Phenomenon of Transformer Sympathetic Inrush and Analysis of an Example

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Abstract. According to a mal-operation accident of differential protection which is caused by the effect of a switching-on transformer with no load on a parallel running transformer in a 35KV substation, the emergency and the development of transformer sympathetic inrush current was analysed from the aspect of the flux. And the three-phase differential current and their second harmonic component were obtained, which shows that the mal-operation wasn’t caused by the low second harmonic component in the differential current but by the changed transfer characteristics of the current transformer, which leads to an increase in the differential current.

1. Introduction
Transformer inrush current is usually caused by the saturation of the magnetic circuit when the transformer is closed with no load. Its magnitude can reach 3-5 times the rated current of the transformer. In order to prevent this from happening, secondary harmonic braking is often used in actual situation to latch the differential protection, and long-standing operating experience has proved its reliability.

However, in recent years, there have been several examples of mal-operation caused by the differential protection of adjacent parallel or cascading transformers and generators when closing transformer with no load (such as a 35KV substation in this article), which has brought great harm to the normal operation of the transformers. This phenomenon is related to the sympathetic inrush. The reason for the occurrence of the sympathetic inrush is that the non-periodic component of the inrush current produces a voltage drop on the system resistance, which leads to the bias of the running transformer, but theoretically the sympathetic inrush has the same feature with the inrush current which should not cause the mal-operation of secondary harmonic latching. Therefore, this article analyses an example of the differential protection mal-operation of an adjacent parallel operation transformer caused by the no-load closing charge of a transformer during a field operation.

A comprehensive analysis of the mechanism of the emergence and the occurrence process of the sympathetic inrush is given, as well as the reason of mal-operation by transformer differential protection.

2. Problem generation
The electrical connection for a 35KV substation is shown in Figure 1. The models of two transformer are shown as yd11 wiring. The capacity of transformer 1 is 600KVA, and transformer 2 is 6300KVA, with rated voltage of 35KV/10.5KV. The main protection of the transformer is differential protection with second harmonic brake, whose coefficient is 0.15.
The main change overhaul work is ready to resume power transmission, when the main change belt load operation. When the main change 35KV side switch is closed to put the main change empty load into the load, the main change ratio of 2 s differential action protection action, jump ingenes the 2 s main change two-sided switch.

After the accident, no problems were found to be tested on the main variant body, the two-sided circuit breaker, the differential protection device and the secondary circuit. At that time, the start-up current of main variable differential protection is fixed, the three differences in protection action are: DIA ;DIB ;DIC, a phase of the differential flow has been greater than the start-up current fixed value, so the ratio differential protection action is correct.0.52A0.6A0.3A0.4A

The video map at the time of the accident is shown below.

Figure 2 is the secondary current of the three phases of the main variable high-voltage side A, B and C when the main variable is empty.

Figure 3 is the secondary current of the three phases of the main variable high-voltage side A, B and C when the main variable is empty.
3. Analysis of the mechanism of the generation of the should surge

The two main sons of the substation become parallel running, and its equivalent circuitry is shown in Figure 4. Among $R_{s0}$ them, the $L_{s0}$ resistance and inductance $R_{11}$ $L_{11}$ of the connection line between the system and the transformer, and, and, $L_{02}$ respectively, $R_{12}$ the first and second windings of the transformer $T_1$, the resistive and leakage inductors, $L_{1m}$ is the excitation inductor of the transformer $T_1$, $R_{21}$ and $i_1$, $i_2$, $L_{2m}$ $R_{22}$, $L_{22}$, and, respectively, the resistance and leakage inductors of the first and secondary windings of the 2-transformer $T_2$, are excitation inductors of the transformer $T_2$, for the system side current, and $L_{21}$ Excitation currents flowing through transformers $T_1$ and $T_2$, $R_3$, $L_3$ equivalent resistors and inductors for the system side, $R_1$ and $L_1$ equivalent resistors and inductors for $T_1$, respectively, $R_2$ and $L_2$ equivalent resistors and equivalent inductors for $T_2$, respectively. Where the transformer $T_2$ normal operation without load, $T_1$ empty load closing.

![Figure 4. The equivalent circuit and the simplified equivalent circuit of transformer](image)

TI empty load before closing, $T_2 i_2 \approx i_s$ normal operation of non-biased magnetic, for $T_2$'s normal excitation current, relatively small, about equal to zero.

