**Keywords:** inrush current; transient simulation; magnetization curve.

**Abstract.** This paper introduces the principle of the excitation inrush transient calculation firstly, including the basic thoughts of simulation calculation and the basic method of numerical calculation. And then the dynamic magnetization of the transformer core is described, and the simulation of inrush current is carried out. At last, the accuracy of the transformer protection test function is verified.

### Introduction

Power transformer is a very important electrical equipment in power system. And it plays a key role in power transformation in the whole power system. Therefore, it is necessary to analyze the change of the physical quantities in the transient and steady state of transformer fault operation to determine the distribution and variation of electrical quantities such as current, voltage and so on.

In this paper, the transient simulation model of transformer is used to develop the simulation program of the inrush current and the internal fault of transformer. And the high-precision electromagnetic transient waveform is output through the DA channel of the lower machine. The comparison between the simulation waveforms and the reference waveforms verifies the accuracy of the transformer protection test function [1].

### Principle of the Transient Simulation Calculations of Transformer Inrush Current

Various components of the power system in the electromagnetic transient process can be used to describe the relationship between the voltage and current of the power system by using some algebraic equations, ordinary differential equations or partial differential equations. We can use the numerical calculation method to solve these equations and replace these components by using equivalent circuits composed of pure resistance and current source. This circuit is called transient equivalent calculation circuit. According to the actual connection mode between components connect their transient equivalent circuit so that a pure resistance network with a known current source can be made up. And by solving this network, we can get the voltage and current of each component of any time.

**The general thought of the simulation.** The solution thought of simulation in this paper is that all objects are abstracted as electricity networks with actual links, and the program is directly facing the specific circuit. Program has strict rules on the processing of each component in circuit. The basic idea is to use differential equation to describe the relationship between the voltage and current in the transition process of each component[2].

When using numerical method, the program divides the whole transient process into a number of time segments using  $\Delta t$  as unit. In a calculation step  $\Delta t$ , transform the differential equation into the corresponding difference equation and put the differential equation into a current source and equivalent resistor in parallel unit, connect these units according to the actual connection mode of the circuit, and then the actual circuit will become a pure resistance network with a current source only. And by solving the network, we can obtain the voltage and current of each component of this moment;

then take this as initial condition, and carry out the recursive solution of next step in sequence and the numerical solution of the transient process is obtained. After each calculation, a new value will be assigned to the current source. The resistance value is changed only when the circuit is transferred from one section to another section. The conversion of circuit operating point is controlled by judging whether the current is beyond the limits of this section. If the calculation results have exceeded the upper limit of this section, it will transfer to the next section to continue, and the resistance becomes the value determined by slope of next section. In this paper, the equivalent nonlinear inductance of the transformer's magnetizing branch is handled by the curve fitting method. So inductance value is determined again after every step of the calculation[3].

**Simulation system description.** The basic electrical main wiring of the system is shown in Fig.1. Components in a power network generally include power supply, line, transformer, etc. In simulation calculation, in the case of considering the internal impedance of the power source, power source is replaced by a power impedance branch, line is replaced by impedance branch, transformer is replaced by coupled impedance branch. The numerical processing method of various branches in the network is introduced below.

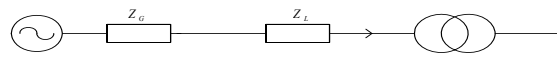


Fig.1. Power system diagram

**The basic method of numerical calculation in electromagnetic transient process.** The numerical method used to turn differential equations which describes power system components into transient equivalent circuit is mostly the implicit trapezoidal integration method. The differential equation is differenced by using the implicit trapezoidal integration method [4]. And then transform it into algebraic equations for solving. Differential rules are as follows:

- (1) a variable  $dx$  with a differential operator  $d$  is expressed by  $dx/dt = \frac{x(t) - x(t - \Delta t)}{\Delta t}$ ;
- (2) variable  $x$  without differential operator is expressed by  $\frac{1}{2}[x(t) + x(t - \Delta t)]$ ;
- (3) the constant term and constant coefficient remain unchanged.

