The Real-Time Simulator for Protective Relays Testing Using MATLAB/Simulink Software

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Abstract—The submitted paper presents a tester designed for testing the protective relays in work conditions close to the real. The device is a simulator operating in real-time of the phenomena taking place in the modeled part of power system. The paper describes the construction (including hardware and software aspects) and operation principle of designed simulator. The MATLAB/Simulink software has been used for modeling the test systems (as parts of the whole power system). Paper includes some example results of distance relay tests performed using designed simulator. In addition, the opportunities for further development of both hardware and software parts of the simulator have also been presented.

Keywords—power system protections; protective relays testing; real-time simulators; closed-loop testing, MATLAB/Simulink software

ACRONYMS

PS  Power System.
DFR  Digital Fault Recorder.
RTS  Real Time Simulator.
RTDS  Real Time Digital Simulator.
IEn-RTS  Institute of Electrical Power Engineering -Real Time Simulator.
RTWT  Real-Time Windows Target.
DC  Direct Current.
DAC  Digital-Analog Converter.
COMTRADE  Common Format for Transient Data Exchange for Power Systems.

I. INTRODUCTION

A quick introduction of the new advanced digital protection relays, and the multitude of features included therein, may result in their operating not in the full accordance with users expectations. For this reason, relays should be tested by the manufacturers both in the production phase as well as during operation. A variety of issues to check means that the tests should be performed according to specific test procedures.

The aim of the relays testing is to confirm correctness of their operation in accordance with manufacturer's design and with user's requirements. Evaluation of their operation during the tests contributes to determine their suitability for intended application, and hence for appropriate protection of particular elements of the power system (PS) and protection of this PS as a whole. Performing the tests allows manufacturers to draw conclusions about the operation of the relays and about improvement of old and creation of new solutions.

Different applicable divisions of protective relays tests have been described in [1]. There are two main types of relay testing: type tests and individual tests [1-3]. Among the type tests, significant are: functional conformance tests, functional performance tests and scheme performance tests. The listed types of tests are carried out using suitable devices known as: (a) the microprocessor testers, (b) simulators reproducing the recorded waveforms or waveforms generated using simulation software (simulators operating in open loop), (c) simulators operating in real-time of phenomena (simulators operating in closed loop). Devices applicable by users for performing the tests of protective relays are more thoroughly described in [4].

The remainder of this paper is organized as follows. Section II presents a brief description of each types of tests and tools for their implementation, with the main emphasis on clarifying the principle of testing in closed loop (using simulators operating in real-time of phenomena). Section III describes the self-designed simulator for testing protective relays in a closed feedback loop. Section IV presents selected results of tests performed using the simulator. Section V concerns the prospects of further simulator development. Summary is stated in Section VI.

II. METHODS FOR TESTING THE PROTECTIVE RELAYS

The following briefly describes some of the methods for testing the protective relays.
A. Functional conformance tests

Within this type of tests, the relay is checked using the signals that can be expressed by simple dependencies between currents and voltages. During the tests, the protective relay is supplied with the analog signals, usually defined as fundamental-frequency phasors. Sometimes an additional aperiodic component is added to pure-sine wave test signals. During the tests are simulated the pre-fault, fault and post-fault conditions. Functional conformance tests are performed using common microprocessor testers cooperating with high-end amplifiers [4, 5].

B. Functional performance tests

These tests concern the operation correctness of the relay in particular PS work conditions and the specific course of fault in PS. They can be performed in such a way that the waveforms of electrical quantities (just before and during the disturbance) are recorded using digital fault recorder (DFR). Then the recorded waveform is transferred via storage medium to the laboratory and uploaded to the tester software (simulator reproducing the recorded waveforms). If the recorded waveforms are not available, then the waveforms of electrical quantities may be obtained using a computer simulation of the PS or its suitable part.

Tester reproduces the recorded waveforms of currents and voltages (modern microprocessor testers typically have the ability to reproduce the recorded waveforms), converts digital signals to analog and amplifies them to the level of tested relay's inputs. These signals are put into the tested device and its operation is observed with the pick-up and trip signals recording. These type of tests are called the open-loop tests.

C. Scheme performance tests

This testing method consists in that the protective relay is treated as a “black-box” wherein all the features are configured and set as in the case of its switch-bay application. The method of relay testing may be similar as in the case of functional performance tests. However, a much more sophisticated and conforming to the reality is a method of testing using the real-time simulators of PS event.

