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HYPERSIM-Based Transmission Line Protection Model for Dominion's System Protection Technician Development Program

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SUMMARY

In this paper, a transmission line protection model based on the Dominion Energy Power Delivery Training Center's 230 kV ring bus was implemented to be used with the OPAL-RT simulator. The purpose of creating such model is to utilize the hardware-in-the-loop (HIL) capabilities of OPAL-RT to train system protection technicians at the Dominion Energy Power Delivery Training Center. The model will allow instructors to better aid their classes, while also giving students a safe, and realistic environment in which to practice standard substation routines. Before running the model in the OPAL-RT real-time simulator, an offline version of the same model was developed in order to test the model and validate its simulation response. With that, the model was simulated and validated, proving that it performs as expected in an offline environment, which is the first step before hardware-in-the-loop simulation.

KEYWORDS

HYPERSIM, Transmission Line Protection, OPAL-RT, HIL, Real-Time Simulator

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I. INTRODUCTION

The electrical grid is recognized as being the most complex and longest-lasting engineering project in human history. Since the early days, electrical engineers have studied the electrical grid to better understand its behavior. Before the invention of the digital computer, utility companies and research departments relied on their employees' ability to solve electrical-grid-related problems, like power flow solutions, by hand. This led to the simplification of several grid components which was necessary at the time to facilitate hand computations. As the grid grew in complexity, so did the need for better models, and the unsuitability of continuing to solve problems by hand became apparent [1].

With the rapid expansion of the electrical grid during the early 20th century and with the expected behavior of the grid becoming harder to predict, a new methodology for system analysis was needed. With the help of engineers from General Electric and two of his graduate students, Professor Vannevar Bush from the Massachusetts Institute of Technology (MIT) developed the "network analyzer" --an AC analog device that could simulate complex power systems and made even more complex calculations possible [2, 3]. The device was first introduced in 1929 and consisted of three generating stations, 200 miles of line, and six load centers that could fit into 50 square feet. Several other companies developed their own circuit analyzers, which consolidated the importance of the newest analog power system analysis tool [4, 5]. During the next two decades, the "grid analyzer" was used by numerous utilities and electric manufacturers, including General Electric, Westinghouse Electric Corporation, and the São Paulo Tramway Light and Power Company. It was the first real-time power system simulator.

Beginning in the 1950s, power system modelling started to transition away from analog-based simulations toward computer-driven models and simulation. The need for AC-powered analog grid replicas started to diminish. Computers allowed faster computations, modelling and simulation and utilized more precise component models. They also had the ability to easily change grid configurations. It was only at the end of the 20th century that digital-based, real-time dynamic simulations became feasible once again, enabled by high-frequency processors. Today the state-of-the-art methodology to conduct real-time power system electromagnetic transient (EMT) studies is considered to be EMT models run using Real Time Digital Simulators such as Opal-RT [6, 7] and RTDS [8]. Dominion Energy has experience with real-time hardware-in-the-loop experiments, conducting fault analysis experiments in dense photovoltaic source grids, where the assessment of relays was conducted [9]. To handle the increased complexity and highly enmeshed nature of electrical grids, simulations can be run through numerous CPUs with parallel computing.

Driven by the need to improve the learning environment used to teach technicians on how to work in substations, Dominion Energy created the Substation Automated Training Simulator (SATS) in 2021, where students can safely interact with field-deployed relays in a non-energized environment. The benefit of the SATS is two-fold:

- The physical environment resembles a substation, allowing students to practice technical routines as they would in the field.
- Students can emulate several different substation scenarios and conditions, based on digital models simulated in Opal-RT, while coupled to real substation equipment.

The purpose of this project was two-fold:

- To create a transmission line protection model utilizing HYPERSIM, an EMT-based power system tool that can be used with Opal-RT for real-time hardware-in-the-loop (HIL) simulation [12]. HYPERSIM was used to simulate a portion of the 230 kV ring that represents the training facility.
- To create a model that instructors in Dominion's System Protection Technician Development Program could use to teach students relay measuring and analysis during both regular transmission line operation and during fault conditions.

This paper focuses on the modelling and validation aspect of the offline transmission line protection model, which was implemented prior to the HIL version model. This allows the development team to run and debug the digital model before deploying it to real-time simulation.

