Review of Protection Approaches for Discrimination between Internal Fault and Inrush Current in Electric Power Transformers

E. Abdallah
Electrical Engineering Department.
Mansoura University, Mansoura, Egypt.
eng.elsaeed2007@mans.edu.eg

A. Helal
Arab Academy for Science Technology &
Maritime Transport, Alexandria, Egypt.
ahmedanas@aast.edu

H. Desouki
Arab Academy for Science Technology &
Maritime Transport, Alexandria, Egypt.
hdesouki@aast.edu

K. Shebl
Electrical Engineering Department.
Mansoura University, Mansoura, Egypt.
kamalshebl@mans.edu.eg

Abstract: *This paper presents a review of different protection approaches used with transformer differential protection to discriminate between internal fault current, magnetizing inrush current during energization, magnetizing inrush current. These approaches include harmonic restraint, voltage and flux restraints, the inductance based method and pattern recognition. The pattern recognition approach has mainly been designed using artificial intelligence (neural networks, fuzzy logic), wavelet transforms and hybrid techniques.*

Key words: *Power Transformer, Inrush Current, Differential Protection, Neural Network, Fuzzy Logic, Wavelet Transforms.*

1. Introduction

As one of the most important elements in modern power systems, transformers are used in power networks transmission and distribution levels. An unscheduled repair work, especially replacement of a faulty transformer, is very expensive and time consuming. The electrical windings and the magnetic core in a transformer are subject to a number of different disturbances during operation, for example:

- Forces due to the flow of through-fault currents.
- Local heating due to magnetic flux.
- Vibration.
- Expansion and contraction due to thermal cycling.
- Excessive heating due to overloading or inadequate cooling.

These forces can cause deterioration and failure of the electrical insulation of the transformer windings [1].

The choice of protection depends on the criticality of the load, the relative size of the transformer compared to the total system load, and potential safety concerns. The most common method for power transformer protection is based on the differential protection. The differential protection scheme is the most widely accepted method for the protection of transformers of 5 MVA and above [2].

The principle of this method is shown in Fig. 1, where the primary and the secondary currents are compared after being reduced by current transformers. The primary and the secondary current transformers (CTs) are connected such that under normal conditions the differential current signal is approximated to zero. If an internal fault occurs, then the differential current (I_d) is not zero, and is used to activate the relay to disconnect the protected power transformer [3].

The major concern in power transformer protection is to avoid the false tripping of the protective relays due to misidentifying the magnetizing inrush current. The magnetizing inrush currents may have a high magnitude, which is indistinguishable from the traditional internal fault currents.

Several approaches for power transformer differential protection have been developed to prevent mal-operation of differential protection. Among these approaches harmonic restraint, voltage and flux restraint, inductance based method and pattern recognition. The pattern recognition approach based on wavelet transform and artificial intelligence, such as, neural network and fuzzy logic.

This paper presents a review of protection approaches used with transformer differential protection to eliminate mal-operation of differential protection. The nature of magnetizing inrush current is described in section (2). The transformer protection approaches for discrimination between internal fault and inrush are been introduced in section (3). Finally, summary of approaches is presented in section (4).

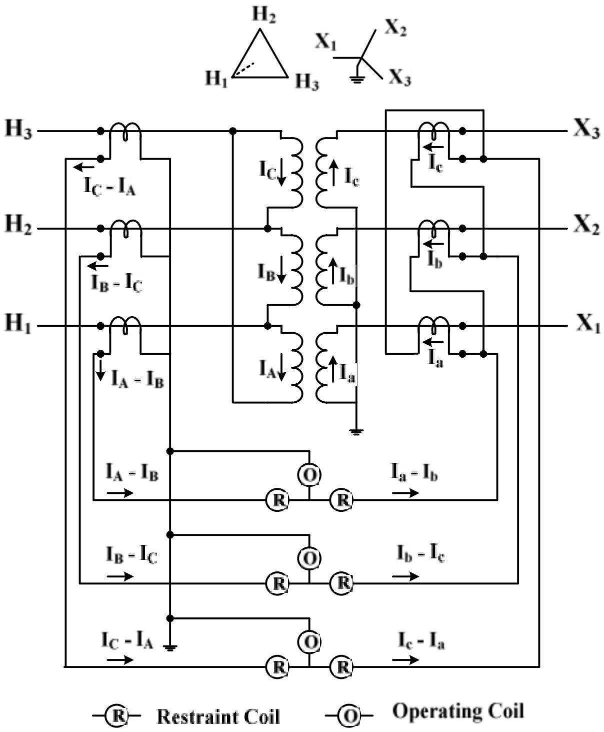

Fig. 1. Basic structure of a differential relay for power transformer protection.

2. Nature of Inrush Current

Transformer inrush currents can be divided into three categories: magnetizing inrush current during energization, magnetizing inrush current during fault removal and sympathetic inrush current. Initial magnetizing due to switching a transformer in is considered the most severe case of an inrush. When a transformer is de-energized (switched-off), the magnetizing voltage is taken away, the magnetizing current goes to zero while the flux follows the hysteresis loop of the core. This results in certain remanent flux left in the core. When, afterwards, the transformer is re-energized by an alternating sinusoidal voltage, the flux becomes also sinusoidal but biased by the remanence. The residual flux may be as high as 80-90% of the rated flux, and therefore, it may shift the flux-current trajectories far above the knee-point of the characteristic resulting in both large peak values and heavy distortions of the magnetizing current.

Fig. 2 shows a typical inrush current. The waveform displays a large and long lasting dc component, is rich of harmonics, assumes large peak values at the beginning (up to 30 times the rated value), decays substantially after a few tenths of a second, but its full decay occurs only after several seconds (to the normal excitation level of 1-2% of the rated current). The shape, magnitude and duration of the inrush current depend on several factors [4, 5].

- Size of the transformer.
- Magnetic properties of the core material.
- Impedance of the system from which a transformer is energized.
- Remanence in the core.
- Timing of transformer switching.
- The way used for transformer switching.

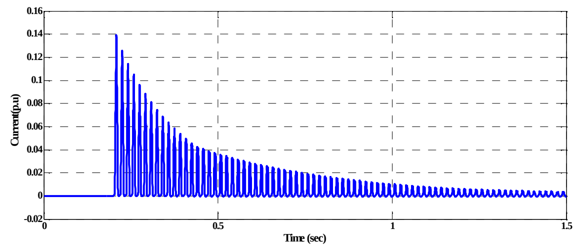

Fig.2. Typical Inrush Current for 50 MVA transformer.

There is no direct evidence that the energization of a transformer can cause an immediate failure due to high inrush currents. Transformer energization harmonics do not normally cause problems unless the system is sharply resonant at one of the predominant harmonic frequencies produced by the inrush current. This can excite the system, causing high-voltage distortion. The interaction between the resonant system and the energizing transformer can produce very high voltages which can degrade and/or damage equipment and eventually lead to equipment failures [6].

