Fast calculation and analysis of excitation inrush current peak of converter transformer under different remanence conditions

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Abstract. In order to solve the problems of fixed model parameters and low efficiency in the traditional numerical method and software simulation method for transformer excitation inrush current. In this paper, the response surface fitting method is applied to the calculation of the excitation inrush current, which realizes the efficient calculation and analysis of the peak value of the excitation inrush current with the change of the closing Angle under the condition of different remanence of the main column. Firstly, the generation mechanism of transformer excitation inrush current was theoretically analyzed, and the key influencing factors were extracted. Secondly, parameter modeling is used to establish the converter transformer model in this paper. Finally, the response surface model between initial winding current, closing Angle and excitation inrush current peak was fitted by response surface test design, and the accuracy of the response surface was verified. It provides technical reference for the fast calculation and analysis of transformer excitation inrush current and the digital twin technology of power transformer.

Keywords: converter transformer; Excitation inrush current; Response surface method; Fast calculation.

1. Introduction

With the progress and development of China's electric power system, the voltage level, transmission capacity and transmission distance of the grid are constantly increasing. In this context, HVDC transmission has lower loss and higher economy. As the core equipment in HVDC transmission, the converter transformer links the AC system and the DC system, and has special working mode, which has the characteristics of large capacity, high knee point working voltage and high remanence level. Therefore, the converter transformer core is easy to saturate, and the excitation inrush current amplitude is higher and decays slowly when the no-load closing occurs[1-3]. The excitation inrush current may cause the misoperation of the relay protection device, resulting in the failure of the transformer closing. It may seriously induce the generation of the rheoconversion and the inrush current in the transport, and then lead to the mistrip of the large area in the transport protection, resulting in a power outage.

In order to avoid the misoperation of the power system relay protection device caused by the excitation inrush current of the converter transformer when it is aircast, the peak value of the excitation inrush current generated by the converter closing under different remagnetization and initial phase Angle conditions is calculated accurately and quickly, which is of great significance for the protection value setting of the power system relay protection equipment and the prevention of the misoperation of the protection device. At present, the calculation of transformer excitation inrush current is mainly divided into analytical method and software simulation method. The analytical method uses the magnetic circuit equivalent of the core and winding of the transformer, the calculation process takes into account the hysteresis characteristics of the core, and can evaluate the transformer excitation inrush current qualitatively, but the quantitative analysis is not accurate enough. The software simulation method is to apply Matlab, EMTP, finite element and other simulation software to model and simulate materials such as transformer core parameters, and then obtain the current of transient process, but it cannot be solved in real time [4-5].

The response surface method is a data fitting method, which is a combination of mathematics and statistics. It is commonly used to change the combination of different input parameter values to achieve the effect of obtaining the best response value [6]. Response surface method (RSM) has a wide range of applications in the field of engineering by virtue of its high efficiency of fitting calculation. In the field of electrical engineering, it is often used in the structural design and optimization of various electrical equipment.

In view of the above research status, this paper proposes to apply the response surface fitting calculation method to the calculation of the transformer excitation inrush current peak. The remagnetic density at the center of the main column and the initial closing Angle are taken as the fitting variables, and the excitation inrush current peak is taken as the response value, so as to realize the real-time calculation of the excitation inrush current peak of the transformer under different remagnetic conditions and different closing angles. Firstly, a simulation model of single-phase converter transformer was established based on finite element software. Secondly, taking the initial closing Angle and the initial winding current (remanence) as variables, the response surface model of the excitation inundation current peak was obtained by multiple response surface fitting in the Design of Experiments (DOE). Finally, the accuracy of the response surface was verified by comparing the calculated values of the response surface model with the calculated values of the full-order finite element method. It provides a certain technical reference for the fast calculation and analysis of transformer excitation inrush current and the research of power transformer digital twin technology.

