Phase Current Differential Protection for Transformers in Wye-delta Mode

Yuxue Wang*, Xianggen Yin, Zhe Zhang, Zhenxing Li
The State Key Laboratory of Advanced Electromagnetic Engineering and Technology, Huazhong University of Science & Technology, Wuhan 430074, China
*corresponding author, e-mail: wyx2005635@qq.com

Abstract

For the current transformers (CTs) on the delta side measure the line current instead of the phase current, line current differential protection is adopted in transformers connected in wye-delta mode currently. However, the symmetry feature of inrush current in line current differential protection may invalidate the inrush current restrained criterion. A calculating method of current through delta windings according the measured current from CT is proposed in this paper. Using this calculated current, phase current differential protection can be realized. Based on the method an adaptive second harmonic restrained scheme for magnetizing inrush current is presented. The scheme not only adaptively adjusts the secondary harmonic ratio of restrained current but also guarantees the fast action when transformers with internal faults are no-load energized. Consequently the performance of transformer differential protection is greatly improved. Simulation results in Matlab/Simulink validate the proposed method.

Keywords: transformer, current differential protection, magnetizing inrush current, secondary harmonic

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1. Introduction

Differential protection is the main protection of transformers to internal faults. How to prevent the mal-operation of differential protection causing by magnetizing inrush current has always been one of the hottest research topic [1]-[9]. At present, a lot of solutions have been presented. However, second harmonic restraint method is most widely used in practice for it is simple and easy to perform [10]-[14].

Generally, large power transformers adopt the wye-delta connection mode, and no CTs are installed inside the delta windings. Consequently, the current through delta windings cannot be measured directly and phase differential current cannot be obtained. Instead, line current differential protection is adopted. In this case the symmetry inrush current may arise which invalidate the restrained criterion for its unobvious features. To solve this problem, maximum harmonic ratio phase restraint pattern is employed which is essentially an or-door restraint pattern. But in this pattern, when transformers with internal faults are no-loaded energized, differential protection would be mal-restrained by the inrush current of normal phases and the speed of isolating fault would be decreased [15].

Based on sufficient studies on features of magnetizing inrush current, Ref. [16], [17] presented an adaptive secondary harmonic restrained scheme using phase angle and amplitude for inrush detection. In this scheme the secondary harmonic restrained ratio can be adjusted adaptively according to the relationship of phase angles between fundamental harmonic and secondary harmonic. This greatly improves the ability of distinguishing magnetizing inrush current and internal fault current. However, when this scheme is applied in transformer connected in wye-delta mode the problem that differential protection cannot operate instantaneously when transformers with internal faults are no-load energized still exists.

In this paper a calculating method of current through delta windings using the measured current from CTs at the two sides of transformers is given. With the calculating current phase current differential protection can be realized and symmetry inrush current can be avoided. Based on this method, an adaptive secondary harmonic restrained scheme for magnetizing inrush current in transformers connected in wye-delta mode is proposed. The scheme not only adaptively adjusts the secondary harmonic ratio of restraint current but also guarantees the fast operation when transformers with internal faults are no-load energized. Simulation results in Matlab/Simulink validate the proposed scheme.

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2. Calculating of Current Through Delta Windings

Figure 1 shows a three phase transformer connected in wye-delta mode which is composed of three single phase transformers. This mode is widely used in large-scale transformers. In the figure, $U_A$, $U_B$, and $U_C$ represent the three phase voltage of system equivalent source respectively. $i_A$, $i_B$, $i_C$, $i_{al}$, $i_{bl}$, and $i_{cl}$ represent the line current of each phase on the wye side and delta side respectively. $e_a$, $e_b$, and $e_c$ represent the induced electromotive force of main magnetic flux on the windings. All the electric quantities and parameters have been converted from delta side to wye side. Ignoring the resistance, there are equations for loops at the wyes ideas following,

$$
\begin{align*}
U_A &= (L_{s1} + L_{v0}) \frac{di_a}{dt} + (L_{v0} - L_{s1}) \frac{di_{al}}{dt} + e_a \\
U_B &= (L_{s1} + L_{v0}) \frac{di_b}{dt} + (L_{v0} - L_{s1}) \frac{di_{bl}}{dt} + e_b \\
U_C &= (L_{s1} + L_{v0}) \frac{di_c}{dt} + (L_{v0} - L_{s1}) \frac{di_{cl}}{dt} + e_c
\end{align*}
$$

(1)

where, $L_{s1}$ and $L_{v0}$ are positive sequence inductance and zero sequence inductance of system side respectively, $L_{v0}$ is the leakage inductance of windings on wye side. $U_A$, $U_B$, and $U_C$ are the voltage of the equivalent system source and they have the relationship as

$$
U_A + U_B + U_C = 0
$$

(2)

The equation for delta windings is

$$
e_a + L_{v0} \frac{di_a}{dt} + e_b + L_{v0} \frac{di_b}{dt} + e_c + L_{v0} \frac{di_c}{dt} = 0
$$

(3)

where, $L_{v0}$ is the leakage inductance of windings on delta side.

