Enhanced Transformer Protection Using Fuzzy-Logic-Integrated Differential Relays: A Comparative Study with Rule-based Methods

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Abstract—**The power transformers are the important part of electrical networks where transformer reliability and operational lifetime depends on sufficiently accurate and reliable protective means. Other traditional forms of differential protection that were developed initially also suffer from the inability to distinguish between a fault and normal operation such as inrush currents in transformers and CT saturation. This paper presents the development of an improved differential relay augmented by Fuzzy-Logic Control System (FLC), to improve (a) dependability, (b) performance of the existing transformer protection systems, and (c) accuracy in fault identification possible due to uncertainty and non-linearity in transformer operation. They include the proposed methodology compared to the traditional Rule-based current differential method in outlining the protection settings. MATLAB/Simulink model of the power transformer and protection methods suggested in the study form a part of the investigation. Computer simulations show that the presented scheme provides a substantial increase in the speed and resolution of fault detection and fault types identification relating to current differential method based on the Rule. The system's accuracy rate is the average of 98% for internal faults and 95% for external faults while its response time is 25ms for internal faults and 30ms for external faults. Furthermore, the Fuzzy-Logic-based system has an 90% efficiency in detect the defect and 85% efficiency in identify the inrush currents. The findings of this research prove that the differential relay based on Fuzzy-Logic enhances the flexibility and reliability of transformer protection and opens the road to the introduction of further improvements in the intelligent protection systems in the future.**

Keywords—Transformer Protection; Fuzzy Logic Control; Differential Relays; Fault Detection; Power System Stability.

I. INTRODUCTION

Like other electricity transmission and distribution equipment, power transformers are significant in the performance of electrical networks; in the process of transformation and conversion of voltages [1]-[2]. Faults are occurrences that are paramount to a power system network, especially from the equipment aspect, because they require speedy and efficient isolation and clear distinction [3]. Energy system protection is even becoming crucial in maintaining continuous and sustainable creation, transfer, and distribution of energy due to costs as indicated in [3]. Since power systems involve complicated and expensive components, protecting these components from defects and normal aberrations is a very important facet of power system controls [4].

Old protection schemes: Traditional protection schemes such as the differential relays have played a very central role in the protection of transformers. Nevertheless, they may face difficulties in identifying the real faults and those occasional disturbances like transformer inrush currents, load fluctuations or extraneous electrical interferences [5]. This can bring about critical mishaps such as false tripping or slow responses which in various ways lowers the dependability of power systems.

Differential relays work by comparing the current flowing into the transformer terminals with that flowing out of it. They become active when the mentioned current is beyond a specific percentage of a restraint current. Differential current occurs when the transformer's currents for each side differ due to an internal fault situation. As for magnetizing inrush currents which appear at the voltage change, their characteristics are similar to functions' behavior in case of fault scenarios. Such inrush currents may result through transformer energization or when voltage is restored after clearance of an external fault [6]. Despite experience indicating that various types of differential relays are often used, adjustments are required to take into consideration inrush currents, saturation of CT, over-excitation of transformer, tap changer settings of transformers [7].

In differential relay circuits, sensitivity and selectivity are said to be its drawbacks even though it is widely used. Transformers used in distribution network circuits may undergo more faults than in other areas which thereby puts the longevity of the transformers in a low level [8]-[9]. Thus, transformers are critical components, and it is important to safeguard them against potential threats in a power system. Protective clothing and equipment are not standard due to the size and cost of transformers ranges and their values. Thus, in the case of a short-circuit, the presence of the transformer must be disconnected from the network to prevent worsening of the situation due to possible damaging effect of continued fault currents [10]-[15].

Fuzzy-Logic control has also been used in different fields to improve stability in various systems like; [16] speed control of wind turbines, temperature and humidity control [17], robot controllers [18]-[23]. Radar control systems [24] and DC motor PID control [25]-[27]. Some more research has been done on the Fuzzy-Logic-based transformer protection techniques to overcome the problems associated with the conventional transformer protection techniques keeping the differential current relaying algorithms in view [28]-[30]. The application of digital relaying for power transformers is where sophisticated algorithms are used in place of analog relaying in order to deliver the optimum of protection and control services; digital relays are used because they are considerably more accurate, flexible, and functional [31][32]. Inverse time overcurrent protection, overvoltage protection, differential protection, and thermal protection are some of the essential protection functions provided by digital relays [13].

Comprehensive input variables like the derivative curve slope of the flux differential current, the second harmonic restraint, as well as the percentage differential characteristic curve are included in the proposed fuzzy based relaying method. The performance of the proposed relaying mechanism is tested through simulations in which the transformer inrush currents, load currents and internal faults are considered for testing [33]-[38].

Thus, this paper suggests the application of the Fuzzy-Logic into the differential relay protection system simulated in MATLAB/Simulink to benefit from the Fuzzy-Logic capabilities, which will enhance the decision-making within the differential relay system to differentiate between real faults and operational dysfunctions. The focus of the paper reduces to the formulation of a highly particular and detailed Fuzzy-Logic controller for transformer differential protection [39]-[46]. To evaluate the effectiveness of the suggested protection scheme and test its resilience as well as flexibility, the study performs computations of the model in both faulty and non-faulty scenarios in the transformer model [47]-[58]. Even for external and internal faults, their differential current method is divided into the basis of current differential protection, and a rule-based current differential method is used to protect the transformer. The comparative analysis is then performed in order to qualify Fuzzy-Logic-based system in terms of its performance against the conventional differential relays. As such, the following comparison is intended to highlight the gains in terms of fault identification precision and reaction time telefaxes from Fuzzy-Logic integration [59]-[65].

This paper is organized as follows: Section II is titled as the current differential protection basics and current differential relay with description of rule based current differential algorithm. In the Section III, this paper focuses on the application process of converting Fuzzy-Logic to the differential protection system. Section IV includes the Simulink models of the proposed protection approaches and the power system setup. Data analysis and discussions are also discussed in Section IV, and the implications and recommendations in Section V. The conclusion is made in Section VI.

II. PRINCIPLES OF CURRENT DIFFERENTIAL PROTECTION

In AC three-phase systems, the voltages and currents are depicted through three phasors, which may exhibit either a balanced or an unbalanced state. A balanced system is characterized by phasors of equal magnitude that are phased 120 degrees apart, whereas an unbalanced system displays phasors that do not share these uniform characteristics. The definition of an unbalanced system encompasses the concepts of positive, negative, and zero sequence components [10]-[15].

