2024 32nd Southern African Universities Power Engineering Conference (SAUPEC) | 979-8-3503-7134-5/24/$31.00 ©2024 IEEE | DOI: 10.1109/SAUPEC60914.2024.10445097

Transformer Differential Protection System with IEC 61850 GOOSE Communication Protocol

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***Abstract*— This paper presents an in-depth exploration of an advanced transformer differential protection system that utilizes the MiCOM-P645 relay and the IEC 61850 Generic Object-Oriented Substation Event (GOOSE) communication protocol. Transformer protection is of paramount importance in ensuring the reliable and stable operation of power systems. The integration of these cutting-edge technologies enhances the coordination and fault detection capabilities of transformer protection systems, ultimately improving the reliability and performance of power distribution networks. The study's primary goal is to demonstrate the scheme's effectiveness, improving both the reliability and performance of transformer protection. To aid postgraduate students in comprehending the setup and operational principles of the system, the paper presents a comprehensive approach encompassing theoretical analysis, an extensive literature review, and practical results obtained from simulation, hardware-in-the-loop (HIL) testing, and real-time simulation using the Real-Time Digital Simulator (RTDS). Simulation results validate the success of MiCOM-P645 relay-based differential protection with IEC 61850, highlighting its faster response compared to traditional hardwired signals during real-time testing.**

***Keywords*-- Current Differential Protection, Hardware-in-the-Loop Testing, IEC 61850 GOOSE, Real-Time Simulation in RTDS, Transformer Protection.**

I. INTRODUCTION:

Power Transformer (PTRF) protection is of paramount importance in ensuring the safe and reliable operation of electrical power systems. The rapid evolution of technology has introduced innovative solutions to enhance the effectiveness of transformer protection systems. This paper delves into the realm of advanced transformer protection by introducing a novel system that leverages the MiCOM-P645 Intelligent Electronic Device (IED) and the IEC 61850 Generic Object-Oriented Substation Event (GOOSE) communication protocol. By combining these cutting-edge technologies, we aim to address the ever-increasing demands for improved coordination, faster fault detection, and enhanced reliability in transformer protection using current differential [1].

Current differential protection is a widely adopted technique for detecting and isolating internal faults in PTRF protection, as it offers fast and sensitive detection. Traditional transformer differential protection schemes have proven effective, but advancements in communication protocols have opened up new possibilities for enhancing the performance and reliability of such systems. The increasing complexity of substation automation systems demands advanced communication protocols [2].

This study emphasizes the importance of advanced communication and coordination among IEDs for an effective protection scheme. The utilization of the IEC 61850 standard, particularly the GOOSE communication protocol, offers significant advantages in transformer protection schemes [3]. The paper's primary focus lies in the design and deployment of an advanced transformer protection system based on the MiCOM-P645 relay and IEC 61850 communication, intending to enhance selectivity and speed in power system protection.

Contributions encompass not only the improvement of transformer protection for power system reliability and performance but also the provision of valuable knowledge resources, particularly beneficial for postgraduate students.

Research Question: How can the integration of modern IED relays and the IEC 61850 GOOSE communication protocol enhance transformer protection systems for improved coordination, faster fault detection, and enhanced reliability across a wide range of devices?

II. LITERATURE REVIEW:

An extensive literature review reveals the significance of current differential protection in PTRF applications utilizing the IEC 61850 standard and GOOSE communication. Several studies have explored the application of IEC 61850 communication protocols in power system protection schemes. The authors in reference [4], emphasize the importance of continuous monitoring and rapid protection for power transformers. They review multiple protection methods, such as percentage differential logic, dissolved gas analysis, and thermography, and conclude by discussing various approaches for enhancing transformer performance. In reference [5], the authors present a comprehensive guideline for practical numerical differential relay testing procedures and detailed relay setting analysis for Extra High Voltage (EHV) autotransformers. Their approach is based on experimental results that are scrutinized to document a detailed theoretical and technical analysis.

In reference [6] the authors propose a novel differential element to enhance power transformer relay performance, particularly in protection coordination. This technique streamlines fault detection without the need for transformer group settings. Overall, the study affirms that the method

CPUT Postgraduate Bursary and Eskom Tertiary Education Support Programme (TESP).

effectively achieves rapid fault clearance under diverse operating conditions. In reference [7] the authors discuss cost-effective and versatile real-time simulators for IEC 61850 compliant protection devices, focusing on Sampled Values (SV) and GOOSE interfaces integrated with Matlab/Simulink. The proposed solution is evaluated using the ABB REL670 relay in hardware-in-the-loop testing. In reference [8] the authors compare the results of the communication configuration with the traditional hardwired signals and show that the IEC 61850-based communication configuration is faster and more reliable than the hardwired signals. It also discusses the challenges and limitations of the proposed communication configuration, such as bandwidth requirements, network security, and interoperability issues.

