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Smart Relay Protection of Electric Networks: an Analysis of the Technical Means for Investigation Tests

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Abstract: The existing equipment for performance test of relay protection devices is not completely suitable for the development of these new devices. The study reviews the technical means which may be used for investigation testing of a breadboard of smart relay protection for electrical network that was designed in University "Dubna". The equipment for testing and adjustment of relay protection and automation devices was reviewed, the possibility of its limited use for breadboard tests was noted. It is shown that obtaining a plurality of analog and digital signals needed for breadboard tests requires creation of a mathematical or physical model of the electrical network. Software and hardware real-time systems allow full hardware-in-the-loop testing, however, they are very expensive and their operation is complicated. Physical modeling is optimal for testing as is free from mathematical modeling errors, allows easily to gain necessary mode parameters in real time and the cost of such a model is relatively small. The questions of interaction between the breadboard of a smart relay protection with a physical model of the electrical network in the tests are discussed.

Key words: Smart relay protection, modeling, investigation testing, analog signals, digital inputs and outputs, hardware and software systems, real-time, physical network model

INTRODUCTION

Modern Relay Protection and Automation (RPA) systems, as a rule, are a set of microprocessor terminals interconnected via communication channels. Each terminal is designed to perform relay protection, automation and alarming functions for any single network object or substation connection (power line, transformer, electric motor, etc.). Individual protection devices operate autonomously and independently deciding on the what protected object is to be disconnected in the event of an emergency. No-operation of individual RPA terminals in an electrical network is usually achieved by proper selection of operate values, i.e., without the use of physical communication channels (Bulychev, 2011). This ensures high reliability of relay protection.

Developments of innovative relay protection systems are underway, in particular, based on using the IEC 61850 protocol within the substation (Dorofeev, 2011; Nudelman, 2011; Orlov, 2012) as well as with centralization of security, automation and alarming functions (Voloshin *et al.*, 2012; Dorofeev, 2011). Implementation of these systems is hampered by the absence or imperfection of normative and technical documentation, problems of matching with traditional relay protection and automation systems, the lack of highly qualified personnel. However, the general trends in the development of relay protection in these areas are clearly seen both in Russia and abroad (Lei and Syuepen, 2012).

The State University "Dubna" performed research on development of smart relay protection for active-adaptive power supply. To date, the relay protection algorithms have been designed with high sensitivity to changes in the topology, parameters and modes of electrical networks, as well as algorithms for improving the safety and adaptive properties of energy systems through the use of Fast Automatic Transfer Switch device (FATS) using a fast actuator. The breadboard of a smart relay protection was made that implements the algorithms.

At the final stages of the research it was planned to carry out investigation tests of the breadboard made by us of a smart relay protection. In this connection there

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arose the problem to select an equipment for their implementation based on the need to verify compliance with the requirements for the breadboard (prescribed in the specification) as well as its technical characteristics. It turned out that the existing equipment for testing relay protection characteristics is not completely suitable for the breadboard of smart relay protection and there are various approaches for testing that have both advantages and drawbacks. This study describes results of reviewing the means that may be used to conduct investigation tests of the designed breadboard of smart relay protection.

MATERIALS AND METHODS

Bread board smart relay: The purpose of the investigation tests of breadboard smart relay protection of an electrical network was:

- Functional testing of relay protection for all kinds of emergencies provided (short-circuit, ground fault, etc.)
- Verification of compliance with the requirements of the specification on relay protection speed and FATS algorithm
- Sensitivity test of a relay protection for different parameters of an emergency mode
- Checking selectivity of operation of a relay protection at emergencies in various points of an electrical network