From Eq. (1), (2) and (3),

$$
(L_{v0} + L_{v0}) \frac{d3i_0}{dt} = L_{v0} \frac{d(i_a + i_b + i_c)}{dt}
$$

(4)

where, $i_0 = i_{v0} = i_{v0} = (i_a + i_b + i_c)/3$. Since the initial values of current are zero, the following equation can be deduced as following,

$$
i_a + i_b + i_c = \frac{3(L_{v0} + L_{v0})}{L_{v0}} i_0 = Ki_0
$$

(5)

where, $K = 3(L_{v0} + L_{v0})/L_{v0}$.

For the delta winding,

$$
\begin{align*}
i_{al} &= i_a - i_b \\
i_{bl} &= i_b - i_c \\
i_{cl} &= i_c - i_a
\end{align*}
$$

(6)

From Eq. (5) and (6), the current through delta winding can be calculated as following,
\[
\begin{align*}
    i_a &= \frac{i_{d1} - i_{d2} + Ki_{h}}{3} \\
    i_b &= \frac{i_{d1} - i_{d2} + Ki_{h}}{3} \\
    i_c &= \frac{i_{d1} - i_{d2} + Ki_{h}}{3}
\end{align*}
\]  

(7)

So the current through delta winding, \(i_a\), \(i_b\) and \(i_c\) can be calculated using the measured current by CTs at the two sides of transformer, \(i_{d1}\), \(i_{d2}\), \(i_{d3}\), \(i_{d4}\), \(i_{d5}\) and \(i_{d6}\) according to Eq. (7).

For transformer in Figure 1,

\[
\begin{align*}
    u_a &= L_{q1} \frac{di_a}{dt} + e_a \\
    u_a &= L_{q2} \frac{di_a}{dt} + e_a = L_{q2} \frac{di_{d1}}{dt} + L_{q2} \frac{di_{d2}}{dt} + e_a
\end{align*}
\]  

(8)

where, \(i_{d1}\) is the circular current through delta winding, \(i_{d2}\) is the current through a-phase, and \(i_{d3} = (i_{d1} - i_{d2})/3\), then,

\[
\begin{align*}
    u_a - u_a &= L_{q1} \frac{di_a}{dt} - L_{q2} \frac{di_{d1}}{dt} - L_{q2} \frac{di_{d2}}{dt}
\end{align*}
\]  

(9)

Similarly, for b-phase and c-phase,

\[
\begin{align*}
    u_b - u_b &= L_{q1} \frac{di_b}{dt} - L_{q2} \frac{di_{d1}}{dt} - L_{q2} \frac{di_{d2}}{dt}
\end{align*}
\]  

(10)

\[
\begin{align*}
    u_c - u_c &= L_{q1} \frac{di_c}{dt} - L_{q2} \frac{di_{d1}}{dt} - L_{q2} \frac{di_{d2}}{dt}
\end{align*}
\]  

(11)

3. Identification of Leakage Inductance

In the above calculating method the transformers’ leakage inductances are necessary. However, only short-circuit reactance is provided on the transformer’s nameplate. Traditionally, the leakage inductances of the high voltage winding and the low voltage winding are both regarded as half of the short circuit reactance. Apparently, they are not accurate. More significantly, the leakage inductance would change if internal faults occurred. To calculate the current through delta windings accurately under normal and abnormal state, this paper adopts parameter identifying principle to identify transformer’s leakage inductance in real time [18].

For transformer in Figure 1,
Eliminating the influence of circular current,

\[ u_a - u_a - u_b + u_p = L_{q1} \frac{d(i_a - i_b)}{dt} - L_{q2} \frac{d(i_p - i_p)}{dt} \]  (12)

where, \( u_a, u_a, u_b, u_p, i_a, i_b, i_p \) and \( i_p \) can be obtained by measuring or calculating, only \( L_{q1} \) and \( L_{q2} \) need to be identified. Through solving Eq. (12) at two sampling point \( L_{q1} \) and \( L_{q2} \) can be identified in real time.

4. Phase Current Differential Protection

Ref. [16], [17] reach the conclusion that the phase angle difference of fundamental harmonic and secondary harmonic is approximately equal to 0° or 180°. Based on this feature, an adaptive secondary harmonic restrained method is proposed. This method considers not only the amplitude relationship between fundamental harmonic and secondary harmonic but also the phase angle relationship between them. If the phase angle difference was approximately equal to 0° or 180°, the secondary harmonic ratio of restrained current would be lowered. Otherwise, it keeps a higher value. Consequently, even if the secondary harmonic components were small the differential protection would be blocked. For the secondary harmonic ratio is not necessary to be set to a low value to avoid the mal-operation of differential protection causing by magnetizing inrush current, the differential protection would not be blocked when internal faults occur (especially sometimes the secondary harmonic components are big). Figure 2 shows the operation area and block area.