After $T_1$ empty load close, $T_2$ is not saturated before, $T_1$ produces the plug surge as $i_1$ shown in Figure 2, when $T_1$'s excitation inductor is very small, excitation current is relatively large, $i_1 \approx i_s$ $T_1$ and $T_2$ magnetic chain equation is as follows

![Figure 3. The secondary waveform of 2# transformer (phase A, B, C in turn)](image)
\[
\begin{align*}
\frac{d\phi_1}{dt} &= u_s - L_s \frac{di_1}{dt} - (R_s + R_l)i_1 \\
\frac{d\phi_2}{dt} &= u_s - L_s \frac{di_1}{dt} - R_s i_1
\end{align*}
\]  
(1)  
(2)

In one period (0-2 inches), the magnetic chain \( u_s \) equation is integrated, taking into account that one cycle integral for the periodic component is zero, and according to the waveform of the \( \theta = 2\pi \) excitation surge flow, \( i_1 \) \( \theta = 0 \) it is in the waveform intermittent period at the time, there is \( i_1(0) = i_1(2\pi) = 0 \), and therefore:

\[
\phi_1(2\pi) = \phi_1(0) - (R_s + R_l) \int_0^{2\pi} i_1(\theta) d\theta
\]  
(3)

\[
\phi_2(2\pi) = \phi_2(0) - R_s \int_0^{2\pi} i_1(\theta) d\theta
\]  
(4)

That is, within a cycle:

\[
\Delta \phi_1 = -(R_s + R_l) \int_0^{2\pi} i_1(\theta) d\theta
\]  
(5)

\[
\Delta \phi_2 = -R_s \int_0^{2\pi} i_1(\theta) d\theta
\]  
(6)

It can be seen from the above formula that T1’s \( R_s \) closing surge not only has attenuation of its own magnetic chain, but also because of the presence of system resistance, the attenuation surge in T2 produces bias, which is also the root cause of T2 generation and should flow. In order to facilitate the discussion, it is assumed that T1’s excitation surge \( i_1 \) is biased towards the positive side of the timeline (the same can be assumed to be biased towards the negative side of the timeline, does not affect the analysis results), it can be seen that with the reduction of the T1 magnetic chain, T2’s magnetic chain inverted increase, before T2 does not reach saturation, \( i_1 \approx 0 \) the above magnetic chain equation has been satisfied, thus T2 magnetic chain gradually increased to saturation, began to appear and should flow.

From the above analysis, it can be seen that and should be chung flow is a few or more cycles after the airdrop transformer closing operation, and the amplitude of the should surge flow increases and then decreases. And should flow in the opposite direction to the excitation surge and interleave on the timeline, as shown in Figure 5.

\[\text{Figure 5. The waveform of inrush current and the induced inrush current}\]

There is the above analysis can be seen, in the moment of the main change empty load close, the production of excitation surge, the surge is supplied by the system, this current appears on the line to produce a voltage drop, resulting in 2, running transformer port voltage changes, resulting in the 2-transformer magnetic chain slowly tend to saturate, so that the excitation current then increases, resulting in the emergence and response to the surge. In contrast to Figure 3, 1, the main change empty load gate to produce excitation surge flow, 2, the main variable three-phase current waveform is very consistent with the waveform of the surge flow, airdrop test is in zero seconds closing, but the should surge did not immediately produce, but after several weeks of wave generation and should flow, and the amplitude of the surge gradually increased, after reaching the maximum. You can also see that the decay rate of the should surge flow is very slow.
4. Analysis of the cause of differential protection action

In the main variable load input, in its side-by-side operation of the 2s main variable power side produced and should flow, the same as the should and excitation surge, only flow through the transformer side, and the should surge flow will also flow all into the differential circuit, resulting in the differential current increase.

There may be two reasons for the mal-operation of differential protection. First, the ratio of the secondary harmonic to the base wave in the should surge flow is relatively small and is not the maximum at the maximum and should flow, so the use of the usual secondary harmonic latching condition can not completely make the protection not to be moved. Second, the flow should contain a larger DC attenuation component, which may cause the current transformer on both sides of the transformer to become transient saturation, resulting in a differential flow, resulting in protection mal-operation.

First of all, the second harmonic analysis of the three different dynamic currents of the main change is as follows.

![Figure 6. The differential current and its second harmonic component of phase A](image)

![Figure 7. The differential current and its second harmonic component of phase B](image)

![Figure 8. The differential current and its second harmonic component of phase C](image)

From the above graph can be seen, after the occurrence and should be surge, the change of differential
current is very obvious, especially the C-phase shown in the figure, the maximum value can reach, far beyond the start value of the differential current. However, the results of harmonic analysis of the differential current after the generation and surge show that the ratio of the amplitude of the secondary harmonic to the base wave in the differential current can reach more than 0.5, which obviously can meet the requirements of the second harmonic latch, and the differential protection should not be misacted. Therefore, it can be inferred that differential protection mal-operation should be the second case, and should be in the surge flow in the larger DC attenuation component, so that the current transformer on both sides of the transformer transient saturation, resulting in differential flow caused.3A

5. Conclusions
In this article, an example of differential protection mal-operation caused by sympathetic inrush is firstly analyzed theoretically for the cause and developing process of the transformer sympathetic inrush. Then two possibilities of mal-operation are proposed. But the subsequent harmonic analysis exclude the case of second harmonic content of the sympathetic inrush could not reach the setting value. So the mal-operation is caused by the large DC attenuation component in the sympathetic inrush, which caused the transient saturation of the current transformers on both sides of the transformer.

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