Numerous researchers have suggested different protection methods for transformers, like neural networks, fuzzy logic, and wavelet analysis to enhance fault detection reliability, this paper concentrates on the development and deployment of an advanced transformer differential protection system, utilizing the IEC 61850 GOOSE communication protocol through the MiCOM-P645 IED to prioritize improved selectivity and speed in power system protection.

III. THEORY: CURRENT DIFFERENTIAL PROTECTION OF TRANSFORMER OPERATING PRINCIPLE

The MiCOM-P645 IED's theoretical functions encompass these key functions, which collectively contribute to the efficient and reliable protection of electrical substations and power systems. Its adaptability, communication capabilities, interoperability, and advanced protection algorithms make it a valuable component in modern power system automation and control. The MiCOM-P645 is a numerical relay commonly used for the current differential protection scheme commonly used to protect transformers from internal faults. It operates by comparing the currents entering and exiting the transformer, with the measurement being facilitated by the use of current transformers (CTs). These CTs step down the currents to a manageable level for protection equipment. To examine the operational principles of the PTRF differential protection system, we refer to Fig. 1, which illustrates two distinct conditions in the circuits: external and internal fault conditions.

When the currents are balanced, the state of currents signifies normal, external fault operating conditions without internal faults. The differential scheme creates a protection zone between two CTs, and any fault within this zone is regarded as an internal fault known as an imbalanced state of currents. The protection scheme typically consists of CTs to measure the currents, a differential relay for current comparison, and circuit breakers for tripping the transformer [9], [10][11].

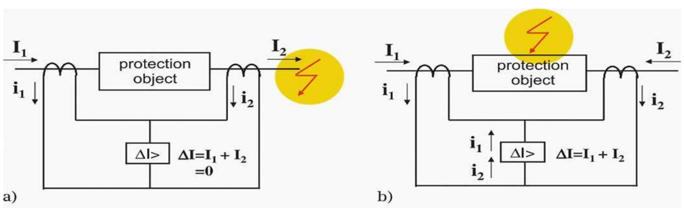

Fig. 1: Measuring principle Current flow on the PTRF differential protection relaying circuit under (a) External fault, (b) Internal fault.

Here are the main steps involved in the operating principle of current differential protection for transformers [2], [9]:

- **Current Comparison:** The currents measured by the CTs are compared using a MiCOM-P645 relay. The relay calculates the difference between the currents and determines whether a fault is present. To ensure equality of the secondary side currents of the CTs, careful selection of ratings is crucial to match them with the PTRF current ratings to which they are connected. This theory is supported and validated using Equation 1.

$$I_{Max\_Load(Pri/Sec)} = \frac{I_{FL-(Pri/Sec)}}{N_{(Pri/Sec)}} \quad (1)$$

As per the IEEE Guide for CT Selection [12], the primary CT turns ratio should be within 120% to 150% of the typical load current, with Equation 2 used for its calculation.

$$Pri/Sec_{Ratio} = (n\%)(I_{FL-W(Pri/Sec)}) \quad (2)$$

Where: $n\%$ is the CT turns ratio between 120% and 150%, $I_{FL-W(Pri/Sec)}$ = Full load current

- **Differential Relay Operation:** The differential relay used in the protection scheme performs the current comparison and decision-making process. The relay operates based on the following equation:

$$I_{OP} = I_{Diff} = (I_{IN} - I_{OUT}) \quad (3)$$

Where: I_{OP} is the operating current, I_{Diff} = Differential current, I_{IN} = Total currents entering the transformer, I_{OUT} = Total currents exiting the transformer.

The relay continuously calculates the differential current and compares it with the percentage restraint setting. If I_diff exceeds the threshold, the relay initiates the tripping action.

