

Overview on Transformer Protection Technology

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Abstract: In this article, an attempt is made to put together developments in digital relays for protection of power transformer after 2000 year. Efforts have been made to include all the techniques and philosophies used to that end. The article includes the most recent techniques, like transformer saturation detection, harmonic usage, waveform processing and analysis techniques, various conversion methods, adding a series of electrical quantities to the differential current, and artificial neural network (ANN) and fuzzy logic concepts, as well as other conventional methods used for transformer protection. This article presents a set of references of all concerned papers and provides a brief summary of the work presented in them.

Keywords; artificial intelligence, differential protection, digital filters, digital relay, fuzzy logic, neural network applications, neural networks, power system protection, power transformer protection, power transformers, protective relaying

I. Introduction

The function of protective relaying is to initiate the prompt removal of faulty element from service in order to minimize the damage to system. Rockefeller first presented role of digital computers in 1969. Later on, with the development of microprocessor in early seventies, its role in digital protective relays has become a very attractive option. [1]

The following modes of operation of power transformer must be considered while considering its protection:

- Inrush condition,
- Stationary over-excitation of transformer core,
- External fault combined with saturation of CTs,
- External fault or high load current without saturation of CTs, but mixed with mismatched ratios of the transformer and CTs,
- Internal faults, and
- Normal operation.

There are many papers reported by considering all the above factors, and still, maloperation of relay continues.

They include:

- Δ -differential principle
- Direct wave shape identification
- Electromagnetic equations

- Adaptive approaches
- Power differential method
- Filtering methods, including various filtering techniques like finite impulse response filter, rectangular Fourier transform, wavelet-based method, etc.

Wave shape analysis, including different techniques for analysis of waveforms like hidden Markov model method, direct wave shape identification method, Rockefeller's method, etc.

All the above-mentioned methods are successful to some extent but practically there are some conditions where predetermined threshold is not sufficient to make a decision, and maloperation of relay occurs.

Some techniques to increase reliability, speed and robustness of existing digital relays are reported in recent literature.

The latest developments to improve power transformer differential protection techniques are described in the following categories.

II. Differential protection scheme with different transformation methods

This technique is presented to distinguish internal fault current from magnetizing inrush current in power transformers [2]. The proposed technique applies two moving windows which both of them estimate magnitude of transformer differential current using different methods. The first moving window method is based on full-cycle Fourier algorithm (long window) which uses one cycle samples of the current and provides precise estimation. The second one is originated from least error square (LES-least error square) method that has five sample point input data (short window). Meanwhile, obtained results demonstrate precise operation of the proposed algorithm for different conditions such as CT saturation and over-flux condition; therefore, it can be a multi-objective technique for transformer protection.

Another proposed digital protection is based on extracting high frequency sub-band contents present in the $d-q$ axis components of the differential currents in order to identify internal faults [3]. The desired high frequency sub-band contents are extracted using a single-stage wavelet packet transform (WPT), which offers parameterizing the energy in the high frequency sub-band contents using a finite number of coefficients. The WPT coefficients contain information that offer accurate, fast, and reliable detection and classification of transient disturbances, including magnetizing inrush and internal fault currents that may be experienced by three phase power transformers.

Another new algorithm based on processing differential current is proposed for digital differential protection of power transformers by considering different behaviors of the differential currents under fault and inrush current conditions [4]. The criterion function is then used for three phases, and internal faults are precisely discriminated from inrush current less than a quarter a cycle after the disturbance; this is one advantage of the method. Another advantage of the proposed method is that the fault detection algorithm does not depend on the selection of thresholds.

HS-transform is used to generate frequency contours from samples of differential current and parseval's theorem is used to extract the features like energy and standard deviation [5]. In this proposed method, frequency contours for two cycles of fault current are generated using HS-transform and features like energy, standard deviation are computed using parseval's theorem are trained and tested using SVM for fault classification.

Another new scheme for power transformers differential protection, in which the concept of the Park's instantaneous differential

powers is introduced [6]. The proposed method is able to detect winding insulation failures and to distinguish them from magnetizing inrush current transients. The computation of the harmonic components of the differential currents is not required and the DFT inherent limitations are overcome. The restraint signal does not depend on the 2nd harmonic of the differential currents, allowing for an efficient fault/inrush discrimination, and thus inhibiting false relay operations.

