

Methodologies for Power Protection Relay Testing: From Conventional to Real-Time Hardware-in-the-Loop (HIL) Simulation Approaches

M. S. Almas, L. Vanfretti

Abstract-- Performance testing of the protection relays ensures that a particular protection scheme will operate reliably and fast enough to disconnect a faulty zone from the rest of the network, thus mitigating the effect of fault on the power system. It is therefore important to validate the settings of power protection equipment and to confirm its performance when subject to different fault conditions. Traditionally, commissioning engineers make use of standalone protection relay test sets for analyzing the performance of relays when subjected to different voltage and current injections. With the advent of digital simulators the model of the power system can be executed in real-time and protection relays can be interfaced as hardware-in-the-loop to evaluate their performance when subjected to different faults in the simulated power system. This gives an added value of analyzing the overall behavior of the power system coupled with the relay performance under faulty conditions. In addition, the utilization of GOOSE messages for status, control and protection purposes puts an extra requirement to completely test the IEC 61850 capabilities of the protection relays.

This paper illustrates two different techniques namely standalone testing and real-time hardware-in-the-loop testing used for protection relays performance verification. Both techniques are evaluated for hardwired and IEC 61850-8-1 (GOOSE) signals. The instantaneous overcurrent protection feature of Schweitzer Engineering Laboratories Relay SEL-421 is used for complete standalone and RT-HIL testing. For RT-HIL testing, the test case is modeled in MATLAB/Simulink and executed in real-time using Opal-RT's eMEGAsim real-time simulator. The event reports generated by standalone and RT-HIL testing for both hardwired and GOOSE signals is used to verify the tripping times achieved. Finally the performance of hardwired and GOOSE tripping times are compared and the overall standalone and RT-HIL techniques are evaluated.

Keywords: Real-Time Simulation, Hardware-in-the-Loop, Overcurrent Protection, Power Protection Relay Testing, Opal-RT, GOOSE, Station Bus

M. S. Almas is a PhD. student at the division of Electric Power Systems, Royal Institute of Technology, Stockholm, Sweden (msalmas@kth.se). He is supported by STRONG²rid project, funded by Nordic Energy Research.

L. Vanfretti is a Docent and Associate Professor at the division of Electric Power Systems, Royal Institute of Technology, Stockholm, Sweden (luigiv@kth.se). He is supported by the STandUP for Energy collaboration initiative, Nordic Energy Research through the STRONG²rid project and the European Commission through the iTesla FP7 project.

Paper submitted to the International Conference on Power Systems Transients (IPST2013) in Vancouver, Canada July 18-20, 2013.

I. INTRODUCTION

POWER protection relays play the most vital role for safeguard the power system from detrimental effects of faults. Microprocessor based relays or IEDs are equipped with current and voltage input modules which receive the voltage and current measurements from VT and CT respectively. The algorithms incorporated in their microprocessors utilize these measured voltage and current values to detect faults in the power system. These IED's generate a trip signal once the algorithm detects the faulty condition. This trip signal is used to open the circuit breaker, send information to the control center, communicate with other devices/controllers in the substation etc. [1].

Mal-functioning of relays can lead to false tripping of circuit breakers which can cause cascading failures. Therefore it is important to verify the settings of protection relays before they are commissioned in the real power system to avoid any unfortunate incident. Traditionally field engineers or commissioning engineers use stand-alone relay test sets to verify protection relays settings. This is also called static characteristic testing set which are provided by different manufacturers (suppliers) [2]. These test sets are actually three phase variable voltage and current sources which are used to provide secondary injections to the protection relays. The features verified are the accurate fault detection by the relay, tripping time, output contact status change etc. These test sets do provide the advantage of being compact and portable; however, most are limited to 6 current channels and 6 voltage channels. With this limitation, it is cumbersome to use several of these test sets to verify complex protection schemes like bus bar protection. In addition the synchronization of the two test sets with GPS will be an additional issue.

Real-time simulators (RTS) are currently being used to simulate large power systems and to analyze their behavior in both steady state and faulted states. These RTSs are equipped with Analog and Digital I/Os and can be interfaced with real hardware devices like protection relays, power electronics based converters and power system controllers to validate their design, performance, and control algorithm in real-time under different operating conditions. Such kind of approach is called RT HIL simulation [3]. This approach allows performing complete functional testing of the protection relays. In this case an accurate model of the power system where the relay is to be placed is modeled and simulated in RT using the RTS with the actual hardware (protection relay) as HIL. The key benefit in RT HIL protection relay testing is that

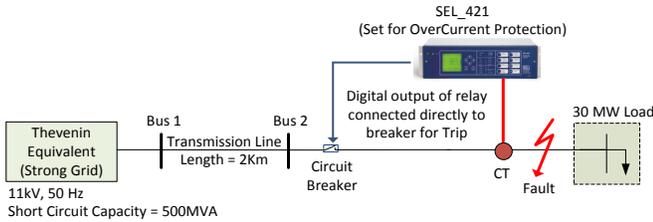


Fig. 1. Single Line Diagram of the Test Case

the impact of the fault on overall power system can be analyzed and the overall protection schemes including the backup protections, system integrity protection schemes (SIPS) and Remedial Action Schemes (RAS) can be verified.

