RTDS Simulation and Testing of a Remedial Action Scheme at Southern California Edison

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Abstract – The goal of this effort is to determine how a real-time digital simulator (RTDS) can be used to simulate the behavior of a remedial action scheme (RAS) in a controlled laboratory environment at the Southern California Edison (SCE) Power Systems Laboratory. The RAS functions with two redundant pairs: System A and System B. The lab test setup includes all actual RAS System A relays and all simulated System B relays. The RTDS scripting capability automates more than 9,000 tests that span various contingencies, arming levels, load flows, and A/B system availability. The simulator demonstrated the ability to re-create an existing RAS in the laboratory environment, which will be a valuable tool in preparing for future RAS applications.

1 Introduction

A remedial action scheme (RAS) is a type of special protection system (SPS) designed to enact a mitigating action during a pre-determined set of circumstances. Southern California Edison (SCE) presently has 17 active RAS on its transmission system and plans further deployments in its rural service territory to support the growing number of renewable generation projects (wind and solar) in those areas. RAS have previously been independently developed, operated and maintained, but their proliferation may cause them to overlap and possibly interfere with each other.

This increased presence of RAS on the transmission system is a primary driver for the work being performed in the SCE's Power Systems Lab in Westminster, California. The goal is to use the lab's multi-rack real-time digital simulators to replicate and test a complex RAS system in a controlled laboratory environment. The laboratory testing will simulate all external RAS inputs such as digital status, analog values, control inputs, and IEC 61850 GOOSE communication messages.

The use of real-time digital simulation technology will allow engineers to accomplish three key objectives:

- Add special protection schemes to system models to account for their behavior in bulk model development and simulation
- Test RAS settings against functional specs (FAT testing)
- Provide a testbed for developing future RAS specifications, an important consideration for the addition of new RAS, particularly when interacting with existing RAS systems

2 Background

The North American Electric Reliability Corporation (NERC) defines an SPS and RAS as:

> "An automatic protection system designed to detect abnormal or predetermined system conditions, and take corrective actions other than and/or in addition to the isolation of faulted components to maintain system reliability. Such action may include changes in demand, generation (MW and MVAr), or system configuration to maintain system stability, acceptable voltage, or power flows."

In this document, the term SPS and RAS will be used interchangeably.

The Western Electricity Coordinating Council (WECC) and its members have used RAS extensively for many years to ensure system reliability and prevent violations of NERC/WECC Reliability Criteria for any event classified as Category B (single contingency) or above [1]. Presently, the WECC has more SPS or RAS than any other Reliability Region and this number is growing due to the unprecedented increase in renewable resource generation by wind and solar power plants. These new generating plants are often built far from load centers and in areas with limited transmission access and capacity. This constraint coupled with more stringent generation in-service schedules and renewable portfolio policy requirements, have led to an even greater dependence on RAS to mitigate transmission thermal overload, voltage and transient instability conditions. Using RAS is a more cost effective approach to the growing number of new interconnection requests than upgrading or building new transmission infrastructures.

The steady increase in customer load growth and the number of interconnection requests from independent power producers in its service territory is causing congestion issues on the transmission system. To accommodate these new interconnections, SCE must rely extensively on remedial action schemes to alleviate potential equipment overload conditions caused by faults and other system events [2]. In most circumstances, a RAS involves a direct tripping or run-back of generation to maintain power system reliability.

This high volume of RAS activity on the SCE bulk power transmission network has led to a greater sense of urgency to investigate new methods for evaluating RAS and the interactions among multiple stand-alone RAS systems. The SCE Power System Lab has 20 Real-Time Digital Simulators (RTDS®) racks making it well-suited for this type of study.

The study first required the Power Systems Lab's dedicated team of engineers to build a large-scale model of the SCE bulk power system in RTDS. The model includes all major 500 kV, 230 kV and some 115 kV transmission system components as well as all neighboring utility interties with their equivalent sources. This bulk system model includes complete generator dynamic models, exciters, governors, power system stabilizers, transmission line series capacitors, transformers, shunt capacitors, shunt reactors and loads. Another important feature of this model is the stand-alone RAS presently in-service. This paper details the study team's analysis of the real-time digital simulator's capabilities, and its ability to perform RAS evaluations with virtual model components and demonstrate RAS performance using accurate models of actual devices.

