Using an Iterative Approach to Mimic Real-Time Closed-Loop Simulation for Protection Testing

C. Pritchard, T. Hensler

Abstract— **Real-time closed-loop simulation to do testing of power system protection in the laboratory is well established. But for commissioning or site acceptance testing in the field the effort for real-time simulation is mostly considered too high and the test setup is quite impractical.**

For testing advanced relay functions and to be able to see the detailed reaction of the devices for more complex protection logic a simulation is required to react on relay behavior (mostly commands to trip or close a circuit breaker) in a real-time closed-loop fashion. Since protection relays behave deterministically, if the same test scenario is applied again and if the device is properly reset in-between, an iterative approach can be used instead of a real-time closed-loop simulation. A test software running on a conventional PC where the network simulation is calculated offline (non-real-time) can repeat a test scenario automatically and incorporate the effect of relay reactions from the previous test run iteratively. If this is done again and again until no more new reactions from the protection device are recognized, the final test run mimics the behavior of a real-time closed-loop execution perfectly.

Using this iterative approach event testing of distributed protection systems or end-to-end testing of line protection is possible with multiple time-synchronized test sets, which is not practical with a real-time closed-loop simulator.

Keywords: **Real-time closed-loop simulation, network simulation, protection testing, time-synchronization, distributed protection testing, end-to-end testing.**

I. Introduction

SINCE the advent of the digital computer numerical power system simulation has been an indispensable tool for the power system engineer. As computer simulation in other engineering disciplines a lot of new possibilities for investigating the behavior of the real primary power system are possible, without the need to execute tests with high voltages and currents. The most common applications for the simulation of a primary power system network include studies for load flow, short-circuit and dynamic simulation of power system events. The most realistic simulation of the dynamic behavior of an electrical power system is possible with a transient simulation in the time domain with algorithms like the Electromagnetic Transient Program (EMTP).

For testing of protection and control devices, which are connected to the primary power system on the secondary side of voltage and current transformers (CTs and VTs), transient voltage and current signals from such transient simulations can be used and injected into the devices under test while observing the behavior of the device, which is usually visible on its binary output contacts, which issue certain control or protection commands to the system.

Since protection and control devices do operate instruments such as circuit breakers or online tap changer (OLTC) according to the current state of the primary power system they feed back to the power system. For a dynamic simulation of a power system this should be considered, to be able to investigate the realistic behavior of such devices. A transient simulation calculated on a standard PC usually does not provide the capabilities to react to such events in real time. Although the calculation power of modern personal computers today do have enough processing power to execute a transient simulation in the time domain with a time step in the range of one millisecond or even 100 microseconds, which would result in sampled signals with a sampling frequency of 1-10 kHz, in real time, usually the possibility to process feedback from a device under test and react on a state change of the power system within a single time step is not possible easily.

Therefore, dedicated computer solutions with a dedicated hardware are used to do real-time closed-loop simulation even for the dynamic simulation of reasonably small power system networks. The protection or control devices under test are then connected to these dedicated simulators, whereas the calculated voltage and current signals are usually applied to the devices under test using conventional voltage and current amplifiers and feedback is looped back via their binary signals.

Real-time simulators are mostly used in a laboratory environment for detailed analysis of the protection behavior during relay development and for analyzing the performance of protection devices during acceptance testing of a certain relay type.

Conventional protection testing devices, capable to inject voltages and currents into protection devices, can easily be used to apply transient signals from offline network simulation calculations. Using an iterative approach, it is possible to mimic the behavior of such a real-time closed loop simulation using standard personal computer hardware and conventional protection test equipment, which opens up new possibilities for testing real-time closed-loop scenarios with a more economic

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and practical setup even for testing in the field and during commissioning of protection and control devices.

A single test software is able to control multiple protection testing devices from one PC to enable testing of whole protection systems with simultaneous injection of a high number of voltage and current signals. Therefore, the start of each test run is time-synchronized using GPS clocks or any other precise time reference. Using this approach even testing of distributed protection systems, such as decentralized bus bar protection with master and bay units, is possible. Additionally, it is possible to control protection testing devices located in a remote substation and use the same approach for end-to-end scenarios too.

