Identification Methods for Transformer Turn-to-Turn Faults and Inrush Current Based on Electrical Information

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Abstract—Power transformer is the most imperative and crucial equipment in electrical power system. Accurately monitoring the occurrence of transformer faults and rapidly isolating the faults are of great significance to ensure the reliability of power supply and avoid serious damage to the transformer. There are many methods used in the transformer to monitor transformer running state. This paper provides a comprehensive overview of transformer turn-to-turn fault and inrush current identification methods based on electrical information, and expounds the systematic research content that needs to be carried out for transformer turn-to-turn fault identification methods based on magnetic flux leakage information.

1. INTRODUCTION

Power transformer, which plays a key role in the power generation, transmission, and distribution, is a kind of significant power apparatus in power system. The reliability of power supply and system operation will be affected by transformer failure, which may cause serious economic losses [1].

As the end of 2017, the statistical number of transformers with voltage levels of 220kV and above in China is 15350, an increase of 3237 units from 2013, and the average annual growth rate in the past five years has reached 4.99% [2]. According to the statistics of China Electricity Council, the average annual failure rate of transformers of 220kV and above during the “Twelfth Five-Year Plan” period is 0.1766 times/100 units [3].

In order to prevent the expansion of transformer faults from causing more serious accidents, it is necessary to install various relay protection devices that meet the technical requirements according to the possible faults and abnormal operating conditions of the transformer.

Differential protection is usually necessary for transformer to be equipped with differential protection in view of phase-to-phase short-circuit of winding and lead-out wires, single-phase grounding short-circuit of winding and lead-out wires of large current grounding system and short-circuit between turns of winding. The differential protection principle is simple, and it also has rapid and sensitive performance, so it is widely used as the main protection of various equipment. Differential protection is based on KCL and is particularly suitable for generator, motor and line protection [4]. However, differential protection will produce a series of problems under the existing conditions.
Practical operation experience shows that the performance of transformer protection is still not comparable to that of line or bus protection [5].

A brief review of modern transformer fault records shows that transformer internal faults are the most common situation, and 70%-80% of transformer faults are turn-to-turn faults (TTFs). If the faults can be detected in time and corresponding measures are taken rapidly to isolate the faults, the greater losses can be avoided [6]. In addition, when the transformer is input in electric network or troubleshooting, large inrush current will be generated, which may result in misoperation of differential protection [7]. Therefore, the transformer protection needs to be able to quickly and accurately identify currents, which is the key to improving the protection performance, reducing transformer protection misoperation rate, and ensuring reliable operation of the power system. At present, many methods have been applied to the offline and online detection of transformer faults and the identification of inrush current. A summary of their content, advantages and disadvantages will help to selectively apply these methods to improve transformer protection performance.

This paper describes the main methods of transformer TTF identification based on electrical information, and then summarizes the research status of transformer inrush current identification. These methods help to find any faults in the transformer and indicate the severity to avoid any unprecedented faults. It also elaborates the identification method based on magnetic flux leakage information and the systematic research content that needs to be carried out, which will provide a fast, reliable and sensitive solution for the identification of TTF and inrush current.

2. OFF-LINE DETECTION METHOD FOR TTFs

For a long time, the detection of inter-turn insulation faults in engineering has mainly used traditional test offline methods including DC resistance test, short impedance test, turns ratio test, no-load test, induced voltage withstand test, frequency response test, insulation resistance measurement, absorption ratio measurement, polarization index measurement, dielectric loss factor and capacitance measurement. These techniques have achieved some results in practical application, but they are not effective or sensitive in diagnosis [8].

The winding DC resistance measurement method is to apply DC voltage on the transformer winding, measure the DC resistance of each phase, and judge whether TTF occurs inside by comparing the three-phase resistance value [9]. Due to the transformer DC resistance changes caused by many reasons, the technical operation error in the test process or transformer itself welding and poor contact will make transformer DC resistance changes, so this test method for TTF detection reliability is not high [10]. By applying AC voltage and measuring short impedance, low voltage short impedance test can reflect the change of transformer impedance value before and after winding deformation, and avoid transformer short circuit damage accident. With these two methods, when the transformer has a minor TTF, since the short-circuited turns occupy a small proportion in the winding, the DC resistance test and the short impedance test alone usually cannot find the fault effectively [11].

