



Fault Analysis and Differential Protection Scheme of Power Transformer using MATLAB/Simulink

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ABSTRACT

This paper presents a comprehensive analysis of power transformer protection through the modeling and simulation of a differential relay system. The research focuses on a three-phase 60 MVA, 50 Hz (132/33) KV power transformer with YnD11 configuration. The system was modeled using MATLAB/Simulink. The differential relay system plays a vital role in detecting internal faults within the power transformer. Upon detecting such faults, the relay generates a trip signal, which triggers the isolation of the faulty section from the rest of the power system. This protective measure aims to minimize damage to the transformer and ensure uninterrupted power supply. Through extensive modeling and simulation, this study evaluates the performance and effectiveness of the differential relay system. Various fault scenarios are tested, including internal faults, to assess the system's sensitivity and selectivity. The results obtained from the simulations provide valuable insights into the behavior and reliability of the proposed differential relay system. The study contributes to the field of power transformer protection by offering a comprehensive analysis and simulation framework, aiding in the design and optimization of protective schemes.

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INTRODUCTION

The advancement of a number of components in power transmission networks, including transformers of various sizes, transmission lines, and protection equipment can be used to study the evolution of the power systems (Azarakhsh, 2017). The contemporary power transformer is one of the critical components of the electrical power systems, and its protection against faults is very essential (Azizan, et al., 2020). The importance of power transformer protection has drawn substantial attention from researchers. Due to the large number of nodes in a typical power system network, its protection becomes complex but critical (Babaita *et al.*, 2022; Sulaiman *et al.*, 2024). Hence, it becomes imperative to critically monitor and maintain the protection equipment so as to ensure maximum security of the power

system components (Abubakar *et al.*, 2019; Iliyasu *et al.*, 2022).

However, deregulation of the power network due to expansion, population growth and increased power demand, is a major concern that leads to malfunctioning of several system parameters. This, in turn, causes reduction in the overall reliability of the power system. Therefore, as a key element of the power system, power transformer protection has a remarkable importance (Patel, 2024). Several factors such as the core nonlinearity, higher power rating, varying voltage and current ratios, different phase angles in primary and secondary, and connection class have made transformer design to be complex. These factors, alongside different operating characteristics of power transformers have made their protection to become multifarious (Abbasi, 2022).

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Also, unwanted tripping of power transformer generates issues not only for consumer or industry but it gives an effect for the ecosystem of society, economy, political scenarios, and the entire nation. Different power transformer failure analysis is carried out by focusing on the failure of protective schemes. One of the most successful techniques for protecting a power transformer is the differential protection algorithm (Aktaibi, and Rahman, 2011). The main aim of power transformer protection is to ensure accurate distinction of internal faults from magnetization inrush current in the transformers and to also safeguard reliable operation of the managing current transformers (Peng et al., 2023).

When the differential current measured from the current measurement of both the primary and secondary side of the transformer exceeded a certain value, referred to as the pick-up current, the differential relay would activate. In order to ensure the system's protection, the circuit breaker would not send a trip signal if the measured differential current did not exceed the relay's pick-up current. However, if internal faults occurred and the differential current surpassed the pick-up current, the relay would send a tripping signal. Upon receiving the tripping signal, the circuit breaker would disconnect and isolate the faults from the power system (Sahu, & Pahariya, 2021). Fig 1 shows a differential relay protection scheme in a power transformer.

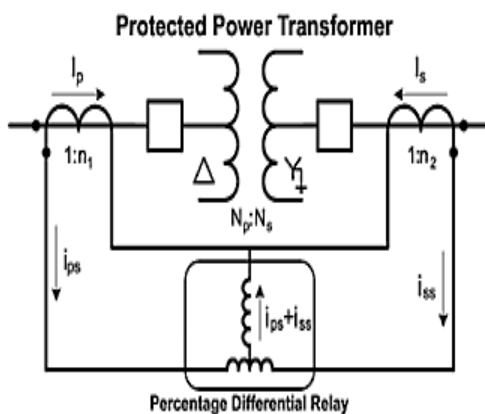


Figure1. Differential Relay Protection (Sahu, & Pahariya, 2021)

