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Comparative Evaluation of Distance and Differential Protection Schemes for Power Transformers under Inrush and Fault Conditions

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Abstract

Power transformers constitute some of the very fundamental parts of power systems and they are important correlations in the delivery of electricity. As a result of their sensitivity and high price, highly reliable protection against abnormal conditions is crucial to system stability and service continuity. This paper involves a detailed study of the transformer protection performance when differential and distance protection schemes are combined to achieve great reliability, selectivity, and speed in different operating conditions. The response was simulated and modeled to provide the reaction of the system to normal operation, external faults, internal faults, magnetizing inrush, and load changes. Time domain current waveforms and frequency domain harmonic spectrums were assessed to differentiate between fault-induced and non-persistent conditions. The differential protection was found to be highly sensitive and fast-acting to internal faults and the distance protection offered effective backup as well as accurate fault localization. A harmonic restraint algorithm designed on the second harmonic ratio (H2/fundamental) was used to prevent maloperation when transformer energizing was going on, which was effective in differentiating between inrush and actual fault conditions. Comparative studies of the two protection schemes evidenced that coordinated operation improves reliability of the protection of transformers. The results of the simulation confirmed that the proposed system of integrated protection can be used in accordance with the necessary requirements of speed, selectivity, and reliability, which ensures the accurate detection of faults without false tripping during non-fault transients. The results demonstrate the necessity of using both conventional protection techniques and signal processing techniques, which will lead to the intelligent protection architectures of the future using wavelet transforms and machine learning-based fault classifiers. Also, a long-performance and sensitivity analysis was performed to determine the effects of second harmonic blocking threshold and high-impedance internal faults on the reliability of protection. The findings indicate that under ideal harmonic restraint settings are effective in minimizing the occurrence of false tripping, whereas the hybrid protection scheme proposed is efficient in enhancing the strength of fault detection in unfavorable operating environments.

Keywords

Fault Conditions, Inrush Current, Distance Protection, Differential Protection, Power Transformer Protection

1. Introduction

The electric power system is recognized as a vital infrastructure for supporting industry, economy, and society in contemporary civilization. The electric power system provides a spine for interconnecting generation, transmission, and distribution networks to provide a stable supply of electricity to consumers continuously. As a result of increasing demands for electric power and an expansion in interconnected systems, stability, reliability, and protection of electric power systems have emerged as operational needs in recent years. Electric current discontinuities in different natures, including current discontinuities, insulation failure, and transient disturbance, threaten electric systems severely, meaning that protection systems play an important role in disconnecting affected regions instantly to limit damage to systems.

Of all the different components in a power system, it is perhaps the transformer that is most expensive as well as most susceptible to unusual events. While playing an immensely critical part in efficiently stepping up/down voltages to transfer electric power from one level of voltage to another, they remain susceptible to unusual events, which include internal anomalies such as winding shorts, insulation failure, external malfunctioning, line-to-line malfunctions in neighboring lines, as well as transient operating conditions, including magnetizing inrush current, which is an event observed during transformer energizing, as well as core saturation because of voltage distortion, which also appear to result in an unusual current level, resulting in potential malfunctions of protective schemes in conventional relays until appropriate methods for discrimination between actual incidents, including those unusual, are devised [1] [2].

The differential protection system is known as one of the most sensitive techniques of transformer protection in use today. The principle behind this protection system is to compare the ·output and input currents of transformer windings. A large deviation in both output and input currents represents an internal malfunction in the transformer [3] [4].

The disadvantage of this protection system is that false trips may result during magnetizing inrush currents or overvoltage conditions, unless restrained by harmonic restraint algorithms [5] [6]. The distance protection system, in contrast to previous protection methods, is designed to function in relation to measurements of apparent impedances ($Z = V/I$) between protection zones, including relaying locations, as well as locations of possible defects in lines [7] [8].

As the apparent values of impedances decrease below predetermined thresholds in cases of malfunction, this technique is primarily placed as an ancillary protection strategy to cover even more accurate results during different scenarios of malfunctions as well as line conditions [9] [10]. It shows how differential and distance protection relays provide protection to a transformer as well as connected transmission lines. While differential protection, as stated earlier, provides protection to the transformer at low- as well as high-voltage sides by current, protection from distance protection is primarily measured as a function of line voltages as well as line currents at transmission lines connected to the transformer. Modern development in Digital Signal Processing (DSP) algorithms is making wave analysis in time as well as frequency domains an imminent requirement in sophisticated protection systems [9] [10]. **Table 1** shows the Comparative Characteristics of Differential and Distance Protection.

Table 1. Comparative characteristics of differential and distance protection.

Parameter	Differential Protection	Distance Protection
Operating Principle	Compares input and output currents of the transformer	Calculates apparent impedance ($Z = V/I$) to determine fault distance
Protection Zone	Limited to the transformer windings	Extends to nearby transmission lines
Response Time	Very fast (<0.05 s)	Moderate (0.1 - 0.3 s)
Accuracy	High for internal faults	Moderate, depends on fault impedance and line conditions
Sensitivity to Inrush	May maloperate without harmonic restraint	Generally immune to inrush current
Practical Role	Primary protection	Backup protection

While time domain analysis offers visual verification of transient current changes during a fault, frequency domain analysis tools, including the Fast Fourier Transform (FFT) function and Discrete Wavelet Transform (DWT), allow accurate detection of frequency bands that correspond to different types of fault conditions. The use of the second harmonic index (H_2/fundamental) has been very useful in distinguishing between inrush current conditions and internal faults. A high harmonic level is an indication of an inrush current, whereas a low level is an indication of actual fault conditions, which makes harmonic-based restraint a very reliable means of improving transformer differential protection.

The importance of this work resides in its purpose of designing and assessing an integrated protection system, which leverages the benefits of both differential protection schemes as well as distance protection schemes to provide increased security, speed, as well as selectivity of transformer fault detection capabilities by examining current and voltage waveforms in both time as well as frequency domains for Enhance internal fault discrimination accuracy when dealing with transient conditions such as magnetizing inrush; Offer analysis improvement methods using harmonic analysis, wavelets, etc.

Simulation-based modeling in this study helps to find ways to minimize false trips, improve dependability, as well as provide constant power supply using advanced protection algorithms.

