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Developing Hands-On Exercises for Teaching Transmission Protection for Systems with Inverter Based Generation

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Abstract

The growing penetration of Inverter-Based Resources (IBRs) in modern power systems has introduced significant challenges for traditional transmission protection schemes. These challenges arise from the unique characteristics of IBRs, including their low short-circuit current contribution and fast dynamic response, which differ significantly from the short circuit response of conventional synchronous generators. This paper presents the development of comprehensive, hands-on laboratory exercises specifically designed to teach advanced transmission protection concepts in systems with substantial large scale IBR integration. The laboratory exercises focus on a critical protection element: line differential (87L) protection. Utilizing a real-time digital simulator integrated with physical digital relays, the exercises replicate realistic system conditions, approximating a real utility system. This setup provides an interactive and immersive learning environment, allowing students to explore the configuration of digital relays, analyze the impact of IBR response characteristics on relay performance, and investigate more effective relay setting strategies. The methodology, design, and implementation of the laboratory setup are detailed, with an emphasis on creating a bridge between theoretical concepts and practical application. This paper highlights the pedagogical advantages of this approach, demonstrating how these exercises enhance the learning experience and prepare students for addressing modern power system protection challenges effectively.

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1 Introduction

The proliferation of Inverter-Based Resources (IBRs), such as solar photovoltaics (PV) and wind turbines, has significantly altered the dynamics of modern power systems.These energy sources are predominantly interfaced with the grid through power electronic converters, commonly referred to as Inverter-Based Resources (IBRs). While the adoption of IBRs offers substantial environmental and economic benefits, their growing penetration is reshaping the operational landscape of modern power systems. Unlike synchronous generators, IBRs exhibit distinct operational characteristics, including low short-circuit current contribution, fast response to disturbances (resulting in reduced system inertia), and rapid changes mix of real and reactive power output [1]. Full converter interfaced IBRs, such as type 4 wind turbines and PV inverters, limit the fault currents to 1.1-1.2 pu within a few power frequency cycles. These fault current characteristics introduce challenges in setting protection schemes in IBR dominated systems [2]. The lack of negative sequence fault current contribution from the inverter may cause misoperation of protection system during certain unbalanced fault conditions [3], [4]. These response characteristics present new challenges for the reliable and secure operation of the grid, particularly with respect to transmission protection schemes.

Phasor-based transmission protection schemes, such as line differential protection and distance protection, were designed based on the predictable behavior of synchronous machines. These schemes depend heavily on high fault current magnitudes and consistent system dynamics to detect and isolate faults effectively. However, the reduced fault current contribution from IBRs often falls below the sensitivity thresholds of conventional protection devices. Further, IBRs can regulate the phase angle of the current relative to the voltage, increasing the risk of delayed or inaccurate fault detection. Line differential (87L) elements are highly suitable for systems incorporating inverter-based resources (IBRs) [5]. Furthermore, the dynamic response of IBRs during disturbances, which is governed by the control algorithms of power electronic converters, adds complexity to fault analysis and protection coordination leading to numerous Challenges encountered by other line protection elements that leads to reduced system dependability [5].

As the global energy transition accelerates, it has become necessary to adapt and enhance existing transmission protection strategies to accommodate the unique characteristics of IBRs. This includes addressing technical challenges such as identifying faults in low-inertia systems, ensuring stability during transient events, and maintaining reliable protection under diverse grid conditions. The adaptation of protection schemes is critical not only for ensuring dependability but also for fostering confidence in the resilience of power systems with high IBR penetration. The 87L element can be configured to transmit additional data within communication packets, leveraging the increased bandwidth provided by modern communication infrastructure. This increased dependability provides advantages for IBR dominated systems [6].

This context underscores the importance of teaching protection students about the challenges and solutions when protecting lines fed by IBRs. Engineering students and professionals need hands-on experience with real-world scenarios to understand the impact of IBRs on transmission protection and to develop effective solutions. By incorporating realistic laboratory exercises into the curriculum, students can bridge the gap between theoretical concepts and practical applications, gaining insights into configuring protection devices, analyzing system performance, and implementing mitigation strategies. Such initiatives are crucial for preparing the next generation of engineers to address the evolving challenges posed by IBR-dominated power systems [7].

