Scientific
Research

Research on the Reason for Transformer Differential Protection Mal-operation Caused by Sympathetic Inrush

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ABSTRACT

The paper is concerned with whether CT transient saturation, which caused by sympathetic inrush, is the direct reason for mal-operation of transformer differential relays. In order to analyze transforming characteristics of saturated CT, the gain of each harmonic current transforming from primary winding to secondary winding of transient saturation CT is calculated. Based on the fact that series sympathetic inrush is easier to lead differential relay mal-operation than parallel sympathetic inrush, the effect of CT saturation on differential relay in the case of both parallel sympathetic inrush and series sympathetic inrush are investigated respectively. Theory analysis and simulation show that higher harmonic will be transferred by saturated CT more easily than lower harmonic, and then the second harmonic proportion of CT secondary side is higher than that of CT primary side. Thus CT transient saturation itself is not essential reason for differential relay mal-operation. Parallel sympathetic inrush and series sympathetic inrush will lead to different location CT saturated. Parallel sympathetic inrush will lead to CT located system side saturated; second harmonic ratio of differential current increase and dead angle is large. Series sympathetic inrush will lead to CT located load side saturated; second harmonic ratio of differential current decrease and dead angle is small.

1. Introduction

When a transformer is energized in either series or parallel with other transformers that are already in service, it will result in a sympathetic interaction between the incoming transformer and those that are in operation [1-4]. In the recent years, it has reported that the transformer differential relay mal-operated due to sympathetic inrush [5-10]. It is worth emphasizing that most of reported events were cause by series sympathetic inrush [6-10].

The physical mechanism and waveform characteristics of sympathetic inrush have been analyzed in many literatures [11-16]. In brief, the reason for generation of both magnetizing inrush and sympathetic inrush is iron core saturation. Moreover, the previous researches show that the waveform of sympathetic inrush is similar to magnetizing inrush in a cycle. But the decay of sympathetic inrush is more slowly and sympathetic inrush will lead to CT saturation more easily.

Therefore, CT transient saturation caused by DC component of sympathetic inrush is the accepted reason for transformer differential protection mal-operation. How- ever, only simple simulations and analysis were given to analyze the effect of CT saturation on transforming sympathetic inrush, and necessary theoretical calculating is not carried out. Moreover, much research assumes that two transformers are in parallel and the operated one is unload. In practice, the operation transformer is always loaded and series sympathetic inrush is easier to lead differential relay mal-operation.

Aim to discover the real reason for mal-operation of transformer differential relay caused by sympathetic inrush, the formula for calculating each harmonic transforming from primary winding to secondary winding of transient saturation CT is derived firstly. Then theoretical analysis and simulation are carried out to discover the internal reason for series sympathetic in rush is easier to lead differential relay mal-operation than parallel sympathetic inrush in detail.

2. Transforming Characteristics of Saturated CT

Because of slowly decaying DC component in sympathetic inrush, the curves of sympathetic inrush deviate from time axes. As we known, CT can hardly transfer decaying DC component, and decaying DC component may cause core of CT in saturation. The equivalent circuit of CT is shown in **Figure 1**. L_1 and R_1 mean the equivalent inductance and resistance of CT primary side respectively; L_2 and R_2 mean the equivalent inductance and resistance of CT secondary side respectively; L_L and

R_L mean the equivalent inductance and resistance of CT load respectively; L_m means magnetizing inductance of CT; i_1, i_2、i_m mean primary side, secondary side and magnetizing current of CT.

The CT primary side current i_1 is the current of power system, and is independent of CT. So, the current i_1 can be looked as a current source. As a result, L_1 and R_1 is independent of CT saturation. L_2, R_2, L_L and R_L is series and can be replaced by L'_L and R'_L. Where $L'_L = L_2 + L_L$, $R'_L = R_2 + R_L$. Then circuit shown in **Figure 1(a)** can be converted to that shown in **Figure 1(b)**. While slowly decaying DC component in sympathetic inrush, the decaying DC current will flow through magnetizing branch of CT mainly after a certain time. Thus CT is in transient saturation.