For the characteristics that inrush current waveform has dead zone and peak wave, while the internal fault current waveform remains fundamental frequency sine wave with high value of current. The current for an internal transformer fault typically has very low levels of second harmonic current.

Discrimination between inrush current and internal fault current is long being challenging task. Since a magnetizing inrush current contains generally a large second harmonic comparison to internal fault, conventional transformer protection system are designed to restraint during inrush transient phenomenon by sensing this large second harmonic [7].

3. Transformer Differential Protection Approaches

Several approaches for power transformer differential protection have been developed to discriminate between internal fault and inrush current. The harmonic restraint approach is one of the most widely used approaches for protecting power transformers [9-18]. As protective relaying shifted toward digital and microprocessor implementations, new approaches have been proposed for power transformer protection.

Among these new approaches are voltage and flux restraints [20-22], the inductance based method [23-28], and pattern recognition. The pattern recognition approach has mainly been designed using artificial intelligence (neural networks (NNs) [29-35], fuzzy logic (FL) [36-42], wavelet transforms (WT) [43-54], and hybrid techniques [55-66]. These approaches are shown in Fig. 3.

3.1 Harmonic Restraint Approach

The harmonic restraint approach is one of the most widely used approaches for protecting power transformers. Harmonic restraint is the classical way to restrain tripping. There are many variations on this method.

All of these methods work on the assumption the magnetizing inrush current contains high levels of second harmonic current. The simplest method of harmonic restraint uses the magnitude of the second harmonic in the differential current compared to the magnitude of the fundamental frequency component in the differential current. Tripping of the differential element is blocked when this ratio exceeds an adjustable threshold. The extraction of the harmonic components can be achieved using passive filters, Fourier transforms, sine-cosine correlations, rectangular transforms, Haar functions, Walsh functions, Kalman filters, least-square algorithms [8].

In [9] and [10], authors use sine and cosine Fourier coefficients to compute the fundamental, second and fifth harmonies. The trip decision can be based on the relative amplitude of the fundamental compared to the combined amplitude of second and fifth harmonics.

While in [11] and [12] Fourier sine and cosine coefficients required for fundamental, second, third and fifth harmonies determination have been calculated using rectangular transfer technique. These harmonics have been used in harmonics restrain and blocking techniques used in differential protection system.

An algorithm depends on the change of negative sequence power to cancel second harmonic restraint is proposed in [13]. The differential protection will operate even if be restrained when the percentage of ratio between the secondary and primary of any phase differential current is larger than the given value if the change of negative sequence power is larger than the setting value.

In [14] the authors use second harmonic for blocking differential relay in power transformers. The ratio of the power spectrum (PS) of second harmonic to the PS of fundamental based on autoregressive processes used for inrush identification.

Two estimator algorithms have been developed in [15], a combination of Walsh and Fourier series algorithm and Least Squares (LS) algorithm. This technique is an extension of the traditional second harmonic method, which uses the angular relationship between the first and second harmonics of the differential current.

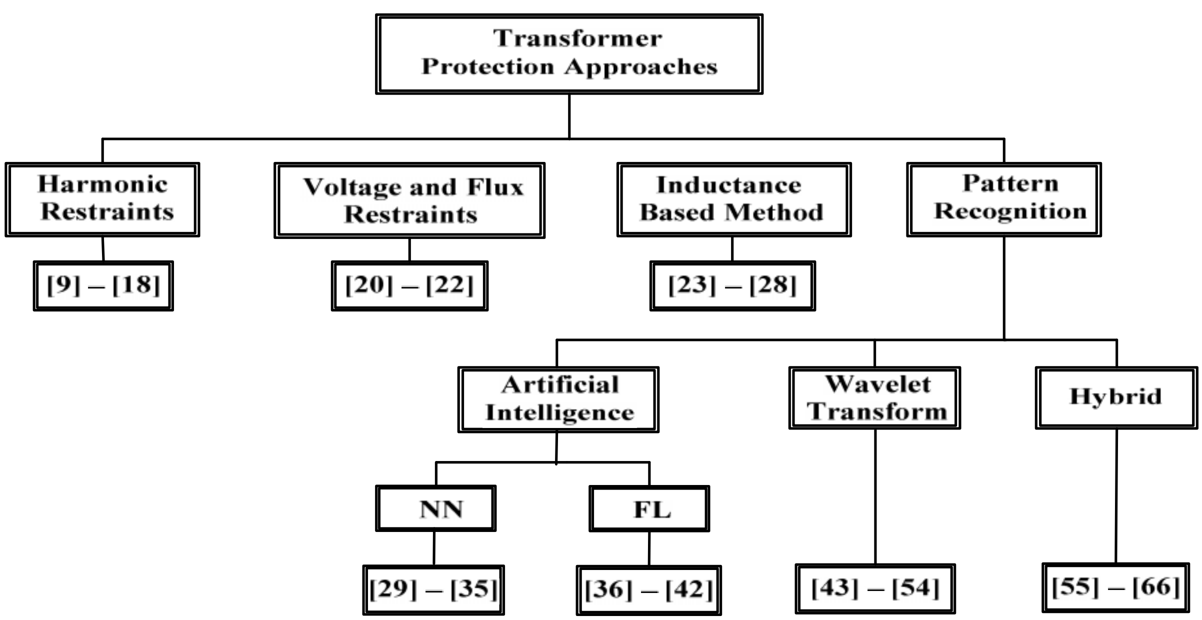

Fig. 3. Transformer protection approach for discrimination between internal fault and inrush

Authors in [16] present an algorithm developed by considering different behaviors of second harmonic components of the differential currents under fault and inrush current conditions. In this method, a criterion function is defined in terms of time variation of second harmonic of differential current. By evaluating the sign of the criterion function for the three phases, the internal faults can be accurately recognized from inrush current conditions about half cycle after the occurrence of disturbance.

In [17] authors design software for Fourier Transform based logic technique for protection of transformer. This software is based on amplitude calculation and harmonic calculation. For the amplitude calculation, if the absolute difference of primary and secondary differential currents between the CTs output currents is greater than zero the logic (1) takes place, which indicates the case of an inrush current or an internal fault. Otherwise the logic (0) takes place, which indicates a detection of an external fault. While, for harmonic calculation if the percentage value of the second harmonic amplitude is in the range of (0.3 to 0.6) of the fundamental component amplitude, then the logic (0) occurs, that means recognition of inrush current. Otherwise the logic (1) takes place, which indicates a detection of an internal or external fault.

While, in [18] authors use Taylor series to extract the fundamental and second harmonic components from inrush and fault currents. If second harmonic ratio is greater than the set value, then it is considered to be inrush condition occurs while, below the set value is assumed to be a fault condition.

3.2 Voltage and Flux Restraints

Voltage restraint is based on the fact that phase voltages decrease only in the case of an internal fault, not under inrush or overexcitation conditions. Therefore, the relay is restrained from tripping if the phase voltages are above a certain threshold [19].