Differential relay is a crucial component, establishing a connection between a transmission line and a three-phase source through a three-phase breaker. The magnitude of the load current flowing between these components is precisely determined using a thorough three-phase V-I (voltage-current) measurement method. Additionally, the system's total demand is accurately represented by integrating a three-phase series RLC load at the end of the transmission line.

To address the significant disparity between primary and secondary currents, it is customary to install CTs at the ends of a transformer. Ensuring the production of similar secondary currents in these CTs is of utmost importance, which necessitates the careful selection of appropriate ratios. The two CTs exhibit distinct magnetizing behaviors due to their differing primary current ratings [36]. As seen in Fig. 1, if the protected unit fails, the current flowing out will differ from the current flowing in, as indicated.

It crucial to measure currents in each phase, ensure adequate restraint windings to match the transformer windings, and account for every potential failure source. When feeder-side CTs are linked in parallel, there should be little to no current differential under load and fault circumstances. Ideally, the currents would be in phase. The strategy uses a rigorous and analytical process that begins with phasing to align the primary and secondary currents. Subsequently, ratio adjustment is performed, which entails precisely determining the appropriate CT ratio and relay tap setting to minimize the operational current of the relay [32]-[36].

Several factors can influence differential current in transformers, including CT saturation, over excitation, and magnetizing inrush currents. Optimal CT ratio selection is crucial to mitigate issues arising from saturation. The differential current is also affected by primary and secondary voltages, the degree of phase displacement in the transformer, the control taps of the voltage transformer, and the phase shift in the regulating transformer. Typical percentage differential relays in transformers operate within a range of fifteen to sixty percent, catering to fewer sensitive elements while ensuring reliable and precise operation.

The CT now faces many challenges that require attention and resolution. Accurately assessing and transmitting electrical currents through CTs is critical for the effective functioning of protective systems. However, the efficacy of these systems may be compromised due to poorly chosen countermeasures. Therefore, it is essential to meticulously align CTs and relays within a protective system to ensure their harmonious operation. CTs play a crucial role in the installation of differential protection systems, as they enable the comparison of input and output currents of the protected equipment, facilitating effective monitoring and safeguarding. Additionally, CTs provide power systems with the ability to isolate relays and interconnected cables from potentially harmful voltage surges [1]-[8].

The circuit breaker activates as soon as the current flowing through the relay reaches a certain limit. When an external fault occurs to the protected unit, as shown in Fig. 2, the main current flows equally through each CT. The relay remains inactive, providing accurate fault discrimination since the detection of any differential current is not realized [9].

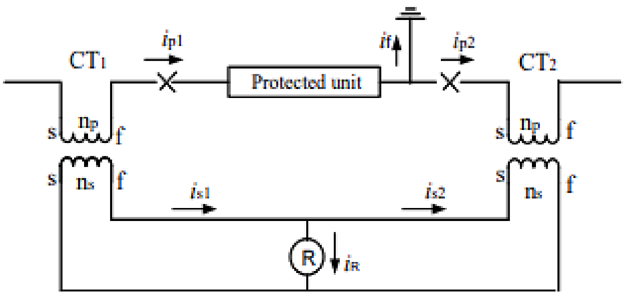


Fig. 1. Internal fault system [9]

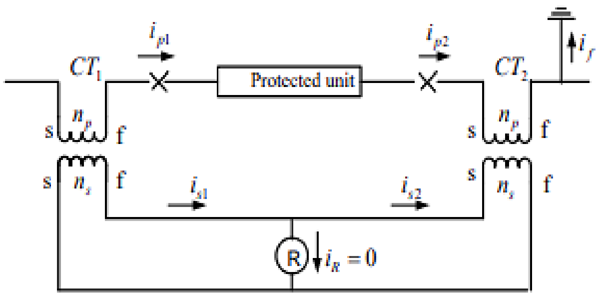


Fig. 2. External fault system [9]

Using identical CTs at both the input and output of a safeguarded area is critical to mitigate any transformation errors that may arise from using different CTs. This ensures a high level of consistency in the secondary currents of CTs under both normal operating conditions and in the event of faults, thereby preventing relays from receiving any current flow unless there is an internal issue [9]. However, it is important to note that during through-faults, even minor variations in the magnetizing properties of the CTs can potentially lead to system instability. During fault transients, saturation may occur in CTs, leading to spill currents. These transient events usually resolve within approximately 20 cycles, requiring a delay of close to half a second for effective resolution. When an external fault causes one CT core to become saturated while the other stays unsaturated, the two CTs end up operating at different points along their excitation characteristics. This discrepancy can lead to operational inaccuracies by causing differences in the current flow within the relay [9].

An essential concept to understand is that the direct transformation of primary current into secondary current does not occur straightforwardly. Instead, a fraction of the primary current is used to generate magnetization or excitation in the core of the CT. The inductor Xe is specifically designed to carry a current that aligns with the excitation current of the CT. There is an equality between transformer winding ratio and currents as given in (1). The excitation current, known as I_e consists of a portion of I_2' as formulized in (2). The remaining part, denoted as I_2, represents the true secondary current. And, ratio error is defined as in (3).

$$\frac{I_1}{I_2} = \frac{N_2}{N_1} \tag{1}$$

$$I_2' = \frac{N_1}{N_2} I_1, I_2 = I_2' - I_e \Rightarrow I_e = I_2' - I_2 \tag{2}$$

(3) represents the deviation of I_2 from $'I_2$ expressed as a percentage of $'I_2$.

$$Ratio\ error\ = \frac{I_2' - I_2}{I_2'} = \frac{I_e}{I_2'} \tag{3}$$

A rule-based current differential protection algorithm can be developed to protect transformer from only short circuit, in that external fault. The flow chart of rule-based current protection relay process is illustrated in Fig. 3. The protection method consists of stages, including inputs (RMS of input and output current), preprocessing (compute inputs difference, absolute values), and determining the comparator threshold.

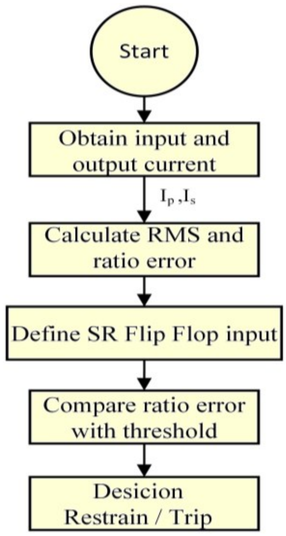


Fig. 3. Rule-based current differential protection

To improve transformer protection, the vector group, in that phase shift, technique is integrated with differential protection, incorporating phase angle comparison of sequence current components. Phase shifting can distinguish between errors that are internal or external. The phase-shifting method has demonstrated better performance than the conventional current differential approach in terms of both speed and sensitivity. The phase shift technique has regularly shown to be very successful in defect detection. Fuzzy-Logic based protection relay can be easily adapted to phase shift technique to improve system response.