II. Real-Time Closed-Loop Simulation

Real-time closed-loop simulation to do testing of power system protection and control devices in the laboratory for detailed analysis of device behavior is well established. There are several manufacturers who offer dedicated hardware solutions, such as the one shown in Fig. 1 from RTDS.

Fig. 1. Real-time simulator for closed-loop simulation from RTDS

Usually these simulators are available with different processor capabilities and can be scaled to bigger assemblies simply by extending the hardware with additional processor cards or by stacking additional computing racks. The simulated power system network is modelled within an interactive computer program, which can run on a conventional personal computer, which finally compiles an executable program for the real-time simulator to be executed on the dedicated hardware. The calculated voltage and current signals, which are sampled at the sampling rate of the real-time simulation time step are putout using DA-converters as analogue signals, which can be amplified to the required magnitudes before applying to the devices under test.

The simulators are capable to react on stimuli from the devices under test within a single time step of the real-time simulation and adapt the power system model accordingly. The results from a simulation run is recorded by the simulators and can be post-processed in an interactive user interface on a standard personal computer.

Usually such real-time closed-loop simulations are done during relay development, for analyzing the performance of protection and control devices and during acceptance testing of a certain device type. But for commissioning or site acceptance testing in the field the effort for real-time simulation is mostly considered too high and the test setup with the dedicated hardware cubicles is quite impractical. For commissioning and protection testing in the field mostly the tests are simpler, because it is sufficient to model only the part of the primary power system network, which is relevant for the protection or control device under test. Processing power of standard personal computers today is sufficient to execute such a transient simulation with simulation time steps in the same range as for dedicated real-time closed-loop simulators. But the processing of the reactions of the devices under test in real-time is not possible with standard personal computers and it is challenging to create sampled signals with precise sampling rates and phase angle accuracy from such an office PC.

Therefore, a solution with an iterative approach, where the actual calculation of the network simulation is done upfront on the PC, and therefore has not to be in real-time too, but which does obtain the same results as from a closed-loop simulation, opens up new possibilities

III. Iterative Closed-Loop Simulation

The core idea of an iterative approach is to mimic the behavior of a closed-loop simulation using multiple repetitions. Therefore, a test sequence is simulated repeatedly, taking into account all the reactions of all the devices under test, recorded during a previous execution. We assume that the devices under test behave deterministically (they are reset properly in between every iteration). When the same scenario is repeated again, the devices will issue its reaction commands at approximately the same time (the software allows for some tolerance in the timing of events) and the simulation can now foresee this and simulate the corresponding reaction accordingly. This procedure is iterated until no more new reactions are recorded. The final execution of the test sequence is then exactly the same as if a real-time closed-loop simulator had been used.

For a first simple example, the following figures show two iterations for a selective bus bar trip on a bus bar protection system with two buses and 4 bays. More details for testing of bus bar protection in the field can be found in [1] and [2]. For the first iteration, the simulation cannot take into account that bay 2-4 trip the breakers. Therefore, the fault current persists on all bays and breaker-failure protection will trip the remaining bay on the non-faulted bus bar with a certain time delay. See Fig. 2.

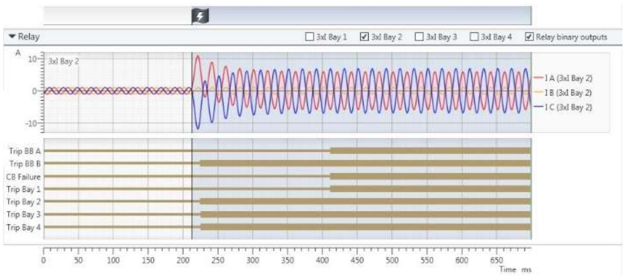

Fig. 2. 1st iteration without simulation of breaker trips

For the next iteration, the simulation considers the instantaneous trips for bay 2-4 and opens the breakers after the CB delay time so that the fault is cleared. Now the relays will not activate the breaker-failure protection and the trip signals will reset. See Fig. 3.

