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Simulated Calculation and Measured Analysis on the Spot with the 750 kV Transformer Switch-In with Load

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Abstract: Through an example of a main transformer switch-in with load during the reverse transmission of a 750 kV power plan, the paper introduces the basic principle of transformer switch-in with load. EMTPE program that is used to establish a calculation model, at the same time mainly considers the excitation characteristics of the transformer, the transient model of the circuit breaker, and the model of high voltage transformer, and calculated the inrush current with transformer switch-in with load in this plan. During system debugging in the plan, the two sets of main transformers passed the closing and opening test, and the data of inrush current in the test are recorded and analyzed. The simulation calculation and measured data show that the results are consistent. The simulation calculation also shows that it is not recommended to perform on-load closing of the transformer except for special circumstances, because of the influence of hysteresis characteristic when the transformer was switched in with load or the terminal voltage of the transformer resumed normal level from a low one after an external near-end fault was cleared, which various transformer differential protection using the characteristics of inrush to implement block scheme may mal-operate.

Keywords: Transformer; Switch-in with load; Inrush current; Ultra-saturation converter station; Hysteresis characteristic; EMTPE

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1. Introduction

Due to the saturation of the core flux and core material nonlinear properties, the power transformer no-load closing into the grid can produce a high amplitude of the excitation inrush current, leading to transformer differential protection error [1,2]. Up till now, many experts and scholars have put forward a lot of measures to deal with this point [3–6]. The circuit breaker with a closing resistor, transformer de-magnetization, and phase-selective closing are usually used in the ultra-high-voltage system as a means of limiting the system closing operation of overvoltage and excitation inrush current measures, to inhibit the transient overvoltage as well as the excitation inrush current. In the ultra-high voltage (UHV) system, circuit breakers with closing resistors, demagnetization of transformers, phase selection closing, and other means are often used as measures to limit the overvoltage of the closing operation of the system and the excitation inrush current, to inhibit the transient overvoltage and the excitation inrush current.

In recent years, transformer differential protection malfunctions during load closing have also been reported [7,8]. The concept of the possibility of the transformer being in a supersaturated state during transformer load closing and voltage restoration after the removal of external faults can lead to longitudinal differential protection malfunctions [9]. They developed a new on-load closing transformer model with simplified core magnetization characteristics and solved it using the 4th-order Lunger-Kutta algorithm, where the transformer differential protection malfunctioning phenomenon in the case of low ride-through inrush is mainly caused by local transient saturation [10]. Previous literature established a nonlinear mathematical model of transformer on-load closing, and through digital real-time simulation proved that there is a possibility of mis-activation when the transformer is closed with load, and pointed out that it should be stipulated that transformer on-load closing is not recommended [11]. However, there are occasions of transformer on-load closing in actual production, for example, the low-voltage side of the transformer of the generation unit of a 750 kV power plant, on the one hand, is "dead-connected" with the plant high-voltage transformer (hereinafter referred to as the plant high-voltage transformer), and on the other hand, is connected to the generator through the circuit breaker of the generation unit, and in the case of reverse power feed there exists a case of closing the main transformer with the plant high-voltage transformer (no load) situation.

To this end, our paper combines the on-load closing example of the main transformer of a 750 kV power plant with reverse transmission. Firstly, we introduce the basic principle of transformer on-load closing, and secondly, establish the transformer on-load closing calculation model based on the EMTPE software, which takes into account the excitation characteristics of the main transformer, the transient characteristics of the circuit breaker, and the long-high-variable equivalence model [12–14]. Using the established transient calculation model, the excitation inrush current of a 750 kV transformer during on-load closing was simulated. Simultaneously, field-measured data and waveforms were provided to verify the correctness of the simulation. The results indicate that, after implementing appropriate measures, the transformer does not trigger the protection system when the circuit breaker is closed under a light load, such as the plant's high-variable load.

2. Modeling

The transformer on-load closing equivalent circuit is shown in **Figure 1** [9].

