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Design of YNd11 Power Transformer Differential Protection Based on Percentage Differential Relay and MATLAB/Simulink

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ABSTRACT

Power transformers require fast and selective protection to prevent equipment damage, power interruption, and safety risks caused by internal faults. This study designs and evaluates a differential protection model for a 10 MVA, 150/20 kV, YNd11 power transformer using MATLAB/Simulink. The proposed model integrates current transformer compensation, differential current calculation, percentage differential relay characteristics, and second harmonic blocking to distinguish magnetizing inrush current from internal faults. The relay settings include a minimum operate current of 0.20 pu, two-slope characteristics of 20% and 80%, a restraint breakpoint of 1.0 pu, and a second harmonic blocking threshold of 15%. Four simulation scenarios were tested: normal operation, transformer energization inrush, phase-to-phase internal fault, and phase-to-ground internal fault on the 20 kV side. The simulation results show that the transformer model achieved a steady-state validation error below 0.25%. During normal operation, the residual differential current remained between 0.021 and 0.024 pu. During inrush, the relay was blocked because the second harmonic component reached 21.4%. For internal faults, the relay operated within 16.5 ms for phase-to-phase fault and 18.5 ms for phase-to-ground fault. These results indicate that the proposed model provides accurate, selective, and fast transformer differential protection.

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INTRODUCTIONS

Power transformers are among the most critical assets in modern electric power systems because they enable voltage conversion across generation, transmission, and distribution networks. Their operational reliability directly affects power system continuity, equipment security, and service quality. A failure in a power transformer may lead to power interruption, severe equipment damage, fire hazards, and high restoration costs. Consequently, transformer protection schemes must be capable of detecting internal faults rapidly while maintaining security against non-fault transient conditions. Among various protection methods, differential protection is widely adopted as the main protection scheme for power transformers because it compares the compensated currents entering and leaving the protected zone and operates when a significant imbalance indicates an internal fault [1].

Despite its well-established operating principle, transformer differential protection remains technically challenging in practical implementation. The differential current measured by the relay is not solely influenced by internal faults, but may also be affected by current transformer (CT) ratio mismatch, transformer vector group phase displacement, CT saturation, tap changer operation, and transient magnetizing phenomena [2], [3]. These conditions can generate residual or false differential current even when the transformer is operating normally. In transformers with the YNd11 vector group, the 30° phase displacement between the high-voltage and low-voltage sides must be accurately compensated. Improper compensation may cause the relay to misinterpret normal operating current as fault current, thereby increasing the risk of mal-operation.

Another important issue in transformer differential protection is magnetizing inrush current during transformer energization. Inrush current may appear as a large differential current because it is supplied from one side of the transformer and does not correspond to an actual internal fault. If this condition is not properly identified, the differential relay may trip incorrectly during energization. Harmonic restraint and harmonic blocking methods are commonly employed to improve relay security under inrush conditions [6]. Among these methods, second harmonic blocking remains one of the most widely used approaches because magnetizing inrush current typically contains a higher second harmonic component than internal fault current. However, previous studies have shown that the reliability of this approach may decrease under CT saturation, low second harmonic inrush conditions, and complex transient disturbances [4], [5].

To address these limitations, various advanced methods have been proposed in the literature. Adaptive differential relays have been introduced to improve relay sensitivity across different operating regions [6]. CT saturation compensation techniques have been developed to reduce measurement distortion and improve relay security [7]. Wavelet-based approaches have also been investigated to distinguish internal faults from magnetizing inrush current, particularly under transient and overlapping conditions [8]. In addition, artificial intelligence, fuzzy logic, and data-aided protection schemes have been explored to enhance fault classification accuracy and reduce dependence on fixed harmonic thresholds [9]. Although these approaches offer promising performance, some of them require complex signal processing, large training datasets, or higher computational resources, which may limit their practicality for basic relay setting studies and simulation-based protection analysis.

For practical and simulation-oriented protection studies, the percentage differential relay combined with second harmonic blocking remains relevant because it is simple, interpretable, and closely aligned with the operating principles of digital transformer relays. This scheme allows the relay to maintain sensitivity to internal faults while improving stability against load current, CT mismatch, and inrush current [10]. Simulation-based evaluation is also essential because it enables relay settings, compensation logic, harmonic blocking, and trip decisions to be tested under controlled operating and fault scenarios before practical implementation [11]. MATLAB/Simulink provides an integrated environment for modeling three-phase sources, power transformers, current transformers, fault injection, signal processing, and relay logic within a single simulation framework [12].