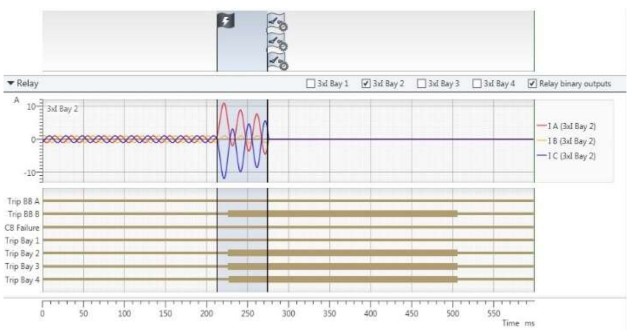

Fig. 3. 2nd iteration with breaker trips

The whole procedure is executed from the simulator software on the controlling PC automatically without any user interaction. It is not restricted to two iterations but is repeated until no more new reactions are seen from the devices within the overall simulation duration.

This principle works of course for more complex scenarios with multiple iterations and can be applied to multiple devices under test simultaneously. Even more complex fault scenarios with multiple faults or evolving faults are possible, because this is simulated consistently by the software in each iteration based on the previous reactions too. This shall be explained in more detail with the following example of a two-cycle auto-reclose scheme of a line distance protection relay, where both of the relays on each line end are under test.

The following figures shows the complete sequence and the operation of the iterative approach. The sequence will grow from the initial simulation until the fifth iteration. There is no need to setup timing of events by the end user upfront, the algorithm will integrate trip and close events automatically into the simulation.

Initial Simulation:

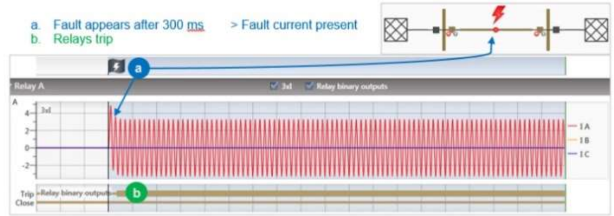

Fig. 4. Auto reclose – Initial simulation

When the fault current persists, the relay won't trigger a reclose cycle. Therefore, the software integrates the opening of the CBs in the simulation when the relays trip. The fault current disappears after the CB operation time.

First Iteration:

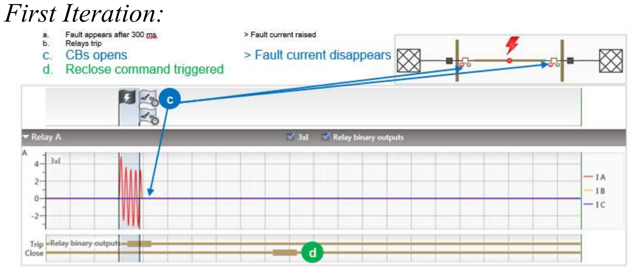

Fig. 5. Auto reclose – First Iteration

When the close command appears, the simulation won't interact in real-time. Instead the close event of the circuit breaker will be added to the second iteration. The fault is still present and so the fault current reappears which causes the relays to trip again.

Second Iteration:

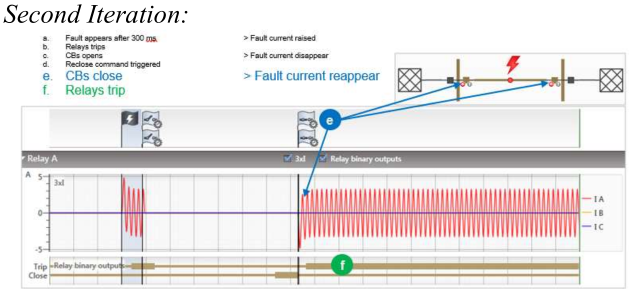

Fig. 6. Auto reclose – Second Iteration

The second trip of the CBs will be integrated in the third iteration.