The theoretical foundations of differential protection, in conjunction with distance protection and second harmonic blocking, are well understood. In this context, this research provides practical contributions by considering the robustness of the proposed scheme, as well as the sensitivity of its performance to certain variables, such as the settings of the relays and the degree of challenge of the fault conditions. In particular, this research considers the extent to which second harmonic blocking, in the presence of high-impedance internal faults, affects protection reliability and speed, as well as protection dependability. While prior studies have considered events from the faults to be ideal or have held the relay settings constant, this research provides an empirical estimation of the performance of the system. In particular, the study demonstrates that operational protection parameters can be refined to increase protection performance, operational security, and reliability to an appreciable degree. This study helps to incorporate practical performance criteria into protection system design rather than protections system design in a vacuum. From this beginning, this section describes in detail an analysis of previous literature that dealt with harmonic analysis, wavelet analysis, as well as intelligent decision-making systems in transformer protection schemes, in an attempt to identify important milestones in past research and provide a reason for this work, which proposes to combine discrimination in both domains for transformer protection purposes.

Although the techniques such as differential protection, distance protection, and second harmonic blocking have been well established in the realm of transformer protection, the significance of this work does not rely upon introducing a new concept for protecting transformers, but rather quantifying an evaluation criterion based up-on performance in a non-ideal environment. As opposed to former works that tend to validate a function in an ideal fault situation, this work highlights the robustness of performance, sensitivity, and the limitations of fault detection for conventional methods.

The key contributions of this study can be stated as:

1) Sensitivity analysis related to the second harmonic blocking threshold, emphasizing the trade-off between security and speed based on normalized perfor-

mance measures.

2) Comparison of the performance of differential and distance schemes under conditions of high impedance for internal faults—a major vulnerability in traditional transformer protection schemes.

3) Development of a hybrid decision-making scheme combining current-based protection conditions with impedance-based protection conditions for improving fault detectability under challenging operating conditions.

4) A method of quantitative evaluation with the ability to facilitate optimal relay setting configurations rather than using mere observations of waveforms.

The work intends to contribute towards filling a gap that exists between theoretical protective principles and their application in a modern power system.

2. Literature Review

Protection of power transformers has been a focal point of research in power systems because of the inrush current problem and internal fault problem. A number of studies have over the years examined sophisticated methods of improving the protection schemes of transformers with a special interest to differential protection, distance protection and hybrid or intelligent schemes.

A time-domain differentiating protection scheme that ensured a much higher quality of faults detection and at the same time has been created, was immune to magnetizing inrush currents [5]. They demonstrated that time-domain signal incorporation resulted in an increase in speed, and selectivity compared to traditional differential relays. In the same manner, a superimposed differentiated method of current that showed high reliability in distinguishing between inrush and fault currents and consequently minimized false tripping has been suggested by [9].

A comprehensive survey of the development of schemes of differential protection in inverter-based resource (IBR) has been performed to dominate microgrids and point out the fact that the traditional schemes of protection are often ineffective when there is a significant penetration of renewable resources [11]. It was found that new grids should have adaptable and intelligent protection measures. On this, [12] designed a wavelet transform-based scheme together with difference function in transformer differential protection. Their findings confirmed the fact that the wave-let-based approach is significantly superior in regards to the differentiation of the transient inrush and permanent fault currents.

Recent studies have also involved the use of artificial intelligence and machine learning. In transformer protection, Vyawhare *et al.* (2025) has applied convolutional Neural Network (CNN) together with discrete wavelet transform (DWT). Their approach was highly precise in fault condition detection and classification, which is better than the traditional schemes in noisy conditions [13]. Zhou *et al.* (2025) suggested a new measure of detecting inrush current using Wasserstein Distance Algorithm because it can be demonstrated to be more effective to enhance the difference between excitation inrush and real internal faults [7].

Other contributions also support this trend. According to Bakhshipour *et al.* (2024), the study proposed a setting-less differential protection scheme that used wavelet transform and did not have any thresholds when setting it up, thus showing high-performance operating under a wide range of conditions in the system [14]. Parihar *et al.* (2024) offered a systematic review of the faults, classification, and methods of protection of transformers and found the hybrid and adaptive techniques to be the most promising in the future. Likewise, Mohammed and Viswambaran (2024) made comparisons between overcurrent protection schemes, emphasizing their inability to work in complex fault cases and the need of differential and distance schemes to increase reliability [15].

Key *et al.* (2024) proposed a deep learning algorithm in the area of intelligent fault detection to detect internal faults under inrush conditions at distribution substations. Their findings also showed that deep models extend false alarms [16]. Similarly, Athamneh and Alqudah (2024) showed that multi-type CNN methods are effective to differentiate between inrush and internal faults and are better in terms of accuracy, and lower misclassification rates than traditional relays [17].

Although the technologies of transformer protection have advanced greatly, the joint efforts of the past have shown that it is considerably complicated to tell between initial operating currents and actual faults, particularly during transformer saturation, load varying conditions and operating angles, and growing integration of renewable energy sources and inverter-based resources (IBRs). Research to this point has been limited by assuming constant second harmonic thresholds and low resistance internal faults, thus reducing the practical applicability of the research. These studies have also predominantly skipped the examination of sensitivity to relay parameter settings, as well as the consideration of high-impedance internal faults. This has resulted in the somewhat ambiguous differentiation of these schemes, as well as a lack of discoveries regarding the more practical constraints of conventional differential or distance protection. In this sense, the present study provides a contribution by focusing on the comparative assessment within a specially defined set of normalized performance indices, and considering both the robustness and operational response effectiveness, all within the context of more realistic fault conditions likely to be encountered in a transformer.

Moreover, the use of conventional protection systems without the addition of modern signal processing methods like the wavelet analysis and additive differential method make the system less accurate and reliable when used in the modern power grid. The aim is to close this gap by creating an integrated transformer simulation model, simulations of various scenarios such as initial operating currents, internal and external faults, performance evaluation and comparison of distance relays and differential relays and sensitivity analysis to change in network conditions to the current research. It also makes viable recommendations on how the dependability and effectiveness of transformer safety can be improved in existing grids.

3. Materials and Methods

The schemes employed in this work are developed based on the fundamental theories of transformer protection. The differential method is based on the difference between the primary and secondary sides of the transformer. It is expressed as follows:

$$I_{diff} = \left| I_P - kI_S \right|$$

where I_P is the primary current, I_S is the secondary current, and k is the current transfer ratio. A large differential current with a non-zero value indicates an internal fault.

