A New Criterion for Transformer Differential Protection Based on Hausdorff Distance Algorithm (Postprint)

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Abstract

This paper analyzes the overall morphological characteristics of transformer inrush current and fault current waveforms, exploits their similarity differences, and combines the advantages of the Hausdorff distance algorithm in graphic similarity measurement to construct a novel criterion for transformer differential protection based on the Hausdorff distance algorithm. The criterion employs the Hausdorff distance value between per-unit normalized differential current sequences and standard sinusoidal wave sequences for discrimination, thereby distinguishing transformer inrush currents (including symmetrical inrush currents) from fault differential currents (including fault currents superimposed with inrush currents). Simulation tests verify the effectiveness, rapidity, and anti-interference capability of the proposed criterion.

Full Text

A Novel Criterion for Transformer Differential Protection Based on the Hausdorff Distance Algorithm

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Abstract

This paper analyzes the characteristics of complete waveforms of magnetizing inrush current and fault differential current in transformers. By leveraging the similarity differences between these two current types and combining the advantages of the Hausdorff distance algorithm in measuring graphical similarity, a novel criterion for transformer differential protection based on the Hausdorff distance algorithm is proposed. The Hausdorff distance between the normalized differential current sequence and a standard sinusoidal waveform sequence is employed to distinguish between inrush current (including symmetrical inrush) and fault differential current (including fault current superimposed with inrush). Simulation tests validate the effectiveness, rapidity, and anti-interference performance of the proposed criterion.

Keywords: transformer; differential protection; symmetrical inrush current; waveform similarity; Hausdorff distance algorithm

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1. Introduction

With the development and application of ultra-high voltage (UHV) transmission technology, the integration of higher voltage level transmission projects has resulted in enormous transformer transmission capacity. For instance, the Hami South-Zhengzhou $±$800kV UHV DC transmission project commissioned on January 27, 2014, has a rated transmission power of 8000 MW. Maloperation or failure to operate of large transformer protection can have catastrophic consequences, making the performance of transformer protection critically important. Due to its simple principle and reliable, sensitive operation, differential protection is widely used as the main protection for transformers. However, the saturation of transformer cores generates magnetizing inrush current during no-load energization and external fault clearance, which represents the most significant problem affecting the reliability of transformer differential protection. Researchers have long been committed to developing more optimized methods for inrush current identification for practical protection systems.

Currently, inrush identification methods fall into two main categories. The first category originates from the physical mechanism of inrush current generation, proposing identification schemes based on theoretical analysis, such as magnetic flux characteristics methods [1,2] and equivalent instantaneous inductance/dynamic impedance methods [3,4]. While these approaches improve the ability of differential protection to identify inrush current, they require voltage measurements, increasing the cost of potential transformers (PT), complicating protection configuration, and introducing the risk of incorrect operation due to

PT disconnection, thereby limiting their practical applicability.

The second category focuses solely on the waveform characteristics of inrush current, achieving identification through comparative waveform analysis. Examples include criteria based on second harmonic characteristics [5], waveform symmetry [6], and dead-angle characteristics [7], which have found wide field application. However, due to improvements in modern transformer core materials, the application of shunt capacitors in power systems, and the more complex electromagnetic transient environment resulting from AC-DC hybrid coupling, the differences in waveform and harmonic characteristics between inrush and fault currents have become less pronounced. The symmetrical nature of inrush can cause second harmonic restraint criteria to fail, leading to maloperation of differential protection [8], with documented cases where both second harmonic restraint and waveform symmetry restraint principles malfunctioned simultaneously [9].

Notably, from a waveform perspective, inrush generation is influenced by transformer core saturation, causing its waveform to differ significantly from the predominantly sinusoidal fault current. This difference can be exploited to construct waveform similarity criteria, which are simple to implement. For example, references [10-14] employ various algorithms to calculate the sinusoidal degree or waveform correlation coefficient of differential current, setting thresholds to effectively distinguish inrush from fault current. However, these algorithms require filtering of the DC component from differential current first; secondly, they need at least a half-cycle or even one full cycle data window to make a decision; and thirdly, the calculation results are significantly affected when there are large distortion points in the differential current sampling sequence, resulting in weak anti-interference capability. Therefore, we consider further research on new waveform similarity identification criteria that are algorithmically simple, rapidly discriminating, and strongly anti-interfering, to improve the operational performance of transformer differential protection.