2 Description of the Modeled Power system

The system is modeled in an electromagnetic transients simulation program as a simple version of an existing transmission network. The equivalent impedance of the grid is depicted as a three-phase 57.1 kV synchronous generator connected through an equivalent impedance. The equivalent source is connected to Bus 1 via Line 1. Bus 1 is also fed by a 6.9 kV, 7.5 MVA hydroelectric turbine generator, which connects to the system through a Y-Delta 57.1/6.9 kV, 7.5 MVA step-up power transformer. The IBR connected at the other end of the line is rated at 0.48 kV, 14 MVA. The IBR is integrated into the system at Bus 2 through a 57.1/0.48 kV, 14 MVA step-up transformer. Fig. 1 illustrates the diagram of the modeled 57 kV power system, with the IBR. Table 1 lists the parameters of the IBR connected to the system.

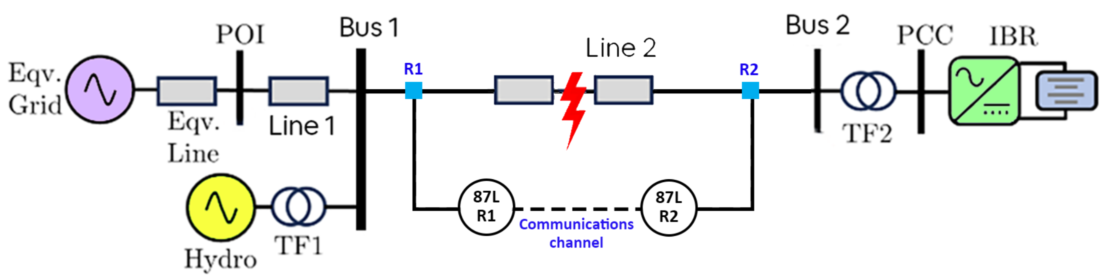


Figure 1: Diagram of the equivalent power system with integrated IBR [8].

Table 1: Parameters of the EMT model of IBRs [8]

Inverter Parameters	**Values**
Ratings (3-ϕ)	480 V (L-L), 60 Hz, 14 MVA
DC side	$V_{dc} = 1200$ V, $f_s = 5$ kHz
LCL filter	$L_f = 15\ \mu$H, $L_g = 1.5\ \mu$H, $C_f = 280\ \mu$F

The Voltage Source Converter (VSC) of the IBR operates in a grid-following (GFL) mode and can be modeled either as a switching or an average representation. The DC link voltage is provided by a PV system, battery storage, or a combination of both. Outer loop controllers support either PQ dispatch or Vdc-Vac control. Inner loop current controllers regulate phase currents in the synchronous dq reference frame, phase currents in the stationary $\alpha\beta$ domain, or sequence current components in dual rotating synchronous reference frames. For the cases evaluated in this lab exercise, the outer loop controller considers PQ-dispatch. Current-limiting capability is based on saturation or latching of the q or d axis components for phase or sequence current controllers, or the saturation and latching of phase quantities in the $\alpha\beta$ domain. In sequence current domain control mode, the converter can inject negative sequence currents under unbalanced conditions to comply with IEEE Standard 2800-2022 [9]. The control of positive and negative sequence currents is implemented using the decoupled double synchronous reference frames [8].

3 Laboratory Design

The laboratory exercises leverage the real time simulator playback block to simulate Common format for Transient Data Exchange for power systems (COMTRADE) files obtained from the electromagnetic transient (EMT) model. A physical digital relay is interfaced with the RTDS, enabling students to observe and analyze protection system performance under various scenarios.

The RTDS is a key component of the lab setup, enabling real-time simulation of power system dynamics and showing how protective elements react. The EMT model simulates the faults, and generates COMTRADE files generated using a built-in COMTRADE block. These files are then uploaded to the RTDS via its playback block, enabling real-time playback testing. This allows students to interact with real-time fault behavior and analyze the protection elements response to the simulated faults. Future semesters will have IBR models implemented directly in the real time simulator for hardware-in-the-loop simulation.

The lab setup also includes two commercial microprocessor relays. These relays have a range of protection functions, including line differential protection element, which is the protection functions to be investigated in these lab exercises. Students program the relay using designated software to adjust its settings. The relay is connected to the RTDS through a ribbon cable via an analog input/output card. By testing the relay under fault conditions, students can see the functionality of the relay and its limitations in IBR-dominated systems.

The lab setup includes a computer with a a human-machine interface for monitoring the real-time data from the RTDS and recording digital relay events. The relay software on the computer allows students to download event records from the relay and then visualize and interpret waveform data, relay logic responses, and overall protection element responses. Fig. 2 shows the testbed for teaching power system protection in IBR-penetrated grids.

