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CONTROL AND INFORMATICS

The real-time simulator using MATLAB/Simulink software for closed-loop coordination protection devices testing

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Abstract. This paper aims to discuss the behavior of the proprietary real-time simulator (RTS) during testing the coordination of distance relay protections in power engineering. During the construction process of the simulator, the mapping of various dynamic phenomena occurring in the modeled part of the power system was considered. The main advantage to the solution is a lower cost of construction while maintaining high values of essential parameters, based on the generally available software environment (MATLAB/Simulink). The obtained results are discussed in detail. This paper is important from the point of view of the cost-effectiveness of design procedures, especially in power systems exploitation and when avoiding faults that result from the selection of protection relay devices, electrical devices, system operations, and optimization of operating conditions. The manuscript thoroughly discusses the hardware configuration and sample results, so that the presented real-time simulator can be reproduced by another researcher.

Key words: real-time simulator; distance protections; protection relays testing; closed-loop testing; MATLAB/Simulink.

1. INTRODUCTION

Over the past few decades, power systems around the world have developed significantly. As the pressure to improve economic efficiency and reduce the negative impact on the environment increases, today's networks are used to the limits of stability and safe operation. To protect the power system against unwanted disturbances, energy operators are introducing newer and more advanced systems and devices for power protection automation. To ensure that protection devices (relays) operate following the schemes and algorithms they are designed for, a series of tests are performed before their introduction into the power system. System performance tests are among those conducted. It is a group of tests during which devices operate in conditions similar to those prevailing in the target location of the device, for example using the settings in force for a specific line field. System operation tests can be performed in two layouts:

- Open-loop – tests are executed with the use of microprocessor testers – the tested device signals an operation that does not affect the tester generating waveforms.
- Closed-loop – tests are executed with simulators emulating a modeled part of the power system – the tested device signals tripping, which influences the waveforms generated by the simulator (an example may be network reconfiguration by opening the circuit breaker).

Real-time simulators (RTS) have become the key tool for conducting closed-loop tests. Real-time simulation recreates the voltage and current output waveforms with the desired accuracy in a way that best matches the behavior of the real system. To achieve this goal, the simulator must solve the model equations in a one-time step. Same step times are the intervals at which the output signals from the simulator are generated. RTS is therefore a technique for simulating power system transients using a digital time-domain model solution. During the simulation, the tested protection device continuously receives the output signals from the simulator (analog and binary signals) and sends appropriate feedback (binary signals). This two-way connection (closed-loop system) implemented in real time adds to the growing popularity of real-time simulators in the field of testing protection devices. Real-time simulations can be divided into two categories [1]:

- Fully digital simulations (real-time simulation)
- Simulations cooperating with physical devices (hardware-in-the-loop, HIL)

The real-time fully digital simulation requires the entire system (including the device under test) to be modeled inside the simulator and not involving an external analog/digital I/O interface. HIL simulation refers to the state where the entire test system is divided into:

- RTS, optionally equipped with an analog signal amplifier and a circuit that adjusts the level of binary signals.
- A device under test (DUT) or hardware under test (HUT) connected to the simulator through its input interface, such as an analog to a digital converter.

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2. STATE OF THE ART

The first commercial real-time simulator of dynamic phenomena in the power system, called RTDS (real-time digital simulator), appeared on the market in the 1990s [2]. Then several other commercial simulators appeared, such as OPAL-RT based on PC architecture [3], Typhoon based solely on FPGA [4], academic FPGA-RTS [5]. Academic centers also develop non-commercial simulators for testing protection and regulation systems [6, 7], including those based on the Linux operating system [8]. An overview of the application and hardware solutions of real-time simulators can be found in the IEEE PES reports [9, 10]. Unfortunately, commercial simulator solutions, regardless of how large fragments of the power system can be mapped with them, are very expensive and many academic centers cannot afford such a financial burden. Moreover, due to their size, mainly analog signal amplifiers (currents and voltages) have significant dimensions.

The new solutions of RTS implement the IEC 61850 standard for the transmission of analog and binary signals (converted into a digital form), and thus they do not use analog signal amplifiers and DC voltage adapters utilized at power stations (e.g. 220 V DC). Consequently, the number of wire connections between the simulator and the tested device is significantly reduced [11–13].

The RTDS uses dedicated RSCAD software [14], while in OPAL-RT simulators the MATLAB/Simulink software, which is popular in academic circles, is adapted to the needs of the simulator [15]. Figure 1 shows an exemplary simulation result in RSCAD, made with the RTDS.

For MATLAB/Simulink real-time simulation software, there was originally a dedicated toolbox called Real-Time Windows Target (RTWT). Its successor is the Simulink Desktop Real-Time (SLDRT) toolbox [17]. It is an application based on a real-time kernel.

Nowadays, simulators operating in real-time of dynamic phenomena are one of the most important elements of the test systems: (a) protection systems [18–20], (b) HVDC and FACTS [21], (c) digital substations, and IEC 61850, (d) wide area schemes and PMUs [21], (e) distribution automation [22], and (f) microgrids and renewable energy.

Despite the huge development of real-time simulators in recent years, their availability remains relatively low, mainly due to their high cost. This is the main reason for exploring the possibilities of designing and building low-cost real-time simulator solutions that from the point of view of testing the protection of power system elements could work as well as expensive commercial solutions.

The authors have built a simulator that enables the mapping of various dynamic phenomena occurring in the modeled fragment of the power system. Both in terms of hardware and software, it is an extended version of the simulator described in [23].

RTS is a good tool for testing power automation devices. Devices can be subjected to operating conditions similar to the actual properties prevailing in the objects they protect. An example may be the tests of distance protections located in a modeled fragment of a high voltage network.

Designed real-time simulator facilitates:

- Mapping of various dynamic phenomena occurring in the modeled fragment of the power system.
- Low construction cost while maintaining high parameters.
- Basing it on a generally available software environment (MATLAB/Simulink).
- Increased adjustment of the binary signal level, which facilitated the exchange of more signals between the test models and the tested devices.

The following sections of the article discuss the construction of the proprietary real-time simulator of the phenomena. Section 3 presents the hardware and software structure of the simulator. Section 4 covers the distance protection coordination systems used in the case of high voltage line protection, which can be tested with the built RTS. Section 5 presents examples of test results performed in a laboratory stand using the RTS.