In this paper, two techniques used for relay testing: standalone testing and RT HIL are compared for both hardwired and IEC 61850-8-1 (GOOSE) testing. Firstly a test system is designed in SPS and its fault analysis is carried out. Based on the fault analysis, the settings of the protection relay from Schweitzer Engineering Laboratories (SEL) relay SEL-421 [4] are configured for instantaneous overcurrent protection. In standalone testing, the secondary injections for three phase currents are provided by the relay test set from Megger and the tripping times are noted for both hardwired and GOOSE testing. Then the SPS model is executed in RT using Opal-RT's eMEGAsim real-time simulator. The same SEL-421 relay with same parameters is used for RT HIL testing for both hardwired and GOOSE signals. The results obtained are verified by retrieving the event report of SEL-421 for the entire test scenarios.

The remainder of this paper is arranged as follows. Section II presents the details of the test case modeled in SPS. Section III focuses on the stand-alone hardwired testing of SEL-421 for over-current protection function. Section IV provides the stand-alone testing with GOOSE (IEC 61850-8-1). Real-time hardwired testing using Opal-RT is discussed in Section V, while Real-Time GOOSE testing is explained in Section VI. Finally in Section VII, conclusions are drawn and future work is outlined.

II. TEST CASE IN SIMPOWERSYSTEMS

The test case is modeled using the SimPowerSystems (MATLAB / Simulink) Toolbox. SPS is a dedicated tool for modeling and simulating power systems [5]. Another motivation behind using SPS toolbox is because the models built in SPS are compatible with Opal-RT eMEGAsim real-time simulator [6] and can be executed in RT. Figure 1 shows the single line diagram of the test case modeled in SPS. The major components of the power system model are;

- Three phase voltage source, 50Hz, 11kV phase voltage and short circuit capacity of 500MVA
- Transmission Line (π -section), 2km
- Three phase fault block to introduce three phase fault
- Circuit breaker to disconnect load with trip signals from overcurrent relay (SEL-421)
- Three phase series RLC load of 30MW
- Simulation time step = 50 μ second

In order to set the parameters of the protection relay (SEL-421) like CT ratio, fault pickup value and characteristic curve selection, fault analysis of the test case was performed. The results are shown in Figure 2. Based on the results from the fault analysis, the settings of the SEL-421 were modified using SEL AcSELeRator Quickset [7]. The key parameters settings for the SEL-421 are shown in Table 1.

TABLE I
TEST SYSTEM ANALYSIS AND RELAY SETTINGS

Measurements	Full Load Current	1500 A
	Maximum Fault Current (Three Phase Fault)	7120 A
Relay Setting	Current Transformer Ratio	1500:1
	Pickup Value	2 A
	Characteristic	Instantaneous
	Event Report	2.5 sec
	Digital Output of Relay	Trip=Normal Close

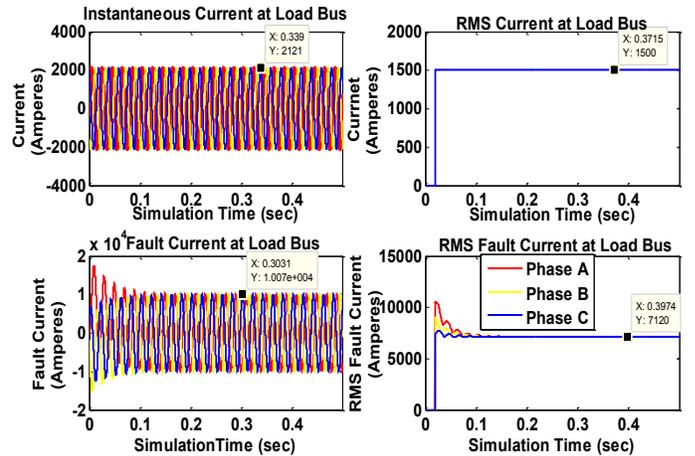


Fig. 2. Fault Analysis of Test Case

III. STANDALONE TESTING HARDWIRED

For standalone relay testing the Freja 300 relay test system was used [8]. The voltage and current sources are connected to the CT and VT input modules of the relay. By injecting different voltage, current magnitudes, phases and frequency, harmonics, different protection functions of the relays can be verified. For the standalone testing we have used Freja 300 along with its software interface Freja Win [9] to provide secondary injections to the SEL-421 relay to test its instantaneous overcurrent protection function.

The instantaneous overcurrent protection function sends a trip command to the breaker as soon as the fault is detected (input current greater than the pre-set value). They don't have any intentional time delay. They are usually implemented close to the source where the fault current level is very high

and a small delay in operation of relay can cause heavy damage to the equipment. So an instantaneous relay is used there to detect and respond to a fault in few cycles. The workflow diagram of testing a relay with Freja-300 is shown in Figure 3 and the screenshot of the graphical interface for Freja-300 test set i.e. Freja Win is shown in Figure 4.

For the test case, three phase current injection of 1 A (RMS) was provided for the first 2 seconds and at $t=2$ sec, the current injection was increased to 4.74 A (RMS). These are the same steady state and maximum fault current values as shown in Figure 2 and Table 1 but on the secondary side of the CT (CT ratio is 1500:1).