Let us first consider the existing equipment for testing and adjustment of relay protection and automation devices that is used in the adjustment organizations, in RPA services for maintenance of substations and electrical networks. The most common domestically produced equipment in addition having the broadest options are RETOM tomography relays of models RETOM-21, RETOM-51, RETOM-61 (Fig. 1). There are also widely used testing units MICRON, relay protection testing devices of series "Neptun" ("Neptun", "Neptun-2", "Neptun-3"), series "Uran" ("Uran-1", "Uran-2"), devices UNEP-2000 for testing electric equipment protection used in 6-10 kV substations. There should be noted such foreign equipment of this class as devices Omicron CMC 356, T-1000 PLUS and T-3000 manufactured by company ISA, DRTS 64 and DRTS 66. Features of individual models of the listed above equipment are significantly different but almost all of them have:

Fig. 1: Test complex RETOM-61

- Three AC power sources (six sources in the new models) allowing to feed the tested device by three-phase sinusoidal industrial-frequency current with the upper range from 20 to over 100 A (depending on model) with smooth or step current value regulation
- Three AC voltage sources allowing to apply to feed the tested device by three-phase sinusoidal industrial-frequency voltage system with smooth regulation of voltage amplitude
- Electronic millisecond timer with a lower limit of measurement from 1 millisecond allowing the relay response time to measure precisely
- Regulated DC power supply source which allows checking the device performance capacity at various levels of the supply voltage
- Built-in short-circuit relay protection (also often with overheating protection) for all sources
- A set of digital inputs and outputs to control the protection operation

Advanced models are provided for operation of the equipment together with a personal computer for data visualization and storage. A computer is connected through a USB port or Ethernet; availability of Ethernet port makes it possible not only to increase the communication speed between the device and the computer but also to include the device to the LAN.

Digital inputs allow registering the fact of contact closure of separate relays and actuation of output circuits of a relay protection terminal as a whole. Digital outputs implemented in powerful relays can not only control a secondary electrical equipment and also to close the enabling and disabling circuits of high-voltage switches. The number of such inputs and outputs is determined by the purpose and functionality of the device. So, RETOM-51 is provided with 8 digital inputs and 4 digital outputs and the model RETOM-61 with 32 digital inputs and 24 digital outputs.

Devices for check and adjustment of relay protection and automation provide not only formation of analog signals and also their measurement that allows the use of equipment such as measuring devices with wide functionality. For example, “Neptun-3” is capable of measuring alternating current rate within the range from 0.001-10 A, an alternating voltage within the range from 0.01-600 V, the phase angle between current and voltage within the range from 0-360° and the sinusoidal signal frequency within the range from 40-550 Hz. Devices of series RETOM, “Neptun”, MICRON are included in the state register of measuring instruments and are subject to periodic verification that ensures the required measurement accuracy and stability of the output characteristics.

Review of the functionality of the considered devices for testing and adjustment of relay protection shows that the number of analog and digital inputs, as well as a list of features are fully sufficient for verification of any individual relay protection and microprocessor terminal assembly. However, there are difficulties if it is necessary to work with devices that have a large number of inputs and outputs. For example, a breadboard of smart relay protection has 13 three-phase current inputs, 2 three-phase and two-phase voltage inputs and 13 digital inputs and outputs. Obviously, the devices designed for checking a single terminal with a limited number of analog and digital inputs are not able to provide the power supply and control of all inputs of the breadboard concerning neither analog, nor digital signals. By performing alternate connection of a RETOM type device or the like to the analog inputs of the breadboard it is possible to check and calibrate them as well as to check the operation of the simplest current protection systems. With such an approach, comprehensive functional testing of more sophisticated security algorithms taking into account control of actuation of all digital inputs and outputs is impossible. It requires either to use a set of RETOM type devices (that is very expensive and also requires their synchronisation) or the use of special research facilities to produce a given number of mode parameters what will be discussed further.

