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A novel criterion applicable to transformer differential protection based on waveform sinusoidal similarity identification☆

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ABSTRACT

The Hausdorff distance (HD) algorithm has superiorities in the recognition of waveform similarity. On this basis, a novel criterion based on the HD algorithm applicable to transformer differential protection is put forward in this paper. The proposed criterion firstly normalizes the differential current sequence and synchronously creates a standard sine wave sequence. Then the HD between the two sequences is calculated to reflect the waveform sinusoidal similarity of the differential current. The proposed criterion can be used to distinguish internal faults, magnetizing inrushes and faults accompanied by CT saturation of the transformer. Simulation and experiment tests are conducted to evaluate the performance of the proposed criterion.

1. Introduction

The differential protection is one of the most prevalent main protections for power transformers, for which, how to identify the magnetizing inrush is a critical issue that needs to be addressed.

Currently, the identification methods of transformer magnetizing inrush are mainly classified into two categories. One category applies both current and voltage measurements to form various criteria, such as the methods based on the variation characteristics of flux [1], impedance [2,3] and power [4]. However, the application of the potential transformers (PTs) hinders the practicability of this category of methods.

The methods of the other category are simply based on the waveform characteristics of differential current [5–13], among which, the second harmonic restraint criterion [5,6] and gap detection criterion [7,8] are the most classical and widely used. However, it is well known that, they still have some drawbacks under certain special conditions, such as current transformer (CT) saturation, symmetrical inrush current and fault current superimposed with inrush current. Under certain extreme conditions, even two protections respectively based on second harmonic restraint and waveform symmetry restraint both mal-operated [14].

Adopting various similarity algorithms, the waveform similarity based criteria were put forward by making use of waveform difference between the inrush current and the fault differential current [15–17]. They are simple and easy to implement, but have some shortages in the selection of data window length and anti-interference performance.

We conduct comparative researches on waveform similarity algorithms and find that there exist a number of implementation methods of similarity identifications, which aim at biomedical signals in the field of biomedical science [18,19]. For instance, the similarity discrimination between actual ECG (Electrocardiograph) waveform and normal ECG waveform can be realized by virtue of the Hausdorff distance (HD) algorithm and it achieves good results [20]. In the relay protection application, the secondary current acquired from the CT can be viewed as a discrete-time sequence, which is similar to the ECG waveform [21]. In addition, the HD algorithm is provided with the flexible selection of data window and strong anti-interference performance. Therefore, the HD algorithm can be considered to be introduced to calculate the waveform similarity of currents for the differential protection.

In this paper, the waveform differences between transformer inrush currents and fault differential currents are analyzed. On this base, combining the advantages of the HD algorithm in data window length selection, frequency adaptability and ability to resist data loss, a novel criterion applicable to transformer differential protection by virtue of the HD algorithm is proposed. The effectiveness of the proposed criterion is validated with extensive simulation scenarios and experimental cases.

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2. The basic principle of the HD algorithm and its adaptability to differential protection requirements

Based on feature points of graphics, the HD algorithm mainly compares the overall characteristics difference between two graphics taking no account of certain small range characteristics of the graphics [22,23]. Given two bounded sets $\boldsymbol{A} = \{a_1 \ldots a_p\}$ and $\boldsymbol{B} = \{b_1 \ldots b_p\}$, the HD between the two sets is calculated according to the formulas given by:

$$H(A, B) = \max[h(A, B), h(B, A)] \tag{1}$$

where

$$h(A, B) = \max_{a_i \in A} \min_{b_j \in B} |a_i - b_j| \tag{2}$$

$$h(B, A) = \max_{b_j \in B} \min_{a_i \in A} |b_j - a_i| \tag{3}$$

In the equations, | | represents the distance norm between two points (usually the Euclidean norm). Eq. (2) defines the directed HD from $\boldsymbol{A}$ to $\boldsymbol{B}$, which finds the minimum distance among point a_i to all points belonging to $\boldsymbol{B}$, then selects the maximum among these minimum distances corresponding to all points belonging to $\boldsymbol{A}$. The directed HD from $\boldsymbol{B}$ to $\boldsymbol{A}$ is defined similarly, seen (3). Eq. (1) is the maximum one between $h(A, B)$ and $h(B, A)$, namely the HD between $\boldsymbol{A}$ and $\boldsymbol{B}$. The HD reflects the maximum mismatch degree between two sets of feature points, that is, the matching degree between the target and the template graphics.

