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A TRENDS OF DIFFERENTIAL PROTECTION UTILIZED FOR POWER TRANSFORMERS: A REVIEW

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ABSTRACT

In the power systems, the power transformers are vital device as they are utilized for conversion of voltage at different levels. The differential Protection is the unit type and one of the main protections of power transformers. In the literature, the invention and modification have been performed in the differential Protection to overcome the various problem, such as a false operation due to magnetizing current and heavy external fault. In this paper, the trend of differential protection from conventional to latest advancement is extensively discussed. Initially, the conventional differential protections are described with their limitations. Subsequently, the advanced differential scheme based on wide area measurement, wavelet, artificial methods and Parks vector. This paper can be useful to the researchers, industrialist and academician involved in the differential protection of transformers for selecting the suitable version of differential protection and future research.

Keywords: Power transformer, Differential protection, Magnetizing current, Internal fault, External fault.

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INTRODUCTION

The power transformer is an utmost important device of the latest power system. For continues and reliable power supply from generation to distribution, power transformers play important role. Therefore, it is essential to restrict the possible impairment of the power transformer for continuity of power supply. Furthermore, the repairing, installing and replacing of transformers are also costly and time consuming. So, it is natural to provide a more focus on the protective relay of the power transformer. However, dependability, stability, and speed of operation are major required concerns associated to protective relays.

The differential protection is one of the momentous protections. It is normally employed for the protection of medium as well as large size power transformer. In this method, the entering and leaving currents at both the end of the power transformer have been compared and observed a differential unstable current. If the magnitude of differential unstable current is higher than the no-load current gain, it shows that an internal fault has been occurred in power transformer. During the switching of the power transformer, high magnetizing inrush current flows and its magnitude is about ten times to the full load current [1]. Because of high current, the relay may get the operating signals. In addition, some times in case of heavy external fault, relay may false trip due to unequal saturation characteristic of Current Transformers (CTs) used in differential protection. To restrict the malfunction of the relay, the differentiation between magnetizing inrush and internal fault condition as well as internal and external faults are necessary [2].

In the literature, to overcome this problem, a range of solution has been presented by the researchers. In this paper, these proposed modified solution for avoiding the false tripping of differential protection are discussed. These efforts facilitate to the researchers and practitioners involved in power system protection to find the appropriate literature for testing and future research of differential protection.

In the Section II, basic methods of differential protection are described. Section III presents the various solution for solving the issues related to differential protection. The substantial discussions on these proposed solutions are given in Section IV. Finally, the conclusion of the review is presented in Section V.

II. BASIC DIFFERENTIAL PROTECTIONS

The differential protection relay is functioning on the principle of quantities comparisons fed from CTs connected at both the end of protected equipment [3]. The differential protection relay is a usually unit type protection and it is necessary that relay responds only to the internal faults and remain stable against external fault, overload and inrush current. The protected zone is determined by the current transformer or voltage transformer location. The vector difference is accomplished by the proper connectivity of the CTs or VTs secondaries [4]. The differential relay is generally employed for the power transformer having the rating more than 2 MVA.

A. Merz-Prize Differential Protection

Figure 1 illustrates the fundamental concept of circulating current differential protection, which can be explained using Kirchhoff's current law. This protection scheme compares the currents entering and leaving the protected zone. If these currents are not equal, it indicates that an additional branch has been created, and the current corresponding to the difference flows through this branch, signifying a fault. This fault current is then passed through a relay, which detects the imbalance and triggers its operation. Under normal conditions or in the case of an external fault, the currents entering and leaving the protected winding will have the same magnitude and phase relationship. Consequently, the secondary currents of the current transformers (CTs), denoted as i1 and i2, will be equal at all times. In this case, the differential current (i1 - i2) flowing through the relay will be zero, and the relay will not operate. However, in the event of an internal fault (such as at point F2), the balance between the currents I1 and I2 is disrupted, resulting in $I1 \neq I2$. Therefore, $i1 \neq i2$, and the differential or spill current (i1 - i2) flows through the relay, causing it to trip. Proper CT polarity is crucial for accurate operation, as incorrect CT connections can result in the sum of the currents i1 and i2 flowing through the relay, leading to erroneous operation [5, 6].

