Analysis on Differential Protection Sensitivity of Traction Transformers Based on Different Conversion Modes

Liu Xiaobao, Zheng Yuping, Long Feng, Wu Tonghua, Pan Shuyan, An Lin
State Key Laboratory of Smart Grid Protection and Control, Nari Group Corporation, Nanjing, Jiangsu, 211106, China
liuxiaobao@sgepri.sgcc.com.cn

Abstract: With the rapid development of high-speed rail technology in China, the traction transformers of various types have been used more and more extensively. The differential protection of traction transformers has different differential conversion modes \(^1\)\(^-\)\(^2\) which are different in their sensitivities. In this paper, taking the YNV traction transformer as an example, by comparing the sensitivities of two different common differential conversion modes and through analysis, it shows that the sensitivities of differential protection are slightly different. The sensitivities of differential protections based on different principles depend on the retention degree of differential current to the positive sequence, negative sequence and zero sequence components in the internal fault current. The sensitivity of phase current minus zero sequence differential is the highest when single-phase grounded, which completely retains all the sequence components in the internal fault current. The sensitivity of interphase differential protection is the highest when interphase fault occurs. The widely used phase current differential and phase current minus zero sequence differential do not reflect the zero-sequence component of internal fault current, which provides the basis for field fault analysis and setting.

1. Introduction
The differential protection is the main protection widely used in traction substation. It has high sensitivity and reliability, and is the standard configuration of traction transformer protection. The traction transformer is more complex than conventional transformer in wiring and more special in LV winding structure. In general, it only has \(\alpha\) phase and \(\beta\) phase \(^3\). The HV side type and LV side type of traction transformer are different and need to be converted. There are mainly two conversion modes for correction of amplitude and phase angle. The principles of the two conversion modes are different, which brings confusion to the field setting personnel and fault analysis \(^4\).

At present, the traction transformer mainly adopts interphase current differential type and phase current differential type.

The phase to phase current is used to convert the high-voltage side current to delta side; the phase current differential is used to convert the low-voltage side current to Y side \(^5\).

In this paper, the YNV type traction transformer is exampled to analyze the sensitivity of the two conversion modes in single-phase grounded and interphase fault so as to provide basis for site value setting and sensitivity analysis.
2. YNV traction transformer differential protection principle

2.1. Structure and vector diagram of YNV traction transformer

The YNV traction transformer is formed by adding two bridge arms on the basis of YD11 transformer. The structure of YNV is shown in Figure 1. During normal operation, the phase angle and amplitude of the HV side and LV side are different and need to be converted. The CT at the HV side and LV side are star type wiring. The relationship between the voltage and current at the HV side and LV side of the transformer is shown as follows:

![Figure (a) Winding structure of YNV traction transformer](image1)

![Figure (b) vector of YNV traction transformer](image2)

Figure 1 YNV traction transformer model
Among that:
\( I_{A} \), \( I_{B} \), and \( I_{C} \) are HV side three-phase currents; \( I_{\alpha} \) and \( I_{\beta} \) are LV side currents; \( U_{\alpha} \) and \( U_{\beta} \) are HV side and LV side voltage; \( I_{a} \), \( I_{b} \) and \( I_{c} \) are LV winding currents, symbol meanings are the same below.

When there is a fault in the transformer area, zero sequence current cannot flow through the low-voltage winding. However, the zero sequence current at the HV side can flow through the neutral point. If the zero sequence current is not subtracted from the high-voltage side, the imbalance current at the high and low voltage side of the transformer is easy to cause the misoperation of the differential protection.

In this paper, the traction transformer of YNV type is analyzed. It is assumed that the voltage ratio of the high and low voltage side is 1, which avoids the tedious calculation of the balance coefficient.