The transformation ratio test is a traditional test item for transformer products. In the process of manufacturing, on-site installation and operation and maintenance, it can be checked whether the number of winding turns is consistent with the design, whether the tap lead assembly is correct, and whether the voltage ratio of each tap is within the range allowed by the standard. The transformation ratio test is more sensitive when detecting TTF of the transformer, but this method can only make accurate judgments when the transformation ratio changes significantly [12,13].

The no-load test of the transformer also examines the loss of the windings and cores of the transformer, which increases the difficulty of diagnosing the fault. The induced voltage withstand test is to directly apply the voltage amplitude to the winding twice the rated voltage [14]. Although this can directly investigate the inter-turn insulation performance, the magnetization characteristic curve of the transformer core has been saturated at this time, so the no-load current is greater than the maximum current allowed by the winding which will cause irreversible damage to the transformer [15].

The transformer coil may deform due to the heat and electromotive force generated by the short-circuit current or the impact during transportation and installation which may lead to TTFs of
transformer. The application of frequency response analysis method to detect transformer winding deformation was first proposed by Dick in Canada. In the early 1990s, my country began to study frequency response analysis to detect transformer winding deformation. A large number of tests and on-site measurement results show that the frequency response of transformer winding in the range of 1 kHz to 1 MHz can reflect faults such as short circuit between turns, twist and bulge of winding. However, for a long time, the use of frequency response analysis is still based on the comparison of graphs. There is no clear quantitative standard and lack of in-depth diagnostic methods. With the wide application of frequency response analysis in winding deformation detection, the accumulation of a large amount of frequency response data provides favorable conditions for the development of intelligent diagnosis research on winding deformation such as artificial neural network, data mining and pattern recognition [16,17].

However, these methods can only detect severe TTFs, and the detection sensitivity needs to be improved. At the same time, most of them require equipment to be powered off. In recent years, the requirements for the production efficiency and economic benefits of power grid operation have also been continuously improved. In view of the problems exposed by the traditional regular maintenance system and offline tests, on the one hand, the majority of intact equipment is blindly repaired regularly, resulting in waste of manpower and material resources [18]. And this kind of over-maintenance may also introduce new hidden troubles; on the other hand, there is the possibility that some product performance defects, including insulation defects, cannot be detected and repaired in time and may develop into major failures. Therefore, people begin to pay attention to the research and application of transformer online monitoring [19].

3. ON-LINE MONITORING METHOD FOR TTFs

3.1 Leakage Inductance Method
When the transformer is in normal operation, external faults and inrush currents, the number of turns of the transformer windings and the magnetic circuit which the flux leakage passes do not change, and the leakage inductance of the transformer windings will not change; however, when a fault occurs between partial turns, the number of turns which the winding current passes will change, and the leakage inductance will definitely change. Based on the characteristics, the leakage inductance and resistance of the transformer windings can be used as the criteria to distinguish the normal operation, internal faults, external faults, and inrush current conditions [20,21].

Many methods have been applied to calculate leakage inductance. In order to improve the sensitivity of the algorithm, the least square algorithm is used to estimate the transformer leakage inductance parameters [22,23]. In addition, using the dynamic vector model based on Fourier theory, the winding resistance parameters are identified when the transformer is closed at no load, and the identified resistance parameters are used to modify the parameter identification model when the transformer is operating in a steady state, and the leakage inductance parameters are identified [24]. Based on the finite element method, the large-scale finite element software ANSYS is used to establish the transformer core and the winding model; the field-circuit coupling method is used to simulate the leakage magnetic field of the transformer, and the energy method is used to calculate the leakage inductance parameters of the transformer [25,26].

However, the transformer protection with leakage inductance method has the following problems in the identification of winding faults: 1) the accuracy of the identification value is not high, only when the transformer fault occurs in the area, the parameters change greatly, so that it can have enough sensitivity to detect the fault. 2) The transformer model established is relatively simple, and usually only a single model is established to detect transformer faults.

3.2 Power Loss Method
When the transformer is operating in a non-fault state, the active power loss of the transformer is relatively minor. When the transformer winding has a TTF, not only may it consume a lot of energy due
to the increase of the current, but also the additional loss of the transformer will increase due to the change of the leakage magnetic field caused by the short-circuit. It is feasible to use the power loss as the characteristic quantity of transformer TTF diagnosis, which is the reason why this method has been maturely applied in engineering practice. Generally, only the electrical quantities on both sides of the transformer need to be collected, and the relevant formula can be used to calculate the power loss of the transformer at this time, and this value can be compared with the reference value to determine whether a TTF has occurred and the severity of the fault. In addition, the criterion is not affected by inrush current and external faults [27].

