A Sympathetic Inrush Identification Method Using Substation-Area Currents

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Abstract. Transformers in power system usually take current differential protection as the main protection, but the protection is easy to be affected by inrush currents and then maloperates. Sympathetic inrush is one kind of inrush currents, which is caused by energization of an adjacent transformer. There were many transformer differential protection maloperation cases caused by sympathetic inrush in the field, while the conventional second harmonic restraint method did not work effectively. In this paper, a method based on substation-area currents and curve fitting is proposed to identify sympathetic inrush. The method is presented using the characteristic that sympathetic inrush and initial inrush alternatively appear in reverse polarities. The characteristic exists continuously during sympathetic inrush. In order to verify effectiveness of the proposed method, PSCAD/EMTDC software is used in this paper to build sympathetic inrush model and obtain simulation data. Simulation results prove that the proposed method can effectively identify sympathetic inrush.

1. Introduction  
The continuous expansion of electricity demand has promoted the rapid development of the power system. The connection of regional power grids is also continuously strengthened, and the power system is becoming more and more complex. If a fault occurs, it may affect the entire power grid, resulting in serious accidents. Therefore, the safe and stable operation of the power system is extremely important. As a main electrical equipment in power system, the transformer plays an important role in voltage transformation. Once the fault occurs, it will cause power supply interruption and maintenance time-consuming. Therefore, it is very important to apply transformer protection device to improve the power supply reliability and security of power system. Using differential protection as the main protection of transformer can timely and accurately identify and clear various internal faults of transformer. Therefore, whether the differential protection can act accurately determines the reliable operation of the transformer. Accurate identification of the initial inrush current, internal fault current and sympathetic inrush current is one of the focuses of current researchers. Transformers in substation operate in parallel. If one of the parallel transformers is energizing without load, it will produce high-amplitude magnetizing current in the in-service transformer in parallel. The high-amplitude magnetizing current is called sympathetic inrush. The conventional second harmonic restraint method may not identify them effectively. At this
time, the protection blocking fails, causing differential protection misoperation. There have been many maloperation cases of transformer differential protection caused by sympathetic inrush in the field.

In recent years, domestic and foreign scholars have done some research on the mechanism and identification of sympathetic inrush. A modal approach to solving equivalent circuit by expressing differential equations in the state-equation form is selected in [1]. According to the derivation of eigenvalues and eigenvectors, sympathetic inrush is systematically investigated. [2] comprehensively analyses influencing factors of sympathetic inrush, then input influencing factors are screened according to characteristic importance calculated by random forest, and obtain the optimal prediction model through the grid search and cross-validation. [3] verifies that inrush current will cause DC transmission system fluctuation. Based on PSCAD simulation tool and Transformer Explorer joint diagnostic observation, [4] briefly discussed the influence of such events. The electromagnetic analysis of single-phase transformer with sympathetic inrush is presented in [5]. The results of [6] show that the second harmonic ratio and waveform discontinuity angle of inrush current depend on the saturation angle of transformer core. The larger the saturation angle is, the smaller the second harmonic ratio is. [7] analyses the influencing factors of sympathetic inrush through simulation cases.

An improved algorithm combining EMD algorithm and permutation entropy algorithm is proposed in [8], which can better identify and respond to inrush current. [9] using gray theory to achieve the identification of the inrush current. EMD algorithm and Permutation Entropy are combined to identify sympathetic inrush in [10]. [11] proposed a method of identifying and inrushing flow based on extension theory. [12] proposes a BP neural network algorithm for transformer inrush identification. The method of [13] is based on the variation of the detail coefficients of different levels of DWT decomposition. Under the sympathetic inrush condition, the detail coefficients present a different variation from that under an internal fault condition. [14] presents a method to identify sympathetic inrush using the second harmonic component of substation-area differential currents. A flow identification method based on morphology is proposed in [15], with the morphological gradient and weighted mathematical morphology operator combined.

In this paper, a method based on substation-area currents and curve fitting is proposed to identify sympathetic inrush. The method is presented using the characteristic that sympathetic inrush and initial inrush alternatively appear in reverse polarities. The characteristic exists continuously during sympathetic inrush. The rest of the paper is organized as follows. In Section 2, generation mechanism of sympathetic inrush is presented. In Section 3, a method based on substation-area currents and curve fitting is proposed to identify sympathetic inrush, and a substation-area differential current is defined. Section 4 verifies the effectiveness of the proposed method by PSCAD/EMTDC. Finally, conclusions are drawn in Section 5.