- **Percentage Restraint (PR):** To avoid unnecessary tripping during external faults or inrush currents, a PR feature is used. This feature sets a threshold for the difference in currents, below which the protection scheme does not operate. The PR setting is typically around 10-20% of the rated current. If the difference in currents exceeds the PR threshold, it indicates an internal fault, and the protection scheme initiates a tripping action. The PR threshold and the differential current threshold use a slope characteristic, which defines the relationship between the operating current and the restraint current. A slope characteristic can be expressed as:

$$I_{OP} = ((S * I_{RT}) + I_{TH}) \quad (4)$$

Where S is the slope expressed as a percentage, I_{RT} is the restraint current, and I_{TH} is the differential current threshold. The choice of the restraining current method depends on the characteristics of the transformer, the CTs, and the system configuration. It is important to consider the trade-offs between sensitivity and security when selecting a method.

$$I_{RT} = \frac{(I_{OP} = I_{Diff})}{K} \quad (5)$$

Where: K = Multiplication factor typical range of K is 0.5 to 1, depending on the desired sensitivity and security. Using

Equation 2, we can derive the percentage restraint threshold and the differential current threshold as:

$$I_{PR} = \frac{I_{TH}}{1-S} \quad (6)$$

Where: I_{PR} = Percentage restraint threshold.

$$I_{TH} = S * I_{PR} \quad (7)$$

The advantage of using a slope characteristic is that it allows for more flexibility and adaptability in setting the differential protection, especially for variable percentage slopes that can provide different levels of sensitivity and security for different operating conditions.

- **Tripping Action:** If the fault condition is confirmed, the MiCOM-P645 relay sends a trip command to the associated circuit breakers to isolate the transformer from the faulted section of the system.

Overall, the current differential protection scheme continuously monitors the currents entering and leaving the transformer and detects any imbalances that indicate internal faults. By using appropriate settings and algorithms, the protection scheme ensures reliable and selective operation during fault conditions, while avoiding unnecessary tripping during normal system operations.

A. Considerations in Differential Protection

When configuring and applying differential protection using the MiCOM-P645 relay, there are several important considerations to ensure effective and reliable protection for transformers. Here are some key considerations: CT Selection and Saturation, CT Circuit Compensation, Restraint Feature, Operating Characteristics, and Time Delays, Communication, and Configuration [2].

B. Difficulties Encountered in Differential Protection

While the MiCOM-P645 relay offers advanced features for differential protection of transformers, there can be some difficulties encountered during its configuration and operation. Here are some common challenges that users may face [2]:

- **CT mismatch** due to different CT types, ratios, burdens, or connections, can affect the accuracy and sensitivity of the differential protection.
- **CT saturation** impact on PTRF differential protection is complex. It can lead to false differential results, potentially causing misoperation of external failure relays during external faults or inrush currents, resulting in undesired tripping. Some relays address this issue with percentage restraint. However, CT harmonics can delay the operation of differential relays with harmonic restraint or blocking in the event of an internal fault. Certain differential relays utilize CT saturation harmonics to add restraint and prevent malfunction, emphasizing key features of CT saturation [2]: According to [13], the high slope 2 (characteristic of the Dual-Slope as shown in Fig. 2) is mostly redundant anywhere harmonic blocking is permitted during CT saturation through-faults.

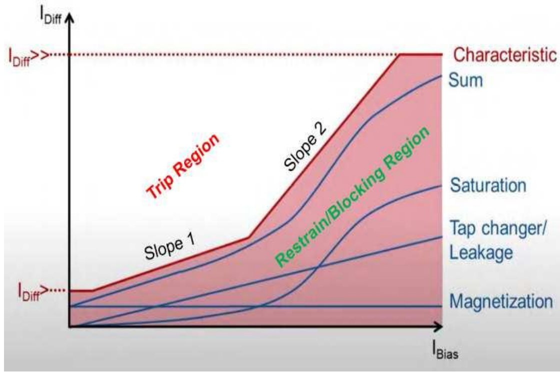

Fig. 2: Transformer Differential Protection Device Operating Characteristic [2].