Based on analysis of waveform differences between transformer magnetizing inrush (including symmetrical inrush) and fault current (including fault current superimposed with typical inrush), this paper combines the advantages of the Hausdorff distance algorithm in time window selection, frequency adaptability, and data loss resistance to construct a novel criterion for transformer differential protection. Simulation tests verify the effectiveness of the new criterion under various conditions including no-load energization, energization with internal faults, internal faults, and faults occurring after inrush. The results demonstrate that the criterion is simple in principle, easy to implement, capable of correctly identifying transformer magnetizing inrush and fault differential current, and offers significant advantages in speed and anti-interference performance.

2. Basic Principles of the Hausdorff Distance Algorithm

Graphical similarity algorithms compare the overall characteristics of two images without being limited by small-scale feature influences. Graphical recognition algorithms generally fall into two categories: those based on grayscale information, such as PCA principal component analysis, and those based on feature points, such as the Hausdorff distance algorithm [15,16].

For two point sets A={a_1,⋯,a } and B={b_1,⋯,b_q}, the Hausdorff distance is defined as:

H(A,B) = max(h(A,B), h(B,A))

where h(A,B) = max_{a A} min_{b B} ||a-b||, and ||•|| represents the distance norm between point sets A and B. In equation (2), for each point in set A (such as a), distances to all points in set B are compared to find the nearest point b to a : ||a -b || ≤ ||a -b || (1≤k≤q and k≠j). The value ||a -b || is the minimum distance corresponding to point a , and h(A,B) is the maximum of all minimum distances for points in set A, called the directed Hausdorff distance from set A to set B. The Hausdorff distance in equation (1) is the larger of the two directed distances h(A,B) and h(B,A).

The Hausdorff distance is a measure describing the similarity between two point sets, quantifying the maximum mismatch degree between them and reflecting the matching degree between edge feature points of the target and template graphics. In the biomedical field, research has employed the Hausdorff distance algorithm to assess similarity of biomedical signals, such as using it to determine similarity between time-varying ECG waveforms and normal ECG waveforms [17,18].

In relay protection systems, current data collected by sensors exist as two-dimensional point sets, which can be viewed as discrete time sequences with time as the horizontal axis and amplitude as the vertical axis. Each current data point corresponds to a feature point of the graphic, similar to the ECG waveforms mentioned above, making them directly applicable for Hausdorff distance calculation.

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3. Characteristics of the Hausdorff Distance Algorithm and Its Adaptability to Differential Protection Requirements

Compared with traditional point-by-point comparison algorithms used in differential protection, the Hausdorff distance algorithm offers several advantages:

First, the Hausdorff distance algorithm allows flexible selection of data window length according to requirements. Traditional protection algorithms generally employ Fourier algorithms, including full-cycle and half-cycle Fourier algorithms. However, both require the time window length to be an integer multiple of the current half-cycle. In practical relay protection engineering, this time window characteristic causes at least a 10ms delay in processing fault signals and prevents flexible setting of time window length. Since the Hausdorff distance algorithm does not involve projection from time domain to frequency domain, time window setting can be more flexible. Considering the rapidity requirement of relay protection, the algorithm design adopts a 1/4-cycle Hausdorff distance calculation window, whose length is only 1/4 to 1/2 of DFT, further demonstrating its adaptability to the rapidity requirements of relay protection.

Second, the Hausdorff distance algorithm is less affected by sampling frequency. Traditional Fourier algorithms impose high requirements on protection device sampling frequency; if the sampling rate is too low, it leads to inaccurate signal projection in the frequency domain. The Hausdorff distance algorithm focuses more on overall feature consistency and does not have strict requirements for temporal alignment of sampling points or sampling rate uniformity. For example, a 1.2kHz sampling rate compared to a 4kHz sampling rate only means sparser selection of waveform feature values, without causing feature value errors or affecting judgment of overall waveform characteristics.