2. Generation mechanism of sympathetic inrush

Take parallel transformers as an example to introduce the generation of sympathetic inrush. As shown in Figure 1, two no-load transformers are connected in parallel at bus. Assume that transformer T1 is already in-service. If the circuit breaker K is closed, initial inrush current $i_2$ will appear in transformer T2. Subsequently, due to the existence of system resistance $R_s$, the initial inrush current $i_2$ will cause the voltage drop of the whole system. The voltage of bus B will be asymmetrical, caused by the unipolar characteristic of $i_2$. Due to the fact that magnetic flux of the transformer is strictly proportional to the area of voltage waveform, the voltage asymmetry of bus will result in saturation of T1. Then sympathetic inrush is generated. Sympathetic inrush has an opposite polarity to initial inrush, and the two kinds of inrush are generated alternately in one cycle.
When the transformer operates in a steady state, its magnetic flux linkage only contains periodic components, and the transformer operates near the knee point. After the no-load transformer is energizing, the superposition of aperiodic components will make the transformer operate far beyond the knee point. Then the energizing transformer enters into the saturation region and generates initial inrush. The periodic components of the flux linkages of the energizing transformer and the in-service transformer are the same, but the non-periodic components have opposite polarities. When the transformer is at the positive half cycle of the periodic component, the positive aperiodic component will make the transformer positively saturated. The negative aperiodic component will reduce the amplitude of the flux linkage, so there will be no inrush current. Similarly, when the transformer is at the negative half cycle of the periodic component, the negative aperiodic component superimposed on it will make the transformer negatively saturated. The positive aperiodic component will not make the transformer saturated. Therefore, the two transformers enter into saturation alternately in the positive and negative half cycles, resulting in positive inrush current and negative inrush current respectively. Thus, double wave peaks appear in opposite polarities alternately during one cycle for the two transformers.

3. Identification method of sympathetic inrush

The waveform characteristics of transformer differential current in substation can be used to reflect the waveform characteristics of sympathetic inrush and initial inrush. The curve fitting method based on the least square is immune to the pseudo peaks, and the curve convexity is well expressed. This section describes the use of substation-area differential current and curve fitting method to identify sympathetic inrush.

3.1. Differential current in substation area

Assume that the substation contains two transformers. The substation-area differential current $i_{ds}$ is:

$$i_{ds} = i_{dT1} - i_{dT2}$$  \hspace{1cm} (1)

$i_{dT1}$ is the differential current of the in-service transformer, and $i_{dT2}$ is the differential current of the energizing transformer. For different transformer connection types, the differential current is calculated in different ways. This paper mainly introduces the Yd11 connection mode, and its differential current is calculated as (2).
Where \( n_T \) is the transformer ratio, and the subscript 1 and 2 represents the primary side and the secondary side of the transformer, respectively.

The substation-area differential current (\( i_{dS} \)) when sympathetic inrush occurs is shown in Figure 2. It can be seen from the Figure 2 that every full-cycle wave contains two wave peaks. In addition, the \( i_{dS} \) waveform will appear some pseudo peaks, which affect the recognition of double peaks. Consider removing the influence of pseudo-peak by curve fitting.

Figure 2 \( i_{dS} \) waveform during sympathetic inrush.

3.2. Sympathetic inrush identification method using curve fitting

According to the analysis of characteristics of substation-area currents, the reverse alternation of sympathetic inrush and initial inrush is the key point for identification. Based on the substation-area currents and curve fitting technology, a new method for identifying sympathetic inrush is proposed.

The idea of the proposed method is as follows. Since the full-cycle wave of \( i_{dS} \) waveform contains double peaks under the condition of sympathetic inrush, a method that identifies two peaks can achieve the purpose of sympathetic inrush recognition. Therefore, it is considered to find the n-order polynomial to fit \( i_{dS} \) under the least square method. By eliminating the influence of pseudo-peak, peaks of the fitted curve can be simply and quickly detected.