4 Teaching Instruction Methods for the Lab.

The teaching approach is designed to give students a thorough hands-on learning experience in power system protection for systems with IBRs. The lab activities are carefully planned to gradually help students understand how digital relays work, use real-time simulations, and conduct playback testing. Prior to these exercises students have performed transmission

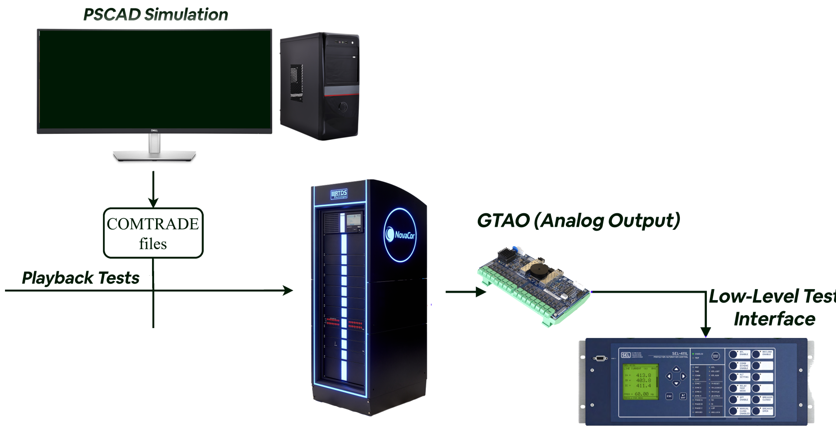


Figure 2: Laboratory set up for protection studies

protection labs for conventional, synchronous machine dominated systems. These practical activities are divided into three parts, focusing on key aspects of IBR protection and building essential skills for modern power system protection. The methods are explained in detail as follows:

4.1 Pre-Laboratory Preparation

To ensure that students gain foundational knowledge before engaging in the laboratory exercises, the instructional approach emphasizes thorough preparation.

- Theoretical Overview: Students receive lectures covering the fundamental principles of transmission protection, focusing on the challenges posed by inverter-based resources (IBRs) in a classroom setting. Key topics include fault characteristics of IBRs. Earlier segments in the course covered line protection for conventional systems, including line current differential protection.
- Laboratory Manual: A detailed lab handout is distributed one week in advance, outlining: objectives and goals of the lab exercise, relay configuration instructions, system parameters and fault scenarios to be simulated, pre-lab tasks, such as calculating relay settings based on provided system data. Previous lab sessions introduced students to digital relay's configuration software and the use of the RTDS. A lab exercise exploring the impact of IBRs on distance protection included instructions for using the COMTRADE playback.

4.2 Laboratory Session Execution

The hands-on laboratory session is structured to build students' practical skills and reinforce theoretical concepts.

- Students work in small groups (2–3 members) to foster collaborative learning. They begin by setting the relays protection function, such as differential zone thresholds based on pre-lab calculations.

- Using the RTDS, students simulate various fault scenarios, phase-to-ground using the fault data imported to the RTDS as COMTRADE files and replayed through playback to observe the response of the relay they configured and to evaluate its response. Unlike a real power system, student can change their settings and try again immediately and learn what works best.
- Students monitor key metrics, including trip time, fault detection accuracy, and relay performance under reduced fault current conditions.
- Students analyze relay outputs and relay event files to understand the operation of protection elements like line differential protection and single-pole tripping.
- The students also are tasked to examine the influence of IBR characteristics (e.g., low fault current and fast control dynamics) on relay performance, identifying potential misoperations or delayed trips.

4.3 Evaluation and Reflection

To test the students understanding of the lab exercise they perform, the instructors introduce the two final steps:

4.3.1 Post-Laboratory Report

Students are tasked to submit a detailed report summarizing their findings. Key sections include:

- Observations and analysis of relay behavior for the fault scenario.
- Emphasize on how theoretical principles connect to the practical results, this encourages critical thinking and problem-solving.

4.3.2 Group Discussion and Feedback

Instructors provide feedback on reports and facilitate discussions on improving lab practices and adapting protection schemes for modern grids. This develops a deep understanding of protection challenges in IBR-dominated systems. enables the students to gain practical experience in configuring and testing advanced protection schemes which goes a long way to strengthen their analytical and technical writing skills through comprehensive reporting.

Students feedback on the hands-on exercises was overwhelmingly positive, with many highlighting the essence of the lab in bridging theoretical knowledge and practical application. The use of RTDS playback testing, combined with physical digital relays, provided a highly interactive learning experience that deepened their understanding of line differential protection (87L) in IBR-dominated systems. Students particularly appreciated the opportunity to analyze real-world fault scenarios using COMTRADE files, which allowed them to observe and interpret relay responses in a controlled yet realistic setting. The structured approach of the lab, from pre-lab preparation to post-lab analysis, was praised for reinforcing key protection principles.