2. Rationale

2.1 Excitation inrush current analysis

Before the transformer is closed, the total flux in the transformer is remanent. At the closing moment, steady state flux will be generated due to the applied voltage. According to the flux conservation theorem (the total flux cannot be mutated), a transient induced flux with the opposite direction and the same magnitude will be generated. The bias flux synthesized by the transient induced flux and the remagnetization inside the transformer will slowly decay with time in the transformer. When the total flux combined by the bias and steady flux exceeds the saturation flux, the transformer winding reactance drops sharply and the excitation inrush current is generated.

The electromagnetic equation of transformer closing is as follows.

$$ri + \frac{d\varphi}{dt} = U_s \sin(wt + \alpha) \tag{1}$$

$$\begin{aligned}\varphi &= \varphi_s + \varphi_\sigma + \varphi_K + \varphi_I = (L_s + L_\sigma + L_K)\mathrm{i} + \varphi_I \\ &= (L_s + L_\sigma + L_K)\mathrm{i} + WSB_I\end{aligned} \tag{2}$$

Where: r is the total resistance of the closing circuit; ψ is the total flux linkage of the closing loop, including the system flux ψs(ψs=Lsi), the self-leakage flux ψσ(ψσ=Lσi), the interleakage flux ψk(ψk=Lki) and the core flux ψI(ψI=WSBI), where BI is the magnetic density of the core. Lk+LH is the linear differential inductance after extreme saturation of the core.

Equation (1) can be solved as follows.

$$\varphi = \frac{U_s}{w}\left(\cos\alpha - \cos(wt + \alpha)\right) + \varphi_r - r\int_0^t i dt \tag{3}$$

Where, ψr is the core remanence flux linkage (ψr=WSBr), and Br is the remanence magnetic density. Here, only the initial inrush current amplitude is studied, the attenuation effect is limited,

Combining Equations (2) and (3), the following can be obtained.

$$\varphi = (L_s + L_\sigma + M_{air})i + \mu_0 WSJ_{Sat} \tag{4}$$

When ψ<μ0WSJSat, that is, B<BSat, H=0 and i=0. When the current is not 0, combined with Equations (3) and (4), the expression of transformer single-phase excitation inrush current is obtained as follows.

$$i = \frac{U_s}{wL}\left(\cos\alpha - \cos\left(wt+\alpha\right) - \frac{w\mu_0 WSJ_{Sat} - w\varphi_r}{U_s}\right) \tag{5}$$

It can be seen from Equation (5) that when the external conditions are consistent, the size of inrush current is only determined by the denominator L.

2.2 Response surface method

The basic idea of the response surface method is to construct a polynomial with an explicit expression form to express the implicit functional function[7]. The first-order polynomial form and the second-order polynomial form are commonly used, and their expressions are as follows:

$$y = \beta_0 + \sum_{i=1}^{n} \beta_i x_i + \varepsilon \tag{6}$$

$$y = \beta_0 + \sum_{i=1}^{n} \beta_i x_i + \sum_{i=1}^{n} \beta_{ii} x_i^2 + \sum_{i<j}^{n} \beta_{ij} x_i x_j + \varepsilon \tag{7}$$

Where y is the objective function, 0 is the constant term, i is the first-order coefficient, ii is the second-order coefficient, ij is the second-order interaction coefficient, is the error variable, xi is the variable, and n is the number of variables involved in the fitting.

Higher order polynomial functions can effectively improve the smoothness in the numerical fitting process and improve the reliability of the fitted model. The accuracy of the first-order model is limited but the model is simple. In this paper, it is necessary to ensure high accuracy of the model while satisfying that the model is not too complex, so the second-order polynomial form is chosen.

3. Transformer model establishment

In this paper, a single-phase converter transformer is taken as the research object, and the simulation calculation is carried out to provide the calculation results for the response surface design, and the specific transformer parameters are shown in Table 1.

According to the theoretical analysis in the above section, the excitation insurge current is related to the closing Angle and the initial remagnetization. Therefore, the winding excitation of the transformer in this paper adopts the way of parameterized setting. In this paper, the initial remagnetization state of the transformer is equivalent, and the initial current I0 is added to the excitation setting, as shown in Figure 3. At the same time, the closing Angle term q is added to simulate different initial phase closing situations.