Supposing that, the fundamental and second harmonic component of CT primary side current i_1 are $\dot{I}_{1,1}$ and $\dot{I}_{1,2}$, and CT is saturated transiently with sympathetic inrush current. Then, the magnetizing inductance of CT will decrease from L_m to L_{ms}. The each harmonic component $\dot{I}_{2,n}$ of CT secondary side current and the magnetizing current $\dot{I}_{m,n}$ of CT will be
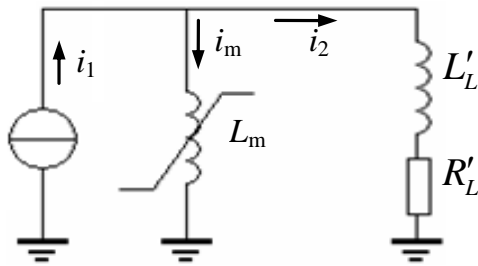
$$\dot{I}_{2,n} = \frac{jnw_0 L_{ms}}{jnw_0(L_{ms} + L'_L) + R'_L} \dot{I}_{1,n} \tag{1}$$

$$\dot{I}_{m,n} = \frac{jnw_0 L'_L + R'_L}{jnw_0(L_{ms} + L'_L) + R'_L} \dot{I}_{1,n} \tag{2}$$

In equation (1) and equation (2), $n=1, 2…N$, means each harmonic，w_0 means angular frequency. Therefore, the gains of each harmonic $K_{CT}(n)$ will be
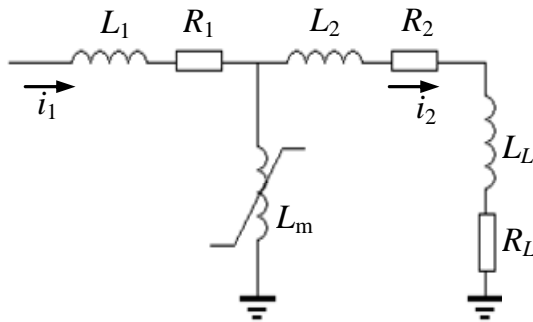
(a) Equivalent circuit of CT

(b) Equivalent circuit for calculating

Figure 1. Equivalent circuits of current transformer.

$$K_{CT}(n) = \left| \dot{I}_{2,n} \Big/ \dot{I}_{1,n} \right| = \left| \frac{jnw_0 L_{ms}}{jnw_0(L_{ms} + L'_L) + R'_L} \right|$$
$$= \frac{nw_0 L_{ms}}{\sqrt{[nw_0(L_{ms} + L'_L)]^2 + R'^2_L}} \tag{3}$$

The derivation of $K_{CT}(n)$ is

$$\frac{dK_{CT}(n)}{dn} = \frac{w_0 L_{ms} R'^2_L}{\sqrt{[nw_0(L_{ms} + L'_L)]^2 + R'^2_L}^{\,3}} \tag{4}$$

From equation (4), $\dfrac{dK_{CT}(n)}{dn} > 0$ can be got. It is can be seen that higher harmonic will be transferred by saturated CT more easily than lower harmonic. This implies that the second harmonic proportion of CT secondary side is higher than that of CT primary side.

3. Effect of Parallel Sympathetic Inrush on Transformer Differential Relay with CT Saturation

The electrical configuration used to analyze the sympathetic inrush that occurs between transformers in parallel is shown in **Figure 2**. Assuming that sympathetic inrush occurs in the transformer T_2 when the transformer T_1 is energized by closing beaker K_1. In **Figure 2**, $\dot{I}_1$, $\dot{I}_2$, $\dot{I}_L$ mean fundamental components of primary side, secondary side current of transformer T_2 and load current respectively. Obviously, the sympathetic inrush mainly flows through CT_1, and will lead to CT_1 transient saturation more easily.

Firstly, supposing T_2 is no-load operating, *i.e.* $\dot{I}_L = 0$, thus the current I_1 in CT_1 is sympathetic inrush. According to section 2, second harmonic ratio of sympathetic inrush will be amplified by saturated CT, which is help to second harmonic restraint method. Even if sympathetic inrush lead to CT_1 saturated, the transformer differential protection of transformer T_2 will not mal-operate.

