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Power Systems Relay Coordination using Hardware-in-the-loop

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Abstract

This research highlights an innovative approach to learning and presentation of power systems relay coordination topics. Traditional approach relies heavily on digital computer simulations to create the model and environment for testing and evaluating performance, primarily due to lack of more appropriate tools. A hardware-based learning method is presented in this work, it combines physical instruments with real-time digital simulated model to create a test environment with real-time response to various faults on the power network. A three-bus model of a physical 50 kVA microgrid testbed is used as a test system featuring effective data communication between physical automation controller, overcurrent relay, and a real-time simulator. Coordination of relay trip signals was achieved for various locations within the microgrid system network through communication protocols linking the automation controller, relays and digital simulator. Through this hardware-in-the-loop automation and control setup, students were able to study important concepts of protection coordination in a safe laboratory environment and obtain performance that reflects real-life system faults.

Key words: SEL-751A Relay, protection systems, fault analysis, hardware-in the-loop, Opal-RT, real-time simulator, SEL RTAC.

Introduction

Power system protection is an integral part of power generation, transmission and distribution. A typical protection scheme is designed to shield critical and expensive network equipment from the potentially devastating effects of short-circuit faults. Zones are designed in protection schemes to offer overlapping layers over system components to increase reliability and security of the electric grid.

Variable operating circumstances, system topologies, fault current magnitudes and phase directions make microgrid protection difficult. Relay Hardware-in-the-loop (RHIL) testbeds typically consist of a real-time simulator running a simulated power system model, which communicates with external protective relays through binary and analog signals. RHIL is an effective method to test performance of relays by interacting with a simulated test system before implementation in a real power system. This method serves as a safe and low-risk validation method and enables engineers to evaluate operations concepts and assess protection algorithms. By testing and validating relay protection functions prior to field implementation, engineers can optimize protection functions under various operating conditions that would be impractical to replicate in practice. RHIL systems simplify the process of designing and testing protection systems for microgrids and can be adopted in learning environments for valuable hands-on experience.

RHIL presents the opportunity to test industry-grade equipment in power protection system studies. Liu et al. [1] modelled the inverse time-overcurrent characteristics of an ABB relion relay in Simulink and tested the performance on a microgrid simulation model, executed on a real-time simulator. The validation of relay performance was carried out through comparison with results from a physical ABB relion relay under same fault conditions in the RHIL environment. Similar to the work done in [1], authors in [2] used an Opal-RT signal amplification interface to connect the real-time simulator to an external SEL-351 Protection System, to perform experiments on overcurrent and over-frequency protection. The performance of the relay model was tested in a simulated radial power environment. Farias et al. [3] utilized the low-voltage analog interface of the SEL-451 Protection, Automation, and Control System to make direct analog connection to the OP 4510 simulator and the relay. This removes the need for voltage/current amplifiers as was typically done in other reviewed literature. The relay sends binary bits to the simulator's digital input to control breaker status in the model.

In RHIL projects featured in literature, authors typically use physical relays in their experiments. This offers limited flexibility due to the effort and work required to install a relay at every point needed in the experiment. There is also a cost factor in procuring multiple relays that would be needed in the experiments.

This paper proposes an innovative approach to relay coordination experiments for undergraduate students using Relay Hardware-in-the-loop (RHIL) concept. The RHIL testbed was created using industry-grade hardware systems, including automation controller, overcurrent relay, real-time simulator, as well as industrial communication protocols linking microgrid components. This approach yielded a solution that reduces the need for installation of multiple relays on the test system (physical microgrid). Overview of the setup for the RHIL testbed and results obtained from relay coordination case studies on a microgrid are presented in the next sections.

PSH Electric Utilities Power Laboratory

Penn State Harrisburg (PSH) houses a 50kW microgrid testbed in its Electric Utilities Power Laboratory. This microgrid testbed, serving as the platform for this protection coordination experiment, is robust, and features typical components utilized in real-world power grid applications. Experiments such as grid synchronization, grid islanding, etc. may be conducted on this microgrid testbed. The testbed was fabricated as three independent microgrids linked together through transmission lines to form a three-bus system. Each bus features a 10kVA generating unit, renewable energy emulators, induction machine loads, transformers, inverter-battery bank systems, and instrumentation devices for data logging. Transmission lines between the buses may be used to connect buses in a ring or radial configuration. The three buses show a level of symmetrical in terms of the range of installed equipment. Figure 1 is a single-line diagram illustration of one of the buses (South bus).

