Review: Differential Protection of Three Phase Transformer

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Abstract : The differential function responds to the total of all the currents of its zone of protection. Ideally, this sum equals 0 under all occurrences except for internal defects. In practise, measurement mistakes and shunt components inside the zone might provide an erroneous differential signal, necessitating the use of appropriate countermeasures. With advancements in the field of differential protection, these countermeasures became more sophisticated, progressing from adding an intentional time delay, percentage restraint, harmonic restraint, and blocking to sophisticated external fault detection algorithms and adaptive restraining techniques.

Relay design and use are complicated by line current differential protection. The dispersed structure of the line current differential system restricts the amount of data that can be transferred between system terminals from a design standpoint, necessitating data alignment techniques to allow the differential protection concept. Line current differential schemes are concerned with CT saturation, particularly in dual breaker applications; in-zone reactors and line-charging current; in-line and tapped transformers; sensitivity to high-resistive faults; single-pole tripping; channel impairment security; application to lines with more than three terminals; and so on.

This article examines technological solutions for line current differential design and application, taking into account typical design restrictions as well as utility-driven application requirements. The article serves as a primer in this difficult field, which combines security concepts and applications with communications and signal processing.

***Index Terms* – Differential Protection, Power Transformer**

I. INTRODUCTION

When compared to directional comparison, phase comparison, or stepped distance schemes, the differential protection principle is considered superior in terms of selectivity, sensitivity, and speed of operation as a unit protection with its zone delimited by the location of current transformers (CTs).

When it came to line protection, the differential concept was limited by the length of the line. Because of signal attenuation caused by series resistance and the pilot's shunt capacitance, analogue systems utilising pilot wires can only be used on extremely short lines. These applications are still useful since distance relays cannot properly secure extremely small connections.

Line protection was revolutionized when microprocessor-based line current differential methods employing digital communications channels were developed. Line current differential schemes grew in popularity as more suitable long-haul digital communications channels became available as a result of the deployment of digital microwave and direct fiber-optic connections, as well as synchronous optical network (SONET) or synchronous digital hierarchy (SDH) systems.

When compared to distance or directional comparison schemes, differential protection provides better performance on multi-terminal and series-compensated lines and lines of any length; significant immunity to changing system conditions, long-term evolution of the system, or nontraditional short-circuit current sources, such as wind generators and photovoltaic.

With the first generation of microprocessor-based line current differential protection relays, advances in data synchronisation, working with wide-area communications equipment, improving protection principles (e.g., the Alpha Plane line differential element), and standardizing physical interfaces between relays and multiplexers were made (IEEE C37.94).

During this time, many lessons were learned. Line current differential systems were originally developed for direct fibre connections, but they were primarily used across multiplexed channels since high-bandwidth fiber pairs were used for shared data traffic. New abilities in digital communications were required of protection engineers. To enable protection applications, the communications equipment that was initially meant to transport voice data has to be modified. The lack of recording and data collection tools at the interface between relays and multiplexers or modems made post-event investigation of communications impairments difficult. This article describes basic design approaches for a future generation line current differential protection system, taking into account both the lessons gained from the first generation of line differential relays and the increasing demands for additional functions and features.

II. DIFFERENTIAL PROTECTION TECHNIQUES

Transformer protection is a well-established topic of study, with the goal of finding the most efficient and quick differential relay algorithm that separates the transformer from the rest of the system while inflicting the least amount of damage. When distinguishing between operating circumstances, the algorithm should also avoid mal-operation. Differential algorithms have been proposed in the past, leaving need for more research. ANN is employed as a pattern classifier in one of the methods [1], which distinguishes between normal, magnetizing inrush, over-excitation, and internal fault currents in a power transformer. The suggested approach was implemented using several ANN architectures, including an unique tailored parallel-hidden layered design that is more accurate in distinguishing between normal and defective waves despite their form similarities.

A Master–Slave configuration of two ANNs has also been explored. The multi-layered feed forward neural network is trained using Back Propagation (BP) and Genetic Algorithm (GA), and the simulated outcomes are compared. The GA-trained neural network is more accurate (in terms of mean square error) than the BP Algorithm-trained neural network. Simulated data is utilised as an input to the ANN to ensure that the algorithm is accurate. Thus, a GA trained Master–Slave ANN based differential protection method for power transformers delivers a quicker, more accurate, more secure, and trustworthy relay.