METHODOLOGY

The study employed a methodology that involved simulating and implementing the power transformer model using MATLAB/Simulink. The analysis focused on a three-phase 60 MVA, 50 Hz 132/33 KV power transformer. In this model, there are 132/33 KV power lines and the transformer, as depicted in Figure 1. To evaluate the switching effects, the power transformer was connected to a power system that incorporated a three-phase power generator. Load was supplied through the transformer between two circuit breakers, the primary side circuit breaker and the secondary side circuit breaker. The differential relay was utilized to detect internal faults and generated a trip signal to the respective circuit breakers, thereby isolating the faulty section from the rest of the power system. This protection scheme aimed to minimize damage to the transformer and the overall power system. The relationship between power, current and voltage in each phase of the power transformer is governed by the equations (1) - (5) (Tenbohlen et al., 2016).

$$P = \sqrt{3} \times V \times I \quad (1)$$

where:

P is the power rating of the transformer.

V is the voltage (132kV for the primary and 33kV for the secondary).

I is the current (primary and secondary to be determined).

For the primary rated current we can rearrange the equation as follows:

$$I_p = \frac{P}{\sqrt{3} \times V_p} \quad (2)$$

where:

I_p is the primary rated current of transformer.

V_p is the primary voltage.

Similarly, equation (3) can be used to obtain the secondary current (I_s).

$$I_s = \frac{P}{\sqrt{3} \times V_s} \quad (3)$$

where:

I_s is the secondary rated current of transformer.

V_s is the secondary voltage of transformer.

To calculate the current in the differential relay and determine the restrain current and operating current, we'll need to use the current transformer (CT) ratios and the transformer specifications. The selection of current transformer (CT) ratings is crucial to ensure they align with the current ratings of the connected power transformer, resulting in equal secondary side currents. However, a challenge arises as the CT ratios available in the market are standardized and do not precisely match the desired ratings. As a result, the primary ratings of the CTs are typically limited to the available standard ratio CTs. Typically, the primary side of the CT consist of a single turn, while the secondary side comprises multiple turns, determined by the selected transformation ratio (N) of the CT.

This ratio is chosen to align with the power transformer's ratings, as the transformation ratio represents the ratio between the number of turns on the primary side and the number of turns on the secondary side. Therefore, the turn ratio of the primary and secondary current transformer is denoted by $1/N_1$ and $1/N_2$ (Tenbohlen et al., 2016). The secondary current of the CT located in the primary side of the power transformer is defined by:

$$I_1 = \frac{I_p}{N_1} \quad (4)$$

Where:

I_p is the primary side current of the power transformer,

I_1 is the secondary side current of CT₁,

N_1 is the number of turns in the secondary side of CT₁.

In the same manner for the CT located at the secondary side of the power transformer, the CT secondary current is:

$$I_2 = \frac{I_s}{N_2} \quad (5)$$

I_s is the secondary side current of the power transformer,

N_2 is the number of turns in the secondary side of CT₂,

I_2 is the secondary side current of CT₂.

Therefore, the differential current is:

$$I_d = I_1 - I_2 \quad (6)$$

Where:

I_d is the differential current

I_1 is the current measured by CT₁

I_2 is the current measured by CT₂

If there are no internal faults happening within the protected zone of the power transformer, the currents I_1 and I_2 are considered to be of equal magnitude but flow in opposite directions. This implies that the differential current $I_d = 0$, as depicted in Figure 1.

Power Transformer Model in MATLAB / Simulink

A power system model has been created utilizing MATLAB/Simulink software as depicted in Figure 2. The power distribution system is contains a three-phase source is connected to a three-phase breaker, and a transmission line is linked to the breaker. Positioned between them are three-phase V-I measurements, which are utilized to determine the load current. At the termination of the transmission line, a three-phase series RLC load is connected, simulating the load for the system. In addition to the components, the power system model also incorporates a three-phase fault generator and stair generator situated before and after the transformer. These fault generators and stair generator introduce simulated faults into the system, allowing for the evaluation of the system's response under different fault conditions.

