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IMPROVED DIFFERENTIAL RELAY PERFORMANCE FOR A THREE-PHASE TRANSFORMER UNDER FAULT CONDITIONS

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Abstract— This research investigates the use of Differential Relay Systems to enhance protective measures for a 15.75/330 kV, 165 MVA power transformer at the Afam Power Generating Station, focusing on mitigating risks associated with overvoltage incidents. Overvoltage poses significant threats to transformer reliability, leading to insulation breakdown, core saturation, and overheating, jeopardizing operational stability and lifespan. The study proposes an improved protection system that utilizes differential relays. Differential relays effectively detect faults by comparing incoming and outgoing currents, identifying discrepancies indicative of faults. The differential relay system achieved a Mean Square Error (MSE) response of 0.03,

Mean Square Error, Three-Phase, Transformer	demonstrating high accuracy in fault signature detection. The differential relay functions as a reliable protector, offering real-time response capabilities. By detecting minute differences between currents in the transformer windings, the relay ensures swift isolation of faults, thereby minimizing potential damage and preserving the integrity of the electrical system. The assessment of the differential relay's performance, alongside MSE calculations, provides a comprehensive understanding of the fault detection system's overall efficiency. This methods amplifies system reliability, fortifying it against emerging faults and optimizing response times to prevent critical incidents. This study marks a significant advancement in transformer protection methodologies, aiming to improve electrical grid reliability and stability through enhanced fault detection and predictive maintenance strategies. The findings underscore the effectiveness of this integrated approach in bolstering the resilience and operational efficiency of power transformers and the wider electrical grid infrastructure.

I. Introduction

In modern power systems, the reliable operation of power transformers is paramount to ensuring a stable and efficient supply of electrical energy. Power transformers play a crucial role in stepping up or stepping down voltage levels, facilitating the transmission and distribution of electricity across networks. These vital components are subject to various operational challenges, ranging from load fluctuations to short circuits, which can result in disruptive events if not effectively managed [1]. To safeguard power transformers from internal faults and abnormal conditions, differential protection schemes have been widely adopted. Differential protection offers rapid and sensitive detection of internal faults by comparing the currents entering and leaving the transformer winding. When a fault occurs, the resulting current imbalance triggers an alarm or initiates a protective action, such as tripping the associated circuit breakers. This ensures the timely isolation of the faulty transformer from the system, preventing further damage and maintaining grid stability.

At the heart of this research is a transformer rated 15.75/330 kV with a capacity of 165 MVA. The differential protection scheme implemented for this transformer is designed to detect internal faults with high sensitivity and speed. By continuously monitoring the current entering and exiting the transformer windings, the protection system can quickly identify discrepancies that indicate faults, thereby enabling prompt protective actions to prevent extensive damage. A Generator Power Transformer is a critical component in electrical power generation systems. Faults and abnormal conditions in a Generator Power Transformer refer to unexpected problems or issues that can occur, potentially disrupting the transformer's normal operation and the overall power generation process. Here are some common types of faults and abnormal conditions associated with Generator Power Transformers [2].

According to [3], power transformer protection during malfunctions was accomplished by identifying the fault location and promptly isolating the affected section to prevent further damage. Differential protection relays, controlled using fuzzy logic, were employed in this disconnection process. The transformer fault was detected swiftly, allowing the defective part to be quickly removed from the system. A relay control software based on fuzzy logic was developed in MATLAB, which effectively and rapidly controlled these relays used for transformer protection. This software was tested on protection relays at the Erdemli Transformer Substation, and it successfully identified transformer faults in a short time, enabling the defective component to be promptly disconnected. As a result, significant damage to power transformers was avoided, leading to a substantial reduction in breakdown costs.

[4] examined differential protection relay used to protect the prototype-Terco power transformer. Matlab/Simulink was used to simulate the protection system. The power differential protection algorithm was simulated and tested on a 2KVA power transformer under different faults. During normal operating conditions, current will flow through all phase of the power transformer within predesigned values which are appropriate to these elements rating and the faults can be classified as the flow of a massive current.