When an TTF occurs in the transformer windings, due to magnetic coupling, in addition to the large change in the power loss of the faulty phase, the power loss of the non-faulty phase also increases correspondingly, but it is not obvious compared to the faulty phase, so it does not affect the power loss method for faulty phase diagnosis of transformer TTFs. However, a significant shortcoming of this method is that it cannot be used for faulty turns diagnosis. The traveling wave analysis technique is combined with the power loss method to diagnosis fault occurrence and location with high accuracy. The positive sequence component and the negative sequence component are used to calculate the corresponding power loss, eliminating the influence of the zero sequence component, improving the diagnostic accuracy, and achieving good results. Since the power loss is not sensitive enough to identify minor TTFs, integrating the power and taking the changes in the electrical energy loss before and after the fault as the monitoring object can improve the sensitivity but reduce the rapidity [28].

3.3 Magnetic Flux Leakage Method

The distribution of magnetic flux leakage of the transformer is very complicated, especially when the transformer has a TTF, the internal magnetic field will change greatly. In addition, since the magnetic flux leakage changes immediately after the fault, a protection scheme with both rapidity and sensitivity can be formulated according to the distribution law of magnetic flux leakage before and after the fault.

To formulate a protection scheme, it is first necessary to clearly analyze the distribution law of the transformer magnetic field. The theoretical law of the axial symmetry of the leakage flux distribution is obtained by simplified analysis [29,30]. And simple sensors, based on air core coils, are used to measure the leakage flux of the transformer, which provides a low cost scheme for TTF identification based on flux leakage information [31,32]. Based on the symmetry principle of magnetic flux leakage distribution, a novel approach to detect transformer TTF by the search coil induced voltage analysis is proposed [33,34]. The distorted leakage flux linking with the search coil induces voltage which can detect presence of fault and also predict its severity. A two-dimensional simulation model was established to verify that the axial symmetry obtained by the approximate calculation is correct. Against the traditional differential protection schemes, tap changer operation, inrush current and over-fluxing cannot impact the proposed technique performance and the results show that the proposed algorithm is a success to detect the minor TTFs as small as ten turns (lower than 0.25% of the winding) [35,36].
Figure 2 Leakage flux lines at two time instances of a steady-state operation cycle of the machine. A: healthy machine. B: transformer with one shorted turn.

4. IDENTIFICATION METHOD OF INRUSH CURRENT

4.1 Criterion of Inrush Current Based on Current Information

The method of identifying inrush current based on the information of current mainly includes the second harmonic method, the principle of dead angle, and the principle of waveform symmetry.

The second harmonic method uses the characteristics of a large number of second harmonic components in the transformer magnetizing inrush current waveform. When the second harmonic component of the differential current flowing into the differential relay is detected, the dynamic protection is blocked to avoid the misoperation of the differential protection due to the inrush current [37].

The dead angle principle mainly uses the characteristics of the dead angle in the inrush current waveform. When it is detected that the discontinuous angle of the differential current flowing into the differential relay is greater than the set value, the differential protection is blocked.

This method mainly faces the problem of discontinuous angular deformation caused by non-periodic components. In addition, current transformer saturation increases the discontinuous angle of the differential current when an internal fault occurs, and may also cause the protection to refuse to operate [38,39].

The principle of waveform symmetry is to use the front/post half-wave symmetry comparison of the derivative of the difference current (to reduce the influence of aperiodic components), and to identify the inrush current based on the comparison result. The principle of waveform symmetrical inrush current recognition is not affected by the offset of the DC component, and is an extension of the discontinuous angle inrush current criterion, and is easier to implement than the discontinuous angle inrush current criterion [40,41].

4.2 Criterion of Inrush Current Based on Voltage Information

The basic idea of using the transformer voltage to identify the inrush current is that when the transformer is severely saturated due to the inrush current, the terminal voltage will be severely distorted. Compared with current harmonic braking, the principle of harmonic voltage braking is relatively insensitive to LC oscillations, and some deficiencies of second harmonic braking can be improved to some extent [42].

