Modeling and Validation of an Overcurrent Relay Using LabVIEW and RTDS

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Abstract

Instability in a power system can be manifested during fault conditions in different ways. To ensure system stability, satisfactory performance of protection systems such as a protective relay is of great importance. Development of more reliable digital protection devices is possible with modeling, simulation and testing. This paper describes a detailed software model of an overcurrent relay developed in the Laboratory Virtual Instrumentation Engineering Workbench (LabVIEW) graphical programming language. The performance of the relay model is tested under different fault scenarios with both the relay model and power system model running in real time. The results obtained are validated against hardware in the loop (HIL) tests conducted with a Schweitzer Engineering Laboratories (SEL)-351S overcurrent relay and power system model in Real Time Digital Simulator (RTDS) to modify the software model to best represent the hardware functionality.

1. INTRODUCTION

The aim of protective relays is to detect abnormal conditions or defective equipment and initiate actions to disconnect faulted parts of the system and minimize the impact on other parts of the system [1]. Thus protecting the power system from detrimental power system conditions, such as high currents, over/under voltages, and over/under frequency are examples of these conditions. One of the research activities at Mississippi State University relates to developing an adaptive protective controller for Shipboard Power System (SPS) protection that can adapt different protective schemes upon requirement. The first step of this process is overcurrent, distance and differential relay model development using different platforms [2]. The research activity within this paper is concentrated towards overcurrent relay model development. The overcurrent relay models in the literature do not provide enough detail and functionality to permit advancements related to adaptive protection and also did not take particular care to meet the exact needs of real time simulation environment. This paper outlines efforts to meet these needs for real time simulation by addressing an overcurrent relay model in LabVIEW graphical programming language, which behaves in the same way as a commercial overcurrent relay does.

In the basic HIL test, if the hardware is a National Instrument controller then it is a National Instruments Controller-in-the-Loop (NICIL) test and if the hardware is an SEL relay then it is an SEL Relay-in-the-Loop (SELRIL) test. The developed model is subjected to NICIL testing with an eight-bus power system running in real time on the RTDS and overcurrent relay model running in real time on National Instruments PCI Extensions for Instrumentation (NI-PXI) Controller. The NI PXI-8196 is a high performance and low cost real time deployment platform for measurement and automation systems. The RTDS is an electromagnetic transient power system simulator that is widely used for real time and HIL simulations. It consists of hardware and software. The hardware part adopts parallel processors and high-speed digital signal processor cards to compute simulation results. The software part called RSCAD is used to model power system with excellent graphical user interface and detailed model library [2]. The developed LabVIEW relay model has excellent real time performance such as fast data acquisition, detecting minute disturbances in the system along with user-defined features such as transient negligence (Providing service continuity by not opening the system for transients) and locking. For validation of the LabVIEW overcurrent relay model, an SELRIL test was conducted between a Schweitzer Engineering Laboratories (SEL) 351S directional overcurrent relay and the eight-bus power system model on the RTDS. The SELRIL test results have been used to validate the NICIL test results to develop the best possible model for the overcurrent relay for desired power system applications.

2. POWER SYSTEM TEST CASE IN RSCAD

The test system used here is an 8-bus model in RSCAD (Fig. 1). The test system has two parallel bergeron type transmission lines of 100km length between the source and load.