According to [5] percentage differential relays remain the most sensitive protection tool applied as backup protection on power transformers, busbar, and generators. Relays sometimes do mis-operate with the current transformer being affected by external fault leading to saturation, and the subsidence current present after clearing external faults. The cause of mis- operation of percentage differential relays cannot be ignored that it entirely depends on magnitudes more than directionality for tripping decisions. This research work covers evaluating differential element performance, analysis of transformer inrush current, internal faults, external faults, and over excitation conditions. The accurate computing of current transformers is also included. This protection only applies to 10MVA and above on transformers; however, it is not limited to transformers, but also transmission lines, bus bars, and generators. The balance of the research work is on reliability assessment based on the HVDC grid protection scheme operation [6].

According to [7] transformer protection is a well-established research field focused on developing the most efficient and rapid differential relay algorithm to isolate transformers with minimal damage. The algorithm must also avoid maloperation by accurately distinguishing between different operating conditions. Although several differential algorithms have been proposed in the past, there remains room for further research. In this study, Artificial Neural Networks (ANNs) are employed as pattern classifiers to discriminate between normal conditions, magnetizing inrush, over-excitation, and internal fault currents in a power transformer. The proposed approach utilizes different ANN architectures, including a new parallel-hidden layered design that has proven more accurate in differentiating between normal and faulty waveforms, even when their shapes appear similar. The study also explores a combination of two ANNs operating in a Master–Slave configuration. The multi-layered feedforward neural network is trained using both the Back Propagation (BP) algorithm and Genetic Algorithm (GA), with comparative analysis showing that the GA-trained network achieves more accurate results, particularly in terms of minimizing mean square error, than the BP algorithm. Simulated data were used as input to the ANN to verify the algorithm's accuracy, and the results demonstrate that the GA-trained Master–Slave ANN-based differential protection scheme provides a faster, more accurate, secure, and reliable relay for power transformers [8]. [9] presents an approach for distinguishing between internal and external faults in a power transformer using an algorithm that combines discrete wavelet transform (DWT) with a probabilistic neural network (PNN). DWT is employed to decompose high-frequency fault components, and the maximum coefficients from a ¼ cycle DWT serve as input patterns for training a decision-making algorithm. The fault detection process relies on a division algorithm that uses the ratio between the zero-sequence post-fault differential current waveforms and the differential current coefficients within the ¼ cycle DWT to identify the maximum ratio and detect faults. The system simulations were based on various scenarios drawn from Thailand's electricity transmission and distribution networks. Results from the simulations indicated that both PNN and BPNN were effectively implemented and provided satisfactory accuracy in detecting faults. However, the PNN method was found to be particularly well-suited for identifying internal and external faults, with the maximum coefficient algorithm emerging as the most efficient for fault detection. This research offers valuable insights for improving differential protection in power transformers [10].

While power transformer differential protection is a well-established technique, the increasing complexity of power systems, integration of renewable energy sources, and evolving fault scenarios demand continuous refinement and enhancement of protection strategies [3]. The project's motivation stems from the need to address challenges such as mitigating false tripping due to transient conditions, improving sensitivity to internal faults, and optimizing protection settings for diverse operating conditions. The main objective of this project is to critically analyse and optimize power transformer differential protection to contribute to enhanced power system performance. By meticulously studying the behaviour of differential protection schemes under various fault scenarios and system conditions, this research seeks to develop novel algorithms, techniques, or enhancements that ensure quicker and more accurate fault detection while minimizing disruption to the power system. The outcomes of this research have the potential to significantly enhance the operational reliability of power transformers and the overall power system.

II. Materials and Method

A. Materials

The materials used for this study are 15.75/330kV 165MVA transformer with a current rating of 303.1A and 5975.1A, a differential relay of 100A with operational speed of less than 20ms, a three-phase breaker of 800A and a laptop for simulation analysis.

B. Methodology

The gas turbine power transformer of Afam power station is modeled in MATLAB/Simulink as shown in Figure 1. The system parameters are therefore evaluated and the mean square error examined.