The application of the principle is closely related to the size of the system impedance. Therefore, the protection using this principle inevitably requires a more accurate understanding of the system impedance, and there is complexity in setting. When the system impedance is minor, the action characteristics of the protection of this principle may deteriorate.
4.3 Criterion of Inrush Current Based on Current and Voltage Information

Based on the inrush current identification method of the transformer admittance type equivalent circuit, the internal and external faults of the transformer are identified by detecting changes in the admittance against the ground. The test results of the criterion used to distinguish between internal faults and inrush current on a simulated transformer prove the effectiveness of the method. The advantage of this algorithm is that it can quickly identify internal faults and inrush currents. Even if the internal fault situation is superimposed on the inrush current situation, the correct judgment result can generally be given within half a cycle [43].

The active power loss of the transformer can be used to identify the inrush current. During normal operation, the active power loss of the transformer is minor; but when the transformer generates the inrush current, the active power loss at the initial stage of the inrush current may be large, but it will soon be reduced to a small value. When the transformer has an internal fault, the active power loss greatly increases, and its value far exceeds the loss during normal operation and magnetizing inrush current. However, it is difficult to obtain the copper loss, which makes parameter setting difficult, which limits its practicability [44].

4.4 Criterion of Inrush Current Based on Magnetic Flux Leakage Information

Since when any fault occurs in the transformer winding, the symmetrical form of the magnetic flux leakage distribution will be disturbed, but the magnetic flux leakage distribution remains symmetrical under the inrush current condition, so it can be regarded as an appropriate standard to implement a suitable protection algorithm.

By setting the action value of the induced voltage of the search coil for detecting the magnetic field to be higher than the value in the case of the excitation inrush current, the protection can be ensured that the protection does not operate in the excitation inrush current state, but the higher action value will reduce the sensitivity to turn-to-turn fault identification [33,34].

A new technology based on flux leakage is used to diagnose the inrush current of transformers. The proposed technology uses a pre-installed flux leakage optical fiber sensor as a magnetic flux sensor near the transformer yoke to measure the flux leakage passing through the yoke at various positions. Since the magnetic flux density when the no-load transformer is energized is very different from the magnetic flux density detected in the normal state, the inrush current of the transformer can be identified. By comparing the different closing angles of the transformer under normal conditions and the difference of the flux leakage near the yoke, the change of the magnetic flux density can effectively identify the transformer magnetizing inrush current. This identification method has been initially verified in Maxwell's simulation [45].

![Figure 3 α=0° inrush current](image)

5. CONCLUSION

Safe and reliable power supply is the guarantee and prerequisite for promoting better and faster economic and social development. Excellent operating conditions of transformers play a very significant role in the security and stability of the power grid and the quality of power.

The main methods of transformer TTF and inrush current identification based on electrical information are detailed reviewed in this paper and their advantages and disadvantages are introduced,
which helps to selectively apply these methods to online or offline detection of faults and indication of the severity of transformers faults.

In summary, when magnetic leakage information is used as the basis for transformer turn-to-turn fault identification, it has the advantages of sensitivity, rapidity, and ability of accurately distinguish inrush current conditions. However, the current research on the magnetic flux leakage of transformers mostly focuses on the influence of magnetic flux leakage during the operation of the transformer, and there is a lack of systematic research on the use of magnetic flux leakage for turn-to-turn fault identification:

- Establish a mathematical model of transformer windings for theoretical analysis of magnetic flux leakage distribution;
- Establish a high-precision transformer simulation model to complete the simulation calculation;
- Develop an installation plan for magnetic flux leakage sensors based on theoretical calculations and simulation results;
- Apply the sensor installation plan in the true transformer for test verification.

Therefore, further research on the distribution and change rule of magnetic flux leakage during transformer operation has important theoretical significance and application value for promoting the development of transformer protection theory.

