Study on the transformer protection scheme based on double thresholds and waveform similarity

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Abstract. As the key device of power transmission, the power transformer has higher requirements for the protection sensitivity and reliability. However, the operation time of the differential protection is limited to the data window of the Fourier transform algorithm. In addition, the differential protection cannot recognize the slight transformer turn-to-turn fault. Moreover, it may maloperate when the current transformer (CT) is saturated. To solve above problems, a novel transformer protection scheme based on double thresholds and waveform similarity is proposed. By comparing the current waveform similarity with the double thresholds, the external faults, internal faults and CT saturation scenarios can be effectively identified, while the waveform similarity is obtained by calculating the Hausdorff distance of the current at each side of the transformer. The PSCAD/EMTDC based simulation results show that the proposed protection scheme can operate quickly and the operation time is as low as 5.5ms. In addition, it has high sensitivity and can effectively identify 0.5% or higher turn-to-turn faults, and it will not be affected by CT saturation.

1. Introduction
Transformers play an important role in power transmission and the interconnection of regional power grids. At present, differential protection is the most widely used transformer main protection, which can identify phase-to-phase, phase-to-ground faults and severe turn-to-turn faults [1-2]. The differential protection scheme generally uses a Fourier transform algorithm to extract the fundamental component. To meet the high-precision calculation requirements, the data window length of the Fourier transform algorithm generally takes at least half of the cycle. In addition, CT saturation has been a perennial problem for the differential protection. The fake differential current will emerge when the external fault with CT saturation occurs and the differential protection may maloperate [3-4]. It should be noted that the differential protection is difficult to identify the transformer slight turn-to-turn fault (the number of short circuit turns is less than 3%) [5-6]. Because of its simple principle and high sensitivity to the difference between waveforms, the Hausdorff algorithm has been initially applied in the field of relay protection [7-9]. On the basis of this, this paper further studies the variation rule of Hausdorff distances of the current at each side of the transformer in different scenes such as transformer slight turn-to-turn fault and CT saturation. Then a
fast transformer protection scheme based on Hausdorff distance and double thresholds. Theoretical analysis and simulation tests verify the effectiveness of the proposed protection scheme.

2. The basic protection principle

2.1. Basic principle of waveform similarity recognition based on Hausdorff distance

Assume there are two sets of finite points as \( A = \{a_1, a_2, \ldots, a_i, \ldots, a_p\} \) and \( B = \{b_1, b_2, \ldots, b_j, \ldots, b_q\} \), the Hausdorff distance between the two sets of points is defined as (1).

\[
H(A, B) = \max\{h(A, B), h(B, A)\}
\]

(1)

\[
h(A, B) = \max_{a \in A} \min_{b \in B} \|a - b\|
\]

(2)

\[
h(B, A) = \max_{b \in B} \min_{a \in A} \|a - b\|
\]

(3)

Where \( \|\| \) represents the Euclidean distance between two points, and \( h(A, B) \) represents the one-way Hausdorff distance from A to B (the same as \( h(B, A) \)). Equation (4) shows the definition of \( h(A, B) \), which is described as follows: for each point in set A, the nearest point can be found in set B.

\[
\|a_i - b_j\| \leq \|a_i - b_k\| (1 \leq k \leq q \& k \neq j)
\]

(4)

The two way Hausdorff distance called \( H(A, B) \) is the larger one between \( h(A, B) \) and \( h(B, A) \), which is used to measure the maximum dissimilarity between two point sets. The larger Hausdorff distance between the two waveforms is, the greater difference between them is, and vice versa.

2.2. The characteristics of Hausdorff distance of current at each side of transformer under different conditions

2.2.1. Transformer normal operation or external fault without CT saturation. Figure 1 shows the schematic diagram of the currents collected by CT of transformer protection. Considering the different connection modes at each side of the transformer, the measured current on the star side should be transformed in the microcomputer protection device as (5) before comparing the waveform similarity of the currents at both sides:

\[
\begin{align*}
\delta_{\text{IA}} &= -N(\delta_{\text{IA}} - \delta_{\text{IB}}) \\
\delta_{\text{IB}} &= -N(\delta_{\text{IB}} - \delta_{\text{IC}}) \\
\delta_{\text{IC}} &= -N(\delta_{\text{IC}} - \delta_{\text{IA}})
\end{align*}
\]

(5)

![Figure 1](image_url)