### 2.2. Phase-phase differential principle of YNV transformer

The HV side current is the phase-phase current, \( I_{A} - I_{B} \) namely, Calculation of Y side differential current:

\[
\begin{bmatrix}
I_{\alpha} \\
I_{\beta} \\
I_{\gamma}
\end{bmatrix} = \frac{1}{\sqrt{3}} \begin{bmatrix}
I_{A} - I_{B} \\
I_{B} - I_{C} \\
I_{C} - I_{A}
\end{bmatrix}
\]

(2)

Calculation of V side differential current:

\[
\begin{bmatrix}
I_{\alpha} \\
I_{\beta} \\
I_{\gamma}
\end{bmatrix} = \frac{1}{\sqrt{3}} \begin{bmatrix}
1.366 & 0.366 & I_{A} \\
0.366 & 1.366 & I_{B} \\
1.0 & 1.0 & I_{C}
\end{bmatrix}
\]

(3)

Where: \( I_{\alpha}, I_{\beta}, I_{\gamma} \) are the three phase differential currents of Y side, \( I_{\alpha}, I_{\beta}, I_{\gamma} \) are the three phase differential currents of V side.

### 2.3. Phase current differential action principle of YNV transformer

With a view to remove the zero sequence current of the HV side, the self-produced zero sequence current can also be eliminated from the phase current of the HV side:

Calculation of Y side differential current:
Calculation of $V$ side differential current:

\[
\begin{bmatrix}
I_{\text{cd}A} \\
I_{\text{cd}B} \\
I_{\text{cd}C}
\end{bmatrix} =
\begin{bmatrix}
I_A - I_0 \\
I_B - I_0 \\
I_C - I_0
\end{bmatrix}
\]  \hspace{1cm} (4)

3. Sensitivity comparison in the event of internal fault

The sensitivity of differential protection is related to the conversion of differential protection. Therefore, it is necessary to take an objective and fair method for comparison. In this paper, different type faults are analyzed. Assumed other conditions are the same, the retentions of fault components in differential current under different conversion conditions are compared.

In the event of internal fault, the magnitude of differential current is related to positive sequence, negative sequence and zero sequence.

\[
\dot{I}_d = k_1 \dot{I}_1 + k_2 \dot{I}_2 + k_3 \dot{I}_0
\]  \hspace{1cm} (6)

In the formula:

- $I_d$: traction transformer differential current,
- $\dot{I}_1$: fault current positive sequence component,
- $\dot{I}_2$: fault current negative sequence component,
- $\dot{I}_0$: fault current zero sequence component.
- $k_1$, $k_2$, $k_3$: the coefficients of differential current with positive sequence, negative sequence and zero sequence reserved.

3.1. Fault volume in the area in the event of different conversion modes

The fault current can be decomposed by sequence component [7]. The relationship between three-phase current and fault sequence component of HV side is shown as follows:

\[
\begin{bmatrix}
I_A \\
I_B \\
I_C
\end{bmatrix} = 
\begin{bmatrix}
1 & 1 & I_{F1} \\
\alpha^2 & \alpha & I_{F2} \\
\alpha & \alpha^2 & I_{F0}
\end{bmatrix}
\]  \hspace{1cm} (7)

Where, $I_{F1}$, $I_{F2}$ and $I_{F0}$ are the positive, negative and zero sequence components of HV side.

Relationship between two-phase current and fault sequence component of LV side:

\[
\begin{bmatrix}
\dot{I}_a \\
\dot{I}_\beta
\end{bmatrix} = 
\begin{bmatrix}
1 & 1 & I_{\hat{F}1} \\
\alpha^2 & \alpha & I_{\hat{F}2} \\
\alpha & \alpha^2 & I_{\hat{F}0}
\end{bmatrix}
\]  \hspace{1cm} (8)

Where, $\dot{I}_{\hat{F}1}$, $\dot{I}_{\hat{F}2}$ and $\dot{I}_{\hat{F}0}$ are the positive, negative and zero sequence components of HV side.

In the event of fault in traction transformer area, the diagram of HV and LV sequence components is shown as Figure 2 below:
Figure 2 Fault sequence component in traction transformer internal fault

The positive sequence and negative sequence fault components can be obtained:

\[
\begin{align*}
I_{FA1} &= I_{A1} + I_{a1} = C_{A1} F_1 + C_{a1} F_1 \\
I_{FA2} &= I_{A2} + I_{a2} = C_{A2} F_2 + C_{a2} F_2
\end{align*}
\] (9)

Where, \(CA1\) and \(Ca1\): are the coefficients of positive sequence current; \(CA2\) and \(Ca2\): are the coefficients of negative sequence current.