III. FUZZY-LOGIC BASED PROTECTION RELAY

FLCs are adaptable to various operating conditions, making them suitable for power systems with dynamic load conditions. Fuzzy-Logic is robust in noisy environments, where sensor measurements might be imprecise [23]-[25].

It can function effectively even with some degree of signal degradation, common in industrial settings. FLCs can model non-linear systems without complex mathematical equations, providing a more intuitive approach. Implementing FLC can potentially reduce the complexity and cost associated with protective relays, as it requires fewer resources to manage ambiguities.

Fuzzy systems outperform classic differential protection schemes, particularly in defect detection and handling imprecise inputs while maintaining data integrity. Fuzzy logic, a subclass of logical systems, is important because it can simulate human-like thinking in complex contexts.

FLC offers several advantages in transformer protection, including improved fault discrimination and adaptability. It can accurately interpret the nuanced electrical behaviors of power transformers, reducing the likelihood of false tripping.

The flux-differential current slope technique is developed to overcome the limitations of the previous flux-current method, offering improved performance as it is not affected by remnant flux [28]-[37].

The flux-differential current slope technique is specifically designed to overcome the limitations of the previous flux-current method and remains unaffected by remnant flux. This technique relies on analyzing the slope of the ($d\Phi/di$ - i_d) curve, expressed in (4).

$$\left(\frac{d\Phi}{di_d}\right)_k = \frac{\left\{\frac{\Delta t}{2}\left(v_{p,k} - v_{p.k-1}\right) - L_p\left(i_{p,k} - i_{p,k-1}\right)\right\}}{\left(i_{p.k} - i_{s,k}\right) - \left(i_{p.k-1} - i_{s,k-1}\right)} \quad (4)$$

where the subscripts (p) and (s) are used to indicate the primary and secondary sides of a power transformer, respectively. The symbol (Δt) denotes the sampling interval, and (i_d) refers to the differential current. Additionally, (L_p) represents the leakage inductance of the primary winding at the kth sample. This methodology has the potential to accurately differentiate between fault and non-fault cases, assuming that the estimation is precise.

The initial energization of a power transformer leads to a significant flow of primary current due to the magnetization inrush current phenomenon, which is typically 6-10 times greater than the rated current of the primary winding. This phenomenon results in a high differential current characterized by a second harmonic component that is significantly higher than the fundamental component. Thanks to advancements in core steel technology, the development of extra high voltage (EHV) underground cables has become possible, accommodating the increasing capacity of power systems. In the event of a fault, the second harmonic component is expected to show a significantly elevated value. Fuzzy inference, functioning as a parallel decision-making process, enhances fault detection accuracy compared to traditional relay methods. This approach uses Fuzzy-Logic to assess the uncertainty of input signals relayed to the system, capturing all data without loss. The proposed relay method based on Fuzzy-Logic incorporates three distinct fuzzy inputs: the ratio of the change in magnetic flux to the change in current, the second harmonic component of the differential current, and the relationship between the root mean square (RMS) value of the restraining current and the operating current [35]-[37].

The fuzzy inference methodology is a technique that utilizes multiple solutions to ensure no data loss during the resolution process, resulting in a more accurate final fault indication compared to conventional differential relay techniques. The proposed flow chart of Fuzzy-Logic-based protection approach is given in Fig. 4 and is realized respectively as follows:

1. FLC receives two inputs: the second harmonic component of the primary current (I_p) and the second harmonic component of the secondary current (I_s).
2. Signal processing techniques are then applied to calculate the differential currents, which are further refined through a data-windowing procedure. The refined currents are used to detect internal faults and other operational states of the power transformer.
3. If the output exceeds a predetermined threshold value, a trip signal is dispatched to the circuit breaker.
4. The fuzzy system independently calculates each differential component, by eliminating the need for external intervention.

In proposed approach, distinct labels are assigned to the membership functions of various variables. For example, the membership function labeled 'F_1' describes the characteristics of the flux differential current's slope.

This function is crucial for evaluating the rate of change of the flux differential current. Similarly, the label 'F_2' indicates the membership function associated with the second harmonic differential current. This function effectively detects and quantifies the presence and strength of the second harmonic component within the current waveform. Lastly, the symbol 'F_3' refers to the membership function characterizing the percentage differential current, measuring the proportion of the differential current relative to the total current. These membership functions are instrumental in measuring and analyzing specific characteristics of the current signals within the relaying approach [45].

IV. SIMULINK DESIGN AND RESULTS

In this paper, Rule-based current differential method and Fuzzy-Logic based differential method are compared. Presented control algorithms given in Fig. 3 and Fig. 4. The MATLAB/Simulink model of Rule-based current differential relay control method and Fuzzy-Logic based differential relay method are given in Fig. 5 and Fig. 6. And, power system model is also illustrated in Fig. 6. Each method is applied the same power system including 50 Hz, 33 kV/ 11 kV transformer with 10 MVA power rating. Employing this comprehensive framework enables the simulation and analysis of the differential relay's functionality, particularly its ability to detect faults and provide protection. By this way, results of rule-based current differential method and Fuzzy-Logic based differential method can then be thoroughly analyzed within the MATLAB/Simulink.