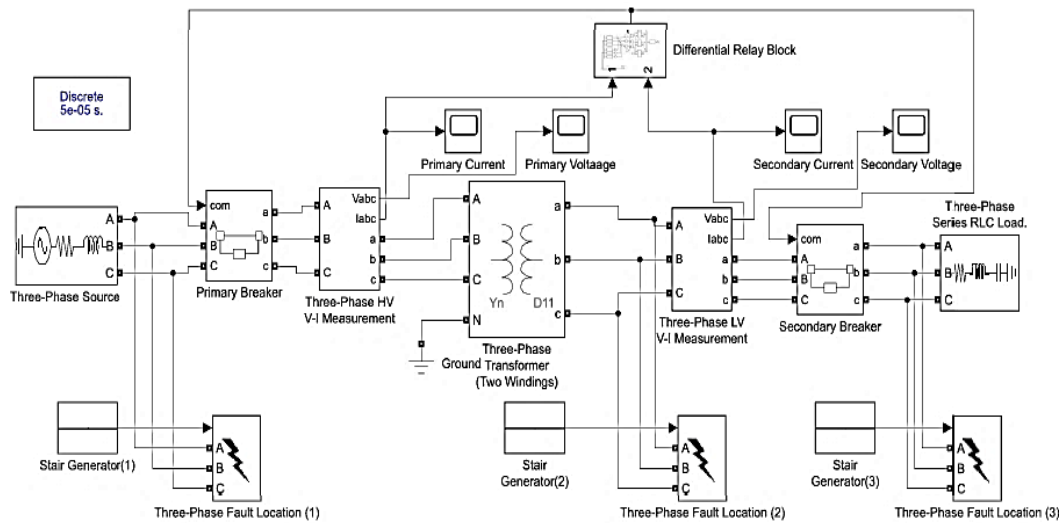


Figure 2. Simulink Model of the System

Implementation of the Differential Relay Model

The differential relay model has been created using MATLAB/Simulink environment. Figure 3, displays the Simulink design of the differential relay consisting of two inputs ports labelled In1 and In2, representing the output current of three-phase V-I measurement block of the primary and secondary side of the power transformer respectively. To analyze the system, these input signals were divided into three parallel paths. All signals were fed into an amplitude comparator block, while the second set of the signals went through a harmonic test and were

sent to a harmonic comparator block. The amplitude comparator compared the input currents' amplitude and generated an indication signal, while the harmonic comparator processed signals from subsystems blocks to determine the presence of harmonics. A gain adjustment of four was applied to the second input to balance the current on the first input, considering the transformer's voltage ratings (132/33 kV). The relay's control system is operated digitally, comparing input current with a desired pickup current using a relational operator, and the output was processed by an SR flip flop.

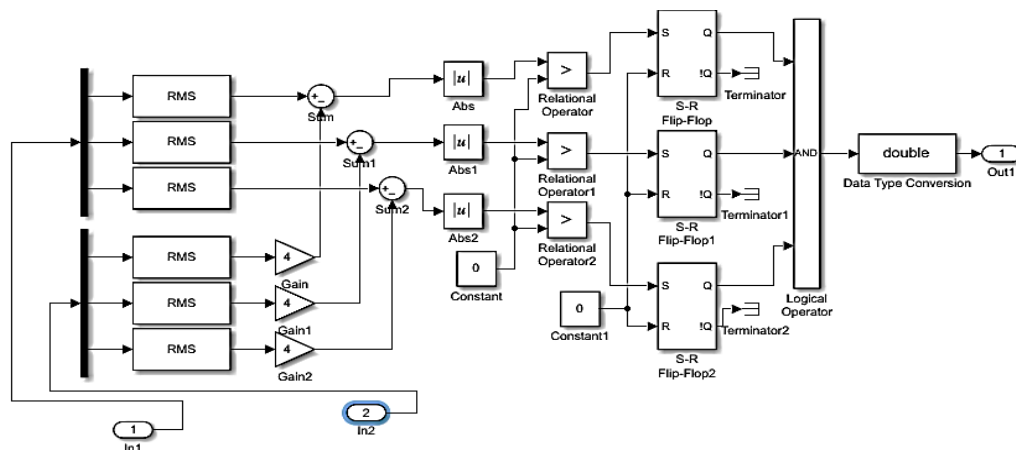


Figure 3. Simulink Model of Differential Relay

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Description of the Fault Scenarios

Simulating various fault scenarios allows us to assess the performance and the behavior of these components under differential fault conditions. Three fault locations were chosen and simulated independently. The following faults were simulated during this analysis at each location: No fault, Single-line-to-ground fault, Double-line-to-ground fault and Line-to-Line fault

Truth Table of SR Flip Flop

Table 1 illustrates the fundamental operation of the SR flip flop. According to the table, in order to trigger the circuit breaker, all the inputs 'R' of the flip flop should be connected to '0'. Additionally, all the 'S' inputs should be linked to the output of relational operators. When a fault occurs, the relation operator will become '1'. By setting the input 'R' to '0', the flip flop output 'Q' will be set to '1' (set). As a result, a trip signal will be transmitted

