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Discrimination between Inrush and Internal Fault Currents in Power Transformers Using Hyperbolic S-Transform

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ABSTRACT

Numerous methods exist to distinguish between inrush current and internal faults, but these approaches have not yet become practical due to their inherent limitations. As a result, conventional methods, despite their well-known drawbacks, continue to be widely used in practice. In this paper, a new method based on time-frequency analysis is presented for detecting inrush current situations. To do this, a diverse array of scenarios involving a power transformer switching ON and internal fault cases are simulated using the PSCAD/EMTDC software package. Then, a hyperbolic S-transformer is employed to extract a determining index from the simulation results. Finally, a suitable threshold value for this index is computed so that inrush current can be distinguished from fault current by comparing the index with its threshold. Evaluation of the efficiency of the proposed method using simulation and real data confirms its excellent accuracy. Therefore, it can be used in algorithms for power transformer differential protection to improve their stability during inrush current transients.

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NOMENCLATURE

$w(t)$	Scalable Gaussian window	DI	Determining Index
γ_{HY}^{F}	Forward-taper parameter	i_a, i_b and i_c	Phase currents
γ_{HY}^{B}	Backward-taper parameter	f	Frequency

1. INTRODUCTION

Power transformers are vital and expensive equipment for any electrical power network. Hence, it is very important to equip this device with a dependable, secure, and fast protective system. Differential protection is the most important and most commonly used protection scheme, which is employed to protect the power transformer with a nominal power above 5 MVA [1]. However, it is prone to false operation in the presence of transformer magnetizing inrush current. Because this relay is designed for detecting transformer internal faults by comparing its primary- and secondary-side currents while inrush currents just appear on one side, which leads to the appearance of a false differential current [2]. Since the harmonic content of the inrush current is usually different from the fault current, many harmonic restraining and harmonic blocking methods have been developed to prevent false operation of the differential relay during inrush current [3]. The use of new materials with better magnetic characteristics for producing transformer cores has decreased the effectiveness of these methods [4]. On the other hand, time-frequency analysis techniques can be used to discriminate between inrush current and fault current. For example, the wavelet transform is useful to analyze signals with non-stationary characteristics, so it is widely used to create new methods to discriminate inrush current from fault current [5]. However, how to choose the mother wavelet can have a great impact on the results, and it is necessary to use a denoizing algorithm along with it. The S-transform, as another time-frequency analysis technique that combines

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the advantages of both Fourier and wavelet transforms, has been employed by many researchers to distinguish inrush current from fault current [6]. The accuracy of the methods presented by these researchers completely depends on the features extracted and selected by them.

Pattern recognition algorithms or machine learning techniques are other methods that have been used in this field. For a power transformer, Khatib and Arar [7] proposed a differential protection technique based on random forest and boosting learning machines. Afrasiabi et al. [8] extracted statistical features from the normalized differential current gradient to train the robust soft learning vector quantization (RSLVQ) classifier for developing a new intelligent differential protection scheme. Jiao et al. [9] proposed a transformer intelligent protection algorithm with strong recognition ability and high recognition accuracy. To do this, image recognition has been used to supervise and study the equivalent magnetization curve by employing a convolutional neural network (CNN). Despite their high accuracy, these methods are complex and have a high computational burden.

In this paper, a time-frequency analysis-based method is proposed for the discrimination of inrush and internal fault currents. To do this, during inrush current and fault cases, differential current is analyzed using the hyperbolic S-transform. Then, an effective index is determined, and a suitable threshold value for this index is computed using analysis of the simulation results of many internal faults and inrush current cases in a real power transformer. Therefore, the condition for detecting an internal fault is that this index value is less than its threshold. It is worthy to say that all power transformer simulations are done by the PSCAD/EMTDC software package, and analysis of simulation results and implementation of the proposed method are done in the MATLAB environment.