The differential current of transformer differential protection can be viewed as a discrete-time sequence. Its abscissa and ordinate are the time and the current amplitude value respectively. Each sampling corresponds to a feature point of the graphic and can be directly used for the HD calculation.

The HD algorithm is provided with following features which are adaptable to the differential protection:

First, it has strong adaptability to the sampling rate. As the HD algorithm considers more about the overall characteristics of the signal sequence acquired, it does not require the strict signal projection from the time domain to the frequency domain. Therefore, the sampling rate is not strictly required. For example, comparing with 4 kHz sampling rate, the selection of waveform feature point corresponding to 1.2 kHz sampling rate is relatively sparser, but it will not affect the identification of the waveform overall characteristics.

Second, the flexible selection of data window length can satisfy the rapidity requirement of relay protection. For the HD calculation, the signal projection process from time domain to frequency domain is not required and hence the selection of data window length has more flexibility. We can adopt the data window length of 1/4 cycle to implement the HD calculation when we construct the criterion in this paper, which is merely 1/2 even 1/4 of that of some traditional criteria, such as the second harmonic restraint and waveform symmetry based criteria. Besides, the data window length can be reset according to different actual requirements.

Third, the HD algorithm has quite strong anti-interference performance. As previously mentioned that the HD algorithm considers the overall characteristics of the signal sequence, the loss of a small number of data points will not affect its identification result. By virtue of this advantage, we design to discard several extreme points according to actual conditions before implementing the HD calculation. Consequently, the HD algorithm has quite strong ability to prevent the random noise of differential current sequence.

3. Differential current waveform similarity identification based on the HD algorithm

Theoretically, there exists significant difference between the waveforms of differential currents during internal fault and magnetizing inrush. In the case of transformer internal fault, the idealized waveform of differential current is basically sinusoidal after disregarding the information of amplitude and aperiodic component. But during the transformer energization, as the transformer core will not saturate immediately, the inrush current will present the waveform with pointed top.

In this sense, we use the standard sine wave as the benchmark to calculate the similarity between it and the differential current acquired. If the similarity is high, the differential current is considered to be caused by an internal fault; otherwise, the differential current is considered to be caused by the magnetizing inrush. We can make use of the calculated similarity to decide whether the differential protection is blocked or unblocked.

Based on the previous analyses of the HD algorithm, we consider to adopt the differential current sequence and the standard sine wave sequence as the target and template waveforms of the algorithm respectively. After calculating the similarity between the two sequences, the differential current can be identified whether being caused by an internal fault.

The calculation of the similarity between the differential current sequence and the standard sine wave sequence, as well as the identification logic by virtue of the results, are designed as follows:

As the HD algorithm considers the overall sinusoidal similarity of the differential current sequence, the amplitude characteristics of the differential current should be removed. The differential current sequence is firstly normalized to form the sequence with the amplitude range of $[-1, 1]$. The normalized differential current sequence serves as the target waveform of the HD algorithm.

A standard sine wave sequence with the same sampling rate is created synchronously (the amplitude range is $[-1, 1]$) and serves as the template waveform of the HD algorithm. Then the HD between the two sequences is calculated according to (1)–(3), which falls within the range of [0, 1]. The smaller the value is, the higher the sinusoidal similarity of the differential current sequence is. Under idealized conditions, the calculated value of the HD is close to 0 during the transformer internal fault, but quite large during the transformer energization.

Firstly, we investigate calculated values of the HD under several typical conditions. Fig. 1(a)–(d) respectively show the similarity comparisons between the standard sine wave and the normalized differential currents under conditions of internal fault, magnetizing inrush, internal fault superimposed with magnetizing inrush and external fault accompanied by CT saturation. In the figures, the dashed and solid lines represent the standard sine wave (i_{sin}) and the normalized differential

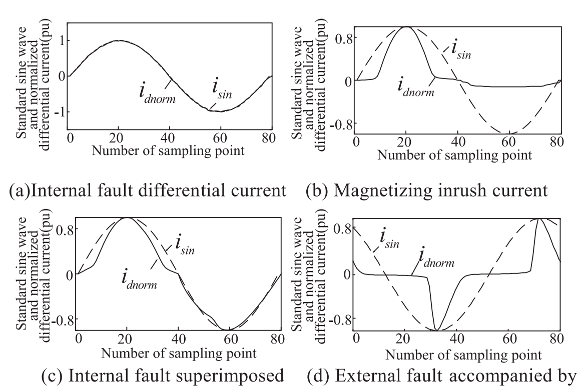

Fig. 1. Similarity comparison between the normalized differential currents and the standard sine wave.