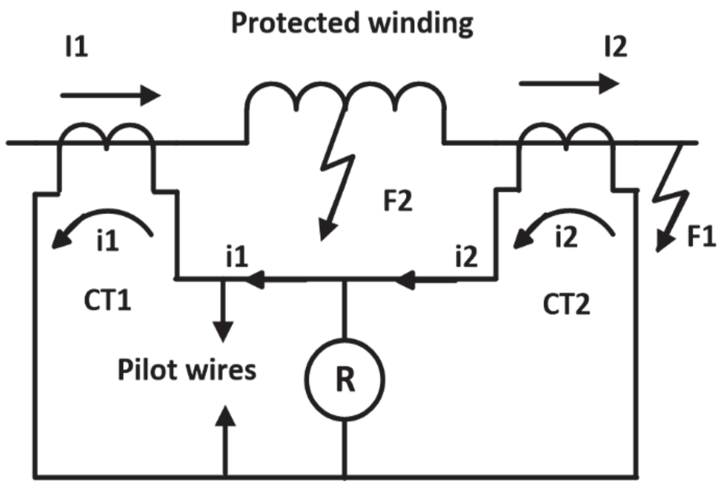

FIGURE 1 MERZ-PRIZE DIFFERENTIAL PROTECTION

B. Biased or Percentage Differential Protection

In the event of a heavy external fault, CT ratio errors can occur due to the different saturation characteristics of the CTs and unequal DC offset components. This can result in a spill current even when the primary currents are equal. If this spill current exceeds the relay's set threshold, it could cause an unwanted relay operation. To prevent this, as shown in Figure 2, a biased restraining coil is often incorporated into the differential protection scheme. A biased differential relay includes two coils: Restraining Coil (Bias Coil): This coil provides restraint to prevent unnecessary relay operation. Operating Coil: This coil activates the relay when a fault condition is detected. The relay also has two settings: Basic Setting (Sensitivity Setting): This is the minimum current through the operating coil required to activate the relay. It is typically expressed as a percentage of the relay's rated current, and the operating quantity is α (i1 - i2), where i1 and i2 are the secondary currents of the CTs. Biased Setting: This is the ratio of the minimum operating coil current needed for relay operation to the average restraining current, expressed as α (i1 + i2)/2. If the pick-up ratio $\frac{(i1-i2)}{(i1+i2)/2}$ for a given situation exceeds the preset value, the relay will trip. This biasing mechanism ensures stability during external faults, helping to prevent false tripping by balancing the restraining and operating forces [5-7].

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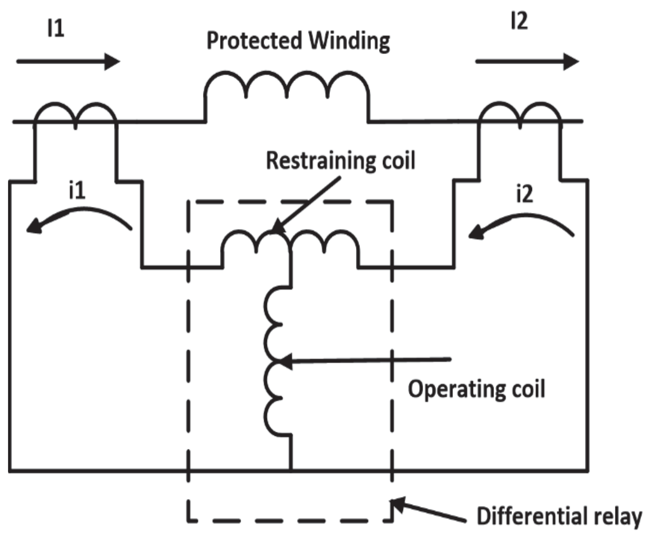