Table 1: Truth Table of SR Flip Flop

| S | R | Q | STATE |
|---|---|----------------|-----------|
| 0 | 0 | Previous State | No Change |
| 0 | 1 | 0 | Reset |
| 1 | 0 | 1 | Set |
| 1 | 1 | X | Forbidden |

RESULT AND DISCUSSION

The simulation results obtain from the analysis of the differential protection relay model of 60 MVA, 132/33 kV YnD11 power transformer under no-fault conditions and various fault scenarios are presented in this section. The simulation data provides valuable insights into the performance and behaviour of these components during fault conditions, allowing us to evaluate their effectiveness in detecting and responding to faults. At each fault location, the primary and secondary faults of the transformer were analysed.

Figure 4, presents the simulation results for no fault condition in the system. Under this condition, the relay did not assign any tripping signal to the breakers hence the signal was in normal condition. Thus, all the three phases

experience equal currents in this regard. The peak magnitudes of the primary and secondary currents were recorded to be 257.2A and 1026A respectively. These results provide valuable information about the behaviour of the components during typical operation. The relay's ability to maintain stability, accuracy, and reliable operation in the absence of fault event can be assessed. The primary side and secondary currents are respectively presented in Figures 4 (a) and (b).

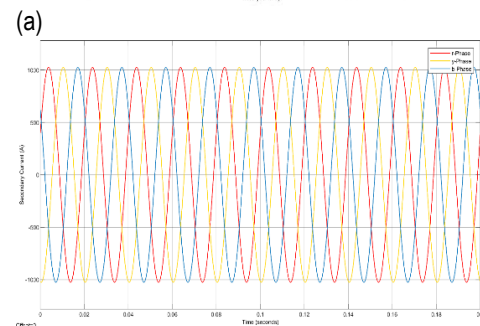
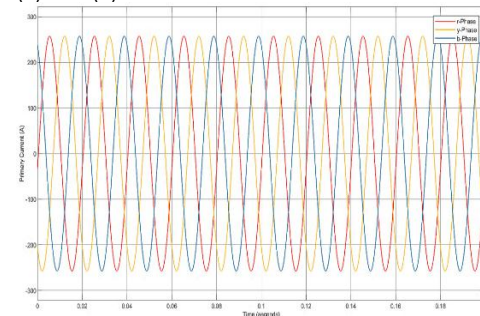


Figure 4. Transformer Currents under No Fault (a) Primary (b) Secondary

Figure 5 and Figure 6 present the simulation results for the single-line-to-ground fault scenario that occurred at the Red-Phase of stair generator 1 for both the HV side and LV side of the power transformer respectively. The trip signal was not initiated to the circuit breaker associated with the affected section because the fault occurred outside the zone of protection of the differential relay, causing the fault location to be outside the protected area. The fault current appears to be higher much higher than the normal operating current.

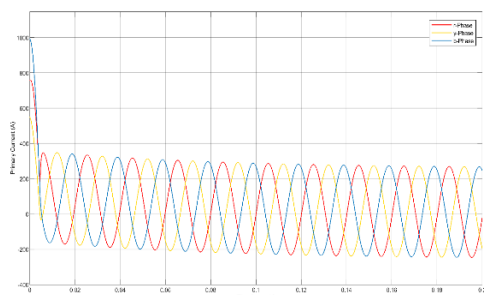


Figure5. Single-Line to Ground Fault Occurs at Red Phase HV Side at Location (1)

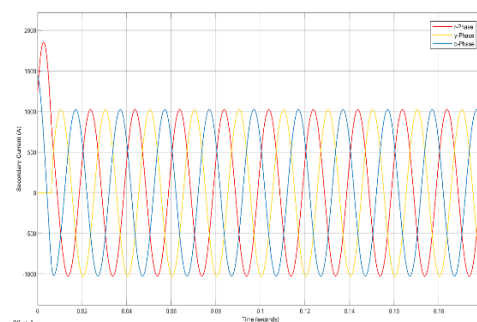


Figure 8. Single-Line to Ground Fault Occurs at Yellow Phase LV Side at Location (2)