Distance protection is based on the principle of apparent impedance, that is:

$$Z = VI$$

V and I are used to represent voltage and current at the relay location. Faults are detected based on impedance values calculated to be within certain protection ranges. To suppress malfunctions during magnetizing current inrush current, a second-harmonic blocking method is employed. Second-harmonic current ratio calculation is done using the formula:

$$H_2 = I_{2nd} / I_{fund}$$

A high second harmonic content is characteristic of inrush currents, whereas internal faults are dominated by the fundamental component. This criterion is used to restrain the differential relay during non-fault transient conditions.

The approach used in this study is a simulation-based methodology that is entirely done in MATLAB/Simulink.

It dwells on comparative analysis of differential and distance protection systems of power transformers during both inrush and fault operation. The procedure includes:

- Real power network system modelling.
- Protection algorithm (differentiating and distance) implementation.
- Signal processing improvement (Fourier, Wavelet, harmonic blocking).
- Evaluation and comparing performance according to major indices.

As presented in Table 2, the general design of the simulated power system designed in MATLAB/Simulink is shown. This is conceptually a realistic electrical network, which consists of a synchronous generator as the primary source of power, a step-up transformer (13.8/500 kV) to couple to the large-scale electrical grid, and a transmission line 25 km long (one section of an external electrical grid). Circuit breakers (CB1 and CB2) are located strategically to isolate faulty circuit, current and voltage sensors (CTs and V sensors) are used to continuously monitor electrical quantities on both sides of the transformer. These measurements are sent to the MATLAB Function Block to be analyzed in real time. Besides, a load of 250 MW and reactive compensation units of 330 Mvar are added to provide the balance of power flow and guarantee the realistic working conditions.

Table 2. Components of the simulated power system and their functions.

Component	Function	Parameter Example
Synchronous Generator	Provides power input	Pm = mechanical torque input, E = excitation voltage
Step-up Transformer	Increases voltage to 500 kV	Rating 300 MVA
Transmission Line	Transfers power & faults	Length 25 km
CB1/CB2	Circuit isolation	Controlled by "Trip" signal
CTs & V Sensors	Measure current and voltage	I_p, I_s, V_{line}
Load + Capacitor bank	Realistic operating load	250 MW load, 330 Mvar compensation

The power transformer that is modeled in the simulation follows a Dyn11 configuration of a vector group, which introduces 30-degree shift of phase between the high and low voltages. This arrangement is a good way to prevent propagation of zero-sequence currents to the high-voltage side to enhance external fault discrimination.

Transformers with 1000/1 A and 2000/1 A ratio current transformers (CTs) were used on the high and low-voltage sides respectively. These ratios were chosen to be used so that there can be proper scalability of current and to reduce errors in measuring under high fault current conditions. The phase shift as well as CT ratios were adequately compensated in the differential protection algorithm to provide proper current comparison.

The protection system core performs three key protection functions (differential protection, distance protection, and harmonic blocking) on the measured quantities (I_p, I_s, and V_{line}). The differential protection compares the current difference ($\Delta I = |I_p - I_s|$) to identify faults in the internal transformer. The distance protection calculates the apparent impedance ($Z = V/I$) to determine external or near faults according to the zone limits. The harmonic blocking mechanism compares the second harmonic ratio (H_2 ratio) with that of inrush currents to differentiate between inrush currents and genuine fault conditions, and thus avoid false tripping (See Table 3).

Table 3. Components of the simulated power system and their functions.

Protection Type	Input Parameters	Decision Rule	Action
Differential Protection	I_p, I_s	$\Delta I >$ threshold	Trip-internal fault
Distance Protection	V_{line}, I_p	$Z <$ zone limit	Trip-external or near fault
Harmonic Blocking	H_2_ratio (2nd harmonic)	H_2_ratio > limit → Inrush	Block Trip Signal

It shows the protection subsystem, in which the differential and distance protection schemes are combined into the general MATLAB/Simulink environment. The interaction between the measurement's units, processing algorithms and relay decision logic is handled by this subsystem. Both protection schemes are run in parallel given the same conditions in such a way that they provide a fair comparison of their responses to faults and inrush. The differential relay block is used to continuously measure the difference between the currents on the windings of the primary and the secondary transformer to counteract the effects of current transformer (CT) saturation and magnetizing inrush. Alternatively, distance relay block uses the apparent impedance ($Z = V/I$) to compute the fault location based on predefined protection zones (Zone-1 and Zone-2). It has a signal processing unit to adjust the precision of fault identification with Fourier and Wavelet transforms and the superimposed current method. Lastly, an output logic unit would send a control signal (Trip) to open the circuit breakers when a fault is detected.

The controlling system installed in the model and it controls the entire behavior of the simulation. The control unit controls the usage of faults, program of operations and coordination of responses between the protection system and the circuit breakers (CB1 and CB2). It guarantees that faults are activated when required, and the route of the trip signals is correct as well as the system self-resets after fault clearing. The control system also organizes the initiation of various kinds of disturbances (e.g., inrush current initiation, internal faults and external short-circuits) to test the functioning of the protection schemes in various operating conditions. These events are very sensitive to their exact timing so that the simulation is stable and the results represent the actual operating conditions in the real world.

The hybrid protection scheme uses decision strategy of logical OR to improve detectability of faults in the unfavorable conditions like high-impedance internal fault. Under this logic, a trip command is given when either the distance protection criterion or the differential protection criterion is met:

$$Trip_{Hybrid} = Trip_{Diff} \vee Trip_{Dist}$$

This reasoning makes certain that the internal faults that would make the generation of adequate differential current insufficient because of a large fault resistance can be detected by the use of impedance-based distance protection. Accordingly, the hybrid scheme fills the natural shortcomings of each protection method used separately with current-based sensitivity and impedance-based robustness which leads to excellent performance.

4. Results

This model seeks to investigate the protection of transformers during different types of faults by using simulation tools available in MATLAB/Simulink software. An integrated system has been designed, which consists of a synchronous generator connected as the source, a step-up transformer rated at 13.8/500kV, a 25 km transmission line, a step-down transformer at the receiving end, disconnectors for disconnecting control, as well as current and voltage measurement devices (CTs, V sensors). Signals from different operating conditions have been applied, which include normal, internal fault, external, as well as magnetizing inrush current conditions. This has been achieved by using an intelligent protection strategy, which is based upon different methods such as differential protection, distance protection, as well as harmonic blocking.