Section II gives a brief overview of the Opal-RT HIL simulator located in Dominion Energy's Power Delivery Center. Section III describes the transmission line protection model implemented in HYPERSIM. Section IV demonstrates a set of simulations for offline model validation purposes, while Section V draws conclusions based on this work.

II. OVERVIEW OF THE SATS TRAINING FACILITY

Dominion's Power Delivery Center is located in Chester, VA. It was originally built in the 1980s as a training facility, where courses for all Dominion Energy technicians and electricians were taught and students could test their skills. The center was renovated in 2019, transitioning from mechanical based-training equipment to state-of-the-art digital real-time equipment. The facility resembles an actual substation with transmission and distribution panels, rows equipped with relays for breaker failure, reclosing, transmission line protection with carrier blocking, transmission line with fiber differential, etc. Inside the control house is the OPAL-RT target, and a set of amplifiers. The Center's current Opal-RT setup is shown in Fig. 1.

A) OPAL-RT Host Computer

B) OPAL-RT Target and Amplifiers

Fig. 1. OPAL-RT Simulator Setup

The digital HYPERSIM model of the substation is compiled and simulated on the Opal-RT simulator, which sends real-time analog signals to the omicron amplifier. The amplified voltage and current analog signals are then passed to the relays in the control house which output command signals to the equipment in the substation yard. The yard equipment will then forward equipment status signal back to the OPAL-RT simulator, closing the simulation loop and enabling the HIL simulation.

III. HYPERSIM SUBSTATION MODEL

The digital model implemented in this paper is based upon a portion of the 230 kV ring bus substation training configuration plant. Instead of implementing a HYPERSIM model that recreates digitally the entirety of the 230 kV ring bus, the current model contains only the portion in which the simulation matches the physical structure of the control house. The transmission line protection model implemented in HYPERSIM is shown in Fig. 2.