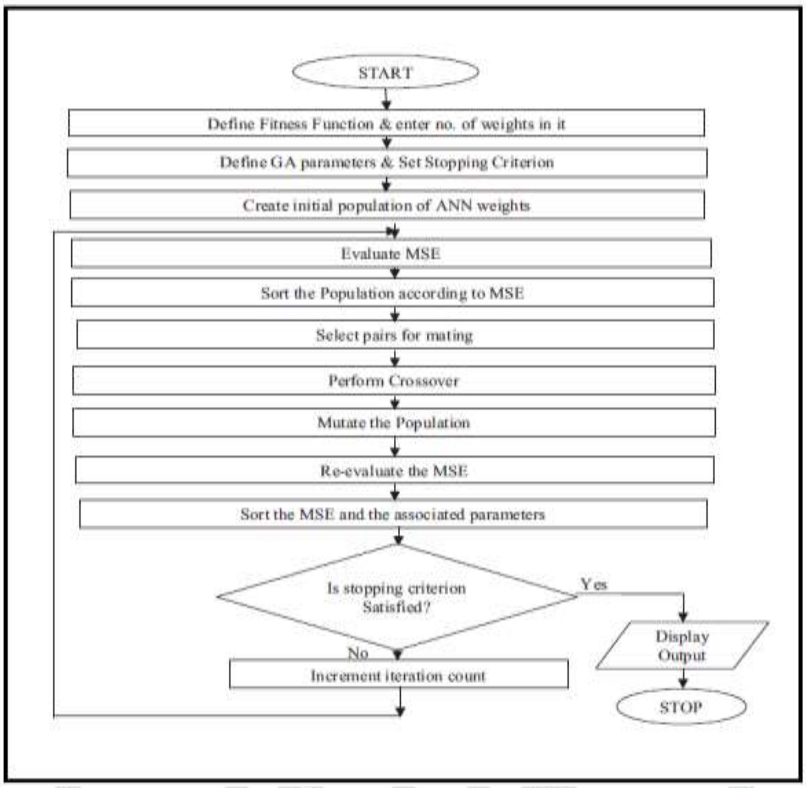

Fig.1. Flowchart for the GA based training of neural network [1]

Three versions of ANN-based three-phase power transformer protection relays were built and evaluated using simulated data. The first model uses a traditional feed forward architecture, while the other two use a modified semi-parallel layer design. The hidden layers in the customized design function in parallel and independently, so the output of one does not impact the outputs or inputs of the others. GA-based training has been used for semi-parallel design to minimise the total number of weights to be tuned, reducing training time and enhancing accuracy in distinguishing fault current waveforms from normal waveforms. In Case 3, the protection system was designed as a combination of two semi-parallel ANNs in Master–Slave mode: a defect detector and a fault classifier. The latest batch of samples recognized as fault by Matser ANN were sent to the Slave ANN for fault classification, and both architectures were trained and evaluated using BP and GA. When compared to cases 1 and 2, the results achieved in this case seem to be superior. In instances 2 and 3, the suggested designs can reliably identify faults and send trip signals in less than half a cycle time (about 8 ms), but ANN in case 1 takes 8–14 ms. Case 3 can only be implemented if the capability of constructing two ANN systems exists.

The differential function is currently the most often employed for power transformer protection, resulting in a solid distinction between internal faults and outside occurrences. The traditional phasor-based differential protection function, on the other hand, has difficulty detecting some internal defects, and its performance is dependent on the harmonic restraint and blocking functions to prevent relay mis-operation during inrush currents. Internal faults and other disturbances, on the other hand, are transitory and may be identified using the wavelet transform. Using the boundary wavelet coefficient energy, this technique [2] recreates the phase current and negative-sequence current differential elements. Representative simulations of internal faults, external faults, and transformer energizations in two distinct power systems were used to test the suggested technique. The suggested approach was fairly quick and accurate, was not influenced by inrush currents in transformer energizations and fault clearing, and could be utilized in a real-time application with a minimal computing burden by employing the boundary wavelet coefficient energy instead of phasor estimate. Furthermore, the suggested technique showed no failure in fault with over-damped transients, was unaffected by the mother wavelet selection, had no time delay due to wavelet filtering, and was unaffected by usual noise.

The proposed method with the boundary wavelet coefficient energy was unaffected by the mother wavelet choice, exhibited no time delay in the filtering process, and detected critical faults with over-damped transients, becoming less susceptible to the effects of fault inception angle and fault resistance. Furthermore, typical signal-to-noise relationships have no effect on the performance of the suggested wavelet-based approach.

Unlike traditional transformer differential relays, which need a large number of logical protection functions, the suggested approach has a 100 percent success rate for internal faults, external faults, external fault clearing, and transformer energizations with only two protection functions. Internal defects were recognized with a median time delay of 26 seconds, which is significantly faster than standard phasor-based differential protection techniques. Furthermore, the suggested technique was simple, insensitive to slope fluctuation, resistant to settings, and unaffected by transformer parameters.