3. CONSTRUCTION OF A PROPRIETARY REAL-TIME SIMULATOR OF PHENOMENA

3.1. Hardware design

The block diagram of the simulator with the environment is shown in Fig. 2. The system consists of two main parts: the

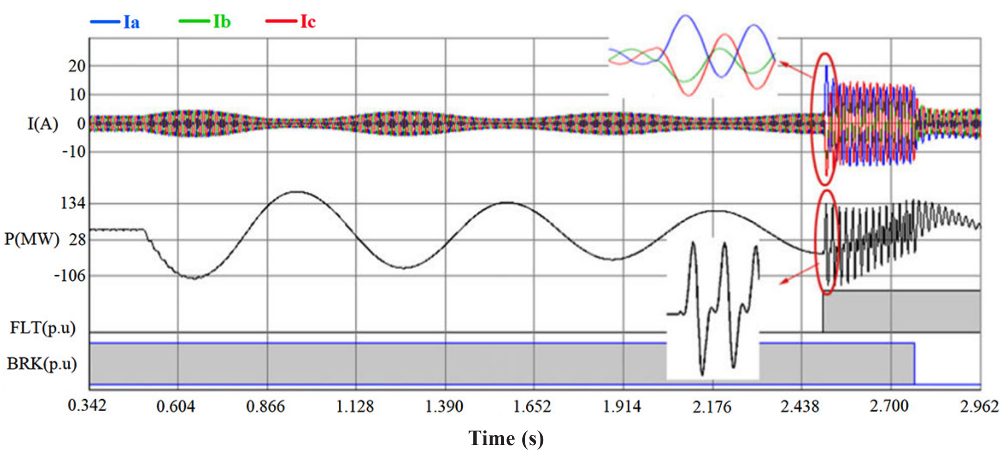
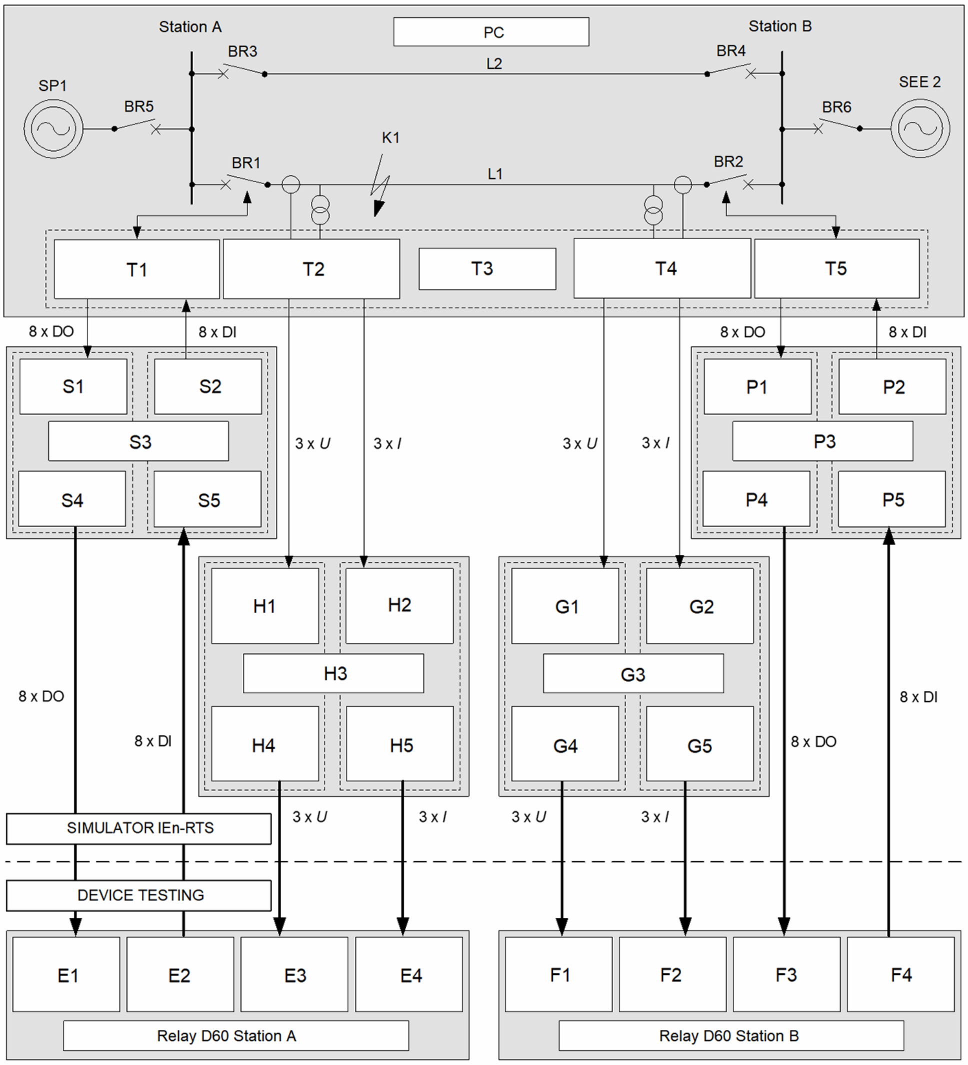


Fig. 1. An example of the simulation result in the RSCAD program made with the RTDS [16]



where:
T1 – PC card PCI-1750, Binary I/O;
T2 – PC cards PCI-1720, Analog Outputs;
T3 – Data acquisition cards;
T4 – PC cards PCI-1720, Analog Outputs;
T5 – PC card PCI-1750 I/O;
S1 (P1) – Binary Inputs 0–5 V DC;
S2 (P2) – Binary Outputs 0–5 V DC;
S3 (P3) – Matching system, Station A (Station B);
S4 (P4) – Binary Outputs 0–220 V DC;
S5 (P5) – Binary Inputs 0–220 V DC;
H1 (G1) – Analog Inputs, voltage, 0–5 V RMS;
H2 (G2) – Analog Inputs, current, 0–5 V RMS;
H3 (G3) – Amplifier CMS 156, Station A (Station B);
H4 (G4) – Analog Outputs, voltage, 0–250 V RMS;
H5 (G5) – Analog Outputs, current, 0–25 A RMS;
E1 (F1) – Binary Inputs, 0–220 V DC;
E2 (F2) – Binary Outputs, 0–220 V DC;
E3 (F3) – Analog Inputs, voltage $U_n = 100$ V;
E4 (F4) – Analog Inputs, current, $I_n = 1$ A

Fig. 2. Block diagram of a system with a real time simulator

original real-time simulator of the phenomena and tested devices, which are two D60 distance relays [24].

The hardware configurations of the simulator are devices that enable testing the coordination of the operation of distance protection (or section protection, e.g. differential or phase comparison). The following are worth highlighting:

- Three data acquisition cards PCI-1720 [25], facilitating the output of twelve analog signals from the test model, representing six voltages and six currents (e.g. a set of analog signals from two ends of the protected HV line).
- Two CMS 156 amplifiers [26] that amplify the analog signals derived from the test model (6 currents and 6 voltages).
- Two systems adjusting the level of binary signals (cooperation with the PCI-1750 data acquisition card [26]), enabling the exchange of signals (16 binary inputs/outputs) between the test model and the tested devices.
- Two D60 distance relays [24], which constitute a pair of HV line protections, installed at their two ends.