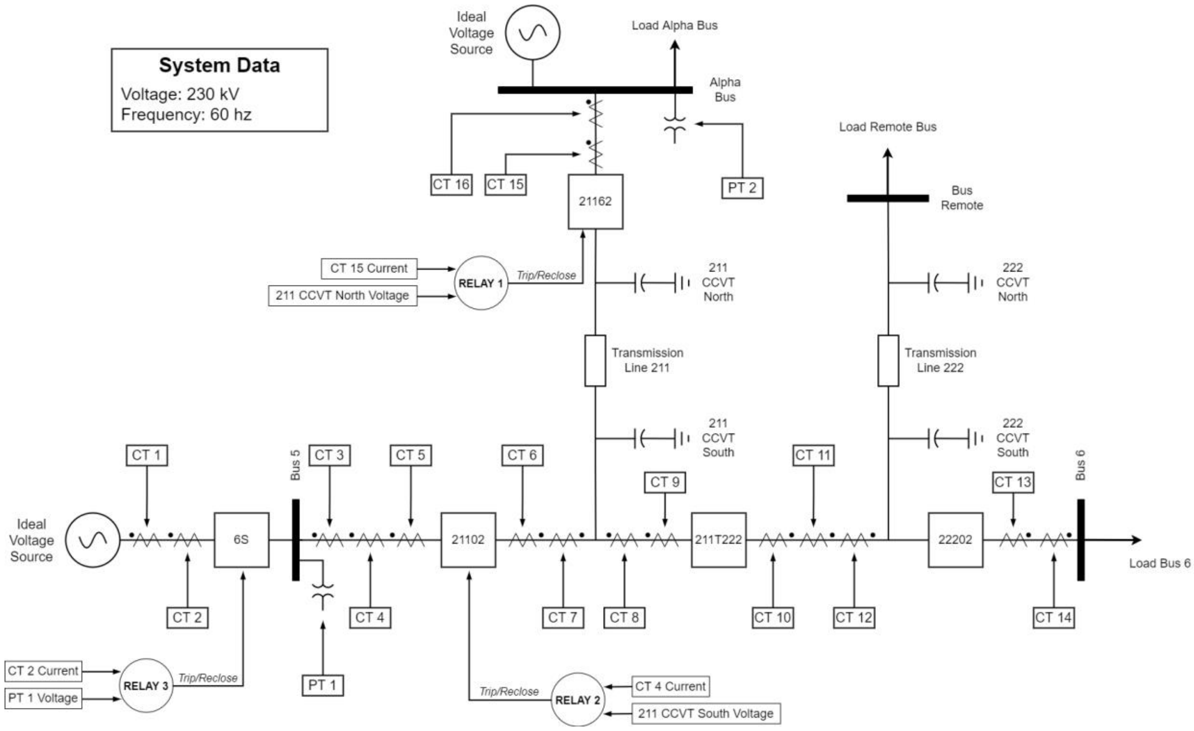

Fig. 2. Transmission Line Protection Model

Buses 5 and 6 are placed in a breaker-and-a-half configuration [10], used primarily in high-voltage substations. Three circuit breakers (21102, 211T222, and 22202) are used in a bay for two transmission line circuits (Transmission Line 211 and Transmission Line 222). The "T" in circuit breaker 211T222 stands for tiebreaker, and it is responsible for either isolating or connecting Buses 5 and 6 together. Circuit breakers 6S and 21162 are used to protect Bus 5 and Load Alpha Bus, respectively. The Coupling Capacitor Voltage Transformers (CCVT) in the 211 Transmission Line point to the fact that the transmission line protection configuration is based on the Directional Comparison Blocking (DCB) scheme, which determines the location of the fault based on whether the fault power is flowing inward or outward at the line terminals [11]. Current transformers CT1-CT16 are responsible for reducing the measured current magnitude to a level that can be used by the relays. PT1 and PT2 represent potential transformers and are used to measure voltage magnitude in Load Alpha Bus and Bus 5 while 211 CCVT North and 211 CCVT South represent the potential transformers that are used in the DCB protection scheme of Transmission line 211. Lastly, the model also contains three impedance relays that send trip/reclose signals to the circuit breakers 6S, 21102, and 21162. For the purpose of this paper, fault contingencies will only be tested in Transmission line 211 and at Bus 5, therefore circuit breakers 211T222 and 22202 will be constantly closed and thus do not contain any logic tripping/reclosing logic. In the model, Buses 5 and 6 represent the substation training facility, while Bus Alpha and Bus Remote represent the remote substations.

For the purpose of the aforementioned model, all substations were considered being located far away from the generation units, allowing the generation source to be modelled as an ideal voltage source. All the loads in Fig. 3 were modelled as constant impedances, and the substation and transmission lines were all at 230 kV with 60 Hz AC sinusoidal voltages and currents. The relay trip/reconnect protection scheme was implemented utilizing the impedance relay from HYPERSIM, allowing the user to adjust the trip command depending on the location of the fault, that is, if it is Zone 1 or Zone 2 fault. The following section will describe HYPERSIM's impedance relay logic and how it was implemented in the model.

IV. HYPERSIM IMPEDANCE RELAY LOGIC

HYPERSIM's impedance relay utilizes three-phase currents and voltages to determine the instantaneous impedance of the transmission line. Figure 3 was taken from HYPERSIM's model manual [13] and exemplifies the R-X diagram of the impedance relay.