The paper organization is as follows: In section 2, the hyperbolic S-transform is briefly described. The specifications of the power system under study are presented in section 3. The process of analyzing differential currents using the hyperbolic S-transform is described in section 4. Section 5 presents the proposed method. The simulation results and the method assessments can be found in section 6. Finally, the paper ends with the conclusion in section 7.

2. HYPERBOLIC S-TRANSFORM

The S-transform is a time-frequency analysis technique that combines the advantages of both short-time Fourier and wavelet transforms and can handle non-stationary signals. It uses a Gaussian window whose height scales linearly and whose width scales inversely with the frequency. The expression of the S-Transform is given below [10]:

$$S(\tau, f) = \int_{-\infty}^{+\infty} h(t)\{w(\tau - t)\exp(-i2\pi f t)\}dt \qquad (1)$$

where, S is the S-transform of $h(t)$, f denotes frequency, and the parameter τ controls the position of scalable the Gaussian window ($w(t)$) on the t-axis.

There is no parameter in the Gaussian window to adjust its width in the time or frequency domain. Hence, the generalized S-transform has been introduced by Nandi et al. [11], which has more control over the window function. For a more detailed explanation, a more symmetrical window can be used at high frequencies, and a more asymmetrical window may be used at low frequencies. Therefore, the hyperbolic window is used instead of the Gaussian window. The discrete version of the hyperbolic S-Transform of $h(t)$ is calculated as follows:

$$S[(n, j)] = \sum_{m=0}^{N-1} H[m+n]G(m,n)\exp(i2\pi mj) \qquad (2)$$

where the total number of samples is denoted by N, $m = [0 \quad 1 \quad ... \quad N-1]$, $n = [0 \quad 1 \quad ... \quad N-1]$ and $j = [0 \quad 1 \quad ... \quad N-1]$. The frequency-shifted discrete Fourier transform of $h(t)$ is denoted by $H[m+n]$. The Fourier transform of the hyperbolic window is represented by $G(m,n)$ and can be expressed as follows:

$$G(m,n) = \frac{2|f|}{\sqrt{2\pi(\gamma_{HY}^{F} - \gamma_{HY}^{B})}} exp\left(\frac{-f^2X^2}{n^2}\right) \qquad (3)$$

In this expression, X is a hyperbola, γ_{HY}^{F} is a forward-taper parameter and γ_{HY}^{B} is a backward-taper parameter. it is assumed that $0 < \gamma_{HY}^{F} < \gamma_{HY}^{B}$.

3. EXPERIMENTAL STUDY

To evaluate the proposed method's performance, a part of a real high-voltage (HV) substation introduced by Bkhaitawi et al. [12], including a 160 MVA, 230/63 kV power transformer, a grounding transformer (GT), and both side current transformers (CTs), is simulated using the PSCAD/EMTDC program (see Figure 1). Tables 1 and 2 show some technical information about the power transformer and CTs, respectively. It should be noted that the simulation of the magnetic behavior of the core of current transformers is based on the Jiles-Atherton (JA) model. The JA model parameters used to simulate the CTs were introduced by Taghipour Gorji et al. [13]. In simulations, the sampling frequency is set to 2500 Hz. It means that each cycle contains 50 samples because the power system frequency is 50 Hz. According to Nyquist's theorem, the maximum frequency that can be accurately represented in a signal is half of the sampling frequency [14, 15], i.e., 1250 Hz.

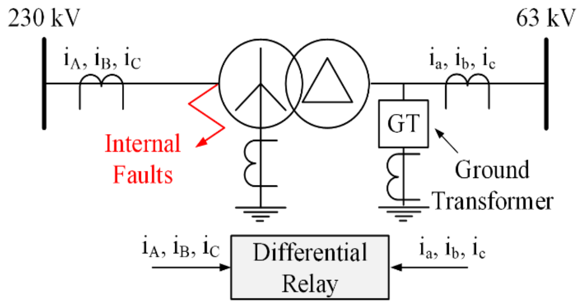


Figure 1. Power transformer protected by differential relay

TABLE 1. Technical information of the power transformer

Technical Data	Nominal Value
Power (MVA)	160
HV voltage (kV)	230
LV voltage (kV)	63
Short-circuit impedance (%)	14
No-load losses (%)	0.06
Ohmic losses (%)	0.2