At $t=2$ sec, when the current injection increases, the relay picks it up as an overcurrent fault and generates a trip signal. The digital output of SEL-421 configured for overcurrent trip changes its status from normal open to normal close which is detected by the binary input of Freja-300 and the test scenario is terminated.

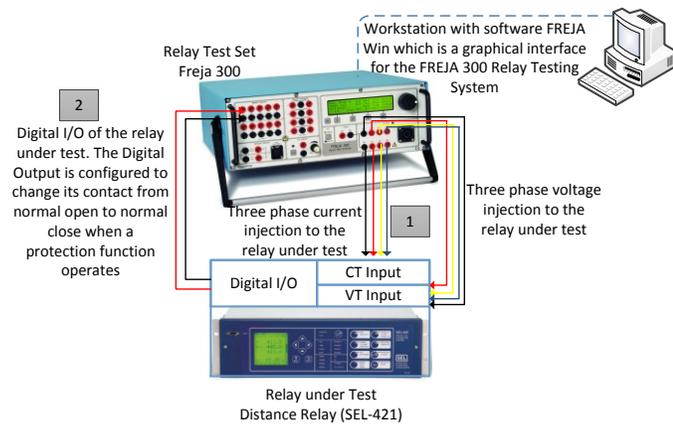


Fig. 3. Hardware Standalone Relay Testing Using Freja-300 Relay Test Set

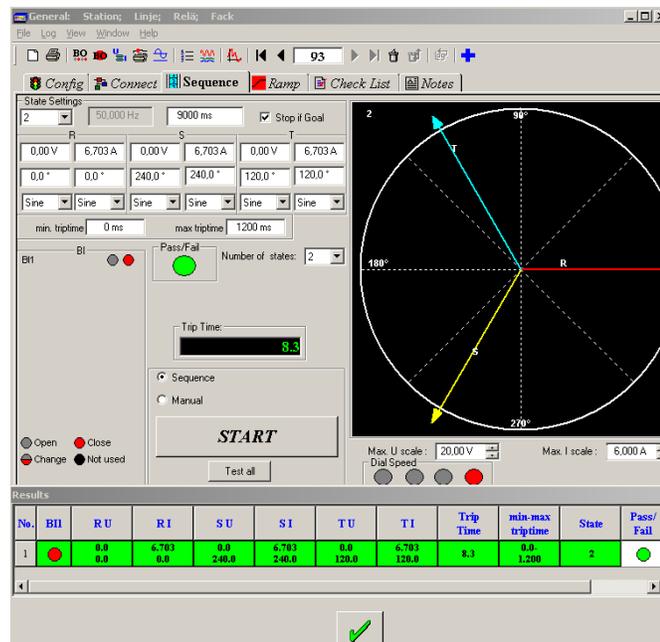


Fig. 4. Software Freja Win Interface for Standalone Relay Testing

The injections given by the test set are shown in Figure 5. Here State 1 is the pre-fault state and State 2 is the faulty state with increased current injections. The results show that at $t=2$ sec, the current injections are increased and the trip signal from the digital output of the SEL-421 is received at 2.0083 sec i.e. the overall time from fault pickup to trip generation and changing output contact status of the relay is 8.3 msec ($t_{operate}$).

In order to verify these results, the oscillography/event report of SEL-421 was acquired by using SEL Analytic Assistant software [10]. Figure 6 shows that the fault is applied at $t=2$ sec i.e. at 100th cycle and the relay has detected the overcurrent situation in almost quarter of cycle i.e. $t=2.005$ sec. So 5 msec (t_{pickup}) is taken by SEL-421 to decide if the instantaneous overcurrent has occurred. The rest 3.3 msec ($t_{contact} = t_{operate} - t_{pickup}$) is utilized by the relay to change its output contact and utilized by the test set to read its binary input status and end the test scenario.

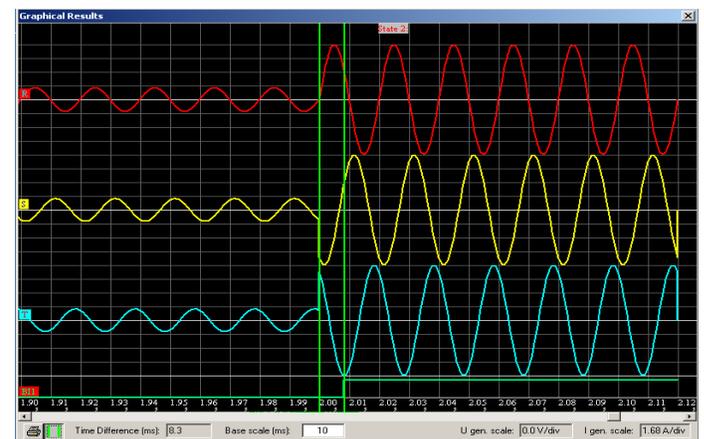


Fig. 5. Test Result for Standalone Testing (Hardwired)