Third Iteration:

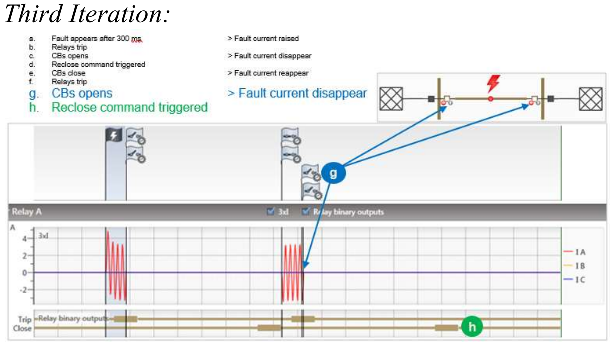

Fig. 7. Auto reclose – Third Iteration

After the close command the relays will trip again because the fault persists. The exact reaction time of the relays can differ a little bit between iterations (as it can be seen from the different close event in Fig. 6 and Fig. 7). The simulation does incorporate the effect after a fixed operating time of the breakers (CB close time), which can slightly jitter in reality too, and a certain time tolerance is accepted, so that a consistent series of iterations is achieved.

Fourth Iteration:

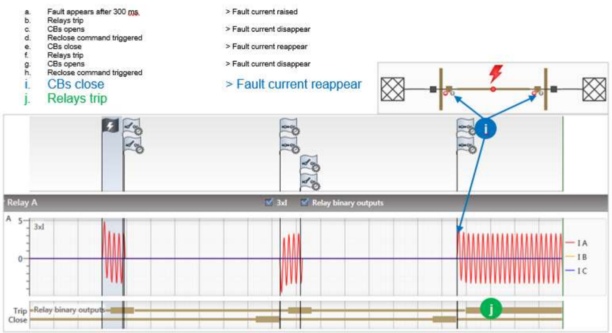

Fig. 8. Auto reclose – Fourth Iteration

Fifth Iteration:

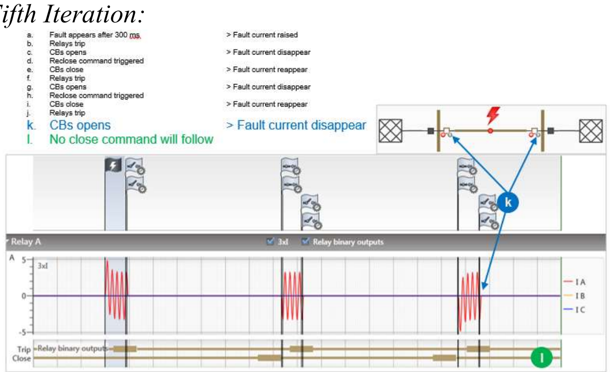

Fig. 9. Auto reclose – Fifth Iteration

After the last iteration (in this case the fifth) the software repeats the simulation once again to ensure that the protection system is not reacting with a new event (in this case a close command). When the last injection is done, the final iteration with all measurements can be displayed as shown in Fig. 10.

Within each iteration only one new reaction of the devices under test is considered to be incorporated into the next repetition. This will guarantee the causality and consistent sequence of events. Final assessment of the overall test is done on the final iteration, where measurements of timings between binary slopes and the times of the simulated events can be done.

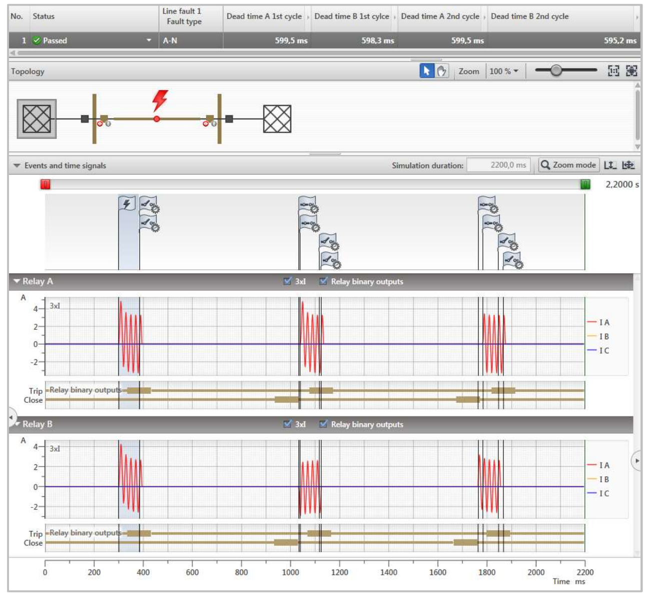

Fig. 10. Auto reclose – Final iteration with results

The final result of the last iteration delivers the same results as if a real-time closed-loop simulation had been used. The iterations of course take some time and for more complex schemes and scenarios the software has to repeat a number of times. But since this is all done by the software automatically no user interaction is required.