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REFERENCES
[1] Y. Xu, J. Ma, and Z. Wang, "Research on novel power transformer protection based on self-correction function," in TENCON 2005 - 2005 IEEE Region 10 Conference, November 21, 2005 - November 24, 2005, Melbourne, Australia, 2007, vol. 2007: Institute of Electrical and Electronics Engineers Inc.
[2] Reliability Management Center of China Electricity Council. 2017 National Electric Power Reliability Index. http://news.bjx.com.cn/html/20180607/903893.shtml
[3] Reliability Management Center of China Electricity Council. 2015 National Electric Power Reliability Index. http://chinaer.ccc.org.cn/zhibiaofabu/linianzhibiao/2017-12-15/176136.html
[4] E. Ali, A. Helal, H. Desouki, K. Shebl, S. Abdelkader, and O. P. Malik, "Power transformer differential protection using current and voltage ratios," Electric Power Systems Research, vol. 154, pp. 140-150, 2018.
[5] S. Mageshwari and K. Sandeep, "Design and simulation of self adaptive differential protection for a power transformer," in 7th International Conference on Electrical Energy Systems, ICEES 2021, February 11, 2021 - February 13, 2021, Virtual, Chennai, India, 2021: Institute of Electrical and Electronics Engineers Inc., pp. 454-459.
[6] K. Antunes Tavares and K. Melo Silva, "Evaluation of Power Transformer Differential Protection Using the ATP Software," in IEEE Latin America Transactions, vol. 12, no. 2, pp. 161-168, March 2014, doi: 10.1109/TLA.2014.6749533.
[7] L.-C. Wu, C.-W. Liu, S.-E. Chien, and C.-S. Chen, "The effect of inrush current on transformer protection," in 2006 38th Annual North American Power Symposium, NAPS-2006, September 17, 2006 - September 19, 2006, Carbondale, IL, United states, 2006: IEEE Computer Society, pp. 449-456.
[8] 1 000 kV preventive test procedures for AC electrical equipment, GB/T 24846-2018, 2018.
[9] H. P. Correa and F. H. T. Vieira, "An approach to steady-state power transformer modeling considering direct current resistance test measurements," Sensors, vol. 21, no. 18, 2021.
[10] A. N. Jahromi, M. Hosseinkhanloo, and L. Lamare, "Under Load Tap Changer Diagnostics Based on Transformer DGA and DC Resistance Tests," in 2018 IEEE Electrical Insulation Conference, EIC 2018, June 17, 2018 - June 20, 2018, San Antonio, TX, United states, 2018: Institute of Electrical and Electronics Engineers Inc., pp. 323-326.

[11] H. Zheng, B. Pu, Y. Shao, Y. Li, W. Wang, and W. Xue, "Study on transformer winding deformation using low-voltage impedance diagnostic method," in 2015 IEEE International Conference on Information and Automation, ICIA 2015 - In conjunction with 2015 IEEE International Conference on Automation and Logistics, August 8, 2015 - August 10, 2015, Yunnan, China, 2015: Institute of Electrical and Electronics Engineers Inc., pp. 1947-1952.

[12] A. Prasetyo and E. Supriyanto, "Failure Analysis of Power Transformer Based on Transformer Turn Ratio Test and SFRA," in 1st International Conference on Computational Intelligence and Energy Advancements, ICCIEA 2020, December 12, 2020 - December 13, 2020, Telangana, Virtual, India, 2021, vol. 1817: IOP Publishing Ltd.

[13] S. Zhai, L. Wei, W. Chen, T. Deng, and G. Ji, "Research on automatic calibration technology of transformation ratio tester," in 2nd International Conference on Wireless Communications and Smart Grid, ICWCSG 2020, June 12, 2020 - June 14, 2020, Qingdao, China, 2020: Institute of Electrical and Electronics Engineers Inc., pp. 221-224.

[14] Y.-F. Wu, H.-R. Hu, W. Luo, T. Wang, and L. Ruan, "Research on no-load test of 1000kV ultra-high voltage transformer," in 2011 Asia-Pacific Power and Energy Engineering Conference, APPEEC 2011 - Proceedings, 2011: IEEE Computer Society.

[15] F. Hu, G. Yang, R. Guo, and N. Zhang, "Field No-load Test and the Uncertainty Calculation of No-load Loss Measurement Uncertainty for UHV Disintegration Transformer," in 3rd IEEE Advanced Information Management, Communicates, Electronic and Automation Control Conference, IMCEC 2019, October 11, 2019 - October 13, 2019, Chongqing, China, 2019: Institute of Electrical and Electronics Engineers Inc., pp. 1844-1849.

[16] N. Shanmugam, S. Gopal, B. Madanmohan, S. P. Balaji, and R. Rajamani, "Diagnosis of Inter-Turn Shorts of Loaded Transformer under Various Load Currents and Power Factors; Impulse Voltage-Based Frequency Response Approach," IEEE Access, vol. 9, pp. 40811-40822, 2021.