For the simulation of three-phase transformer inrush current, the basic equation for transient calculation is:

$$[u] = [R] \cdot [i] + [l] \cdot \left[ \frac{di}{dt} \right] \quad (1)$$

In the simulation of three-phase transformer inrush current,  $[u]$ ,  $[i]$  and  $[l]$  are variables,  $[R]$  is a constant. So the differential form of the above formula is:

$$\frac{1}{2}[u(t) + u(t - \Delta t)] = \frac{1}{2} \cdot [R] \cdot [i(t) + i(t - \Delta t)] + \frac{1}{2} \cdot [l(t) + l(t - \Delta t)] \cdot \frac{i(t) - i(t - \Delta t)}{\Delta t} \quad (2)$$

In the process of calculation, variable  $[u(t - \Delta t)]$ ,  $[i(t - \Delta t)]$  and  $[l(t - \Delta t)]$  at time  $(t - \Delta t)$  are known. After finishing the above formula, the expression of  $[i]$  at time  $t$  is:

$$[i(t)] = \left[ [R_l(t)] + [R] \right]^{-1} \cdot [u(t)] + [l_l(t - \Delta t)] \quad (3)$$

$$[R_l(t)] = \left[ \frac{[l(t) + l(t - \Delta t)]}{\Delta t} \right] \quad (4)$$

$$\begin{aligned}
[I_l(t-\Delta t)] &= \{[R_l(t)]+[R]\} \cdot [u(t-\Delta t)] +^{-1} \{[R_l(t)]+[R]\}^{-1} \cdot \\
&\{[R_l(t)]-[R]\} \cdot \{[R_l(t-\Delta t)]+[R]\}^{-1} \cdot [u(t-\Delta t)] + \\
&\{[R_l(t)]+[R]\}^{-1} \cdot \{[R_l(t)]-[R]\} \cdot [I(t-2\Delta t)]
\end{aligned} \tag{5}$$

### Simulation Function Design of Transformer Inrush Current

The magnetization curve is a curve describing the relationship between magnetic induction density B (flux  $\Psi$ ) and the magnetic field intensity H (excitation current  $i_0$ ). Magnetic circuit of the core has saturation characteristics, as well as the hysteresis effect, so B-H curve shows as hysteresis loop. The curve composed of the normal apex of the magnetic hysteresis loop is called the basic magnetization curve, as is shown in Fig.2.

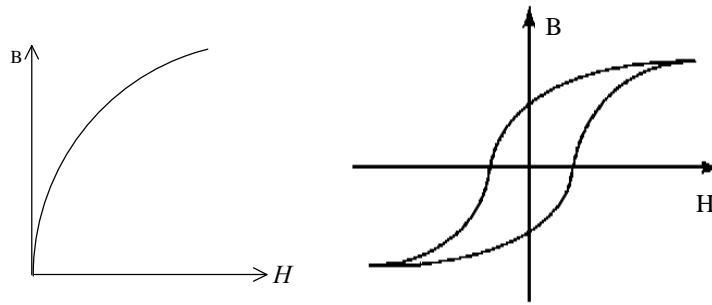


Fig.2. Basic magnetization curve and hysteresis loop of ferromagnetic materials

The research content of this paper is to establish the equivalent model of transient simulation of transformer based on the node voltage method, and its engineering application object is the research and use department of transformer protection, so the simulation model is based on the basic magnetization curve [5]. Therefore, the influence of the magnetic hysteresis and the eddy current in the transformer core excitation characteristics is neglected, and the basic magnetization curve is counted only.

Check the curve of the corresponding material according to the model of the transformer core ferromagnetic material, and we can obtain the sample data  $(B_i, H_i)$ ,  $i=(0,1,\dots,n)$  after the discretization. Use function  $H = f(B, p_1, p_2)$  as a fitting function of the basic magnetization curve, where the variable  $p_1, p_2$  are undetermined coefficients. Use the least square method to calculate the minimum value of variance  $\varepsilon$ :

$$\varepsilon = \sum_{i=0}^n (f(B_i, p_1, p_2) - H_i)^2 = \min \tag{6}$$

Solve partial derivative and we can get:

$$\frac{\partial \varepsilon}{\partial p_j} = 2 \sum_{i=0}^n (f(B_i, p_1, p_2) - H_i) \cdot (\partial f(B_i, p_1, p_2) / \partial p_j) \quad (j=1,2) \tag{7}$$

$$\text{Making } E_j = \sum (f(B_j, p_1, p_2) - H_i) \cdot (\partial f(B_i, p_1, p_2) / \partial p_j) \quad (j=1,2),$$

According to the limit theorem, in order to get the minimum value of  $\varepsilon$ , we need to calculate the zero point of formula (3-2), that is to solve the equations:

$$f_j(p_1, p_2) = E_j = 0 \dots \dots (j=1,2) \tag{8}$$

After getting  $p_1, p_2$ , the fitting expression of the basic magnetization curve is obtained.

$$H = f(B, p_1, p_2) \quad (9)$$

Above is the solution process of fitting curve using the least square method. In this thesis, we use arc tangent function  $B = a \cdot \arctan(bx)$  as fitting function to fit the base curve of the transformer[6], the fitting result is shown in Fig.3.