Thanks to such the simulators, simulation results are lead out as fast as the system's phenomenon runs. With this type of simulator, tested relay can be incorporated into the PS model in such a way that the instantaneous values of voltages and currents (obtained from the simulator) are converted to analog signals, properly amplified and then put into the relay. The other hand, binary output signals from the relay are put into the PS model mapped in simulator. If the output signal is a tripping signal and this signal occurs during the simulated phenomenon, then the corresponding circuit in a system model is interrupted. Such a test is said to be carried out with a closed loop, as the behavior of the modeled system is affected by operation of the tested relays (as in a real PS). Described above method of the signal flow is visually presented in Fig. 1 and the construction and operation principle of PS real-time simulators are described in [4, 5].

Commercial simulators such as Real Time Digital Simulator - RTDS [6] or HYPERSIM Power System Real-Time Simulator [7] are very expensive devices. Therefore, some academics are trying to build (with greater or lesser success) their own simulators working in real-time of phenomena [8] which could be used for testing the protective relays.

III. THE SIMULATOR FOR TESTING PROTECTIVE RELAYS IN REAL-TIME

The laboratory has created the IEn-RTS simulator for testing protective relays in real-time of phenomena. The concept of a simulator working under the laboratory stand is described in [9].

The task of the simulator is the simulation of different phenomena (short circuits, power swings, voltage spikes, switching on the network, etc.) in the modeled parts of PS using the software able to simulate the dynamic states in PS. Obtained from the selected measurement point, appropriate voltage and current waveforms and the signals of breaker poles positions, which are the results of the simulation, appear at the outputs of measurement cards after the proper scaling. After signals amplification to the values corresponding to secondary sides of current and voltage transformers (using the current-voltage amplifier) and matching binary signals (using circuit which matches this signals to 220 V DC voltage), analog and binary signals are put into the device under test. In return, from the tested relay are taken the binary signals (e.g. signals indicating opening or closing the poles of appropriate circuit-breaker) which (through the matching circuits and acquisition card) affect to the status of switch devices in modeled (using simulation software) part of PS. The changes,
being a result of tested relay operation in modeled part of PS, occur in the real-time of modeled phenomena (i.e., time in which they occur in reality).

Currently, using the created simulator may be tested protective relays which use analog signals (3 current signals and 3 voltage signals) and binary signals from the one of line's ends. This limitation is due to the number of installed measurement cards and capabilities of used amplifier allowing to generate up to 3 current signals and 3 voltage signals.

Built IEn-RTS simulator consists of hardware and software parts. Fig. 2a shows a view of hardware implementation of the simulator, while Fig. 2b illustrates its block diagram.

In laboratory stand have been used Advantech measurement cards: two PCI-1720 cards (Fig. 3a) [11] and one PCI-1750 card (Fig. 3b) [12]. All measurement cards have been mounted in PCI busses of the PC. Each PCI-1720 card is equipped with four isolated analog channels (2.5 kV DC isolation) with controlled output voltage in the range of 0 to +/-5 V for voltage peak value. Resolution of each channel of digital-analog converter (DAC) is 12 bits. Voltage within the above-mentioned range (one of the card ranges foreseen by the manufacturer) is required by the input circuits of amplifier which has been used. In the laboratory stand, one card is used to amplify (using external amplifier) 3 current signals (L1, L2, L3 phases) and the other card to amplify 3 voltage signals (L1, L2, L3 phases).

A. Simulator’s hardware

The hardware part of IEn-RTS simulator consists of: a) a PC; (b) acquisition PCI cards; (c) amplifier of current and voltage signals; (d) 220 V DC matching circuit; (e) the protective relay.

PC computer has been equipped with an Intel Pentium 4 2.4 GHz processor, a P4P800SE motherboard from ASUSTeK company, 1.5 GB of RAM memory and a 500 GB hard drive. PC worked under Windows XP with Service Pack 3.
PCI-1750 card is equipped with 16 isolated digital inputs and 16 isolated digital outputs (2.5 kV DC isolation). For digital inputs, voltage should be in the range of 0 – 2 V (low state) and in the range of 5 – 50 V (high state). For digital outputs, voltage should be in the range of 5 - 40 V. In the simulator, PCI-1750 is used (along with a circuit matching to 220 V DC voltage) for putting signals to the binary inputs of protective relay (information on the switch poles positions) and to read information from the binary outputs of the relay (indicating its tripping) and affecting the switches status (open/close signal) in modeled part of PS. The use of 8 digital inputs and 8 digital outputs of PCI-1750 card has been provided for in the simulator.