Based on these considerations, this study designs and evaluates a differential protection model for a 10 MVA, 150/20 kV, YNd11 power transformer using MATLAB/Simulink. The proposed model integrates CT ratio compensation, vector group phase compensation, differential current calculation, two-slope percentage differential relay characteristics, and second harmonic blocking. Four operating scenarios are evaluated, namely normal operation, transformer energization inrush, phase-to-phase internal fault, and phase-to-ground internal fault on the 20 kV side. Relay performance is assessed using residual differential current, second harmonic ratio, blocking decision, trip decision, and operating time.

The main contribution of this study lies in the development of an integrated and quantitatively evaluated MATLAB/Simulink model for transformer differential protection. Unlike studies that focus primarily on advanced classification algorithms, this work emphasizes a practical relay protection structure based on percentage differential characteristics and second harmonic blocking. The proposed model provides a clear representation of CT compensation, YNd11 phase shift correction, differential current calculation, and relay decision logic. Therefore, this study contributes to transformer protection analysis by providing a simulation-based framework that can be used for relay setting verification, protection performance evaluation, and further development of digital transformer protection studies.

RESEARCH METHODS

This study employed a simulation-based method to design and evaluate a differential protection model for a three-phase power transformer. The theoretical basis of transformer differential protection was integrated into the simulation procedure because the relay algorithm, mathematical formulation, current compensation, harmonic analysis, and trip decision logic were directly implemented in the MATLAB/Simulink model [13]. This structure allows the method section to describe not only the simulated system, but also the operating principle of the proposed protection scheme.

Research Design and Simulation Framework

The research was conducted through four main stages: system parameter definition, MATLAB/Simulink modeling, relay algorithm implementation, and performance evaluation. The simulated system consisted of a three-phase source, a 10 MVA power transformer, current transformers (CTs), a three-phase load, a fault injection block, and a differential relay block. The relay block included CT ratio compensation, vector group phase compensation, differential current calculation, restraint current calculation, percentage differential relay logic, fast Fourier transform (FFT)-based second harmonic detection, and final trip/blocking decision. This simulation framework was developed to evaluate the ability of the relay to remain stable during normal and inrush conditions while operating rapidly during internal faults.

The general simulation workflow is shown in Fig. 1. The measured currents from the high-voltage and low-voltage sides were first converted into secondary CT quantities. The low-voltage side current was then compensated to account for the YNd11 vector group phase displacement. After compensation, the relay calculated the differential current and restraint current [14]. The percentage differential element determined whether the operating condition was satisfied, while the second harmonic blocking element verified whether the detected differential current was caused by transformer energization. A trip signal was issued only when the differential condition was fulfilled and the blocking condition was not active.

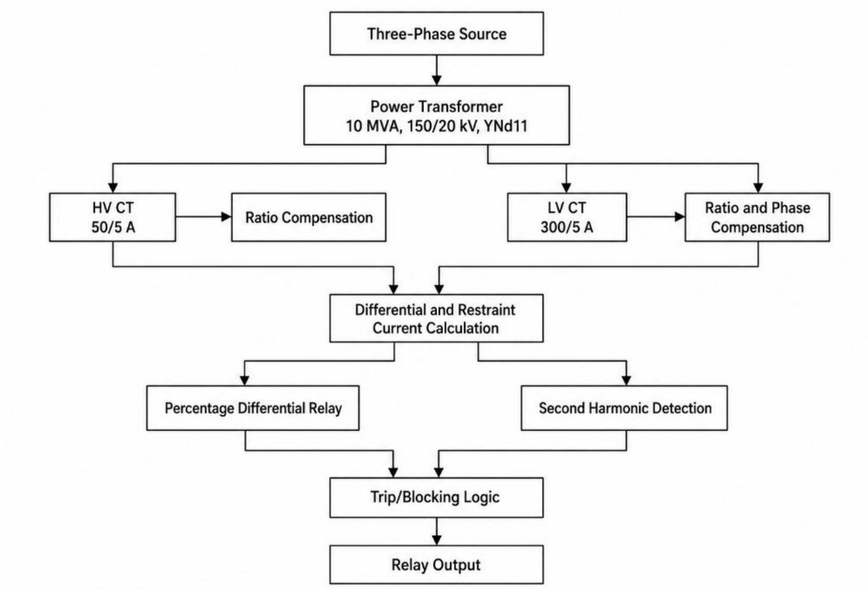

Figure 1. Block diagram of the proposed transformer differential protection model