TABLE 2. Technical information of CTs

Technical Data	HV side CTs	LV side CTs
Nominal primary current (A)	600	2000
Nominal secondary current (A)	1	1
Magnetic path length (cm)	84.8	54.8
Core cross section area (cm^2)	32.9	10.36
CT winding resistance (ohm)	4.3	7.77
Total burden (VA)	30	30

4. DIFFERENTIAL CURRENT SIGNAL ANALYSIS BASED ON HYPERBOLIC S-TRANSFORM

The hyperbolic S-transform is applied in this section to analyze differential current signals in two scenarios: one is a severe inrush current, and another is a severe internal fault. The goal is to extract the determining characteristics of the signals. It is worthy to say that the output of the S-transform is a complex matrix called the S-matrix, whose columns and rows pertain to the time and frequency domains, respectively.

In the first scenario, the unloaded transformer with a residual flux value of 80% (in phase *a*) is energized from the HV side winding at t=0.1 s. In this situation, the power transformer draws large magnetizing inrush currents from the power supply. Hence, differential currents appear in the relay. Figure 2 shows the phase *a* differential current. It is seen that the magnitude of this current is very high, so it may cause the relay to malfunction. Figure 3 shows the 3D representation of the S-matrix element magnitudes obtained from the differential current signal. According to this figure, the elements of this matrix have the largest magnitudes in the fundamental frequency and the second harmonic, so the magnitude of the second harmonic is significant. For more detailed analysis, the ratios of the magnitude of the second harmonic to the magnitude of the fundamental harmonic are shown in Figure 4. It is seen that these ratios are high during inrush currents.

In the second scenario, a ground fault with a fault resistance of 2 Ω occurs at t=0.1 s on the phase *a* terminal of the Y winding. Figure 5 shows the phase *a* differential current in this situation, whose waveform is somewhat distorted due to saturation of CTs. The 3D representation of S-matrix element magnitudes obtained from the differential current signal is shown in Figure 6. As can be seen, the magnitudes of S-matrix elements in the second harmonic are not considerable in comparison with the fundamental frequency. For better understanding, the

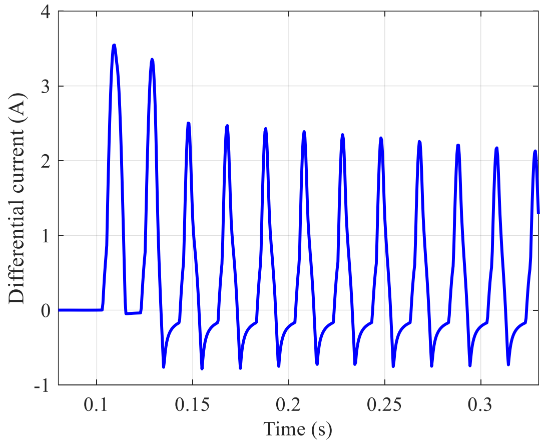


Figure 2. The Phase *a* differential current during unloaded power transformer energization at t=0.1 s

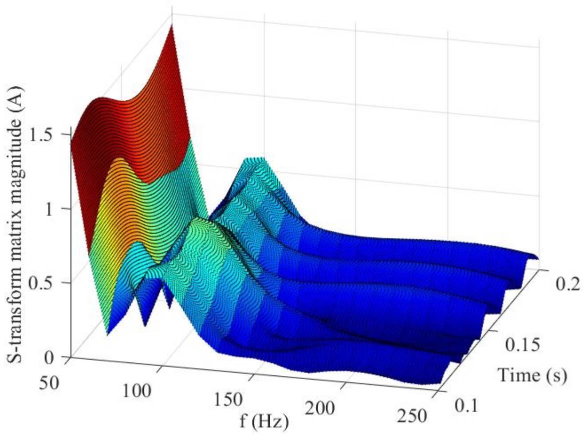


Figure 3. S-matrix elements magnitudes obtained from the differential current during inrush current