2.1 Special Protection Schemes

A typical RAS designed to mitigate a thermal overload conditions has these common stages: (1) monitoring and detection, (2) logic processing and decision, and (3) taking action or mitigation [2,3].

Monitoring and detection involve measuring line current values, and determining circuit breaker (CB) open or close status. Logic processing and decision involve processing of line undercurrent condition that when combined with CB open status the central decision logic declares a line outage condition. Based on specific studies, each RAS design establishes appropriate N-1, N-2 line outage conditions, RAS arming levels and generation run-back/trip conditions. RAS arming can be either manual by operators or automatic via Energy Management System (EMS). Once, the decision is made to act or mitigate, the central logic processor will send to remote generators appropriate trip or run-back commands via dedicated high speed communication network.

2.2 Real Time Power System Simulation

Real-time digital simulators are widely used in the electric power industry by utilities, equipment manufacturers and research organizations. Electric power utilities use digital simulators as a tool to study their network and different strategies for their protection and control systems. They also provide equipment manufacturers with the most comprehensive means available for testing their products during design and manufacturing. Research organizations commonly use real-time simulation to explore new approaches to power system design, control and protection.

In a real-time simulation devices connected to the model operate as if connected to the actual power system. Real-time digital simulators operating in a closed-loop fashion allow actual devices to fully interact with the power system. The outcome of the simulation is directly coupled to the performance of the devices under test. Real-time digital simulators such as the RTDS system being used at the SCE lab have built-in scripting functionality that allows thousands of cases to be automatically run and the results to be documented automatically under repeatable conditions. Combining scripting with closed-loop testing in this manner provides engineers with a powerful and comprehensive method of testing.

The interface between the simulator and the actual hardware is an important aspect of any simulation system. Real-time simulators provide scalable I/O interfaces such as analog and digital input and output for connecting to amplifiers or directly to the actual devices. Low latency input and output interfaces allow the highest quality testing with realistic results. Precise input and output timing is available to allow sub-timestep resolution of digital signals. Real-time simulators synchronized with satellite GPS clocks allow the frequency and phase of signals to be tightly controlled, which is increasingly important for applications such as phasor measurement unit (PMU) deployments. Real-time digital simulators with communication protocol interfaces such as IEC 61850, IEC 60870-5-104 and DNP provide a direct interface to the actual devices under test and allow these devices to be tested with the same interfaces used in the final application.

Real-time simulations can include a combination of actual devices and simulation models of the actual devices. Using simulation models of the actual devices enables large scale closed-loop simulations to be performed without requiring a great number of actual devices to be interfaced.

2.3 Simulation of RAS on RTDS

Real-time simulation is an integral part of testing advanced protection applications, including remedial action schemes [4-6]. Closed-loop real-time simulation allows engineers to test RAS interactions and settings. Both white box and black box testing methodology can be used. Under white box testing, details about the system-under-test are known, and tests scenarios are carefully designed to exercise the system under test and directly compare them with the expected results. In black box testing, details about the system-under-test are not used to design the tests. The system is tested as a whole under a variety of conditions, verifying general operation with no unexpected interactions or failures. Real-time digital simulator scripting provides the necessary automation to perform both types of testing in a repeatable test environment capable of executing and documenting thousands of test runs.

3 RAS Model Development

The goal of laboratory testing is to replicate a full RAS system in a controlled environment. The RAS functions with two redundant pairs as illustrated in the lab test setup diagram presented in Figure 1. System A includes actual General Electric N60 relays and System B is implemented entirely with virtual relays on the RTDS Simulator. The two RAS sides run in parallel and receive the same current transformer and voltage transformer (CT/VT) signals and energy management system (EMS) arming commands as they would in the field environment. They each receive commands from and send output decisions to the same interface display. Testing these RAS systems simultaneously allows for a comparison between the actual and virtual sides, while validating the behavior of the overall RAS concept.