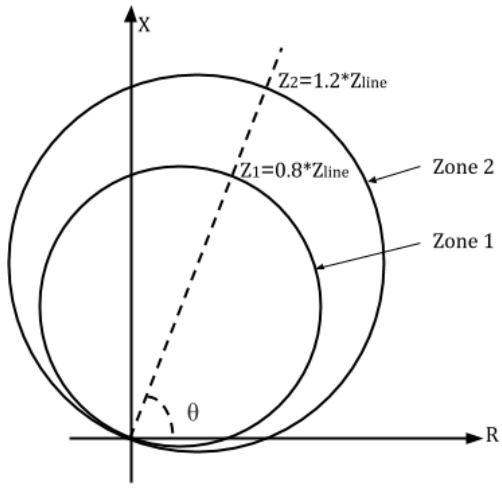

Fig. 3. R-X diagram of HYPERSIM's impedance relay

In a normal operation condition, the impedance of the transmission line is obtained by determining the positive sequence impedance magnitude of the transmission line in which the relay is protecting. If the impedance calculation of the transmission line is outside of the R-X diagram zones, then the relay understands that the transmission line has no fault and is currently operating as it should. An electrical fault, on the other hand, reduces the perceived transmission line impedance calculated within the relay, meaning that there is a fault in some location of the transmission line. Hence, a fault would place the impedance calculation inside the circle zone and a timer begins to count the time at which the impedance falls in the circle zone. If the impedance stays inside for the time delay setting of this zone, the trip signal changes from 0 to 1, thus tripping the circuit breaker and disconnecting the transmission line. Transmission line faults, specifically in non-radial systems, can be categorized into either Zone 1 or Zone 2. Zone 1 faults are within 80% of the under-reaching section of a transmission line, which requires the circuit breakers for both extremities to trip simultaneously and block fault current from flowing. Zone 2 faults are typically within 120% of the under-reaching zone, meaning the faults are outside the transmission line. But given the over-reaching nature of transmission line protection (specifically when using impedance-based relays), the front-facing transmission line relay will sense the fault, as well. Therefore, there must be a communication protocol that prevents transmission line circuit breakers from tripping. The following tests demonstrate some examples of circuit breaker operation.

V. HYPERSIM TEST CASE MODEL SIMULATION AND VALIDATION

This section showcases two fault simulations that were implemented to validate the digital model:

- Test 1 – Three-Phase-to-Ground Fault within Zone 1 of Transmission Line 211.
- Test 2 – Three-Phase-to-Ground Fault within Zone 2 of Transmission Line 211.

For both simulations, the model considered to have all its circuit breakers closed at the start of the simulation, and the relays send out the respective trip/reconnect signals depending on the contingency applied.

A. *Test 1 – Three-Phase-to-Ground Fault within Transmission Line 211*

In Test 1, the selected fault was inside Zone 1 of Transmission Line 211, at exactly 50% of the transmission line as measured from the north or south extremity of the line. The impedance relays for Transmission line 211 are expected to trip Circuit breakers 21162 and 21102 to eliminate the fault current. The fault chosen for this first test was a 3-phase-to-ground temporary fault, which meant that the contingency disappears during the trip/reconnect protection protocol. The fault was applied at *t=0.1s* with a fault duration of *0.2s*; Circuit breakers 21162 and 21102 tripped and reconnected the transmission line in one control instance. The simulation run time was chosen to be 0.5 seconds.
Figure 4 illustrates the AC currents during the trip/reconnection protocol for CT 5, CT 15, and CT 2, while Fig. 5 illustrate the trip/reconnect logic signals for all three CT's.