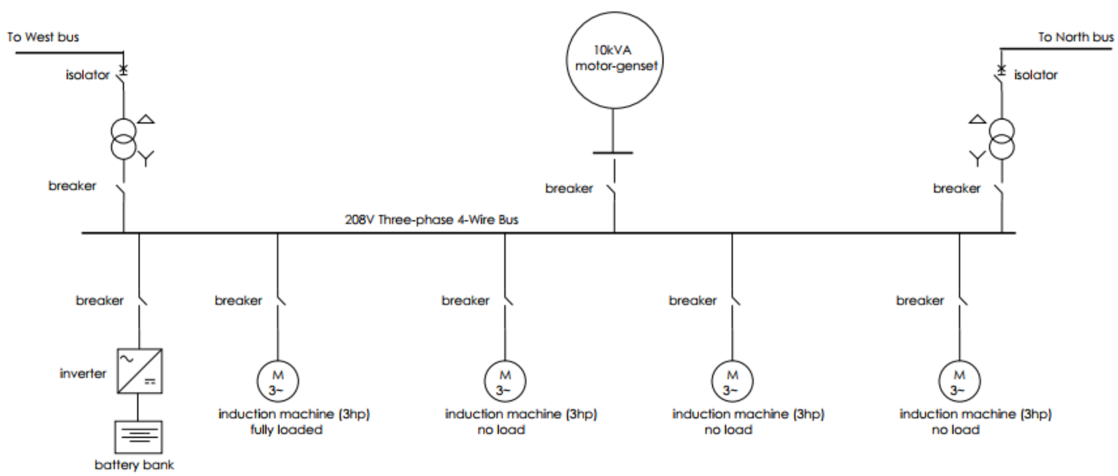

Figure 1. South bus single line diagram

Structure of Relay Protection Coordination Experiment

The laboratory experience is designed to span a period of four three-hour weekly sessions, in addition to pre-lab group work. Specific tasks involved in the process include the following:
1. Safety and support - the laboratory Graduate Assistant provides guidance throughout the stages of the project that involves interaction with energized equipment in the laboratory environment.
2. Familiarity with testbed system - students review previously developed detailed Simulink model of the 3-bus 50kW microgrid testbed.
3. Model validation – students run load studies on the Simulink model, as well as the ETAP model of the testbed, and compare results with those obtained from the physical microgrid.
4. Protection coordination studies – design and testing stages are organized as follows:
a. Select an area of the microgrid (2-bus radial, ring, etc.) that will be the primary focus area for the protection coordination studies.

b. Run fault studies to determine possible fault current levels that could be experienced on the microgrid during faults. Tabulate results (fault currents, voltages, etc.)
c. Use the reference material provided (manual for SEL-751A, RTAC-3530) as a guide in developing MATLAB/Simulink blocks to model overcurrent relays for the coordination studies.
d. Insert relays, breakers and fuses into the microgrid test system, and run coordination studies in the Opal-RT 5700 digital simulator. Print and document the time-current coordination chart and all other important results. Discuss your observation from the time-current coordination chart.
e. If the protection is uncoordinated in the previous step, modify the time current curves to achieve coordination. Document your work, clearly showing the relays settings, circuit breaker and fuse specification that achieves the desired coordination.
f. Test your design with a new set of faults, including simultaneous faults on two locations.
g. Implement a Relay Hardware-in-the-Loop (RHIL) system by interfacing digital relays, SEL-751A, RTAC-3530, SEL-421 with the Opal-RT real-time simulator.
h. Repeat coordination studies with one of the Simulink relays replaced with physical relays. Modbus communication protocol would be used in moving data between the relays and the simulator.

Microgrid testbed simulation model

The physical three-bus microgrid testbed is modeled in Simulink and compiled in RT-LAB for execution on the Opal-RT real-time simulator. The Simulink model for the West bus, shown in Figure 2 reflects the protection scheme of the physical microgrid, with switches placed at various locations in the network to function as circuit breakers to disconnect loads, buses and generators. This Simulink model is handed over to students to review and perform validation studies. Results from load studies on the laboratory microgrid are compared with those obtained from the digital simulator-based model when subjected to identical loading pattern.