Third, the Hausdorff distance algorithm has data loss resistance capability. Loss of individual data points often causes sampling-value differential algorithms to fail. However, for the Hausdorff distance algorithm, this does not affect its judgment of overall graphic features. Utilizing this characteristic, several extreme points can be deliberately discarded before distance calculation without affecting the overall distance calculation result, providing strong anti-interference capability against random noise in differential current sequences.

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4. Waveform Similarity Assessment for Differential Current Based on the Hausdorff Distance Algorithm

Theoretically, for an ideal fault current without considering non-periodic components and amplitude variations, its waveform exhibits essentially sinusoidal characteristics. For inrush current (unidirectional or symmetrical), however, its generation is affected by transformer core saturation, causing an acceleration in amplitude rise and resulting in a spiked morphology that differs significantly from sinusoidal waves. Therefore, we can use a sinusoidal waveform as the reference template and compare the similarity between the sampled differential current waveform and this reference. If the waveform closely matches the reference sinusoid, it is identified as fault differential current; if it deviates beyond a certain threshold, it is considered inrush current, thereby determining whether to block or enable differential protection.

Based on this discussion, the comparison process can be designed as follows: the target waveform (differential current) is evaluated for similarity or matching degree against a standard sinusoidal reference waveform (template) constructed in a specific manner to determine whether the disturbance corresponds to an internal fault or inrush. As previously described, the Hausdorff distance algorithm reflects the matching degree between edge feature points of target and template graphics, making it suitable for similarity assessment between differential current waveforms and the template.

Since the comparison focuses on waveform morphology characteristics, the influence of amplitude should be eliminated in Hausdorff distance calculation. The elimination method involves: at a certain sampling rate, first obtaining amplitude information of the differential current using a very short time window, then using this amplitude information as a reference to scale and vertically shift the differential current to obtain a per-unit normalized differential current sequence. The amplitude variation range of the normalized sequence is set to [-1,1]. This normalized differential current sequence serves as the edge feature points of the target graphic for Hausdorff distance algorithm, while a standard sinusoidal sequence with amplitude 1 at the same sampling frequency serves as the edge feature points of the template graphic. The Hausdorff distance between the two is then calculated. After per-unit normalization, the calculated Hausdorff distance value necessarily falls within [0,1], where smaller values indicate the differential current waveform is closer to sinusoidal, and larger values indicate lower similarity to the sinusoid.

Theoretically, for internal faults, the Hausdorff distance between the normalized fault differential current sequence and the standard sinusoidal sequence should approach 0; for inrush current cases, the distance should be relatively large. We first examine the Hausdorff distance values between several groups of ideal fault differential currents/inrush currents and the standard sinusoidal sequence, then formulate reasonable setting principles based on specific conditions to effectively distinguish between faults and inrush.

[Figure 1: see original paper] shows the similarity comparison between normalized differential currents and standard sinusoidal waveforms for: (a) internal fault differential current, (b) no-load energization unidirectional magnetizing inrush, (c) symmetrical inrush, and (d) energization with fault (fault current superimposed with inrush). The differential current sequence sampling frequency is 4kHz (80 points per cycle). Using a 1/4-cycle Hausdorff distance algorithm window, the distance calculation values (denoted as H) at the end of the 1/4, 1/2, 3/4, and full cycle are listed in .