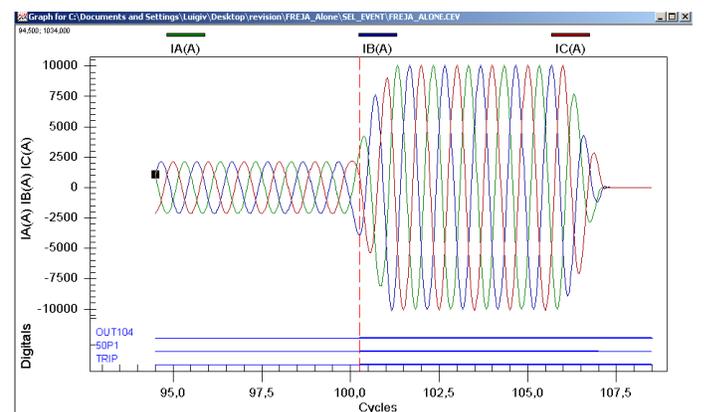


Fig. 6. Event Report from SEL-421 for Hardwired Standalone Testing

IV. STANDALONE TESTING GOOSE

The substation automation architecture standard IEC 61850 is currently being implemented a large number of currently available IEDs are IEC 61850 compliant [11]. One major benefit of the IEC 61850 standard is the reduction in

construction cost due to eliminating the need of copper wiring. In addition the standard allows multi-vendor interoperability and high speed peer to peer communications. Substations have already implemented the concept of Station Bus [12] and GOOSE [13] is being utilized for breaker failure, back up protections, fault recording, disconnecter and circuit breakers interlocking. This calls a need for accurately testing the GOOSE features of the IEDs. SEL-421 is also IEC 61850-8-1 complaint.

The software SEL AcSELErator Architect [14] is used to create GOOSE transmits messages for the SEL-421. The GOOSE message was configured for overcurrent protection trip. This overcurrent protection trip is a binary value which gives '0' in normal state and '1' in case of overcurrent trip. The overall test setup is shown in Figure 7. The secondary injections are provided by the Freja Relay Test Set as explained in Section III. However the trip signal is not received by the digital output of the relay. Instead test set GOOSER [15] along with its software interface PC-GOOSER [16] is used to capture the GOOSE message from the network and translate this GOOSE message to its binary outputs. This binary output of the GOOSER is connected to the binary input of the Freja-300. So as soon as the overcurrent situation is detected by SEL-421, it transmits a changed status of GOOSE message which is captured by GOOSER and it changes status of its binary output which is sensed by Freja-300 to terminate the test scenario i.e. stop the secondary injections of three phase current.

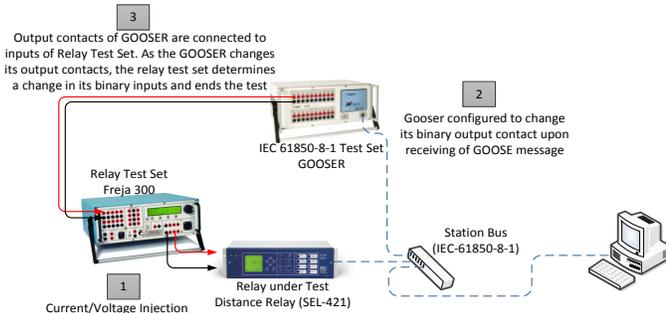


Fig. 7. GOOSE Testing of Relay (standalone) using GOOSER Test Set

Figure 8 shows the screen shot of the PC-GOOSER software interface for the GOOSER test set. In normal conditions the GOOSE messages appear as green. As soon as the GOOSE status is changed due to overcurrent detection, these GOOSE messages turn red. Once the overcurrent situation has ended due to the termination of the test case by Freja-300, these GOOSE messages appear as purple showing that there was a status change for these GOOSE messages.

The waveforms obtained by standalone GOOSE testing are shown in Figure 9. By using GOOSE, the tripping time of the relay is about 6 msec. This 6 msec involves the transmission delay of the GOOSE message from the relay through the Ethernet network to the GOOSER test set. As can be seen, tripping by GOOSE has proved to be faster than the hardwired solution. The reason being that in case of hardwired, there is an extra delay due to the status change of the digital output of

the relay. However in case of GOOSE, the digital I/Os are not involved and the information is sent through the Ethernet network.