PC with data acquisition cards installed has been equipped with an Intel Core 2 Duo 3.00 GHz processor, a GA-P43-ES3G motherboard from GIGABYTE company, 8 GB of RAM and a 500 GB hard drive. PC worked under Windows XP with SP 3.

The central unit, as the main part of the simulator, creates a software environment that provides the best possible conditions for real-time simulation. The PC should have sufficient computing power to handle the operating system installed along with the application software designed to build the model and simulate it in real-time. Data acquisition cards are designed to generate analog signals and exchange binary signals with the tested devices. The source of the signals sent by the simulator is the real-time model. The tested devices are the source of signals received by the simulator. The matching circuits enable the simulator to exchange binary signals with the tested devices – those adjust the level of data acquisition cards (0–5 V DC) binary signals to the level of binary signals generated by the tested distance relays D60 (0–220 V DC). The CMS 156 amplifiers are designed to increase the level of analog signals (current and voltage) issued by data acquisition cards to the level corresponding to the range of analog inputs of the tested devices. The matching circuits, amplifiers, and tested devices consist of

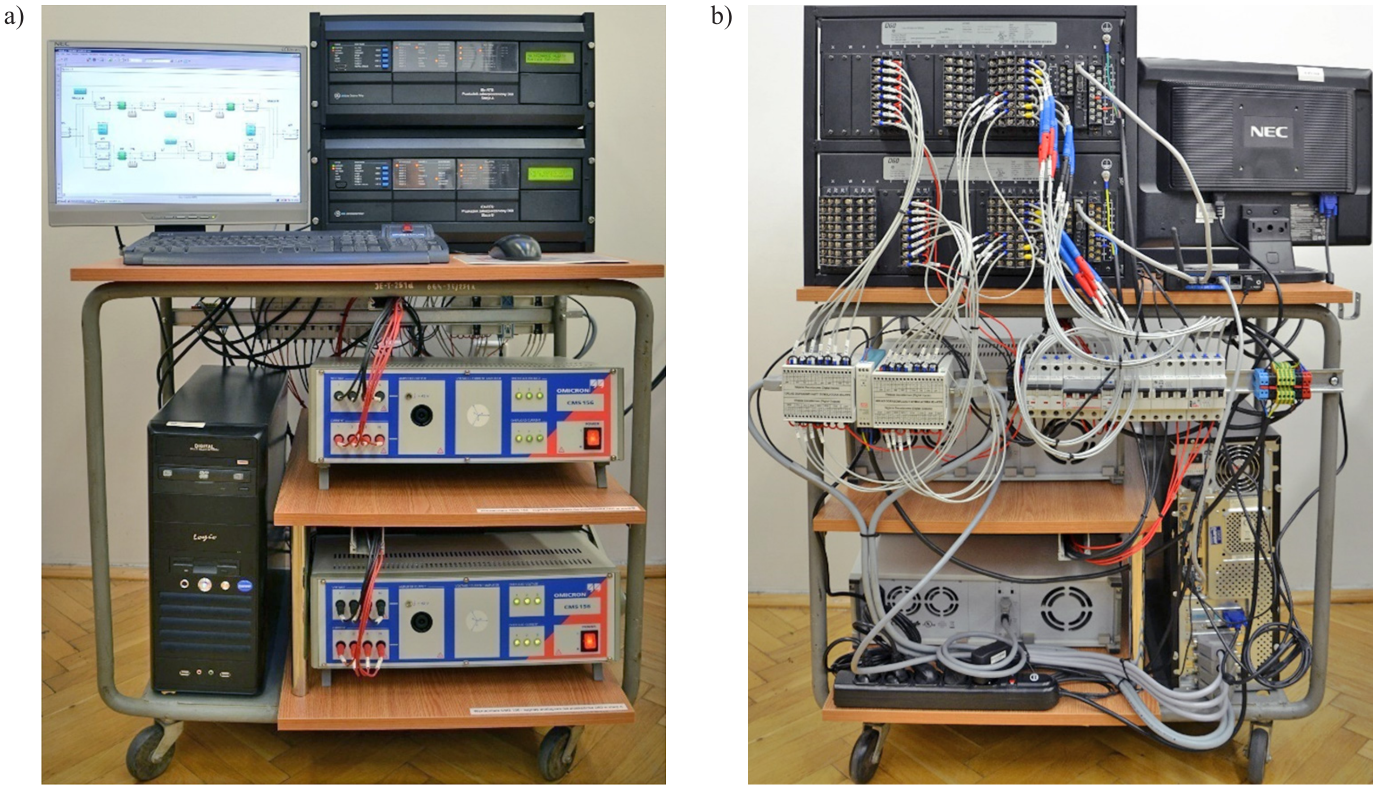


Fig. 3. The physical appearance of the proprietary RTS laboratory stand: a) front view, b) rear view

two paths, mapping two relay points. The physical appearance of the RTS laboratory stand is shown in Fig. 2.

3.2. Software configuration

The proprietary RTS uses MATLAB/Simulink software that enables the construction of test systems and real-time simulation software. Several test arrangements have been built. These include systems for checking the connection between the simulator and the tested devices, an implementation system for familiarizing oneself with the elements of the Simscape library, and systems for testing protection relays.

Figure 4 shows one of the test systems consisting of a generator (2nd order model), infinite busbar system, and two lines modeled with the coupled PI sections. The current and voltage measurements at both ends of the L1 line, in station A and station B, are transferred to the D60 relays, which control the BR1 and BR2 single-phase circuit breakers in fault conditions. For the processing, visualization, and analysis of data resulting from real-time simulations, programs (*.*m* files) and models (*.*slx* files) of the MATLAB/Simulink environment were used to record analog signals (currents, voltages) and binary or the course of the positive sequence impedance trajectory as seen by the D60 relays on the $X(R)$ plane.

As part of the work [27], several other models with a similar structure were built, which differ in the type of G generator used (e.g. 5th order generator model, controlled voltage source).

Figure 5 shows the second of the test systems consisting of two generators (2nd order model), two subsystems, and four