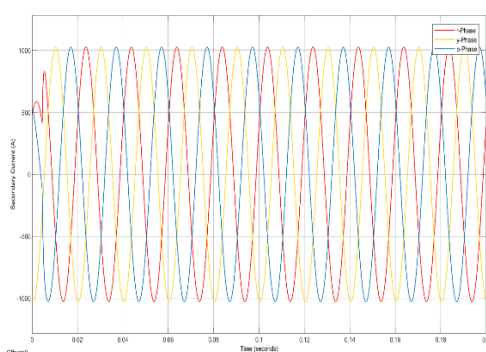


Figure6. Single-Line to Ground Fault Occurs at Red Phase LV Side at Location (1)

Figure 7 and 8, displays the simulation results for the single-line-to-ground fault that occurred at the Yellow-Phase 2. The simulation results for the single-line-to-ground fault scenario demonstrate the relay's ability to detect the fault and initiate appropriate protective actions. The relay accurately measures the current imbalances between the Yellow-phase and the ground, and promptly triggers the fault clearing mechanism to the LV side breaker to trip in response at $t=1.065\text{ms}$ and cleared the fault at 0.01sec

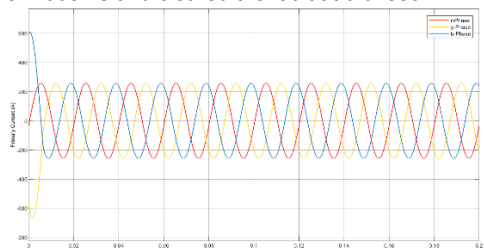


Figure 7. Single-Line to Ground Fault Occurs at Yellow Phase HV Side at Location (2)

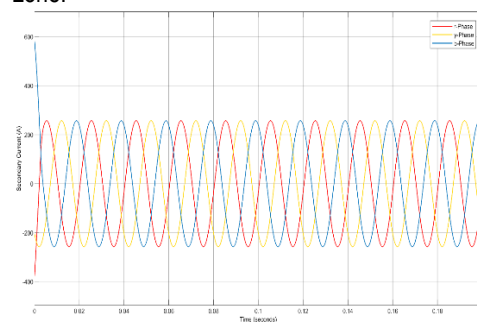


Figure 9. Single-Line to Ground Fault Occurs at Blue Phase HV Side Location (3)

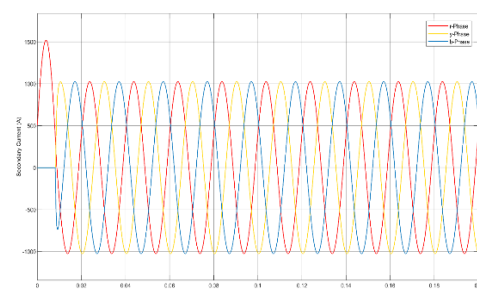


Figure10. Single-Line to Ground Fault Occurs at Blue Phase LV Side at Location (3)

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The simulation results for the double-line-to-ground fault scenario at the Red-Phase and Yellow-Phase, stair generator 1 of the HV and LV side of the power is shown in Figures 11 and 12 respectively. The double-line-to-ground fault scenario reveals the relay's capability to identify and react to faults involving multiple grounded phases. The relay analyses the current imbalances and successfully operates the protection scheme to isolate the faulted section (Red-Phase) at time $t=1.065\text{ms}$ and cleared the fault at $t=0.1\text{s}$ at the LV side of the system, while on the HV side, the amplitude of the current increases beyond the normal operating current.

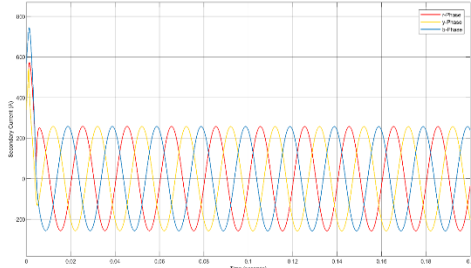


Figure 11. Double-Line to Ground Fault Occurs at Red and Yellow Phase HV Side at Location (1)

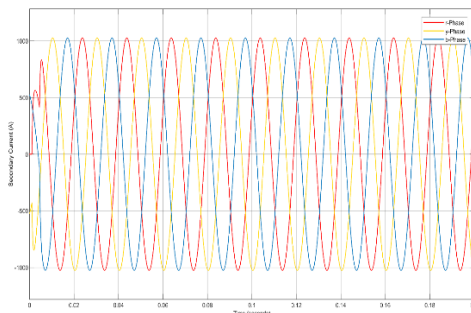


Figure 12. Double-Line to Ground Fault Occurs at Red and Yellow Phase LV Side at Location (1)

Figures 13 and 14 display the currents for a double-line-to-ground fault that occurred in Yellow and Blue-Phase at the location of the stair generator 1 on both the HV and LV sides of the power transformer respectively. The double-line-to-ground fault case demonstrates the relay's ability to detect and respond to faults involving multiple phases grounded simultaneously. By analyzing current imbalances, the relay effectively

triggers the LV circuit breaker to prevent the fault from propagating further at $t=1.065\text{ms}$ and clears the fault at 0.1s while the HV side remains unaffected but the magnitude of the current for the phase increased beyond the normal operation current.