[17] R. Talukdar, "Transformer winding movement differentiated using frequency response analysis," in 1st IEEE International Conference on Advances in Electrical, Computing, Communications and Sustainable Technologies, ICAECT 2021, February 19, 2021 - February 20, 2021, Bihlai, India, 2021: Institute of Electrical and Electronics Engineers Inc.

[18] B. Chen and G. Liu, "Research Progress in On-line Monitoring Methods of Micro-water Content in Transformer Oil," Gaodianya Jishu/High Voltage Engineering, vol. 46, no. 4, pp. 1405-1416, 2020.

[19] H. Fan, Y. Zhu, W. Zheng, X. Qin, D. Wu, and D. Zhong, "Research on On-line Monitoring and Regulation Technology of Pressure of High Voltage Transformer," in 2019 5th International Conference on Advances in Energy Resources and Environment Engineering, ICAESEE 2019, December 6, 2019 - December 8, 2019, Chongqing, China, 2020, vol. 446: IOP Publishing Ltd.

[20] L. M. R. Oliveira and A. J. M. Cardoso, "Leakage inductances calculation for power transformers interturn fault studies," IEEE Transactions on Power Delivery, vol. 30, no. 3, pp. 1213-1220, 2015.

[21] T. Zheng, Y. Shu, S. Dong, and Y. Cao, "Interturn fault protection for transformer type controllable shunt reactor based on leakage inductance change," Dianli Xitong Zidonghua/Automation of Electric Power Systems, vol. 35, no. 12, pp. 65-69, 2011.

[22] H. Yang, X. Zeng, and J. Luo, "A three-phase transformer leakage inductances parameter identification algorithm based on the constrained least squares method," Dianli Xitong Zidonghua/Automation of Electric Power Systems, vol. 33, no. 13, pp. 68-72, 2009.
[23] Z. Zhao et al., "Leakage inductances matrix identification of new converter transformer based on Levenberg-Marquadt nonlinear least squares algorithm," Diangong Jishu Xuebao/Transactions of China Electrotechnical Society, vol. 28, no. 4, pp. 212-220, 2013.

[24] X. Deng, X. Xiong, L. Gao, Y. Fu, and Y. Chen, "Method of on-line monitoring of transformer winding deformation based on parameter identification," Zhongguo Dianji Gongcheng Xuebao/Proceedings of the Chinese Society of Electrical Engineering, vol. 34, no. 28, pp. 4950-4958, 2014.

[25] A. Ehsanifar, M. Dehghani, and M. Allahbakhshi, "Calculating the leakage inductance for transformer inter-turn fault detection using finite element method," in 25th Iranian Conference on Electrical Engineering, ICEE 2017, May 2, 2017 - May 4, 2017, Tehran, Iran, 2017: Institute of Electrical and Electronics Engineers Inc., pp. 1372-1377.

[26] N. Wang, K. Xu, J. Yang, and J. Hu, "Leakage inductance characteristics of power transformer winding fault based on ANSOFT," Journal of Power Technologies, vol. 99, no. 3, pp. 231-238, 2019.

[27] Y. Zheng, X. Liu, B. Yu, Z. Zhang, S. Pan, and F. Long, "A method of adaptive transformer turn-turn fault protection based on power loss," Dianli Xitong Zidonghua/Automation of Electric Power Systems, vol. 37, no. 10, pp. 104-107, 2013.

[28] X. Zhu, "Design of on-line monitoring system for transformer turn-to-turn short circuit Fault," Master, Shandong University, 2017.

[29] M. F. Cabanas et al., "Detection of insulation faults on disc-type winding transformers by means of leakage flux analysis," in 2009 IEEE International Symposium on Diagnostics for Electric Machines, Power Electronics and Drives, SDEMPED 2009, August 31, 2009 - September 3, 2009, Cargese, France, 2009: IEEE Computer Society.

[30] M. F. Cabanas et al., "Insulation fault diagnosis in high voltage power transformers by means of leakage flux analysis," Progress in Electromagnetics Research, vol. 114, pp. 211-234, 2011.

[31] P. A. Venikar, M. S. Ballal, B. S. Umre, and H. M. Suryawanshi, "Search coil based transformer inter-turn fault detection," in 2014 18th National Power Systems Conference, NPSC 2014, December 18, 2014 - December 20, 2014, Guwahati, India, 2014: Institute of Electrical and Electronics Engineers Inc.