Figure 1 illustrates the three-phase primary and secondary current waveforms under normal balanced operating conditions, indicating negligible differential current and stable system operation. The voltage and current waveforms of both the primary and secondary sides are sinusoidal, having equal values, but phase-shifted by an angle of 120˚, which is symmetrical. The value of current in phase I is represented by i, in phase II by i lead, because in this phase, current leads; in phase (I_b-I_s) stays close to zero, thus ensuring that no internal problems exist. Small differences in waveforms are due to copper losses as well as magnetic leakage. **Figure 1** serves as a standard for comparison, suggesting that the system is normal, in addition to the protection function properly maintaining the trip set to zero.

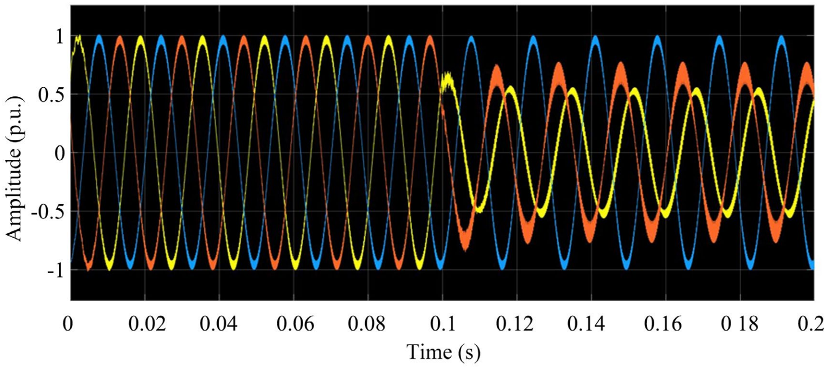

Figure 1. Normal operation-balanced three-phase conditions.

Figure 2 shows the transformer's response to an internal fault, which is a short circuit between windings. It shows the variation in differential current between protection arms during an internal fault. The current of the transformer's primary Ip rises sharply whereas the secondary current IS deviates greatly, resulting in a large amount of differential current. The system voltage drops, indicating a low-impedance internal fault. The protection function triggers due to excessive differential current above the threshold, but low second harmonic, resulting in a trip signal (Trip = 1). The fastacting trip proves sensitivity as well as the response speed of the differential protection against internal faults.

Figure 3 shows the response of the protection system for an external fault taking place in the transmission line. Both Ip and IS of rises because of the external short circuit, but they remain approximately equal, causing a negligible value of differential current. The algorithm is able to recognize this as an external fault, but no trip is sent (Trip = 0). The voltage signals in this figure display slight variations but recover quickly, signifying that the transformer is undisturbed. This figure verifies that only internal faults trigger the protection logic, but during externally caused instabilities, stability is maintained. It shows magnetizing inrush current during transformer energizing. The current in the primary winding is characterized by a large transient that is non-sinusoidal, whereas in the secondary winding, the current is small at this instant. The wave is dominated by a strong second harmonic, which is measured by H_2_ratio = I_{2nd}/I_{fund}.

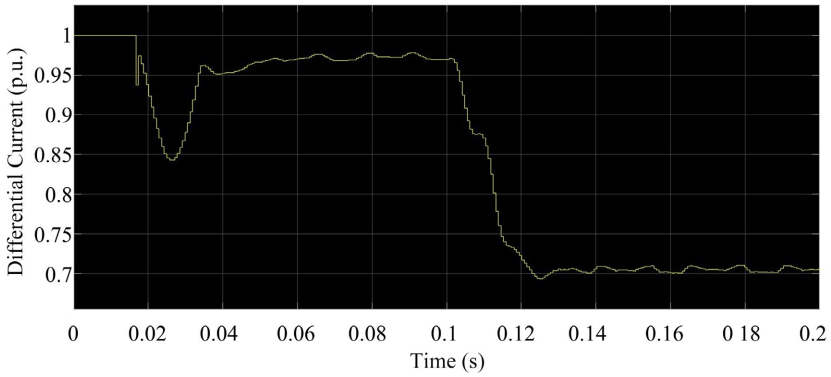

Figure 2. Internal fault-rapid differential protection response.

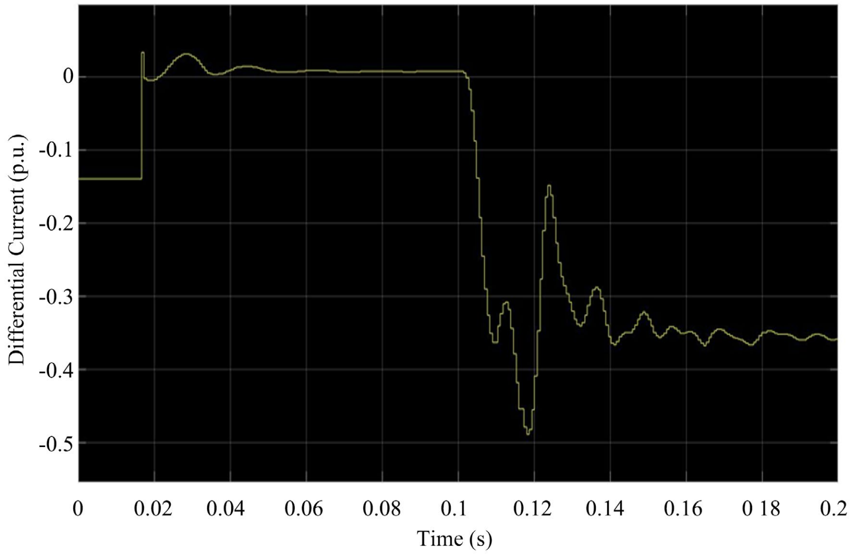

Figure 3. External fault-selective stability of the protection system.

Given that this value is above the blocking threshold, it is marked as an inrush current rather than a fault, which maintains the trip signal at zero (Trip = 0). This outcome shows that harmonic blocking is efficient in preventing false trips during energizing current conditions.

Figure 4 shows the apparent impedance $Z = V/I$ calculated from the distance protection formula. It represents magnetizing inrush behavior and harmonic blocking functionality. Impedance is high in normal conditions, which is normal, hence a healthy grid, but during Z drops greatly, even more when the fault is close to the transformer (Zone 1). As the fault location is further away from the transformer, either in zone 2 or zone 3, *Z* drops moderately, which leads to a time-delayed trip. The differences in *Z* values demonstrate that the zone discrimination function of the distance protection function is working properly, providing backup protection during an inactive differential protection.