For amplification of the analog signals (currents and voltages) which have been generated by PCI-1720 card, a CMS 156 amplifier (from OMCIRON electronics) has been used (Fig. 4a) [14]. It is equipped with 3 current channels and 3 voltage channels. The input voltage for the current and voltage channels should be in the range of 0 to 5 V for RMS values. Gain for particular current channels is 5 A/V, while for the voltage channels is 50 V/V. The range of output currents (RMS value) is from 0 to 25 A for each channel for three-phase amplifier operating-mode. The range of output voltages is from 0 to 250 V (RMS value) for each channel (for three-phase amplifier operating-mode too). The values of these signals conform to the analog signals at the secondary side of transformers and they are sufficient for testing most of protection relays with input rated current $I_n = 1$ A and with rated phase-to-phase input voltage $V_n = 100$ V.

Connections between PCI-1720 measurement cards and CMS 156 amplifier have been made, in addition to standard connectors, using the 6-pin Lemo FGG.2B [15] to which the amplifier's analog inputs system is adapted. To adjust the digital input and output voltages of the PCI-1750 card to values acceptable by binary inputs and outputs of tested protection relay, it has been made the circuit matching the card's voltages to 220 V DC level (Fig. 4b). This circuit can work with up to 8 digital inputs and 8 digital outputs of acquisition card, and hence with 8 binary inputs and 8 binary outputs of tested relay. Due to the fact that many relays often uses only 3 binary inputs and 3 binary outputs (breaker poles for L1, L2 and L3 phases) a large number of available binary inputs/outputs of matching circuits will be used after simulator development, for example to testing the operation coordination of the distance relays or the section relays (differential relays and phase comparison relays). As is known, relays of this type could work together (by transferring digital signals to each other) using a telecommunication link, a direct fiber or using a IEC 61850 standard.

B. Simulator's software

The software part of the simulator includes MATLAB/Simulink software (ver. 2010b) along with Real-Time Windows Target (RTWT) and SimPowerSystems toolboxes [16]. Order to run correct interaction of PCI-1720 card and PCI-1750 card with RTWT library items, it was also necessary to install the C++ compiler available in the Microsoft Visual Studio 2005 programming environment.

The MATLAB/Simulink software along with the listed libraries is used to simulate (in modeled part of PS) dynamic phenomena such as faults (metallic faults, resistive faults, developing faults), power swings, switching on the network, etc. Moreover, analog and digital signals are forced from the software using the acquisition cards. They are taken from selected measurement points of modeled system, as the results of performed simulation. In addition, software is used to read the information (digital signals) resulting from the operation of tested relay (e.g., tripping signals for opening the poles of selected breaker) which affect the configuration of the modeled PS part.

Simulation of selected PS part is performed with use of PS components available in SimPowerSystems library. In this library could be found the models of elements such as: synchronous and asynchronous machines, direct-current machines, regulators, current and voltage sources, transmission lines, one- and three-phase switches, transformers, passive elements, power electronic devices (diodes, thyristors, transistors, etc.). This allows to build a variety of electric power systems.

The RTWT library contains elements such like (among the others) analog inputs and outputs or digital inputs and outputs, designed to work with acquisition cards. These elements are used in the simulator to lead out analog and digital signals (which are the simulation results) to acquisition card outputs (for their further processing through analog-signal amplifier and matching-circuit for digital signals) and to read the states of external digital signals affecting the course of the simulation. The choice of RTWT library has made possible the real-time simulation of phenomena in modeled PS parts. Analog and digital waveforms turn up at the inputs of tested relay in real-time (as in a real system), and the tested relay affects the modeled system configuration (and consequently the further course of the simulation) in a real-time using its binary outputs.

IV. SELECTED RESULTS OF SIMULATOR OPERATION CORRECTNESS TEST

The following describes the example test results for selected distance protection performed using created simulator. Currently, the following test systems are prepared in MATLAB/Simulink software:
• 1st system - system with a voltage source operating on-load;
• 2nd system - system with two voltage sources (in this one controlled voltage source) connected by two transmission lines;
• 3rd system - system with a generator (2nd order model, equation of motion only) and a voltage source which are connected by two transmission lines;
• 4th system - system with a generator (5th order model) and a voltage source which are connected by two transmission lines.