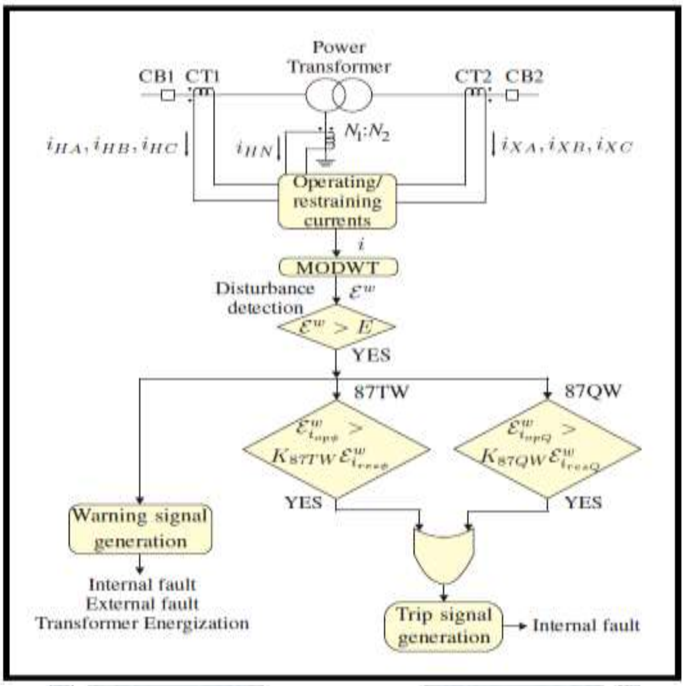

Fig.2. The proposed wavelet-based differential protection algorithm [2]

The wavelet-based negative-sequence current differential element that was presented was the quickest and most accurate (100 percent of success rate). As a result, it may be utilised as a unique protection unit based on the assessed data instead of a unit to support the wavelet-based phase current differential element.

CT saturation, transformer energization with an internal defect, and transformer energization with low-second harmonic content are all recognized to be serious problems. In these three scenarios, the proposed approach may encounter difficulties. However, in these situations, strategies for reliable detection were explored. The suggested technique was created for real-time applications and was implemented in a digital signal processor enabling real-time analysis with little computational overhead.

As a result, the suggested wavelet-based protection system is a viable alternative for future practical implementations in differential protection relays, especially when combined with traditional differential protection.

Energy difficulties are becoming more of a worry on a daily basis, and the transformer is the most crucial piece of equipment in delivering electricity. For the power transformer to function properly, it must be able to distinguish between inrush current, CT saturation, external fault, and internal fault. For continuous transformer operation, the failure of the transformer protection system during external fault and inrush conditions should also be avoided. Using the sequence component of current from both sides of the transformer, this approach [3] uses a new methodology to distinguish between internal and exterior fault conditions. The Fast Fourier Transform (FFT) is used to compute the magnitude and phase angle of current signals, as well as the sequence component of current. To identify internal and external fault conditions of the transformer, a differential protection principle is used with estimated magnitude and phase angle of sequence component of current.

PSCAD simulates a variety of internal and exterior fault scenarios, including magnetising inrush, high resistance fault, and CT saturation situations. The suggested approach successfully distinguishes between internal and exterior fault conditions and has been proven to be effective for transformer protection.

A new technique for transformer protection is presented in this method [3] based on comparisons of consecutive components of current to distinguish internal fault from all other circumstances. For the validation of the proposed algorithm, several fault scenarios with variable system characteristics are simulated in PSCAD. The needed mathematical computation in the method is so basic that it may easily be applied to relay programming, resulting in the fastest possible execution. With the provided algorithm, various internal faults, external faults magnetising inrush situation, CT saturation phenomena, and high resistance internal faults are examined. Simulation results show that the algorithm is completely capable of distinguishing internal fault from external fault/various circumstances.

Internal and non-internal faults/disturbances such as different types of inrushes, over-excitation condition, and external faults are distinguished by the author's suggested [4] power transformer differential protection method combining S-transform and Support Vector Machine (SVM). The suggested approach uses feature vectors created by conducting an S-transform of a power transformer's differential currents as an input to SVM to categories internal and non-internal faults. By modelling a 3-phase power transformer from Gujarat Energy Transmission Corporation, the suggested system is validated by producing over 12000 simulation instances comprising internal faults, external faults, and other disturbances.

GETCO Limited (GETCO), Gujarat, India, using PSCAD/EMTDC software. The suggested method is implemented in MATLAB, and simulation results show that it is capable of successfully discriminating various internal problems from other non-internal faults with an accuracy of more than 97 percent. Furthermore, a comparison of the current scheme with another digital system based on Probabilistic Neural Network (PNN) is made, and the findings show that the latter is superior.