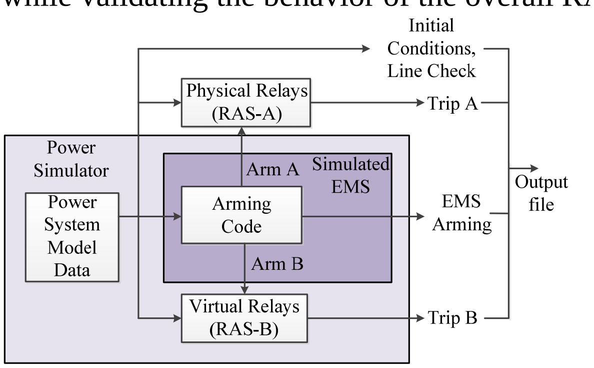

Figure 1: Major Elements of the RAS Model

3.1 Power System Model

The core attribute of the power system simulator is its ability to model the system area around the RAS in real time. A simplified diagram of the relevant system model for this RAS is presented in Figure 2. The substation load is lumped together, but split where there are multiple mitigation relays or the mitigation relays do not control all load. Small generators are aggregated into customer load, but dynamic models of larger generators are included. Substation ‘F’ has strong connections to the rest of the bulk system in this area, and is therefore used as the slack bus. Transmission lines are modeled as traveling wave lines or PI sections.

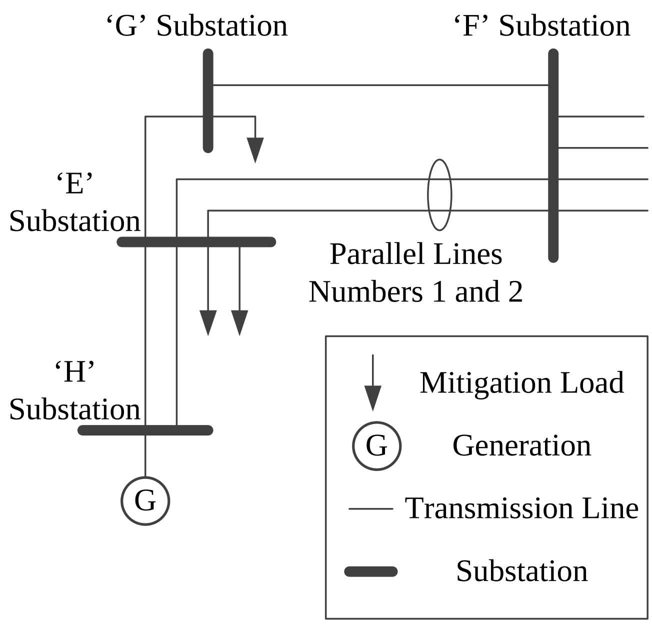

Figure 2: Diagram of the RAS Local Power System

The selected RAS is an N-2 local capacity requirement (LCR) RAS. A portion of the bulk system is solely fed by three transmission lines: parallel lines E-F Numbers 1 and 2, and a single line G-F. Loss of any two lines would require the third to carry all remaining power. The objective for the RAS is to trip customer load if this N-2 contingency causes overloading of the third line. There are three blocks of load that can be mitigated independently: two at ‘E’ and one at ‘G’. The three load blocks are represented as arrows in Figure 2. As the parallel transmission lines E-F Numbers 1 and 2 share a right-of-way and have identical capacity, the three lines create two types of N-2 contingency: (1) both parallel lines out and (2) either one of the parallel lines and the single line G-F. Thus there are six different arming points as each load can be mitigated differently depending upon which line is remaining. The three substations that participate in the RAS are ‘E’, ‘F’, and ‘G’.