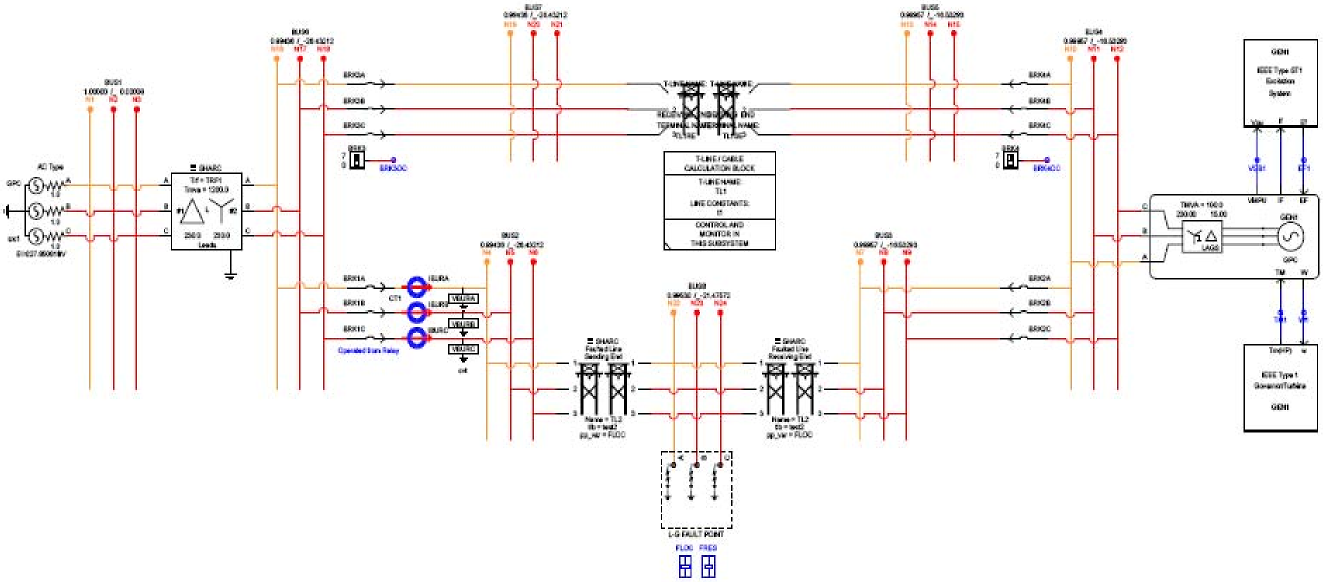

Figure 1. Eight bus Power system model

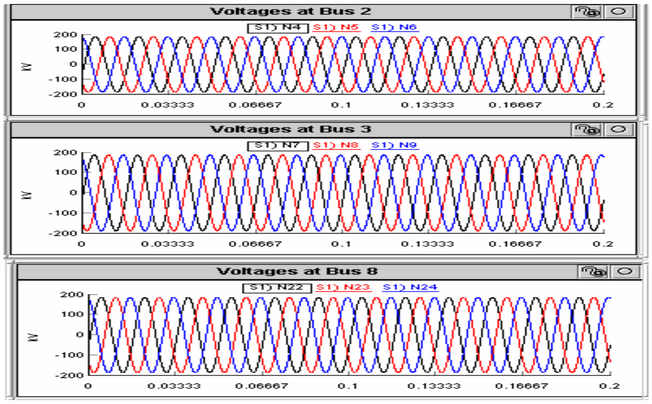

Figure 2. Three-phase voltages at bus-2, 3, 8

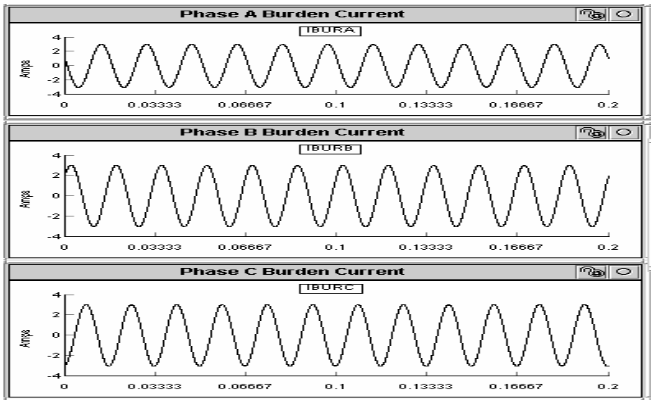

Figure 3. Three single-phase currents at bus-8

The system specifications are:

- 230kV AC source
- Fault inception logic
- Bergeron type transmission lines
- 1200MVA, 15kV synchronous motor
- C.T's, P.T's and circuit breakers

The transmission lines presented in the test system have been modeled using 'T-Line' module of RSCAD. The load is a synchronous machine, which acts in motoring mode. The transformer on the load side is connected to the synchronous machine internally. The fault inception logic is used to put faults into A, B, and C phases of the transmission line. The fault block is placed on bus-8, which is at 50% length of the transmission line. The breaker in transmission line near source (BRK1) is directly controlled by signal coming from LabVIEW relay model running in NI PXI in NICIL testing. In SELRIL testing, BRK1 was controller by SEL-351S relay. The CT and PT are modeled in detail to reflect more realistic characteristics. The test case is run in real time without any fault on the system. Fig. 2 depicts the system three-phase voltages at bus2, bus-3 and bus-8 in run time window of RTDS. Fig. 3 depicts the three single-phase system currents at bus-8 in run time window of RTDS.