The algorithm described in [20] uses voltages rather than current harmonics for the restraint function. The authors in [21] suggest the possibilities of using the transformer flux as a restraining quantity. If the flux could be estimated correctly, then it would provide a sound discriminate for overexcitation as well as magnetizing inrush conditions. Although the voltage at the transformer terminals shows severe distortions (primarily a reduction for fraction of a cycle), the flux levels during these periods are high. Consequently, the uncertainties associated with the windows of voltage magnitude for restraining function no longer exist when the flux is used as a restraining quantity.

Authors in [22] present method based on the ratio of voltage and fluxional differential current to overcome flux-restraint limitation. When the transformer has internal faults, the ratio is usually small even to zero in one cycle. While, in magnetizing inrush currents in the transformer, the ratio is very big in one part of one cycle and very small in the other part.

3.3 Inductance Based Method

In the internal fault and normal operation states of power transformer, the iron core is not saturated and the magnetizing current is very little, which results in the approximate constant magnetizing inductance owing to the operation in the linear area of the magnetizing characteristic. However, the inrush current is a result of the transformer core saturation. Furthermore, the iron core will alternate between the saturation and non-saturation during the inrush current, which causes a drastic variation of the magnetizing inductance [23].

In [23], [24], and [25] authors use the equivalent instantaneous inductance (EII) to distinguish between internal fault and magnetizing inrush.

In [23] authors use EII based scheme, which is derived from the inherent difference of the magnetic permeability, due to the saturation and non-saturation, in the transformer iron core between the inrush current and an internal fault. Two criteria are respectively proposed in the time domain and the frequency domain, which can be called as the direct method and indirect method. The method in the time domain directly detects the variation of the EII, but that in the frequency domain indirectly reflects the variation by using the fundamental frequency component.

For direct method, if the variation of the EII exceeds a threshold, the relay judges that there is an inrush current and rejects the tripping. Or else, the relay judges an internal fault occurs if variation of the EII is less than the threshold. In theory, the threshold is close to zero.

For indirect method, if the amplitude of the fundamental frequency component in the EII is larger than a threshold, then we make the decision of the inrush current in the transformer and block the relay tripping of the differential protection. Or else, we make decision of detection of an internal fault and let the relay trip.

The ratio of average equivalent instantaneous inductances between the non-saturation and the saturation zone, which are divided according to a threshold of differential current, has been used in [24]. During the inrush, the value of equivalent instantaneous inductance varies severely from small to large as the transformer entering into the saturation and withdrawing from it, so the ratio of average equivalent instantaneous inductances between the non-saturation and the saturation zone is very large in one cycle.

However, for the short-circuit fault in transformer, the equivalent instantaneous inductance is very small, and keeps little variation, so the ratio is approximately equal to one. While, in [25] authors use the same criteria in [24] without using any ratio. The algorithm based on the double-side average equivalent instantaneous inductance in the non-saturation zone (AEII-in-NZ). During the internal fault occurring, both of the AEIIs-in-NZ at the primary and secondary winding of the fault phase are very small. However, for the normal running, magnetizing inrush and external fault occurring, at least one side of the AEII-in-NZ keeps a high value.

In [26] authors proposed algorithm for the main protection of transformers, based on inverse inductance. Transfer inverse inductance had a constant value without reference to the internal conditions of the transformers. The value of transfer inverse inductance was calculated from leakage inductance, a known value. The calculated value of the inverse inductance was set into the relays. Then, shunt inverse inductance could be calculated by sampling voltage and current at each terminal. The value of the shunt inverse inductance at an internal fault was very different from that at magnetizing inrush.

For magnetizing inrush the shunt inverse inductances had a constant value much larger than zero. While, in internal fault the shunt inverse inductance of the faulted winding increased in accordance with the increased faulted turn ratio, but that of non-faulted windings remained nearly zero or became slightly negative.

Authors in [27] presented basic principle of the transformer protection principle based on the change of inductances. The method can't be acted on the inrush current and does not need the internal parameters got difficultly. When the transformer runs normally, energized and has external fault, the three leakage inductances (L2) must be same in the normal condition. Only when there are internal faults, the three L2, should be different. These are the basis of protection criterions. An inductance based-algorithm is introduced for discrimination between inrush currents and internal faults [28]. This method calculates the instantaneous differential inductance (criterion) from primary view of the transformer sides. If the calculated criterion is over than the threshold, disturbance will be inrush current. Otherwise, if the calculated criterion is lower than the threshold, disturbance will be internal fault.

3.4 Pattern Recognition

As protective relaying shifted toward digital and microprocessor implementations, pattern recognition approach have been proposed for power transformer protection. Some techniques to increase reliability, speed and robustness of existing digital relays are reported in recent literature. Those techniques are based on artificial intelligence, wavelet transform and hybrid approach. These developments are discussed in the following section of this paper.

3.4.1 Artificial Intelligence

Artificial Intelligence (AI) is a subfield of computer science that investigates how the though and action of human beings can be mimicked by machines. The most widely used and important ones of AI tools, applied in the field of differential power transformer protection are NN and FL.

•Neural Network

The application of ANN to discriminate the fault has given a lot of attention recently. Neural networks can be used to discriminate between magnetizing inrush and internal fault currents based on wave shape analysis of current signals. Neural networks are trained using feed forward back propagation algorithm. Many papers are presented in past, only few recent papers are discussed here.

Two approaches to detect inrush current by recognizing its wave shape, more precisely from the wave shape of internal fault current have been proposed in [29]. In the proposed algorithm, the Neural Network Principal Component Analysis (NNPCA) and Radial Basis Function Neural Network (RBFNN) are used as a classifier. The proposed algorithm is used to discriminate between internal faults from inrush and over-excitation condition. The algorithm also makes use of ratio of voltage-to-frequency and amplitude of differential current for detection transformer operating condition. A comparison among the performance of the FFBPNN (Feed Forward Back Propagation Neural Network), NNPCA, RBFNN based classifiers and with the conventional harmonic restraint method based on DFT method is presented in distinguishing between magnetizing inrush and internal fault condition of power transformer. The results confirm that the RBFNN is faster, stable and more reliable.

In [30], authors proposed differential algorithm based on ANN to discriminate between inrush and internal fault current of power transformer. The ANN based method is designed and trained with experimental inrush and fault current data obtained from a laboratory prototype power transformer. Both off-line and on-line test results show that the algorithm is capable of distinguishing between the internal faults and magnetizing inrush currents. Also, the method neither depends on the transformer equivalent circuit model nor the harmonic contents of the differential currents.