While the laboratory manual served as a useful reference, students suggested more step-by-step guidance, particularly for setting protection thresholds and troubleshooting relay responses. Minor technical difficulties with relay connections and software occasionally disrupted workflow like fixing the 87L communication. leading to recommendations for more real-time simulations. Many students expressed that the lab significantly enhanced their confidence in configuring and testing modern protection schemes, making them feel better prepared to tackle real-world challenges in power system protection.

5 Performance of the Protection Scheme Under Study.

This section examines the response of two different unbalance classified as four cases. The fault types are phase to ground faults and phase to phase faults. Each fault type has two different IBR control schemes, one with the IBR injecting negative sequence current in accordance with IEEE 2800-2022 during unbalanced condition and a scenario where the IBR does not provide negative sequence during unbalance faults. These cases are designed to assist students in understanding the response of line differential protection (87L) elements during transmission line faults in IBR dominated systems. In recent years there has been widespread industry debate about how protection elements respond to regulated negative-sequence current contributions from IBRs during unbalanced faults.

The cases simulated in the EMT program provide the students with valuable insights into the performance of line differential protection (87) elements. This discussion addresses how line differential performs in IBR dominated systems.

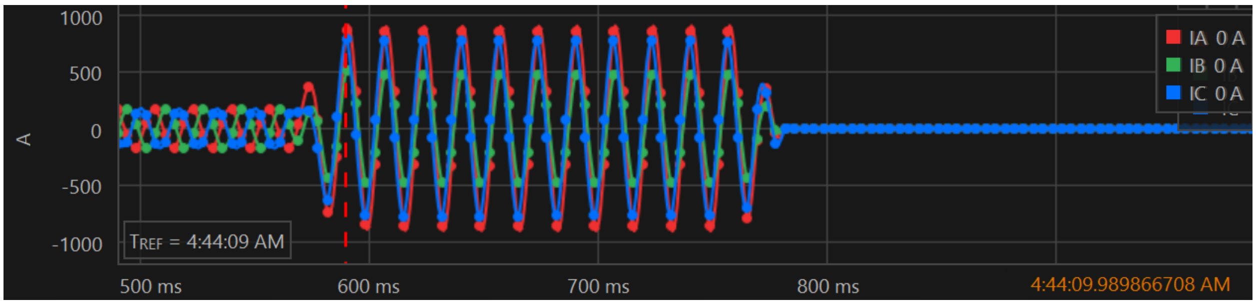
5.1 Line Current Differential (87L) Protection

Line differential protection is a widely used scheme in power system protection, offering fast and reliable fault detection for transmission lines [10]. The protection operates by comparing the current entering and leaving a protected line section, based on the principle of Kirchhoff's Current Law [11]. If the difference between the currents exceeds a predefined threshold, the relay identifies a fault within the line section and initiates a trip command. The relays at the two ends of the line exchange phasor information on all three phases along with negative sequence and zero sequence currents. The line current differential protection schemes require high-speed communication links and an approach to synchronize current measurements from both ends of the line. Older schemes periodically test channel communication time by exchanging messages that are echoed back. Newer systems also support the use of time stamped measurements using an absolute time reference such as a GPS signal.

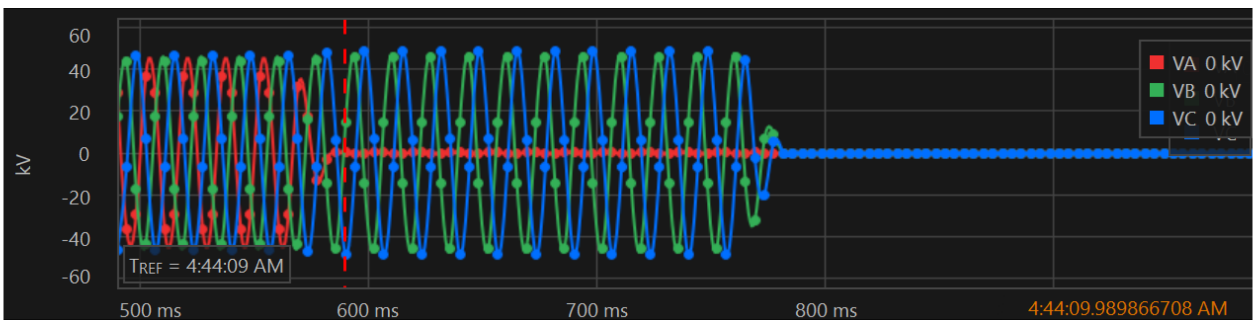
The lab exercises use phase differential elements on each phase (87LA, 87LB, and 87LC). If any of one of these elements picks up, the phase current differential element (87LP) picks up. The lab also include a negative sequence current differential (87Q), and a ground current differential element (87G).