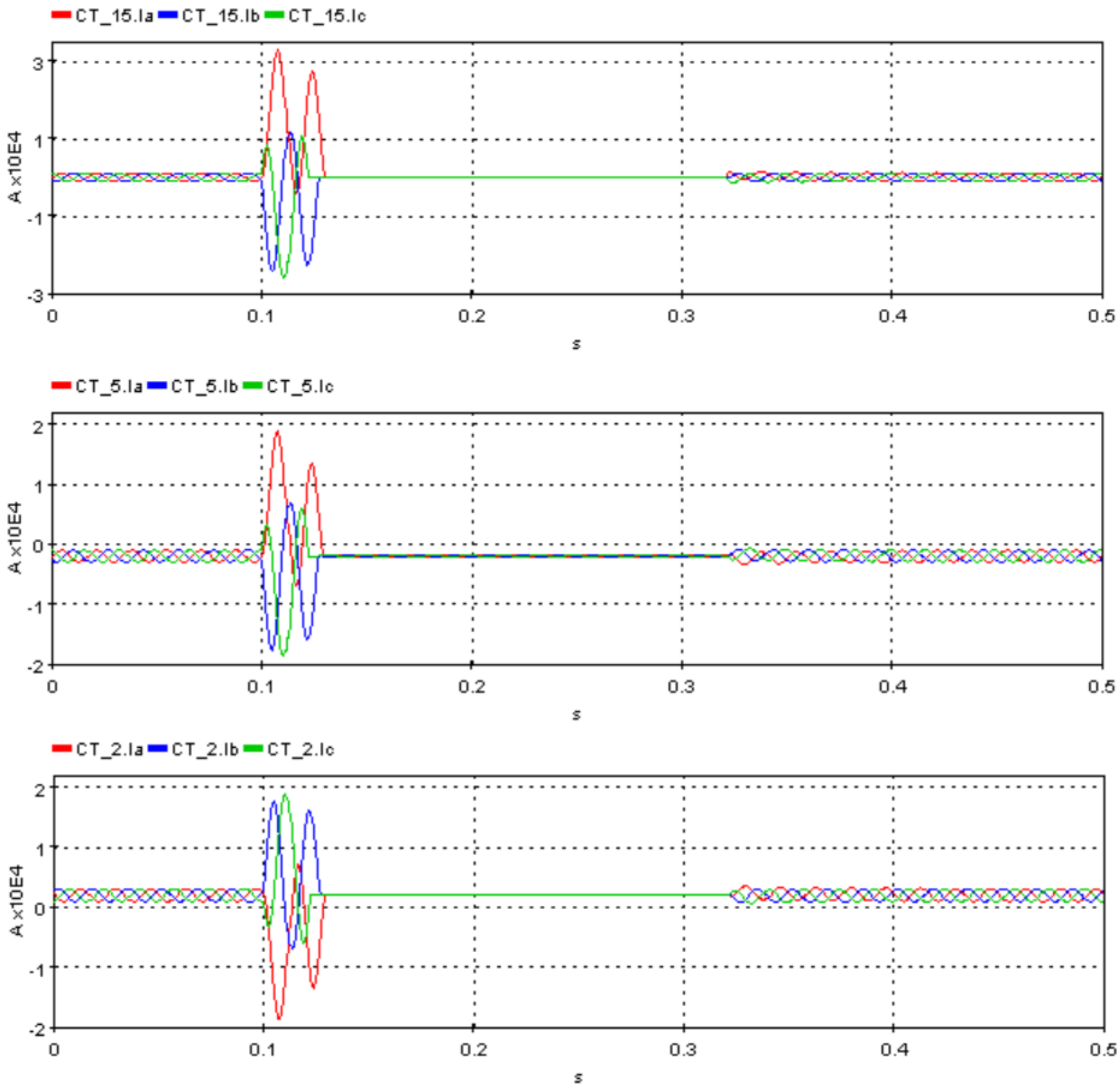

Fig. 4. CT4, CT15, and CT 6S current measurement during the trip/reconnect for test 1