Obtaining the required number of analog and digital signals that is sufficient for simultaneous delivery to all inputs of relay protection breadboard is possible provided a full simulation of the electrical network with the generation of the respective mode settings (current and voltage) as well as digital signals of breaker positions. There are two ways to implement the electrical network model:

- Mathematical modeling in which the network is designed in a specialized software in the form of a computer model and the mode parameters and digital signals are obtained as a result of such simulation
- Physical modeling when models of individual network elements (transformers, transmission lines, electric motors, switchgear bus) is created as small copies of actual devices, upon that, the mode parameters and digital signals of the model by their physical nature fully correspond to those in the real network and differ only by scale factors

Let’s consider these two methods one after another. There are many software packages for simulating steady and transient modes of electrical networks operation (EnergyCS, SiemensPSS-E, PowerFactory, PSCAD, etc.). Their capabilities in modeling the modes are sufficient for the purposes of calculation and verification of relay protection systems in networks of virtually any dimension. The programs are characterized by a user-friendly graphical interface, extensive libraries; they have a variety of settings and allow receiving accurate and detailed simulation results. This may also include Simulink simulation environment with Sim Power Systems library.

Mathematical modeling with use the above mentioned software packages gives a result as an array of numerical values stored in computer memory. Direct use of these data for interaction with protection, automation and control equipment is impossible; it requires additional hardware and software devices for formation of physical signals on the basis of numerical data. Further, mathematical modeling based on personal computers is normally carried out not in real time and with a significant deceleration (for example, rendering of 1 sec transient process requires 10 sec of real time) due to the need to process data bulks. At the same time, the coordinated work of the mathematical model on the computer and physical protection, automation and control equipment requires real-time calculations.

The solution is the creation of software and hardware systems which combine a real-time simulator which is a high-performance hardware for quick calculation of mode parameters (multi-processor computer systems with hardware computation parallelization) and a set of hardware outputs for connection to external devices and transfer of calculations results to them. Such systems allow simulating the operating conditions of the power equipment, control systems, relay protection and automation of electrical systems in real time, as well as implementation of HIL (Hardware-In-the-Loop) testing the relay protection and automation algorithms. HIL is a common modern method of research and testing of control and protection systems what allows comprehensive assessment of hardware and software functionality of the system. With this approach, the

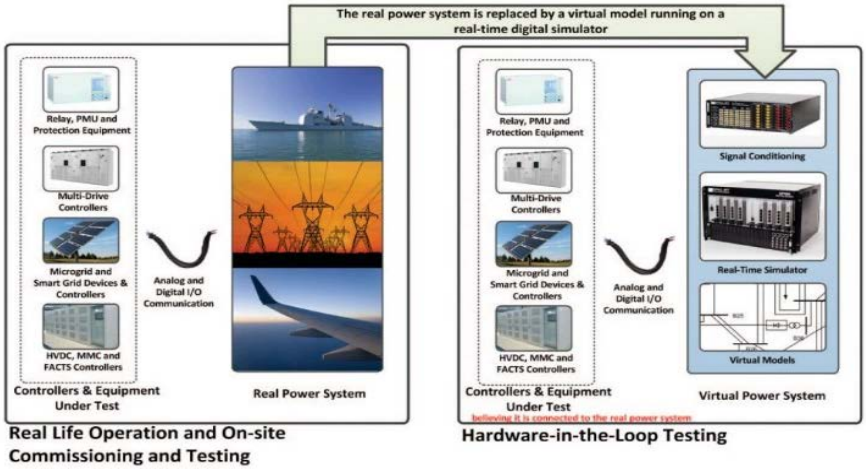

Fig. 2: HIL (Hardware-In-the-Loop) testing

equipment under test (for example, a relay protection device) is connected to the simulator via analog current and voltage interfaces and digital inputs/outputs as well as to the actual system (Fig. 2). The simulator incorporates the virtual model of the electrical system within which the device is to operate. During a test the simulator generates in real time voltages and currents that best meet the real operation modes of the electrical network (steady state, transient processes in various emergency situations). Thus, it is possible to test operation of the device in all typical situations and conditions that may arise during its actual operation in the electrical network.