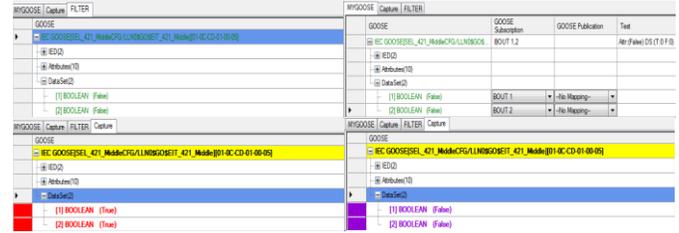


Fig. 8. PC GOOSER: Software Interface for GOOSER Test Set

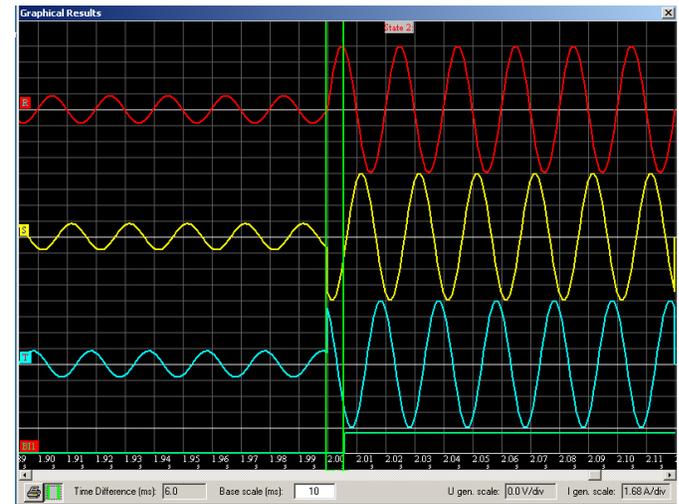


Fig. 9. Results from GOOSE Standalone Testing

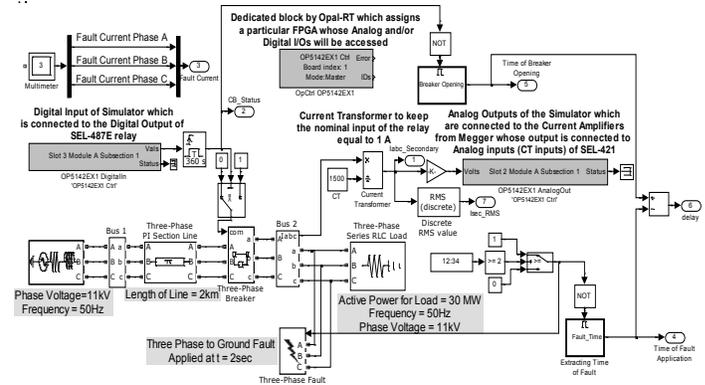


Fig. 10. Modified SPS Model for RT Execution

V. REAL-TIME HIL HARDWIRED TESTING

In order to achieve the RT HIL execution, some specific blocks from the RTS vendor were added to the SPS model to access the analog outputs and digital inputs of the RTS. These blocks are available in the RT-Lab library [17]. The overall SPS model along with the modifications is shown in Figure 10. The steps involved in executing the SPS model in RT using Opal-RT are shown in Figure 11.

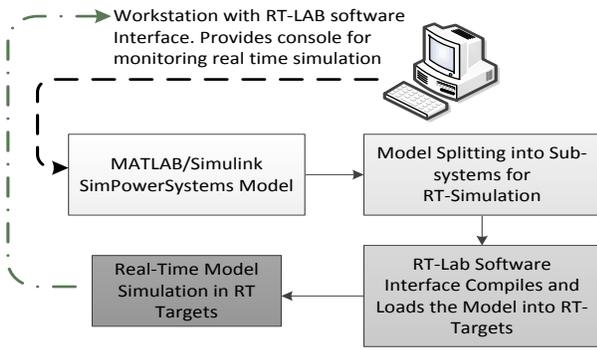


Fig. 11. Steps Involved for RT Execution

The model was executed in RT using the Opal-RT simulator. The three phase current at the load bus was sent to the analog outputs of the simulator. These analog outputs were fed to the current amplifiers from Megger [18]. The amplified three phase current signals were connected to the SEL-421 CT inputs. The overall work flow diagram is shown in Figure 12.

The digital output of the relay was connected to the digital input of the simulator. This digital input of the simulator was used to open the circuit breaker in the SPS model which was being executed in RT. Further calculations were performed to find the overall tripping time of the relay for RT HIL testing. The results are shown in the Figure 13. It shows a tripping time of 8.5 msec ($t_{operate} = t_{contact} + t_{pickup}$) which is 0.2 msec more than the standalone testing. The reason is that in this case, there is an additional delay of 0.2 msec due to the amplifiers. Figure 14 shows the results from the event report of SEL-421 after performing the RT HIL hardwired testing using the Opal-RT RTS.

VI. REAL-TIME HIL GOOSE TESTING

Opal-RT has the provision to publish and subscribe to GOOSE messages. The GOOSE messages from the SEL-421 can be configured to be read by the Opal-RT GOOSE Subscription block which can open the breaker in SPS model executing in the RT. The single line diagram for this RT HIL GOOSE testing concept is shown in Figure 15.

The test model in Figure 10 was modified to subscribe to the GOOSE message from the SEL-421 relay under test. The modified model is shown in Figure 16. The digital input of the simulator which was used to trip the circuit breaker in the SPS was replaced by the GOOSE Subscriber block offered by Opal-RT. This GOOSE subscriber block requires the IED Capability Description (ICD) file. This ICD file describes the complete capability of the IED. All the necessary information to monitor a specific GOOSE message is obtained by this ICD file. In order to subscribe to a GOOSE message the Multi-cast address of publication as well as its identifier (AppId) are used to produce control signals corresponding to the GOOSE message received through the IEC 61850 network.

The overall workflow diagram is shown in Figure 17. In this case the Digital I/O of the relays are ignored and instead the GOOSE message which is transmitted by SEL-421 upon successful detection of overcurrent condition is used to open

the circuit breaker in the SPS model which is executing in RT. The tripping times thus calculated by using this test case are shown in the Figure 18. The tripping time calculated is 6.2 msec which is faster than the hardwired i.e. 8.5 msec (Section V). When compared with the standalone GOOSE test case (Section IV), the tripping time by RT HIL is about 0.2 msec slower. The reason is the delay due to the amplifier.