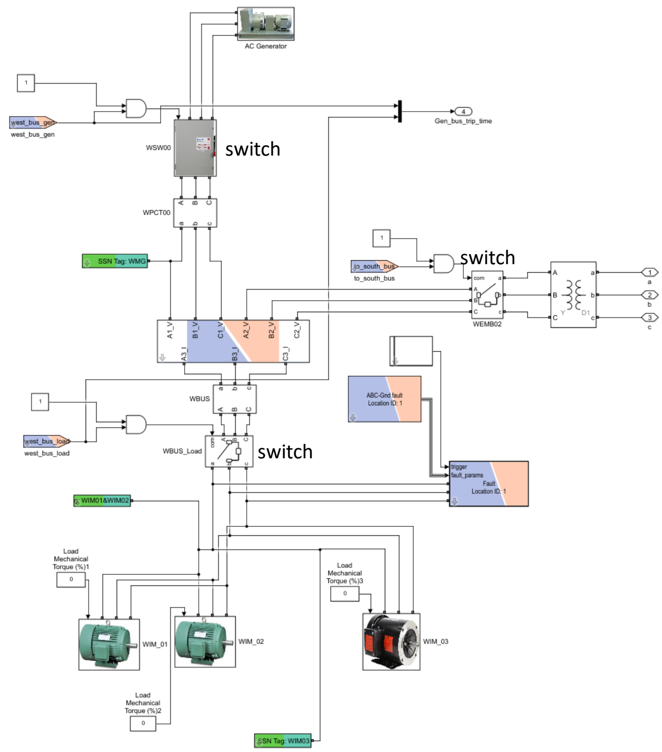

Figure 2. Simulink model of the West bus (one of three buses)

Fault Analysis on the simulation model

The real-time digital model of the physical microgrid offers students a safe environment to perform fault studies. Students model various fault-types such as three-phase, line-line and line-ground faults at different locations on the microgrid. The radial connection of the microgrid (Figure 3) is selected for further studies.

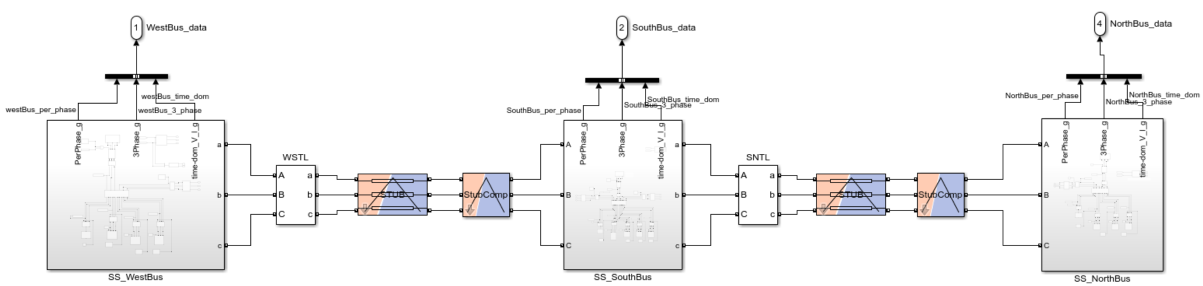

Figure 3. Radial connection of all three buses (Simulink model)

Relay Hardware-In-the-Loop (RHIL) setup

The real-time simulator testbench comes with analog and digital I/Os to facilitate connection to external hardware systems in the laboratory, such as relays and automation controllers. All components in the laboratory, including the real-time simulator are connected through laboratory local area network via ethernet or wireless communication. The automation controller has the capability to communicate with various devices using different communication protocols [7]. With this existing facility, the real-time simulator is connected to the external automation controller and bidirectional data transfer is achieved via MODBUS. This is illustrated in Figure 4. Power system data from the simulated model executed on the real-time simulator is made available to the automation controller, and likewise control signals from the controller is transmitted to the real-time simulator.