Table.1 Evaluation of differential protection schemes with different transformation methods

method	Strengths	Weaknesses	application	Evaluation
LES [2]	fast response	Its estimation might not be quite accurate.	multi-objective technique	Good (laboratory analysis stage)
a single-stage WPT [3]	CT mismatches, saturation, and transient unaffected	the need for many learning and skill materials	as a stand-alone differential protection scheme	Very good (Improvement of in-service protection)
criterion function [4]	computing time 1/4 cycle	Use of a specific frequency band	inrush current estimation	Good (Complementary to algorithm)
HS-transform [5]	high accuracy	computation time two cycle	classifying transient's events	Good (laboratory analysis stage)
Park's transform [6]	no depend on the 2nd harmonic	differential use of braking signal	fault/inrush discrimination	Good (laboratory analysis stage)

III. Waveform Processing and Analysis Techniques

An algorithm makes use of the characteristics of differential current waveform in the nonsaturation zone that it is similar to a part of the sinusoidal wave under the short-circuit fault and far different with the sinusoid under the inrush condition [7]. To realize this algorithm, the nonsaturation zone of the transformer is decided by comparing the algebraic sum of sampling data in a short slide window of the differential current under the magnetizing inrush or the short-circuit fault, then two kinds of normal sinusoidal waveforms are structured according to the value and position of the peak point of differential current in the nonsaturation zone. The correlation coefficients between the original waveform and two structured sinusoidal waveforms are calculated, and the magnetizing inrush or fault current is judged according to the average of two correlation coefficients.

MDS (morphological decomposition scheme) for the identification of transformer magnetizing inrush, the scheme decomposes a current signal into multiresolution levels based on synthesis and analysis operators of mathematical morphology [8, 9]. It is able to discriminate between inrush and internal fault currents even in the case of an inrush with a low second harmonic component and an internal fault current with a high second harmonic component. This scheme is able to distinguish between an internal fault and inrush even in the case of the inrush with low second harmonic components.

An adaptive approach distinguishes internal faults and disturbances based on the differential current trajectory and adopted weighting factors depending on the differential current locus in the relay characteristic [10]. Based on current trajectory and fault condition, the operational zone of relay characteristic is divided into three operating regions. A weighting factor is adapted to the current trajectory signals of each phase according to associated region, in which higher weights are considered for the faults with a

higher degree of certainty. Afterwards, the cumulative WF of three phases is utilized to send trip command.

The technique, comprising a percentage differential relay supervised by a PAD (Phase angle difference) scheme, uses the phase shift between the 60Hz components of the respective line currents as a restraint signal to prevent differential relay from mal-operation on magnetizing inrush current [11]. The PAD calculations are conducted using an amplitude comparator with inputs of the difference and the sum of the line currents and an output indicates the phase angle relative to a threshold value 90° . If the phase angle is greater than the threshold value, it implies that the power transformer experiences an internal fault and, hence, a trip signal from the PAD is generated to release the differential relay for switching-off the power transformer.

Table.2 Evaluation of waveform processing and analysis techniques

method	Strengths	Weaknesses	application	Evaluation
correlation analysis [7]	Low computation and requirements	data at unsaturation and saturation	turn-to-turn short-circuit fault	Good (laboratory analysis stage)
morphological scheme [8,9]	required calculation is very simple	solely dependent on the second harmonic	scheme of MDS	Good (still under study)
current trajectory and adopted weighting factors [10]	rapidly detects all internal faults	Use of the cumulative WF	phase differential units	Excellent (230/63kV power transformer)
Phase angle difference [11]	independent of harmonic contents and adversely effect of CT saturation	the presence of more than 90° phase shift	Discriminating internal fault from various disturbances	Excellent (existing digital differential relays)

IV. How to apply artificial intelligence

The behavior of FIRANN (Finite Impulse Response Artificial Neural Network) applied to a transformer differential protection is presented [12]. Three FIRANNs are designed, trained and tested. The first one has an output, which identify internal faults from any other cases like inrush current and external faults. The two others FIRANNs, each have two outputs that classify between internal and external faults, so that, a backup protection is included. These FIRANNs have six inputs, one for each sampled current signal from both transformer sides. The sample rate selected is 2 kHz for a 50 Hz power frequency.

Alternative approaches using artificial neural networks (ANNs) for the protection of power transformers, complete protection schemes were implemented [13]. Concerning the ANN approaches for protection purposes, two different algorithms were implemented. The first approach used an ANN with MLP *backpropagation* for pattern recognition. The best results showed the accuracy of 98.65% and 97.80% for power transformers of 25 MVA and 6.25 MVA, respectively. The time response was 1/4 of a cycle. The second approach included a routine for saturation reconstruction. For this application, the best results showed the accuracy of 99.92% and 99.31% for power transformers of 25 MVA and 6.25 MVA, respectively.

The proposed scheme has been realized through two different Artificial Neural Network (ANN) architectures [14]. These two ANNs were trained using Back Propagation Neural Network Algorithm (BPN) and PSO technique and the simulated results are compared. If the initial values of the weights are not properly selected, the optimization will be trapped in a local minimum or maximum. But, while PSO algorithm was used, that has overcome the above-mentioned drawbacks of BPN and gives improved results.