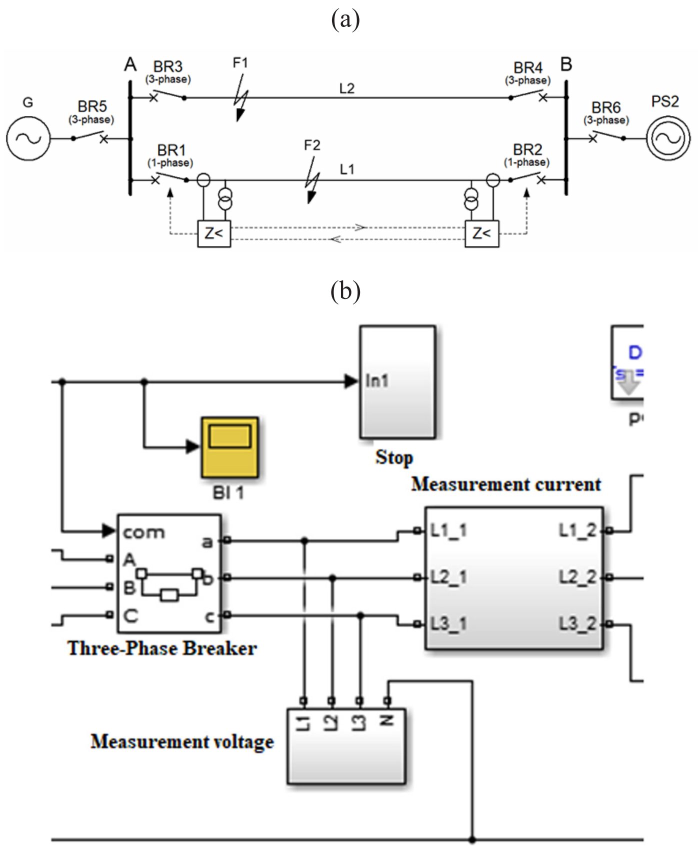


Fig. 4. Exemplary test system with one generator: a) schematic diagram, b) implementation of the system in MATLAB/Simulink

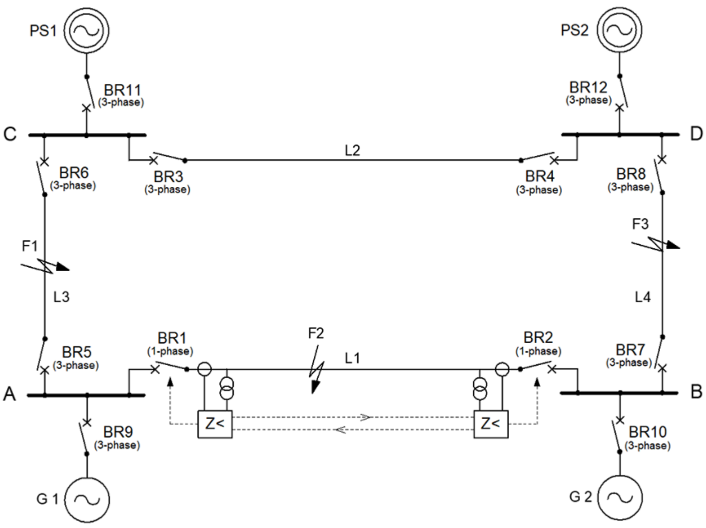


Fig. 5. Exemplary test system employing two generators: schematic diagram

lines modeled with the coupled PI sections. The current and voltage measurements at both ends of the L1 line, in station A and station B, are transferred to the D60 relays, which control the BR1 and BR2 single-phase circuit breakers in fault conditions.

3.3. Test object

The devices tested with the proprietary RTS are two D60 distance relays. The D60 device is a microprocessor protection relay intended for use in power lines of any voltage level, both in systems with single-pole and three-pole circuit breakers. The main function of the D60 relay is the distance protection function consisting of five measurement zones (separate from phase-to-phase and earth fault detection). The function was subjected to laboratory tests as part of the tests of the D60 relays performed with the RTS distance with active power swing detect (PSD), auto reclose (AR) and the concurrent coordination scheme excluding the extended zone (POTT – permissive overreaching transfer trip) – in the case of relays D60, it is the zone Z2. In addition, some tests were executed using the direct underreaching transfer trip (DUTT) coordination scheme, the permissive under-reaching transfer trip (PUTT), and with no coordination scheme between the D60 relays.

4. DISTANCE PROTECTION COORDINATION SYSTEMS – LABORATORY SETUP

As part of checking the correctness of the operation of the constructed RTS, various coordination systems of distance protection operation were tested. This chapter describes the anticipated ways of their operation.

4.1. Direct underreaching transfer trip

The method of realization of the common unconditional coordination system (direct underreaching transfer trip – DUTT) in the D60 relays is shown in Fig. 6. Activation of the D60 relay in station A, during a short circuit in its zone Z1, is used to generate a remote trigger signal for the D60 relay in station B. The D60 relay in station B receives this signal and unconditionally generates a signal to open the circuit breaker.

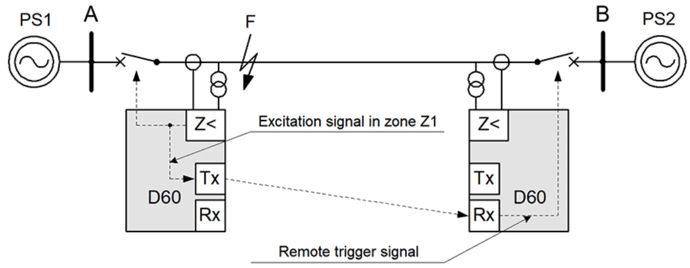


Fig. 6. Implementation of the coordination of the operation of D60 distance relays in the DUTT system

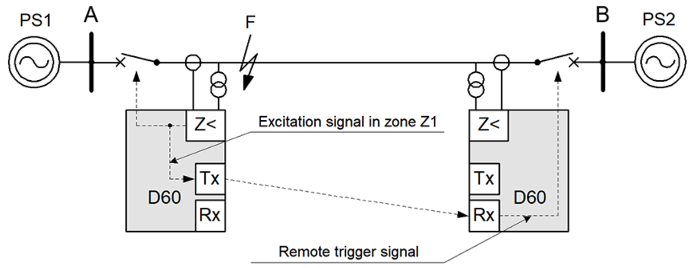


Fig. 7. Coordination of the operation of distance relays D60 in the PUTT system

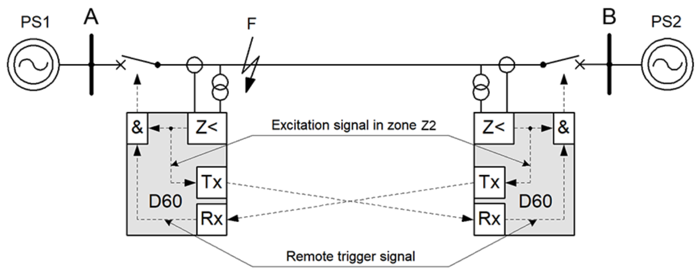


Fig. 8. Coordination of the operation of D60 distance relays in the POTT system

4.2. Permissive underreaching transfer trip

The implementation of the concurrent coordination system with permission (permissive underreaching transfer trip – PUTT) in the D60 relays is shown in Fig. 7. The activation of the D60 relay in station A, during a short circuit in its zone Z1, is used to generate a remote trigger signal for the D60 relay in station B. The circuit breaker is generated by the D60 relay in station B after two conditions are met: local pick-up in one of the "forward" zones and receiving a remote trigger signal from the D60 relay in station A.

4.3. Permissive overreaching transfer trip

The implementation of the coordination system with exclusion from the extended zone (permissive overreaching transfer trip – POTT) in the D60 relays is shown in Fig. 8. To generate a remote trigger signal for a relay in the opposite station, the D60 relays use the Z2 zone. The signal to open the circuit breaker is generated by the relay D60 after two conditions are met: local pick-up in zone Z2 and receiving a remote trigger signal from the relay D60 from the opposite station.