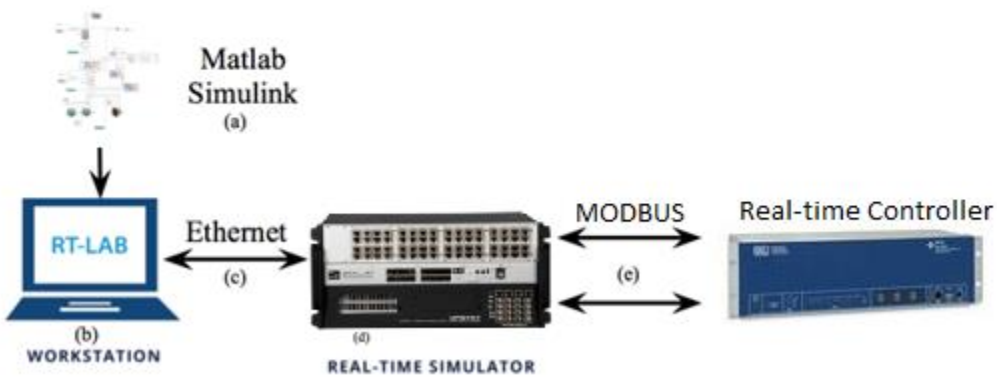

Figure 4. Block diagram of the real-time RHIL implementation.

Relay Programming

Automation and control logic can be programmed in the automation controller using IEC 61131-3 programming. Taking advantage of this feature, and the ease of data communication between the automation controller and real-time simulator, it was feasible to program several relay-types for different locations in the microgrid network. Overcurrent protection is chosen as a focus of this experiment and SEL 751A protection relay as the critical hardware to recognize and clear faults when they occur. The device has overcurrent features that conform to the IEEE C37.112-1996 Standard Inverse-Time Characteristic Equations for Overcurrent Relays. These equations are listed in the SEL 751A instruction manual. Figure 5 is a plot of moderately inverse time curves at different Time Dial Setting. These are programed in IEC61131-3 structured text and executed on the RTAC-3530.

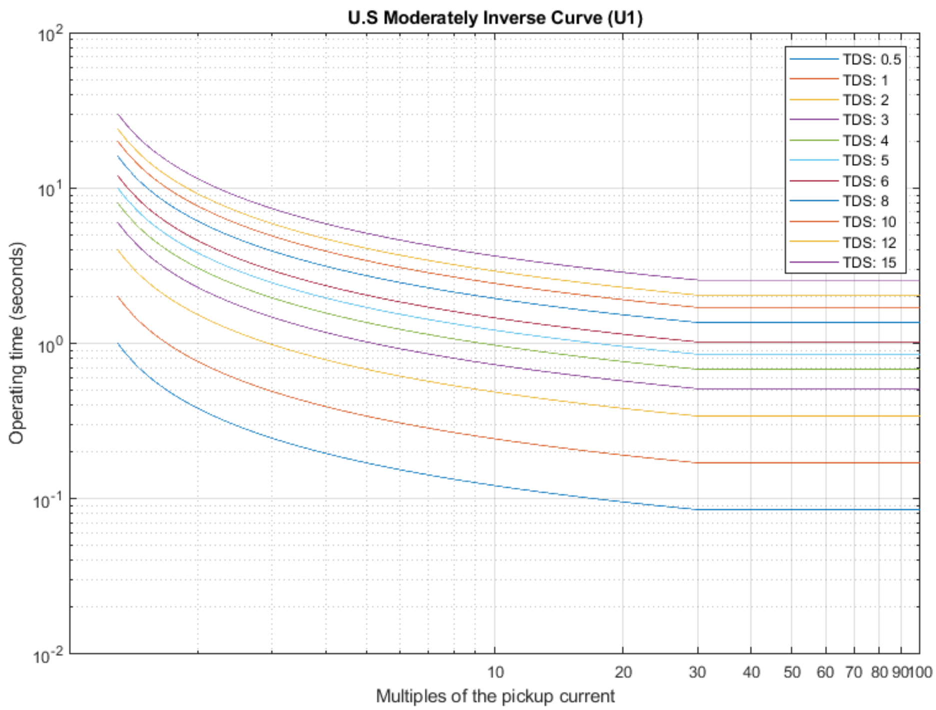

Figure 5. Moderately Inverse Time-Overcurrent curves (programed in IEC61131-3 structured text)