**Figure 1.** Currents on both sides of the transformer.

According to Kirchhoff’s current law, the transformed currents satisfy (6).

\[
I_{\text{IA}} = I_{\text{IA}}', I_{\text{IB}} = I_{\text{IB}}', I_{\text{IC}} = I_{\text{IC}}'
\]

(6)
It can be obtained that transformed currents of the star side $\tilde{I}_{ka}$, $\tilde{I}_{kb}$ and $\tilde{I}_{kc}$ are exactly the same with the triangle side current $\tilde{I}_{ta}$, $\tilde{I}_{tb}$ and $\tilde{I}_{tc}$, respectively when the transformer is under normal operation or external fault. Therefore, the corresponding Hausdorff distance is zero.

2.2.2. Transformer internal fault. When an internal fault occurs at the transformer, the original three-phase symmetrical state of the transformer will be broken. Then, the star side currents obtained from (5) and triangle side currents will no longer meet (6).

2.2.3. Transformer external fault with CT saturation. When a transformer external fault occurs, the involved CT may be saturated due to the influence of DC component and CT parameters. Then the CT works alternately in saturated and unsaturated state, and there is always a period of time for CT to work in the linear transmission area. Considering that the length of the data window of Hausdorff distance algorithm can be adjusted to a small one, the two waveforms in the window are almost the same as long as the data window is within the linear transformation area, and the Hausdorff distance will be near zero. The above characteristics can be used to identify the external faults with CT saturation.

3. The novel transformer protection scheme based on double thresholds and waveform similarity

According to the analysis in the section 2, the Hausdorff distances under above three conditions can be correspondingly divided into the following three categories when a short data window is selected (1/8 cycle (2.5ms) is selected in this paper): 1) the waveforms on both sides of the transformer are the same, then the Hausdorff distance is near 0 for a long time; 2) the waveforms on both sides of the transformer are almost opposite, then the Hausdorff distance is at a high level for a long time; 3) there exists a certain time when Hausdorff distance drops to around 0 in one cycle. Figure 2 shows the diagram of three types of Hausdorff distances discussed above.

![Figure 2. Diagram of three types of Hausdorff distances.](image)

According to the above analysis, the setting method of double thresholds is designed as follows:

1) Low threshold $H_{set1}$

The low threshold $H_{set1}$ is set as the starting threshold. When the Hausdorff distance is larger than the threshold $H_{set1}$, it is determined that there is an internal fault or external fault with CT saturation occurs. The setting principle of $H_{set1}$ shall be based on the maximum value (denoted by $H_{max1}$) of Hausdorff distance in the cases of transformer normal operation and external fault with CT unsaturation. That is to say, $H_{set1} = H_{max1} \times K_{rel}$, where $K_{rel}$ represents reliability and is set as 1.15~1.3.

2) High threshold $H_{set2}$

The high threshold $H_{set2}$ is used for further identification between internal fault and external fault with CT saturation. Its setting principle is based on the maximum Hausdorff distance under the condition of transformer external fault with CT saturation, and the reliability coefficient $K_{rel2}$ shall be considered. That is to say, $H_{set2} = H_{max2} \times K_{rel2}$. Once the Hausdorff distance is larger than the threshold value, it is determined that a serious internal fault occurs, and the circuit breaker shall be tripped immediately. When the Hausdorff distance is between the above two threshold values, it is judged that slight internal fault or external fault with CT saturation occurs. At this time, move the data window forward in single sample point and continue to calculate the Hausdorff distance for one
cycle. When the Hausdorff distance falls below the low threshold value during this period, it is judged an external fault with CT saturation occurs, and protection criterion shall be blocked. If the Hausdorff distance is always between two threshold values within one cycle, it is judged a slight internal fault occurs and the circuit breaker will be tripped.

4. Case study

Figure 3 shows the simulation model built in PSACD/EMTDC. The transformer parameters are as follows: the ratio is 220/110 kV and the capacity is 100 MVA. The leakage reactance is 0.2 p.u and copper loss is 0.02 p.u. The power voltage is 220 kV and the equivalent system impedance is $Z = 27.5 \angle 85^\circ \Omega$. The sampling frequency is 4 kHz. The high and low thresholds are set as 2.5 and 0.05, respectively.