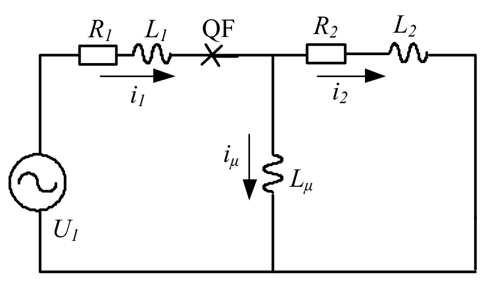


Figure 1. The circuit of the loaded transformer switch-in

In **Figure 1**, the power supply is a sinusoidal voltage source with an internal impedance of ($R_1 + j_\omega L_1$), and a flowing current of i_1, ignoring the core losses, the excitation impedance is set to be a pure inductance L_μ, and the flowing excitation current is i_μ, the load impedance is ($R_2 + j_\omega L_2$), and the flowing current is i_2. Let the induced main flux in the core be Φ, then $\frac{d\Phi}{dt} = L_\mu \frac{di_\mu}{dt}$, according to the circuit theory, the following equation can be obtained.

$$\left(\frac{L_1}{L_\mu} + \frac{L_1}{L_2} + 1\right)\frac{d\Phi}{dt} + R_1 i_\mu + R_1 i_2 = U_1 \quad (1)$$

From **Equation (1)**, it can be seen that during the transformer closing process, the excitation inductance L_μ is time-varying, and **Equation (1)** is a differential equation with time-varying coefficients, which makes it difficult to obtain its analytical solution. Meanwhile, when there is a load on the secondary side of the transformer, $i_1 \neq i_2$, and i_2 and i_μ interact with each other, it is also difficult to obtain its analytical form. Literature treats L_μ as a constant value without considering the time-varying effects and can approximate the more complex analytical form [9,10]. Literature simplifies the nonlinearity of the transformer core into a segmented linear single-valued polyline segment and obtains a set of more complex matrix equations [11].

This paper considers the application of EMTPE software to establish a transformer on-load closing calculation model, taking into account the excitation characteristics of the main transformer, the transient model of the circuit breaker, and the plant high variable calculation model, and calculates the transformer on-load closing excitation inrush current through the simulation software to meet the requirements of the actual engineering calculations.

3. Simulation calculations

3.1. Calculation parameters

According to the requirements of the electromagnetic transient calculation program, a 750 kV power plant back-feed network is simplified, and the simplified system wiring is shown in **Figure 2** [14]. In **Figure 2**, the equivalent power supply is the effective value of phase voltage, the equivalent internal impedance is the inscribed value, the main transformer circuit breaker is the sulfur hexafluoride (SF_6) circuit breaker with rated voltage of 800 kV, configured with a closing resistance of 570 Ω and a throwing time of 10 ms, the generating unit circuit breaker adopts the SF_6 engine complete set, and the transformer-side and generator-side capacitances are 132 and 260 nF.

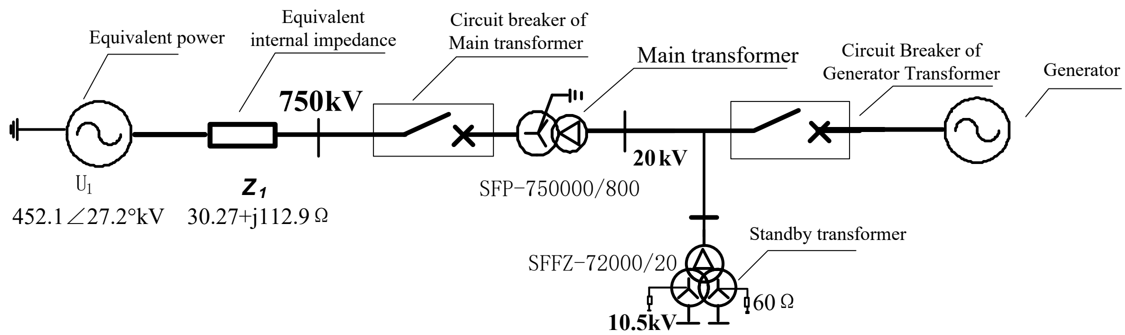
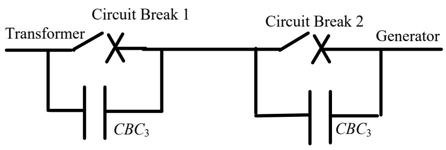
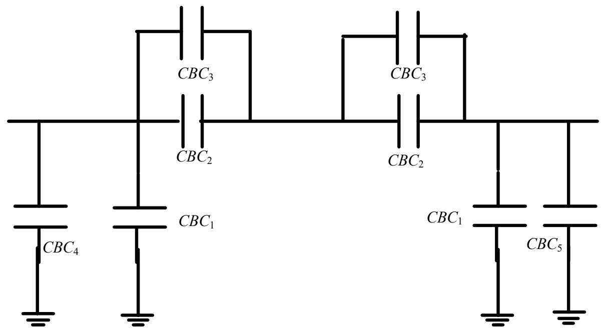