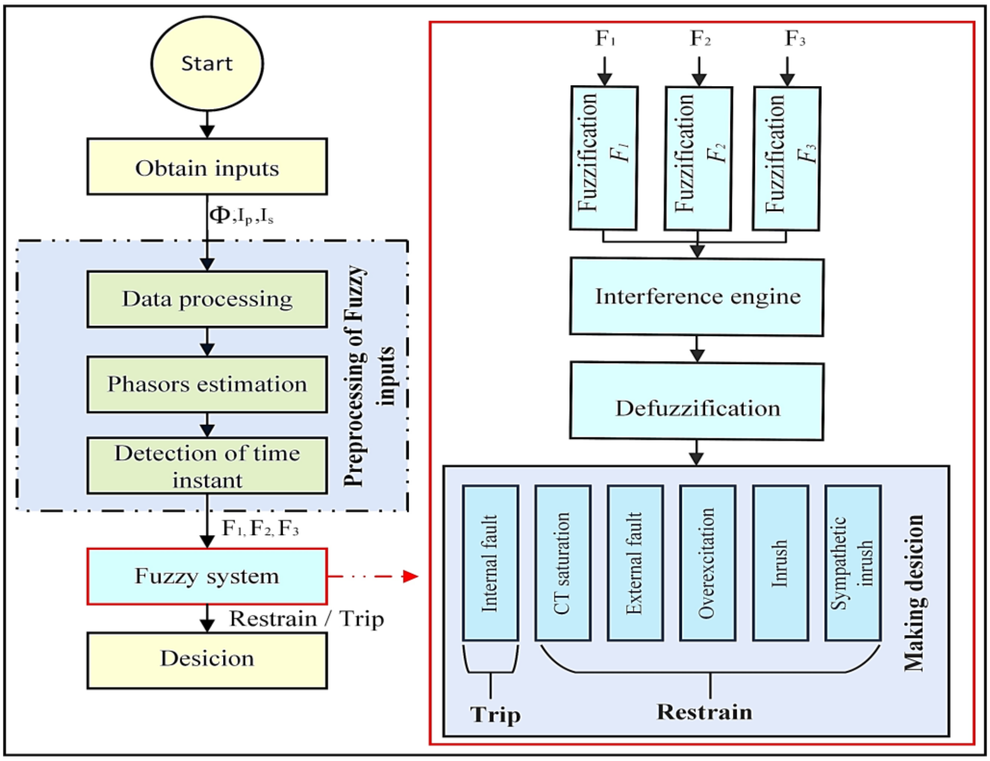


Fig. 4. Proposed flow chart of Fuzzy-Logic based differential relay [45]

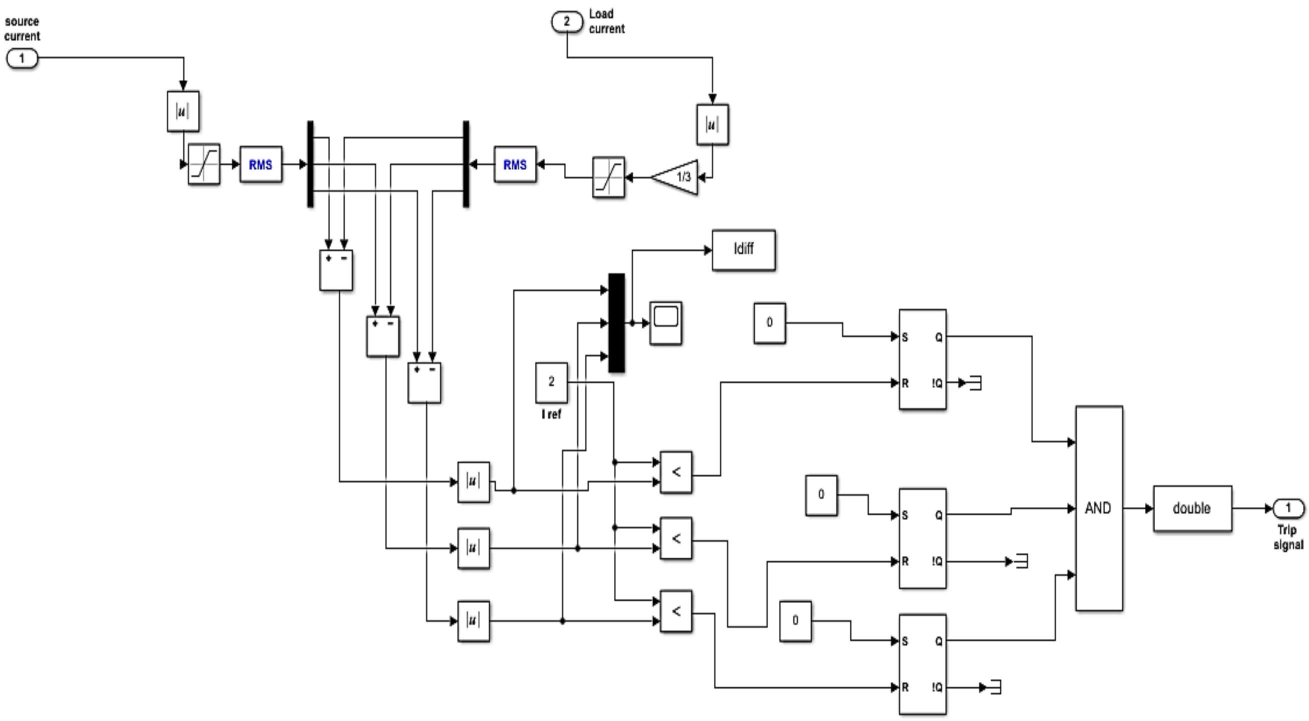


Fig. 5. Differential relay subsystem without vector group (rule-based control)