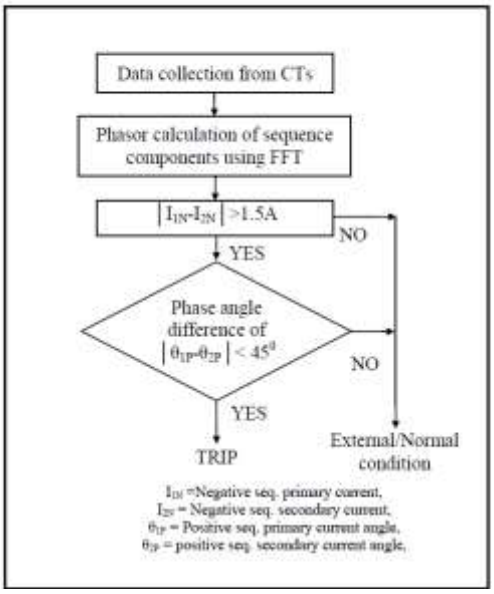

Fig.3. Relay algorithm for sequence component [3]

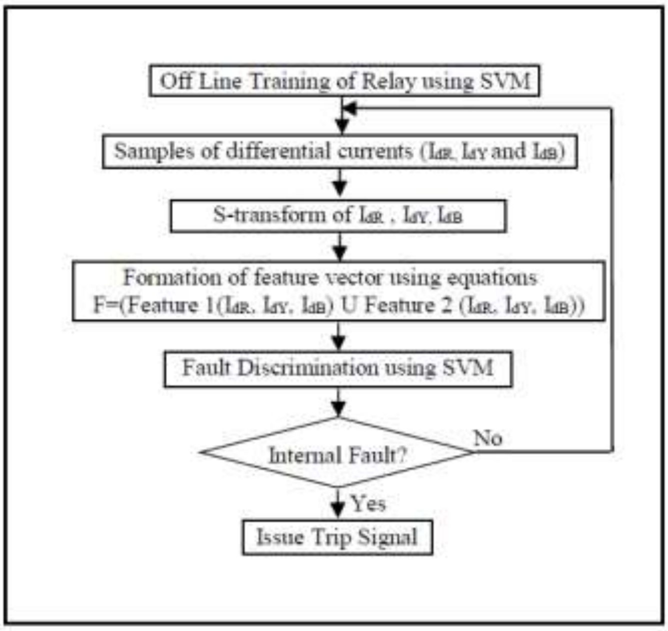

Fig.4. Block diagram of the proposed scheme [4]

This approach presents a unique fault classification scheme for power transformer protection using the S-transform and SVM. To differentiate internal faults from non-internal faults/disturbances, the proposed S-transform and SVM-based system uses one cycle post disturbance CT secondary three phase differential current. The S-transform is used to extract features, and SVM is given two features: the standard deviation of the phase contour and the maximum magnitude of each frequency component. The suggested scheme's feasibility was determined by modeling the power transformer in the PSCAD/EMTDC software package. The suggested system has been validated using a large number of test cases and has a fault discrimination accuracy of over 97.9%. A simulation dataset for 12864 instances with diverse system and failure circumstances has been created. Finally, a comparison of the new plan to the current scheme reveals that the suggested design is preferable to the existing scheme.

The current transformer (CT) saturation phenomena has been a major issue for power transformer differential protection, resulting in inaccurate current measurements and relay failure. After external fault detection, the author proposed [5] a fast and efficient transformer differential protection scheme with additional differential CT saturation and cross-country fault detection modules, all based on differential wavelet coefficient energy with border distortions to stabilize the relay during external faults and accurately distinguish CT saturation from clogging. Internal faults, transformer energizations, and external faults with CT saturation followed by cross-country internal faults were used to evaluate the suggested approach, and satisfactory results were obtained.

A power transformer differential protection method based on the boundary discrete wavelet transform with external fault, CT saturation, and cross-country internal fault detection modules was given by the author [5]. Internal faults, transformer energizations, and exterior faults with CT saturations were used to evaluate the suggested method's performance, followed by cross-country internal faults. With an expressive average relay operating time of 214 s, the proposed wavelet-based differential protection scheme had a success rate of 100 percent for detecting internal faults, whereas a phasor-based conventional protection scheme had only 92.60 percent success rate with an average relay operating time of 19 ms. As a result, the recommended approach was the most straightforward, quick, and accurate.