Simulated Transformer and CT Parameters

The object of this study was a three-phase power transformer rated at 10 MVA, 150/20 kV, with YNd11 vector group and 50 Hz operating frequency. The transformer was modeled with a short-circuit impedance of 10%. The CT ratio on the high-voltage side was 50/5 A, while the CT ratio on the low-voltage side was 300/5 A. The simulated load was set at nominal loading condition with a power factor of 0.85. The selected transformer and CT parameters are presented in Table 1.

Table 1. Simulated transformer and CT parameters

Parameter	Symbol	Value	Unit/Description
Rated power	(s)	10	MVA
Primary voltage	V_1	150	kV, line-to-line RMS
Secondary voltage	V_2	20	kV, line-to-line RMS
Frequency	(f)	50	Hz
Vector group	-	YNd11	30° phase displacement
Short-circuit impedance	$Z_{\%}$	10	%
Primary CT ratio	-	50/5	A
Secondary CT ratio	-	300/5	A
Load power factor	$\cos v$	0.85	lagging

The nominal current on the primary and secondary sides was calculated using the three-phase power equation:

$$I_{(1n)} = S/\left(\sqrt{3}V_1\right) \quad (1)$$

$$I_{(2n)} = S/\left(\sqrt{3}V_2\right) \quad (2)$$

where I_{1n} is the nominal current on the primary side, I_{2n} is the nominal current on the secondary side, $(S)$is the rated apparent power, V_1 is the primary line voltage, and V_2 is the secondary line voltage. Based on these equations, the nominal primary and secondary currents were 38.49 A and 288.68 A, respectively.

Differential Current and Current Compensation

The relay algorithm was developed based on the principle that the current entering and leaving the protected zone should be balanced under normal conditions after ratio and phase compensation. In transformer differential protection, the measured currents cannot be compared directly because the transformer ratio, CT ratio, and vector group phase shift may produce unequal secondary currents. Therefore, the measured currents were first referred to a common base before calculating the differential current.

The compensated currents are denoted as I_1' and I_2', where I_1' represents the compensated current from the high-voltage side and I_2' represents the compensated current from the low-voltage side. Under normal conditions, the compensated currents should satisfy:

$$I_1' \approx I_2' \tag{3}$$

The differential current was then calculated as:

$$I_d = |I_1' - I_2'| \tag{4}$$

where I_d is the differential current. In this study, the symbol (I_d) was consistently used to represent differential current, while I_{1n} and I_{2n} were used to represent nominal currents. This notation avoids ambiguity between differential current and nominal current.

For the YNd11 transformer, phase compensation was required because the vector group produces a 30° displacement between the high-voltage and low-voltage side quantities. In the simulation model, this compensation was implemented numerically in the relay block before calculating I_d. Ratio correction was also applied to reduce false differential current caused by CT ratio mismatch. This compensation stage is essential because uncompensated transformer vector group displacement and CT mismatch can cause false differential current and reduce relay security [15].

Percentage Differential Relay Algorithm

The percentage differential relay was implemented to improve relay stability during load current variation, CT mismatch, and high-current operating conditions. Instead of using differential current alone, the relay compared I_d with a dynamic operating threshold determined by the restraint current. The restraint current was calculated as:

$$I_r = (|I_1'| + |I_2'|)/2 \tag{5}$$

where I_r is the restraint current. The relay operating threshold was defined using a two-slope characteristic. For the first operating region, the differential threshold was calculated as:

$$I_{(d,th)} = k_1 I_r + I_{(s,min)}, I_r \leq I_{(r,bp)} \tag{6}$$

For the second operating region, the threshold was calculated as:

$$I_{(d,th)} = k_1 I_{(r,bp)} + k_2\left(I_r - I_{(r,bp)}\right) + I_{(s,min)}, I_r > I_{(r,bp)} \tag{7}$$

where $I_{d,\text{th}}$ is the differential current threshold, k_1 is the first slope, k_2 is the second slope, $I_{r,\text{bp}}$ is the restraint breakpoint, and $I_{\text{s,min}}$ is the minimum operate current. The relay entered the operate region when:

$$I_d \geq I_{(d,th)} \quad (8)$$

The two-slope characteristic was used because it provides higher sensitivity at lower restraint current and higher stability at larger restraint current, particularly under CT saturation or high-current conditions. This approach is consistent with practical transformer differential protection principles discussed in IEEE-based transformer protection studies [16].