Evaluation of Line Data

- **Resistance of line per kilometer**

$$R = \frac{\rho}{A}\Omega/L \tag{1}$$

where:
ρ = Resistivity of aluminum
A = Area of conductor
L = Route length of the feeder

- **Reactance of line per kilometer**

$$r = \sqrt{\frac{A}{\pi}} \tag{2}$$

To develop an equation for the reactance of a transmission line per kilometer for a 165 MVA transformer, we need to consider the parameters of the transmission line such as its inductance and capacitance per unit length.

The reactance of a transmission line is primarily determined by its inductance. The inductance per unit length, L, of a transmission line can be calculated using the formula:

$$L = \frac{2.\pi.f.GMD}{In\left(\frac{D_2}{D_1}\right)} \tag{3}$$

where:
f = frequency of the transmission line
GMD = Geometric Mean Distance between conductors
$D1$ and $D2$ = diameters of the conductor

For a given transmission line, f, would typically be 50 Hz or 60 Hz. Given inductance per unit length, L, reactance per km can be calculated using the formula:

$$x = 2.\pi.f.L \quad (4)$$

where:
f = frequency
L = inductance per unit length
π = constant.

For a 165 MVA transformer, this reaction can be used in transmission line models to calculate voltage drops, power losses during load flow studies or fault analysis.

Evaluation of Differential Relay

Differential relay provides a unit protective scheme for large power transformers. The protected equipment or zone is connected to current transformers of similar characteristics and ratio on both side and a relay is connected between the two current transformers by using pilot wires. Differential relay does not provide backup protection for other system components. In large substation, it replaces over current protection as the main protection.

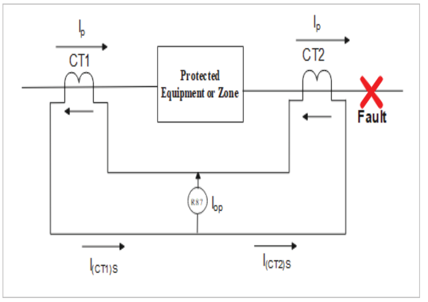

Figure 1: Differential relay current during normal operation or external fault [3]

Figure 1 shows the current distribution during normal operation or external fault. Under normal or external fault conditions, the current Ip entering the protected unit would be equal to the current leaving it at every instant as shown in Figure 1. Therefore, the secondary current of current transformer CT1 is giving by

$$I_{(CT1)S} = \alpha_{(CT1)} * I_p - I_{(CT1)e} \quad (5)$$

where:
$\alpha_{(CT1)}$ = transformation ratio of current transformer *CT1*
$I_{(CT1)e}$ = excitation current of current transformer *CT1* on the secondary side
I_p = current entering the protected zone

Similarly, the secondary current of current transformer *CT1* is giving by

$$I_{(CT2)S} = \alpha_{(CT2)} * I_p - I_{(CT2)e} \quad (6)$$

where:

$\alpha_{(CT2)}$ = transformation ratio of current transformer *CT2*

$I_{(CT2)e}$ = excitation current of current transformer *CT2* on the secondary side

I_p = current entering the protected zone

Assuming current transformers has similar characteristics therefore transformation ratio on both side is giving by

$$\alpha_{(CT1)} = \alpha_{(CT2)} = \alpha \quad (7)$$

The relay operation current I_{op} is given by

$$I_{op} = I_{(CT2)e} - I_{(CT1)e} \quad (8)$$

During normal system operation and during external faults, the relay operating current I_{op} is small, but never zero ($I_{op} \neq 0$). Figure 2 shows the current distribution during internal fault. In the event of a fault in the protection zone, the input current is no longer equal to the output current. Therefore, the secondary current of current transformer *CT1* is giving by

$$I_{(CT1)S} = \alpha_{(CT1)} * I_{F1} - I_{(CT1)e} \quad (9)$$

where:

$\alpha_{(CT1)}$ = transformation ratio of current transformer *CT1*

$I_{(CT1)e}$ = excitation current of current transformer *CT1* on the secondary side

I_{F1} = Fault current entering the protected zone

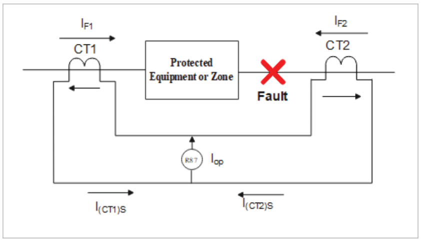

Figure 2: Differential Relay Current During Internal Fault [3]

Figure 2 shows the current distribution during internal fault. In the event of a fault in the protection zone, the input current is no longer equal to the output current.