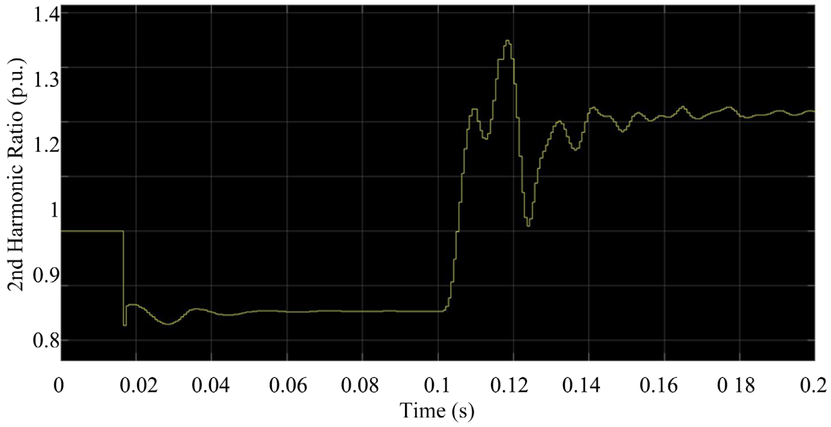

Figure 4. Magnetizing inrush-harmonic blocking functionality.

Figure 5 shows the binary trip signal resulting from using the MATLAB Function Block. The trip signal is low (Trip = 0) for normal, inrush, and external conditions but is high (Trip = 1) only for internal conditions. The transition of the trip signal exactly matches the internal fault occurrence, ensuring that the algorithm is responsive to this condition. The coordination between the differential protection zone and the distance protection zone is clear from this result.

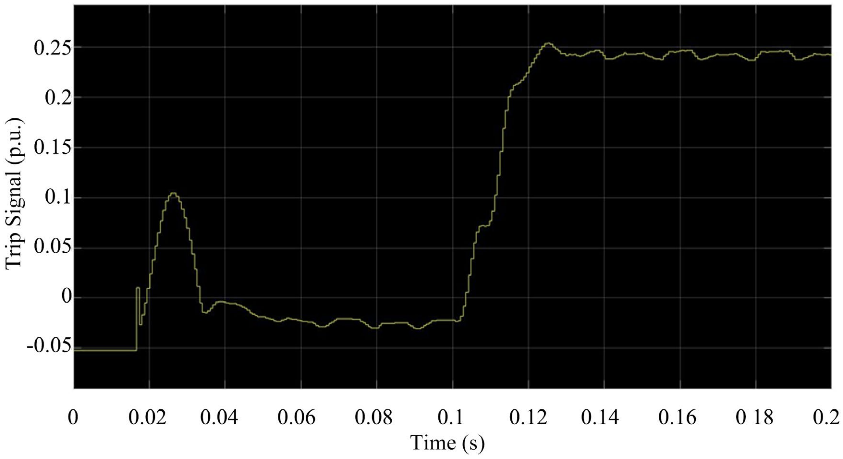

Figure 5. Trip signal-coordination between protection schemes.

Figure 6 shows how current measurement is distorted due to CT saturation during heavy fault current conditions. A flat top wave is observed, which shows that CT's magnetic core is saturated. Current measurement is also affected because of this saturation, which may result in incorrect measurement of fault current, leading to under evaluation of fault current as well as stability in the differential protection system. Refer to **Figure 7** to know the significance of using CTs of correct accuracy and saturated value or a digital compensator to rectify this issue in addition to using CT saturation detection logic for better protection of the system during heavy fault conditions.

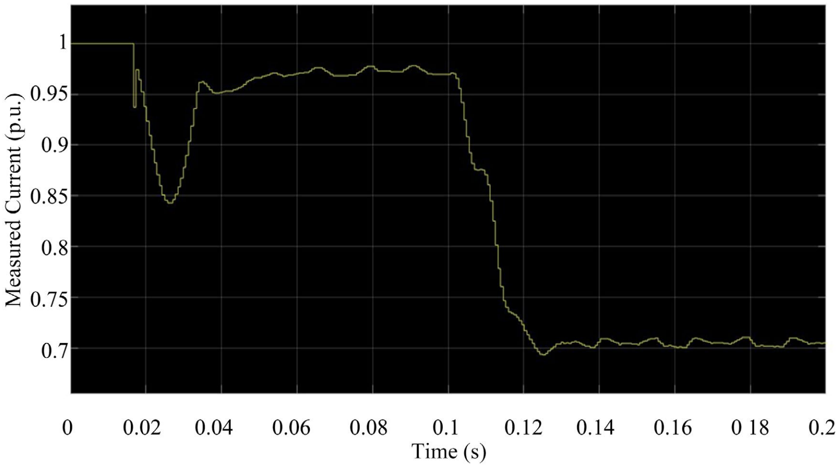

Figure 6. CT saturation-distortion and measurement error.

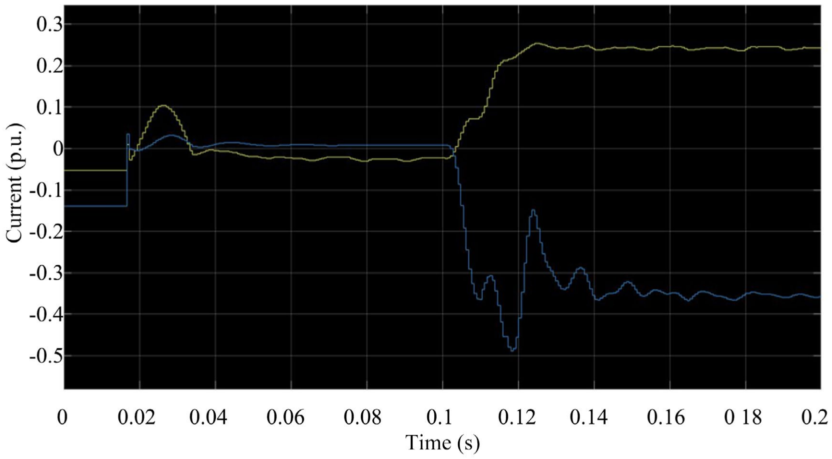

Figure 7. Load step change-protection restraint and system stability.

Figure 7 shows the response of the system to an abrupt current change in loading conditions. A step rises or fall in current is reflected, together with small changes in voltage, as the system approaches a steady state equilibrium point. Nonetheless, the differential current is always below the trip threshold, without sending a trip command signal in this process. This further validates that the protection function is safely restrained from normal system loading conditions, which in reality does not compromise system stability at all.