FIGURE 2 BIASED DIFFERENTIAL PROTECTION

C. Harmonic Restraint Differential Protection

While energizing the transformer, large magnitude magnetizing inrush current flows through the primary winding causing dissimilar output from both CTs and ultimately results in unwanted operation of relay [1]. This problem can be solved by providing (1) the larger current setting of the relay (more than inrush current), (2) larger time setting up to subsiding the inrush phenomenon and (3) the integration of harmonic restraint circuit. The first and second solutions cannot be applicable for the transformers used in extremely high voltage systems. The third solution is basically developed based on unlike characteristics of magnetizing inrush and fault currents. The magnetizing inrush current has a high component of harmonics (mainly 63 % of second harmonics and 26.8% of third harmonics), whereas it is negligible in case of fault current [6]. Therefore, during the event of inrush, the harmonic components are filtered from current flowing through the operating coil and included in restraining coil. Thus, differential protection with harmonic restraint is unresponsive to the magnetizing inrush and sensitive to the fault current [4-7].

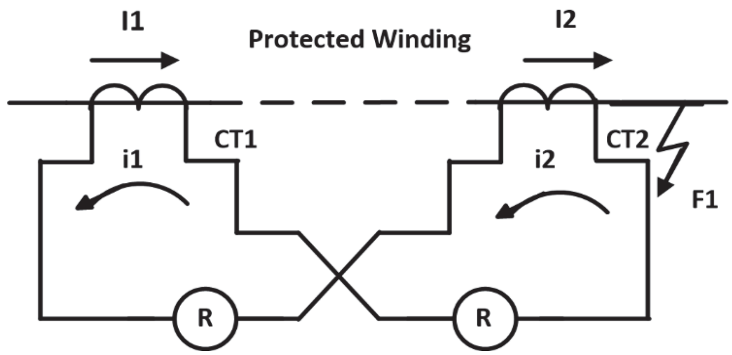

FIGURE 3 BALANCED VOLTAGE DIFFERENTIAL PROTECTION

D. Balanced Voltage Differential Protection

Figure 3 demonstrates the working principle of balanced voltage differential protection. In this system, the secondary windings of the current transformers (CTs) are connected in such a way that, under normal operating conditions and during external faults, the secondary currents from the CTs on both sides oppose each other, resulting in balanced voltages.However, in the event of an internal fault, this balance is disturbed, and a current proportional to (i1 + i2)/2 flows through the relay coils at each end, causing the relay to operate.To prevent issues like core saturation and overvoltage, the CTs used in this type of protection typically have air-gap cores. This design ensures that the core remains unsaturated and no overvoltage is generated when there is zero secondary current under normal working conditions [5].

E. Challenges Of Conventional Differential Protections

The problems associated with above discussed different schemes of differential protection are as follows [1-7].

1. The Circulating current differential protection is susceptible to errors during heavy external faults. It struggles to differentiate between the high magnetizing inrush currents, which occur when equipment like transformers are energized, and actual fault currents. As a result, this can lead to mis-operations or false tripping since the protection system may interpret magnetizing inrush currents as fault conditions, even though no fault is present within the protected zone.

2. The bias differential protection can provide the somehow better performance against the heavy external fault. However, this protection in its simple form can be operative in case of magnetizing inrush.

3. In the balanced voltage differential protection, because current does not flow through the CTs, they act as open circuit and provide the high impedance. Also, the turn ration of power transformer greatly affects to the operation of this protection scheme.

4. The harmonic restraint based differential protection may fail in case of internal fault with larger harmonics. This condition can be arisen due to an arc and saturation of CTs.

III. ADVANCED DIFFERENTIAL PROTECTION SCHEMES

Due to better capability to differentiate between external and internal fault as well as fault and magnetizing inrush, the harmonic restraint based differential protection gain more popularity compared to other conventional differential protections. However, due to improvement in core steel, the harmonic components are significantly reduced and cause the difficulties to extricate the inrush and fault. the Therefore, various modification adopted in differential protection for strengthen the differential protection are proposed in the literature which are discussed as follows.

A. Wide-Area Based Differential Protection Scheme

The current differential relay operates by detecting imbalances in the current flow within a defined protection zone. The power grid is divided into differential protection zones, comprising both primary and backup protection zones. An expert system, integrated with a Supervisory Control and Data Acquisition (SCADA) system, is used to define and manage these differential protection zones [8]. With advances in information technology, synchronization of numerical current differential protection systems with Global Positioning System (GPS) is now possible. This allows for precise coordination of protection systems using various communication media [9].