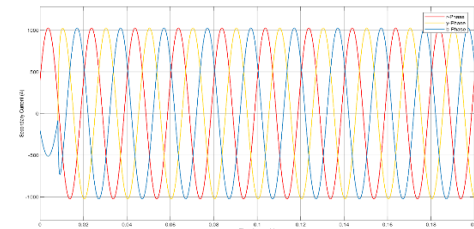


Figure 13. Double-Line to Ground Fault Occurs at Yellow and Blue Phase HV Side at Location (2)

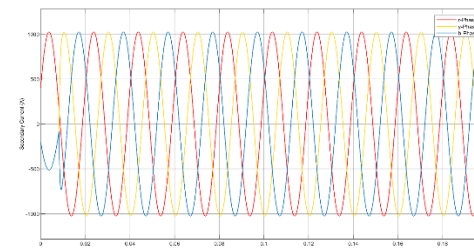


Figure 14. Double-Line to Ground Fault Occurs at Yellow and Blue Phase LV Side Location (2)

Figures 15 and 16 illustrate the simulation results for a double-line-to-ground fault in Red-Phase and Blue-Phase stair generator 3. The simulation analysis examines the response of both the high-voltage (HV) and low-voltage (LV) sides of the transformer to this fault condition. However, it is important to note that the trip signal of the differential relay was not activated in this case. This is because the fault occurred outside the protective range of the relay, causing the fault location to lie beyond the safeguarded zone.

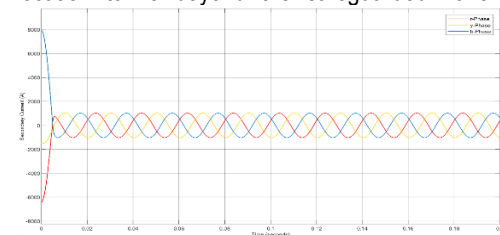


Figure 16. Double-Line to Ground Fault Occurs at Red and Blue Phase LV Side Location (3)

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Figures 17 and 18 demonstrate the simulation result for a line-to-line fault in Red-Phase and Blue-Phase stair generator 1 on both the HV and LV sides of the power transformer. The double-line-to-line fault case demonstrates the relay's ability to detect and respond to faults involving two phases simultaneously coming in contact with each other. By analyzing current imbalances in the HV side whose current amplitude is higher the normal operating current, the relay effectively triggers the protection scheme for the LV circuit breaker to isolate the faulty section (Red phase) at $t=1.065\text{ms}$ and clears the fault at $t=0.0102\text{s}$.

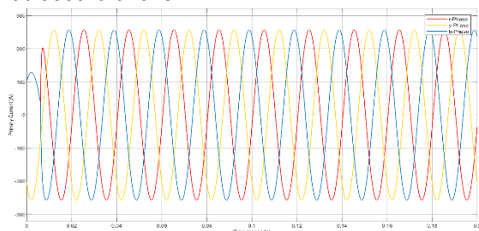


Figure 17. Line-to-Line Fault Occurs at Red and Blue Phase HV Side Location (1)

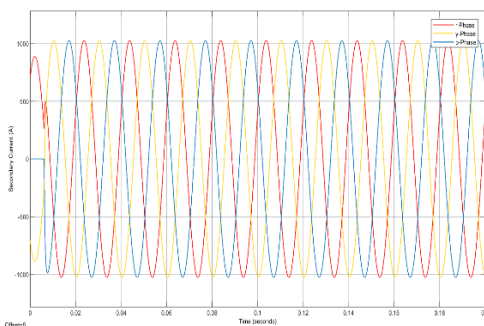


Figure 18. Line-to-Line Fault Occurs at Red and Blue Phase HV Side Location (1)

Figures 19 and 20 illustrate the simulation results for a line-line fault in Yellow-Phase and Blue-Phase stair generator 3. The simulation analysis examines the response of both the high-voltage (HV) and low-voltage (LV) sides of the transformer to this fault condition. However, it is important to note that the trip signal of the differential relay was not activated in this case. This is because the fault occurred outside the protective range of the relay, causing the fault location to lie beyond the safeguarded zone.