Figure 8 illustrates an indication of the harmonic analysis of the current wave, using FFT analysis, which provides an insight into how inrush and fault currents influence harmonic analysis, where, in normal conditions, only fundamental current is significant, but during inrush conditions, second harmonic is dominant.

From this analysis, fault current detection is vital because, by using an analysis of harmonic values, such as an assessment of second harmonic, current distinguishing is achievable, which is an important aspect in transformer protection using logic analysis of harmonic values.

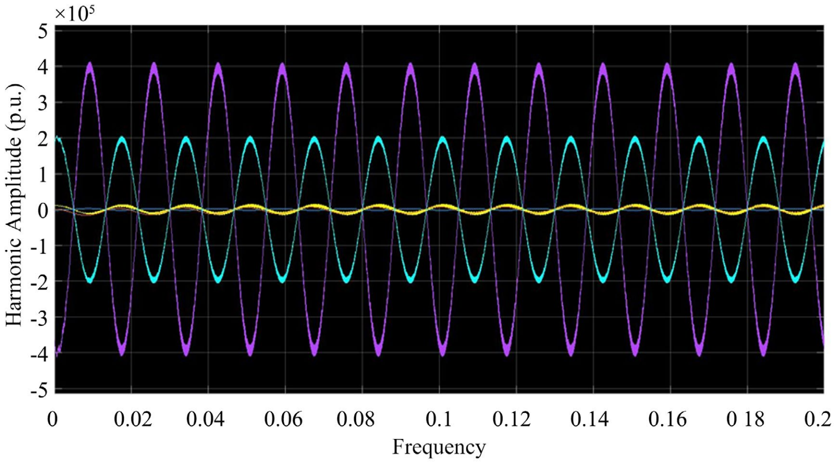

Figure 8. Harmonic spectrum-frequency-domain fault discrimination.

Table 4 indicates that the use of differential and remote protection offers an integrated system of transformer protection. Differential protection is defined as quick in response to internal fault, whereas remote protection provides a wide span of domestic faults with a controlled delay, which provides the differentiation of an internal fault and external fault and provides a better selectivity. The net result is this combination of systems, which causes an optimal balance of speed and reliability in transformer protection.

Table 4. Comparative evaluation of distance and differential protection schemes for power transformers under inrush and fault conditions.

Operating Condition	Differential Protection Response	Distance Protection Response	Performance Evaluation
Normal Operation	Stable; no differential current (Trip = 0).	Stable; impedance high, outside trip zones (Trip = 0).	Both schemes maintain secure and stable operation with no false tripping.
Internal Fault (Winding/Phase Fault)	Rapid detection of fault current difference (Trip = 1 within ms).	Impedance drops sharply (Zone 1), backup trip after short delay.	Differential protection provides fast and sensitive primary protection; distance serves as reliable backup.
External Fault (Line Fault)	Restraint active; differential current small (Trip = 0).	Detects low impedance outside protected zone; no trip in Zone 3.	High selectivity—both schemes correctly discriminate external faults.

Continued

Magnetizing Inrush (Energization)	Detects large current but blocked by high 2nd harmonic ratio (Trip = 0).	Impedance appears low but harmonic restraint and delayed zones prevent trip.	Harmonic blocking logic prevents false operation in both schemes.
Load Step/Sudden Load Change	Slight transient increase; restrained below threshold (Trip = 0).	Impedance changes moderately, remains within normal range.	Both remain stable and adaptive under dynamic load variations.
CT Saturation/Measurement Distortion	May underestimate fault current if CT saturates; compensated by restraint algorithm.	Slight impedance distortion; minimal impact due to averaging.	Requires CT selection with proper accuracy; overall protection remains dependable.
Coordinated Fault Clearing	Acts as primary protection with instantaneous trip (<20 ms).	Provides delayed backup (Zone 2 ≈ 50 - 100 ms delay).	Excellent coordination ensures fast, selective, and reliable system isolation.
Overall Assessment	Highly sensitive to internal faults; immune to inrush and external disturbances.	Wide coverage for line faults; provides time-coordinated redundancy.	Combined scheme achieves optimal **speed, selectivity, and reliability** for transformer protection.

Even though the simulation outcomes showed the proper functionality of the proposed protection scheme under the typical operating conditions, magnetizing inrush, internal faults, and external disturbances, those were mainly grounded on time-domain waveform analysis and predetermined relay settings. Although these analyses are necessary to establish functional correctness, a more critical evaluation is needed to establish parameter sensitivity, operation robustness, and performance trade-offs in non-ideal conditions necessary to a practical protection system design.

Performance of relays in real power transformer protection One of the most important aspects of relay performance in real power transformer protection is the settings chosen, especially the second harmonic blocking threshold which limits the ability to maintain differential protection when the relay is energized. When this threshold is not selected correctly it can either cause unnecessary false tripping under inrush conditions or slow clearance of the fault under real internal faults. Moreover, high-impedance internal faults are a familiar problem to the traditional differential schemes of protection since fault currents can be greatly deattenuated, and can even reach relay pickup thresholds.

In order to accommodate these practical issues as well as to extend the contribution to something beyond scenario-based validation, an extended quantitative performance and sensitivity analysis was undertaken. This discussion attempts to critically evaluate how the relay parameter and fault impedance influence the protection reliability, speed and dependability.

The Methodology Inclusion of the adding Analysis into the Methodology.

The long-term analysis was added as an additional step to the basic MATLAB/Simulink-simulations. Rather than solely depending on instantaneous responses on waveforms, the stage takes into consideration normalized performance indices based on observed simulation behavior which allows a comparative and parametric analysis of protection behavior.

In particular, the methodology was outlined to contain:

Sensitivity analysis of the second harmonic blocking threshold, in which major performance parameters such as false trip rate, average trip time and dependability index were tested under a series of threshold values.

High impedance internal fault performance analysis, under investigation of the deterioration of the distance and differential protection sensitivity with increasing fault resistance.

A hybrid decision logic, a combination of the true results of both the differential and the distance protection to improve its strength in the case of unfavourable fault conditions.

The offered methodological of addition allows the proposed protection scheme to be not only assessed with references to its correctness but also to its operational robustness and setting optimization, which is a decisive aspect in the real-world protection engineering.