The backup protection system operates on a larger scale, incorporating new types of differential fault detection rings and Real-Time Digital Simulators (RTDs) that run on relay locations to emulate fault conditions [10]. All relay agents within the same protection zone are connected, enabling communication across the network. If a fault occurs in any security zone, it can be detected using current differential protection in both the primary and backup zones. Fault identification and tripping within a protection zone are managed independently by the differential relay. Backup protection systems monitor the primary relay to prevent false tripping due to local issues, such as Current Transformer (CT) errors [8].

B. Wavelet Based Differential Protection Scheme

The Wavelet Packet Transform (WPT)-based differential relay can be implemented using a digital signal processing (DSP) board, which handles the required discrete filtering functions [11]. This system is capable of distinguishing between magnetizing current, normal load current, and internal fault currents under various loading conditions [12]. The proposed algorithm offers several advantages, including reduced computational load, faster processing speed, high reliability, lower memory requirements, and increased accuracy. WPT is a relatively new development in power system protection, and the algorithm efficiently identifies magnetizing current, enhancing the relay's performance in detecting high magnetizing inrush currents [13]. The algorithm uses filters to extract second-level high-frequency components present in 3-phase differential currents. This extraction is essential for capturing transients in power transformers. The key benefits of this approach include low cost, accurate identification, and fast response times. The WPT-based differential protective relay, which employs a Butterworth passive filter, can operate effectively in both offline and online modes. It responds within half a cycle, ensuring quick and accurate fault detection [11].

Differential protection for large power transformers is typically based on the circulating current principle. In this method, the primary and secondary currents are converted and compared on a common reference base. Under normal operating conditions or during external faults, the difference between these currents is small. However, during external faults, the current difference is slightly larger compared to normal operation. The main advantages of digital relaying the term of the economics, dependability, and adaptability, significant endeavors have made to the development of digital relaying algorithms [14, 15]. The basic function is spread over low frequency and is compressed to high frequency so that the user to acquire low-frequency elements of large window signal, while a smaller window reflects discontinuities [16]. In the [17], the use of wavelet transform has been provide analysis the instantaneous magnetizing current of the experimental three phase transformer and to recognize fault conditions with the selection of four types wavelet transformer. This method utilizes the wavelet transform to distinguish internal faults from inrush currents. The proposed algorithm can identify fault currents within less than half a cycle. Its key advantages are high speed and accuracy. Additionally, the algorithm can aggregate offline data from a prototype 3-phase power transformer in the lab [18]. This application wavelet transforms, analysis of the power systems includes fault detection, data compression and identification of electromagnetic transients [19].

The development of two indices and an algorithm based on the discrete wavelet transform (DWT) enhances the ability to differentiate between internal faults and magnetizing inrush currents in the digital differential protection of power transformers. This advanced technical solution provides a simple and robust scheme, relying on the analysis of 3-phase differential currents using the discrete wavelet transform (DWT) [20]. Many transformer protection techniques employ the 2nd harmonic method to distinguish between internal faults and high inrush currents. Typically, the magnitude of this harmonic is greater during inrush conditions compared to internal faults or normal currents [21, 22]. The main sources of inrush current harmonics are the nonlinear behavior of the transformer core, overexcitation due to dynamic overvoltage situations, and transformer switching, which can mitigate issues related to new content [23].

The new technique of the Neuro-wavelet is introduced for the power transformer protection [24]. This feature is derived from the development of the first energy sources, second energy sources and third energy sources, which come from the differential current signal and the discrete wavelet transform [25]. The other features in addition to wavelet multiplication, root mean squares and restraining current as well as second harmonics and fifth harmonics, percent differential currents at were applied. The cascade artificial neural network, combined with an entropy approach, effectively selected vectors for Neuro-wavelet-based identification of transformer inrush currents and internal fault currents. The present method alone can be put as a separate protection plan or can be applied as a developer to present protection system [24].