It should be noted that when using a sliding 1/4-cycle window to intercept current sampling data, for the no-load energization unidirectional magnetizing inrush corresponding to Figure 1: see original paper, the data within the time window during the 3/4 and 4/4 cycles are nearly zero and cannot form the amplitude of the standard sinusoidal template. For such cases, the H value is defined as 1.

shows that: (1) For transformer internal faults, the similarity between normalized differential current sequence and standard sinusoid is very good, with low H values close to 0 calculated across four 1/4-cycle windows; (2) For unidirectional and symmetrical inrush sequences, calculated H values exceed 0.5, indicating low similarity to the sinusoid; (3) For transformer energization with fault, where differential current is superimposed fault current and inrush as shown in Figure 1: see original paper, similarity to the sinusoid is relatively high within the first 1/2 cycle (H values between 0.4-0.5), but during the negative half-cycle with smaller inrush amplitude, the differential current begins to exhibit typical fault current characteristics. In the 3/4 to full cycle range, similarity increases with H values below 0.12.

Based on this analysis, the theoretical H value during internal faults serves as the basis for criterion setting. However, since the H value between fault differential current and standard sinusoid theoretically approaches or equals 0 under ideal conditions, using 0 as the setting baseline would prevent effective reliability coefficient calculation and sensitivity verification. Considering that calculated H values after per-unit normalization necessarily fall within [0,1], we adopt the complement of H as the criterion baseline, defining HS(k)=1-H(k), k=1,2,3··· After calculating the Hausdorff distance H between normalized fault differential current sequence and standard sinusoidal sequence, the corresponding HS value is computed, using HS magnitude to discriminate between internal faults and inrush.

The setting principle is formulated as follows:

HS > HS_{set} = K_{rel} × HS_{theory}

where K_{rel} is generally taken between 1.15 and 1.3. Since HS_{theory} = 1, taking K_{rel} = 1.3 yields HS_{set} = 0.77.

Based on the data in , corresponding HS values and criterion discrimination results are calculated as shown in . For inrush cases, whether unidirectional or symmetrical, HS values remain consistently below the 0.77 threshold, reliably blocking protection. For internal faults, the criterion makes correct decisions within just 1/4 cycle (5ms). For fault current superimposed with inrush, correct judgment is made within at most 3/4 cycle (15ms).

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5. Transformer Differential Protection Criterion Based on the Hausdorff Distance Algorithm

Based on the preceding analysis, the Hausdorff distance algorithm can discriminate between transformer internal fault differential current and magnetizing inrush. The algorithm primarily relies on overall sequence characteristics without involving time-to-frequency domain projection, allowing flexible time window selection. For differential protection applications, to ensure acquisition of periodic sequence extreme points for waveform per-unit normalization, the time window can be set to 1/4 cycle. Starting from the 1/4 cycle point, each sampling point shift of the time window updates a Hausdorff distance value, generating an H value sequence and consequently an HS value sequence for real-time assessment of differential current transient characteristics.

For general transformer internal fault differential current or magnetizing inrush (including symmetrical inrush), the algorithm can make correct judgments within 1/4 cycle (5ms). For special scenarios such as fault current superimposed with inrush, correct action can be achieved within at most 3/4 cycle (15ms), demonstrating the algorithm' s rapidity. The flowchart of the transformer differential protection criterion based on the Hausdorff distance algorithm is shown in [Figure 2: see original paper].

It should be noted that this criterion operates after differential current amplitude exceeds the startup threshold. Current field acquisition requires at least half a cycle, during which data can simultaneously be used for the first amplitude acquisition for this criterion. After obtaining the first amplitude value, corresponding sampling points can be traced backward to synchronously generate the standard sinusoidal sequence for comparison with the normalized differential current waveform. As the time window advances, old sampling points exit while new ones enter, continuously incorporating new samples into amplitude calculation to form new normalization baselines. Theoretically, the fastest operation speed of this criterion can match the protection startup speed, and even if immediate judgment is not possible, using a 1/4-cycle sliding window combined with at least half-cycle sampling points already available from the differential current amplitude limit startup criterion provides sufficient data for discrimination. Generally, judgment can be made within 5ms after criterion startup.

In terms of computational load, at a 4kHz sampling rate, a 1/4-cycle window contains 20 sampling points, and one Hausdorff distance calculation requires approximately 2000 addition/subtraction operations—negligible time for modern microprocessors and causing no additional delay to differential protection discrimination.