Second Harmonic Blocking Algorithm

Second harmonic blocking was implemented to prevent relay mal-operation during transformer energization. Magnetizing inrush current may produce high differential current because the current appears mainly on the energized side of the transformer. However, unlike internal fault current, inrush current typically contains a significant second harmonic component. Therefore, the relay used FFT analysis to calculate the second harmonic ratio of the differential current.

The second harmonic ratio was calculated as:

$$R_2 = (|I_{(d,100Hz)}|)/(|I_{(d,50Hz)}|) \times 100\% \quad (8)$$

where R_2 is the second harmonic ratio, $I_{d,100\text{Hz}}$ is the second harmonic component of the differential current, and $I_{d,50\text{Hz}}$ is the fundamental component of the differential current. The blocking condition was defined as:

$$R_2 \geq R_b lk \quad (9)$$

where R_{blk} is the second harmonic blocking threshold. In this study, R_{blk} was set to 15%. The final relay logic was formulated as:

$$Trip = \{1, I_d \geq I_{(d,th)} and R_2 < R_b lk 0, I_d < I_{(d,th)} or R_2 \geq R_b lk) \quad (10)$$

This logic ensures that the relay operates for internal faults but remains blocked during transformer energization when the second harmonic component exceeds the blocking threshold. Harmonic-based blocking remains a widely used method in transformer differential protection, although previous IEEE and MDPI studies have reported that CT saturation, transient distortion, and low second harmonic inrush conditions may affect its reliability [17].

Relay Setting Parameters

The relay setting parameters used in the simulation are summarized in Table 2. These parameters were selected to provide sensitivity to internal faults while maintaining security against normal load current, CT mismatch, and inrush current.

Table 2. Differential relay setting parameters

Setting parameter	Symbol	Value	Description
Minimum operate current	$I_{\text{s,min}}$	0.20 pu	Minimum differential pickup

First slope	k_1	20%	Sensitivity region
Second slope	k_2	80%	Stability region
Restraint breakpoint	$I_{r,\text{bp}}$	1.0 pu	Transition point between slopes
High-set pickup	I_{HS}	8.0 pu	Unrestrained high-current operation
Second harmonic threshold	R_{blk}	15%	Inrush blocking threshold

The high-set element was included to represent fast operation for severe internal faults. The high-set condition was defined as:

$$I_d \geq I_H S \tag{11}$$

where I_{HS} is the high-set pickup current. However, the trip decision still considered the harmonic blocking condition to prevent unwanted operation during inrush conditions with high differential current.

Simulation Scenarios

Four simulation scenarios were designed to evaluate relay performance under normal, transient, and internal fault conditions. The first scenario was normal operation at nominal load to verify that the compensated differential current remained below the minimum operate threshold. The second scenario was transformer energization inrush with a switching angle of $0°$ and residual flux of $+0.8\sim\text{pu}$, representing a severe energization condition. The third scenario was a phase-to-phase internal fault between phases A and B on the 20 kV side. The fourth scenario was a phase-to-ground internal fault on phase A on the 20 kV side. The internal faults were injected at $t = 0.05\sim\text{s}$ with a fault impedance of $0.01\sim\Omega$.

Table 3. Simulation scenarios

Scenario	Operating condition	Fault location/condition	Evaluation objective
S1	Normal operation	Nominal load, $(\cos\varphi = 0.85)$	Verify no mal-trip
S2	Transformer energization	$(0°)$ switching angle, $(+0.8\sim\text{pu})$ residual flux	Verify inrush blocking
S3	Phase-to-phase fault	AB fault on 20 kV side, $(Z_f = 0.01\sim\Omega)$	Verify internal fault trip
S4	Phase-to-ground fault	AG fault on 20 kV side, $(Z_f = 0.01\sim\Omega)$	Verify internal fault trip

Performance Evaluation Criteria

Relay performance was evaluated using five indicators: residual differential current, maximum differential current, second harmonic ratio, trip/blocking decision, and operating time. Under normal operation, the relay was considered secure if (I_d) remained below $(I_{\text{s,min}})$ and no trip signal was generated. Under inrush conditions, the relay was considered selective if the trip signal was blocked when $(R_2 \geq R_{\text{blk}})$. Under internal fault conditions, the relay was considered dependable if it generated a trip signal when $(I_d \geq I_{d,\text{th}})$ and $(R_2 < R_{\text{blk}})$. The operating time was measured from the instant of fault injection to the instant when the relay output changed to trip status.