Authors in [31] use an intelligent ANN based scheme for digital differential protection to distinguish inrush from internal fault in a transformer. The scheme based on multi-condition restraint criterion. The voltages, basic currents and second harmonic currents of three phases are used as the inputs. Five outputs are designed to represent three kinds of inrush conditions and two kinds of fault conditions. If the output approaches is high, that is as close to 1 as possible, then the corresponding condition occurs. If all the outputs are small, then it represents the power system runs normally. Multi-condition restraint for inrush overcomes the shortcoming from traditional harmonic restraint, which is applied to modern large transformers, cannot exactly distinguish short circuit and inrush.

In [32] authors use another type of ANN model, the probabilistic neural network (PNN). Two methods are proposed to achieve the optimal smoothing factor of PNN. These methods are particle swarm optimization (PSO) and the conventional method. The selection of PSO is because of its efficiency in solving a plethora of applications in sciences and engineering. Authors compare PNN, feed forward back propagation (FFBP) neural network and harmonic restraint based on discrete Fourier transform (DFT). The comparison shows that PNN is faster than FFBP and independent of the harmonics contained in differential current. While, the conventional harmonic restraint technique may fail because high second harmonic components are generated during internal faults and low second-harmonic components are generated during magnetizing inrush with such core materials.

While, in [33] authors use feed forward neural network (FFNN) to discriminate between inrush and internal fault current of power transformer. The method is based on the fact that magnetizing inrush current has large harmonic components. The harmonic components are extracted using DFT. The application of a finite impulse response artificial neural network (F1RANN) on digital differential protection design for a three-phase transformer has been presented in [34].The FIRANN has 6 inputs and 2 outputs. The inputs are normalized sampled currents taken from the transformer. The first output goes high in case of internal fault, while the second goes high in case of external fault on load side. Authors use the second output as a backup protection. The FIRANN was trained to have a 3.5 ms tripping time which is considered as a very fast protection.

Authors in [35] proposed a classification method based on Slantlet Transform (ST) combined with an automated classification mechanism based on ANN for power transformer protection. The proposed algorithm has been realized through two different ANN architectures. One is used as an internal fault detector (IFD) and the other one detects and discriminates the other operating conditions like normal, inrush, over excitation, and CT saturation due to external faults. The developed ANN architectures are trained by using RBF algorithm. ST has been regarded as a contemporary development in the field of multi resolution analysis, which proposed as an improvement over DWT. The proposed scheme shows classification accuracy nearly as high as 100%. In addition, the model issues tripping signal in the event of internal fault within 12 ms of fault.

- **Fuzzy Logic**

A multi-criteria and fuzzy logic based differential protective algorithm for power transformers have been presented in [36] and [37]. Fuzzy logic is used for internal fault detection. The protection criteria, criteria signals and their fuzzy settings have been formulated. Algorithm of fault detection is based on ruled out non-internal fault phenomena. For internal fault detection are considered some criteria for inrush current, over excitation, saturation of current transformers and mismatch of current transformers and are defined appropriate membership functions and criteria signals. The criteria have been aggregated and combined with two supporting factors in order to generate more reliable tripping signal.

In [38] fuzzy logic approaches are used, to enhance the fault detection sensitivity of traditional percentage differential current relaying algorithm. Input variables of the proposed fuzzy based relaying are flux-differential current derivative curve, second harmonic restraint, and percentage differential characteristic curve.

In [39] authors propose an extended magnetizing inrush restraining technique employing a fuzzy-logic-based method. This technique uses the angular relationship between the first and second harmonics of the transformer currents as well as the magnitude relation of them. The fuzzy logic approach fits this problem because of the uncertainty involved in the phase and magnitude relationship between fundamental and second harmonics of differential currents.

Authors in [40], present a method based on Clarke transform with fuzzy sets. The input variables of the fuzzy-based relay are differential currents resulting from Clarke's transform. The fuzzy system is designed to distinguish internal faults from other operating conditions of the power transformer, even for faults near the neutral.

An improved fuzzy logic based differential relay is proposed in [41]. This is capable of differentiating between magnetizing inrush current, internal faults and external faults. Inputs of the proposed fuzzy based relaying are voltage to frequency ratio, 2nd harmonic content in current and differential current in the power transformer.

Authors in [42] present a multi-criteria stabilization algorithm that employs fuzzy reasoning technique for better discrimination of inrush conditions. To limit computational complexity, the simplest membership functions (triangular, trapezoidal and ramp) have been employed.

Authors in [43] present an algorithm to detect incipient fault by monitoring the magnitude and phase shift associated with negative sequence currents. The two variables magnitude and phase shift are fed as inputs to fuzzy logic. The output variable is consists of three membership functions such as Incipient fault (IF), Minor fault (MF), and Severe fault (SF).

3.4.2 Wavelet Transform

The first time using wavelet in discrimination between magnetizing inrush and internal fault is introduced in [44]. The scheme is based on the distribution of energy of the signals into both time and frequency. For inrush current, the discriminate function is greater than zero. The internal fault is detected if discriminate function smaller than zero.

Author in [45] use a wavelet packet method to distinguish between the internal and external faults to the transformer protection zone. The proposed technique is also used to distinguish between the magnetizing inrush and internal faults in power transformers. The technique uses the fault current and prefault voltage signal as a directional signal. If the directional signal goes lower than negative threshold value, the technique will identify that the fault is external. On the other hand, if the directional function goes higher than some positive threshold value, a forward fault is identified. For discrimination between inrush and internal fault current a sum of the different wavelet coefficients from window 1 to window 7 is used. This value is compared with the wavelet coefficient in window 0.

Authors in [46] and [47] use method based on discrete wavelet transform and correlation coefficient for digital differential protection. The algorithm includes offline and online operations. A criterion is based on the sum of energy of detail coefficients at level 5 of three-phase differential currents for 10 half cycles. After 10 half cycles correlation coefficient between sum of energy of detail coefficients at level 5 of three-phase differential recorded currents and the same energy for pre-recorded signal of inrush current can be used as a criteria for discrimination between inrush current and internal faults. In [46], if this correlation coefficient is higher than 0.8, the recorded current is inrush otherwise it is internal fault currents. While, in [47] if the number of dips in each correlation coefficient is greater than 1.0, the case is inrush current otherwise it is internal fault currents.

A method for recognizing the different natures of power transformer currents is achieved in [48]. The proposed technique is a five level of resolution discrete wavelet transform. The algorithm is based on evaluating the DWT coefficients of the third and fourth level details. The ratio of the median approximate deviation of detail 4 coefficients to that of detail 3 is evaluated for each sliding window. The ratio plot wave shape and its time locations represent the needed signatures to identify the type of the investigated currents.

In [49] a method is presented to control the unusual false trip of a three-phase power transformer differential protection due to ultra-saturation phenomenon based on Clarke's Transform and DWT. Input signals are analyzed by DWT for extracting the information of the transient signal in the time and the frequency domain. The standard deviation of coefficients and the energy coefficients are used to distinguish between transient phenomena in this method. While, in [50] the authors use also DWT based on wavelets coefficient spectral energy variation to identify and discriminate correctly internal and external faults, inrush currents and incipient internal faults all under or not current transformer saturation.