3. LabVIEW OVERCURRENT RELAY MODEL

This section of the paper describes the methodology to develop the overcurrent relay model in LabVIEW. LabVIEW programming language is user friendly and is used to develop complex measurement and control applications very quickly and easily.

In most instances of a fault, the current level increases dramatically from its prefault value. The overcurrent relay will pick this abnormal situation and do the necessary analysis/action. Fig. 4 shows the general diagram of functionality of instantaneous overcurrent relay. The three phase currents at bus-8 in the power system are step-downed using a current transformer with a CT ratio of 300:1. These signals are collected by NI PXI 6251 device at 1000 samples per channel with a sampling rate of 600 samples/sec. These signals are analog in nature with high noise levels. An analog filter is used to filter the noisy analog input. It is a 5th order band pass Butterworth filter with band pass frequency ranging from 40 to 80Hz. Even though Butterworth filter has a slower roll-off at lower orders, it has more linear phase response in the pass band than the Chebyshev Type I/Type II and elliptic filters [3]. After the signals are filtered, they are converted to digital form using an Analog to Digital converter (ADC). An ADC is implemented by using Zero-order Hold device.

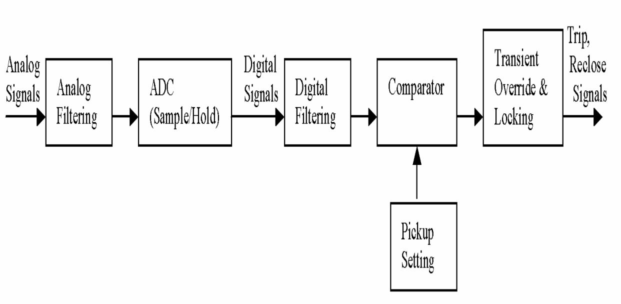

Figure 4. Design of overcurrent relay

The ZOH device chops the signal at the rate of 16 samples/cycle. An ideal sampler and ZOH are equivalent to an ADC unit. Since an ideal sampler is not a physical sampler, a ZOH is used in modeling, which works similarly to the sampler and the ZOH device, in physical sense, to convert an analog signal to a digital signal [4, 9]. The digital filter is a very important part in microprocessor based digital relays. In this LabVIEW relay model, a low pass digital FIR filter is used [5]. The analog filter performs well to remove noise levels from the analog input signals. So the noise levels remaining on the digital side are almost negligible. After digital filtering, the signals are passed through a comparator. The comparator compares the peak values of the signal against the threshold value. The threshold is set at a level so that it is above the maximum load current at peak load situations [6]. As shown in Fig. 3, the normal system currents at steady state are 6A peak-peak (p-p) at the CT secondary side. The threshold is set at 12Ap-p, well above the normal operating current range of 6Ap-p. When the fault current is above the threshold, the model issues a digital trip signal to open the system. After the user defined time period, it issues the reclose signal to close the system. Fig. 5 is the front panel of relay model. In this front panel, the operator can see the secondary current of CT, fault indicators, trip signals as well as reclose signals.