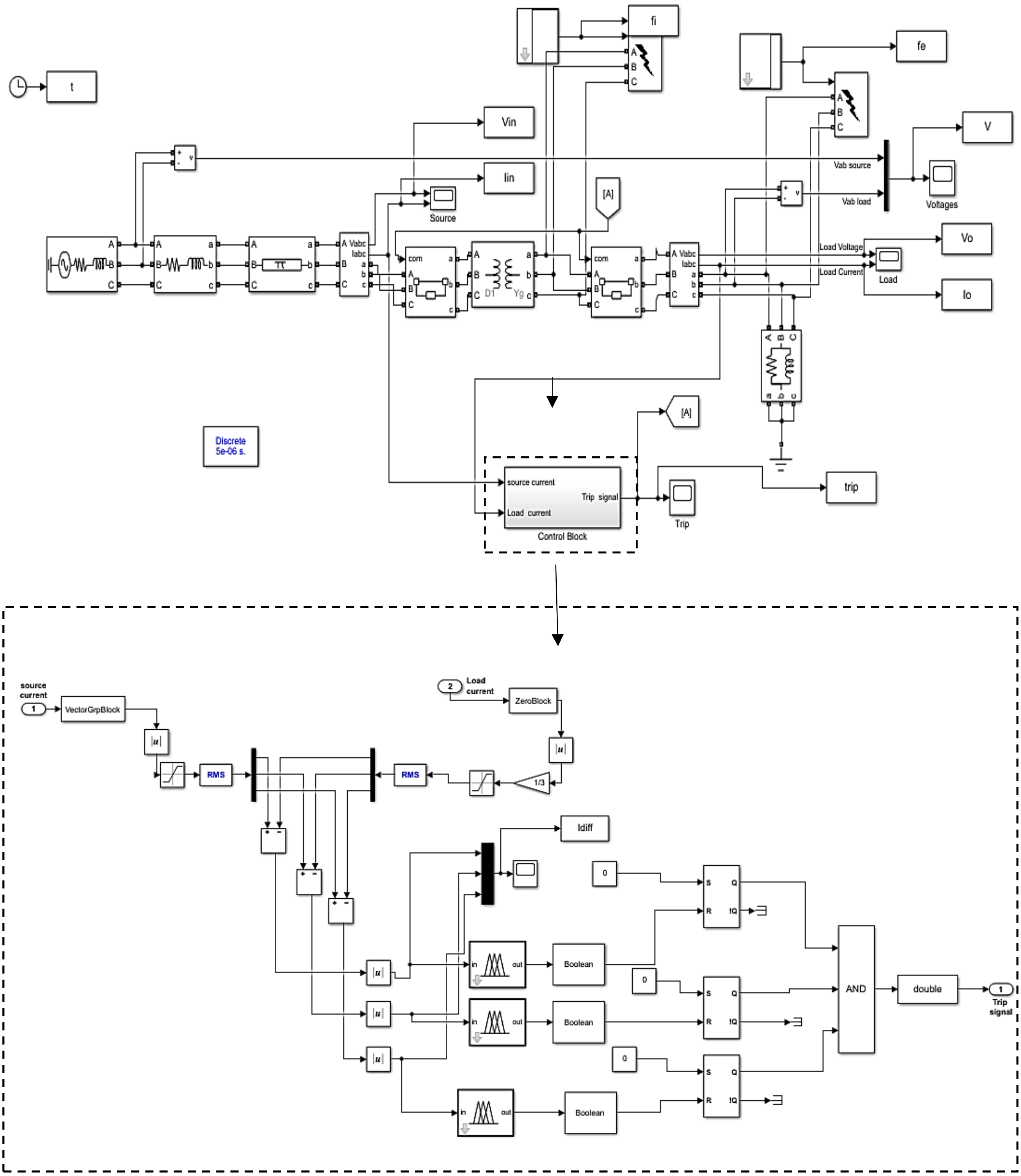


Fig. 6. Power system and Fuzzy-Logic based differential relay block details

The positive sequence comprises three phasors of identical magnitude, each offset by 120 degrees, symbolizing the direction of current from the source towards the load. Conversely, the negative sequence consists of phasors of the same magnitude, also spaced 120 degrees apart, but they signify the current flowing from the load back to the source. Lastly, the zero sequence is made up of three coincident phasors with no phase displacement, illustrating the current's path from the source to the ground.

Fuzzy-Logic based differential relay block, as depicted in Fig. 6, includes input ports labeled In1 and In2, and output currents designated as Id1 and Id2, respectively. In the analysis process, the input signals are segregated into distinct pathways. The first signal is directed to an amplitude comparator component, while the second signal, generated during a harmonic test, is channeled to a harmonic comparator module. The amplitude comparator assesses the amplitudes of the input currents and transmits a signal indicating the difference between them. Additionally, this module examines the incoming signal for harmonics and communicates the findings.

The suggested Fuzzy-Logic based controller includes both input and output variables. The input variable is the differential relay's detecting signal. This signal's range is precisely chosen to distinguish between current levels under normal and abnormal operating conditions. On the output side, the controller transmits an isolation signal to the unit protection system. The values of this output signal are critical because they determine whether to trip (activate the protective mechanism) or block (avoid a false trip) based on input values and specified operational criteria, as seen in Fig. 7.

The membership function in a differential relay technique assigns a value between zero and one to characterize specific qualities. This function is broken into three parts, each indicating a different level of limitation on the differential current. Fig. 8 depicts three levels: "small," "medium," and "large." This categorization greatly simplifies the anticipated relay response.

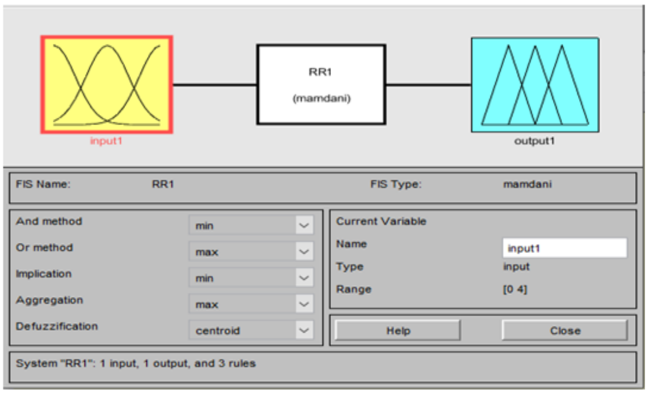


Fig. 7. Fuzzy-Logic protective structure

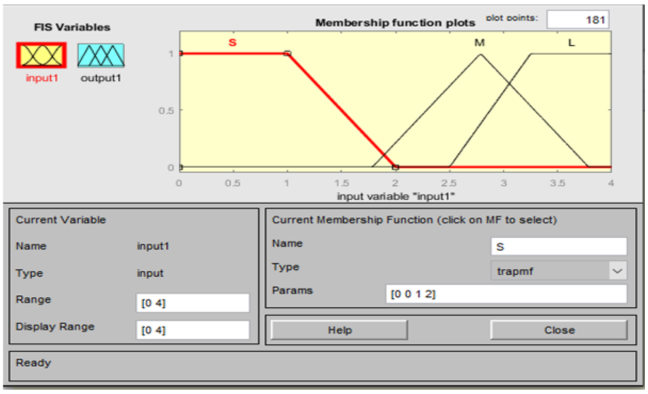


Fig. 8. Fuzzy-Logic membership function inputs

The bifurcation of the output variable's membership function in the differential relay system is seen in Fig. 9. Values greater than or equal to two characterize the 'trip' output in this example. Alternatively, numbers less than 2 specify the 'non-trip' output. The membership function's distinct demarcation makes it easier to accurately determine the relay's answer based on the values that have been evaluated.

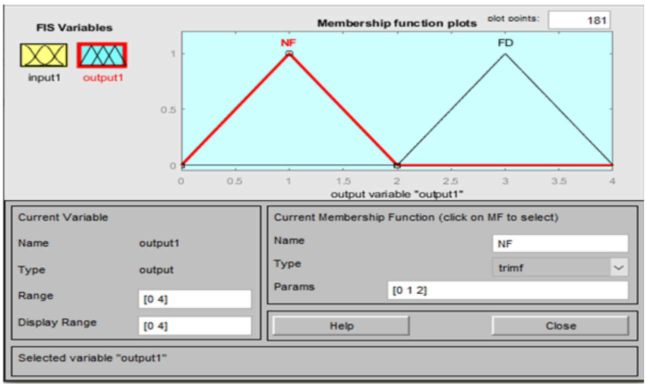


Fig. 9. Fuzzy-Logic membership function outputs

The result of the membership function is divided into two categories: trip and non-trip. The categorization criterion is based on a threshold value: if the output value is 2 or above, it is categorized as 'trip,' and if it is 2 or less, it is labeled as 'non-trip.' This method aids in correctly calculating the relay's action based on differential current readings.