The WPT is used to discriminate between inrush current and internal fault current because it was found that both the magnetizing inrush and normal currents don't have any frequency component in the highest sub-band (dd) [51], [52], [53] and [54].

In [51] authors use WPT based on second level details as a signature to diagnose the type of the current flowing through the transformer. The WPT algorithm is implemented offline. In the case of inrush current, a second level detail is less than zero. While, in the case of internal fault a second level detail is greater than zero. While, author in [52] use the same technique in [51] include neutral resistance-grounded power transformers, as well as capacitive loads. The experimental results show no significant effects of grounding type, loading type, and/or CT saturation on the WPT performance.

A WPT-based differential relay for protecting power transformers using Butterworth passive (BP) filters has been introduced in [53]. The BP filters are designed to extract the second-level details consisting of high-frequency components of the three-phase differential current in order to detect and diagnose fault currents. This method tested for both offline and online performances. There was not a single case in which the BP-filter WPT-based differential protective relay response took more than half a cycle based on a 60-Hz system (4–7 ms). The main reason for selecting BP filters is their inherent capabilities to provide monotonic and ripple-free magnitude responses and their ability to provide an accurate approximation of the WPT-associated digital filters.

In [54] and [55] authors develop technique based on the synchronously rotating reference frame (dq) axis transformation of 3-phase differential current signals and WPT hybrid technique. Using dq-WPT, only 1st level sub-band frequencies of the dq axis component of the differential current is required to provide enough information in diagnosing the current flowing in the power transformer. The advantages of this hybrid technique are; changing the sinusoidal signals to dc signals simplifies the implementation, no percentage characteristics required, insensitive to the non-periodicity of the signal.

3.4.3 Hybrid Approach

The hybrid technique can be a combination of neural with fuzzy, wavelet with neural and wavelet with fuzzy.

In [56], the inputs to fuzzy-neuro approach are the ratio between primary and secondary voltages, 1st harmonic component of differential current to transformer current ratio, 2nd harmonic component of differential current to 1st harmonic component of differential current ratio and 5th harmonic component of differential current to 1st harmonic component of differential current ratio. Magnitudes and angles of harmonics of voltages and currents are obtained using DFT. The output layer is consists of one neuron. Which has value 1 for tripping conditions and otherwise no tripping. While, a neuro -fuzzy approach is introduced in [57]. This approach is based on the amplitude ratio of symmetrical components between the second and first harmonics.

An adaptive neuro-fuzzy method is introduced in [58]. This algorithm uses the second harmonic and the dead angle methods joint to each other utilizes the neuro fuzzy technique. In this method, an inrush detector is defined as an output of neuro fuzzy system. If an inrush transient occurs in a power transformer, the neuro fuzzy output will approximate to 1; otherwise it will to 0. For the purpose of classification, a threshold value is set to 0.5 and then all the cases whose neuro fuzzy outputs are less than 0.5 are classified as NO INRUSH, while those exceeding the threshold are recognized as INRUSH cases which are preceded to blocking signal emission.

Authors in [59] present a method consists of three main steps: data acquisition with CT saturation correction by ANNs (using Shannon's entropy), the estimation of the current harmonic components by genetic algorithms (GAs) and decision making by FS. After acquiring the data and CT saturation correction, the signals are processed using GAs, and the differential and flux- restraint differential currents are calculated. If the output of the FS is currents are greater than the threshold value, 0.5, the control counter is increased by 1. When this counter has exceeded 3, the relay sends a trip signal to the circuit breaker.

In [60] a combination between wavelet and neural is introduced. Wavelet transformation analysis is considered as a preliminary feature extractor and an ANN as the pattern classifier. The ANN inputs are a set of first details (dl) coefficient, which are obtained from wavelet transform. While, in [61] authors use two different ANN architectures, one is used as an Internal Fault Detector (IFD) and another one is used as a Condition Monitor (CM). The CM is used to differentiate between normal, inrush, over-excitation and CT saturation. The inputs of ANN are approximation and details coefficients which obtained from WT.

Also, in [7], [62], [63] and [64], authors present a method by combining wavelet transforms with neural networks. The wavelet transform technique is firstly applied to decompose differential current signals of power transformer systems into a series of detailed wavelet components the spectral energies of the wavelet components are calculated and then employed to train ANN in [7], [62], [63] and PNN in [64] to discriminate internal faults from magnetizing inrush currents.

Authors in [65] propose a cascade of minimum description length criterion with entropy approach along with ANN as an optimal feature extraction and selection tool for a WPT based transformer differential protection. Authors highlighted the importance of using feature selection methods in implementing an intelligent based monitoring of power system equipment for reduction of the classifier dimensionality, and thus redundancy.

On the other hand, authors in [66] present a combination between wavelet and fuzzy. The transient differential current is analyzed into its details and approximate waveforms using DWT. The maximum values of details waveform are used as an input to FL algorithm for building the membership functions. The input variable is divided into three variables one for the internal fault, one for the external fault and the third for inrush current case. The output variable is divided into three partitions with triangular membership function representing the external fault, the internal fault and the inrush current case. In [67] the authors use the same strategy used in [66], but the output variable is divided into two partitions with triangular membership function representing trip (internal fault) or no trip (Magnetizing inrush current).

While, a method uses wavelet transform (WT) and adaptive network-based fuzzy inference system

(ANFIS) is introduced in [68]. The WT is considered as a feature extractor and a Fuzzy as the pattern classifier. The algorithm is based on the differences of peaks of wavelet coefficient at d5 in first half-cycle.

4. Summary

Several approaches for power transformer protection have been developed based on employing information extracted from differential currents. Some of proposed approaches have its advantages and disadvantages.

The harmonic restraint approach is one of the most widely and simplest used approaches for protecting power transformers. However, sometimes, the second harmonic component may be generated in the case of internal faults in the power transformer and this is due to CT saturation or presence of a shunt capacitor or the distributive capacitance in a long EHV transmission line to which the transformer may be connected [8], [30], [38] and [69].

In addition, the new low-loss amorphous core materials in modern power transformers is capable of producing magnetizing inrush currents with low 2nd harmonic contents in inrush current [17], [30], [36] and [38]. One of the main drawbacks of these techniques is the slow operating speed imposed on the relay for internal faults. Practically, the delay will be one power frequency cycle. This delay can damage the transformer more and decrease the useful life of the transformer [39].

So, the discrimination between magnetizing inrush current and internal fault current will be difficult using harmonic restraint.

The previous work on power transformer protection has included other approaches, among these approaches; transformer inductance based method, flux and voltage restraints. These approaches have high dependence on parameters of the protected transformer and they require complex algorithms to carry out the required computations [46] and [51].

Also, flux restraint need to make some hypothesis on the protected transformer or to determine the parameters of the transformer experimentally [24]. While, inductance based method choose the absolute magnitude of instantaneous inductance as the threshold, so that they are hard to be set for different transformers in practice [26].