SEL-751A Overcurrent features for U1 and U2 Curve types are implemented in this experiment. Relay operating time (tp) equations for curve type U1 and U2 given by (1) and (2):

$$tp\ (U1\ curve) = TDS * \left(0.0226 + \frac{0.0104}{M^{0.02} - 1}\right) \tag{1}$$

$$tp\ (U2\ curve) = TDS * (0.180 + \frac{5.95}{M^{2} - 1}) \tag{2}$$

TDS is the time-dial setting of the relay and

$$Multiple\ of\ pickup\ current\ (M) = \frac{Realtime\ RMS\ current\ at\ a\ microgrid\ location}{Expected\ nominal\ Current\ at\ a\ microgrid\ location}$$

Equations (1) and (2) are programmed into the RTAC automation controller. Real-time RMS current is made available through data communication between the real-time simulator and the automation controller. The Time Dial Setting and pickup current are set in the relay program. The pickup current is set as the expected nominal current.

During simulation of the microgrid model, the automation controller receives real-time voltage and current values from various locations of the microgrid network. When the simulated relay reads a current value greater than the nominal value, it calculates an operating time (tp) according to equations (1) and (2). When this operating time elapses, the relay checks again if the fault current persists. If the fault current still exists, the automation controller sends a binary bit to trip a breaker in the microgrid being simulated to remove the fault from the system.

Effective protection relay coordination ensures that the fault is isolated from the system while maintaining uptime in other locations within the microgrid.

Relay Coordination Experiment

The West bus generator is the only generating unit in operation for this experiment. The generator supplies power to all loads on the microgrid including loads on South and North bus. After the simulation is executed, a three-phase fault is placed on the West bus load zone at 105 second time mark for 0.5 seconds. Students observed the impact of this fault on the West bus generator. This is seen in Figure 6. The nominal current before the fault is approximately 52A, but surges as high as 126A when the fault occurred. The fault current settles to approximately 66A following the initial surge possibly due to energy storage systems in the microgrid, such as the induction machine loads. The generator contributes 66A to the fault.

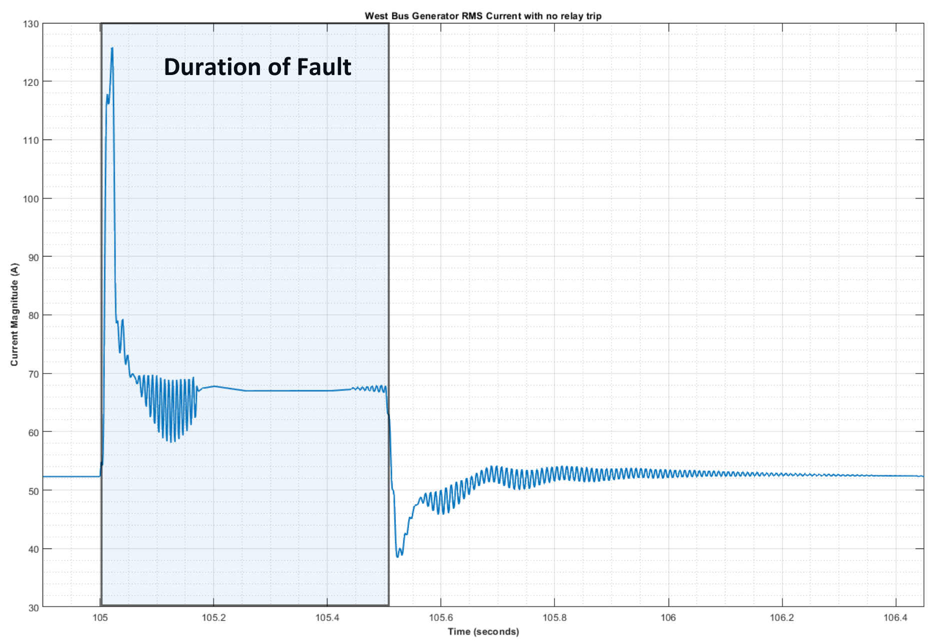

Figure 6. West bus generator RMS current (three-phase fault)

U1 and U2 time overcurrent curves are used in this relay coordination experiment. To demonstrate relay coordination, a U1 curve is programmed into the relay at the West bus load while a U2 curve is programmed into the relay at the second layer of protection, protecting the entire West bus. This is illustrated in Figure 7.