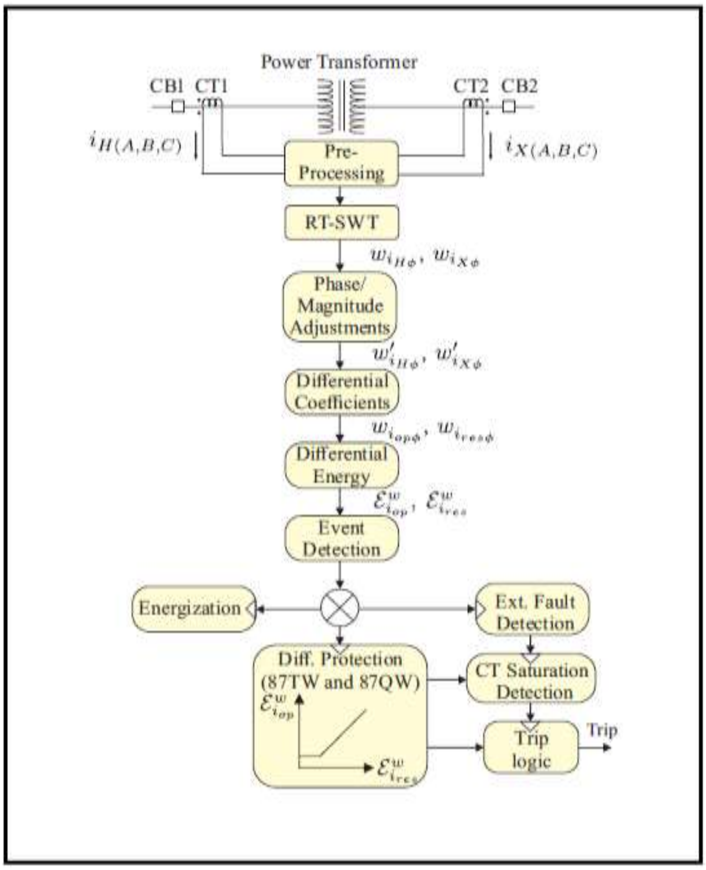

Fig.5. The proposed wavelet-based transformer differential protection [5]

A power transformer differential protection strategy based on the boundary discrete wavelet transform with external fault, CT saturation, and cross-country internal fault detection modules was described [7]. Internal faults, transformer energizations, and exterior faults with CT saturations were used to evaluate the suggested method's performance, followed by cross-country internal faults.

Both the suggested and traditional methods were resistant to CT saturation in the case of repeated events to the power transformer. The suggested CT saturation detection module, on the other hand, is simpler than the previous approach since it just requires the inclusion of a wavelet coefficient energy increment/ decrement counter rather than the standard harmonic based functions. Furthermore, the suggested approach detected cross-country internal faults from the database 4 with a success rate of 100 percent, whereas the standard method detected only around 89 percent utilising both independent and cross-blocking modes.

In the case of databases 5 and 6, the suggested approach had a success rate of 99.11 percent in identifying cross-country internal defects, compared to 100 percent and 87.05 percent, respectively, for the conventional method using the independent and cross-blocking modes. As a result, the suggested technique was immune to CT saturation and had a high level of accuracy when it came to detecting cross-country internal defects.

A unique differential protection strategy based on deep neural networks was presented by the author [6]. (DNN). As the most demanding topic in power transformer protection, the objective is to provide a quick, reliable, and independent protection method for differentiating inrush current from internal fault in power transformers.

In this major, shallow-based strategies necessitate spectrum analysis and handmade feature extraction as suitable procedures. However, they come at a high expense in terms of computation. To solve this issue, an unique DNN-based technique based on merging convolution neural network (CNN) and light-gated recurrent unit (LGRU), dubbed CLGNN, is suggested in this method. The findings demonstrate that it outperforms three distinct shallow and three state-of-the-art DNN-based methods in terms of accuracy and reliability. The suggested scheme's adaptability and robustness are assessed in terms of CT saturation, superconducting fault current limiter (SFCL), and series compensation impacts. The collected findings show that the suggested DNN-based protection strategy is effective and valid in this approach.

A novel DNN-based differential protection system for power transformers was presented [6]. This technique for power transformer protection verifies the applicability of the proposed CLGNN in a simulated power system and an experimental test scenario. The dependability indices are 100 percent in certain situations and greater than 99 percent in all others. The accuracy, reliability, safety, and security indices outperform shallow architecture methods such as ANN, KNN, and SVM, as well as deep architecture methods such as CNN, GRU, and LGRU. Furthermore, in order to increase flexibility, the effects of CT saturation, series capacitor, and SFCL are addressed extensively, and the robustness and efficacy of a unique suggested DNN-based method are demonstrated. Despite the proposed CLGNN method's excellent reliability and speed, it requires a big dataset for the training step, which may be challenging to gather or produce using simulations. As a result, we must employ artificial and intelligent data generating approaches to enhance the dataset gathered, which will require additional research in the future.