![Figure 2. Operation area and block area of an adaptive secondary harmonic restrained scheme](image)

For transformers connected in wye-delta mode, the conventional adaptive secondary harmonic restrained method still has no solution to the acquisition of current through delta windings and adopts maximum-harmonic-ratio-phase restraint pattern to avoid the influence of symmetry magnetizing inrush current. The criterion is demonstrated by Eq. (13). Therefore, this method still has the problem mentioned in Part 1.

\[ \left( \frac{I_{d_{a2}}}{I_{d_{a1}}} > k_{seta} \right) \cup \left( \frac{I_{d_{b2}}}{I_{d_{b1}}} > k_{setb} \right) \cup \left( \frac{I_{d_{c2}}}{I_{d_{c1}}} > k_{setc} \right) \]  (13)

where, \( I_{d_{a2}}, I_{d_{b2}} \) and \( I_{d_{c2}} \) are respectively the secondary harmonic amplitude of line differential current in phase-a, phase-b and phase-c, \( I_{d_{a1}}, I_{d_{b1}} \) and \( I_{d_{c1}} \) are respectively the fundamental harmonic amplitude of line differential current in phase-a, phase-b and phase-c. \( k_{seta}, k_{setb} \) and \( k_{setc} \) are respectively the secondary harmonic ratio of restrained current in phase-a, phase-b and phase-c which are adaptively adjusted according to the phase angle relationship between fundamental harmonic and secondary harmonic.
Based on the proposed calculating method in Part 2, combining the adaptive secondary harmonic restrained method presented in Ref. [16], [17], this paper presents an adaptive secondary harmonic restrained scheme.

Firstly, the method in Part 3 is used to identify the leakage inductances. Then, using these leakage inductances, the current through delta windings can be calculated according to the method in Part 2. Next, the phase differential current can be obtained. The phase differential current is essentially transformer’s magnetizing current which cannot produce symmetry magnetizing inrush current. Consequently, the restrained scheme is feasible. The criterion is

\[
\left( I_{\Delta I_2} > k_{\text{seta}} \right) \cap \left( I_{\Delta I_3} > k_{\text{setb}} \right) \cap \left( I_{\Delta I_1} > k_{\text{setc}} \right) > 0
\]

(14)

where, \( I_{\Delta I_1}, I_{\Delta I_2}, I_{\Delta I_3}, I_{\Delta I_1}, I_{\Delta I_2}, I_{\Delta I_3}, k_{\text{seta}}, k_{\text{setb}}, k_{\text{setc}} \) represent the same quantities as in Eq. (13).

The scheme not only adaptively adjusts the secondary harmonic ratio of restraint current but also guarantees the fast action when transformers with internal fault are no-load energized. It greatly improves the performance of differential protection in transformers connected in wye-delta mode.

5. Case Studies

To validate the proposed scheme, a simulation mode of transformer is built in Matlab. The transformer is connected in YN, D11 mode and its parameter is: 600MVA (capacity), 500kV/20kV, 0.002(pu) (resistance of windings), 0.08(pu) (leakage inductance), 500(pu) (magnetizing resistance). The saturation characteristic is: 0, 0(pu); 0.0024, 1.15(pu); 1, 1.5(pu). Program based on Matlab programming language is wrote to realize identification of transformer’s leakage inductances and the calculation of current through delta winding.

The transformer is no-load energized at 1s. Figure 3 shows the calculated curve and the measured curve of current through the delta windings. From the figure the conclusion can be reached that the error of calculating method is very small.

Figure 3. The measured curve and calculated curve of current through delta windings

Figure 4 and Figure 5 show the phase differential current and line differential current of three phases. From Figure 4, it can be concluded that the curve of phase differential current has typical features of magnetizing inrush current. So the secondary harmonic restrained scheme based on phase differential current can block differential protection effectively. From Figure5, it is found that the line differential current in phase-b was symmetry to some extent. The second harmonic ration is low than 15% from its spectrum shown in Figure 6. Consequently, the restrained scheme based on line differential current sometimes may become invalid.
6. Conclusions

For transformers connected in wye-delta mode, the current through delta windings cannot be measured directly, and line differential current is employed in differential protection. The resulted symmetry inrush current may invalidate the restrained criterion for inrush current. This paper presents a calculating method of current through delta windings utilizing the measured current from CTs is proposed in the paper. With this calculated current the phase differential current can be computed and the phase current differential protection method is realized. Based on the method, an adaptive second harmonic restrained scheme is presented. The scheme not only adaptively adjusts secondary harmonic ratio of restrained current according to the phase relationship between fundamental and secondary harmonic, but also guarantees the fast action when transformers with internal faults are no-load energized. Case studies prove that the scheme greatly improves the performance of transformer differential protection.
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