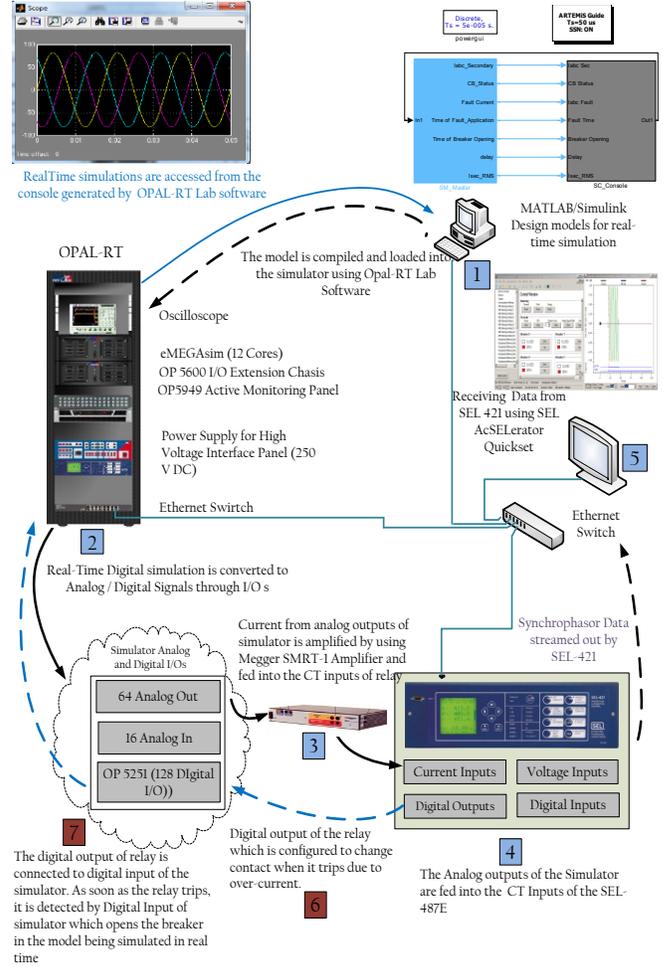


Fig. 12. Workflow Diagram for RT Execution

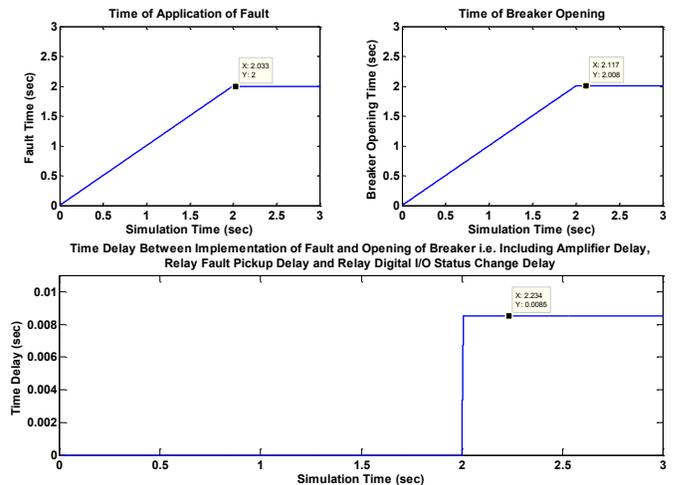


Fig. 13. Results from RT Hardwired

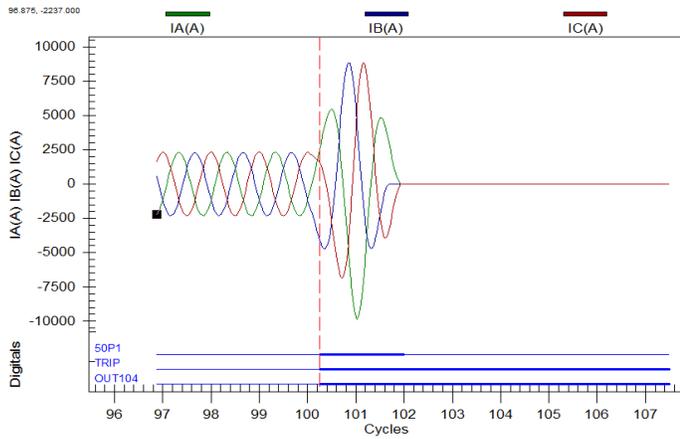


Fig. 14. Event Report from SEL-421 for RT-HIL Testing showing that fault is applied at 100th cycle ($t=2\text{sec}$) and is picked up in about quarter of a cycle