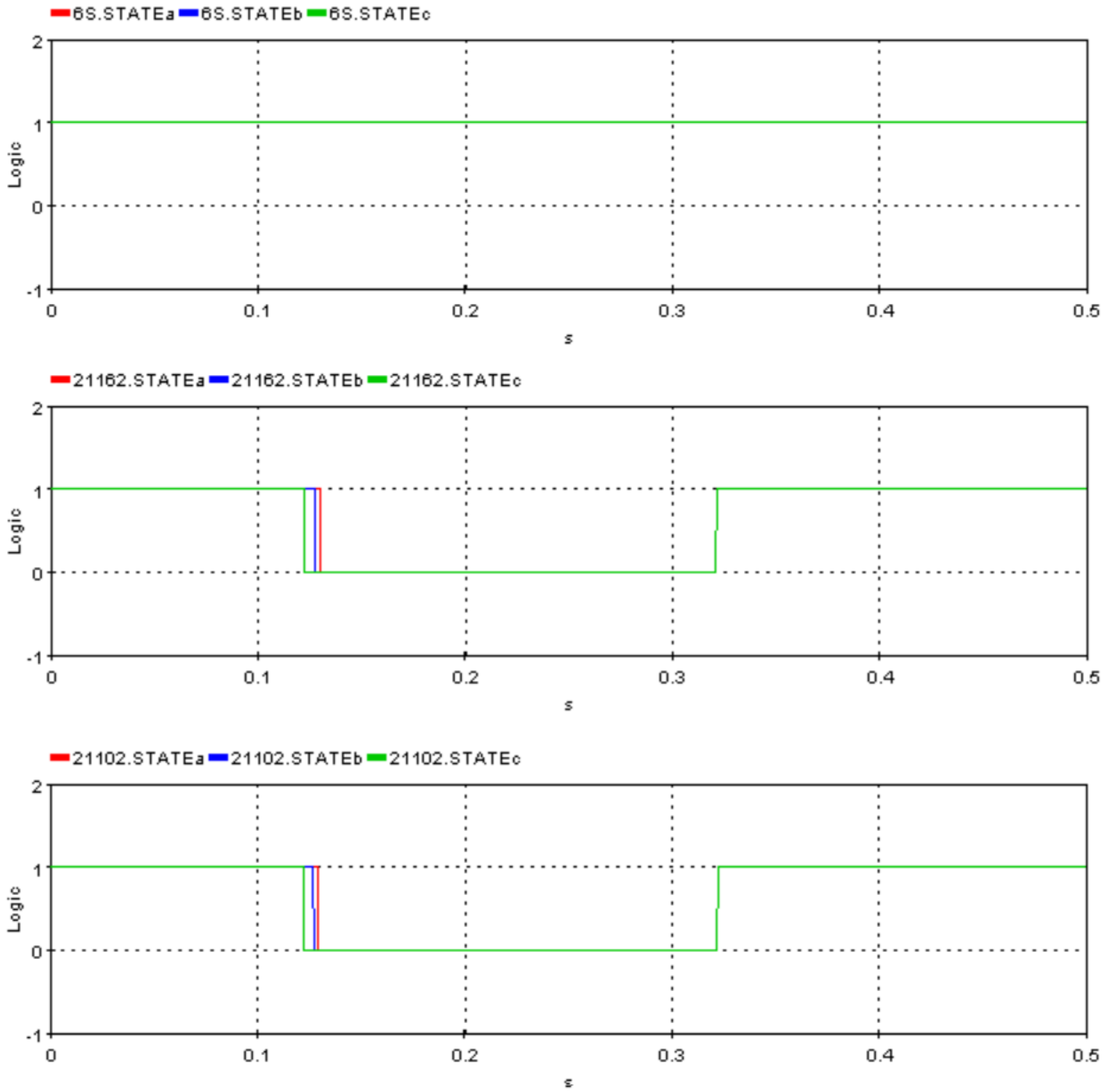

Fig. 5. CT4, CT15, and CT 6S trip/reconnect logic signal

The plots from Fig. 4 demonstrate that before the fault detection at *t=0.1s*, all the CT currents were in steady state, with an RMS value of roughly 325 A in all phases. The fault took place at the midpoint position of the 211 Transmission Line and thus, in the DCB protection scheme, only circuit breakers 21162 and 21102 must trip. That is because the contingency is considered a Zone 1 fault, which means that it is located within the underreaching protection zone of both relays 1 and 2. Fig. 4 confirms the circuit breaker actuation, displaying that all three phases of both circuit breakers 21162 and 21102 tripped at roughly *t = 0.12s*. Given the transient nature of the fault, it disappeared at *t = 0.3s*, although the circuit breaker only reclosed at *t = 0.32s*. The time delay is due to the relay time delay logic, which waits for 0.2 seconds before reclosing.

B. *Test 2 – Three-Phase-to-Ground Fault outside Transmission Line 211*

For Test 2, a transient fault was applied at Transmission line 211, but located at 90% of its length measured from CCVT 211 North Bus. Similarly to Test 1, circuit breakers 21102 and 21162 tripped, leaving the system completely de-energized as shown in the measured currents from CT 2, CT 5, and CT 15 in Fig. 6. In this test case example, relays 1 and 2 sensed the fault at *t=0.1s* and the 21102 circuit breaker tripped after 2 cycles while the 21162 circuit breaker tripped after 3.125 cycles. The difference in tripping signal is due to the positioning of the fault since it is a zone 2 fault for relay 1 but a zone 1 fault for relay 2. After the tripping signal, both circuit breakers tried the first reconnection after 0.2 seconds from their respective tripping signal. By then, the contingency had disappeared (considering a transient contingency) and circuit breakers 21102 and 21162 reclosed and the system regained power. Fig. 6 illustrates the AC currents during the trip/reconnection protocol for CT 2, CT 5, and CT 15. It is worth mentioning that before *t=0.1s*, the model was in steady state and the RMS value of the current flowing in CT2, CT5, and CT 15 was roughly 325 A.