Next, the influence of sympathetic inrush on differential protection with loaded transformer T_2 will be analyzed as follow.

If CT_1 is not saturated, the differential current $\dot{I}_{cd}$ of T_2 can be expressed as
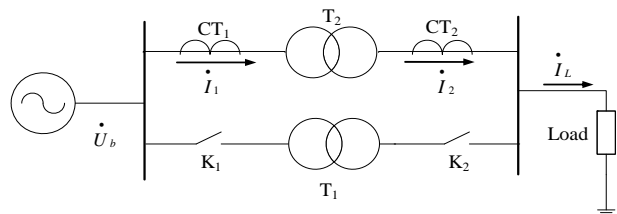
Figure 2. Electrical configuration of sympathetic inrush between transformers in parallel.

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$$\dot{I}_{cd} = \dot{I}_1 - \dot{I}_2 \qquad (5)$$

If CT_1 is saturated, the current $\dot{I}_1$ transfer from primary side to secondary side of CT_1 wound be distorted to $\dot{I}'_1$. As a result, differential current $\dot{I}'_{cd}$ will be

$$\dot{I}'_{cd} = \dot{I}'_1 - \dot{I}_2 = \dot{I}_{cd} - (\dot{I}_1 - \dot{I}'_1) = \dot{I}_{cd} - \Delta\dot{I} \qquad (6)$$

where $\Delta\dot{I} = \dot{I}_1 - \dot{I}'_1$ is the fundamental component of magnetizing inrush of CT_1. Due to $\dot{I}_{cd}$ decreased by $\Delta\dot{I}$, the fundamental component of differential current $\dot{I}'_{cd}$ reduced accordingly. Moreover, second harmonic will be transferred by saturated CT_1 more easily than fundamental component according to section 2. Therefore, second harmonic proportion of differential current $\dot{I}'_{cd}$ increases, which is help for second harmonic restraint method. In a word, the transformer differential protection of transformer T_2 will not mal-operate when T_2 operates with load and CT_1 is saturated.

According to analysis above, parallel sympathetic inrush has a few effect on differential relay whatever the transformer operating with load or not.

4. Effect of Series Sympathetic Inrush on Transformer Differential Relay with CT Saturation

It is worth emphasizing that most reported events about transformer differential protection mal-operation caused by sympathetic inrush happened in power plants. The system electrical configuration is shown in **Figure 3**. Generator G_2 is in normal operation and supplies to the system by breaker K_3. Generator G_1 is cut off from the system, when no-load transformer T_1 carry out energizing test by closing breaker K_1, differential protection of transformer T_2 may mal-operate.

The corresponding equivalent circuits of **Figure 3** are shown in **Figure 4**. Assuming that T_1 is connected to system with no-load by closing breaker K_1, and magnetizing inrush is generated, which lead to the sympathetic inrush in T_2. In fact, this sympathetic inrush is series sympathetic inrush.

In **Figure 3** and **Figure 4**, i_1、 i_{m1}、 i_L mean the primary winding current of CT_1, magnetizing inrush of T_1 and load current respectively, that is

$$i_1 = i_{m1} + i_L \qquad (7)$$

i_2、 i_{m2} mean the primary winding current of CT_2 and sympathetic inrush of T_2 respectively, that is

$$i_2 = i_{m2} + i_1 = i_{m2} + i_{m1} + i_L \qquad (8)$$

Because the magnetizing inrush and sympathetic inrush have the opposite polarity, the primary winding current i_2 is almost symmetrical. Thus, the DC component of i_2 is small. On the contrary, the DC component of i_1 is great. Therefore, CT_1 is easily saturated as well as CT_2 is

not saturated. The influence on differential protection with CT_1 saturation will be analyzed in detail as follow.