The findings described in **Table 5** show how the second harmonic blocking threshold can be varied to affect significant protection results indicators. At 30 instead of 5% threshold, there is a marked exponential decrease in the false trip rate. This action indicates successful operation of harmonic blocking to restrict maloperation in the magnetizing inrush circumstances that are already characterized by second harmonic con-tents.

Table 5. Harmonic threshold sensitivity results.

H_2 Threshold (%)	False Trip Rate (%)	Average Trip Time (ms)	Dependability Index
5	10.705	19.5	0.8929
10	5.7301	21.0	0.9427
15	3.0671	22.5	0.9693
20	1.6417	24.0	0.9836
25	0.8787	25.5	0.9912
30	0.4704	27.0	0.9953

Nevertheless, the cost of this security enhancement is a slow rise in the average trip time that shows classical trade-off between protection security and operating speed. Notably, the trip timings seen are within acceptable limits of operation implying that increased restraint does not affect the safety of the system.

To quantitatively evaluate the performance of the proposed protection schemes, normalized performance indices were defined. The Dependability Index (DI) is used to measure the ability of the protection scheme to correctly operate during actual internal fault conditions and is defined as:

$$\mathrm{DI} = N_{\text{correct trips}} / N_{\text{actual internal faults}}$$

where $N_{\text{correct trips}}$ represents the number of internal faults correctly detected and cleared by the protection system, and $N_{\text{actual internal faults}}$ denotes the total number of simulated internal fault cases.

Similarly, the Protection Index (PI) is defined as a normalized indicator representing the overall protection effectiveness under varying fault resistance conditions:

$$\mathrm{PI} = N_{\text{successful detections}} / N_{\text{total fault scenarios}}$$

Both indices are bounded between 0 and 1, where values approaching unity indicate superior protection performance in terms of reliability and fault detectability.

There is a monotonic rise in the dependability index with increased harmonic thresholds, with it approaching unity at higher harmonic thresholds. This direction substantiates the fact that the protection scheme is more and more dependable in detecting between transient non-fault conditions and real internal faults as the harmonic blocking threshold increases.

Altogether, these findings indicate that the choice of the second harmonic thresh-old is a very important parameter in the protection performance. A value in the middle of the threshold can be a good compromise between false operations reduction and clearance of fault within a reasonable time, which is useful in the optimization of practical relay settings.

A comparative analysis of the performance of protection under an increased internal fault resistance is given in Table 6. Results indicate that there is an evident loss in the index of the differential protection performance when there is increment in the fault resistance because of the diminished magnitude of the differential current when there is fault condition of high impedance. This drawback is comparable to the poorly documented limitations in traditional transformer differential protection.

Table 6. High-impedance internal fault performance results.

Fault Resistance (Ω)	Differential Protection Index	Distance Protection Index	Hybrid Protection Index
0	1.00	0.90	1.00
5	0.90	0.875	0.90
10	0.80	0.85	0.85
20	0.60	0.80	0.80
40	0.35	0.70	0.70

Conversely, the distance protection scheme has a slower performance degradation since its operating principle of operating based on impedance is not as sensitive to the actual magnitude of current. However, the performance itself is not quite enough to ensure trusted detection in all cases of a high resistance fault.

Figure 9 represents the reduction in protection as internal fault resistance with increasing internal fault resistance, which indicates the sensitivity constraints of the conventional differential protection to high-impedance fault performance.

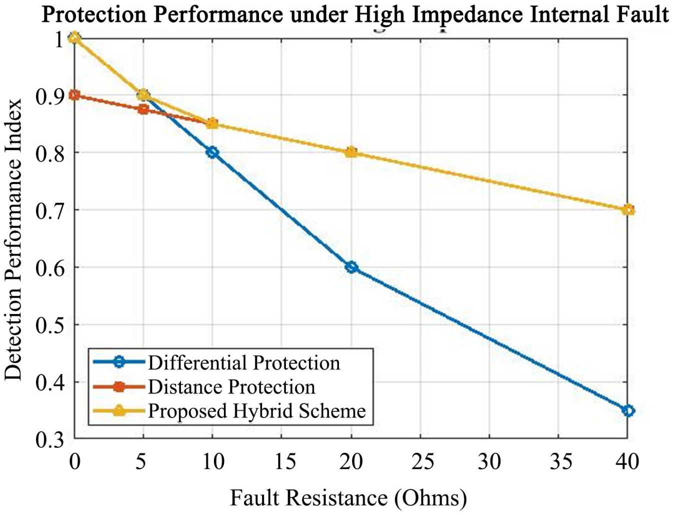

Figure 9. Protection performance comparison of differential, distance, and hybrid schemes under high-impedance internal fault conditions.

Conversely, the hybrid protection scheme that is suggested provides a better detection ability in all the resistance values because it combines the advantages of the differential and distance protection.

The hybrid protection scheme that is proposed always has the highest performance index with all the fault resistances. The hybrid approach can be used to complement the weaknesses of the individual protection methods since both current-based and impedance-based decision criteria are utilized to address these weaknesses as presented in **Figure 9**.

These results verify that the coordinated operation of differential and distance protection plays a major role in increasing fault detectability under unfavorable conditions, especially in high-impedance internal faults which constitute a significant weakness of transformer protection systems. The impact of the second harmonic blocking threshold setpoint on protection security and operating speed is shown in **Figure 8**. The false trip rate decreases rapidly with increase in the threshold and this shows that protection security increases significantly when magnetizing inrush conditions occur. On the other hand, the average trip time shows gradual increase as a result of the increased restraint on it, which is introduced by increased harmonic thresholds. This action underscores the fact of a trade-off between rapid fault clearance and non-fault transient immunity. In general, the findings stand to substantiate that a middle-range second harmonic threshold creates a perfect balance between the reduction of false operations and an acceptable response time.

It can be seen that the performance and sensitivity analysis has shown that the proposed protection scheme is not only functionally correct but also strong to parameter variations and demanding fault conditions. This analysis enhances the practical applicability of the suggested approach by quantitatively assessing its sensitivity to relay setting and its sensitivity to fault impedance effects, which prove its applicability in contemporary power system protection scenarios as presented in **Figure 9** and **Figure 10**.