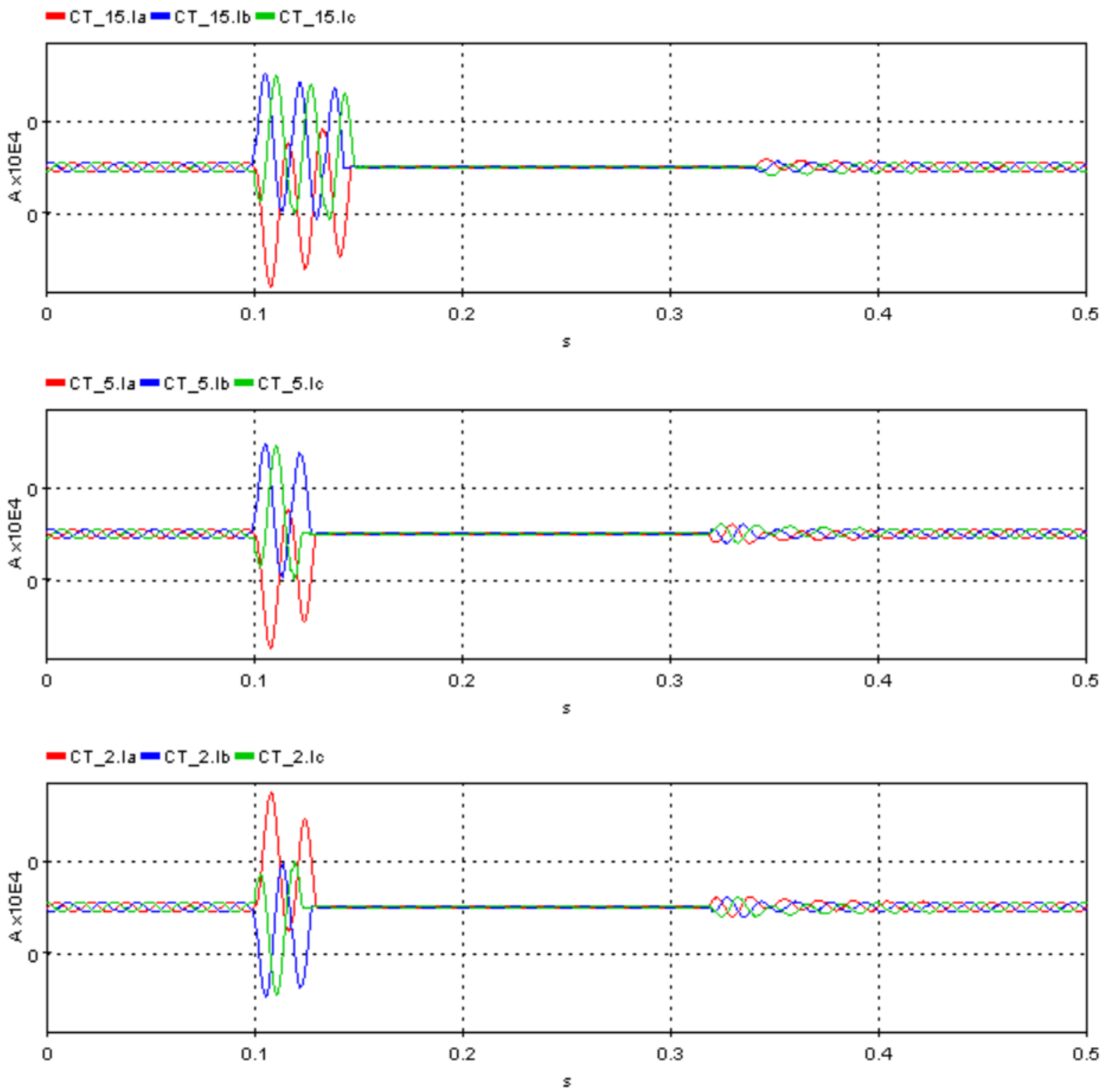

Fig. 6. CT4, CT15, and CT 6S current measurement during the trip/reconnect for test 2

Figure 7 displays the trip/reconnect logic in all three relays from the model, pointing to the correct expected operation. Since the fault was inside Transmission line 211, and within zone 2 for relay 1 and within zone 1 for relay 2, the expected operation is to have both circuit breaker 21102 and 21162 trip, thus eliminating the fault current source that derives from both voltage sources in the model, and consequently isolating the fault. Both relays await 0.2 seconds to reclose the circuit breaker and given that the fault was no longer present, the system was fully reconnected and returned to its pre-fault condition.