C. Artificial Neural Network Based Differential Protection Scheme

The aim in this work is comparable in both artificial neural network architectures related to the accuracy of preparing techniques and responses. This an ANN approach is also introduced for improving the current signals. The different types of architectures were assessed and special training techniques are this work achieve best artificial neural network configurations obtained. The difference between the Multi-Layer Perceptron (MLP) and Radial Basis Function (RBF) algorithms was examined in the ANN study and many artificial neural network designs were shown to be the use of this problem [26]. The differential current is compared with a threshold, and if an internal fault is detected, the transformer is disconnected from the rest of the system. However, simply identifying differential current is not enough to distinguish internal faults from other conditions that may produce similar currents. A conventionally used approach to the identities of the internal faults as well as opposition to the inrush high currents is the aforementioned differential logic with the current restraint [27].

The transformer protection is a build extent of the testing to locate the faster and effective differential relay algorithm that minimizes the damage to the transformer the rest of the system. The ANN prepared by GA gives more exact results than by BP algorithm. The same method to connect the artificial neural network and genetic algorithm apply a genetic algorithm to select optimal values for the artificial neural network parameters equal to learning rate and velocity [28].

D. Fuzzy Logic Based Differential Protection Scheme

The progress of another algorithm better the protection, implementation by using the fuzzy logic scheme. The power transformer is part of an electrical device that requires constant observation and protection as it is very costly and is a basic element of a power system to perform effectively. Fuzzy reasoning technique employs new multi-criteria stabilizing algorithms for better segregation of inrush current. The protection algorithm is tested with true information, give to be solid and significantly more sensitivity than excellence algorithms with conventional criteria and chips settings [29]. In fuzzy logic based on the conventional second harmonics restraint stabilizing technique may lead to both mal-operation below internal fault and mal-operation during the transformer energisation. It has been shown that if the proposed tuned correctly tends to increase the digital relay sensitivity and capacity of choice and traditionally reduce the problems associated with the schemes. The traditional approach to mitigating these issues involves applying the percentage differential characteristic along with second and fifth harmonic restraints to address inrush current and over-excitation conditions [30]. Additionally, fuzzy logic can be integrated with the conventional dissolved gas analysis method for more effective fault detection and decision-making. The better results in the papers have been reported compared to traditional methods of finding a power transformer error [31, 32].

E. Parks Vector Based On Differential Protection Scheme

The Parks vector approach is an advanced method for power transformer protection, focusing on analyzing the harmonic content of the differential current through Parks vector modules. This technique is adept at detecting turn-to-turn insulation winding failures and differentiating them from magnetizing inrush currents. While this method offers improved fault detection, it is less economical compared to traditional protection schemes, as it does not significantly reduce the primary cost of protecting the power transformer. Traditional differential protection relays, which have been in use for a long time, often face issues with mal-operation due to transformer inrush currents. These inrush currents can lead to transient changes in the transformer's magnetic flux [33]. To address these challenges, the harmonic current steady principle was introduced to help differentiate between transient conditions and internal faults. Modern transformers, with improved core materials, generally exhibit lower second-order harmonic components in magnetizing currents. However, second-order harmonics can still appear during internal faults. The development of the Parks vector approach is crucial for enhancing the sensitivity of differential relays to inter-turn winding faults, particularly by overcoming the limitations associated with second harmonic components. This method involves a detailed examination of the spectral content of Parks vector modules to improve fault detection capabilities [34].