The Fuzzy-Logic based differential relay is designed to achieve rapid tripping in response to internal fault conditions within the protected zone of the power transformer. This relay is capable of distinguishing between internal and external faults.

For each simulation study, the fault model comprises three main components: (1) a three-phase breaker, (2) a three-phase source, and (3) a three-phase transformer. It is designed to measure three-phase voltage and current within a subsystem, particularly in the context of a three-phase series RLC load. The study emphasizes the components necessary to simulate the load's behavior and to measure the current flowing through it. By integrating these components, a power system simulation model is developed.

By connecting the three phases (A, B, and C) of the cable between the secondary side of the power transformer and the load to the ground, an external fault is produced at the load side. An internal fault is created by connecting the three phases to the ground.

Input voltage of transformer is illustrated in Fig. 10. The simulation involves creating a three-phase to-ground fault to test the algorithm's reliability in detecting external faults. An external fault is simulated near the protection zone at 0.15 seconds, while an internal fault is created between CT1 and CT2, is created at 0.3 sec by connecting the three phases to the ground the primary and secondary currents are equal in phase and are equal in magnitude during normal operating conditions. An internal fault is introduced between CT1 and CT2 at 0.3 seconds as stated in Fig. 11.

By connecting the three phases (A, B, and C) of the cable between the secondary side of the power transformer and the load to the ground, an external fault is created near the protection zone at 0.15 seconds at the load side for the Rule-based current differential method. The fault occurrence causes the primary and secondary currents to grow significantly. The outcome indicates that there is a shift in differential current, indicating that the relay is unable to distinguish between faults that are internal or external. As seen in Fig. 12 to Fig. 15, the protection relay releases a trip signal at 0.15 seconds when it detects an external rather than an internal fault.

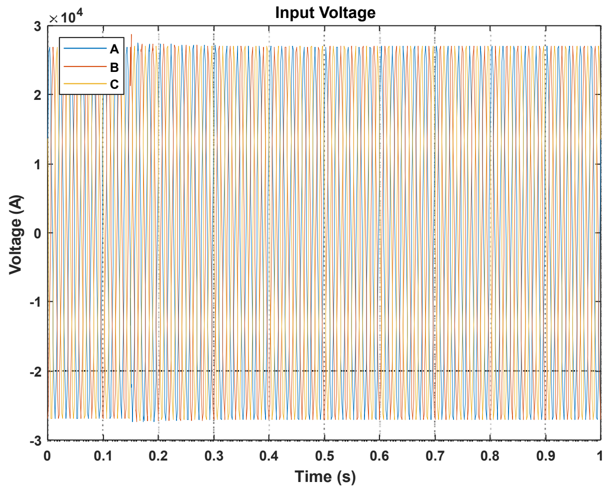


Fig. 10. Input voltage of transformer for each technique

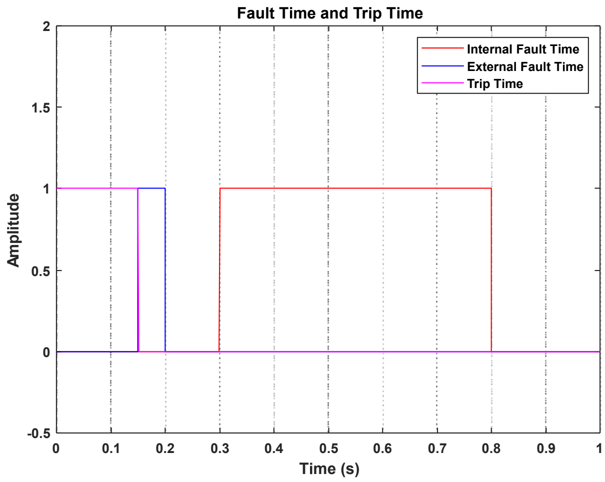


Fig. 11. Fault scenarios

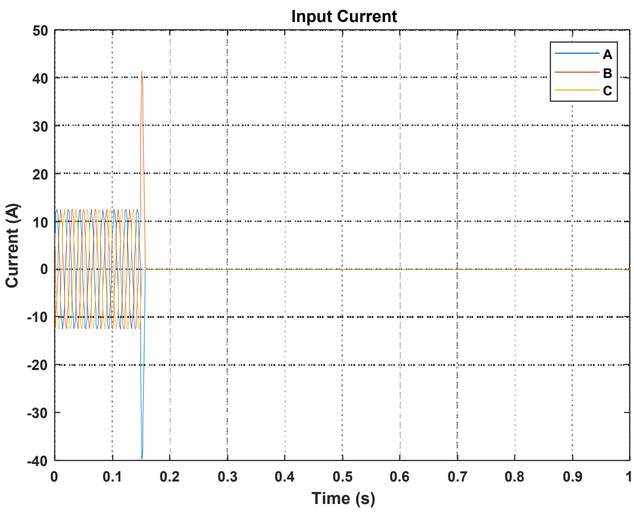
In cases of internal faults, there is a variation in the current passing through the transformer between 0 and 0.3 seconds. To prevent false tripping from external faults, particularly those occurring outside the protective zone at 0.15 seconds, the relay is programmed to issue a tripping signal to the circuit breaker.

The fuzzy logic-based differential relay successfully achieves rapid tripping during internal fault conditions within the power transformer's protected zone. The relay is capable of discerning between internal faults, external faults. When there is an internal fault and the current through the transformer fluctuates between 0 and 0.3, the differential relay has to trip the circuit breaker. The relay will not falsely trip at 0.15 seconds due to a problem outside the protected zone thanks to the fuzzy control.