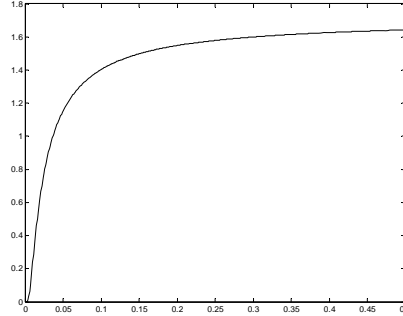


Fig.3 Basic magnetization curve after fitting

### Verification of Inrush Current Waveform

In this example, the three-phase transformer MTP1-7.5 in the dynamic model laboratory of Tsinghua University is adopted, parameter data are as follows. Rated capacity  $S_N = 7.5KVA$  ; rated voltage  $U = 200/800 \pm 2 \times 2.5\%V$  ; number of turns  $N = 104/239$  ; core type:D330,0.35mm thick cold-rolled silicon steel sheet; core effective area  $S = 0.01m^2$  ; core midline length  $l = 1.12m$  , winding resistance  $R = 0.2/0.8\Omega$  ; leakage reactance  $L = 0.002/0.01H$  ; connection type Yd-11, amplitude of supply voltage is 120V, the internal resistance of the power supply is 0.0002 ohm, reactance is 0.00628ohm, line resistance is 0.0003 ohm, reactance is 0.00942 ohm, the simulation circuit diagram is shown in Fig.4:

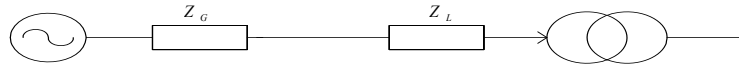


Fig.4. Simulation circuit diagram

Inrush current test without load. Test time is set to 0.10 seconds, inrush current waveforms are shown in Fig.5 under different winding connection mode when the closing angle is  $0^\circ$  ,  $30^\circ$  ,  $90^\circ$  .

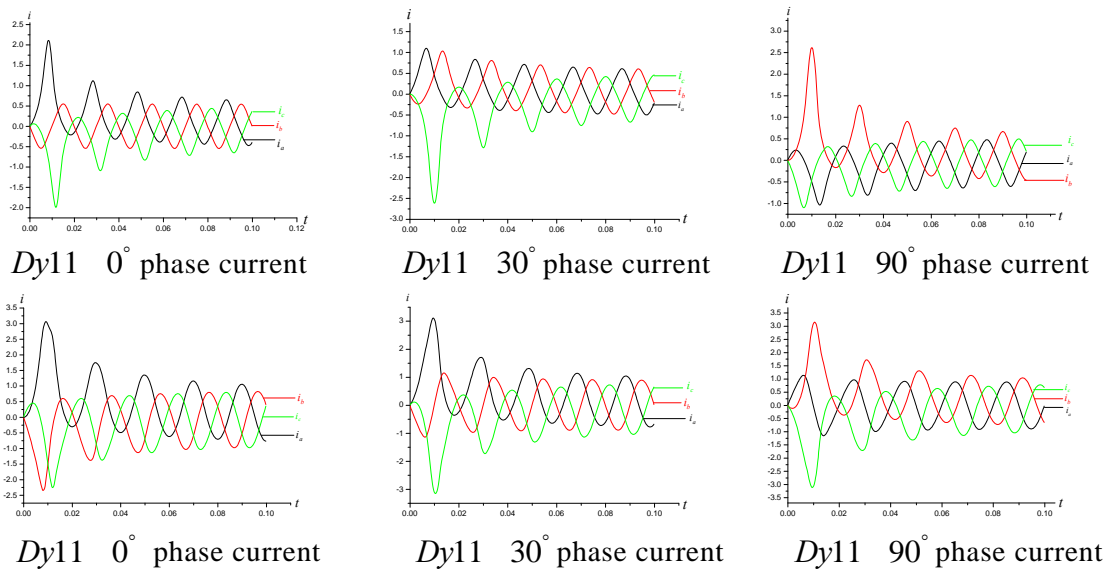


Fig.5. Three phase inrush current waveforms

Inrush current test when transformer closes with load. The resistance of the load converted into the high voltage side is 4 ohm, and the reactance is 9.42 ohm, Test time is set to 0.10 second, inrush current

waveforms are shown in Fig.6 under different winding connection mode when the closing angle is  $0^\circ$ ,  $30^\circ$ ,  $90^\circ$ .