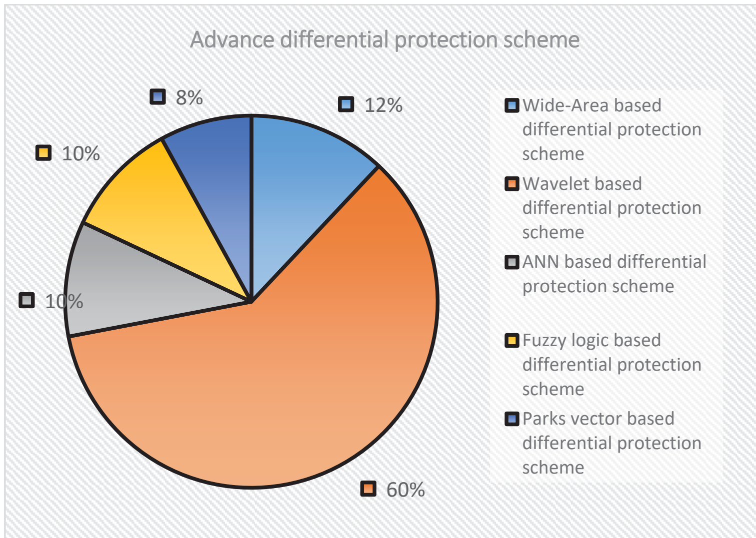

FIGURE 4. ADNANCED DIFFERENTIAL PROTECTION SCHEME

TABLE 1- TYPES OF IMPROVED DIFFERENTIAL PROTECTION

Sr. No.	**Different types of differential protection**	**Remarks**
1	Wide-Area Based Differential Protection Scheme [35]	• The wide-area differential protection is both fast and effective, making it well-suited for industrial power systems. • The algorithm is improved the performance and increase the load angle.
2	Wavelet Based Differential Protection Scheme [11, 24]	• The wavelet packet transformer is better signal representation. • The relay provide a cost benefits, good detection and quick response.

		• This scheme provide good selectivity, high speed and high accuracy.
3	Artificial Neural Network Based Differential Protection Scheme [26]	• The scheme is more effective and easy to understand. • Fault detection accuracy very good. • Able to deal with a different of data condition
4	Fuzzy Logic Based Differential Protection Scheme [30]	• Capable of withstanding magnetizing inrush situations regardless of the second harmonic ratio of the power transformer. • Requires very little fault clearing time even under high currents during internal faults.
5	Parks Vector Based On Differential Protection Scheme [34]	• This system provides enhanced sensitivity for detecting early-stage turn-to-turn winding faults. • The result of the internal faults current transformer saturation in the results indicates enhanced sensitivity for the combination of stable performance and the ratio of the tap changer differences.

IV DISCUSSION

The various types of differential protections studied in this paper are separated according to the type of differential protection as graphically shown in Figure 4. As clearly seen in Figure 4, 64 % of the total reviewed paper are of wavelet based differential protection which are substantial higher than the other referred protections. Furthermore, some important remarks of these advanced differential protections are given in Table 1 and also discussed in following sub-sections.

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A. Wide-Area Based Differential Protection Scheme

In the wide-area differential protection scheme, the emulated relay will be replaced by a new digital signal processing system that incorporates the features of the emulated relay as its specifications. This new system will enhance the speed and effectiveness of wide-area differential protection, making it well-suited for industrial power systems.

B. Wavelet Based Differential Protection Scheme

The Wavelet Packet Transformer is very easy to implement and simple to code with a little amount of memory needed for storage and integration. The proposed algorithm is less computational weight, high dependability as well as little essential memory, high speed, and high accuracy. This application wavelet transforms, analysis of the power systems includes fault detection, data compression and identification of electromagnetic transients.

C. Artificial Neural Network Based Differential Protection Scheme

This an ANN approach is also introduced for improving current signals. The aim of this work is to compare both artificial neural network architectures related to the accuracy of preparing techniques and responses.

D. Fuzzy Logic Based Differential Protection Scheme

In fuzzy logic based on the conventional second harmonics, the restraint stabilizing technique may lead to both mal-operation under internal fault and mal-operation during the transformer energisation. The most important features in fuzzy logic are under the transformer energisation as well as improve performance with ultra-saturation impact and transformer energisation with Current transformer saturation followed by turn-to-turn faults.

E. Parks Vector Based On Differential Protection Scheme

The result of the internal faults current transformer saturation in the results indicates enhanced sensitivity for the combination of stable performance and the ratio of the tap changer differences. The evolution of this protection scheme is of Crucial importance to increase the susceptibility of the differential relay to identify the inter-turn winding fault and which can provide 2nd harmonic restraints drawback.

VI CONCLUSION

In this paper, the trends of differential protection for power transformers are presented. First, the conventional methods are explained. Also, the limitations of these protection schemes are given. Amongst, the harmonic restrained based differential protection are more widely used compared to other differential protections. Again, due to development of core material, the harmonic restraint-based protection is also facing the challenges in distinguishing the magnetizing inrush and fault. To overcome this difficulty, the advanced methods proposed in the previous literature are discussed.