The assay systems for testing the protection relays were made with use of the components available in the SimPowerSystems library. Schemes for the 2nd, 3rd and 4th test systems are shown in Fig. 5. These systems differ from each in the PS1 source type connected to the BB1 busbar.

![Fig. 5. The test system modeled in MATLAB/Simulink software.](image)

In this system were modeled: (a) generator (PS1); (b) infinite busbar system (PS2) mapped by the voltage source; (c) two transmission lines (L1, L2) length 200 km each and modeled by the coupled PI sections; (d) BR3 and BR4 breakers three-phase controlled using time components, (e) BR1 and BR2 breakers single-phase controlled by the tested distance relay (Z<).

The BR5 and BR6 are controlled (opened) triphasic using the time components and selected binary input of PCI-1750 card. They are used for the purposes of safety order to prevent the damage of CMS 156 amplifier or of tested relay in cases of long-term forcing of large currents values (e.g. arising from any malfunction of the test system model built in MATLAB/Simulink).

Current and voltage signals are put into the tested Z< relay from the measurement point located at the beginning of L1 line using the 'Analog Output' components of RTWT library. Binary signals, combining the tested Z< relay with BR1 breaker, are taken from and put into the PCI-1750 card with use of the RTWT library components called 'Digital Output' and 'Digital Input'.

A. Checking the correctness of simulator operation with the protection relay – example 1

The result for selected test (example 1) of General Electric D60 protection device [17], performed using the simulator, is presented in Fig. 6. The test has been performed using the 3rd test system. There have been used overcurrent protection function (PHASE IOC1) and auto-reclosing function (AR) of the tested relay.

![Fig. 6. Recording made by an internal digital fault recorder of D60 relay during the performed test (a part of the screenshot from EnerVista UR software).](image)

The sequence of events occurring during the test is as follows: (a) at the time 0.5 s from the beginning of the simulation in the L2 line has occurred the three-phase metallic fault (F1), located 20 km from the BR3 breaker and cleared after 100 ms time by opening the BR3, BR4 breakers with use of the time components; (b) the PS1 generator swings with respect to the PS2 subsystem (synchronous swings); (c) at the time 2.5 s from the beginning of the simulation, in the L1 line has occurred the three-phase metallic fault (F2) in the point located 20 km from the BR1 breaker (and therefore from the measurement point); (d) D60 relay has sent the tripping signal (PHASE IOC1 OP) for BR1 breaker opening after 23 ms time, as a result of the PHASE IOC1 function operation; (e) auto-reclosing function has sent the signal (AR CLOSE BKR1) for closing the BR1 breaker (this signal has been also brought to the BR2 breaker) after the time of 0.496 s from the reset of PHASE IOC1 function. Successful auto-reclosing cycle has been performed. After the successful auto-reclosing cycle, by observing the waveform of the active power (SRC1 P signal) it can be noted that the PS1 generator operates asynchronously in relation to the PS2 subsystem (infinite power busbar). For the test it has been assumed that BR1 and BR2 breakers act instantaneously and do not introduce any delays (which of course is unheard of in real conditions).

In the modeled system for demonstration purposes is shown the simulator operation correctness while using PHASE IOC1 overcurrent function of D60 relay. In fact, the distance protection function should be used instead of the overcurrent function (see example 2).

B. Checking the correctness of simulator operation with the protection relay – example 2

The result for selected test (example 2) of General Electric D60 protection device [17], performed using the simulator, is presented in Fig. 7. The test has been performed using the 3rd test system. There have been used distance protection function (Phase Distance) and auto-reclosing function (AR) of the tested relay.