3.2 Actual Hardware

3.2.1 Relay Hardware

System A is replicated using relays with the same firmware and modules as the field relays. The same settings files are used, but these include modifying:

- Low voltage input modules
- Reduction in contact input/output voltage from 120 to 24 V

- Fixed Generic Object Oriented Substation Events (GOOSE) signals to System B replaced with standard GOOSE
- EMS arming replaced by GOOSE arming message

Low voltage input modules can accept signals directly from the simulator. This avoids having to use amplifiers, which reduces lab safety risks and equipment requirements. The contact input/output voltage is similarly reduced to improve safety.

Fixed GOOSE is a proprietary protocol for the relays and used for communications between RAS Systems A and B. The systems are functionally independent, but can generate certain alarms when the two disagree. As System B is implemented with software, the proprietary protocol is not available and replaced with an interoperable one.

The SCE Power Systems Lab does not include a remote terminal unit or connection to the EMS. The purpose of these systems is to automatically arm the RAS based on system conditions. Instead GOOSE IEC61850, which is available in the lab, is used to send arming points to the relays from a simulated EMS. Manual arming would normally be done at the relay, but this was not practical for the automated tests; therefore, the relays are manually armed in the simulator interface and this output is also transmitted with GOOSE.

These modifications are considered acceptable given the scope of the test.

3.2.2 Simulator Hardware

Several hardware I/O cards interface the actual system with virtual simulation. The relays monitor a total of six line terminals, and require three-phase current and voltage at each. The simulator also outputs digital signals for detection of the line open circuit breaker status, and accepts the relay trip signals as input. The digital inputs and outputs are wetted with a 24 V power supply.

The simulator also publishes and subscribes to GOOSE messages, which are used for (1) communication within a substation for the B relays, (2) arming of Systems A and B, and (3) status alarms for agreement between the A and B sides.

3.2.3 Communications

Three types of communication are used in the RAS system: copper wire, Ethernet, and fiber optic. A diagram of the interaction of these communication types is presented in Figure 3. Copper wires are used to interface actual relays to the simulated power system as described in 3.2.2. Ethernet is used for IEC 61850 GOOSE communication between relays in a substation. There is one switch defined per substation and that switch is a hub for all its actual/virtual relays. Fiber optic cables connect the substations together, which is implemented directly for the actual relays. The virtual relays use a signal in the simulator.

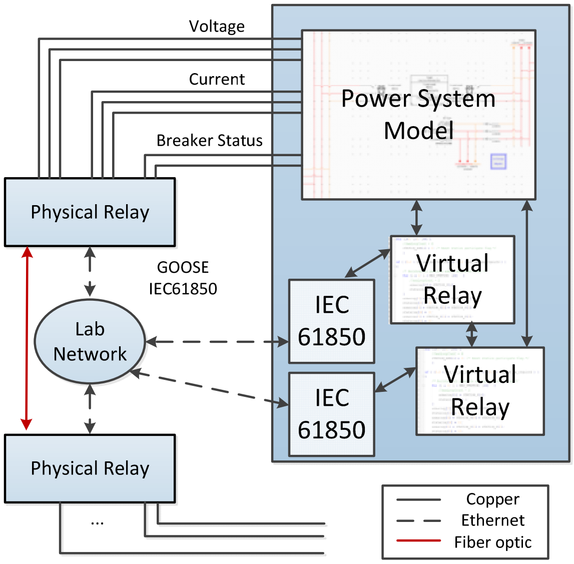

Figure 3: Lab test setup

3.3 Virtual Relay Model

The virtual relays are designed to function as a parallel, redundant system with the hardware, in the same way the two RAS systems operate in the field. The relay functionality is built by modeling the internal logic and active elements from the actual relay settings. The simulator sends each model relay the same CT/VT and status inputs as the actual relays, without external hardware. The model relays send GOOSE messages to their substation switch and subscribe to messages from the other local relay. The trip outputs of the virtual relay are mirrored with the trip signals received from the actual relay—a trip from either relay will open the mitigation breaker.