[32] M. Arivamudhan, N. Vanamadevi, and S. Santhi, "Measurement of axial leakage flux for the detection of winding deformation in transformer," in 2008 IEEE Region 10 Conference, TENCON 2008, November 19, 2008 - November 21, 2008, Hyderabad, India, 2008: Institute of Electrical and Electronics Engineers Inc.

[33] F. Haghjoo, M. Mostafaei, and H. Mohammadi, "A New Leakage Flux-Based Technique for Turn-to-Turn Fault Protection and Faulty Region Identification in Transformers," IEEE Transactions on Power Delivery, vol. 33, no. 2, pp. 671-679, 2018.

[34] F. Haghjoo, M. Mostafaei, and M. Mohammadzadeh, "A novel flux-based protection scheme for power transformers," in 9th Power Systems Protection and Control Conference, PSPC 2015, January 14, 2015 - January 15, 2015, No. 424, Hafez Ave., Tehran, Iran, 2015: Institute of Electrical and Electronics Engineers Inc., pp. 25-30.

[35] F. Haghjoo and H. Mohammadi, "Planar Sensors for Online Detection and Region Identification of Turn-to-Turn Faults in Transformers," IEEE Sensors Journal, vol. 17, no. 17, pp. 5450-5459, 2017.

[36] M. Mostafaei and F. Haghjoo, "Flux-based turn-to-turn fault protection for power transformers," IET Generation, Transmission and Distribution, vol. 10, no. 5, pp. 1154-1163, 2016.

[37] J. Song et al., "Magnetizing Inrush Current Identification Method Based on Second-Order Taylor Derivative," Zhongguo Dianji Gongcheng Xuebao/Proceedings of the Chinese Society of Electrical Engineering, vol. 40, no. 3, pp. 1020-1029, 2020.

[38] Y. Quan, H. Li, and Z. Yan, "New method for measuring dead angle with the wavelet transform," Dianli Xitong Zidonghua/Automation of Electric Power Systems, vol. 22, no. 1, pp. 33-35, 1998.
[39] M. Tripathy and N. Nirala, "Power transformer differential protection algorithm based on dead angle of Wavelet Energy Waveform," in 35th IEEE Region 10 Conference, TENCON 2015, November 1, 2015 - November 4, 2015, Macau, China, 2015, vol. 2016-January: Institute of Electrical and Electronics Engineers Inc.

[40] Y. Li, J. Chen, and B. Yao, "A novel method to identify the inrush current based on waveform longitudinal symmetry coefficient for transformer protection," in IEEE TENCON 2004 - 2004 IEEE Region 10 Conference: Analog and Digital Techniques in Electrical Engineering, November 21, 2004 - November 24, 2004, Chiang Mai, Thailand, 2004, vol. C: Institute of Electrical and Electronics Engineers Inc., pp. C393-C396.

[41] L. Zhang, M. Li, T. Ji, and J. Zeng, "Identifying magnetizing inrush in power transformers based on symmetry of current waveforms," IEEJ Transactions on Electrical and Electronic Engineering, vol. 12, no. 6, pp. 959-960, 2017.

[42] J. S. Thorp and A. G. Phadke, "A Microprocessor Based Three-Phase Transformer Differential Relay," in IEEE Transactions on Power Apparatus and Systems, vol. PAS-101, no. 2, pp. 426-432, Feb. 1982, doi: 10.1109/TPAS.1982.317124.

[43] K. Inagaki et al., "Digital protection method for power transformers based on an equivalent circuit composed of inverse inductance," in IEEE Transactions on Power Delivery, vol. 3, no. 4, pp. 1501-1510, Oct. 1988, doi: 10.1109/61.193949.

[44] K. Yabe, "Power differential method for discrimination between fault and magnetizing inrush current in transformers," in IEEE Transactions on Power Delivery, vol. 12, no. 3, pp. 1109-1118, July 1997, doi: 10.1109/61.636909.

[45] Y.-P. Zheng, Z.-Y. Zhang, C.-H. Wu, S.-Y. Pan, and Z. Li, "Leakage flux-based method to identify the inrush current in transformers," in 12th International Conference on Measuring Technology and Mechatronics Automation, ICMTMA 2020, February 28, 2020 - February 29, 2020, Phuket, Thailand, 2020: Institute of Electrical and Electronics Engineers Inc., pp. 1083-1088.