A new approach, based on neuro-fuzzy technique is approach is able to handle the “vague” information rather than only the “crisp”

information [15]. This helps in taking accurate decision, in spite of vagueness present in the relay operating signal, either due to measurement inaccuracies/uncertainties and transient components present in relay signal or due to noise. The propose and reliably for a wide range of variations in fault and magnetizing inrush conditions, especially in the case of modern power transformers, which use high-permeability low coercion core materials.

A new approach to power transformer differential protection based the concept of decision tree (DT) classification, the proposed technique is used on processing the differential current [16]. The suggested method detects winding insulation failures and distinguishes them from magnetising inrush and sympathetic inrush conditions with classification accuracies of 100% for simulations and 95% for real-time studies.

Table.3 Evaluation of how to apply artificial intelligence

method	Strengths	Weaknesses	application	Evaluation
FIRANN [12]	fault detection time 3.5 ms	many learning database requirements	Internal faults from inrush and external faults.	Excellent (still under study)
recurrent ANNs [13]	response time 1/2 of a cycle	dependence on neural network selection	differential protection algorithm	Very Good (25 MVA and 6.25 MVA)
PSO [14]	using BPN and PSO algorithms	To stuck or oscillating around a local minimum.	detection of normal, inrush, over excitation, internal faults and CT saturation	Excellent (still under study)
neuro-fuzzy technique [15]	“crisp” information processing	The effect of hidden layer neurons	internal fault and magnetizing inrush	Excellent (still under study)
decision tree (DT) classification [16]	no depend on the selection of thresholds	recognised by inrush in a few sampling cycle	detecting winding insulation failures	Good (laboratory analysis stage)

V. Detection of current transformer saturation and inrush current after external shorting removal

A method of symmetrical component analysis for the detection of current-transformer (CT) saturation in a numerical current differential feeder protection relay is presented in this paper [17]. The major conclusion of this study is that the proposed algorithm allows for a differential relay to improve its’ ability to be more sensitive while still maintaining the high level of protection stability.

Recently, several cases of mal-operation of the differential protection with second harmonic blocking due to transformer switching on with load have been reported. Quite a few mal-operations occurred at the nonrestraint region of percentage restraint plane. This point of view is verified with the simulation tests. This paper analyses the mechanism of the mal-operation of the differential protection caused by the low through inrush during the loaded transformer energization [18]. In this case, the differential current may exceed the minimum operation threshold together with low second harmonic content, leading to above-mentioned unusual mal-operations of the differential protection.

A new algorithm for detection of internal inter-turn faults in power transformers are described [19]. The algorithms developed are based on the differential equation of the equivalent circuit of the transformer. In one version additional information from a CT installed inside of the triangle of delta side windings is used, which brings very promising results. Three new algorithms for detection of internal turn-to-turn faults in power transformers are presented. The techniques presented enable detecting even small

number of the short-circuited turns wherever they are located. If the zero sequence current is directly measured (not calculated from the saturated phase currents) then the saturation phenomenon does not write off the distinguishing abilities of proposed criteria, especially the ones based on zero sequence quantities.

Table.4 Evaluation of detection of current transformer saturation and inrush current after external shorting removal

method	Strengths	Weaknesses	application	Evaluation
symmetrical component analysis [17]	Using the third harmonic current component	having bias threshold characteristics	zero-sequence differential protection	Good (laboratory analysis stage)
using second harmonic blocking [18]	Detecting the internal faults and CT saturation	Dependence on Core Materials and Structures	malfunction analysis of protection	Good (still under study)
differential equation [19]	detecting even small number of the short-circuited turns	Delay effect by second harmonics	detection of internal turn-to-turn faults	Very Good (laboratory analysis stage)

VI. A method of applying different additions to current signals

Modern power transformers have lower values of the second harmonic and also due to transient its value might become small enough to give wrong indication to the relay system. The relationship between the inrush current and fault current maximum magnitudes and the phase angle α of the energizing voltage shows that the highest value of the inrush or fault current occurs when energizing the transformer at $\alpha = 0^\circ$ while the lowest currents occurs at $\alpha = 90^\circ$. It is based on estimating the value of the fictitious equivalent resistance R_w whose possible range is between zero and the value of the transformer's resistance in its no-load equivalent circuit. Too small values of this resistance imply internal faults, whereas higher values describe situations involving inrush current [20].

This paper aims at the appropriate applications of two important current differential protection criteria by quantitative analyses [21]. Combining theoretical analysis with simulation tests, the overall performances of two typical percentage differential protection criteria are compared in terms of the operation sensitivity and security. With the conclusion drawn from this paper, the applications of both criteria can be arranged more reasonably. The sensitivity and the security of the percentage differential criteria using the phase current and the superimposed phase current were studied comparatively in this paper. In terms of the security analysis, and based on the existing setting principles, the superimposed-current-based differential protection is also better than the phase-current-based differential protection in most cases. Generally, the operating correctness of the superimposed-current based protection cannot be guaranteed if the fault exists for a long time. Under this condition, the phase-current-based differential criterion is capable of taking over the task of the protection independently. Therefore, these two criteria can complement each other, and they should not be replaced by each other.