- **Transformer magnetizing inrush** Energization or switching actions can generate high harmonic currents and distort the differential current waveform in transformers. Inrush current occurs when sudden operational changes expose the transformer's magnetic field to such conditions. It's a temporary phenomenon associated with magnetization and flows exclusively within the transformer, creating a differential current that can trigger differential protection mechanisms [2].
  A transient current called magnetizing inrush current occurs when the system voltage is applied to a transformer at a time when steady-state flux should be at a value other than that present on the transformer as stated in IEEE Std. C37.91-2000 [12].
- **Transformer overfluxing** Overvoltage or under-frequency conditions can result in excessive core heating and saturation in transformers. This happens when the magnetic flux in the core surpasses the design limit, which is directly related to the applied voltage. When the transformer experiences voltage levels higher than its rating, it leads to an increase in core magnetic flux, a phenomenon known as overfluxing.
- **Over-excitation of a Transformer:** The magnetic flux in a transformer core is inversely proportional to system frequency and directly affected by the applied voltage. Over-excitation can saturate the core, causing heat and potential damage. This condition often produces unusual, odd harmonics in the excitation current. Core saturation can occur under-frequency or with overvoltage, making the 5th harmonic a crucial indicator for reliable detection of over-excitation [2].
- **Transformer tap changer** operation, which can cause transient differential currents and affect the differential setting.

To overcome these difficulties, the MiCOM-P645 offers various features such as [2]:

- **CT saturation and no gap detection** methods to enhance the operational speed of the low-set differential element in situations of CT saturation, including addressing potential second harmonic blocking.
- **External fault detection** is an algorithm designed to mitigate the impact of CT saturation and no-gap detection

on second harmonic blocking in the presence of external faults.

- **Transient bias** technique to enhance relay stability and reduce CT requirements.
- **Second harmonic blocking** to prevent false tripping due to inrush currents.
- **Overfluxing restraint** to prevent false tripping due to transient overfluxing.
- **Tap changer compensation** to adjust the differential setting according to the tap position.

1) Inrush and Over-excitation Approaches to Discriminate Internal Faults

Internal faults are distinguished from over-excitation, inrush conditions, and external CT saturation faults by the harmonic portion of the differential present. It is possible to use a harmonics transformer to either block or restrain [13]. The differences between harmonic restraint and harmonic blocking are historically different, commonly interchangeable using both, but have not been clearly defined in the technical literature on this subject. To block or restrain the relay, the differential current harmonic material may be used to provide a means of differentiating between inrush or over-excitation internal faults and conditions [2]. The internal transformer fault current normally has a low 2nd harmonic value, based on the calculated values of the PTRF and CTs. The simplest type of harmonic restraint uses the magnitude of the 2nd harmonic in the differential current, in contrast to this magnitude of the fundamental frequency variable. If this ratio is at an adjustable threshold, the differential element tripping is blocked [2]. The fifth harmonic is used more commonly as the third harmonic, to avoid undesired operation during over-excitation, differential relays can also use fifth-harmonic blocking [2].

C. Differential Operating Characteristic

For the majority of the numerical transformer differential protection relays, there are two percentage differential slopes to address differential CT mismatch at CT saturation. Normal operation is handled by the first slope (SLP1), and security and sensitivity are handled by the second slope (SLP2) [14]. Fig. 2 shows an Operating characteristic of a transformer differential protection system, where small differential currents are also possible under normal conditions that exist due to transformer magnetization, tap change or leakage, and saturation effects. The maximum differential current under normal conditions results from the cumulative effects mentioned. The differential characteristics, which approximate these effects, define a restrain/blocking region and a trip region. In most cases, the characteristics start at the lower set value ($I_{diff>}$) which is 0.25 × the nominal current value and it rises to 6 × the set value ($I_{diff\gg}$). Above this value the relay will trip independent of the stabilizing current [14].

IV. TRANSFORMER DIFFERENTIAL CONFIGURATION

The MiCOM-P645 relay offers flexible configuration options for transformer differential protection. This section provides a comprehensive overview of the typical configuration settings employed in transformer differential protection, utilizing the MiCOM-P645 relay:

A. Hardware laboratory setup

To configure the differential protection of a three-phase transformer, several factors need to be taken into account. These include the characteristics and connections of the system CTs, the possible mismatch or saturation of the CTs, the polarity of the CTs, and the vector group of the transformer. The vector group is a code that indicates the winding arrangements and phase shifts of the HV and LV sides of the transformer, according to the IEC standard. The lab-scale Hardware-in-the-Loop (HIL) implementation utilizes the ALSTOM MiCOM-P645 IED for rapid transformer fault protection (87T), responding in less than 20 milliseconds, and employs IEC 61850 protocol communication. This HIL simulation models the PTRF protection scheme using RTDS RSCAD software and integrates CMS356 Omicron Amplifier, as illustrated in Fig. 3.