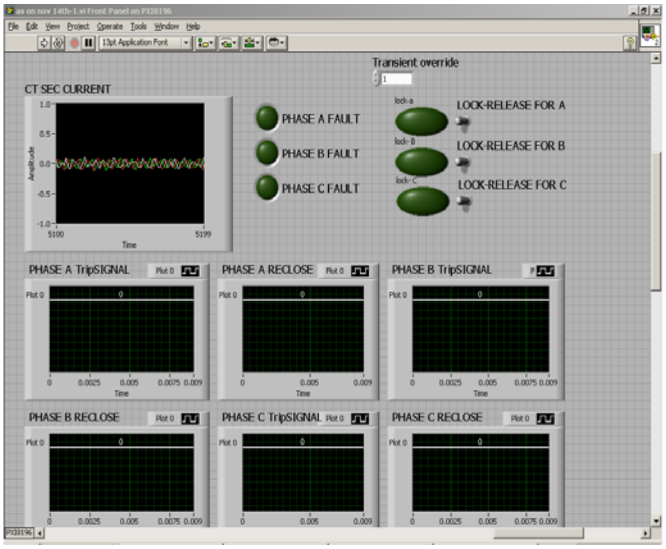

Figure 5. Front panel of LabVIEW Overcurrent Relay

Apart from the normal instantaneous operation of the overcurrent relay, the relay model consists of two more features. They are transient override and locking features. Transient override is a feature, where the operator can set the relay to ignore switching transients on the system that cause high peak currents in short periods of time. This feature is also useful in coordinating relay model with other relays by introducing a delay. If the operator selects number 1, the model ignores one fault cycle and does not give a trip or reclose signal. Similarly the relay functionality will be disabled for any user defined cycles.

Locking is another feature where the relay locks itself for severe faults on the system by only giving out trip signal but no reclose. For example, if a fault occurs on the system, the relay model performs its trip and recloses action. If the fault is still there, it again performs its trip and reclose action. If the fault is still there on the system up to 60 cycles (this number can be set at user defined value), then the model assumes it as a severe fault. The model locks out and gives only trip signal but no reclose signal. At this stage, the “Lock” button glows red on the model showing that the relay is locked. After the fault is cleared, the operator has to reclose the system by pressing the “Lock-Release” button. Then the system returns to its normal operation. Fig. 6 shows a single phase-A to ground fault on the system. For the phase-A fault, the fault indicator glows and the corresponding trip signal is generated.

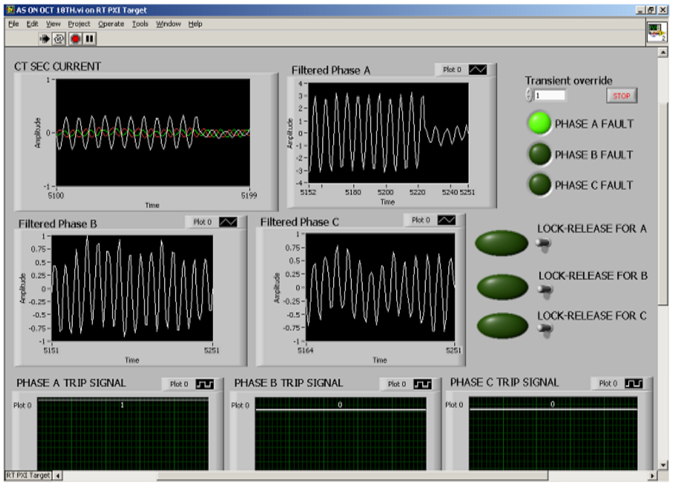

Figure 6. LabVIEW instantaneous/ time delay overcurrent relay model showing ‘Phase-A’ fault

The functionality of the instantaneous/time delay overcurrent relay model can be best explained through an algorithm. In the relay algorithm, currents are sampled and compared to threshold value. If there is a fault on the system, the relay counts the fault cycles. If the fault cycles are more than the transient over ride then it issues a trip signal. After 10 cycles, it recloses the system. The process continues again for sampling, comparing, counting and giving a trip and reclose. If there is a fault and once the count equals 60 cycles, the relay locks out by giving a trip signal only but not reclose. The system will be returned to normal operation once the operator pushes the lock release button.

4. NICIL TEST AND ITS RESULTS

In this NICIL test, a real time simulation environment is created by protecting the power system with the relay model. Fig. 7 shows the setup for NICIL testing. The eight-bus power system model (Fig. 1) is run on the RTDS in real time. The developed overcurrent relay model is downloaded to an NI-PXI. The current signals taken from the RTDS are fed into the relay model running on NI-PXI.