The overall protection performance was assessed using sensitivity, selectivity, and response time. Sensitivity was defined as the ability of the relay to detect internal faults, while selectivity was defined as the ability of the relay to avoid mal-trip during normal and inrush conditions. The response time was used to evaluate the speed of the relay in isolating internal faults.

RESULTS AND DISCUSSION

This section presents the simulation results of the proposed transformer differential protection model under normal operation, transformer energization, and internal fault conditions. The results are evaluated using steady-state model accuracy, residual differential current, second harmonic ratio, trip/blocking decision, and relay operating time. The discussion focuses on the ability of the proposed scheme to maintain security during non-fault conditions and dependability during internal faults.

Transformer Model Validation

Before evaluating the relay response, the transformer model was validated under steady-state full-load operation. The simulated quantities were compared with theoretical values calculated from the transformer rating. The validation results are shown in Table 4. The relative errors of all evaluated parameters were below 0.25%, indicating that the simulated model accurately represents the rated operating condition of the transformer.

Table 4. Transformer model validation under steady-state operation

Parameter	Theoretical Value	Simulated Value	Error (%)
Primary voltage (V_1) ($kV, L-L$)	150.00	149.85	0.10
Secondary voltage (V_2) ($kV, L-L$)	20.00	19.97	0.15
Primary current (I_1) (A, RMS)	38.49	38.45	0.10
Secondary current (I_2) (A, RMS)	288.68	288.01	0.23
Input active power (MW)	8.500	8.487	0.15
Power factor	0.850	0.849	0.12
Phase displacement ($V_1 - V_2$) ($degree$)	30.00	29.97	0.10

The small deviation between theoretical and simulated values confirms that the transformer, CT ratio, loading condition, and YNd11 phase displacement were modeled consistently. This validation is important because an inaccurate transformer model may produce incorrect differential current and lead to misleading relay performance assessment. The obtained error level also indicates that the relay response observed in the subsequent scenarios is mainly caused by the simulated operating or fault conditions rather than by steady-state modeling mismatch.

Relay Response Under Normal Operation

The normal operation scenario was used to verify the security of the differential relay during rated load condition. After CT ratio and YNd11 phase compensation, the residual differential current remained in the range of 0.021–0.024 pu. This value is significantly lower than the minimum operate current of 0.20 pu. Therefore, the relay did not enter the operate region and no trip signal was generated.

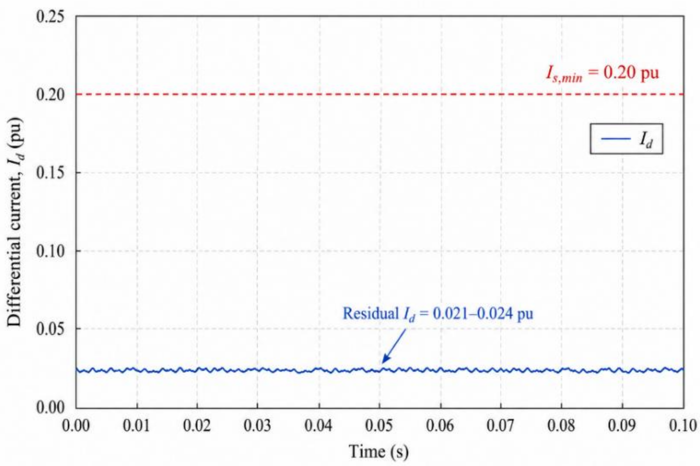

Figure 2. Differential current waveform under normal operation.

The result demonstrates that the compensation process successfully reduced false differential current caused by transformer ratio, CT ratio, and vector group phase displacement. In practical transformer differential protection, residual current may appear even under healthy operating conditions due to CT mismatch, measurement error, and phase compensation error [18]. However, the residual value obtained in this study provides a margin of approximately 0.176 pu from the minimum operate threshold. This margin indicates that the relay setting is sufficiently secure for the simulated normal operating condition.