4.4. Directional comparison blocking scheme

The implementation of the coordination with the transmission of the blocking signal (directional comparison blocking scheme – DCB) in the relays D60 is shown in the example in Fig. 9. The relays D60 use their reverse zone to generate a remote blocking signal for a relay in the opposite station. When an external short-circuit occurs, relay D60 in station B picks up in the reverse zone and sends a blocking signal to relay D60 in station A. Relay D60 in station A receives this signal and does not generate a signal to open the switch.

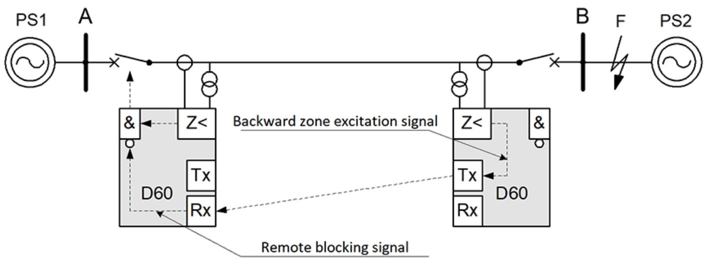


Fig. 9. Implementation of coordination of operation of D60 distance relays in the DCB system

4.5. Directional comparison unblocking scheme

The operation of the coordination with transmission of the unlocking signal (directional comparison unblocking scheme – DCUB) is analogous to that of the DCB system, with the DCUB sending the signal enabling the fast operation. To generate a remote unlocking signal for a relay in the opposite station relays, D60 was using zone Z2. When an internal fault occurs, relay D60 picks up an unlock signal in the "forward" zone and sends it to relay D60 in the opposite station. Relay D60 in the opposite station receives this signal, which is equivalent to allowing the generation of the signal to open the circuit breaker.

5. RESEARCH RESULTS

Below, the selected research results on D60 relay testing are presented. The investigation was performed based on the models described above. Figure 10 shows the settings of the Phase Distance function zones (detection of phase-to-phase short-circuits) and the settings of the inner and outer zone of the Power Swing Detect function used during the tests.

5.1. Three-phase short circuit at the beginning of the protected line L1

The test was executed on the test circuit shown in Fig. 4. A three-phase short circuit in the L1 line was simulated; at a distance of 20 km from the relay point in station A (10% of

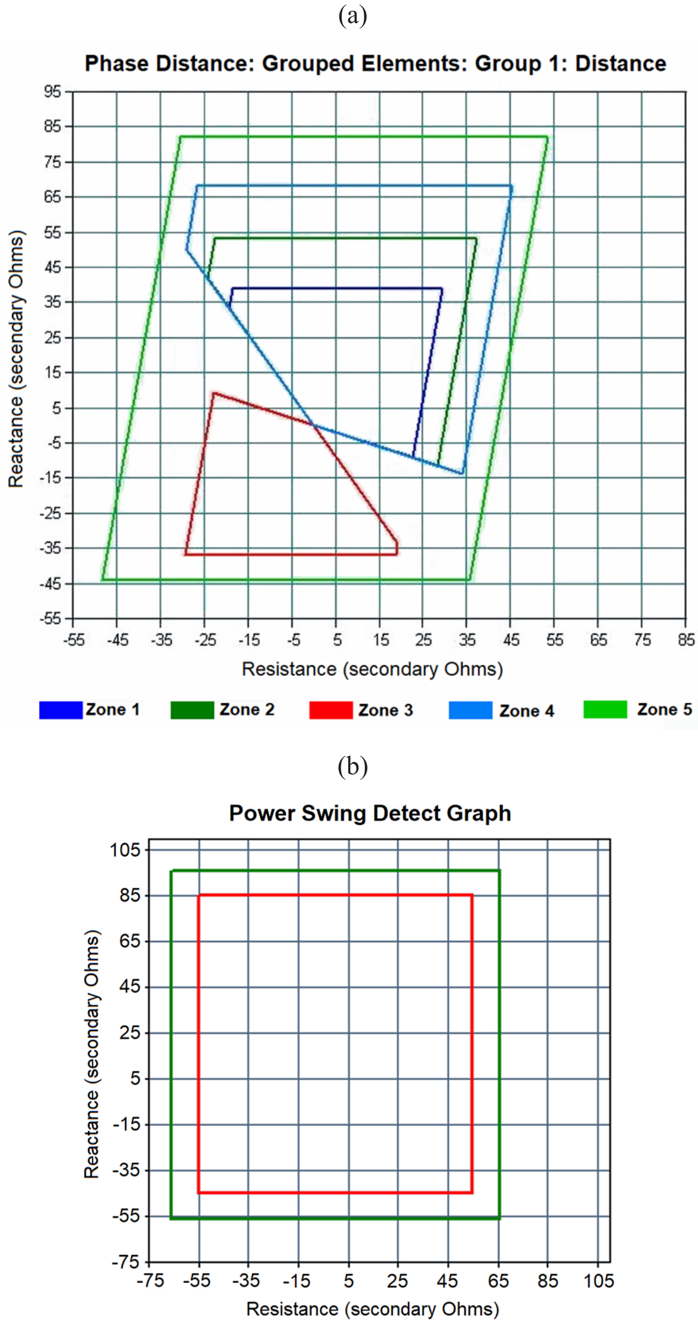


Fig. 10. Settings of D60 relay functions: a) ranges of zones of the Phase Distance function, b) settings zones of the Power Swing Detect function

the length of the L1 line). The short circuit was in the Z1 zone of the relay in station A and the Z2 zone of the relay in station B. In the D60 relays located at both ends of the L1 line, the distance protection and swing blocking functions were activated, automatic reclosing (single action), and POTT protection coordination system.

Relays D60 worked properly, the POTT coordination system was correctly implemented. Each of the relays met two conditions: local excitation occurs in the Z2 zone (PH DIST Z2 PKP signals) and sends (POTT TX4 signal) and receives the POTT