The major safety method for power transformers is differential protection, which nevertheless has the danger of transmitting erroneous trips due to inrush currents. To reduce the danger of false tripping, this technique [7] attempts to build a differential protection strategy that can distinguish power transformer magnetizing current from internal defects. An accelerated convolution neural network (CNN)-based technique is used in this method [7] to distinguish between internal defects and inrush current. The proposed algorithm's major competitive advantage is its ability to combine the feature extraction and defect detection blocks into a single deep neural network (DNN) block, allowing the network to automatically find essential features. The method is therefore more efficient in terms of speed, hardware use, and accuracy as a result of this argument. A simulated 230kV network and an experimental prototype are used to test the suggested technique. To compute reliability indices, several situations with diverse external elements are simulated. The suggested algorithm outperforms the accelerated CNN, conventional CNN, and nine other frequently used approaches in terms of speed and reliability.

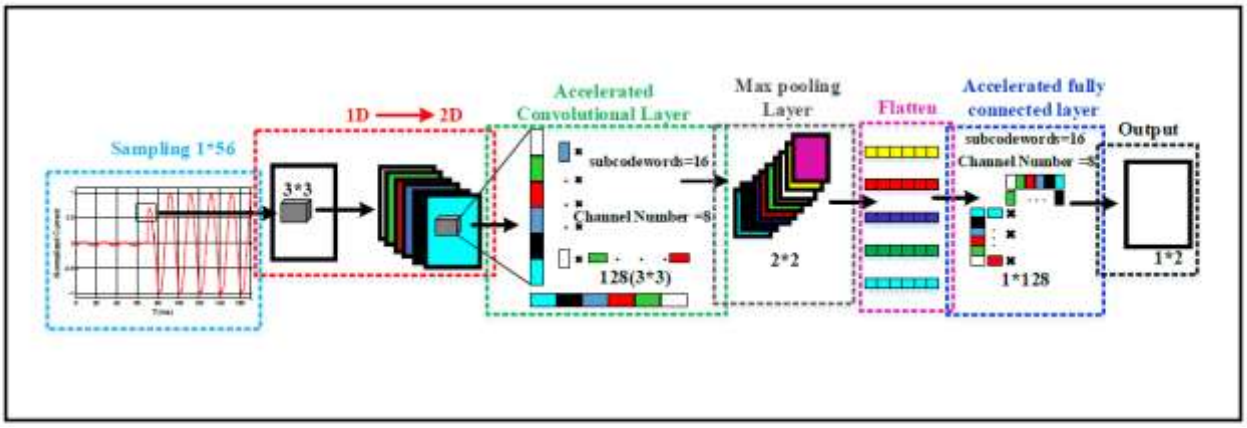

Fig.6. Procedure of the proposed differential protection scheme of the power transformers [7]

Traditional approaches in differential protection to identify internal defects from inrush current in power transformers have flaws that reduce the process's dependability and generality, such as computing complexity and reliance on a model and predefined threshold. The suggested technique is a significant step toward realistic intelligent automation of power transformer safety, since it takes advantage of the huge amounts of data collected by contemporary data gathering systems. To speed up the convolution and FCN layers, we created an accelerated CNN utilising the product quantization approach. The accelerated CNN is four times quicker than the basic CNN, not only without sacrificing accuracy but also with a 1% gain in accuracy. Furthermore, once the CNN structure is defined, the proposed machine learning-based security approach may be used to a variety of systems independent of system characteristics. In both simulated and experimental situations, the proposed approach was applied to a system. The findings of the accelerated CNN technique were compared to those of ten other methods, eight of which were data-driven and two of which were signal processing methods. The numerical results prove that the suggested approach is of high quality. Despite the suggested method's excellent accuracy, reliability, and speed, the training procedure necessitates a big dataset, which may be challenging to gather or create. The algorithm recognises the occurrence as a fault situation if the magnitude of the SCM exceeds the limit. Other than that, the occurrence is classified as a transitory or steady-state situation. If the transformer parameters change or the harmonic content of the differential current changes, the threshold is set-free. In addition, if the power system is changed, the threshold does not need to be recalculated. When current transformers become saturated, the D index was created to enhance fault detection time. To identify the fault current, this index utilises the magnitude of the SCM as a baseline and compares it to a set limit. Both indices operate in parallel, and a fault condition is established if one of them crosses their respective thresholds. The method is developed in MATLAB and evaluated in a real-time digital simulator (RTDS). To test the efficacy of both indices in critical situations, the algorithm was compared to traditional differential protection with harmonic restriction. The results support the algorithm's performance and suggest that it might be used as the foundation for a new power transformer protection algorithm.