In **Figure 4**, L_S and R_S are inductance and resistance of generator G_2 respectively. R_{21} and L_{21} are leakage impedances of T_2 primary winding; R_{22} and L_{22} are leakage impedances of T_2 secondary winding. R_{11} and L_{11}, R_{12} and L_{12} are leakage impedances of T_1 primary and secondary winding respectively. L_{1m} and L_{2m} are exciting inductances of T_1 and T_2 respectively.

If CT_1 and CT_2 are not saturated, the differential current i_{cd} of T_2 can be expressed as

$$i_{cd} = i_1 - i_2 \qquad (9)$$

If CT_1 is saturated, the current i_1 transfer from primary side to secondary side of CT_1 wound be distorted to i'_1. Equation (8) and Equation (9) show that $i_{cd} = -i_{m2}$. As a result, differential current i_{cd} will be

$$i'_{cd} = i'_1 - i_2 = i_{cd} - (i_1 - i'_1) = i_{cd} - \Delta i = -i_{m2} - \Delta i \qquad (10)$$

where, which is the magnetizing in rush of CT_1. Due to the load current i_L has opposite phase with $-i_{m2}$, the magnetizing inrush of CT_1 makes the fundamental component of differential current i_{cd} increased.

Second harmonic components of i_{cd}, i_{m2}, i_{m1} and are represented by $\dot{I}_{cd,2}$, $\dot{I}_{m2,2}$, $\dot{I}_{m1,2}$ and respectively. Then, Equation (10) can be rewritten as

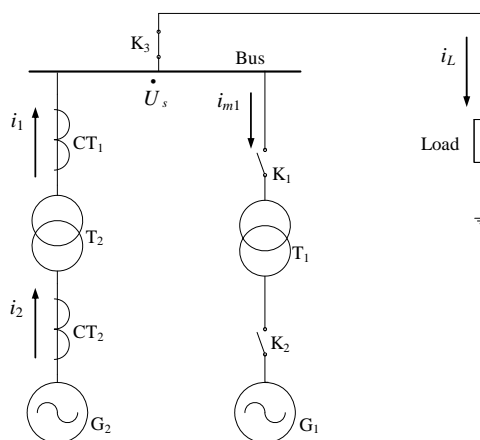$$\dot{I}'_{cd,2} = -\dot{I}_{m2,2} - \Delta\dot{I}_2 \qquad (11)$$

Figure 3. Electrical configuration of sympathetic in rush between transformers in series.
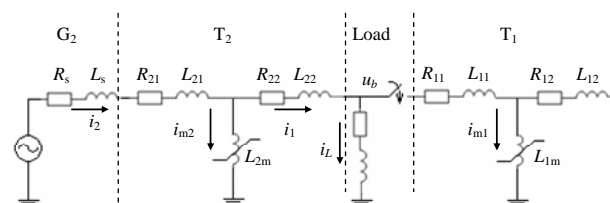

**Figure 4. Equivalent circuits of sympathetic in rush between transformers in series.**

According to Equation (11), the corresponding pastors' graph is shown in **Figure 5**. As indicated in **Figure 5**, $|I'_{cd,2}|$ will less than because $I_{m2,2}$ is decreased by. That means CT_1 saturation will make the second harmonic component of differential current decreased.

In conclusion, CT_1 saturation leads to the fundamental component of differential current increased whereas the second harmonic component of differential current decreased. As a result, the second harmonicratio of differential current will decrease. If second harmonic ratio is less than threshold, the second harmonic restraint method will become invalid. So bad influence will be caused to differential protection，the series sympathetic inrush is easy to lead differential relay mal-operation.

5. Simulation Result and Analysis

According to the simulation model shown as **Figure 2,** simulation results are shown in **Figure 6**. For clearly, **Figure 6** shows the partial waveforms only. **Figure 6(a), (b), (c)** show that parallel sympathetic inrush lead to CT_1saturated, that is slowly decaying DC component in sympathetic inrush cause core of CT_1 saturated, thus magnetizing inrush generates in CT_1. As expected, **Figure 6(d)** shows second harmonic ratio of differential current of transformer T_2increaseafter CT_1 saturate. Furthermore, **Figure 6(e)** indicates that dead angle of differential current is large enough. Therefore, parallel sympathetic inrush is not easy to cause differential protection mal-operation either adopting second harmonic restraint method or adopting dead angle restraint method.