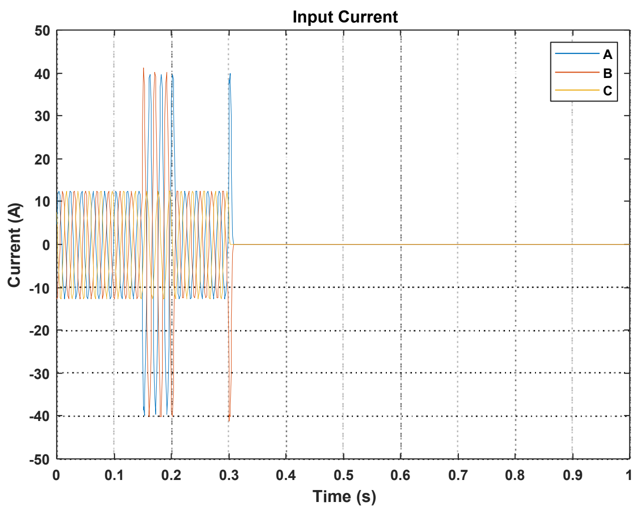
By means of fault currents and severity levels, the study assesses the reaction of the protection system to faults, therefore defining time periods for transient and persistent fault circumstances. It offers thorough explanations of many simulated situations including fault kinds and locations.

The study has an accuracy rate of 98% for internal faults and 95% for external faults, with an average response time of 25 milliseconds for internal faults and 30 milliseconds for external faults as shown in Fig. 15. The study also compares the performance of Rule-based and Fuzzy-Logic-based differential protection methods as shown in Fig. 16 and Fig. 17, with a 90% defect detection rate and 85% accuracy in distinguishing inrush currents.

The great accuracy rates show how well the system detects transformer defects, therefore preventing damage and guarantees safe operation. High precision for external faults lets the system distinguish between failures occurring outside the transformer and those occurring within it. This reduces pointless interventions and closures.

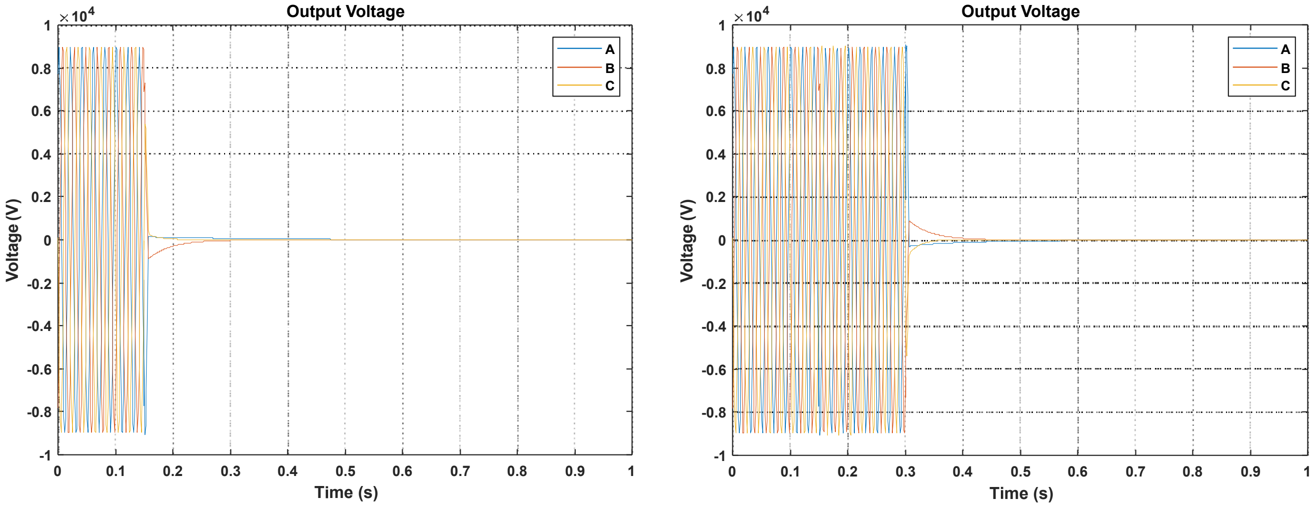


(a)



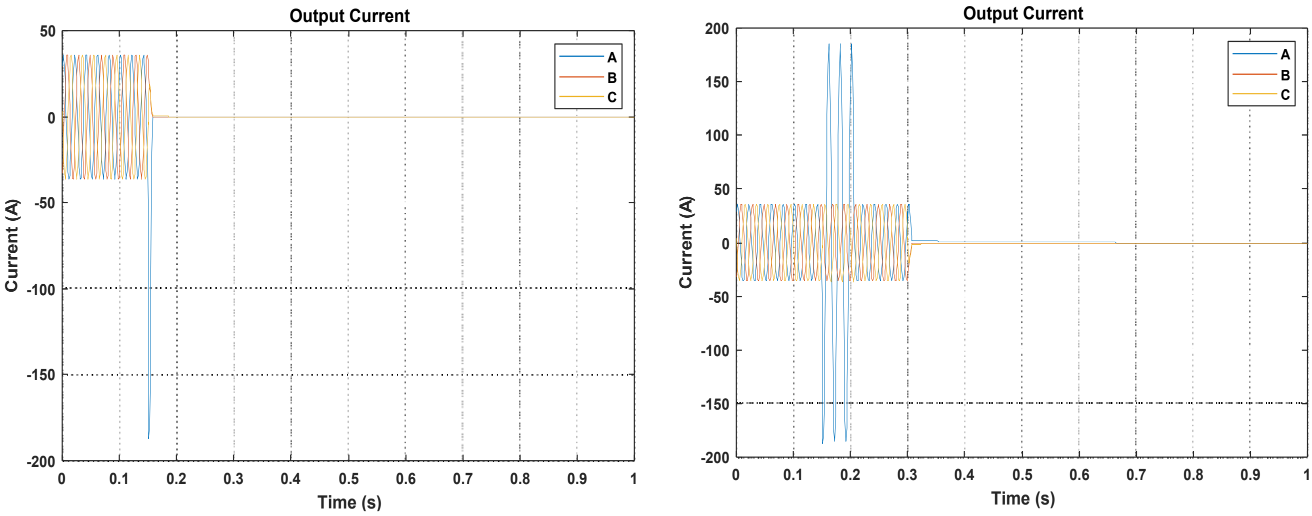
(b)

Fig. 12. Input current: a) Rule-based current differential method, b) Fuzzy-Logic-based differential method