![Fig. 7. Recording made by an internal digital fault recorder of D60 relay during the performed test (a part of the screenshot from EnerVista UR software).](image)
simulation in the L2 line has occurred the three-phase metallic fault (F1), located 20 km from the BR3 breaker and cleared after 100 ms time by opening the BR3, BR4 breakers with use of the time components; (b) the PS1 generator swings with respect to the PS2 subsystem (synchronous swings); (c) at the time 2.5 s from the beginning of the simulation, in the L1 line has occurred the three-phase metallic fault (F2) in the point located 20 km from the BR1 breaker (and therefore from the measurement point); (d) D60 relay has sent the tripping signal (PH DIST Z1 OP) for BR1 breaker opening after 17 ms time, as a result of the Phase Distance function operation; (e) auto-reclosing function has sent the signal (AR CLOSE BKR1) for closing the BR1 breaker (this signal has been also brought to the BR2 breaker) after the time of 0.501 s from the reset of Phase Distance function (reset time set to 0.1 s). Successful auto-reclosing cycle has been performed. After the successful auto-reclosing cycle, by observing the waveform of the active power (SRC1 P signal) it can be noted that the PS1 started to work asynchronously in relation to the PS2 subsystem (infinite power busbar). Due to the fact that the power-swing blocking function (called Power Swing Detect in D60 relay) has not been activated for blocking the Phase Distance function during the power swings, the Phase Distance function has send (after the reset time equal to 0.1 s) the PH DIST Z1 OP tripping signal for BR1 breaker opening.

The L1 line has been permanently switched off and thus the connection between the PS1 generator and PS2 system has been definitively broken. For the test it has been assumed that BR1 and BR2 breakers act instantaneously and do not introduce any delays (which of course is unheard of in real conditions).

V. PROSPECTS FOR THE SIMULATOR DEVELOPMENT

At the present stage the created IEn-RTS simulator, operating in the real-time of phenomena, allows the testing of protective relays which use up to 3 current signals, up to 3 voltage signals and up to 8 binary inputs and 8 binary outputs.

Ultimate goal is to expand the simulator hardware by an additional PCI-1720 card and an additional CMS 156 amplifier (which the laboratory is equipped in). With such an expansion of the simulator there will be available 6 current signals and 6 voltage signals. This will allow testing the operation correctness of the following protective relays (including coordination of their operation):

- distance relays located at the two ends of the line and cooperating with one another via telecommunication link or direct fiber connection;
- section relays (differential relays and phase comparison relays) for protecting the line;
- differential protections for transformers, busbars, etc.;
- protection systems using the digital signals transmission through the IEC 61850 standard.

It is planned to use in test systems the PCI-1711 measurement card which (due to a large number of analog inputs) will allow to test (in real-time) the prototype systems of control or regulation equipped with analog outputs. Examples of such systems are described in [18, 19].

From the software point of view, it is planned to prepare additional test systems with different power network configurations containing the subsystems with the exactly mapped generators and their control systems, to test the operation correctness for tested devices in dynamic PS conditions such as power swings, developing faults etc. It is planned to prepare the test systems (including universal assay system [20] for testing the HV network protection devices) containing up to four generators, including the possibility of using the distributed generation sources models.

In a further stage of the simulator development it is planned to increase the ability of: (a) analyzing the signals which occur during the modeled disturbance cases; (b) analyzing the operation of tested relay. The planned improvements come down to calculating the waveforms of the symmetrical components of currents, voltages, power, resistance and reactance and to calculating the impedance trajectory on the $\sigma(R)$ plane in relation to the impedance characteristics of a distance relay. It is planned to save the selected waveforms (currents, voltages, digital signals) to the COMTRADE file format for their further analysis.
VI. SUMMARY

The most sophisticated method for testing the digital protective relays is testing them in the closed feedback loop, using simulators working in the real-time of phenomena. In the case of such a test, the behavior of the modeled PS part is significantly affected by the operation of tested devices (as in real conditions).

Commercial simulators operating in real-time that can be used to test large parts of the PS, and which could be used for testing the correctness of operation of many devices at the same time, are very expensive. Often for checking the operation correctness of individual relays it is enough to model a small part of PS using the real-time simulator. Commercial simulators that can be used to test small parts of PS are also the big expenses. Many technical universities and research laboratories cannot afford such a big financial effort.

Created real-time simulator will be used to test individual (up to two) protective relays working in a small part of PS (up to four generators). The simulator will be used among the others to test the functions of distance protections, differential protections, overcurrent protections, directional overcurrent protections and to test the control and regulation systems in small parts of PS. So far the results of tests performed using the created simulator (described in Sec. IV) are promising.

It seems that the created simulator could be a cheaper alternative to commercial real-time simulators. It is able to be used for testing the protective relays. It also has an invaluable educational value and may be used in the teaching process.

REFERENCES