The virtual relay must model both the behavior and the response time of the actual relay. As the power system simulator has a time step of 60 µs and the relay a time step of 2 ms (480 Hz) – all virtual relay inputs are down-sampled to 480 Hz. The virtual mitigation relay also adds a 4 ms delay at the trip contact output for the A-form delay [7].

Systems A and B must also have similar communication delays. Both systems use GOOSE IEC61850 for intra-substation communication; therefore, no intentional modification is required. However, the delay for inter-substation communication is not captured in the virtual model. The relay fiber optic delay is estimated empirically by using the simulator to send a status change simultaneously to two actual relays connected by direct fiber. The time difference from when a relay detects the change locally to when it receives the signal from the fiber is approximately 4 ms and this value is added to all direct fiber virtual communications.

3.4 Arming Logic

The test RAS can be armed either manually or through an automatic function. Manual arming allows the user to specify any combination of the six arming points. Automatic arming senses system conditions and runs a program to determine the best arming combination. This program runs in the EMS, which was not available for the test. Instead, an arming stub (module that replaces a function not otherwise available for test [3]) is created in the power simulator by replicating selections of code from the EMS program in a user-defined component.

3.5 Simulator Interface

The simulator interface is designed to output all information necessary to determine success or failure of a test. This includes measurements of the initial conditions, verification that the test was properly executed, and status/timing for both Systems A and B. The interface must also be configurable to any test plan case requiring user inputs for:

- Real and reactive power demand
- Generator breaker control
- Breaker control for each terminal of lines E-F Numbers 1 and 2, and G-F
- Mitigation load breaker control
- Manual arming inputs
- Auto/solid switches for Systems A and B

4 Testing Methodology

The test plan defines a set of test cases to assess how effectively the model:

- Compares actual and virtual RAS relays
- Tests RAS settings against functional specifications
- Creates a testbed for developing future RAS specifications

4.1 Compare Actual and Virtual Relays

Both Systems A and B must exhibit the same monitoring and tripping performance measured according to two metrics: behavior and timing.

4.1.1 Behavior

The RAS behavior is tested with a series of black box tests for N-1 and N-2 contingencies. For completeness, cases where an N-2 contingency *should* cause a trip are simulated along with N-1 and different N-2 contingencies that *should not* result in a trip. The tests are armed manually and span all $2^6 = 64$ arming combinations, though not all are actually meaningful. Controlling each line circuit breaker terminal independently generates nine types of N-1 and 27 types of N-2 contingencies. In total this creates (9+27)*64 = 2,304 arming/contingency combinations. The criteria for a *pass* is that each system (A and B) trips according to the arming.

To verify the systems are fully redundant, System B is made solid and the same tests are run with only System A. The test is reversed and then only System B is functioning. As these tests are executed a total of three times (A and B, only A, only B), the behavior is tested across 6,912 tests.

4.1.2 Timing

The execution time of each RAS system is measured by initiating a set of timers at the contingency. When the mitigation relay (either A or B) sends a trip signal, the associated timer stops and records the total time. Figure 4 shows the predicted delays for the RAS relays, where the processing occurs at E MO-1 (‘E’ Substation Monitor 1). The fastest RAS execution path is an outage detected at E MO-1, processed locally and sent to the local mitigation relay E TR-1 (‘E’ Substation Trip 1). When the monitoring and mitigation functions occur at a substation that is remote from the processing relay, the additional communication delays will add to the overall RAS execution time. The longest RAS execution time would occur when the outage is detected at F MO-2 and results in mitigation of the G TR-1 relay. Only one side of each line is opened for an N-2 contingency to ensure different execution paths are captured.