Figure 2. Demonstration of networking

3.2. Generating unit circuit breaker model

The internal structure of the generating unit circuit breaker and the simulation model in the open state are shown schematically in **Figure 3(a)** and **Figure 3(b)** [15,16]. In the equivalent model, CBC_1 is the equivalent capacitance to the ground of the circuit breaker interrupter chamber, CBC_2 is the equivalent capacitance of the circuit breaker main break, and CBC_3 is the parallel capacitance.





(a) Schematic diagram of circuit breaker structure in open state (b) Schematic of the simulation model in the on-off state

Figure 3. Internal structure of circuit breaker

3.3. Main transformer model

The main transformer is simulated according to literature using an ideal transformer model plus 96 nonlinear resistors [17]. The EMTPE subroutine BCTRAN calculates the R and L matrices for the simulation of transformer coupling branches based on the data from the transformer excitation and short-circuit tests for single-phase and three-phase transformers with arbitrarily many windings. The hysteresis effect of the transformer is simulated by adding a Type 96 nonlinear hysteresis inductor element to the transformer's high-voltage or low-voltage side. The Type 96 element is added to the high-voltage side of the transformer in the calculation. According to previous literature, 1.10 p.u. is adopted as the saturation starting point, and the EMTPE subroutine HYSDAT is used to obtain the quasi-nonlinear hysteresis inductance of the 96-type, i.e., the core magnetization curve with taking into account the hysteresis characteristic which is shown in **Figure 4** [17]. Considering the two cases of residual magnetization as φ = 0 φm and φ = 0.8 φm, the simulation is carried out by closing the gate at the time when the voltage waveform of the power supply is over zero (the initial phase angle of the closing is π).

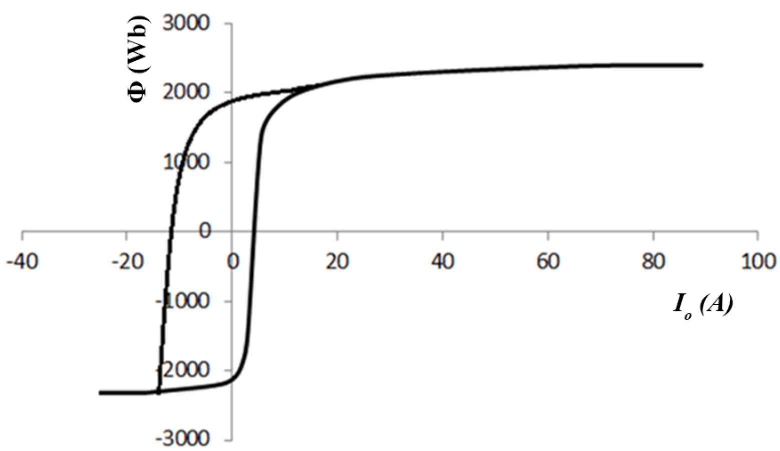


Figure 4. The excitation curve of the 750 kV transformer in consideration of remnant magnetic flux

3.4. Plant height variation modeling

In **Figure 2**, the transformer is a three-phase double-split design, with two primary windings and two secondary windings sharing the same core column. Typically, the primary windings are connected in parallel, while the secondary windings operate independently. Its single-phase equivalent circuit is shown in **Figure 5**.