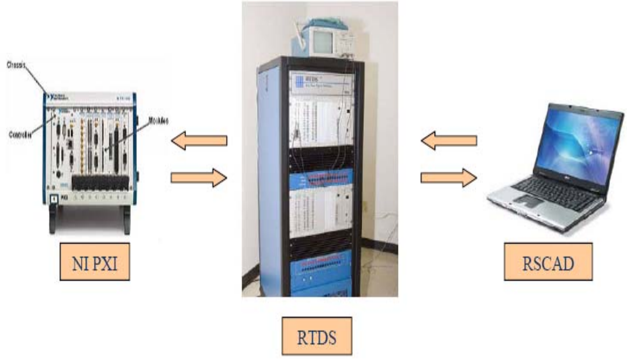

Figure 7. Setup for NICIL testing

The NI PXI-1042Q is an 8-slot chassis. The NI PXI-8196 controller is installed in the system controller slot of NI PXI-1042Q chassis. NI PXI-8196 is a high performance real time embedded controller [7]. The NI PXI-6251 is an M-series multifunctional data acquisition device. The NI PXI-6608 is a high precision counter/timer with digital I/O [7]. The current signals coming from RTDS are routed to NI PXI-6251 DAQ device through the SCB-68 (Shielded I/O connector block for DAQ devices with 68-pin connectors) interconnector. The relay model samples the current signal and provides appropriate trip and reclose signals. The trip and reclose signals are generated using NI PXI-6608. These digital signals generated by the relay model are fed into RTDS digital channels.

A NICIL test is conducted for a single phase to ground fault on phase C. Fig. 8 shows single-phase currents at bus-8 for a single-phase to ground fault on phase C. The fault location is at 50% of the transmission line with a fault resistance path of 0.1Ω. The fault occurs at 0.2 sec and the relay immediately recognizes the fault and gives a trip signal at 0.3 sec. This is an instantaneous operation as the fault detection/action period is about 0.1sec, 7 cycles on a 60Hz base. Commercial relays take around 4 to 5 cycles on a 60Hz base. The reclose signal is issued at 0.438 sec. The transient override is set as 2 in this test. It allows the relay to give a trip if the fault is for more than 2-cycles. If the fault is only for 1 or 2 cycles then the relay thinks it is a transient and does not give a trip signal. Eventually the transient dies and the system is restored to its normal operation. These trip and reclose signals are falling edge signals. Fig. 9 represents the digital trip and reclose signals given by relay model and as seen on RTDS -RUN window.

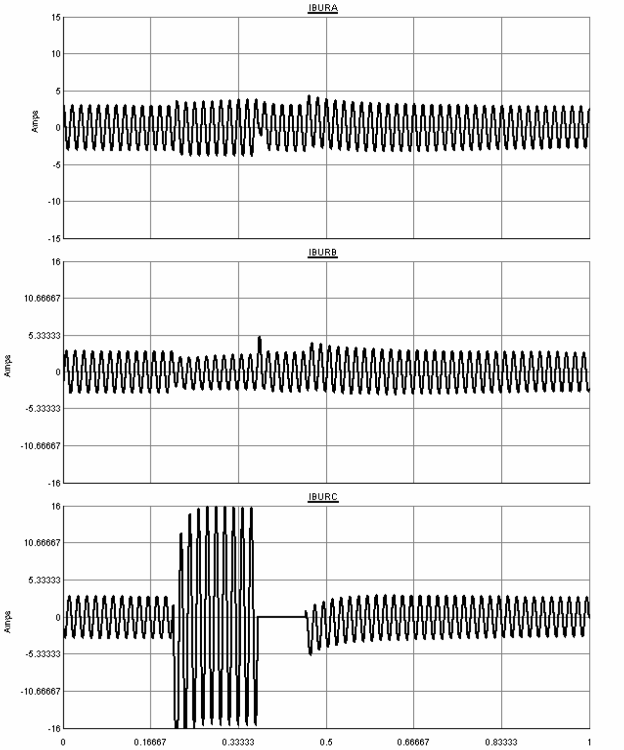

Figure 8. Single-phase currents at bus-8 for a single-phase to ground fault on ‘Phase C’ during closed loop testing.

As the fault occurs on the system, the system becomes unbalanced. This is the reason for the disturbances of phase A and phase B currents in Fig. 8 due to a single phase to ground fault on phase C. The relay model has excellent fault detection mechanism and the NICIL test results demonstrate its capacity.