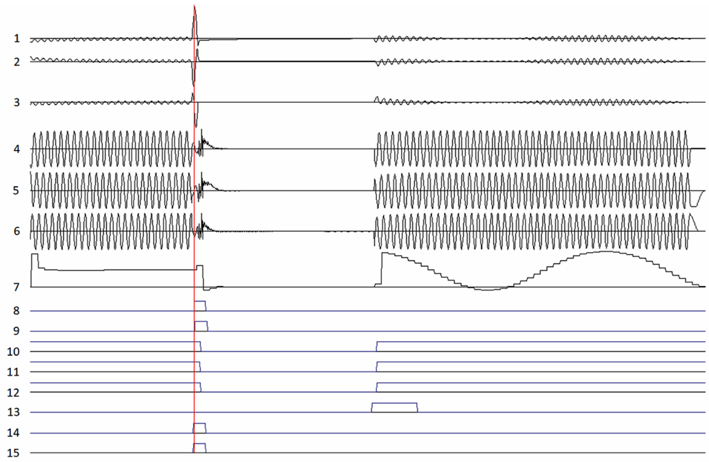


Fig. 11. Readout of the D60 relay recorder in station A, where: 1 – F1-IA; 2 – F2-B; 3 – F3-IC; 4 – F5-VA; 5 – F6-VB; 6 – F7 – VC; 7 – SRC 1P; 8 – PH DIST Z1 OP; 9 – TRIP 3-POLE; 10 – BREAKER 1A CLOSED; 11 – BREAKER 1B CLOSED; 12 – BREAKER 1C CLOSED; 13 – AR CLOSE BKR1; 14 – POTT TX4; 15 – PH DIST Z2PKP

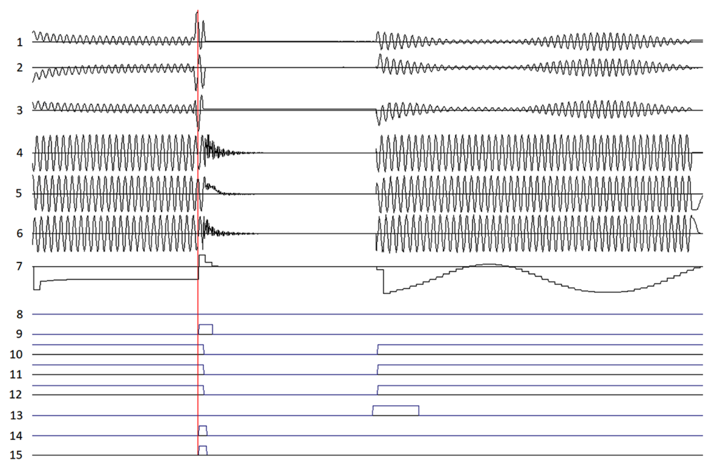


Fig. 12. Readout of the D60 relay recorder in station B, where: 1 – F1-IA; 2 – F2-B; 3 – F3-IC; 4 – F5-VA; 5 – F6-VB; 6 – F7 – VC; 7 – SRC 1P; 8 – PH DIST Z1 OP; 9 – TRIP 3-POLE; 10 – BREAKER 1A CLOSED; 11 – BREAKER 1B CLOSED; 12 – BREAKER 1C CLOSED; 13 – AR CLOSE BKR1; 14 – POTT TX4; 15 – PH DIST Z2PKP

signal from the opposite station. The readout of the D60 relay recorder in station A is shown in Fig. 11. The D60 relay in station A operated in zone Z1 (PH DIST Z1 OP signal) and sent the POTT signal (POTT TX4 signal) to the relay in station B. Relay sent a signal to open the BR1 switch (signal TRIP 3-POLE) with a time of 12 ms, all poles of switch BR1 were opened (BREAKER CLOSED signals set to low state). The no-current time was 533 ms, after which a three-phase one-time ARC cycle was successful (AR CLOSE BKR1 signal high). The readout of the D60 relay recorder in station B is shown in Fig. 12. The D60 relay in station B did not work in zone Z1 (PH DIST Z1 OP signal in the low state), but after receiving the POTT signal from the relay from station A, it sent a signal to open the BR2 switch (signal TRIP 3-POLE) with a time of 17 ms, all poles

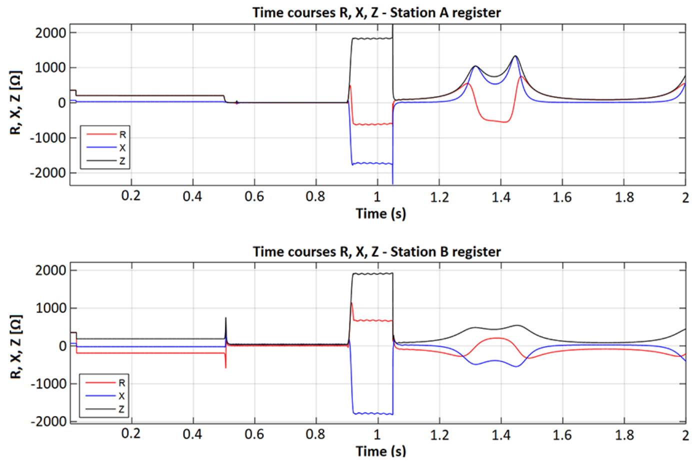


Fig. 13. Time courses of positive components *R*, *X*, *Z* as seen at relay points A and B

of the switch were opened (BREAKER CLOSED signals set to low state). The no-current time is 526 ms, after which a three-phase one-time ARC cycle was successful (AR CLOSE BKR 1 signal high). Relay D60 in station B, despite the lack of activation in zone Z1, worked for a short time. This was the result of the correct operation of the POTT type coordination system. Time histories of the positive sequences *R*, *X*, *Z* seen in the relay points are shown in Fig. 13. The positive sequence trajectory of the positive sequence impedance at the relay point A on the *X*(*R*) plane is shown in Fig. 14. The figure shows the moving impedance input to the relay zone Z1 D60 in station A. After the fault was cleared, synchronous swings appeared in the L1 line, which on the *X*(*R*) plane were manifested by the course of the impedance trajectory along the characteristic arc.

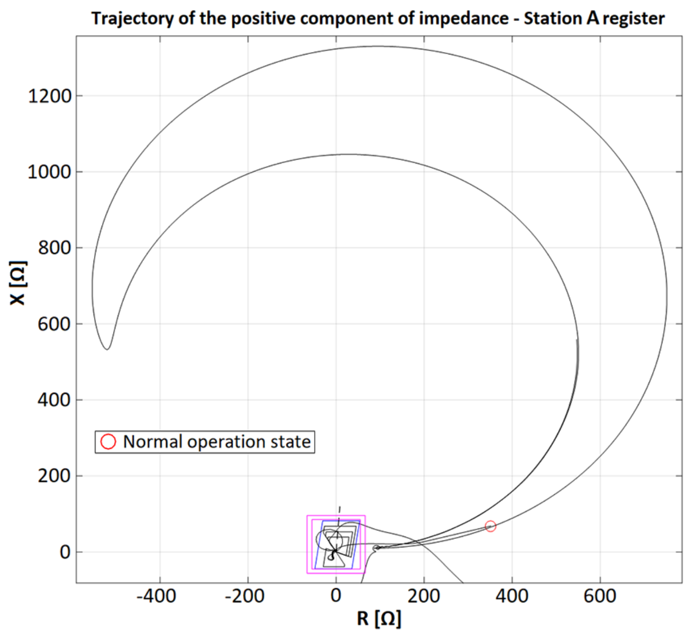


Fig. 14. Positive sequence path of impedance at the relay point A on the *X*(*R*) plane

5.2. Three-phase short circuit with earth at the beginning of the L2 line (the line adjacent to the protected line)

The test was executed on the test circuit shown in Fig. 4. A three-phase short circuit with earth on the L2 line was simulated, at a distance of 20 km from the busbars of station A (10% of the L2 line length) with a duration of 400 ms, interrupted by switching off the L2 line 150 ms after the short circuit occurred. The following functions are activated in the D60 relays: distance, automatic auto-reclose (single action), and power swing blocking function. The POTT coordination scheme of distance protection operation was used.