Similarly, the secondary current of current transformer, *CT1*, is giving by

$$I_{(CT2)S} = \alpha_{(CT2)} * I_{F2} - I_{(CT2)e} \quad (10)$$

where:

$\alpha_{(CT2)}$ = transformation ratio of current transformer *CT2*
$I_{(CT2)e}$ = excitation current of current transformer *CT2* on the secondary side
I_{F2} = Fault current entering the protected zone

The relay operation current I_{op} is given by

$$I_{op} = I_{(CT1)S} + I_{(CT2)S} \quad (11)$$

Substituting $I_{(CT1)S}$ and $I_{(CT2)S}$ into (7),

$$I_{op} = \alpha_{(CT1)} * I_{F1} - I_{(CT1)e} + \alpha_{(CT2)} * I_{F2} - I_{(CT2)e} \quad (12)$$

$$I_{op} = \alpha_{(CT1)} * I_{F1} + \alpha_{(CT2)} * I_{F2} - I_{(CT1)e} - I_{(CT2)e} \quad (13)$$

Assuming current transformers has similar characteristics, therefore transformation ratio on both side is giving by

$$\alpha_{(CT1)} = \alpha_{(CT2)} = \alpha \quad (14)$$

$$I_{op} = \alpha(I_{F1} + I_{F2}) - I_{(CT1)e} - I_{(CT2)e} \quad (15)$$

Differential Relay MSE Evaluation

The MSE for a differential relay in a protective transformer system can be calculated by comparing the relay's measured values or responses with the expected or ideal values. The MSE formula can be represented as

$$MSE = \frac{1}{n}\sum_{i=1}^{n}(X_i - Y_I)^2 \quad (15)$$

where:
MSE = Mean Square Error
n = Number of samples or observations
X_i = Measured or actual value from the differential relay
Y_i = Expected or ideal value

This formula computes the average of the squared differences between the measured and expected values. A lower MSE indicates that the relay's responses closely align with the expected values, signifying higher accuracy in detecting and responding to faults within the transformer.

Figure 3 shows a MATLAB/Simulink model of an injection substation connected to a three-phase source and a load via three-phase breaker at the primary and secondary of the transformer. In between the circuit breaker and the transformer are three-phase V-I measurement used for measuring the value of load current, a differential relay scheme for protection of the power transformer and a scope for visualization. The Simulink model shown in Figure 3 depicts the Gas Turbine Generator Power Transformer at Afam Power Station. The rated capacity of the substation is 15MVA-33/11kV.

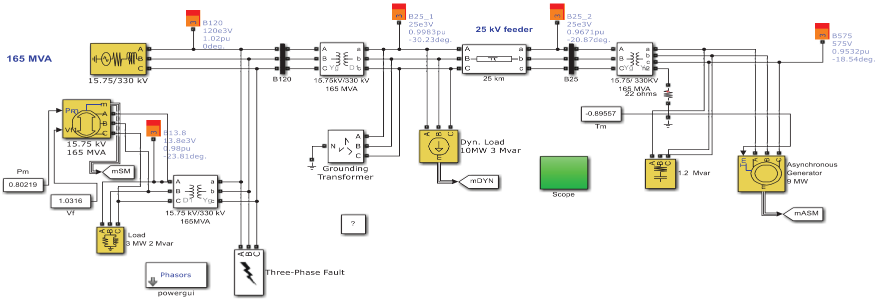

Figure 3: A Simulink Model of the Gas Turbine Generator Power Transformer at Afam Power Station

III. Results and Discussion

A. Response of the Three Phase Transformer

Figure 4 shows the 3-phase 15.75/330 kV 165 MVA transformer generated waveforms representing electrical quantities in three phases.