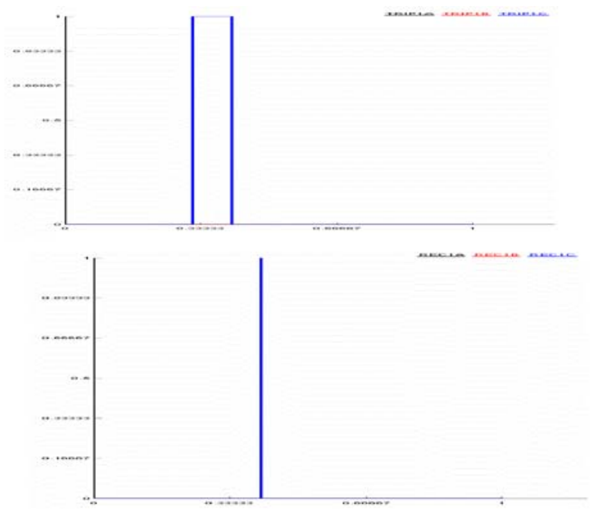

Figure 9. Trip and reclose signals given by relay model

5. MODEL VALIDATION

To validate the instantaneous/time delay overcurrent relay model, SELRIL test is conducted between the RTDS (power system) and SEL 351S relay. These SELRIL test results will help develop the best possible model for the overcurrent relay. The setup for SELRIL test is shown in Fig. 10.

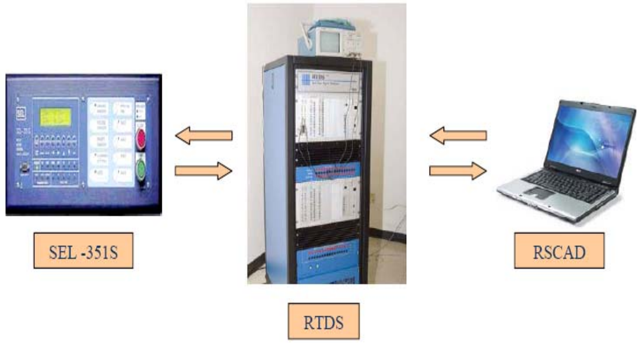

Figure 10. Setup for SELRIL test

Fig. 11 shows the results of SELRIL test with a single phase to ground fault on phase C. The power system used in this SELRIL test is the same as the power system used in NICIL testing.

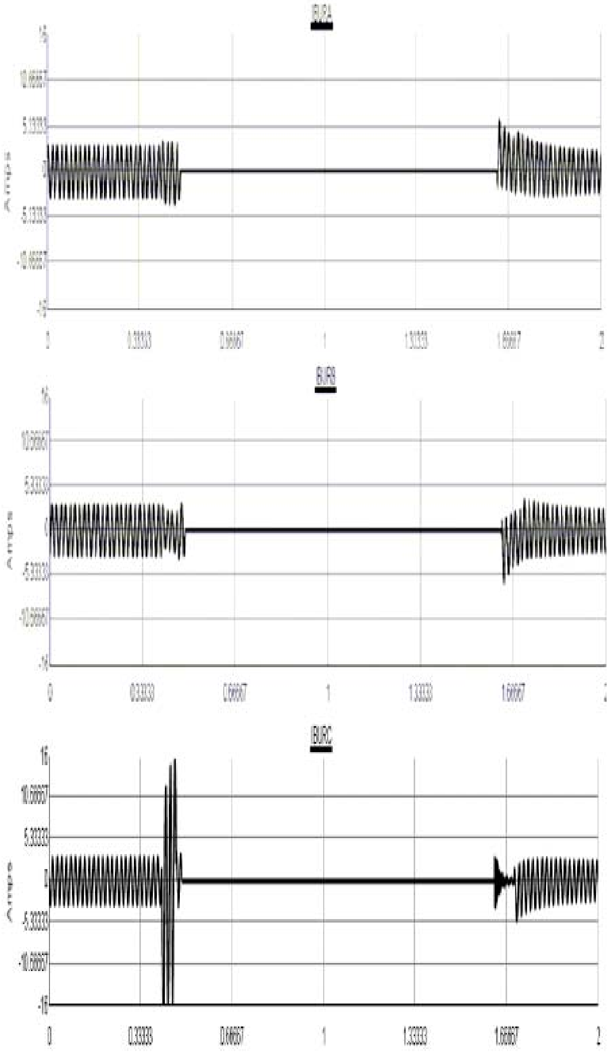

Figure 11. Single-phase currents at bus-8 for a single-phase to ground fault on phase C during HIL test.

The single phase to ground fault occurs at 0.4 sec of the simulation time. The trip signal is issued at 0.47 sec. The reclose signal comes at 1.62 sec (i.e.) after a time gap of 1.147 sec (69 cycles on a 60Hz base), the system again recloses and returns to its normal state of operation. Fig. 12 shows the corresponding trip and reclose signals given by SEL- 351S overcurrent relay for a single phase to ground fault on phase C.