In summary, this criterion offers high operational reliability. When applied to large transformer differential protection, a phase-segregated blocking scheme can be adopted, together with traditional second harmonic restraint criteria, to form two main protection schemes with different principles, meeting the requirement of protection duplication.

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6. Simulation Verification of the Criterion

This section presents simulation verification of the proposed transformer differential protection criterion based on the Hausdorff distance algorithm. Using the $±$800kV UHV DC transmission project simulation model from reference [8], the high-voltage converter transformer group at the rectifier side converter station is studied. Primary and secondary side currents are converted to the secondary side to form differential currents for the large differential protection group under various disturbance scenarios. Simulation duration is 1s, with differential current and standard sinusoidal sequence sampling frequency of 4kHz

(80 points per cycle). The differential current amplitude limit threshold uses the conventional value of 0.25 p.u., Hausdorff distance algorithm window length is 1/4 cycle, and operation threshold HS_{set} = 0.77.

Typical disturbance cases are presented below, including transformer internal fault, no-load energization unidirectional inrush, no-load energization symmetrical inrush, energization with fault, internal fault after normal no-load energization, and external-to-internal fault conversion. Anti-interference performance is also verified. For inrush intermittent angle portions, H value is directly set to 1 and corresponding HS value to 0 per the processing principle described above.

Case 1: Normal internal fault scenario—three-phase ground fault at Y/Y transformer primary side outlet at t=0.405s.

[Figure 3: see original paper] shows: (a) differential current sequence id; (b) comparison between normalized differential current sequence id_{norm} (solid line) and standard sinusoidal sequence i_{sin} (dotted line) during 0.3-0.6s; (c) HS value sequence calculated using the Hausdorff distance algorithm. The criterion startup occurs at t=0.41s (approximately 1/4 cycle after fault inception), when HS exceeds the 0.77 threshold, enabling rapid correct protection action.

Case 2: Unidirectional magnetizing inrush scenario—no-load energization at t=0.4s with A-phase closing angle of -120° and zero initial remanence in all phases of Y/Δ and Y/Y transformers.

Case 3: Symmetrical inrush scenario—no-load energization at t=0.4113s with A-phase closing angle of -120°, A-phase remanence of 0.85 p.u. and -0.85 p.u. in Y/Δ and Y/Y transformers respectively, and zero remanence in other phases.

[Figure 4: see original paper] and [Figure 5: see original paper] show simulation results for Cases 2 and 3 respectively. For both unidirectional and symmetrical inrush, the HS values remain stably below the 0.77 threshold, reliably blocking protection. Notably, analysis of second harmonic percentage in Case 3 (Figure 5: see original paper) shows values below the typical 15% blocking threshold, which would cause maloperation with second harmonic restraint criteria, whereas the proposed criterion effectively prevents such misoperation.

Case 4: Fault superimposed with inrush scenario—converter transformer energized at t=0.4s with A and C phase high-resistance ground fault (70Ω) in Y/Y converter transformer and zero initial remanence.

As shown in [Figure 6: see original paper], during the positive half-cycle with prominent inrush characteristics, HS values remain below the 0.77 threshold, temporarily blocking protection. However, during the negative half-cycle with smaller inrush values, HS rapidly increases beyond the threshold. At t=0.4105s (approximately half a cycle after energization), the criterion removes the block and enables correct protection action. For this case, second harmonic percentage may exceed the 15% threshold ([Figure 7: see original paper]), causing incorrect blocking or delayed action with second harmonic restraint, whereas the proposed criterion enables correct action within a short time.

Case 5: Inrush followed by internal fault scenario—no-load energization at t=0.4s, followed by three-phase ground fault at Y/Y transformer primary side outlet at t=0.605s.

[Figure 8: see original paper] shows that during the typical inrush stage, HS values remain stably below the 0.77 threshold, reliably blocking protection. After internal fault occurrence, HS exceeds the threshold at t=0.61s (approximately 1/4 cycle after fault), removing the block and enabling immediate correct action.