The detail process of the proposed method is as follows. After the identification algorithm is started, three-phase currents on both sides of the parallel transformers are obtained. Differential currents of the two transformers are then calculated. The substation-area differential currents \( i_{dS} \) are obtained according to (2). Each half cycle of \( i_{dS} \) is fitted, and wave peak of the fitting curve is then recognized. When the peak value is greater than the set threshold \( i_{tv} \), the wave peak is detected. If two full-cycle waves contain double peaks, the sympathetic inrush is identified and the blocking signal is continuously sent to the transformer protection.

4. Simulation and Verification

In order to verify the effectiveness of the proposed identification method, the sympathetic inrush model and internal fault model are built by PSCAD/EMTDC software on the basis of the above theoretical analysis. The simulation data of sympathetic inrush and internal fault currents are obtained. The obtained data are imported into Matlab software to verify effectiveness of the proposed method.
The simulation model is built as Figure 1. Parameters of equivalent voltage source is set as $U_s=220kV$ and $Z_s=50\angle85^\circ\Omega$. Double-winding Yd11 transformers are used. Parameters of the two parallel transformers are the same. Ratio of the transformers is 220/38.5. The rated capacity is 90MVA. The no-load loss is 90kW and the load loss is 320 kW. The impedance voltage is 13.1% and the knee voltage is 1.15p.u.. Based on the model, sympathetic inrush at different switching angles, different kinds of internal fault of the in-service transformer, and Phase-A-to-ground fault at the primary side during sympathetic inrush are simulated. It is difficult to find the optimal fitting polynomial under the least square method using the full-cycle differential current, and the fitting effect is poor. Therefore, this paper adopts the half-cycle wave fitting to improve the fitting effect.

4.1. Simulation results under sympathetic inrush condition
The switching angle of the sympathetic inrush simulation model is set to 60°. The $i_{ds}$ waveform is shown in Figure 3 (a). The identification results of the algorithm are shown in Figure 3 (b). The fitting curve of $i_{ds}$ continuously presents two full cycle with double peaks, which are identified as the occurrence of sympathetic inrush, and the blocking signal is sent.

![i_{ds} waveform during sympathetic inrush.](image)

![Blocking signal during sympathetic inrush.](image)

Figure 3 Simulation results under sympathetic inrush condition.

4.2. Simulation results under internal fault condition
The internal fault condition is simulated in this part. A-to-ground fault occurs in the in-service transformer at $t=0.3s$. The $i_{ds}$ waveform is shown in Figure 4 (a) and the identification result is shown in Figure 4 (b). The fitting curve of the $i_{ds}$ does not contain double peak in a cycle, so blocking signal is not sent.

![i_{ds} waveform during sympathetic inrush.](image)

![Blocking signal during sympathetic inrush.](image)

Figure 4 Simulation results under internal fault condition.
4.3. Simulation results under the condition of internal fault during sympathetic inrush

Internal fault during sympathetic inrush is a special case, thus only A-to-ground at primary side is used for simulation. The circuit breaker is closed at 0.3s, and the no-load transformer is put into operation in the power grid. At 0.4s, A-to-ground fault occurs at the primary side of the in-service transformer. The $i_{dS}$ waveform is shown in Figure 5 (a).

The identification of the proposed algorithm is shown in Figure 5 (b). When the no-load transformer is put into operation at $t = 0.3s$, as shown in Figure 5 (b), there are two full-cycle waves with double peaks in the fitting curve of $i_{dS}$, which are identified as occurrence of sympathetic inrush, and the blocking signal is sent. A-to-ground fault occurs at 0.4s, and there is no double peak at 0.42 s, thus blocking signal is not sent.
5. Conclusion

To prevent maloperation of transformer differential protection, a sympathetic inrush identification method based on substation-area currents is proposed in this paper. This method first extracts the current of two parallel transformers to calculate the differential current. Curve fitting method based on the least square is used to perform polynomial fitting for half-cycle differential currents, so as to eliminate the influence of pseudo-peak and retain the inrush peak. And then the full-cycle wave peak is counted. When two full-cycle waves have double wave peaks, sympathetic inrush is identified and the blocking signal is sent. PSCAD/EMTDC is used to simulate the sympathetic inrush model with different switching angles, various types of internal faults, and sympathetic inrush with internal faults. The experimental results verify that the method can effectively identify sympathetic inrush.

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