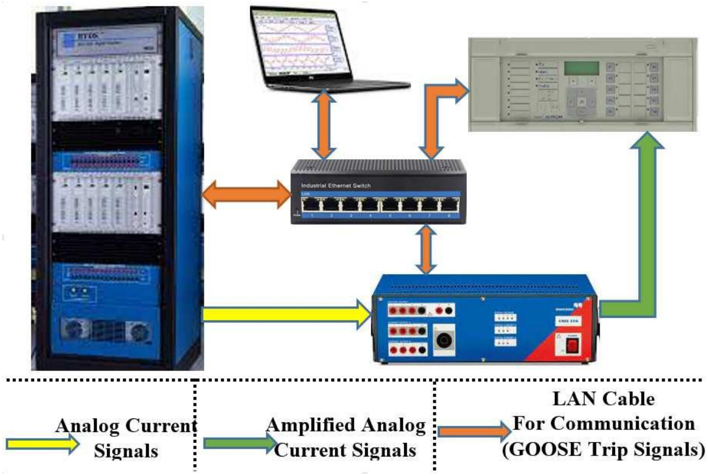

Fig. 3: The fundamental design of HIL's test setup

Fig. 4 presents a comprehensive flowchart of the developed differential protection illustrating the sequential steps and processes used to simulate and analyze the proposed system. This visual representation offers a lucid overview of the simulation workflow, aiding in comprehending the system's overall structure and operation.

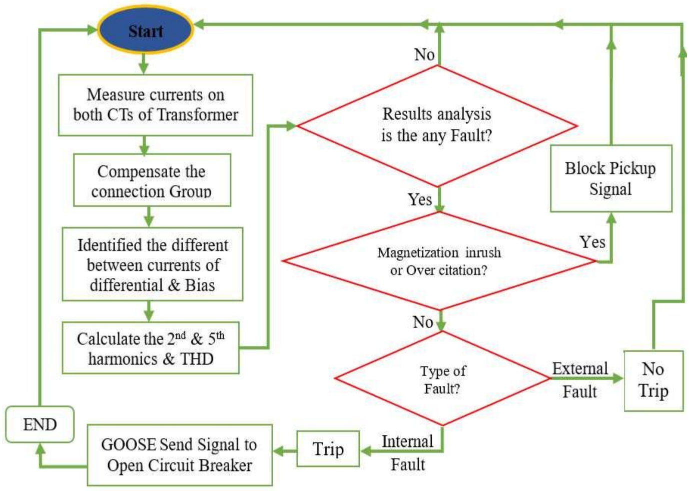

Fig. 4: Simulation process flowchart of the differential relay

B. Design and Implementation of A Lab Scale in HIL Transformer Current Protection

This study focuses on the transformer within the modified IEEE 9 Bus Power System, addressing its modeling requirements. The RSCAD environment is used to complete this implementation as shown in Fig. 5. Control logic was also developed for the network to function as required, such as fault controls.

- *Calculations*

To calculate the full load current of primary and secondary windings, Equation 8 was used.

$$I_{FL-W(P/S)} = \frac{S(VA)}{\sqrt{3} \times V_{P/S}} \quad (8)$$

The ratios of the CTs may not always correspond to transformer winding ratios. As a result, CT correction factors can be selected based on the transformer's current ratings, this can be done by using Equation 7.

$$TAP_{HV/LV(Pri/Sec)} = \frac{N_{Pri/Sec-stardard}}{N_{Pri/Sec-Calculated}} \quad (9)$$

The IEC 61850 GOOSE signal, which is sent by the GTNET Communication Card, will trip the circuit breaker. The logical nodes (LNs), whose purpose is to carry data comprising status events over Ethernet, are replacing the relay word bits hardwire in the GTNET card. A GTNet's function is to subscribe to GSSE/GOOSE messages from physical devices and utilize these signals to detect and isolate faults by triggering virtual circuit breakers within the system. This scheme's configuration is accomplished in such a way that the operating conditions of the interconnected resultant system are met.