5.2 Results for Phase to Ground Faults

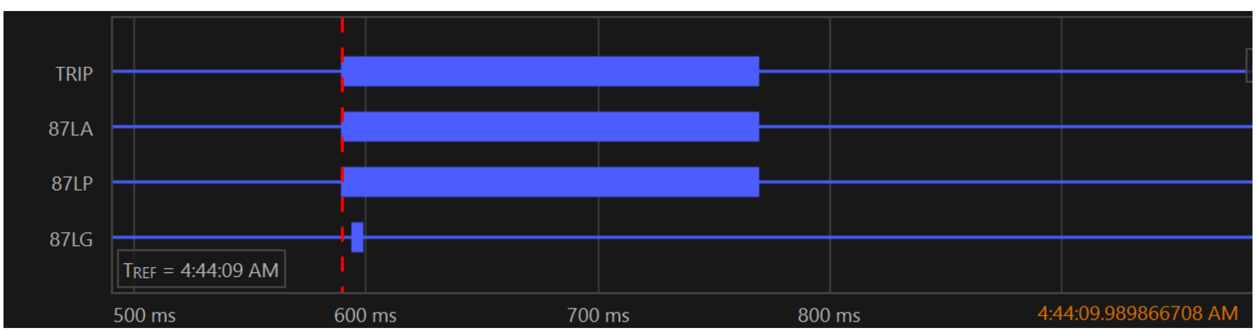
Figure 3 represents the current, voltage waveform, and trip digital output of the elements operating for a case with the IBR not regulating negative sequence current. Students need to observe the relay digital output to draw conclusions using an analyzing software that is used to reproduce the relay recorded event. Looking at the relay digital output in Figure 3c, the expected elements, 87LA and 87LG, trip for the phase-to-ground fault as expected. Note that the 87LG only asserted briefly.



(a) Current waveform



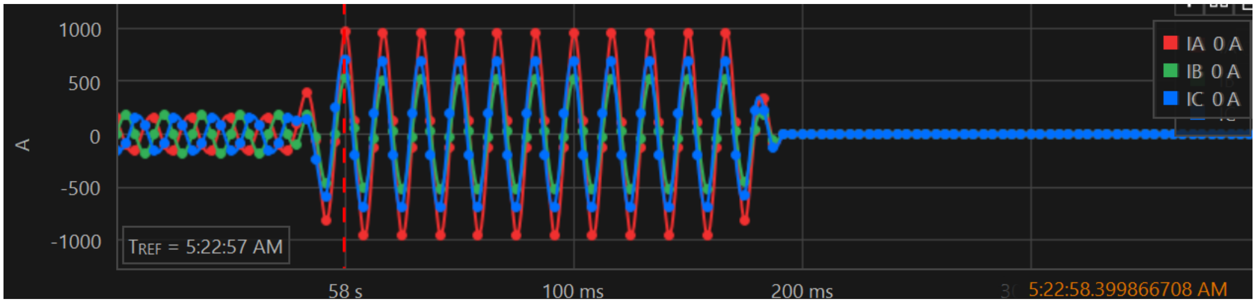
(b) Voltage Waveform



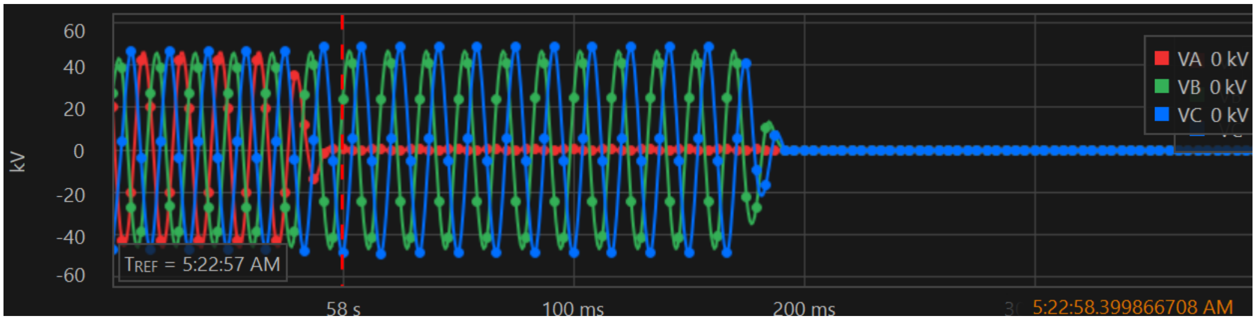
(c) Digital outputs

Figure 3: Phase to ground fault with IBR not controlling negative sequence current control.