The disconnection of the L2 line during a short circuit causes the appearance of synchronous power swings in the L1 line (with D60 relays installed). The D60 relays in both stations record the operational impedance input to the swing blocking zones and the distance function zone Z5. The readout of the D60 relay recorder in station A (analog signals and internal logic signals of the relay) is shown in Fig. 15.

The time waveforms of the impedance seen in the relay points A and B are shown in Fig. 16. The positive sequence path of the impedance is shown in Fig. 17. in the case of the D60 relay in station B during a short circuit in the L2 line. After the short-circuit is cleared, synchronous swings appear in the L1 line, which on the $X(R)$ plane is manifested by the impedance trajectory along the characteristic arc. The input of the operational impedance to the Z5 zone of the relays is visible during power swings.

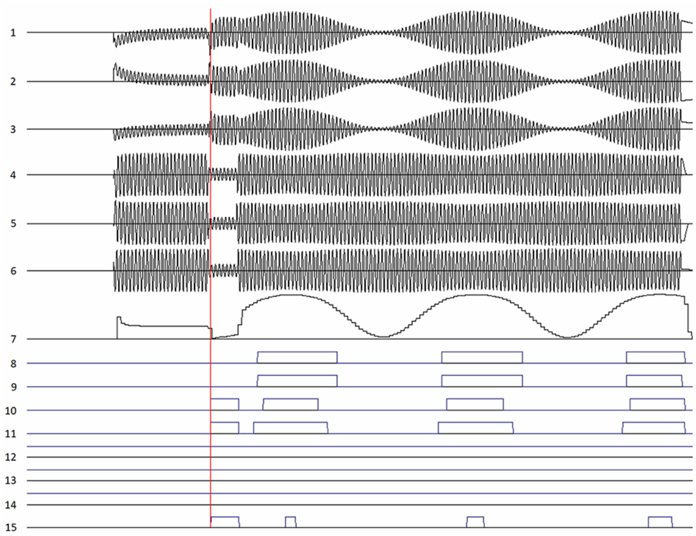


Fig. 15. Recordings of time characteristics of the relay D60 in the relay point in station A, where: 1 – F1-IA; 2 – F2-B; 3 – F3-IC; 4 – F5-VA; 5 – F6-VB; 6 – F7 – VC; 7 – SRC 1P; 8 – Power swing block; 9 – Power swing un/block; 10 – Power swing inner, 11 – Power swing outer; 12 – BREAKER 1A CLOSED; 13 – BREAKER 1B CLOSED; 14 – BREAKER 1C CLOSED; 15 – PH DIST Z5 PKP

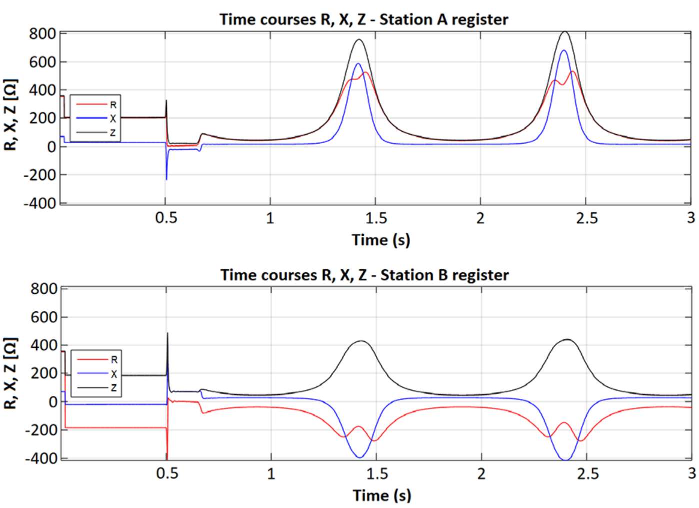


Fig. 16. Impedance time characteristics in the relay point in stations A and B

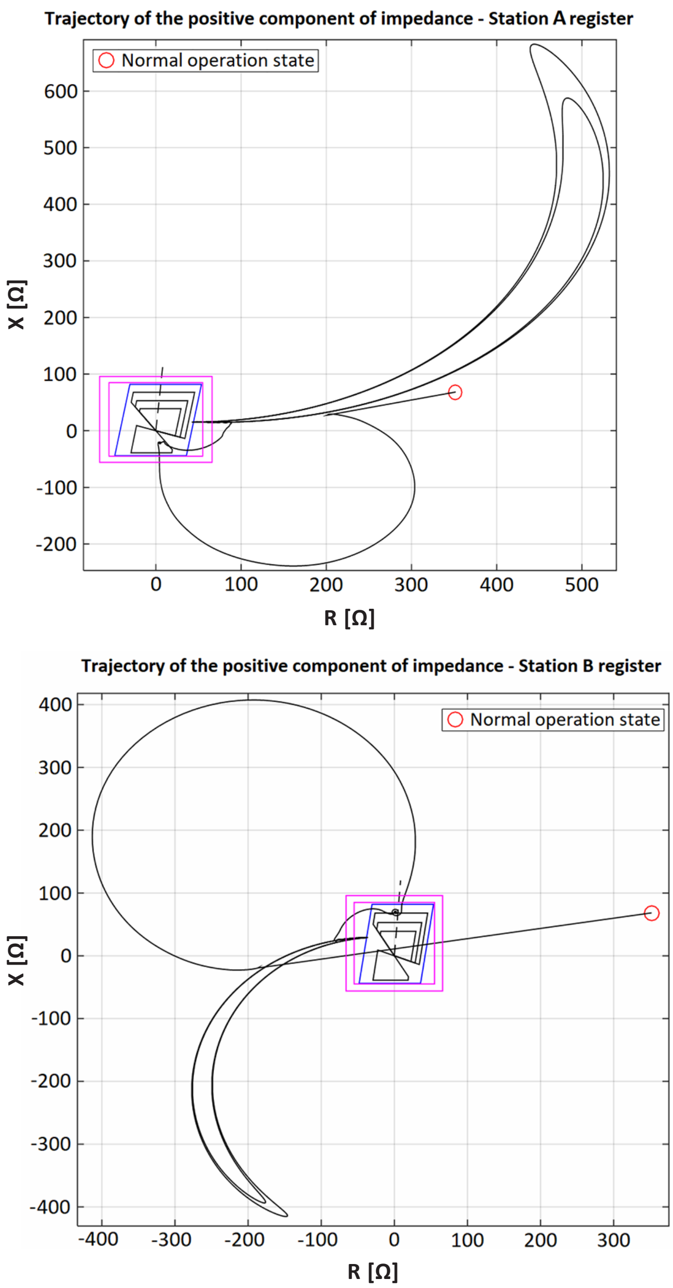


Fig. 17. Positive sequence path of impedance on the impedance plane at relay points in stations A and B