To distinguish transient from fault circumstances, the author suggested [8] a setting-free differential protection for power transformers based on the second central moment. The SCM was utilized to heighten the differential current's distinctive patterns. The D index was created in order to speed up the defect identification process. The differential current was utilised to determine the magnitude of the SCM and the D index for each phase in the proposed method. To distinguish the type of occurrence, both indices were compared to their respective thresholds. An inrush current or an event that does not need urgent protective action was identified if the SCM or D index did not meet the set requirements. Otherwise, it was thought to be an internal flaw. The algorithm was 99.63 percent accurate, compared to 89.95 percent for the traditional technique. Furthermore, the suggested method revealed an average fault detection time of less than 60 Hz. These findings indicated that the algorithm may be used to develop a novel differential protection scheme for three-phase power transformers.

Using the integral concept, this technique provides [9] a new way to differential protection of power transformers. In certain stages, the needed criterion signals are computed directly from the operational and restraining currents. The second harmonic is also utilized for additional support. The suggested integral concept is easy to understand and outperforms other frequently used methods. Theoretical investigations are followed by simulation runs and recorded signals for testing.

A new strategy and comprehensive algorithms based on the integral principle have been suggested to increase differential protection performance. Several different versions of the criterion arising from different ways of defining the operating and restraining currents have been investigated. The criterion that used derivatives of differential and restraining currents, as well as the usage of an integrated second harmonic component, yielded the greatest results. The suggested methods have also been evaluated for internal failures, for which the protection should immediately clear the fault. The testing indicated that the solution could respond appropriately to all internal events while causing no additional operating delays.

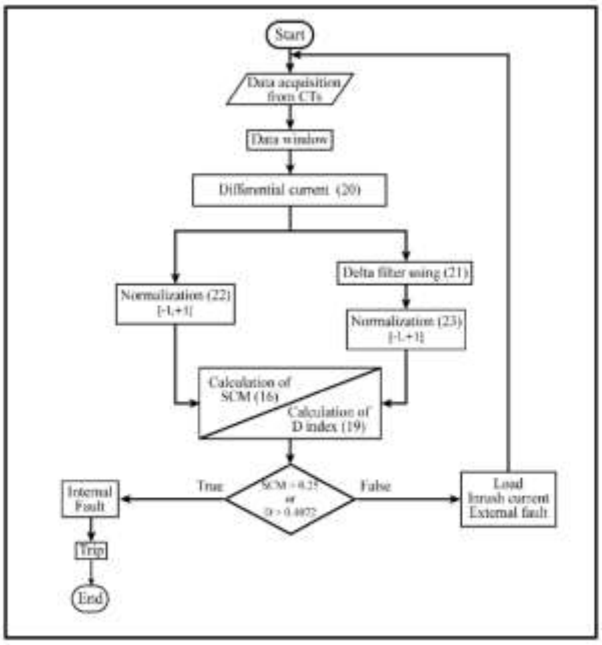

Fig.6. Proposed algorithm of second central moment (SCM) [8]

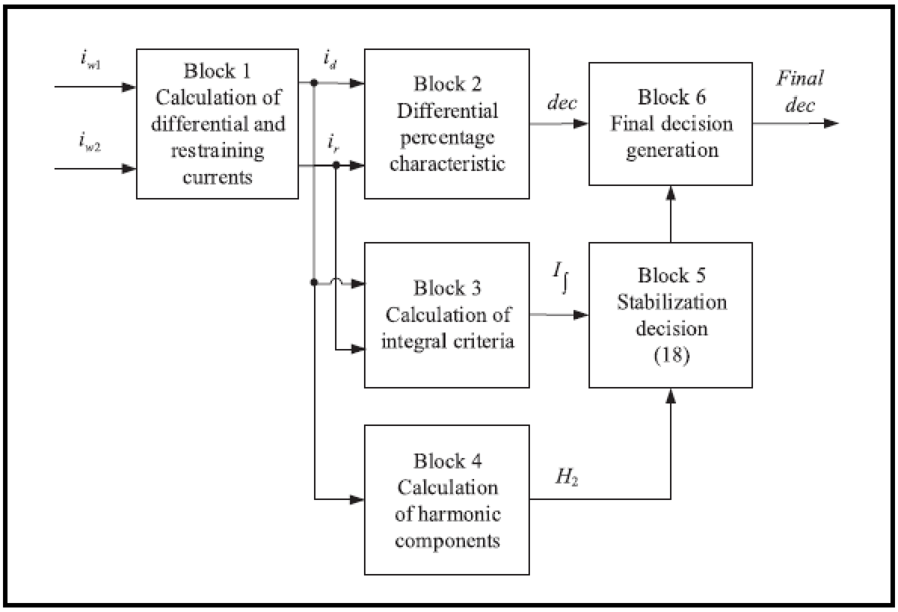

Fig.7. Block scheme of the proposed transformer differential protection with integral and harmonic stabilization [9]

The novel algorithm's operating time is quite similar to that of existing approaches that utilize full-cycle measurement and 2nd harmonic restraint. Simulation studies demonstrate that the protection speed is comparable, but that the stability for inrush and other external events, for which the protection should prevent tripping, is superior.