Neural network approach has flexibility with noisy data. Also, ANN method compared to the conventional method shows that ANN is the non-algorithmic parallel distributed architecture for information processing and inherent ability to take intelligent decision [30]. The main problems facing the use of ANN are the selection of the best inputs and how to choose the ANN parameters making the structure compact, and creating highly accurate networks.

On the other hand, ANN require a large computational burden training or comparing, large data storage for either memory to accommodate the required algorithms, complex experimental setups and/or large dependence on the transformer parameters [16], [47] and [48].

Also, the main problem is the generalization capability of neural network, where a network designed and trained to protect a certain system cannot be used to protect another system [48].

Fuzzy inference is a process that makes a decision in parallel. Because of this property, there is no data loss during the process and so final fault detection will be far more precise than that of conventional relaying techniques [38] and [40].

Fuzzy logic methods have not good performances when there are rapid changes in the power system. Also, these methods use a lot of rules to make a decision and to create these rules need much work [47]. The basic fuzzy systems cannot deal with noisy or distorted inputs. Also, the fuzzy systems are not flexible and cannot be easily adapted to new elements or functionalities in the power system. The time response of fuzzy systems is considered relatively slow for protection purposes, as it is required to search through a large pool of rules till a decision is reached [48].

Wavelet based signal processing technique is an effective tool for power system analyze and feature extraction and has better ability of time- frequency location [35], [45], [46], [64] and [68].

However, disturbances in power systems are non-periodic, non-stationary, and of short duration nature. The wavelet analysis is one of the newly applied frequency analysis tools for processing signals with complex characteristics [48].

On the other hand, their disadvantages are that they need long data window and are also sensitive to noise and unpredicted disturbances, which limit their application in relaying [70].

5. Conclusions

Power transformers play an important role in modern power systems, and their protection is of great importance to assure stable, reliable and secure operation of the whole system. The nature of inrush current has been presented in this paper. Protection approaches used with transformer differential protection to eliminate mal-operation due to magnetizing inrush current during energization, magnetizing inrush current during fault removal and sympathetic inrush current have been presented. Among these techniques are harmonic restraint, voltage and flux restraints, the inductance based method and pattern recognition using artificial intelligence, wavelet transform and hybrid technique. As shown in this paper each approach has its advantages and disadvantages. The choice of the protection approach used is mainly depending on the rating of transformer, application and detection time.

References

[1] *IEEE Guide for Protecting Power Transformers*, IEEE Power Engineering Society. 30 May, 2008.

[2] Badri Ram, D. N. Vishwakarma: *Power System Protection and Switchgear*. 1 Oct., 1994.

[3] M. A. Rahman: *Advancements in Digital Protection of Power Transformers*. In: Proceedings of International Power and Energy Conference, PECon '06, IEEE, 2006, p. 1 – 6.

[4] Blume L. F.:*Transformer Engineering*. Wiley & Sons, New York,1951.

[5] Karsai K., Kerenyi D. and Kiss L.: *Large Power Transformers*. Elsevier, New York, 1987.

[6] J. F. Witte, F. P. De Cesaro and S. R. Mendis: *Damaging Long-Term Overvoltages on Industrial Capacitor Banks due to Transformer Energization Inrush Currents*. In: IEEE Transactions on Industry Applications, Vol. 30, July – August 1994, p. 1107 – 1115.

[7] P. L. Mao and R. K. Aggarwal: *A Novel Approach to the Classification of the Transient Phenomena in Power Transformer Using Combined Wavelet Transform and Neural Network*. In: IEEE Transactions on Power Delivery, vol.16, Oct.2001, p. 654-660.

[8] Rich Hunt, Joe Schaefer and Bob Bentert: *Practical Experience in Setting Transformer Differential Inrush Restraint*. In: Proceedings of Annual Conference for Protective Relay Engineers, 1-3 April, 2008, p. 118 – 141.

[9] D. B. Fakruddin, K. Parthasarathy, B. W. Hogg and L. Jenkins: *Application of Haar Functions for Transmission Line and Transformer Differential Protection*. In: Electrical Power & Energy Systems, Vol. 6, July 1984, p. 169 – 180.

[10] S. R. Kolla: *Application of Block Pulse Functions for Digital Protection of Power Transformers*. In: IEEE Transactions on Electromagnetic Compatibility, Vol. 31, May 1989, p. 193 196.

[11] R. Bouderbala, H. Bentarzi and A. Ouadi: *Digital Differential Relay Reliability Enhancement of Power Transformer*. In: International Journal of Circuits, Systems and Signal Processing, Vol. 5, 2011, p. 263 - 270.

[12] Raju, K. Ramamohan Reddy, and M.Tech: *Differential Relay Reliability Implement Enhancement of Power Transformer*. In: International Journal of Modern Engineering Research (IJMER), Vol. 2, Sep-Oct, 2012, p. 3612 - 3618.

[13] Kaihua Tian and Pei Liu: *Improved Operation of Differential Protection of Power Transformers for Internal Faults Based on Negative Sequence Power*. In: Proceedings of International Conference on Energy Management and Power Delivery, EMPD '98, 1998, p. 422 – 425.

[14] Hao Zhang, Pei Liu and O.P. Malik: *A New Scheme for Inrush Identification in Transformer Protection*. In: Electric Power Systems Research 63, 2002, p. 81-86.

[15] M. Sanaye-Pasand, M. Zangiabadi and A.R. Fereidunian: *An Extended Magnetizing Inrush Restraint Method Applied to Digital Differential Relays for Transformer Protection*. In: IEEE Power Engineering Society General Meeting, 2003, p. 2077 - 2082.

[16] M.E. Hamedani Golshan, M. Saghaian-nejad, and A. Saha, H. Samet: *A New Method for Recognizing Internal Faults from Inrush Current Conditions in Digital Differential Protection of Power Transformers*. In: Electric Power Systems Research 71, 2004, p. 61-71.

[17] Adel Aktaibi and M. A. Rahman: *A Software Design Technique for Differential Protection of Power Transformers*. In: International Electric Machines & Drives Conference (IEMDC), IEEE, 2011, p. 1456 – 1461.

[18] S. R. Wagh, Shantanu Kumar and Victor Sreeram: *Extraction of DC component and Harmonic Analysis for Protection of Power Transformer*. In: IEEE 8th Conference on Industrial Electronics and Applications (ICIEA), 2013, p. 32 – 37.

[19] Michel Habib and Miguel A. Marin: *A Comparative Analysis of Digital Relaying Algorithms for the Differential Protection of Three Phase Transformers*. In: IEEE Transactions on Power Systems, Vol. 3, August 1988, p. 1378 - 1384.

[20] J.S. Thorp, A.G. Phadke: *A Microprocessor Based Voltage-Restrained Three-Phase Transformer Differential Relay*. In: Proceedings of the South Eastern Symposium on systems Theory Conference, April 1982, p. 312 -316.