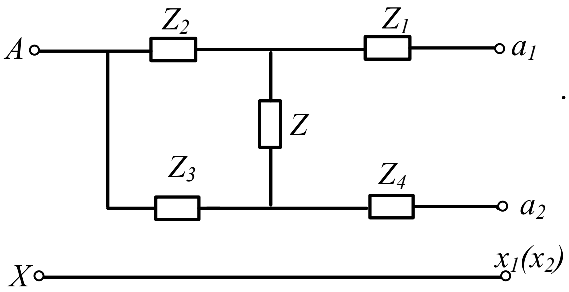


Figure 5. Equivalent model of split transformer

The three-phase split transformer excitation parameters are determined by the no-load test of any winding, and each parameter in **Figure 5** is obtained under ride-through operation, half ride-through operation, and split operation, considering the symmetry, it is usually assumed that $Z_1 = Z_4$, $Z_2 = Z_3$.

The parameters of **Figure 5** can be obtained from **Equation (2)** and **Equation (3)**. Considering that the analytical formula of the ternary equation is complicated, it is considered that $X_1 \approx X_2 \approx X_3 \approx X_4 \approx X_K$, and under the condition of ignoring the additional loss, **Equation (4)** and **Equation (5)** are obtained, and the measured values of R_1, R_2, R_3, and R_4 can be differentiated with the method of measuring the direct current (DC) resistance, and the measured values are 18.27 mΩ, 18.40 mΩ, 3.42 mΩ, and 5.59 mΩ respectively. This will enable us to calculate each of the parameters in the figures. It should be noted that **Table 3** in the half traversing load test and split load test needs to be converted to capacity.

$$Z_K = {(Z_1+Z_2)}/{2} = {(Z_3+Z_4)}/{2} \quad (2)$$

$$Z_B = Z_2 + \frac{Z_1+Z}{2Z_1+Z} Z_1 \quad (3)$$

$$Z_F = 2\left(Z_2 + \frac{Z_1 Z}{2Z_1+Z}\right) \quad (4)$$

$$Z = Z_2 \left(\frac{Z_2}{2Z_K - Z_B} - 2\right) \approx \frac{2Z_B - 3Z_K}{2Z_K - Z_B} Z_K \quad (5)$$

3.5. Calculations

A simulation model is established based on the aforementioned data, and the simulation is performed by closing the gate at the time when the power supply voltage waveform is over zero (the initial phase angle of the gate is π), taking into account the two cases of remanent magnetization of φ = 0 φm and φ = 0.8 φm.

The calculation assumes that the distribution probability of the closing phase angle is equal everywhere in a circumferential wave, i.e., it is uniformly distributed. The maximum non-simultaneous time of the three-phase circuit breaker closing is measured in 5 ms. Within 5 ms, the closing phase angle is a random value and such randomness is modeled in the simulation study. To include various possible closing phase angles, the number of random closing times for each state is set to 120 times, and the probability distribution of the time difference of three-phase closing is also uniform. The calculated results are shown in **Table 2, Figure 6** shows the calculated waveforms, and **Figure 7** shows the calculated results of the harmonic content of the excitation inrush current.

Table 2. Statistical switching overvoltage

Residual magnetism	Maximum excitation inrush current, peak (A)				
	Within 0.1 s	0.1 s later	0.2 s later	0.4 s later	0.6 s later
0	859	751	749	607	575
80%	2010	1871	1609	1217	981

As can be seen from **Table 2**, when closing the null-variable from the 750 kV side, the closing inrush current is larger under the consideration of remanent magnetization, and the maximum closing inrush current peaks at 2,010 A, and decays with time, until it decays to a smaller load current. From **Figure 6**, it is known that the decay time from the high-voltage side of the closing-null variable is longer, which is related to the equivalent impedance of the system. From **Figure 7**, it can be seen that the 2nd and 3rd harmonics are the largest, except for the DC component, and the higher harmonic components are smaller and decay with time. Calculations in this case show that the second harmonic content is large, greater than 20%, and will not trigger the differential protection action.