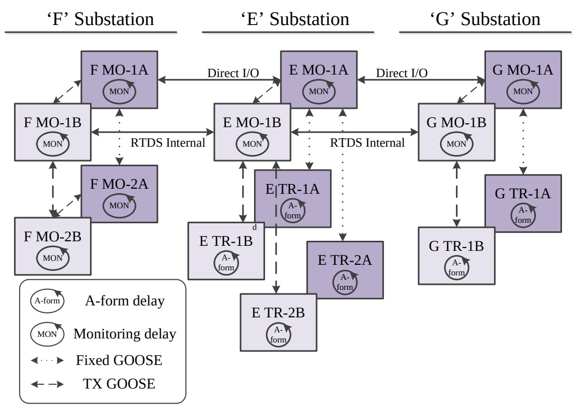

Figure 4: Major Delays in RAS Processing and Communication

Even in a controlled lab environment the RAS execution time varies because the delay from signal receipt to processing varies from 2.0 to 0.0 milliseconds for an intelligent electronic device (IED) relay. Every event detection and relay communication adds this length of additional uncertainty to the overall execution time. To get an accurate sense of the execution delay, each test was repeated 50 times without intentional communication delay. As expected, this generated a cluster of times that overlapped between Systems A and B. An example of these times is presented in Figure 5.

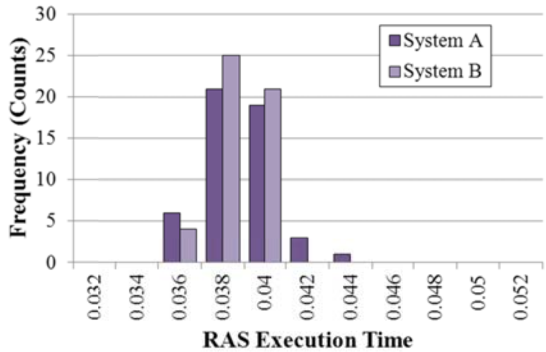

Figure 5: Sample Histogram of RAS Execution Time for E-F No. 1 and 2 N-2 Contingency

4.2 Functional Testing of RAS

The RAS functional test is defined to determine whether the RAS operates according to its specification. This test is part of an acceptance test; it could be used in the future to verify that the proposed system behaves in a wide variety of conditions.

For these tests the EMS arming function is set to arm the RAS automatically. The system's condition is varied by changing the load demand and generator status. The maximum load is set according to the WECC 2015 heavy summer base case, which would represent the peak value for this area. The loads span from this maximum to a minimum at a third of this value in a total of six steps. Generators at 'H' Substation are connected/disconnected to create nine generation scenarios. For both generators and loads there are a total of 54 load flow scenarios for the RAS.

Each of the load flow scenarios is tested by executing a series of six N-2 line outages, which are all unique combinations for four lines: E-F Numbers 1 and 2, G-F, and G-E. Although transmission line G-E is included, it should not generate any RAS trips. The criteria for the pass/fail portion of the functional test are whether the test result (1) matches the RAS specification and (2) responds according to the arming.

4.3 RAS Testbed

In functional testing the RAS specification is already established so testing entails comparing the actual outcome with the desired result. However, simulation of the RAS directly in a bulk system model (RAS testbed) allows the RTDS to a check for the specification itself. Because the RAS tests are performed in a full closed-loop simulation, designated model changes occur in real time. Thus a RAS designed to prevent line overload can monitor all lines of interest after the event and check that they all remain below the required rating.

This round of testing repeats the 54 load flow scenarios from Section 4.2 and verifies that the three monitored lines are below their emergency rating. When an overload is detected different loads are armed to drop and mitigate the event. A load combination that avoids overload while minimizing the dropped customer load is considered the ideal action. The load drop scenarios are automated to quickly test all conditions, but can also be manually executed. This type of freeform exploration provides education and insight into system behavior. Figure 6 illustrates this testbed along with the user-controlled elements.