[21] J.S. Thorp, A.G. Phadke: *A New Computer Based, Flux Restrained, Current Differential Relay for Power Transformer Protection*. In: IEEE Transaction on power apparatus and Systems, Vol. PAS-102, November 1983, p. 3624 - 3629.

[22] Xu Yan, Wang Zengping, Liu Qing and Shang Guocai: *A Novel Transformer Protection Method Based on The Ratio of Voltage and Fluxional Differential Current*. In: IEEE Transmission and Distribution Conference and Exposition, 2003, p. 342 – 347.

[23] Ge Baoming, Aníbal T. de Almeida, Zheng Qionglin, and Wang Xiangheng*: An Equivalent Instantaneous Inductance-Based Technique for Discrimination Between Inrush Current and Internal Faults in Power Transformers*. In: IEEE Transaction on Power Delivery, Vol. 20, Oct. 2005, p. 2473-2482.

[24] D. Q. Bi, X. H. Wang, W. X. Liang, W. J. Wang: *A Ratio Variation of Equivalent Instantaneous Inductance Based Method to Identify Magnetizing Inrush in Transformers*. In: Proceedings of Eighth International Conference on Electrical Machines and Systems, 29 Sept. 2005, p. 1775 – 1779.

[25] D. Q. Bi, S. S. Li, X. H. Wang and W. J. Wang: *A Novel Double-side Average Equivalent Instantaneous Inductance in Nonsaturation Zone Based Transformer*

Protection. In: Proceedings of the International Conf. on Electrical Machines and Systems, Oct. 2008, p. 4364 – 4369.

[26] K. Inagaki, M. Higaki, Y. Matsui, K. Kurita, M. Suzuki, K. Yoshida, and T. Maeda: *Digital Protection Method for Power Transformers Based on An Equivalent Circuit Composed of Inverse Inductance*. In: IEEE Transaction on Power Delivery, Vol. 3, Oct. 1988, p. 1501-1510.

[27] Z. P. Wang, Y.Xu and Q. X Yang: *A Novel Transformer Protection Principle Based on The Change of Inductances*. In: Proceedings of the Eighth IEE International Conference on Developments in Power System Protection, Amsterdam, Netherlands, April 2004, p. 356-359.

[28] H. Abniki, H. Monsef, P. Khajavi, and H. Dashti: *A Novel Inductance-Based Technique for Discrimination of Internal Faults from Magnetizing Inrush Currents in Power Transformers*. In: Modern Electric Power Systems, 2010, p. 1 – 6.

[29] ManojTripathy: *Power Transformer Differential Protection Using Neural Network Principal Component Analysis and Radial Basis Function Neural Network*. In: Simulation Modeling Practice and Theory 18, 2010, p. 600-611.

[30] M.R. Zaman and M.A. Rahman,: *Experimental Testing of The Artificial Neural Network Based Protection of Power Transformers*. In: IEEE Transaction on Power Delivery, Vol. 13, April 1998, p. 510 - 518.

[31] Yu-Ping Lu, L. L. Lai and Li-Dan Hua: *New Artificial Neural Network Based Magnetizing Inrush Detection in Digital Differential Protection for Large Transformer*. In: Proceedings of Fourth International Conference on Machine Learning and Cybernetics, Guangzhou, August 2005, p. 441 – 447.

[32] Manoj -Tripathy, Rudra Prakash Maheshwari and H. K. Verma: *Power Transformer Differential Protection Based on Optimal Probabilistic Neural Network*. In: IEEE transaction on power delivery, Vol. 25, January 2010, p. 102 - 112.

[33] M. Nagpal, M. S. Sachdev, Kao Ning and L.M. Wcdcphol: *Using a Neural Network for Transformer Protection*. In: Proceedings of International Conference on Energy Management and Power Delivery, EMPD '95, 1995, p. 674 – 679.

[34] A. L. Orille, Nabil Khalil, and J.A. Valencia: *A Transformer Differential Protection Based on Finite Impulse Response Artificial Neural Network*. In: Computers & Industrial Engineering 37, 1999, p. 399-402.

[35] Masoud Ahmadipoura and Z. Moraveja: *A New Approach in Power Transformer Differential Protection*. In: International Journal of Current Engineering and Technology, Vol.3, March 2013, p. 46 - 57.

[36] Andrzej Wiszniewsli and Bogdan Kasztenny: *A Multi-Criteria Differential Transformer Relay Based on Fuzzy Logic*. In: IEEE Transactions on Power Delivery, Vol. 10, October 1995, p. 1786 - 1792.

[37] Iman Sepehri Rad, Mostafa Alinezhad, Seyed Esmaeel Naghibi and Mehrdad Ahmadi Kamarposhti: *Detection of Internal Fault in Differential Transformer Protection Based on Fuzzy Method*. In: International Journal of the Physical Sciences, Vol. 6, 30 October 2011, p. 6150-6158.

[38] Myong-Chul Shin, Chul-Won Park and Jong-Hyung Kim: *Fuzzy logic-based Relaying for Large Power Transformer Protection*. In: IEEE Transactions on Power Delivery, Vol. 18, July 2003, p. 718 – 724.

[39] F. Zhalefar and M. Sanaye-Pasand: *A New Fuzzy-Logic-Based Extended Blocking Scheme for Differential Protection of Power Transformers*. In: Electric Power Components and Systems, 2010, p. 675–694.

[40] Daniel Barbosa, Ulisses Chemin Netto, Denis Vinicius Coury and Mário Oleskovicz: *Power Transformer Differential Protection Based on Clarke's Transform and Fuzzy Systems*. In: IEEE Transactions on Power Delivery, Vol. 26, April 2011, p. 1212 - 1220.

[41] M. Haris, M. Salik, A. A. Safdar and U. Rashid: *Improved Fuzzy Logics Based Differential Protection Scheme*. In: Proceedings of IEEE 7th International Power Engineering and Optimization Conference, 3-4 June 2013, p. 261 – 266.

[42] D. Bejmert, W. Rebizant and L. Schiel: *Transformer Differential Protection with Fuzzy Logic Based Inrush Stabilization*. In: International Journal of Electrical Power and Energy Systems 63, 2014, p. 51 – 63.

[43] K. Ramesh and M.Sushama: *Incipient Fault Detection in Power Transformer Using Fuzzy Technique*. In: Journal of Electrical Engineering, Vol. 15, 2015, p. 1 – 6.

[44] Moisés Gómez-Morante and Denise W. Nicoletti: *A Wavelet-based Differential Transformer Protection*. In: IEEE Transactions on Power Delivery, Vol. 14, Oct. 1999, p. 1351 - 1358.

[45] M. M. Eissa: *A Novel Digital Directional Transformer Protection Technique Based on Wavelet Packet*. In: IEEE Transactions on Power Delivery, Vol. 20, July 2005, p. 1830-1836.