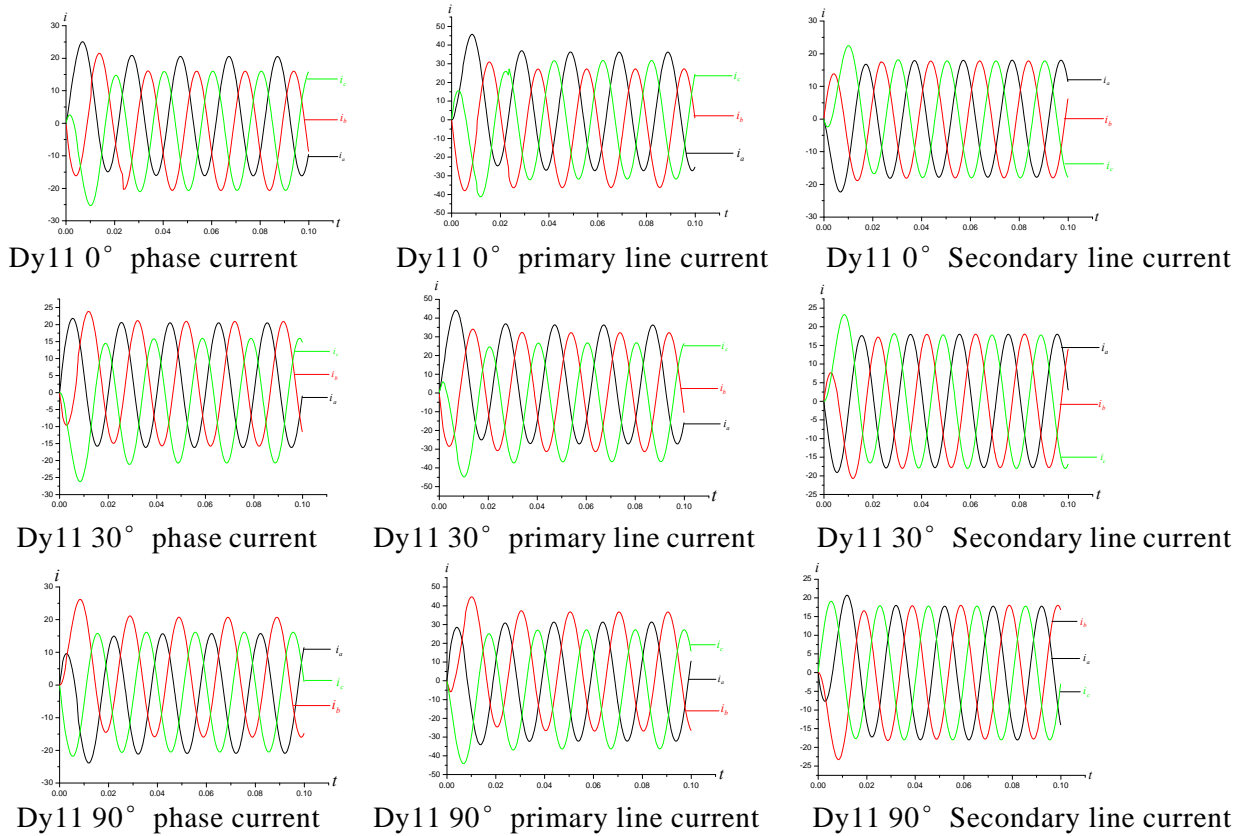


Fig.6. Three phase inrush current waveforms

## Conclusions

This paper introduces the principle of the excitation inrush transient calculation firstly, including the basic thoughts of simulation calculation and the basic method of numerical calculation. And then the dynamic magnetization of the transformer core is described, and the simulation of inrush current is carried out. At last, the accuracy of the test device is verified by comparing the output waveform with the actual fault waveform data.

## References

- [1] Yi Zhu, Dazhong Fang, Power System Technology, J. 36 (2012) 116-120.
- [2] Baohui Zhang, Xianggen Yin, Power System Protective Relaying, second ed., Beijing, 2010.
- [3] Richang Qi, Power Transformer, first ed., Beijing, 2006.
- [4] Xue Wang, Zengping Wang, Study of simulation of transformer with internal faults, J. Power System Technology. 28 (2004) 50-52 (in Chinese).
- [5] Yongrong Huang, Qunzhan Li, Simulation for magnetic inrush and fault current of three phase transformer based on EMTDC, J. Relay. 35 (2007) 26-30 (in Chinese).
- [6] Zeyi Zhao, Zhibizo Feng, Digital real time simulation model and digital integral of autotransformer, J. Journal of Tongji University. 29 (2001) 416-420 (in Chinese).