Table 1. Main parameters of transformer

parameters	Numerical value
Number of phases	1
Rated frequency/Hz	50
Rated capacity/MVA	412.3
Grid side, valve side rated voltage/kV	441.7/174.9
Net side, valve side rated currenA	467/1179

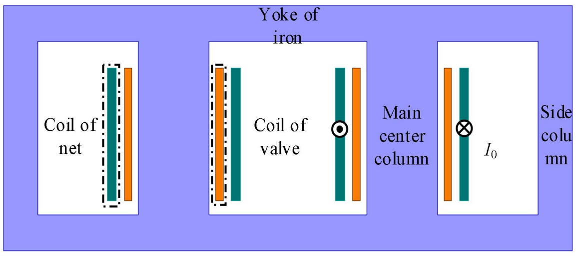

Fig. 3 Transformer simulation model

4. Generation and analysis of excitation inrush current peak response surface

4.1 Response Surface Design

The response surface fitting accuracy largely depends on the layout of DOE sampling points, and reasonable layout design can greatly reduce the number of required data points and improve the response surface fitting accuracy[8]. In order to make the fitting smoother, this paper uses the Latin Hypercube Sampling (LHS) method with high sampling efficiency. LHS includes two processes: sampling and permutation[9]. Lattice sampling (LS) is used in the sampling process, and Gram-Schmidt sequence orthogonalization method is used in the permutation process to eliminate the correlation between rows[10-11].

In the response surface design of this paper, the initial current I0 and the closing Angle q of the converter transformer are taken as variables, and the peak inundation current of the grid-side winding Imax is taken as the research object of the response value. The specific fitting variables and their distribution ranges are shown in Table 2.

Table 2. Fitted variables and their range distributions

variables	Minimum value	Minimum value
I0 /mA	0	1000
q /deg	0	90

For the sample size N, the central composite design (CCD) method is used in this paper, and the required number of runs is consistent as follows.

$$N = 2^{n-f} + 2n + np \tag{8}$$

In Equation (8), n is the number of variables, f is the partial factor, and np is the number of central point runs.

According to Equation (5), the number of fitting variables n is 2, f is 0, and np is 1. It can be calculated that each variable Xk (k=1, 2) needs to be sampled by LHS for 9 times (22+2 × 2+1). After the Gram-Schmidt permutation process, the sampling matrix L of order 2 × 9 is finally generated, and the rows of the matrix represent all the sampling values of a variable in 2. The columns of this matrix represent the input values of all variables in a given DOE calculation. That is, the response surface fitting in this paper needs to run 9 DOE calculations.

4.2 Analysis and evaluation of response surface results

After response surface fitting, the response surface is obtained as shown in Figure 5. Obviously, with the increase of initial current (remagnetization), the peak value of excitation inrush current increases sharply, and with the increase of closing Angle, the excitation inrush current decreases.

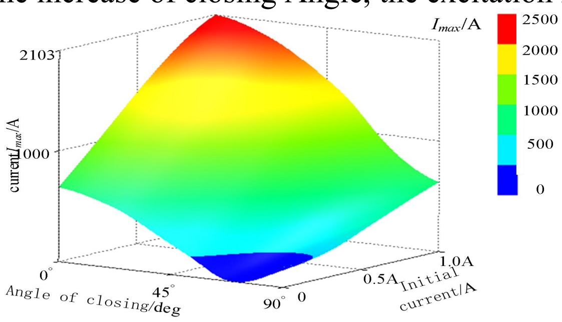

Fig. 5 Response surface model

Based on the response surface model obtained by fitting, the response value prediction results under any combination of variables are obtained in this paper. In order to verify the prediction accuracy of the response surface, nine groups of data samples in the variable interval were uniformly selected in this paper, and the response surface prediction value of the excitation inrush current peak Imax was compared with the actual finite element calculation results, as shown in FIG.