[46] B. Vahidi, N. Ghaffarzadeh, and S. H. Hosseinian: *A Wavelet-based Method to Discriminate Internal Faults from Inrush Currents Using Correlation Coefficient*. In: Electrical Power and Energy Systems 32, 2010, p. 788-793.

[47] M. Rasoulpoor and M. Banejad: *A Correlation Based Method for Discrimination Between Inrush and Short Circuit Currents in Differential Protection of Power Transformer Using Discrete Wavelet Transform: Theory, Simulation and Experimental Validation*. In: Electrical Power and Energy Systems 51, 2013, p. 168-177.

[48] A. A. HossamEldin and M.A. Refaey: *A Novel Algorithm for Discrimination Between Inrush Current and Internal Faults in Power Transformer Differential Protection Based on Discrete Wavelet Transform*. In: Electric Power Systems Research 81, 2011, p. 19-24.

[49] Bahram Noshad, Morteza Razaz and Seyed Ghodratollah Seifossadat: *A New Algorithm Based on Clarke's Transform and Discrete Wavelet Transform*

for the Differential Protection of Three-phase Power Transformers Considering the Ultra-saturation Phenomenon. In: Electric Power Systems Research 110, 2014, p. 9 – 24.

[50] Mario Orlando Oliveira, Arturo Suman Bretas and Gustavo Dornelles Ferreira: *Adaptive Differential Protection of Three-phase Power Transformers Based on Transient Signal Analysis*. In: Electrical Power and Energy Systems 57, 2014, p. 366–374.

[51] S. A. Saleh and M. A. Rahman: *Off-line Testing of a Wavelet Packet-Based Algorithm for Discriminating Inrush Current in Three-phase Power Transformers*. In: Proceedings of Large Engineering Systems Conference on Power Engineering, 2003, p. 38-42.

[52] S. A. Saleh and M. A. Rahman: *Testing of a Wavelet-Packet-Transform-Based Differential Protection for Resistance-Grounded Three-Phase Transformers*. In: IEEE Transactions on Industry Applications, Vol. 46, May/June 2010, p.1109-1117.

[53] S. A. Saleh, Benjamin Scaplen and M. A. Rahman: *A New Implementation Method of Wavelet Packet Transform Differential Protection for Power Transformers*. In: IEEE Transactions on Industry Applications, Vol. 47, March – April 2011, p. 1003-1012.

[54] S. A. Saleh, A. Aktaibi, R. Ahshan and M. A.Rahman: *The Development of a d – q Axis WPT-Based Digital Protection for Power Transformers*. In: IEEE Transactions on Power Delivery, Vol. 27, October 2012, p. 2255 - 2269.

[55] Adel Aktaibi, M. A. Rahman and Azziddin M. Razali: *An Experimental Implementation of d-q axis Wavelet Packet Transform Hybrid Technique for 3ϕ Power Transformer Protection*. Industry IEEE Transactions on Industry Applications, Vol. 50, July – August 2014, p. 2919 - 2927.

[56] H. Khorashadi-Zadeh: *Fuzzy-neuro approach to differential protection for power transformer*. In: Proceedings of IEEE Region 10 Annual International Conference, 21-24 Nov. 2004, p. 279 – 282.

[57] H. Khorashadi-Zadeh and M.R. Aghaeb Rahimi: *A Neuro-Fuzzy Technique for Discrimination between Internal Faults and Magnetizing Inrush Currents in Transformers*. Iranian Journal of Fuzzy Systems, Vol. 2, 2005, p. 45 – 57.

[58] A. Esmaeilian, M. Mohseninezhad, M. Khanabadi and M. Doostizadeh: *A novel technique to identify inrush current based on adaptive neuro fuzzy*. In: Proceedings of10th International Conference on Environment and Electrical Engineering, 8-11 May 2011, p. 1 – 4.

[59] D. Barbosa, D.V. Couryand M. Oleskovicz: *New approach for Power Transformer Protection Based on Intelligent Hybrid Systems.* In: IET Generation, Transmission and Distribution, Vol. 6, 2012, p. 1009–1018.

[60] H. Khorashadi-Zadeh and M. Sanaye-Pasand: *Power Transformer Differential Protection Scheme Based on Wavelet Transform and Artificial Neural Network Algorithms*. In: Proceedings of 39th International Universities Power Engineering Conference, 2004, vol. 1, p. 747 – 752.

[61] M. Geethanjali, S. Mary Raja Slochanal and R.Bhavani: *A Novel Approach for Power Transformer Protection Based upon Combined Wavelet Transform and Neural Networks (WNN)*. In: Proceedings of 7th International Power Engineering Conference, 29 Nov. – 2 Dec. 2005, p. 1571 – 1576.

[62] Peilin L. Mao and Raj K. Aggarwal: *A Novel Approach to the Classification of the Transient Phenomena in Power Transformers Using Combined Wavelet Transform and Neural Network*. In: IEEE Transactions on Power Delivery, Vol. 16, October 2001, p. 654 – 660.

[63] Manoj Tripathy, Rudra Prakash Maheshwari and Neha Nirala: *Transformer Differential Protection Based on Wavelet and Neural Network*. In: International Journal of Electronic and Electrical Engineering, Vol. 7, 2014, p. 685 – 695.

[64] S. Sendilkumar, B. L. Mathur, and Joseph Henry: *Differential Protection for Power Transformer Using Wavelet Transform and PNN*. In: World Academy of Science, Engineering and Technology, Vol. 4, 2010, p. 643 – 649.

[65] Okan Ozgonenel and Serap Karagol: *Transformer Differential Protection Using Wavelet Transform*. In: Electric Power Systems Research 114, 2014, p. 60–67.

[66] Samah El Safty, Samia Gharieb, Abd El LatifBadr and Mohamed Mansour: *A Wavelet Fuzzy Expert Technique for Classification of Power Transformer Transients*. In: Proceedings of International Conference on power system technology, 2006, p. 1-5.

[67] K. Ramesh and M.Sushama : *Power Transformer Protection Using Wavelet based Fuzzy Logic*. In: Journal of Electrical Engineering, Vol. 14, 2014, p. 1 – 8.

[68] H. Monsef and S. Lotfifard: *Internal Fault Current Identification Based on Wavelet Transform in Power Transformers*. In: Electric Power Systems Research 77, 2007, p. 1637–1645.

[69] T. S. Sidhu, M. S. Sachdev, H. C. Wood, and M. Nagpal: *Design, Implementation, and Testing of A Micro-processor Based High Speed Relay for Detecting Transformer Winding Faults*. In: IEEE Transactions on Power Delivery, Vol. 7, Jan. 1992, p. 108-117.

[70] H. Zhang, J. F .Wen, P. Liu, and O. P. Malik: *Discrimination between Fault and Magnetizing Inrush Current in Transformer Using Short-time Correlation Transform.* In: Electric Power Energy System, Vol. 24, Oct. 2002, p. 557–562.