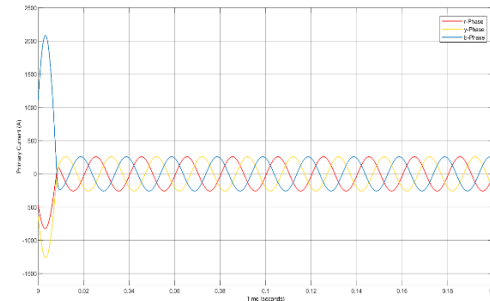


Figure 19. Line-to-Line Fault Occurs at Yellow and Blue Phase HV Side at Location (2)

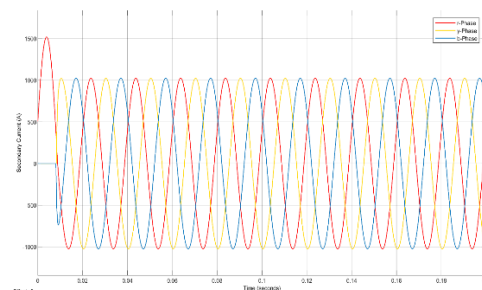


Figure 20. Line-to-Line Fault Occurs at Yellow and Blue Phase LV Side at Location (2)

Figures 21 and 22 illustrate the simulation results for a line-line fault in Red-Phase and Blue-Phase stair generator 3. The simulation analysis examines the response of both the high-voltage (HV) and low-voltage (LV) sides of the transformer to this fault condition. However, it is important to note that the trip signal of the differential relay was not activated in this case. This is because the fault occurred outside the protective range of the relay, causing the fault location to lie beyond the safeguarded zone.

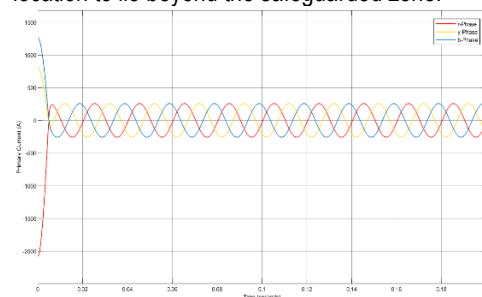


Figure 21. Double-Line-to-Line Fault Occurs at Red and Blue Phase HV Side at Location (3)

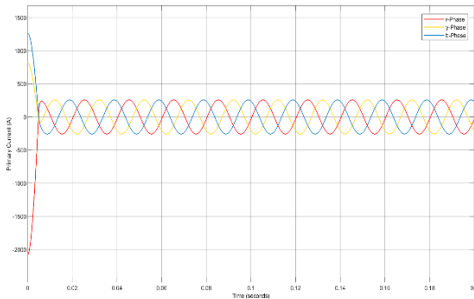


Figure. 22. Double-Line-to-Line Fault Occurs at Red and Blue Phase HV Side at Location (3)

Table 2: Fault Type and Clearing Scheme.

| Type of Fault | Fault Location | Relay Tripped |
|-----------------------|----------------|---------------|
| Single-Line-to-Ground | 1 | Not Tripped |
| | 2 | Tripped |
| | 3 | Not Tripped |
| Double-Line-to-Ground | 1 | Tripped |
| | 2 | Tripped |
| | 3 | Not Tripped |
| Line-Line | 1 | Tripped |
| | 2 | Not Tripped |
| | 3 | Not Tripped |

CONCLUSION

This study analyzed and simulated the differential protection relay of a 60MVA, 132/33 KV transmission line power transformer. The findings highlighted the relay's effectiveness in accurately detecting various fault scenarios, its swift response time, selectivity, and accuracy in fault detection. The research contributes to the understanding and advancement of differential protection relay technology and its practical applications in power system protection. The project's outcomes have implications for enhancing the design, operation, and maintenance of power transmission systems, improving system reliability and safety. Future work can explore advanced algorithms, intelligent systems, and fault location assessment techniques for further improvements in differential protection relays. Overall, the study provides valuable insights for power system operators, engineers, and researchers, laying the

groundwork for future advancements in power system protection.

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