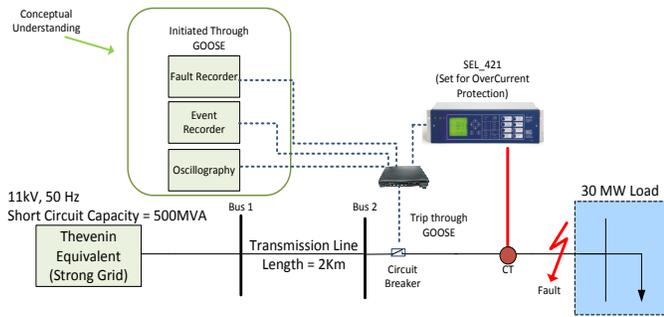


Fig. 15. Single Line Diagram for RT GOOSE Testing

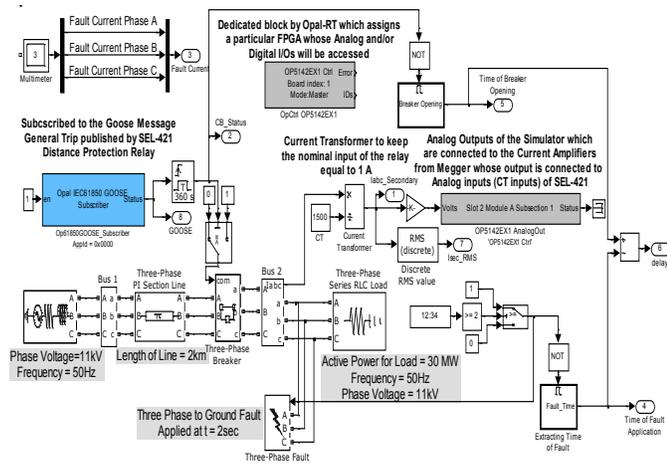


Fig. 16. SPS Model Modification for RT HIL GOOSE

VII. CONCLUSIONS

The two different testing techniques for power protection relays i.e. standalone tests using relay test sets and RT HIL using the Opal-RT eMEGAsim real-time simulator is performed for both hardwired and GOOSE testing.

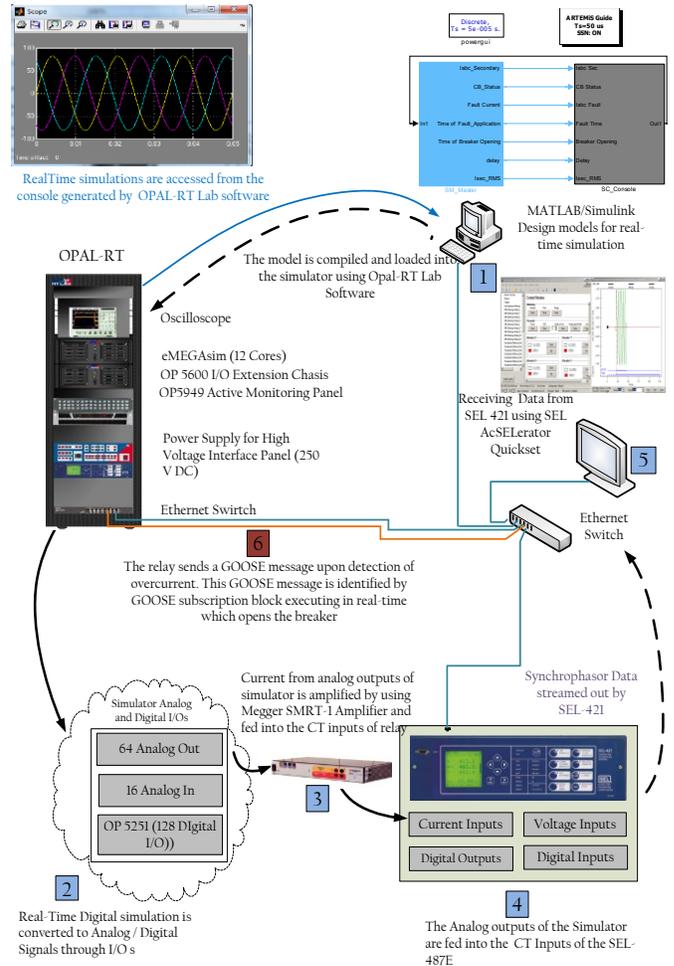


Fig. 17. Workflow Diagram for RT HIL GOOSE Testing

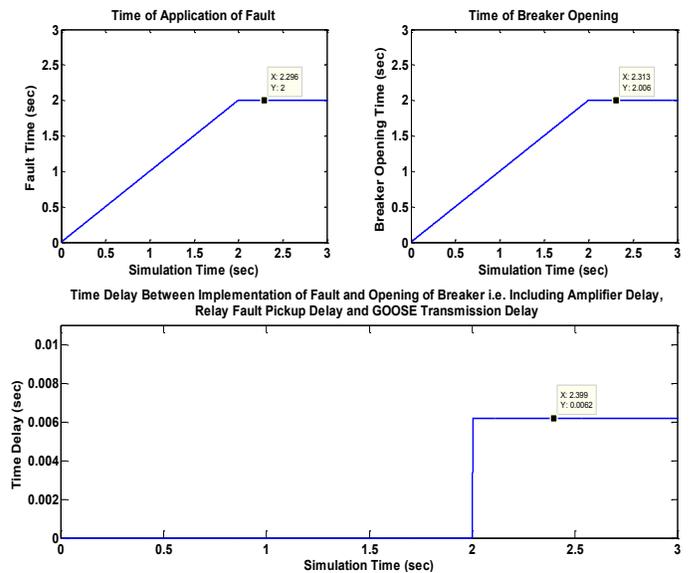


Fig. 18. Results from RT HIL GOOSE Testing

The relay tripping time was observed for all scenarios and the results were verified by visualizing the event reports and oscillography from SEL-421. These results are summarized in

Table II. The results show that GOOSE is a bit faster than the hardwired solution (about 2.3 msec). The reason for tripping through GOOSE being faster is because in case of GOOSE, the trip messages are sent over Ethernet and doesn't involve time required for digital output of the relay to change its contact from normal open to normal close. However it depends on the number of GOOSE messages present in the network. In a real substation with hundreds of IEDs and thousands of GOOSE messages, the trip time might be a bit higher than the hardwired solution. In case of RT HIL testing, there was an additional 0.2 msec delay due to the amplifiers.