Table.5 Evaluation of a method of applying different additions to current signals

method	Strengths	Weaknesses	application	Evaluation
harmonic restraint and the waveform-based restraint [20]	Using magnitude and phase change characteristics of 2 and 5 harmonics	The set point of the virtual equivalent resistance is opaque.	to distinguish between inrush current and fault current	Good (still under study)
sensitivity and the	the sensitivity of the	Influence of power	Protection Based on	Very Good

security of the percentage differential criteria [21]	superimposed-current-based differential criterion exceeds that of the phase-current	system frequency variation	Overlap Current	(laboratory analysis stage)
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VII. Overexcitation and inrush current estimation using harmonics

This paper describes a new approach for transformer differential protection that ensures security for external faults, inrush, and overexcitation conditions and provides dependability for internal faults [22]. This approach combines harmonic restraint and blocking methods with a wave-shape recognition technique. This new method uses even harmonics for restraint, plus dc component and a fifth harmonic for blocking. The second harmonic component is commonly used for blocking differential relay in power transformers.

The altitudes of harmonics and fundamental are computed by discrete Fourier transform (DET). However, this method is not effective in some cases. A new scheme to discriminate fault current and inrush current is presented in this paper [23]. The ratio of the power spectrum (PS) of second harmonic to the PS of fundamental based on autoregressive process is used for inrush identification. Test results with the sampled data from a prototype device on a dynamic power system model verify the effectiveness of the proposed scheme.

A combined power-current spectrum blocking for current differential protection of power transformer is proposed [24]. The proposed algorithm can exclusively classify the internal faults associated with transformer inrush currents. This combination is assessed based on the individual analysis of the second harmonic current, differential power, and power spectral blockings. The simulation results have been carried out on 220 kV/70 kV, 120 MVA, 50 Hz, earthed star/earthed star connection of modern design power Transformers. However, the experimental phase is incorporated using a laboratory ordinary transformer with 2 kVA rating. It is found that, a novel ORing gate fed by the common second harmonic blocking, negated power differential output, and negated second harmonic power output have revealed a superior blocking performance of the traditional current differential relay. Also, the relay was sensitive for all internal fault associated with the switching operation as 40 ms intentional delay is included. A sensitivity limit of 200 on the 70 kV side has been measured. Also, it is stable for all external faults.

Table.6 Evaluation of overexcitation and inrush current estimation using harmonics

method	Strengths	Weaknesses	application	Evaluation
harmonic and a wave-shape recognition [22]	Dc component and a fifth harmonic	Using even-harmonic restraint	external faults, inrush, and overexcitation	Excellent (Addable to existing devices)
PS ratio restraint principle [23]	Using the ratio of second harmonic to the PS	Reliability Impairment	blocking differential relay for	Good (Reliability Problems)
second harmonic and power spectral blockings [24]	power-current spectrum blocking	Reliability Impairment	blocking differential protection for	Good (laboratory analysis stage)

VIII. Conclusion

Analysis of transformer protection literature is carried out in this paper. Digital relays are being offered and implemented in a number of ways and techniques, but with the introduction of embedded devices, advanced technologies, and various modern

mathematical tools with high speed and skills in terms of complete reliability and technology development to meet today's needs, they are found to be practical, fast and reliable.

These methods may fail under various typical and practical conditions and may fail in digital relays. Since many studies from the aforementioned data are still in the laboratory and theoretical stage of research, it is thought that much effort, experience and practice are required to fill and update the deficiencies of transformer protection devices in actual operation and to make them practical. Therefore, further knowledge development of power transformer protection and the effective application of more reliable technology should be pursued. The lack of adequate attention should be added to the discussion of the broad reference points on the issues of current technologies used for power transformer protection.

It is sincerely attempted to present the most comprehensive set of references on the subject of recent techniques used in power transformer protection, the presence of omission is bound to be there. It is found that since the development of digital relays to date, many methods and techniques are proposed and implemented, but in reference to full-security and development of techniques to meet present day requirements, the recent mathematical tool of ANN and fuzzy logic concept seems to be reliable, fast and robust. Further work is currently in progress, concerning the refinement of the proposed protection technique, with the aim of dealing with transient overvoltages, current transformers severe saturation, sympathetic and recovery inrush currents, or even, the surrounding presence of power electronics equipment. Researchers in the field of protective relaying should recognize this phenomenon and propose reasonable solutions. The author apologizes for any errors or omissions, and the problems to be added are to be improved through publication.

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