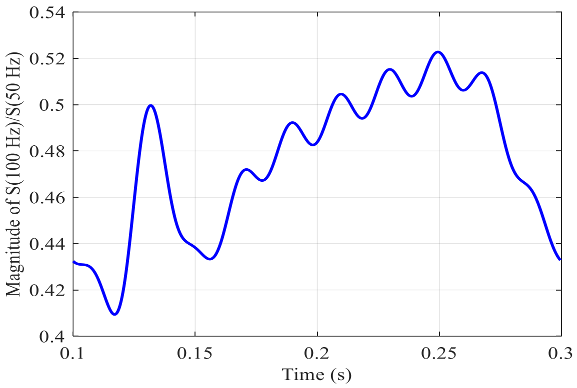


Figure 4. The ratios of the magnitude of the second harmonic to the magnitude of the fundamental harmonic of the differential current signal during inrush current

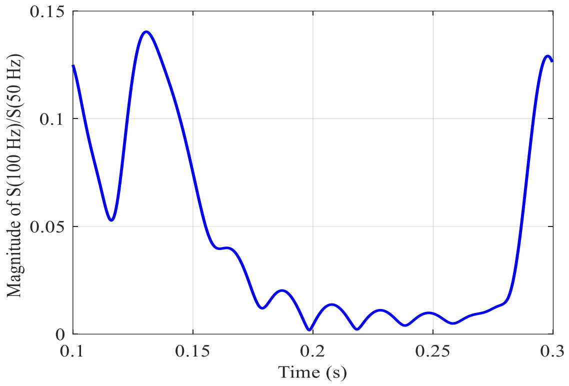


Figure 7. The ratios of the magnitude of the second harmonic to the magnitude of the fundamental frequency of the differential current signal during internal fault

ratios of the magnitude of the second harmonic to the magnitude of the fundamental frequency are depicted in Figure 7.

According to the above explanation, the ratio of the magnitude of the S-matrix element at the second harmonic to the magnitude of its element at the fundamental frequency can be used as a determining index (DI) for the discrimination of inrush current from fault current. But to achieve this goal, it is necessary to first determine a suitable threshold value for this index.

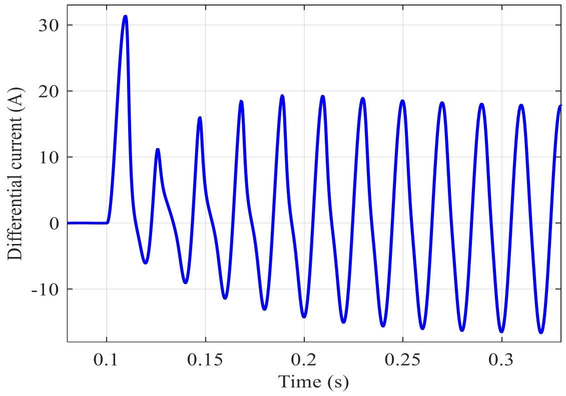


Figure 5. The phase *a* differential current internal fault occurs at t=0.1 s

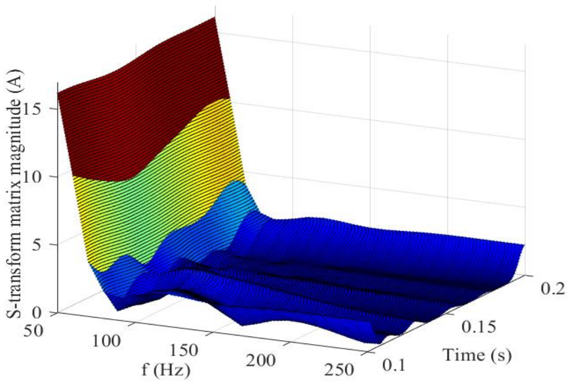


Figure 6. S-matrix elements magnitudes obtained from the differential current during internal fault

5. PROPOSED METHOD

The new method is based on the parameter DI introduced in the previous section and can be implemented by the following steps:

Step 1: A large number of inrush current and internal fault cases in a power transformer must be simulated.