These waveforms in Figure 4 typically depict the voltage or current in each phase over time. The transformer operates using three conductors, each carrying an alternating current that's 120 degrees out of phase with the others, forming a balanced system. The waveform for each phase typically looks like a sine wave. In a balanced system, the three waveforms have the same frequency and shape, but they differ in phase by one-third of the cycle (120 °) from one another. The 165 MVA rating indicates the transformer's power handling capacity, specifically its maximum apparent power capability, which is distributed among the three phases. This rating signifies the amount of power the transformer can transfer under normal operating conditions.

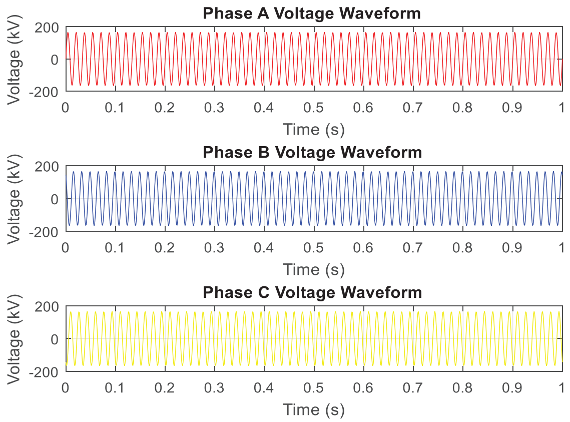

Figure 4: 3 Phases of the transformer

Visualizing these waveforms helps engineers and operators understand how electrical quantities vary across the phases, aiding in monitoring and controlling the transformer's behavior. They are essential for analysing the transformer's performance, ensuring balanced operation, and diagnosing any abnormalities or faults in the system.

B. Detected Fault on Transformer Response

Figure 5 shows the detected faults in a 165MVA transformer. It represents voltage waveforms of three phases of the transformer to identify anomalies indicating potential faults within the system.

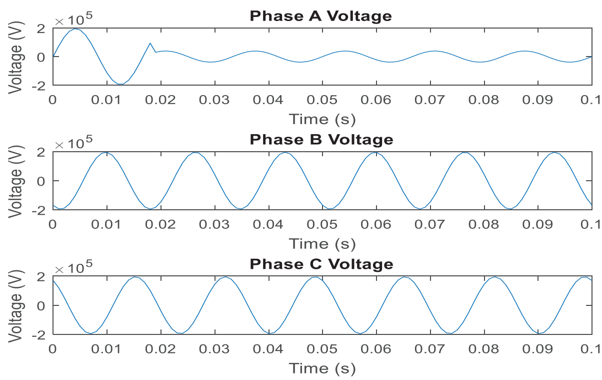

Figure 5: Fault detection on Phase 1 of the transformer

These waveforms in Figure 5 offer critical insights into the transformer's condition, aiding engineers in diagnosing and addressing issues promptly. In fault detection, waveform analysis entails observing deviations or irregularities in the expected patterns of electrical quantities. Under normal operating conditions, the transformer's waveforms exhibit a specific behavior characterized by balanced voltages or currents across the three phases – A, B, and C. Any deviation from these anticipated patterns could signal a fault.

For instance, a fault waveform in a 165MVA transformer might manifest as abrupt changes or distortions in the voltage or current wave forms. These anomalies often differ based on the type of fault. Short circuits might result in sudden spikes or disturbances in the wave forms, while open circuits could cause interruptions or complete absence of certain phases' signals. Analyzing these wave forms involves scrutinizing the magnitude, phase relationship, and frequency content of the electrical signals across the transformer's phases. An oscilloscope or other monitoring equipment captures and displays these waveforms, enabling engineers to assess the system's behaviour in real-time or through recorded data. Waveform analysis for fault detection also includes considering transient responses during fault occurrences. Transients are temporary disturbances in the electrical signals, often characterized by high-frequency oscillations or sharp changes. Detecting and analysing these transients aids in pinpointing the fault's location and severity. Furthermore, the waveform analysis may involve comparing observed wave forms with reference or expected patterns generated from healthy operating conditions. Deviations beyond acceptable limits trigger alarms or protective measures, prompting operators to take corrective actions or isolate the transformer to prevent further damage.