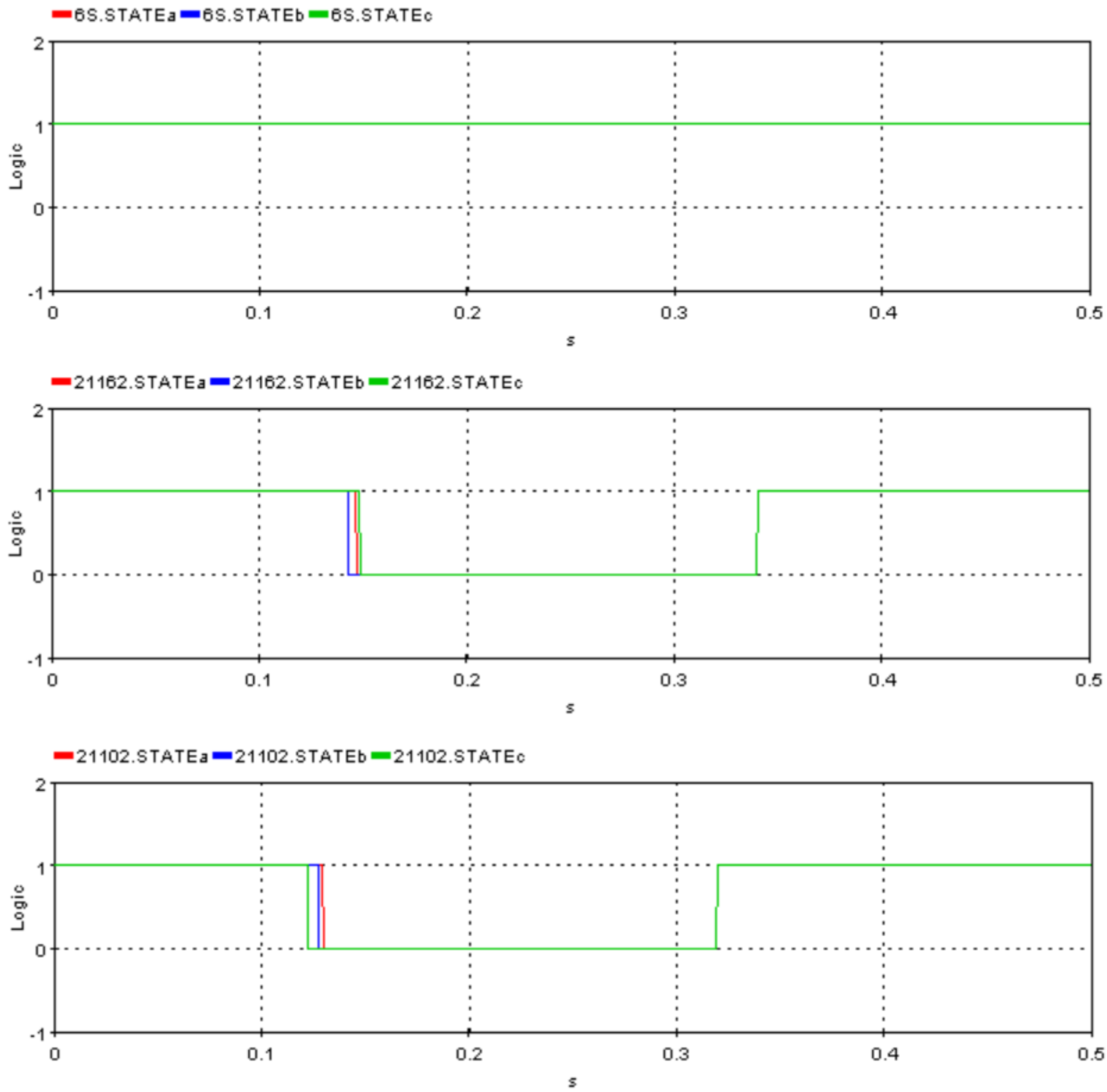

Fig. 7. CT4, CT15, and CT 6S trip/reconnect logic signal

V. CONCLUSION

This work presented the implementation and validation of a transmission line protection test case model utilizing HYPERSIM, which is intended to be used during the system protection training program. The model emulated a portion of the 230 kV ring bus substation training facility, modelled with all its circuit breakers, loads, and current/potential transformers. The results point to success of the project and the model will now be a part of the training material used in SATS. In future work, this test case model combined with other models will be used and tested with OPAL-RT in a HIL setup for substation technician training and research purposes.

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