Step 2: For each internal fault, a one-cycle sliding window starts to move once the I_D is greater than 0.02 p.u. and it continues to one cycle later and DI will be calculated for all points. Then, the minimum DI is saved. It must be done for the differential current of all three phases. After doing this for all internal faults, the maximum of saved values (DI_{Mm}) is considered for finding the threshold value of DI. The use of DI_{Mm}, according to the above description, guarantees the detection and operation of the relay in the first cycle of the fault.

Step 3: By adding a safety margin to DI_{Mm}, the threshold value of DI^{TH} can be calculated. The condition for confirming the appropriateness of the obtained value for DI^{TH} is the accuracy of the method in detecting the inrush current. It is worth noting that the condition for detecting an inrush current is:

$$DI \geq DI^{TH} \tag{4}$$

It should be mentioned that this condition should be checked for the differential currents of all three phases.

6. SIMULATION RESULTS

In this section, a wide range of internal faults are simulated, and DI^{TH} is computed using the obtained simulation results. Then, a large number of inrush current conditions are simulated and the accuracy of the proposed method in detecting the inrush current is evaluated using the mentioned condition.

6. 1. Calculation of DI^{TH}

Four types of internal faults on the HV side terminal of the power transformer are simulated. They are single-line-to-ground, line-to-line, line-to-line-to-ground and three-phase faults. Five values are considered for each fault resistance, including 0, 2.5, 5, 10, and 20 ohms. On the other hand, fault instants are 11 points of equal distance on the 6th time cycle. Therefore, 220 internal faults are simulated, and many of which are considered severe. Using simulation results, the value of DI_{Mm} is calculated as 0.136 and by adding a safety margin to it, the DI^{TH} value is set to 0.15.

6. 2. Accuracy Analysis of the Proposed Method

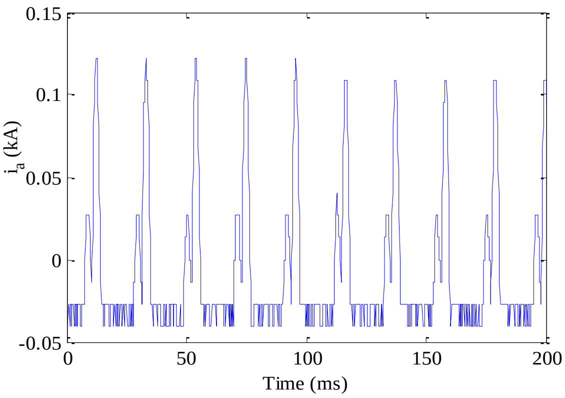
To simulate inrush current cases, the no-load transformer is energized once from the HV side and again from the LV side. The switching-on instants are 51 points of equal distance on the 6th time cycle. On the other hand, when the transformer is energized from the LV side, the core residual flux is 0%, but for energizing from the HV side, it is assumed to be 0% and 80% in simulations. Thus, the number of simulated power transformer energization situations is 153. Using the DI^{TH}, the proposed method is implemented, and the obtained results are presented in Table 3. It is seen that all internal faults and inrush currents are truly detected by this new method. It means that the accuracy of the proposed method is 100%.