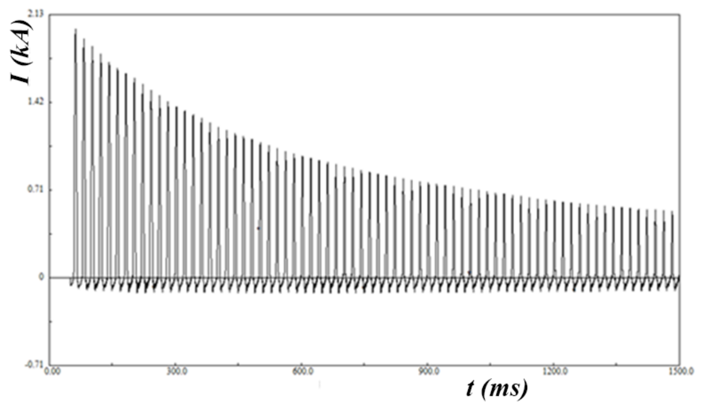


Figure 6. The maximum magnetizing inrush current form switching loaded transformer during 0.8 φm

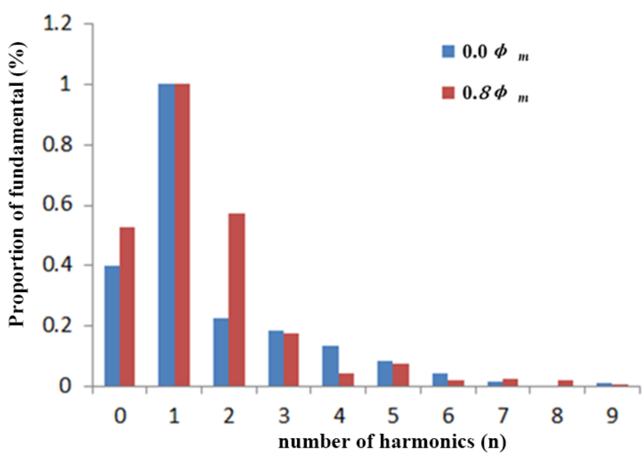


Figure 7. Harmonics components of the surge current

4. Test results and analysis

4.1. Test results

The measured results of the excitation inrush current of the closed on-load main transformer are shown in **Table 3**.

Table 3. The measured excitation inrush current

Main variable	Ordinal number	Excitation inrush current at closing (A)		
		A Phase	B Phase	C Phase
No. 1 main transformer	1st	578	689	584
	2nd	1,013	866	564
	3rd	569	866	560
	4th	599	1,011	575
	5th	569	1,014	578
No. 2 main transformer	1st	722	1,011	578
	2nd	866	1,299	569
	3rd	1,944	1,389	573
	4th	1,155	1,279	576
	5th	1,152	578	599

The excitation inrush current is a decaying spike wave, the peak value of the first wave is the largest, with the maximum peak value of 1,944 A (appearing in the 3rd closing of No. 2 main transformer) and the minimum value of 564 A (appearing in the 2nd closing of No. 1 main transformer), which is basically in line with the simulation calculations. The size of this wave is related to the residual magnetism and the angle of the closing of the circuit breaker, which is not smaller with the inputs one by one but is a random value. In **Figure 8**, the decay time of the excitation inrush current (the time taken to decay to 1/2 of the maximum peak value) is about 0.1 s. The waveform of the excitation inrush current has an obvious intermittent angle, and the larger the peak value is, the more obvious the intermittent angle is.

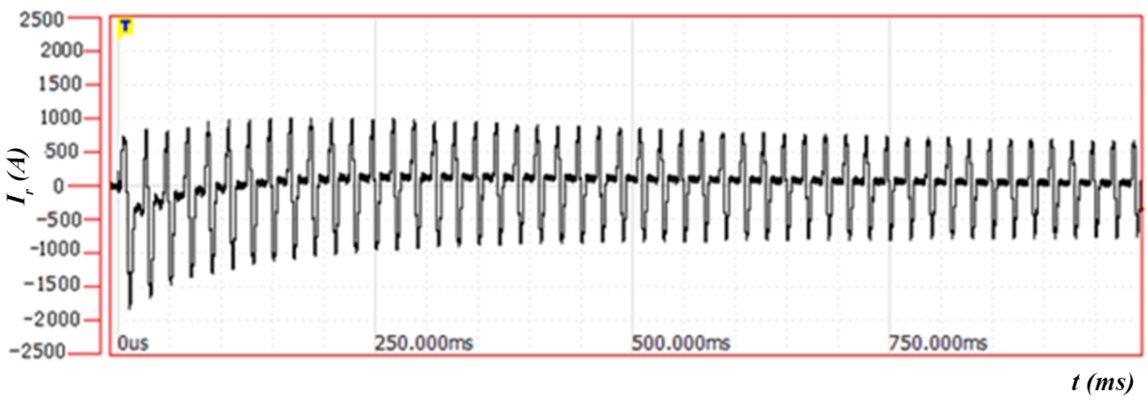


Figure 8. The measured excitation inrush current waveforms during transformer switch-in load