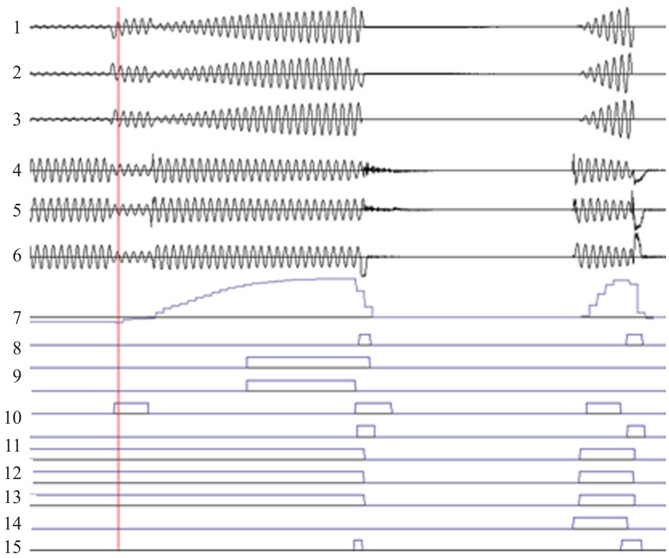


Fig. 18. Recordings of time courses of the relay D60 in the relay point in station A, where: 1 – F1-IA; 2 – F2-B; 3 – F3-IC; 4 – F5-VA; 5 – F6-VB; 6 – F7 – VC; 7 – SRC 1P; 8 – PH DIST Z1 OP, 9 – POWER SWIG 50DD, 10 – TRIP 3-POLE, 11 – BREAKER 1A CLOSED, 12 – BREAKER 1B CLOSED, 13 – BREAKER 1C CLOSED, 14 – AR CLOSE BKR 1, 15 – POTT TX4

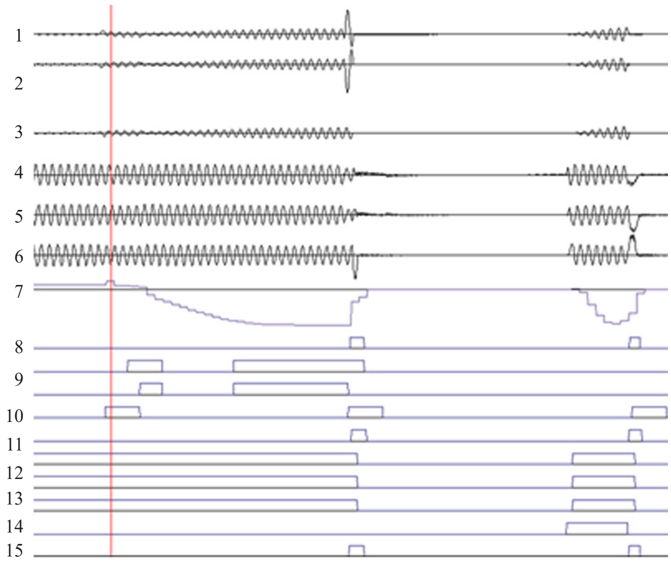


Fig. 19. Recordings of time courses of the relay D60 in the relay point in station B, where: 1 – F1-IA; 2 – F2-B; 3 – F3-IC; 4 – F5-VA; 5 – F6-VB; 6 – F7 – VC; 7 – SRC 1P; 8 – PH DIST Z1 OP, 9 – POWER SWIG 50DD, 10 – TRIP 3-POLE, 11 – BREAKER 1A CLOSED, 12 – BREAKER 1B CLOSED, 13 – BREAKER 1C CLOSED, 14 – AR CLOSE BKR 1, 15 – POTT TX4

5.3. Two-phase short-circuit at the end of the protected line L1, preceded by a three-phase short-circuit with earth at the end of the L3 line (the line adjacent to the protected line)

The test was executed on the test circuit shown in Fig. 5. A three-phase short circuit with earth on the L3 line was simulated, at a distance of 40 km from the busbars of station A (80% of the length of the L3 line) with a duration of 400 ms, interrupted by switching off the L3 line 100 ms from the moment of the short circuit. During synchronous swings of power, there is a two-phase A-B fault on the L1 line, at a distance of 180 km from the D60 relay in station A (90% of the L1 line length) with a duration of 100 ms. The short-circuit occurs at the moment when the motion impedance trajectory enters the inner zone of the power swing blocking function. The following functions are activated in the D60 relays: distance, automatic auto-reclose (single action), and power swing blocking function. The POTT coordination scheme of distance protection operation was used.

When a short circuit occurs on the L1 line, both relays D60 work properly. The UN/BLOCK power swing blocking function signals are reset by the high state of the 50DD disturbance detector signals (indicating that the D60 relays may operate). The scheme of POTT protection operation coordination is correctly implemented because each of the relays meets two conditions: local activation in the Z2 zone and receiving the POTT signal from the relay from the opposite station.

Relay D60 in station A sends a signal to open the circuit breaker with a time of 6 ms (information from the relay internal disturbance recorder this time is longer), all poles of the circuit breaker are open. The dead time (no current time) is 530 ms, after which a three-phase one-time failed ARC cycle is performed. Again, after 138 ms, all poles of the circuit breaker open. The recording by the internal fault recorder of relay D60 at station A is shown in Fig. 18.

Relay D60 in station B sends a signal to open the circuit breaker with a time of 7 ms (information from the relay internal disturbance recorder this time is longer), all poles of the circuit breaker are open. The dead time is 524 ms, after which the three-phase one-time failed ARC cycle is performed. Again, after 158 ms, all poles of the circuit breaker open. The recording by the internal fault recorder of relay D60 at station B is shown in Fig. 19.

6. SUMMARY

Commercial simulators with which power engineering automation devices can be tested cost hundreds of thousands of dollars. Many technical universities and research laboratories cannot afford such a large financial burden. The authors of the article have developed a real-time simulator of the phenomena that facilitates testing the correct operation of up to two power relays. Using the simulator it is viable to check, two-section protections (differential, phase comparison) or distance protections (including coordination of their operation). The advantage of the built simulator is that it uses the MATLAB/ Simulink software, often used and well-known in the academic environment.

The built RTS is an alternative to commercial simulators operating in real-time of power system phenomena. It can be used to test power relays of leading manufacturers. The presented results indicate the correctness of the hardware configuration, the software, and the idea of building an original real-time simulator.

At a later stage of the research, the expansion of the simulator is planned to enable testing the protections of renewable energy systems and control systems improving the overall stability of the power system.

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