Figure 4 presents the voltage and current waveforms for a phase to ground fault with the transformer TF2 with a Delta connection facing the system. In this fault case the IBR is operated to have negative sequence current control. Observation from the relay digital output 4c, indicated that the expected phase element, 87LA and the ground element, 87LG trip for the phase-to-ground fault as expected. For this case the expected elements to pick up are the ground and the phase elements.The 87LA and 87LP elements operate first. The 87LG element follows. Finally, the TRIP signal is issued, confirming the relay detected a fault and acted to isolate the faulted section.

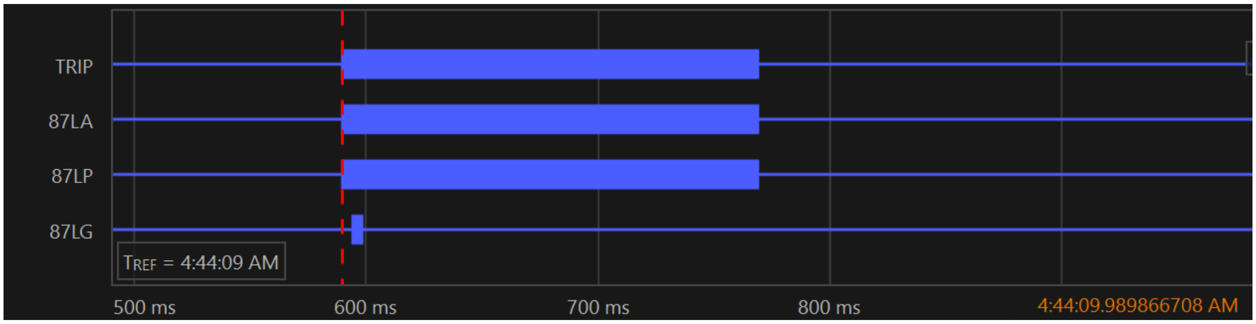


(a) Current waveform



SLGWContro

(b) Digital Output



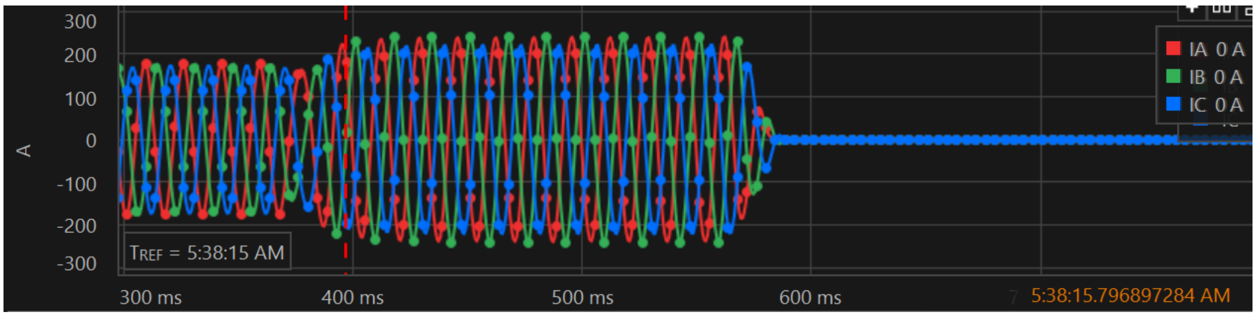
(c) Voltage waveform

Figure 4: Phase to ground faults with IBR controlling negative sequence current

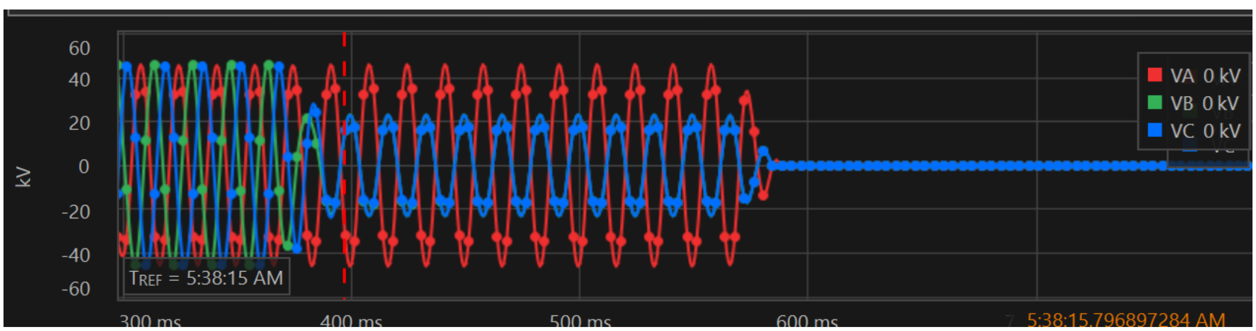