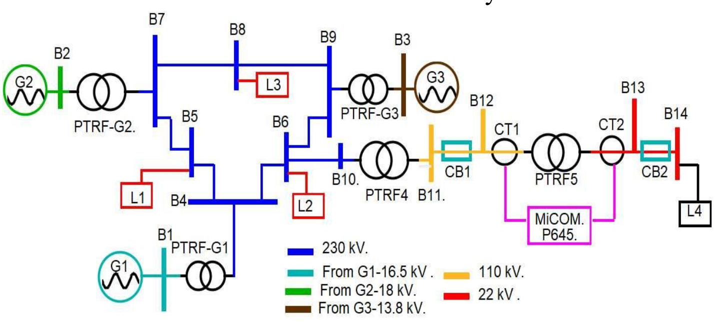

Fig. 5: RTDS model of the modified IEEE 9 bus network

V. SIMULATION RESULTS AND DISCUSSION

The designed PTRF differential protection system was implemented and tested using HIL testing and real-time simulation in the RTDS for external and internal faults. Both internal and external faults, such as phase-to-phase faults, turn-to-ground faults, and turn-to-turn faults, are likely to occur frequently. During the simulation's operation, the power system must uphold both the voltages and the currents. Table I illustrates the simulated parameter values of the PTRF network.

A. Inrush current and CT saturation

The initial testing phase involves assessing the inrush current upon switching on the PTRF, leading to system energization and flux activation. To control the PTRF's power state & signals, use pushbuttons in RSCAD RUNTIME for energization or de-energization of the protected PTRF.

Table I: Simulated Parameter Values for the PTRF Network During Active Simulation

Protected Power Transformer					
High Voltage Side (Primary)			Low Voltage Side (Secondary)		
$I_{FL-W1Pri}$	$I_{Max\_Load(p)}$	V_{TRF_HV}	V_{TRF_LV}	$I_{FL-W2Sec}$	$I_{Max\_Load(S)}$
$0.219KA$	$0.721A$	$130.5\ KV$	$21.45\ KV$	$1.316KA$	$0.723A$

During the PTRF re-energization, inrush currents occur upon closing CB1, saturating the B-H loop, as depicted in Fig. 6, with the top two waveforms representing primary winding currents and the B-H curve, and the bottom two illustrating Flux (kWb-turn) and Magnetizing currents.

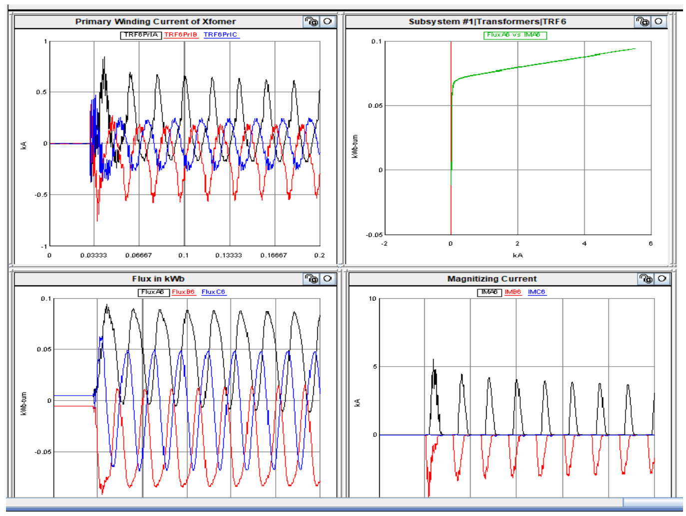

Fig. 6: B-H curve, Flux, and Magnetizing currents signals

B. External fault

The purpose of this simulation is to verify the relay's non-tripping response to a specific fault scenario. The external fault was introduced on the outer PTRF HV side, and the outcomes are depicted in Fig. 7, displaying voltage and current waveforms, respectively.

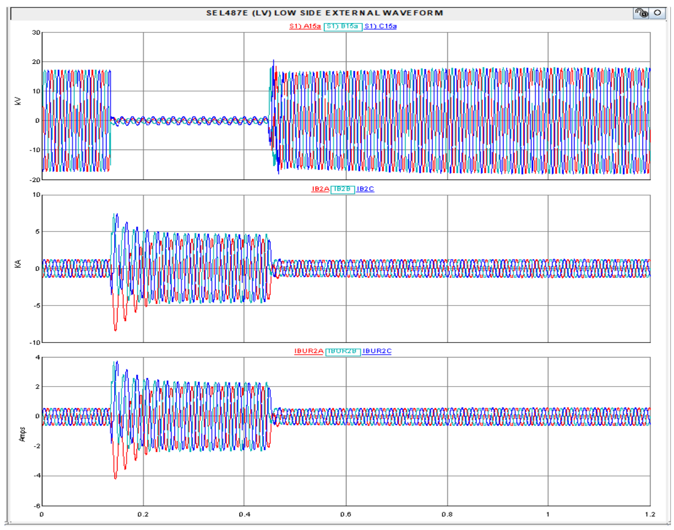

Fig. 7: 3ph fault on the PTRF's HV side protected by MiCOM-P645

C. *Internal fault*

In this study, the protection relay's crucial role is to swiftly detect faults and initiate a trip signal sent via the GOOSE communication protocol to isolate the fault using the circuit breaker (CB). The applied internal fault on the HV core windings of the transformer is effectively handled, as demonstrated in Fig. 8. Furthermore, Fig. 9 showcases the seamless operation of the IEC61850 GOOSE trip signal, promptly leading to the opening of the circuit breaker, successfully isolating the winding fault.