The amplifiers from Megger (SMRT-1) are single phase voltage and current amplifiers. Their synchronization is an issue as well. Sometimes due to the non-synchronization of the three amplifiers, there is a delay in the three phases of the current as seen by the relay. This delay may result in the wrong detection of fault by the relay (i.e. the relay might see it as a double phase fault instead of a three phase fault).

This paper presents different methods for power protection relay testing and compares the RT HIL testing with traditional testing, along with comparison of hardwired and GOOSE trip times. Only the instantaneous overcurrent protection function is discussed in this paper however the same testing techniques can be used to validate different protection functions like distance, differential, over/under voltage, over/under frequency, etc. Opal-RT has the provision for streaming out sampled values i.e. IEC 61850-9-2 [12]. The RT HIL simulation results for the same scenarios with both process bus and station bus implementation will be presented in the future publication.

TABLE II
COMPARISON OF THE RESULTS FROM STANDALONE AND RT-HIL TESTING

<i>Comparison of Results for Standalone and RT-HIL Approach (Fault Applied at $t = 2$ sec)</i>			
<i>Testing Methodology</i>	<i>Feature</i>	<i>Tripping Time (sec)</i>	<i>Delay (msec)</i>
Standalone	Hardwired	2.0083	8.30
	GOOSE	2.0060	6.00
RT-HIL	Hardwired	2.0085	8.50
	GOOSE	2.0062	6.20

VIII. ACKNOWLEDGMENT

The generosity of Schweitzer Engineering Laboratories, Pullman, WA, USA; for their donation of protection relays, and Megger/Programma, Täby, Sweden; for their donation of different hardware and technical support is deeply acknowledged.

Technical support by Mr. Viktor Appelgren who works as a Laboratory Technician at SmarTS Lab (KTH) is highly appreciated.

IX. REFERENCES

- [1] J. L. Blackburn and T. J. Domin, Protective Relaying - Principles and Applications, Third Edition. CRC Press, 2006.
- [2] H. Gao, et al., "Performance testing of complete digital relays based on ATP-EMTP and IEC61850-9-2." Electric Utility Deregulation Restructuring and Power Technologies (DRPT), July 2011.
- [3] L. Vanfretti, et al., "SmarTS Lab A Laboratory for Developing Applications for WAMPAC Systems." San Diego, USA: IEEE Power and Energy Society, 2012 General Meeting, July 2012.
- [4] SEL, "Protection Relays by Schweitzer Engineering Laboratories," available on-line: <http://www.selinc.com/protection/>.
- [5] The MathWorks, "SimPowerSystems User's Guide," available on-line: <http://www.mathworks.com/help>.
- [6] Opal-RT, "eMEGAsim PowerGrid Real-Time Digital Hardware in the Loop Simulator," available on-line: <http://www.opal-rt.com/>.
- [7] SEL, "SEL AcSELeRator Quickset - Tool for modifying SEL Relays Settings," available on-line: <http://www.selinc.com/SEL-5030/>.
- [8] Megger, "Freja 300 - Relay Test System," available on-line: <http://tinyurl.com/Freja300>.
- [9] Megger, "Freja Win - Graphical Interface for Freja-300 Relay Test System," available on-line: <http://tinyurl.com/FrejaWin>.
- [10] SEL, "SEL AcSELeRator Analytic Assistant SEL-5601 Event Analysis Software," available on-line: <http://www.selinc.com/SEL-5601/>.
- [11] R.E. Mackiewicz, "Overview of IEC 61850 and benefits." Power Engineering Society General Meeting, 2006. IEEE, 2006.
- [12] IEC Standard, "Communication networks and systems in substations - Part 8-1: Specific Communication Service Mapping (SCSM) - Mappings to MMS (ISO 9506-1 and ISO 9506-2) and to ISO/IEC 8802-3."
- [13] J. Ekanayake, et al., Smart Grid-Technology and Applications. John Wiley and Sons Ltd, 2012.
- [14] SEL, "SEL AcSELeRator Architect SEL-5032 Software," available on-line: <http://www.selinc.com/sel-5032/>.
- [15] Megger, "GOOSER - IEC 61850 Test System," available on-line: <http://tinyurl.com/goosers>.
- [16] Megger, "PC-GOOSER - Software Interface for IEC 61850 Test System GOOSER," available on-line: <http://tinyurl.com/pe-gooser>.
- [17] Opal-RT, "RT-LAB Real Time Simulation Software," available on-line: <http://www.opal-rt.com/product/rt-lab-professional>.
- [18] "Current and Voltage Amplifiers by Megger," available on-line: <http://www.megger.com/cae/story/Index.php?ID=527>.