3.2. Differential current of phase-phase differential action in the event of internal fault

The phase-phase differential current is detailed as Formula (10). In this paper, C-phase is exampled for analysis:

\[
\begin{align*}
I_{cc} &= \frac{I_c - I_A}{\sqrt{3}} \\
I_{ac} &= \frac{I_a + I_\beta}{\sqrt{3}} \\
I_{clc} &= I_{cc} + I_{ac}
\end{align*}
\] (10)

Where, \(I_{cc}\) is HV side Phase C differential current, \(I_{cc}\) is LV side Phase C differential current, \(I_{clc}\) is traction transformer Phase C differential current.

3.3. Phase current differential current expression in the event of internal fault

The phase differential current formulas after conversion is detailed as Formula (11):

\[
\begin{align*}
I_{cc} &= I_c - I_0 \\
I_{ac} &= \frac{0.577}{\sqrt{3}} (I_\alpha - I_\rho) \\
I_{clc} &= I_{cc} + I_{ac}
\end{align*}
\] (11)

4. Comparison of sensitivity in the event of internal fault in different conversion modes

4.1. Analysis of phase-phase differential sensitivity in the event of single-phase grounded and interphase fault

Exampled by phase C, the relationship between differential current and sequence component of YNV traction transformer can be deduced by introducing the sequence component into Formula (9):
\[ \dot{I}_{cle} = \dot{I}_{cc} + \dot{I}_{\omega} = \frac{(I_C - I_A)}{\sqrt{3}} - \frac{I_A + I_B}{\sqrt{3}} \]
\[ = \frac{1}{\sqrt{3}}(1 - \alpha^2)I_A + \frac{1}{\sqrt{3}}(1 - \alpha)I_{a2} + \frac{1}{\sqrt{3}}(1 - \alpha^2)I_{a1} + \frac{1}{\sqrt{3}}(1 - \alpha)I_{a2} \]
\[ = \frac{1}{\sqrt{3}}(1 - \alpha^2)(I_{F1} + I_{a1}) + \frac{1}{\sqrt{3}}(1 - \alpha)(I_{F2} + I_{a2}) \]
\[ = \frac{1}{\sqrt{3}}(1 - \alpha^2)I_{F1} + \frac{1}{\sqrt{3}}(1 - \alpha)I_{F2} \] (12)

In the event of single-phase grounded, the sequence component satisfies the relationship:
\[ I_{F1} = I_{F2} = I_{B0} \] (13)
So we can obtain:
\[ \dot{I}_{cle} = \frac{\sqrt{3}}{3} \dot{I}_F \] (14)

It can be seen that in the event of single-phase ground fault, the differential current is only \( \frac{\sqrt{3}}{3} \) of the fault current.

In the event of interphase fault, the sequence component will satisfy the relationship:
\[ I_{F1} = -2\dot{I}_{F2} \] (15)
So we can obtain:
\[ \dot{I}_{a0} = \frac{2\sqrt{3}}{3} \dot{I}_F \] (16)

4.2. Analysis of phase current differential sensitivity in the event of single-phase grounded and interphase fault

The Phase C differential current obtained by phase current differential. According to Formula 11, it can be deduced as follows:
\[ \dot{I}_{a0} = (\dot{I}_C - \dot{I}_0) - \sqrt{3}(0.2113\dot{I}_a - 0.2113\dot{I}_b + 0.7887\dot{I}_b - 0.7887\dot{I}_c) \]
\[ = \dot{I}_C - \sqrt{3}(0.2113\dot{I}_a + 0.5774\dot{I}_b - 0.7887\dot{I}_c) \]
\[ = \dot{I}_C - \sqrt{3}(-0.2113(2.732\dot{I}_b - \dot{I}_c) + 0.5774\dot{I}_b - 0.7887\dot{I}_c) \]
\[ = \dot{I}_C - \sqrt{3}(-0.5774\dot{I}_b + 0.2113\dot{I}_c + 0.5774\dot{I}_b - 0.7887\dot{I}_c) \]
\[ = \dot{I}_C - \dot{I}_c \] (17)

For single-phase grounded:
\[ \dot{I}_{cle} = I_{F1} + I_{F2} \]
\[ = \frac{2}{3} \dot{I}_F \] (18)

For interphase fault:
\[ I_{clc} = I_F \]

5. Verification of dynamic model
A 220kV traction transformer based on the actual parameters of the project is taken as the research object.