In wide-area differential protection, both primary and backup protection are utilized. If primary protection fails, backup protection is available to ensure continued system reliability. This protection scheme is known for its speed and effectiveness, making it highly suitable for industrial power systems. A key feature of fuzzy logic in this context is its ability to handle transformer energization scenarios and improve performance during ultra-saturation impacts and current transformer saturation, particularly in the presence of turn-to-turn faults. The main advantages of this approach include high security, shorter fault clearing times, and increased sensitivity. Additionally, wavelet-based differential protection presents a novel approach for detecting inrush currents and internal fault currents. This method optimizes wavelet analysis to deliver robust performance under inrush conditions and enhance sensitivity for identifying internal faults.

In the literature, the wavelet based differential protection are found to be more prevalent among the advanced methods. This protection scheme can offer the better detection of fault and magnetizing inrush, great accuracy, higher speed and good selectivity.

REFERENCES

[1] A. C. Franklin and D. P. Franklin, *The J & P transformer book: a practical technology of the power transformer*: Elsevier, 2016.

[2] M. Tripathy, R. Maheshwari, and H. Verma, "Advances in transformer protection: a review," *Electric Power Components and Systems,* vol. 33, pp. 1203-1209, 2005.

[3] A. v. C. Warrington, *Protective Relays: Their Theory and Practice Volume One*: Springer Science & Business Media, 2012.

[4] S. Rao, "Swichgear Protection and Power Systems, 13th," ed: Khanna Publisher Delhi. 2009.

[5] N.-K. C. N. Bhuvanesh A Oza , Rashesh P Mehta,Vijay H Makwana, *POWER SYSTEM PROTECTION & SWITCHGEAR*: Tata McGraw-Hill Education, 2010.

[6] B. Bhalja and N. Chothani, *Protection and Switchgear*: Oxford university press, New Delhi, India, 2011.

[7] B. Ravindranath and M. Chander, *Power system protection and switchgear*: New Age International, 1977.

[8] S. Sheng, K. Li, W. Chan, X. Zeng, D. Shi, and X. Duan, "Adaptive agent-based wide-area current differential protection system," *IEEE Transactions on Industry Applications,* vol. 46, pp. 2111-2117, 2010.

[9] H. Li, E. Southern, P. Crossley, S. Potts, S. Pickering, B. Caunce, *et al.*, "A new type of differential feeder protection relay using the global positioning system for data synchronization," *IEEE Transactions on Power Delivery,* vol. 12, pp. 1090-1099, 1997.

[10] J. Tang, Y. Gong, N. Schulz, M. Steurer, and P. McLaren, "Implementation of a ship-wide area differential protection scheme," *IEEE Transactions on Industry Applications,* vol. 44, pp. 1864-1871, 2008.

[11] S. A. Saleh, B. Scaplen, and M. A. Rahman, "A new implementation method of wavelet-packet-transform differential protection for power transformers," *IEEE Transactions on Industry Applications,* vol. 47, pp. 1003-1012, 2011.

[12] S. Saleh and M. Rahman, "Real-time testing of a WPT-based protection algorithm for three-phase power transformers," in *Industry Applications Conference, 2004. 39th IAS Annual Meeting. Conference Record of the 2004 IEEE*, 2004, pp. 2430-2436.

[13] S. Saleh, C. Moloney, and M. A. Rahman, "Implementation of a dynamic voltage restorer system based on discrete wavelet transforms," *IEEE Transactions on Power Delivery,* vol. 23, pp. 2366-2375, 2008.

[14] M. Rahman and B. Jeyasurya, "A state-of-the-art review of transformer protection algorithms," *IEEE transactions on power delivery,* vol. 3, pp. 534-544, 1988.

[15] M. Habib and M. A. Marin, "A comparative analysis of digital relaying algorithms for the differential protection of three phase transformers," *IEEE Transactions on power systems,* vol. 3, pp. 1378-1384, 1988.

[16] M. Gomez-Morante and D. W. Nicoletti, "A wavelet-based differential transformer protection," *IEEE Transactions on Power Delivery,* vol. 14, pp. 1351-1358, 1999.