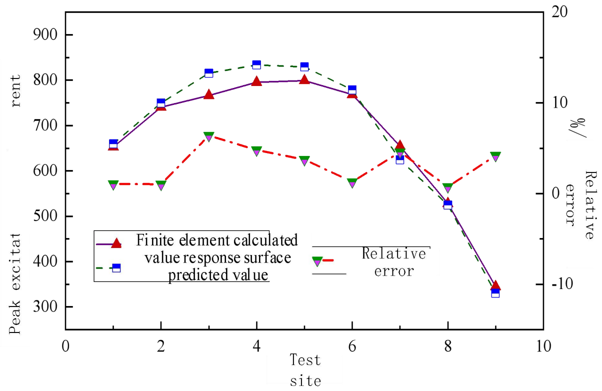

Fig. 6 Validation of the accuracy of the response surface model

It can be seen from Figure 6 that the predicted value of the response surface model is very close to the calculated value of the full-order finite element model, indicating that the response surface model has high fitting degree and good prediction accuracy. The maximum prediction error is less than 5%, which meets the requirements of engineering accuracy.

4.3 Relationship between initial current and remanence

In this paper, the response surface design obtains the fitting relationship between the initial current I0 and the closing Angle, but in the actual engineering, the initial remagnetization of the main column is measured, and the inundation current is estimated according to the remagnetization condition. Therefore, it is necessary to study the relationship between the remanence of the core column and the initial current variable I0 in the response surface model in this paper. Since the existence of ferromagnetic materials is highly nonlinear and short, the relationship between the initial current and remanence Br is also nonlinear. Therefore, the univariate response curve is used to fit. That is, as shown in Figure 7.

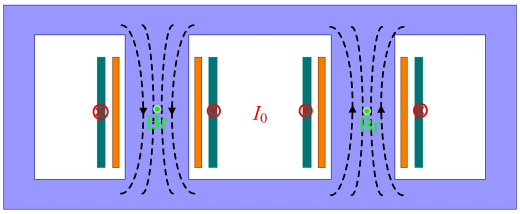

Fig. 7 Diagram of variables

In this paper, the initial current of different side windings is taken as the variable, and the magnetic flux density in the middle of the main core column is chosen as the response value, and the response curve model of the two variables is fitted. The initial current I0 range of the fitting variable is [0,1000]mA, and the variable is discretized by LHS sampling method. After interpolation fitting, the one-to-one mapping between the initial current and the remanent magnetic relationship of the transformer main core column is obtained as shown in Figure 8. Combined with the response surface model in Section 3.2, the rapid calculation and analysis of the inrush current peak of the converter under different remanent magnetic states is realized.

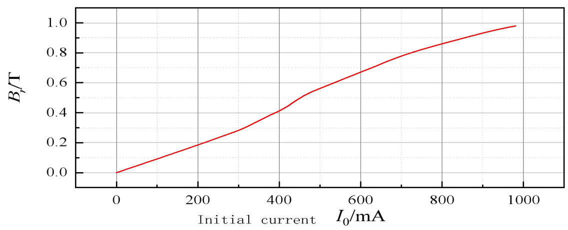

Fig. 8 Remanence - initial current response curve

5. Conclusion

In this paper, a response surface fitting method is proposed to calculate the inrush current of the converter transformer. Based on this method, the peak value of inrush current in the grid-side windings can be efficiently calculated under different remanence conditions. The specific research content is as follows:

(1) The mechanism of excitation insurge current generated by transformer closing is analyzed, and then the key influencing variable parameters are extracted from it.

(2) The response surface fitting test design is developed, and the response surface relationship between the initial current, the closing Angle and the peak of the inrush current is constructed. After calculation and verification comparison, the response surface prediction accuracy is high, and the maximum error is within 5%.

(3) The relationship between the initial current variable defined in this paper and the remanence of the core column is studied, and then the efficient calculation and analysis of the excitation inundation current of the converter transformer under different remanence conditions is realized.

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