According to the simulation model shown as **Figure 3,** simulation results are shown in **Figure 7**. Since switching K_1 to energize transformer T_1 lead to series sympathetic in rush generate in the already connected transformer T_2. As analyzed in section 4, the series sympathetic in rush cause CT_1saturated. **Figure 7(a)** shows that CT_1 saturation lead to second harmonic ratio of differential current of transformer T_2decreased. While second harmonic ratio is less than 15%，the second harmonic restraint method is invalid. As the result, the differential protection will mal-operate, the corresponding motion curves is shown in **Figure 7(b)**. **Figure 7(c)** indicates that dead angle of
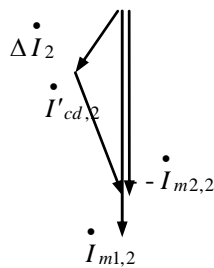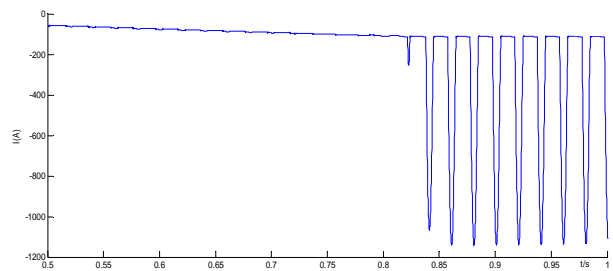

Figure 5. Phasors of second harmonic component under sympathetic inrush between transformers in series.
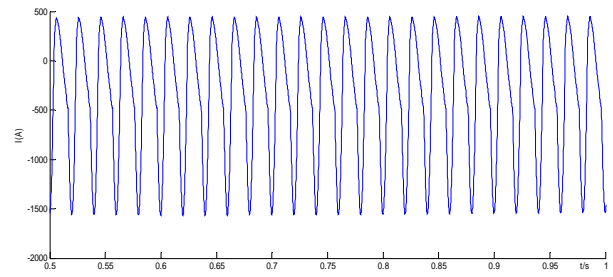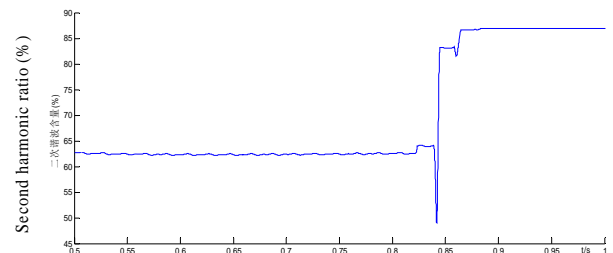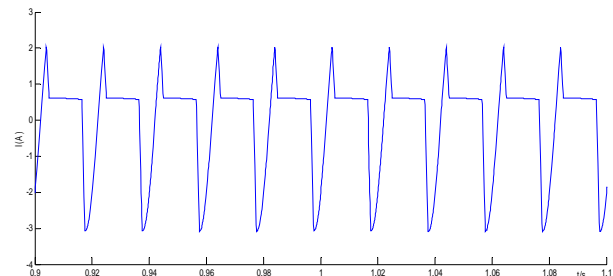
(a) Waveform of Phase A primary winding current of CT_1
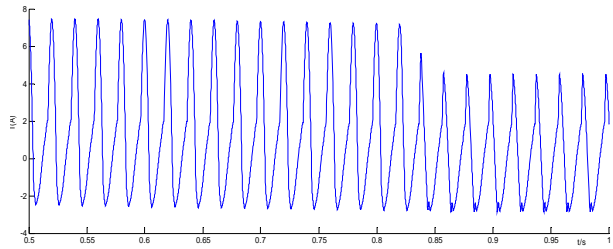
(b) Waveform of Phase A secondary winding current of CT_1