6. 3. Method Verification using Real Data

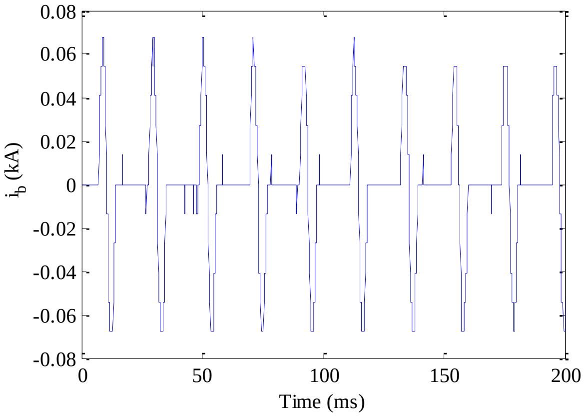
Figures 8 show the inrush currents of a real 400/230 kV autotransformer extracted from a differential relay. It must be noted that the relay has malfunctioned because of these currents. But our proposed method remains stable in this situation. It means that this new method is suitable for use in practical conditions.

TABLE 3. The proposed method implementation results

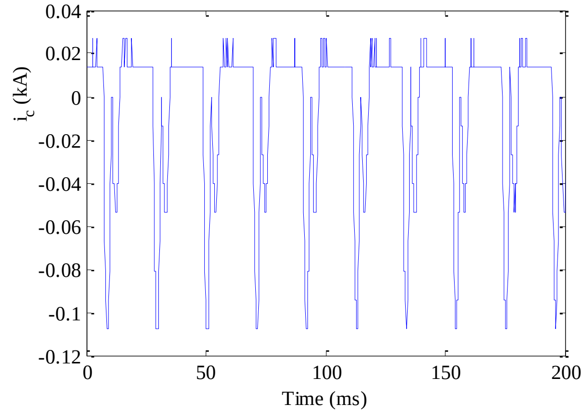
Method Setting	# of undetected cases of 220 faults	# of mis-operation during 153 inrush current cases	Accuracy (%)
$DI^{TH} = 0.15$	0	0	100



(a)



(b)



(c)

Figure 8. Phase *a*, phase *b*, and phase *c* inrush currents extracted from a differential relay of a 400/230 kV autotransformer

7. CONCLUSION

In this paper, the hyperbolic S-transform is used for discrimination between inrush and fault current in power transformers. To do this, a wide range of internal faults and energizing conditions of a power transformer are simulated using the PSCAD/EMTDC program. Then, differential currents are analyzed by the hyperbolic S-transform, and an effective determining index is extracted. Simulation results show that inrush current can be detected accurately using this index. Also, the accuracy of the new method has been verified using real data. Therefore, it is suitable for use in practical applications. The authors decided to extend this method for discriminating between internal and external faults in their next research.

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Persian Abstract

چکیده

روش‌های متعددی برای تمییز دادن بین جریان هجومی و خطاهای داخلی وجود دارند اما به دلیل محدودیت‌های ذاتی شان هنوز عملی نشده‌اند. در نتیجه، روش‌های مرسوم، علی رغم معایب شناخته شده‌شان، همچنان در عمل به طور گسترده مورد استفاده قرار می‌گیرند. در این مقاله، یک روش جدید مبتنی بر تحلیل زمان – فرکانس برای تشخیص وضعیت جریان هجومی ارائه شده است. برای انجام این کار، ابتدا موارد متنوعی از سناریوها شامل برق دار شدن یک ترانسفورماتور قدرت و موارد خطای داخلی با استفاده از بسته نرم‌افزاری PSCAD/EMTDC شبیه‌سازی می‌شوند. سپس، از تبدیل S هیپربولیکی برای استخراج یک شاخص متمایز کننده از نتایج شبیه‌سازی استفاده می‌شود. در نهایت، یک مقدار آستانه مناسب برای این شاخص محاسبه می‌شود تا بتوان جریان هجومی را از جریان خطا با مقایسه شاخص مذکور با آستانه آن متمایز کرد. ارزیابی کارایی روش پیشنهادی با استفاده از شبیه سازی و داده های واقعی دقت عالی آن را تایید می کند. بنابراین، این روش می تواند در الگوریتم های حفاظت دیفرانسیل ترانسفورماتور قدرت استفاده شود تا پایداری آن ها را در وضعیت گذرای جریان هجومی ارتقاء دهد.