In a 165MVA transformer, due to its substantial power capacity, the waveform analysis for fault detection demands precise and thorough scrutiny. Engineers rely on sophisticated monitoring systems and analysis tools to interpret these waveforms accurately. Fourier analysis, harmonic analysis, and advanced signal processing techniques might be employed to delve deeper into the waveform characteristics and isolate fault-related signatures. Understanding the intricacies of these waveforms is essential for effective fault detection strategies. It empowers maintenance personnel to swiftly detect faults, initiate protective measures, and perform necessary repairs or replacements, minimizing downtime and ensuring the transformer's operational reliability.

C. Detected Fault Due to Over-Voltage

Figure 6 shows the over voltage fault in a 165MVA transformer which represents a critical deviation from the acceptable voltage levels across its terminals.

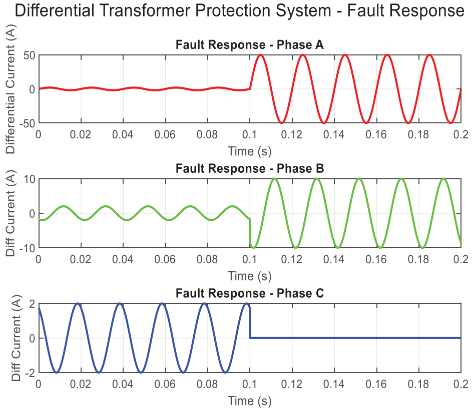

Figure 6: Detected fault due to over voltage

Figure 6 shows anomaly characterized by an excess in voltage beyond the transformer's design limits, poses severe risks to the equipment's integrity and operational stability. This fault can originate from various sources, both internal and external to the power system. External factors such as lightning strikes, grid disturbances, or switching surges can induce transient over-voltages, impacting the transformer. Internally, issues related to voltage regulators, tap changer malfunctions, or insulation degradation within the transformer can contribute to sustained overvoltage conditions. When an overvoltage fault occurs, its manifestations become evident in the electrical parameters and behaviours of the transformer. The voltage waveforms, which under normal conditions exhibit sinusoidal patterns, undergo distortion and irregularities, showcasing peaks or spikes that surpass the expected voltage magnitudes. These deviations are observable indicators of the fault's presence and severity.

However, the implications of an overvoltage fault extend beyond the immediate distortion in waveforms. This fault poses imminent risks to the transformer's components, primarily the insulation system. Elevated voltages induce excessive stress on the insulation materials, accelerating their aging process. Over time, this stress weakens the insulation, potentially leading to insulation breakdowns or partial discharges, creating pathways for short circuits or insulation failure. Thermal stress on the transformer's windings and core also escalates with overvoltage faults. The increased temperature resulting from prolonged exposure to high voltages can deteriorate the insulation and other critical components, impairing the transformer's functionality and longevity.

Moreover, the introduction of harmonics or higher-frequency components in the electrical signals due to overvoltage faults affects the power quality and can disrupt the operation of connected equipment. These harmonics might propagate through the electrical system, impacting other devices and potentially causing malfunctions or failures in the broader network. To prevent or mitigate the impacts of overvoltage faults, protective measures are indispensable. Continuous monitoring and detection systems, including relay protection, aid in promptly identifying and isolating overvoltage conditions. Automatic voltage regulation mechanisms, surge protection devices, and maintenance practices, such as insulation testing and oil analysis, contribute to managing and mitigating the risks associated with over voltage faults. Understanding the waveforms associated with overvoltage faults and their implications is pivotal for safeguarding the 165MVA transformer. Timely detection, informed responses, and robust protective measures ensure the transformer's reliability, longevity, and sustained performance within the electrical grid, preventing disruptions and ensuring uninterrupted power supply.

IV. Conclusion

The analysis of power transformer protection using differential relay technology enhances the operational reliability and safeguards critical electrical infrastructure for the 165 MVA transformer. The differential relay functions as a reliable protector, offering real-time response capabilities by detecting minute differences between currents in the transformer windings, the relay ensures swift isolation of faults, thereby minimizing potential damage and preserving the integrity of the electrical system. The assessment of the differential relay's performance, alongside MSE calculations, provides a comprehensive understanding of the fault detection system's overall efficiency.

V. Acknowledgement

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