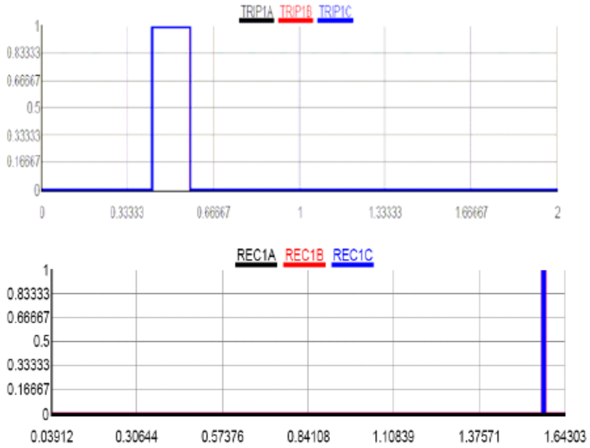

Figure 12. Trip and reclose signals for SELRIL test

Comparing the results of both the SELRIL and NICIL tests can provide model validation. The performance of relay is a good first order model for the SEL-351S relay. The fault detection periods of both the model and the SEL 351S are almost the same. Depending on the application, some systems need faster reclose and some need slower reclose. The relay model can be designed for faster reclosing or slower reclosing. In the NICIL test, the model was designed for faster reclose. The reclosing time for overcurrent relay model is 0.15 sec after the system is opened while it is 1.1 sec for the SEL-351S relay. The double phase to ground fault (L-L-G) is also conducted but those results are not presented here due to space constraint. The LabVIEW instantaneous/time delay overcurrent relay is very flexible and can be designed according to the requirements of the user.

6. SUMMARY

In this work, a model for an overcurrent relay has been developed and implemented using NI-PXI. The SELRIL and NICIL tests have been conducted to validate and improve the model. The results have proven that the overcurrent relay model can provide a first order approximation for a commercial overcurrent relay. The developed model can be useful for virtual or HIL testing, where cost and time implications come into effect.

7. ACKNOWLEDGEMENTS

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Biography

Sunil Palla is pursuing his master's degree in Electrical and Computer Engineering at Mississippi State University (MSU). He received B.Tech. from Chaitanya Engineering College affiliated to JNT University, A.P, India in 2006. He is an active member of IEEE and the Power and Energy Society. He is the recipient of Research Assistant of the year award for 2007-2008 at MSU and a nominee for the same for 2006-2007. His fields of interest include power system modeling and simulation, Protection and power system operation and control.

Anurag K. Srivastava received his Ph.D. degree from Illinois Institute of Technology (IIT), Chicago, in 2005, M. Tech. from Institute of Technology, India in 1999 and B. Tech. in Electrical Engineering from Harcourt Butler Technological Institute, India in 1997. He is working as Assistant Research Professor at Mississippi State University since September 2005. Before that, he worked as research assistant and teaching assistant at IIT, Chicago, USA and as Senior Research Associate at Electrical Engineering Department at the Indian Institute of Technology, Kanpur, India as well as Research Fellow at Asian Institute of Technology, Bangkok, Thailand. His research interest includes real time simulation, power system modeling, power system security, power system deregulation and artificial intelligent application in power system. Dr. Srivastava is member of IEEE, IET, Power Engineering Society, Sigma Xi and Eta Kappa Nu. He is recipient of several awards and serves as reviewer for IEEE Transactions, international journals and conferences.

Noel N. Schulz received her B.S.E.E. and M.S.E.E. degrees from Virginia Polytechnic Institute and State University in 1988 and 1990, respectively. She received her Ph.D. in EE from the University of Minnesota in 1995. She has been an Associate Professor in the ECE department at Mississippi State University since July 2001.She currently holds the TVA endowed professorship in power systems engineering. Her research interests are in computer applications in power system operations including artificial intelligence techniques. She is a NSF CAREER award recipient. She has been active in the IEEE Power & Energy Society and served as Secretary for 2004-2007 and Treasurer for 2008-2009. She was the 2002 recipient of the IEEE/PES Walter Fee Outstanding Young Power Engineer Award. Dr. Schulz is a member of Eta Kappa Nu and Tau Beta Pi.