(c) Waveform of Phase A magnetizing inrush of CT_1

(d) Waveform of Phase Asecond harmonicapp: ds: proportionratio
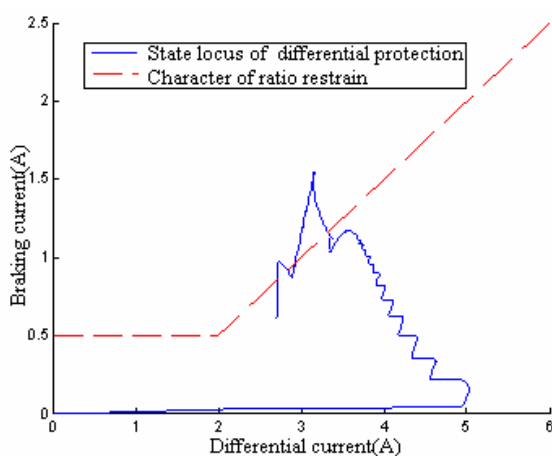
(e) partial waveform of Phase A differential current

Figure 6. Simulation waveforms of differential current under sympathetic inrush between transformers in parallel.
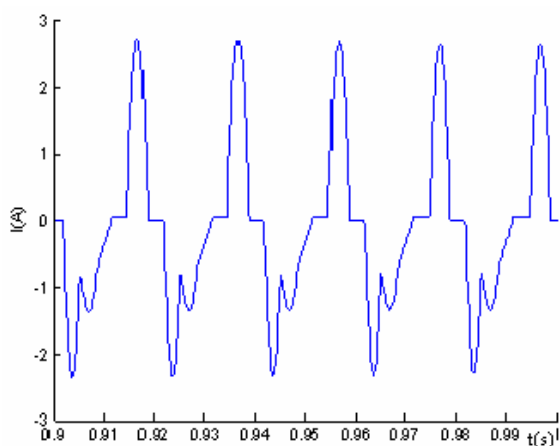
differential current become very small, so dead angle restraint method will be invalid too.
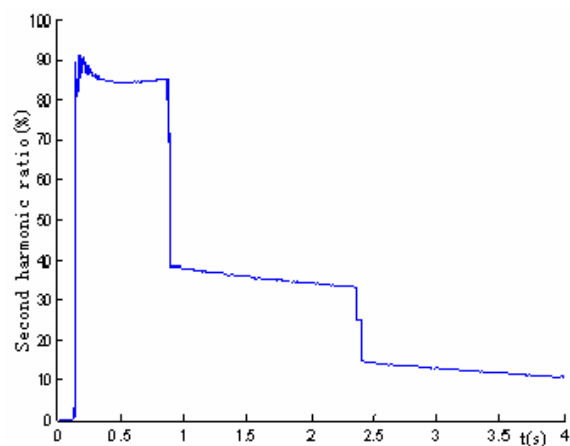
(a) Changing of second harmonic ratio

(b) Motion locus of differential protection

(c) Partial waveform of differential current

Figure 7. Waveforms of mal-operation of differential protection cased by under sympathetic in rush between transformers in series.

6. Conclusions

Through theoretical calculating the gain of each har-

monic transforming from primary winding to secondary winding of transient saturation CT, it is can be proved that the ability of saturation CT transforming higher harmonics is stronger than that of transforming lower harmonics. Therefore, second harmonic ratio will be amplified by saturated CT. In other word, CT transient saturation itself is not essential reason for differential relay mal-operation.

Theoretical analysis and simulation results show that parallel sympathetic inrush and series sympathetic inrush will lead to different location CT saturated. Parallel sympathetic inrush will lead to CT located system side saturated. Due to second harmonic ratio of differential current increase and dead angle is large, which is help to second harmonic restraint method and dead angle restraint method, so differential protection will not maloperate under parallel sympathetic inrush.

Series sympathetic inrush will lead to CT located load side saturated. While CT saturation leads to the fundamental component of differential current increased where as the second harmonic component of differential current decreased. As a result, the second harmonicratio of differential current will decrease. Moreover, the dead angle of differential current is small. Thus series sympathetic inrush is easy to lead differential relay mal-operation.

7. Acknowledgements

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