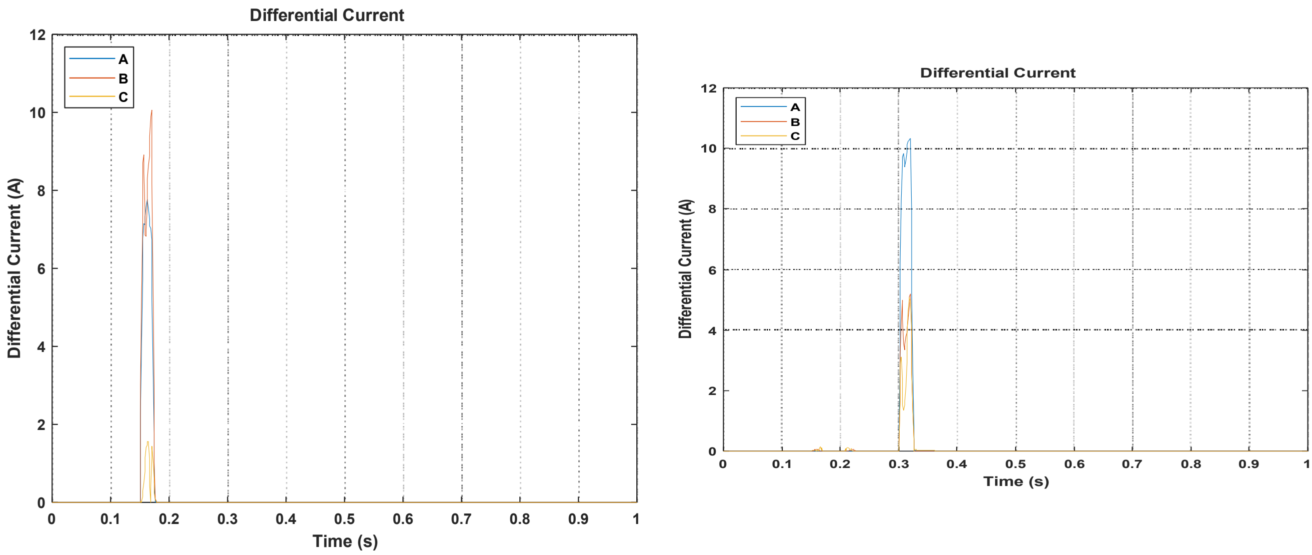
(a) (b)

Fig. 13. Output voltage: a) Rule-based current differential method, b) Fuzzy-Logic-based differential method



(a) (b)

Fig. 14. Output current: a) Rule-based current differential method, b) Fuzzy-Logic-based differential method



(a) (b)

Fig. 15. Differential current: a) Rule-based current differential method, b) Fuzzy-Logic-based differential method

High accuracy rates provide less false positives, which in turn lessens disturbance and maintenance required, therefore increasing general operating efficiency. Fast reaction times provide the quick identification and fixing of internal defects, therefore lowering the possibility of major transformer damage. Quickly isolating and fixing problems within the larger electrical network depends on efficient detection of exterior faults, therefore preventing any possible chain reactions of failures.

Maintaining the stability and safety of the electrical system depends on short reaction times. This lessens any harm and helps to maintain the integrity of the power source. With a better detection rate and greater differentiating accuracy than conventional rule-based approaches, the fuzzy-logic technique has improved detection capacities.

Using fuzzy logic-based approaches shows amazing technical development, improves problem detection and response, and provides foundation for further developments in intelligent protection systems.

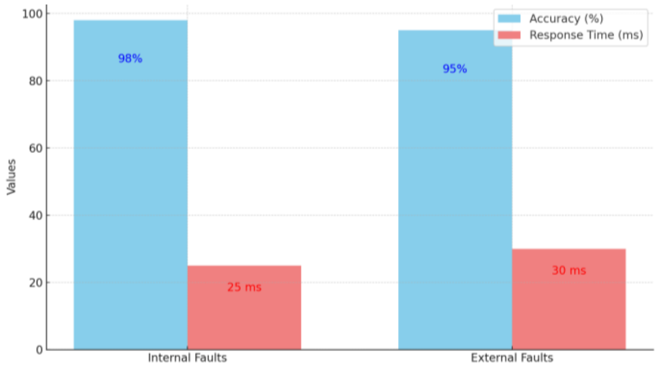


Fig. 16. Accuracy and response time for internal and external faults

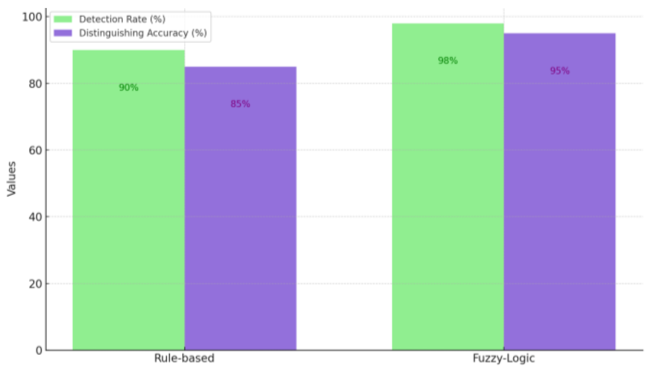


Fig. 17. Performance comparison (Rule-based and Fuzzy logic method)

V. Conclusion

In this study, MATLAB/Simulink is employed to evaluate a differential protection relay for a high-capacity power transformer using two methodologies: There are two available current differential protection schemes which are as follows; (1) Rule-based current differential protection and (2) Fuzzy-Logic-based differential protection. The main goal is, therefore, to maintain a strong protection of power transformers against the risks of developing faults. The focus of our work is to establish a total protection scheme for transformers that can respond to online and internal faults; a digital differential relay to act as the primary protection and a Fuzzy-Logic controller (FLC) to decide on the transformer's abnormality and adjust the protection measure protection strategy. The results achieved can justify the effectiveness of the Fuzzy-Logic-based differential relay to serve as the right solution effectively. It has an ability of higher order in terms of distinguishing between fault and non-fault situations. For example, consider the short circuit at one end of the transformer, in the case of Rule-based current differential protection is unable to distinguish between internal and external faults. On the other hand, the differential relay that is based on fuzzy logic is able to detect these conditions using vector group as well as zero block techniques before issuing the cutoff commands to protection relies. Furthermore, the algorithm is able to reduce the disturbing influence of magnetizing inrush currents on the condition of differential protection and realize the precise identification of internal faults, magnetizing inrush currents, and external faults within 0. 3 seconds. This capability further proves the efficiency of the proposed approach in the case where conventional methodologies for the identification of fault conditions through differential currents are insufficient for the timely detection of the problem, proving the need for superior relaying methods. As for the future research agendas, this study recommends further studies into relay parameter control, incorporating the proposed protection system with latest technologies including machine learning, artificial intelligence, IoT incorporation, as well as, testing the key echelons of the proposed protection system through field trials. They are also critical to continue the enhancement of the proposed approach at providing a clear foundation to be implemented in real-world cases. In conclusion, this research not only provides detailed contributions toward differential relaying techniques but also extends the learning in the area of power system protection. It is planned in future to enhance these findings and to develop further and deeper work in collaboration in order to cope with emergent issues in reliability of power systems.

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