**Figure 3.** 220kV/110kV transformer model.

4.1. Slight turn-to-turn fault

Assume a slight 0.5% turn-to-turn fault occurs at the phase A winding at 0.4s. Under this condition, phase A current waveform on both sides of the transformer and corresponding Hausdorff distance is shown in Figure 4. The simulation results show that the maximum distance of Hausdorff is 0.16, which is far below the high threshold value of 2.5, so the protection device will continue to judge in one cycle. During this period, the Hausdorff distance is always higher than the low threshold value of 0.05, so the protection scheme determine that transformer internal fault occurs. Then the protection will operate at 0.42s.

**Figure 4.** Phase A current waveforms and Hausdorff distance when slight turn-to-turn fault occurs.

If differential protection is adopted, the differential current is too small to exceed the threshold and cannot identify the fault.
4.2. External fault with CT saturation

![Image of phase A current waveforms and Hausdorff distance]

Figure 5. Phase A current waveforms and Hausdorff distance when external fault with CT saturation occurs

It is assumed that a phase A grounded fault occurs at the first end of the transmission line at 0.4s and the CT is saturated. Figure 5 shows the phase A current waveforms and Hausdorff distance. It can be seen that CT starts to saturate at 4ms after the occurrence of the fault and the Hausdorff distance increases to the low threshold value of 0.05. In the following one cycle after the occurrence of the fault, the Hausdorff distance is always lower than the high threshold value of 2.5. The Hausdorff distance drops to the low threshold value at 0.417s. Thus, the protection scheme identifies that a transformer external fault with CT saturation occurs and does not issue a trip command.

5. Conclusion

To solve the problem that the traditional transformer differential protection cannot deal with slight turn-to-turn faults and CT saturation, a novel transformer protection scheme based on double thresholds and Hausdorff distance is proposed. The validity and superiority of the proposed scheme are verified by PSCAD/EMTDC based simulation tests. The basic conclusions are as follows:
1. The proposed scheme has a strong CT saturation tolerance ability, and its operation speed is faster than that of the traditional differential protection in identifying serious transformer internal faults;
2. The proposed scheme has a strong ability to response to turn-to-turn fault. It can identify the slight turn-to-turn faults whose short circuit turn ratio is as low as 0.5% within one week after the occurrence of the fault.

References

[1] D. Zacharias and R. Gokaraju, "Prototype of a Negative-Sequence Turn-to-Turn Fault Detection Scheme for Transformers," in IEEE Transactions on Power Delivery, vol. 31, no. 1, pp. 122-129, Feb. 2016.
[2] Jun Guan, Zhiguo Hao, Wenzhe Chen, Zhiyuan Liu and Xiaojun Yu, "Novel power transformer differential protection scheme based on improved short-window algorithm," 2016 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC), Xi'an, 2016, pp. 830-834.
[3] T. Zheng, T. Huang, Y. Ma, Z. Zhang and L. Liu, "Histogram-Based Method to Avoid Maloperation of Transformer Differential Protection Due to Current-Transformer Saturation Under External Faults," in IEEE Transactions on Power Delivery, vol. 33, no. 2, pp. 610-619, April 2018.
[4] F. Costa and R. Prado, "A Wavelet-Based Transformer Differential Protection With Differential Current Transformer Saturation and Cross-Country Fault Detection," 2018 IEEE Power & Energy Society General Meeting (PESGM), Portland, OR, 2018, pp. 1-1.
[5] L. M. R. Oliveira and A. J. M. Cardoso, "Comparing Power Transformer Turn-to-Turn Faults Protection Methods: Negative Sequence Component Versus Space-Vector Algorithms," in IEEE Transactions on Industry Applications, vol. 53, no. 3, pp. 2817-2825, May-June
2017.

[6] O. Ozgonenel and S. Karagol, "Maximum overlap discrete wavelet based transformer differential protection," 2017 25th Signal Processing and Communications Applications Conference (SIU), Antalya, 2017, pp. 1-4.

[7] A. Wang, X. Sun, X. Zhou, and W. Hu, “Difference squared hausdorff distance based medical image registration,” in Proc. Chin. Control Decis. Conf., Mianyang, China, 2011, pp. 4270–4272.

[8] L. Chen et al., "Similarity Comparison Based High-Speed Pilot Protection for Transmission Line,” in IEEE Transactions on Power Delivery, vol. 33, no. 2, pp. 938-948, April 2018.

[9] ZHAO Hang, LIN Xiangning, YU Kun, et al. A High-speed Protection Scheme for HVDC Transmission Line Based on Hausdorff Distance Comparison[J]. Proceedings of the CSEE, 2017.