Relay Response During Transformer Inrush

The transformer energization scenario was simulated using a switching angle of ($0°$) and residual flux of ($+0.8{\sim}\mathrm{pu}$). This condition generated a high magnetizing inrush current. The peak inrush current in phase A reached 346.2 A, equivalent to approximately 9.0 pu of the primary nominal current. The maximum differential current increased to 8.70 pu, which is far above the differential pickup threshold. Without a blocking mechanism, this condition could be incorrectly interpreted as an internal fault.

The FFT-based harmonic analysis showed that the second harmonic component reached 21.4% of the fundamental component. Since this value exceeds the blocking threshold of 15%, the second harmonic blocking element was activated and the trip signal was inhibited. The harmonic components of the inrush current are summarized in Table 5.

Table 5. Harmonic content during transformer inrush condition

Component	Frequency	Magnitude	Protection Implication
Fundamental	50 Hz	100.0%	Main inrush component
Second harmonic	100 Hz	21.4%	Blocking active
Third harmonic	150 Hz	8.2%	Minor harmonic component
DC offset	0 Hz	15.3%	Indicates waveform asymmetry

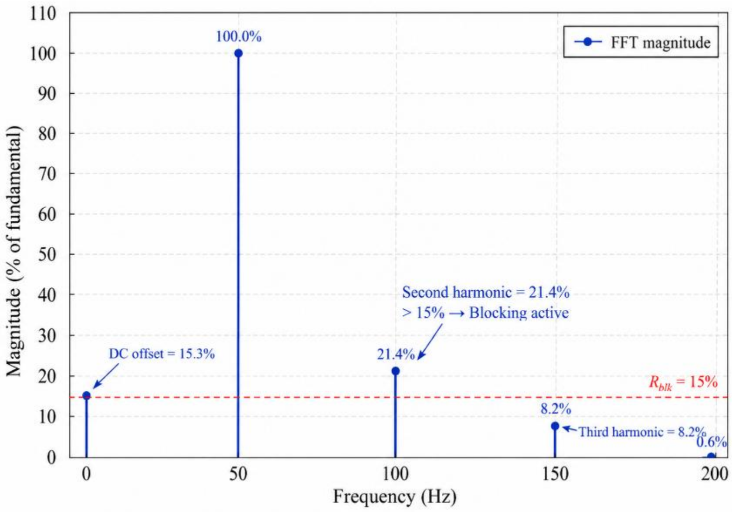

Figure 3. FFT spectrum of differential current during transformer inrush.

This result confirms that the second harmonic blocking logic improves relay security during transformer energization. The relay identified the high differential current as inrush rather than an internal fault because (R_2) was higher than (R_{blk}). This is consistent with the principle of harmonic restraint and harmonic blocking in transformer protection, where inrush current generally contains a larger second harmonic component than internal fault current. Nevertheless, the result should be interpreted within the tested scenario because previous studies have reported that harmonic-based blocking may become less reliable under low second harmonic inrush conditions, CT saturation, or complex transient disturbances [19].

Relay Response Under Phase-to-Phase Internal Fault

The phase-to-phase fault scenario was applied between phases A and B on the 20 kV side at ($t = 0.05 \sim s$) with a fault impedance of ($0.01 \sim \Omega$). The fault produced a peak current of 1,847 A, equivalent to approximately 6.4 pu. The maximum differential current in phase A reached 6.10 pu, while the calculated operating threshold in the second slope region was 2.16 pu. Since (I_d) exceeded ($I_{d,\mathrm{th}}$), the percentage differential element entered the operate region.

The second harmonic ratio during this fault was only 2.3%, which is lower than the 15% blocking threshold. Therefore, the blocking element remained inactive and the relay issued a trip signal within 16.5 ms after fault inception. This response confirms that the proposed scheme can distinguish an internal phase-to-phase fault from an inrush condition. The low second harmonic content also supports the decision that the detected differential current was caused by an internal fault rather than magnetizing inrush.

Relay Response Under Phase-to-Ground Internal Fault

The phase-to-ground fault scenario was applied on phase A of the 20 kV side using the same fault impedance of ($0.01 \sim \Omega$). This condition produced a lower current magnitude than the phase-to-phase fault. The peak fault current reached 1,234 A, equivalent to approximately 4.3 pu. The maximum differential current was 4.00 pu, while the calculated operating threshold was 1.28 pu. Therefore, the relay correctly entered the operate region.