It can be observed that, the 87L elements (87LG , 87LP, 87LA) operates the same for the two different cases above. signifying that converter control does not really affect the elements operation during phase to ground fault. There is sufficient current from the conventional grid end of the line for the differential elements to operate.

5.3 Results for Line to Line Faults

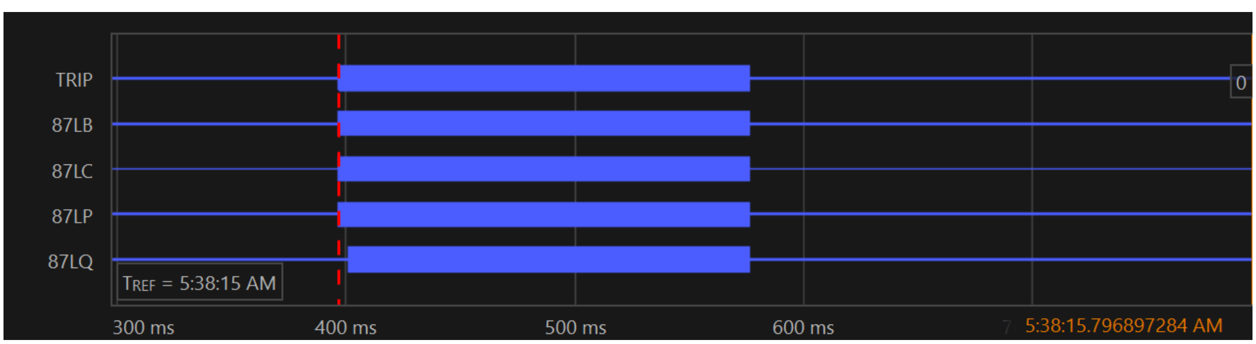
Figure 5 presents the voltage and current signals for a phase to phase fault with the transformer TF2 with a Delta connection facing the system. In figure 5c 87LQ pick up first, and then 87LB, and 87LC follow, confirming a fault in both the B-phase and C-phase. The TRIP signal is issued last, ensuring the fault is isolated to prevent further damage or instability. The timing and element activations point to a multi-phase fault (B-phase and C-phase) with negative-sequence current involvement.