Case 6: External-to-internal fault conversion scenario—external three-phase short-circuit fault at t=0.305s, converting to internal three-phase ground fault at t=0.505s.

[Figure 9: see original paper] shows that during the external fault stage, differential current amplitude is small and the criterion does not start. Upon conversion to internal fault, the criterion starts immediately, with HS exceeding the threshold at t=0.51s (1/4 cycle after conversion), enabling rapid correct action.

Case 7: Anti-interference analysis

As previously analyzed, the Hausdorff distance algorithm primarily relies on overall sequence characteristics, making it minimally affected by non-periodic components and high-order harmonics in differential current. Additionally, partial data loss has minimal impact when overall features remain consistent, providing inherent data loss resistance. This capability can be utilized without any additional filtering to achieve excellent anti-interference performance. The implementation method involves deliberately discarding several extreme points within each time window before Hausdorff distance calculation. For noise-free differential current sequences, discarding some points does not affect overall waveform characteristics and thus has almost no impact on calculated distance values. For noisy sequences, discarding one extreme point per time window allows identification and rejection of at least four noise interference points within one cycle of differential current sequence when using a 1/4-cycle window, sufficient for engineering practice where at most one noise interference point per cycle is considered.

[Figure 10: see original paper] shows the noisy fault differential current waveform from Case 1, HS calculation sequences without discarding extreme points, and HS sequences discarding one extreme point per time window. While numerous noise points affect the original HS calculation, causing fluctuations near the threshold, the simple extreme-point discarding method quickly stabilizes HS values above the threshold. Correct judgment is made at t=0.41s (approximately 1/4 cycle after fault), demonstrating the criterion' s superior anti-interference performance.

7. Conclusion

This paper proposes a novel transformer differential protection criterion based on the Hausdorff distance algorithm by analyzing waveform morphology differences between inrush and fault currents and leveraging the algorithm’ s advantages in waveform similarity discrimination. Simulation results demonstrate that the proposed criterion can rapidly and correctly distinguish between transformer magnetizing inrush and fault differential current. It shows strong identification capability for symmetrical inrush that can cause misoperation in second harmonic and waveform symmetry criteria, and effectively identifies cases of fault current superimposed with inrush. The algorithm’ s advantages are twofold: (1) small computational load and rapid discrimination without additional delay to protection startup, achieving simultaneous discrimination with protection startup in the fastest case and making decisions within 5ms for general faults; (2) strong data loss resistance enables discarding some extreme points before calculation without affecting discrimination results, demonstrating superior anti-interference performance for differential current waveforms with individual noise interference points.

Since inrush waveform characteristics are affected by remanence, winding connection type, and closing phase angle, criteria based on waveform characteristics and their threshold settings cannot guarantee protection will never misoperate under all conditions, just as second harmonic restraint criteria cannot ensure reliable blocking for all inrush disturbances even with very low threshold settings due to technological advances and manufacturing improvements. The proposed criterion represents a new attempt at current waveform feature-based protection, providing a novel implementation approach for transformer differential protection algorithms. Future work will include dynamic model testing and field data validation, using extensive data to select reasonable settings and continuously optimize the algorithm.

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Project Overview: Based on studying the inherent complex electromagnetic scenarios of converter station main equipment and potential mal-operation scenarios of converter station differential protections caused by AC-DC deep coupling trends, combined with optimal selection of TA transmission models adapted to various complex electromagnetic scenarios, this project thoroughly investigates complex inrush/circulating current transmission effects, long-time-scale high DC bias, multiple consecutive commutation failures, and TA transmission variation patterns. It reveals the mechanisms behind various unexplained mal-operations of current converter station bridge differential, large differential, and zero-sequence differential protections, as well as potential mal-operation risks due to further external environment complexity. Utilizing advanced signal processing technologies including Hausdorff graphical recognition algorithms, the project proposes new principles and schemes for converter station main equipment differential protection, validated through PSCAD simulation and RTDS closed-loop testing.

Note: Figure translations are in progress. See original paper for figures.

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