[17] O. Özgönenel, G. Önbilgin, and Ç. KOCAMAN, "Transformer protection using the wavelet transform," *Turkish Journal of Electrical Engineering & Computer Sciences,* vol. 13, pp. 119-136, 2005.

[18] H. Monsef and S. Lotfifard, "Internal fault current identification based on wavelet transform in power transformers," *Electric power systems research,* vol. 77, pp. 1637-1645, 2007.

[19] T. Lai, L. Snider, E. Lo, and D. Sutanto, "High-impedance fault detection using discrete wavelet transform and frequency range and RMS conversion," *IEEE Transactions on Power Delivery,* vol. 20, pp. 397-407, 2005.

[20] M. H. Zendehdel and M. Sanaye-Pasand, "Development of two indices based on discrete wavelet transform for transformer differential protection," *European Transactions on Electrical Power,* vol. 22, pp. 1078-1092, 2012.

[21] M. Zaman and M. Rahman, "Experimental testing of the artificial neural network based protection of power transformers," *IEEE Transactions on Power Delivery,* vol. 13, pp. 510-517, 1998.

[22] T. Sidhu, M. Sachdev, H. Wood, and M. Nagpal, "Design, implementation and testing of a microprocessor-based high-speed relay for detecting transformer winding faults," *IEEE Transactions on Power Delivery,* vol. 7, pp. 108-117, 1992.

[23] O. A. Youssef, "Discrimination between faults and magnetising inrush currents in transformers based on wavelet transforms," *Electric Power Systems Research,* vol. 63, pp. 87-94, 2002.

[24] O. Ozgonenel and S. Karagol, "Transformer differential protection using wavelet transform," *Electric Power Systems Research,* vol. 114, pp. 60-67, 2014.

[25] P. L. Mao and R. K. Aggarwal, "A novel approach to the classification of the transient phenomena in power transformers using combined wavelet transform and neural network," *IEEE Transactions on Power Delivery,* vol. 16, pp. 654-660, 2001.

[26] D. Coury and E. Segatto, "An alternative approach using artificial neural networks for power transformer protection," *European transactions on electrical power,* vol. 16, pp. 63-77, 2006.

[27] J. Pihler, B. Grcar, and D. Dolinar, "Improved operation of power transformer protection using artificial neural network," *IEEE transactions on power delivery,* vol. 12, pp. 1128-1136, 1997.

[28] H. Balaga, N. Gupta, and D. N. Vishwakarma, "GA trained parallel hidden layered ANN based differential protection of three phase power transformer," *International Journal of Electrical Power & Energy Systems,* vol. 67, pp. 286-297, 2015.

[29] D. Bejmert, W. Rebizant, and L. Schiel, "Transformer differential protection with fuzzy logic based inrush stabilization," *International Journal of Electrical Power & Energy Systems,* vol. 63, pp. 51-63, 2014.

[30] A. Wiszniewski and B. Kasztenny, "A multi-criteria differential transformer relay based on fuzzy logic," *IEEE Transactions on Power Delivery,* vol. 10, pp. 1786-1792, 1995.

[31] Y.-C. Huang, H.-T. Yang, and C.-L. Huang, "Developing a new transformer fault diagnosis system through evolutionary fuzzy logic," *IEEE Transactions on Power Delivery,* vol. 12, pp. 761-767, 1997.

[32] M.-C. Shin, C.-W. Park, and J.-H. Kim, "Fuzzy logic-based relaying for large power transformer protection," *IEEE transactions on Power Delivery,* vol. 18, pp. 718-724, 2003.

[33] A. Guzman, Z. Zocholl, G. Benmouyal, and H. J. Altuve, "A current-based solution for transformer differential protection. I. Problem statement," *IEEE Transactions on power delivery,* vol. 16, pp. 485-491, 2001.

[34] L. Oliveira, A. Cardoso, I. S. De Engenharia, U. Do Algarve, I. De Telecomunicacoes, U. O. Coimbra, *et al.*, "Extended Park's vector approach-based differential protection of three-phase power transformers," *IET electric power applications,* vol. 6, pp. 463-472, 2012.

[35] F. Namdari, S. Jamali, and P. Crossley, "Power differential based wide area protection," *Electric Power Systems Research,* vol. 77, pp. 1541-1551, 2007.