A novel approach for power transformer protection is given, which is based on the computation of the fault detection ratio (FDR) using the quartile of superimposed differential currents. Internal defects are discovered by comparing FDR to a predefined threshold established from analytical analysis and confirmed using simulation findings. Modeling an existing Indian power transmission network with PSCAD/EMTDC software is used to evaluate the performance of the proposed plan. Numerous forms of aberrant circumstances have been examined, including magnetising inrush (including sympathetic and recovery) and over-excitation, as well as several types of internal (winding, inter-winding, and turn-to-turn) defects. Its validity was further tested using data from the real network, which included magnetising inrush and simultaneous inrush with an internal transformer malfunction. The findings show that the recommended approach is efficient in distinguishing internal defects from other abnormal situations. Furthermore, during a heavy through fault with current transformer saturation, it stays stable. It may be used on power transformers of various ratings and winding connections. Finally, a comparison of the proposed system to many current strategies reveals that it is superior in terms of increased sensitivity during internal faults and enhanced stability during non-internal faults.

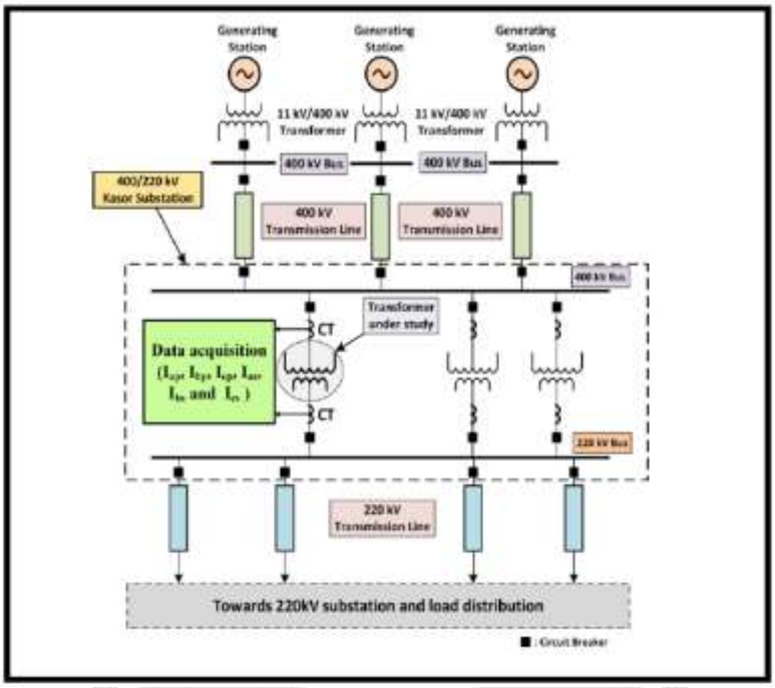

Fig.8. Single line diagram of simulation model [10]

A novel FDR-based approach for power transformer protection is described, which is generated from quartiles of superimposed differential currents. With the exception of turn-to-turn faults in the presence of inrush current, the derived FDR is shown to be capable of differentiating all forms of internal faults from magnetizing inrush and over-excitation situations. Within one power frequency cycle, the proposed approach detects winding and inter-winding defects, as well as turn-to-turn problems. In the case of both external and internal fault situations, it is not susceptible to the effects of CT saturation. It is safe in the face of all sorts of magnetizing inrush and over-excitation conditions, even if the collected signals contain noise. At the same time, it may be used on power transformers of various ratings and winding connections. Furthermore, testing its performance on real-world data (including faulty transformer energization and magnetizing inrush situation) demonstrates its accuracy in identifying internal faults and immunity to nuisance trips during non-internal faults. Finally, a comparison of the proposed methodology to other current methods reveals its advantages in terms of coverage of various types of internal faults, stability during external disturbances, average relay operating time, and sampling frequency need.

III. CONCLUSION

This article does a literature review on transformer protection. Many methods and techniques have been proposed and implemented since the development of digital relays to date, but in terms of full-security and development of techniques to meet current requirements, the recent mathematical tool of ANN and fuzzy logic concept appears to be reliable, fast, and robust. However, even these approaches can fail in some real-world conditions, and digital relays can malfunction. As a result, it appears that there is a substantial area of study for a faster and more reliable power transformer protection approach. Although every effort has been made to provide the most comprehensive list of references on the subject of contemporary approaches employed in power transformer protection, omissions are unavoidable. The author apologizes for any errors or omissions, and hopes that further references will be provided as part of the debate on this publication.

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