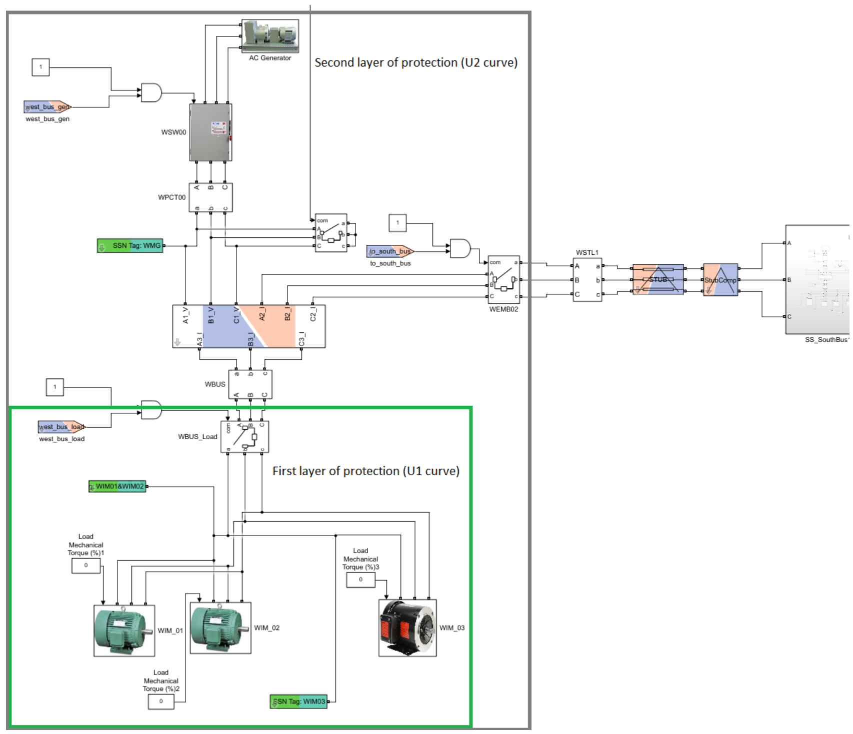

Figure 7. Protection Zones for West bus

The U1 curve calculates a faster trip time to a fault according to equation (1). So, it is expected that in presence of a fault on the West bus load, the first layer of protection should trip first.

Simulation Results

The relay protecting the West bus load zone detects the three-phase fault when it occurs at 105 seconds and calculates an operating time before a trip signal is sent to a circuit breaker. This successfully isolates the faulted zone alone from the rest of the microgrid network. In Figure 8 the three-phase fault occurs at 105 seconds mark and the relay sends a trip signal after 400 milliseconds (at 105 + 400ms) thereby taking out the faulted West bus load zone from the rest of the power grid network. The West bus generator continues to supply power to the South bus load and North bus load. This can be observed in Figure 8 (2nd graph), as the nominal current at the West bus generator prior to the fault is approximately 53A. After the faulted area is isolated from the microgrid, the nominal supply current drops to approximately 40A. The second layer of protection remain connected (no tripping) throughout the duration of the fault as expected.