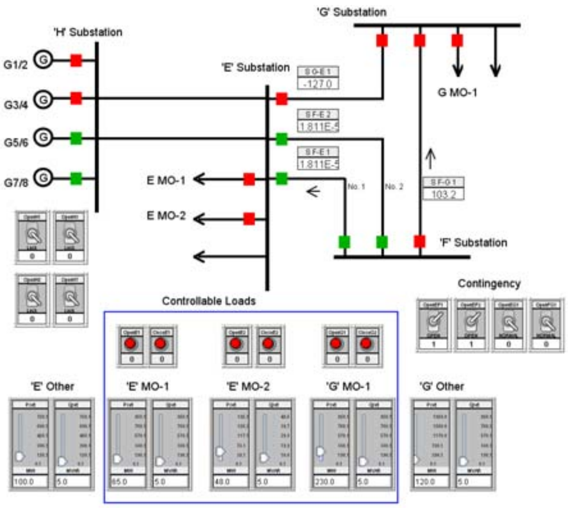

Figure 6: Testbed Simulator Interface

5 Results

5.1 Lab Testing of RTDS RAS Model

5.1.1 Comparison of actual and virtual RAS

Behavior tests resulted in 2,376 cases with no trips and 2,592 trips for each arming point. As multiple trips can occur within a test, the number of mitigation trips recorded exceeds the number of tests. For all cases, the same outcome resulted independent of whether A and B, only A, or only B RAS systems were on automatic. This indicates that the overall system behavior matches and either the actual or virtual system can be used for judging overall RAS execution.

The next test involved determining whether the execution time is consistent between the two RAS systems. As only one side of each line is opened, there are four different combinations to open lines E-F Numbers 1 and 2, which are numbered Tests 1a-1d. Similarly, Tests 2a-2d refer to all ways to open E-F Number 1 and G-F, and Tests 3a-3d refer to all ways to open E-F Number 2 and G-F. Each of these tests is repeated 50 times and the average execution time for Tests 1a-2d is presented in Table 1. The results for Tests 3a-3d are identical to Tests 2a-2d and therefore not repeated. Some N-2 detection cases resulted in no noticeable detection error between Systems A and B, as was seen with Test 1a. Other cases showed System B was consistently 1 to 2 milliseconds slower (2a) or 1.5 milliseconds faster (2d). Overall, the average error is still well within the uncertainty of any given test and therefore determined to be sufficiently accurate on timing as well as behavior.

Table 1: Difference in Average Execution Time by Mitigation Load and Event

Test #	N-2 Outage	ΔT_{B-A} E1(ms)	ΔT_{B-A} E2(ms)	ΔT_{B-A} G1(ms)
1a	E-F No 1 at E and E-F No 2 at E	+0.0	-0.0	+0.5
1b	E-F No 1 at E and E-F No 2 at F	+1.5	+1.5	+0.5
1c	E-F No 1 at F and E-F No 2 at E	+1.5	+1.5	+0.5
1d	E-F No 1 at F and E-F No 2 at F	+0.5	+0.5	+0.0
2a	E-F No 1 at E and G-F No 1 at G	+1.0	+1.0	-2.0
2b	E-F No 1 at E and G-F No 1 at F	+0.0	+0.0	+0.0
2c	E-F No 1 at F and G-F No 1 at G	+1.0	+1.0	+1.0
2d	E-F No 1 at F and G-F No 1 at F	-1.5	-1.5	-1.5

5.1.2 Functional Testing of RAS

Of the 54 load flow combinations 42 do not arm any points and should never cause load to trip. Of the 12 scenarios that arm the RAS only 5 arming combinations occur. For each load flow combination the required arming is calculated by inputting simulated line flows into the RAS arming equations. The lowest cost load mitigation that exceeds this minimum arming is then selected manually. This result is compared with the automated results from the user-code arming function. The only load flow that did not agree was one that landed in the deadband under the arming threshold. Because the script had approached this value from above the threshold, it registered in the RAS auto-arm function as *armed*. Simple application of the equations assumes this region is *not armed*. Thus further analysis showed that the EMS stub had generated the correct result for all cases.