IV. Practical Testing in the Field

Iterative close-loop simulation can be done with a standard PC running the simulation software, which calculated the transient signals even not in real-time. The calculated transients are executed and applied to the devices under test using conventional protection test equipment. Reaction of the device under tests is recorded by this test sets too and uploaded to the controlling PC to calculate the next iteration.

This setup is as simple as a setup for normal protection testing. Therefore, it can be applied in the field during commissioning or routine testing of protection and control devices in a substation environment easily. Practically there is no difference to normal protection testing using a PC software, which is a common solution today.

The approach is not limited to a test of a single protection or control device under test. It can be applied to test a whole protection system, where multiple devices are under test and which interact with each other. For injection even multiple protection test devices can be used, which ensure that the injected signals are time-synchronized, which is usually achieved using GPS clocks attached to the protection test devices.

The solution is scalable for multiple distributed points of injection of test signals simply by using multiple test sets controlled from the single PC software. It has been applied for distributed busbar protection testing with more than 10 simultaneous bay units and used for practical end-to-end testing of 3-terminal line protection in the field successfully.

V. Testing of Distributed Protection Schemes

If the devices under test are not located in the same substation, as it is the case for an end-to-end protection on a power line, the iterative closed-loop approach can be used for a distributed protection test too. There distributed protection test devices are used in local and remote substation, which are again time-synchronized using reference clocks (mostly GPS-based). The controlling software is run on a PC on one end of the test and has network connection to the remote devices. If there is no direct network connection even a solution with a connection via an Internet cloud service is possible as shown in Fig. 11. More details about this approach is explained in [4] and [5].

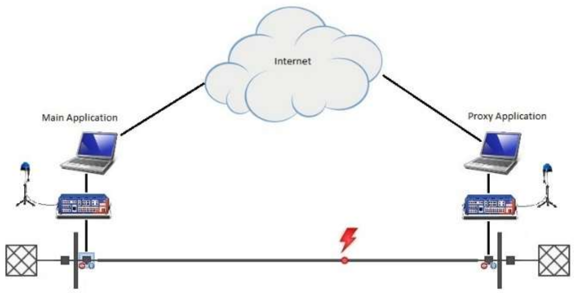

Fig. 11. Setup for a distributed test using a connection via an Internet cloud service

VI. Summary

Using conventional protection testing devices, capable to inject voltages and currents into protection devices, can easily be used to apply transient signals from offline network simulation calculations. But for testing advanced relay functions and to be able to see the detailed reaction of the devices for more complex protection logic the simulation is required to react on relay behavior (mostly commands to trip or close a circuit breaker) in a real-time closed-loop fashion. Since protection relays behave deterministically, if the same test scenario is applied again and if the device is properly reset in-between, an iterative approach can be used instead of a real-time closed-loop simulation. A test software running on a conventional PC where the network simulation is calculated offline (non-real-time) can repeat a test scenario automatically and incorporate the effect of relay reactions from the previous test run iteratively. If this is done again and again until no more new reactions from the protection device are recognized, the final test run mimics the behavior of a real-time closed-loop execution perfectly.

A single test software is able to control multiple protection testing devices from one PC to enable testing of whole protection systems with simultaneous injection of a high number of voltage and current signals. Therefore, the start of each test run is time-synchronized using GPS clocks or any other precise time reference. Using this approach even testing of distributed protection systems, such as decentralized bus bar protection with master and bay units, is possible. Additionally, it is possible to control protection testing devices located in a remote substation and use the same approach for end-to-end scenarios too.

A solution which is reusing already existing conventional portable protection test equipment is much more economical for application in the field than a complex real-time closed-loop simulator. Additionally, the approach can be scaled for more complex and distributed setups simply by adding additional test sets, which are used for protection testing in a substation environment every day.

VII. References

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