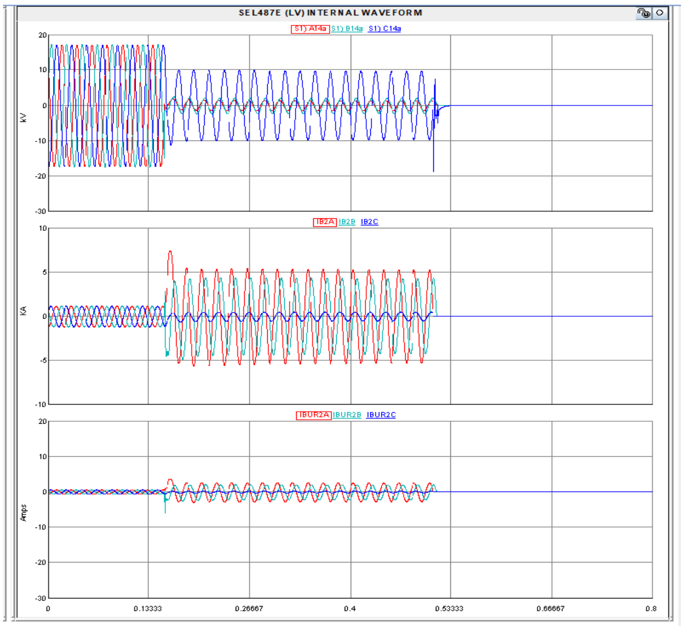

Fig. 8: Internal Phase AB and Phase B to ground fault on PTRF's HV side

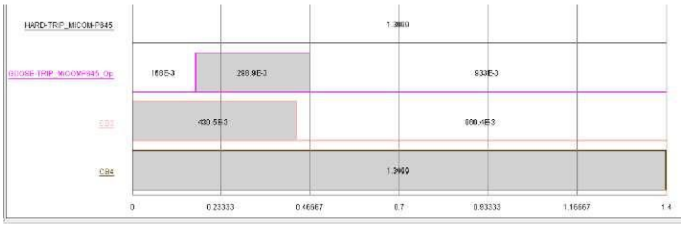

Fig. 9: GOOSE Trip and Circuit Breaker (CB) Status Signals

The discussion: Performance and effectiveness of the designed PTRF differential protection system using IEC 61850 GOOSE communication are evaluated through extensive experimental analysis and simulation studies. The results validate the system's ability to accurately detect and locate faults in transformer windings. The response time of the protection scheme is significantly reduced compared to traditional hardwired systems. The utilization of the MiCOM-P645 IEDs and the IEC 61850 GOOSE communication protocol enables efficient coordination and rapid response, enhancing fault detection capabilities.

VI. CONCLUSIONS AND FUTURE WORK

In conclusion, the design and implementation of a MiCOM-P645 transformer differential protection system using IEC 61850 GOOSE communication offer significant advantages in terms of speed, reliability, and interoperability. The results of this study contribute to the existing body of knowledge by demonstrating the feasibility and effectiveness of utilizing GOOSE messaging for transformer protection. The explanation of the protection system configuration with MiCOM-P645 enhances scholarly understanding and facilitates application, benefiting researchers, professionals, postgraduate students, and utility companies. The proposed system holds promise for enhancing the overall performance and reliability of power system protection, paving the way for advanced and intelligent protection solutions in the future.

Future work: will enhance the security of GOOSE message processing on commercial devices to mitigate the risk of potential malicious activities, particularly data manipulation attacks, within power systems.

VII. ACKNOWLEDGMENTS

The authors would like to express their gratitude to the DEECE at the Cape Peninsula University of Technology for allowing them to conduct this research at the CSAEMS Lab. This research was funded in part by the Eskom Tertiary Education Support Programme (TESP).

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