(a) Current waveform



(b) Voltage Waveform

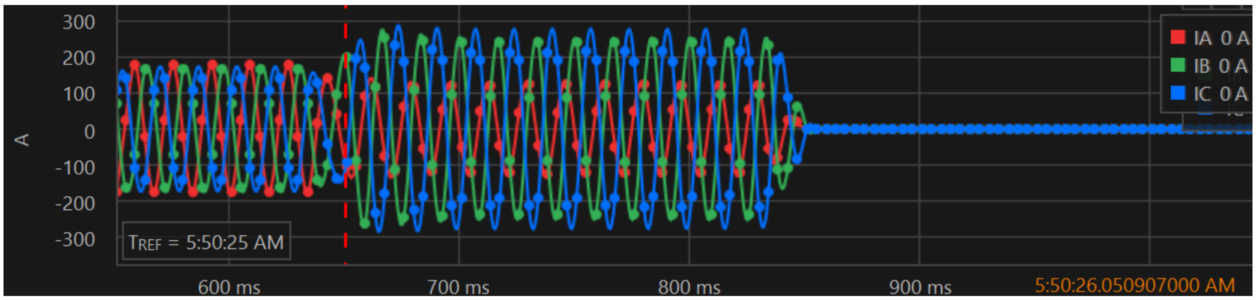


(c) Digital Output

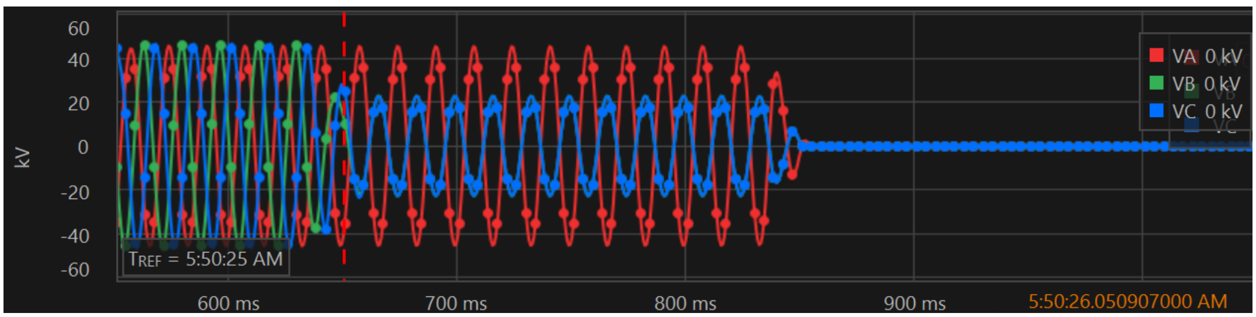
Figure 5: Phase to Phase faults with IBR not controlling negative sequence current

Figure 6 presents the voltage and current signals for a phase to ground fault with the transformer TF2 with a Delta connection facing the system. In this fault case the IBR controls negative sequence current. In this case the IBR not regulating negative sequence current. In figure 6c

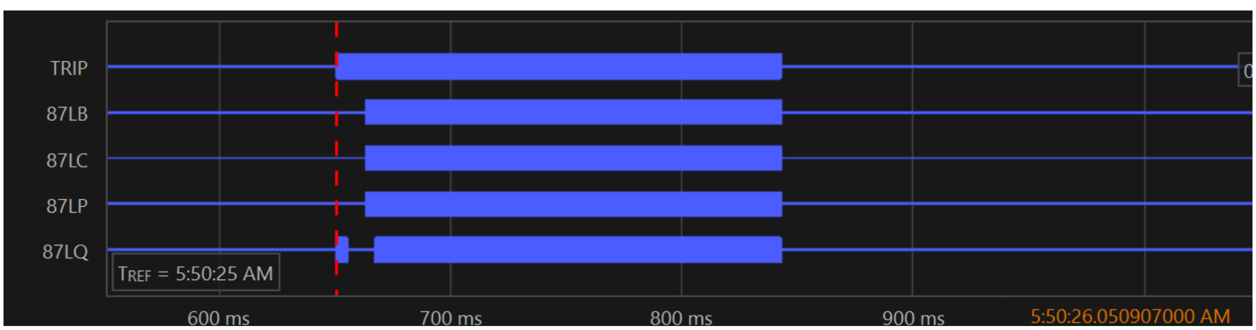
87LQ is the first element to operate, indicating a fault with unbalanced or negative-sequence currents. 87LP, 87LB, and 87LC follow shortly, confirming a fault involving multiple phases (B and C). Finally, the TRIP signal is issued to isolate the faulted line section. This sequence suggests a fault scenario involving the B-phase and C-phase, with unbalanced current contribution, possibly due to a line-to-line or two-phase-to-ground fault.



(a) Current waveform



(b) Voltage Waveform



(c) Digital Output

Figure 6: Phase to Phase faults with IBR controlling negative sequence current

In the case where IBR control negative sequence current (I2), the IBR provides negative sequence current during fault conditions, resulting in a strong unbalanced fault signature. Protection element, 87LQ rely on I2 to detect fault and operate without suppression effects. 87LQ, activates promptly due to the presence of significant I2. However, in the case where there is no control I2 , the converter masks the fault signature, especially for protection element 87LQ (negative-sequence differential element), which delays relay operation.

As part of the analysis following these exercises, students are asked to compare the performance of the line current differential elements to that of the distance elements in a prior lab. Their analysis should conclude that line current differential elements perform much better than distance elements (especially the supervisory elements) in cases with high penetration of IBRs.

6 Conclusion

The integration of high penetrations of IBRs into power systems calls for modification in teaching protection studies in engineering. The laboratory exercise provides a practical framework for understanding the impacts of IBR dominated systems online differential protection. By applying the RTDS playback testing together with the physical relays responding to simulated fault scenarios exported as COMTRADE files from EMT simulations, students are able to perform real time simulation. The exercise offers a realistic and interactive platform for students to experience modern protection challenges. The lab exercise presented above, when coupled with an earlier lab applying distance elements, demonstrate to students that in IBR dominated systems, the most reliable element for transmission line protection with IBR dominated lines is the line differential protection element(87L). Since distance elements act as backup with loss of communication, students still need to learn to solve the challenges with distance elements.

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