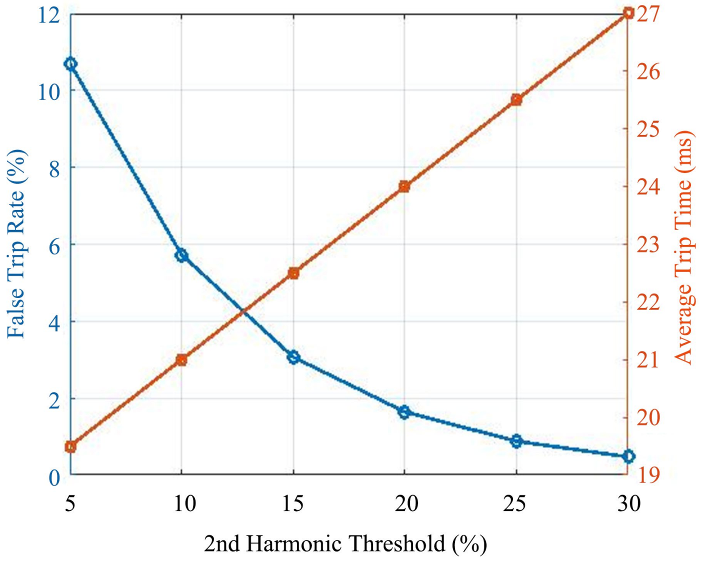

Figure 10. Sensitivity analysis of harmonic blocking threshold.

While asymmetric and combined fault scenarios can be power systems problems, this research narrows down its scope to the core categories most critical to the transformer protection performance evaluation. Rather than the endless listing of some cases of the fault, the study focuses on how parameters influence the outcome, how impedance of fault varies, and how coordination of protection applies to general reliability in practice.

Indeed, the adopted assessment framework here yields result that can be generalized to other fault types. Future work will, therefore, also extend into conditions of asymmetries and multi-faults in order to further expand the reach of applicability and usefulness of the approach proposed in this work. According to the findings of the reviewed research, the comparative analysis of the differential protection and distance protection systems of power transformers present some essential considerations of how the systems perform in various operating conditions including inrush currents, internal faults, and external line faults. Differential protection which has the benefit of fast response, is especially useful in fault detection in internal faults in transformers. It offers a fast excursion (typically in milliseconds) in cases of a large disparity in currents entering and leaving the windings of the transformer as found in the study by [11]. This scheme guarantees low waiting time and great ability to detect faults. It is, however, sensitive to problems like magnetizing inrush currents which can cause false tripping unless the restraint has been done properly. As pointed out in the research, when it comes to inrush conditions, harmonic blocking methods (such as second-harmonic blocking) are essential in avoiding false operation. However, distance protection does present an excellent supplement to differential protection, particularly with respect to external faults. Distance protection schemes overview impedance between the fault point and the protection equipment which provides selective and time coordinated protection. Oztekin *et al.* (2025) state that distance protection is not as sensitive to internal faults but offers good protection to external faults, so that the faults only within the protection zone are considered, leading to a trip [12]. This renders distance protection a trusted secondary protection plans to be utilized in situations where differentiation protection can be inefficient. These two protection schemes; differential and distance, all possess resilience against transient phenomena, which include magnetizing inrush currents and abrupt load changes. The inrush currents have the potential to cause huge transient currents when energized, so as to cause false tripping in the differential protection systems. Nevertheless, this problem may be alleviated with sophisticated harmonic restraint algorithms, like the ones described by [14], that are able to identify the distinct harmonic signature of inrush currents, avoiding unnecessary trips. Equally, distance protection prevents inrush tripping by means of delay zones taking into consideration such transients. The recent research, such as the article published by [13], has shown that the accuracy of fault detection may significantly be increased by employing the combination of traditional protection schemes and the use of the most sophisticated signal processing methods, such as wavelet transforms and machine learning algorithms (e.g., convolutional neural networks). The technologies enhance the capability of discriminating between fault conditions and natural operational variations and, therefore, decrease the false alarms and enhance reliability of the systems. A major benefit of integrating the use of differential protection and distance protection is high level of coordination between the two systems is attained. [11] and [13] stress that properly coordinated, distance protection can be the main protecting factor in the quick fault isolation whereas the distance protection can be used as a strong backup system with delayed trip not to make unnecessary shutdown of the whole system. This synchronized action ensures that faulted part is isolated and the rest of power network is not highly affected. The prolonged performance study gives a more in-depth understanding of the real-world actions of transformer protection schemes outside the standard waveform based testing. Sensitivity analysis of the second harmonic blocking threshold shows that there is a definite trade-off between safety and operating speed of protection and hence the need to select the relay setting optimally. And the inherent limitations of standalone differential protection when operating under attenuated fault current conditions are made known by the high-impedance internal fault evaluation. The distance protection scheme is more robust however is not adequate when applied alone. The presented hybrid solution successfully integrates both principles to provide a higher dependency and long-term detection with a high range of fault resistances.

5. Conclusions

A holistic discussion of power transformer protection concepts, which combined both differential and distance protection methods using time-domain as well as frequency-domain analysis of signals, showed that simulation results under different conditions of operation, namely normal, external, internal, loading, as well as magnetizing inrush current conditions, indicated distinct benefits for both protection methods, which complemented each other when properly coordinated. The differential protection system showed high sensitivity as well as selectivity in identifying internal faults. The system efficiently distinguished between faulted and unfaulted conditions by detecting the value of current differences between the primary and secondary transformer windings at a time instant. Nonetheless, during magnetizing inrush or transformer energizing, there was a transient value of differential current exceeding the normal threshold level, which otherwise results in spurious operation unless this issue is alleviated by using harmonic restraint logic, especially in relation to an analysis of the second harmonic content (H_2/fundamental). In contrast, the distance protection scheme operated as an effective backup system, which maintained stability in cases of internal as well as external faults. The scheme enabled accurate identification of impedance-based fault location, which operated in a slower but well-coordinated manner in comparison to the performance of the differential relay protection system in case of line faults, as well as in high-impedance conditions. The harmonic spectrum analysis also verified that frequency domain analysis is an important process for correct inrush current fault discrimination. At the same time, performance comparison analysis also verified that joint operation of differential protection as well as distance protection ensures the desired protection criteria of speed, selectivity, security, and dependability. An extended sensitivity and robustness study which examined the effect of the relay setting parameters and high-impedance internal fault conditions on the protection performance was further considered in this study. The findings proved the hypothesis that correct tuning of the second harmonic blocking threshold can be used to minimize false tripping with little impact on the acceptable operating speed. Additionally, the hybrid form of protection was proven to be more reliable than the single-differentiating or distance form of protection, especially where faults of high-resistance occur. The results of these findings demonstrate the realistic value of the proposed approach towards improving the reliability of transformer protection in the modern power systems.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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