The rated voltage is 220/27.5 kV and the rated capacity is 60 MVA [8, 9].

When C phase ground fault occurs on the Y side of the transformer, the ground fault current and the differential current waveforms when the above two principles are adopted are shown in Figure 4. According to Figure 4, the differential current when the phase differential principle is adopted is \( \frac{2}{3} I_F \); the differential current when the phase-phase current differential principle is adopted is \( \sqrt{\frac{2}{3}} I_F \). This is completely complied with the result of theoretical analysis.

When CA phase resistive ground fault occurs on the Y side of the transformer, the ground fault current and the differential current waveforms when the above two principles adopted are shown in Figure 5. According to Figure 7, the differential current is IF of the fault terminal current when phase differential principle is adopted; the differential current is \( \frac{2\sqrt{3}}{3} I_F \) of the fault current when phase-phase differential principle is adopted. This is completely complied with the result of theoretical analysis.
8

Figure 5 differential current of phase current mode when single-phase grounded

Table 1. Analysis of Single Phase Grounded and Interphase Fault Sensitivity

| Conversion mode sensitivity | Single-phase fault | Phase-phase fault | Three phase fault |
|-----------------------------|--------------------|-------------------|------------------|
| Fault mode                  |                    |                   |                  |
| Interphase differential     | $\frac{\sqrt{3}}{3} I_F$ | $\frac{2\sqrt{3}}{3} I_F$ | $I_F$ |
| Phase current differential  | $\frac{2}{3} I_F$   | $I_F$             | $I_F$            |

6. Conclusion
Through the analysis hereunder, it can be found that the sensitivities of two kinds of YNV transformers are not the same in the event of internal fault:

1)  The sensitivity of phase-phase current differential and phase current differential is related to the type of fault. From the perspective of action quantity, the sensitivity of phase-phase differential fault is the highest, and the sensitivity of phase current differential to single-phase ground fault is the highest, but there is no difference in the sensitivity in essence, and the sensitivity difference can be compensated by setting value.

2)  In the case of heavy load (generally overload operation of traction transformer), it is necessary to adjust the differential inflection point and slope to ensure the sensitivity.

3)  In this paper, only the sensitivity of different conversion modes in the event of internal fault is analyzed. The transformer inrush current and CT saturation recognition are reflected differently, which is related to saturation algorithm.

Acknowledgments:
This work is supported by National Natural Science Foundation of China (Grant No.U1866603), project name: Fundamental Research on Multivariable-Based Adaptive Protection and Safe Operation for Power Transformers.
References
[1] ZHAO RAN. Study On the protection of YNVD connected three-phase to two-phase transformer [D]. Tianjin University, 2015.
[2] HUANG Zhenning. Research on impedance matching balance transformer protection [D], 2008.
[3] Journal of Hefei University of Technology Natural Science), 2000, 23(5): 636-641.
[4] LIU Miao, SHI Dong-yuan, YANG Xiong-ping. Comparison of fault calculation methods for transmission network considering unsymmetrical two—phase railway power supply system[J]. Realy, 2007, 35(8): 21—26.
[5] DING Suyang, LIN Xiangning, WENG Hanli, et al. Mal-operation risk analysis and countermeasure on zero-sequence differential protection of converter substation during existence of recovery inrush due to fault removal [J]. Proceedings of the CSEE, 2017, 37(S1): 12-20. DOI: 10.13334/j.0258-8013.pcsee.162277.
[6] LIANG Deliang. Analysis of Development Trend for Intelligent Distribution Transformer [J]. Automation of Electric Power Systems, 2020, 44(07): 50-54.
[7] LIU Zhongping, LU Yuping, YUAN Yubo. Study of transformer recovery inrush after clearance of external faults [J]. Automation of Electric Power Systems, 2005(08): 41-44+95.
[8] FENG Cunliang, BI Daqiang, GE Baoming. Sympathetic Inrush Identification for Traction Transformer Based on Time Differential Method [J]. Automation of Electric Power Systems, 2012, 32(06): 8-11+14.
[9] Mohsen Kalantari Mohammad Javad Sadeghi Seyed Saeed Fazel Siamak Farshad. Journal of Electromagnetic Analysis and Applications, 2010, 11(4): 618-626.