4.2. Analysis

According to previous literature, the forced DC flux (influenced by the primary and secondary systems and the parameters of the iron core) and the free DC flux (determined by the primary and secondary system parameters) combine, causing the synthesized flux to enter the supersaturation region. This results in intermittent excitation surge waveforms and a weakening of the second harmonic content. The second harmonic content may drop below the braking threshold of 15%, potentially leading to differential protection misoperation [9–11]. However, in this case, there is no phenomenon where the second harmonic content is reduced to less than 15%. During the switching process, no longitudinal differential protection action is triggered. The entire process is similar to the transformer in a no-load state, primarily because the no-load loss of the plant high-variable is small, and the load on the main transformer is very light. This switching scenario is comparable to the common state of switching a no-load transformer.

If different loads are considered on the low-voltage side of the transformer, the excitation inrush current exhibits various changes. For example, simulations were performed with a shunt reactor (90 MVar) and a shunt reactor (90 MVar with 12% reactance), and the results are shown in **Table 4**.

Table 4. The calculated excitation inrush current during transformer switch-in with different load

Nature of load	Unladen	Situational change	Reactance	Capacitors
Excitation inrush current (A)	2,460	2,010	3,000	1,660
Decay time (s)	4.7	0.1	2.4	1.23

As shown in **Table 4**, the excitation inrush current varies depending on the type of load present on the low-voltage (LV) side (e.g., no-load, plant high-variable, shunt reactor, or shunt capacitor). The largest excitation current occurs when the load is a shunt reactor, followed by the no-load condition. When the load is the plant high-variable, the excitation current is smaller than in the no-load condition. This indicates that the combined inductive nature of the plant high-variable load and the capacitive nature of the generating unit circuit breaker slightly reduce the no-load excitation current, although the reduction is not significant. When a shunt capacitor is used as the load, the excitation current is less than the no-load condition but is insufficient to effectively suppress the inrush current. However, the attenuation time of the inrush current is shortened.

Harmonic analysis of the load condition with shunt reactor revealed that the three-phase second harmonics accounted for 7.3%, 10.9%, and 9.2% in sequence, which was less than 15% and lasted for a long period of time, and may cause the transformer longitudinal differential protection action with inrush current characteristics as the blocking link. In summary, a transformer may enter a super-saturation state, especially when connected to a load with a certain reactance. Under such conditions, the use of inrush current characteristics as a blocking criterion for transformer longitudinal differential protection carries a high probability of false operation. In practical operation, transformers are typically energized in a no-load condition from the high-voltage side. Examples of on-load transformer closing, such as the one described in this paper, are rare and generally occur only in power plants. Instances of transformer longitudinal differential protection malfunction have also been reported during the removal of external faults. Based on the previous analysis, except under special circumstances (e.g., the scenario described in this paper, involving a dead connection between the plant and the main transformer), on-load transformer closing is not recommended.

5. Conclusion

In this paper, EMTPE simulation software, along with the BCTRAN, CONVERT, and HYSDAT subroutines, is applied to simulate the excitation inrush current during transformer on-load closing. Field tests confirm the accuracy of the simulation calculations. The results demonstrate that using the ideal transformer model and the 96-type nonlinear inductor model effectively simulates the dynamic magnetization characteristics of the transformer core, accurately describing the transformer's behavior during transient processes.

Simulation calculations reveal that during on-load closing (e.g., with the plant high transformer), the transformer experiences a significant excitation inrush current, characterized by an intermittent angle and high second harmonic content. Additionally, simulations indicate that supersaturation occurs when the transformer is closed with a shunt reactor. Therefore, on-load transformer closing is not recommended except under special circumstances.

Disclosure statement

The authors declare no conflict of interest.

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