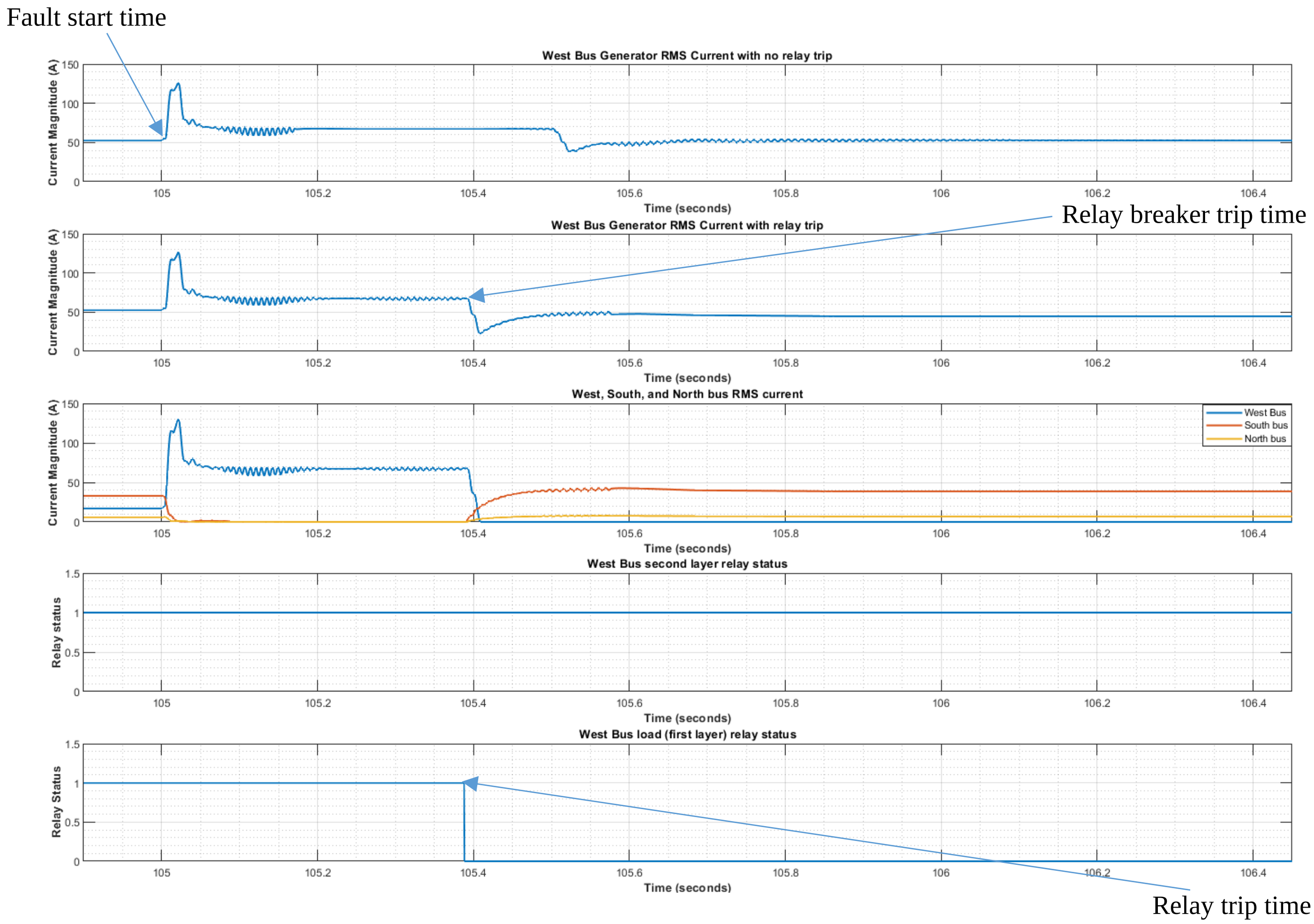

Figure 8. Relay performance and bus loads due to three-phase fault.

The three-phase fault causes a short circuit to occur at the West bus load which isolates current flow from the rest of the circuit, this is observed on Figure 8 (3rd graph). Current flowing in the South and North buses goes to 0A. After the fault is cleared by the circuit breaker the microgrid continues to operate safely and the South and North bus loads continue to receive power from the West bus generator.

Conclusion

This RHIL experiment successfully demonstrated a positive relay coordination design and resulted in an improvement in the learning experience of power protection studies for electrical engineering undergraduate students at Penn State Harrisburg. The RHIL setup achieves the ability to easily implement relay characteristics at desired locations in a microgrid experiment. Students could easily observe the impact of faults executed at various locations on the microgrid and learn about the concept of relay coordination. Students also received valuable hands-on experience in creating faults at various locations in a microgrid, studying the impact, designing protection systems, and testing the performance of the protection systems.

The RHIL is a safe and easy approach to the power systems protection study while still obtaining realistic results. Future work in this project could involve testing relay coordination further if the first layer of protection fails to trip. More protection zones could also be added to the microgrid and the number of relays programmed within the automation controller can be increased to test performance of the overall system. Relays also have reset time characteristics where the relay resets if the fault has been cleared prior to the operating time elapsing, this can also be explored in future work built on this paper.

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