The second harmonic ratio was 3.1%, which is also below the blocking threshold. As a result, the relay generated a trip signal within 18.5 ms. The operating time was slightly longer than that of the phase-to-phase fault because the differential current magnitude was lower. However, the relay still operated rapidly and consistently within the evaluated fault scenario.

Overall Protection Performance

The overall simulation results are summarized in Table 6. The proposed relay remained stable during normal and inrush conditions while operating correctly during internal faults.

Table 6. Summary of differential relay performance

Scenario	$(I_{d,max})(pu)$	$(R_2)(\%)$	Blocking	Trip	Operating Time
Normal operation	0.023	-	No	No	-
Transformer inrush	8.70	21.4	Yes	No	-
Phase-to-phase fault	6.10	2.3	No	Yes	16.5 ms
Phase-to-ground fault	4.00	3.1	No	Yes	18.5 ms

The relay achieved 100% sensitivity for the two tested internal fault cases and 100% selectivity for the two tested non-fault cases. The average operating time for internal faults was 17.5 ms. These results indicate that the combination of two-slope percentage differential characteristics and second harmonic blocking can provide fast and selective protection in the simulated transformer model.

A comparison with relevant studies is provided in Table 7. The comparison is not intended to claim universal superiority because each study may use different transformer ratings, relay settings, sampling methods, and fault conditions. Instead, it is used to position the obtained results within the performance range reported in previous transformer differential protection studies.

Table 7. Comparison with related transformer differential protection studies

Study	Main Method	Main Focus	Reported/Relevant Finding
IEEE C37.91-2021 [1]	Transformer protection guideline	Practical protection requirements	Provides guidance for power transformer protection application
Hamilton [6]	Harmonic restraint analysis	Inrush identification	Discusses harmonic restraint methods for transformer protection
Lee *et al.* [8]	Blocking scheme	CT saturation and differential protection	Shows the importance of secure blocking under transient conditions

Medeiros and Costa [9]	Wavelet-based protection	Internal fault detection during inrush	Improves discrimination under transient conditions
Lin *et al.* [13]	Data-aided protection	Protection without inrush blocking module	Reduces dependence on conventional inrush blocking

Compared with more advanced methods such as wavelet-based or data-aided protection, the proposed method is simpler and more interpretable. Its main advantage is that the relay decision is based on measurable protection quantities, namely differential current, restraint current, and second harmonic ratio. This makes the model suitable for relay setting studies, simulation-based learning, and preliminary protection performance evaluation. However, the method still depends on a fixed second harmonic threshold. Therefore, its performance may be affected if the inrush current contains low second harmonic content or if severe CT saturation distorts the measured current.

The main limitation of this study is that the evaluation was conducted in a simulation environment and only covered four operating scenarios. External faults, evolving faults, CT saturation under high through-fault current, transformer tap variation, noise in measurement signals, and hardware implementation were not included. Future studies should extend the testing scenarios, compare fixed harmonic blocking with adaptive or signal-processing-based methods, and validate the relay logic using real-time simulation or hardware-in-the-loop platforms.

CONCLUSION

This study has designed and evaluated a MATLAB/Simulink-based differential protection model for a 10 MVA, 150/20 kV, YNd11 power transformer. The proposed model integrates CT ratio compensation, YNd11 phase shift correction, differential and restraint current calculation, two-slope percentage differential relay characteristics, and second harmonic blocking. The transformer model was validated under steady-state operation, with all evaluated parameters showing relative errors below 0.25%, indicating that the simulation model accurately represents the rated transformer condition.

The simulation results show that the relay remained stable during normal operation, where the residual differential current was only 0.021–0.024 pu, far below the minimum operate current of 0.20 pu. During transformer energization, the relay successfully blocked the trip signal because the second harmonic component reached 21.4%, exceeding the 15% blocking threshold. For internal faults, the relay operated within 16.5 ms for the phase-to-phase fault and 18.5 ms for the phase-to-ground fault, resulting in an average operating time of 17.5 ms. These results demonstrate that the proposed scheme achieved 100% sensitivity for the tested internal fault scenarios and 100% selectivity for the tested non-fault scenarios.

The main limitation of this study is that the evaluation was conducted in a simulation environment and was limited to four operating scenarios. External faults, severe CT saturation, tap changer variation, measurement noise, evolving faults, and hardware implementation were not considered. Future work should extend the testing scenarios, compare fixed second harmonic blocking with adaptive or signal-processing-based methods, and validate the relay logic using real-time simulation or hardware-in-the-loop platforms.

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