The test exhibited 322 pass results and 2 failures. Repeating each failed test numerous times showed that most executions generated a pass, but occasionally over-tripping of load caused a failure. The failures were due to the EMS arming code stub running once every 4 seconds. After two lines are cleared and a load is tripped, the remaining line experiences a severe power flow transient. If the EMS re-run happens to occur before this transient falls below the arming threshold, it arms a different load and that trip is executed as well. An example of this behavior is captured in Figure 7 where the two E-F lines open at 0.6 second. The armed Point 3 is tripped, but the EMS re-runs at 0.7 second, sees a total flow above 100% of the line rating, then arms Points 1 and 2, which are subsequently tripped to result in a steady-state flow of less than 30% of the line rating. This failure mode shows a limit on the simulator EMS arming function block—it is a test stub that takes the place of a complex series of measurement and communication. The result is still important as it highlights the importance of repetitive testing and the value of including a transient model of the power system.

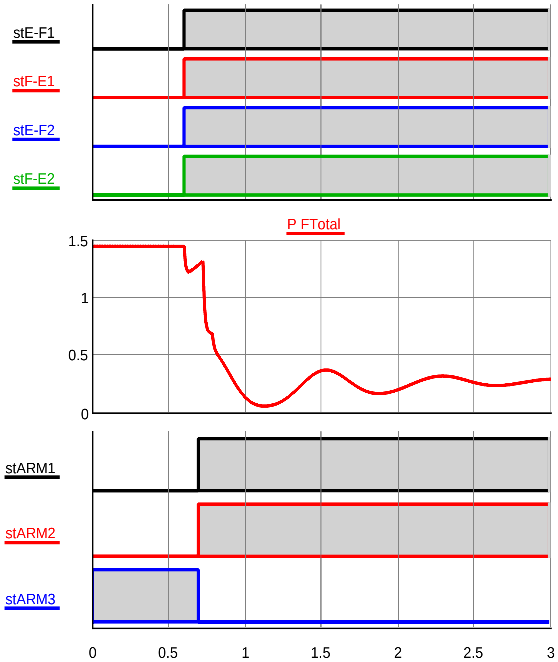

Figure 7: Contingency Transient (Top to Bottom): E-F Line Breakers, Total Power Flow on the Three Lines Normalized to the F-G Rating, and the Arming During Transient

To test that the virtual EMS behavior is the only factor causing failure, the arming points are locked immediately before executing the test. The test is repeated for all 324 cases and the new set of tests generated all pass results.

5.2 RAS Testbed

The RAS testbed successfully allowed the user freedom to explore the area behavior under any feasible circumstances. The structured testing uses different criteria than the RAS specification, so the two results were close, but not identical. In one case the testbed result recommended slightly less armed load, and in another the testbed recommended slightly more.

6 Conclusion

The real-time power simulator clearly has the ability to model, test and explore RAS systems. Depending on the application the RAS can either be modeled by (1) hardware-in-the-loop or (2) functionally similar software models. The exact hardware is necessary to test relay settings and communication, but a software version may be sufficient for systems studies.

The simulator is tested for three different simulation functions: power system, EMS arming, and virtual RAS relay. The power system function successfully creates a sophisticated and flexible environment for the RAS. In total, the simulator scripting function recorded over 9,000 contingency events at various generation, load, arming, and status conditions. The virtual relay function is limited because some communications available to an actual relay have no clear analog on the simulator. After replacing these with interoperable protocols, the virtual relays perform identically to the actual ones with an average difference in execution time of less 1-2 milliseconds. The EMS arming function is simplistically created with a program in the simulator. The arming maintains the correct macro-scale behavior, but does not include alarms, data processing and other detailed processes. The simplification of the EMS appeared to cause over-tripping failures in <1% of N-2 cases.

The particular RAS explored herein is an existing, commissioned RAS, but the simulator could facilitate development of new RAS in the future. In particular, the flexibility to model schemes actually or virtually could test a system area with a new RAS added to an existing one. The new RAS requires extensive hardware testing itself while also checking for conflicts with the existing scheme, which could be included as a virtual model. No amount of laboratory testing can replace conventional site acceptance tests, but RAS commissioning requires a huge effort with crews coordinated across multiple substations and the number of tests executed is necessarily limited. Real-time RAS simulation is a promising way to augment these tests by running thousands of cases, and by catching issues before installation and increasing confidence in the final installation.

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