The most powerful, famous and widespread among software and hardware complexes for real-time modeling of electrical systems is the RTDS. Complex RTDS is used by many of the world's leading manufacturers of electrical equipment, relay protection and control devices (ABB, AlstomGrid, GE, Siemens, etc.). It provides both open loop testing (i.e., reading in COMTRADE format or the open-loop simulation) and testing in a closed HIL cycle (with feedback) (Zakonshek and Slavutskiy, 2012). RTDS has an extensive library of components of a power system and control systems, including power electronics elements, HVDC, STATCOM and other devices. RTDS has a modular design: a set of cartridges (cubicles) each of which includes processor boards and communication boards (Fig. 3). If the network size exceeds the capacity of one cubicle it must be broken down into subsystems then each cubicle will perform calculations for its subsystems. The maximum size of a network solution is 72 single-phase nodes, two network solutions can be modeled on the same cubicle (Zakonshek and Slavutskiy, 2012). The graphical user interface is implemented as a RSCAD

Fig. 3: The full-size version of RTDS cubicle

program that allows convenient displaying the scheme of a modeled network, set and control the modeling parameters, record and document the results.

RTDS complex cost is very high, so for many applications it is efficient to use eMEGAsim which is a Simulink specially designed for the digital simulation of electric power systems in real time. The Tomsk Polytechnic University has developed a hybrid multiprocessing software and technical system-all mode real-time modeling complex EES (EPS WMC PB) (Borovikov *et al*., 2014). This complex is designed within the framework of the "hybrid modeling" concept combining analog, digital (numerical) and physical modeling. As mentioned above, it also allows for verification of Relay Protection (RP) or Emergency Automation (EA) in HIL cycle (Fig. 4). An amplifier unit is used to match the low-power outputs VMK RV EPS with RPA device. Complex VMK RV EPS has several important advantages over RTDS and eMEGAsim; for example, it eliminates the methodological error in solving differential

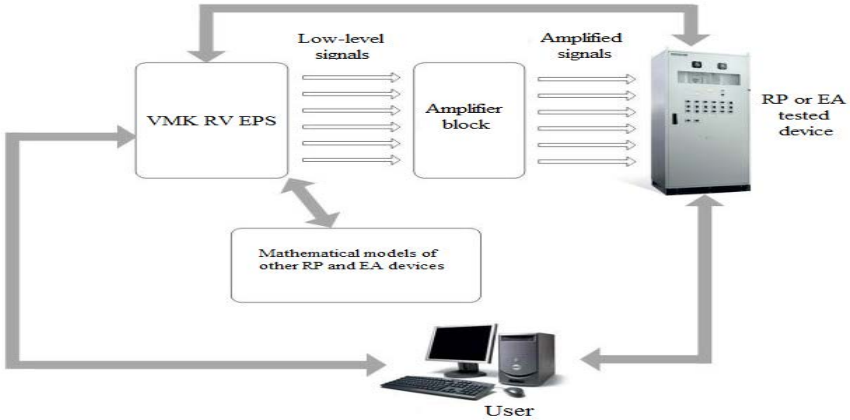

Fig. 4: RP or EA device testing in HIL cycle using VMK RV EPS complex

equations that provides an exact solution, regardless of the differential order, solution stiffness and interval (Borovikov *et al*., 2014).

RESULTS AND DISCUSSION

In general, it should be noted that the simulation of the electrical network with software and hardware real-time allows virtually to explore all operating modes, any network diagrams (with the limitations on the number of units imposed by the hardware implementation), as well as to achieve a high degree of computerization and automation of research. However, for a variety of applications, these complexes have excess functionality, difficult to operate and have a high cost.

Therefore, the optimal solution to carry out researches not related to a detailed study of processes at small time intervals (e.g., at microsecond intervals that is required for today's manufacturing of power electronics and FACTS devices) is the use a physical model of the electrical network. Compared with the computer model this decision has a greater clarity of the physical processes and its cost is less than the cost of real-time systems such as RTDS or eMEGAsim. Physical modeling is free from a number of sources of uncertainties and errors inherent to computer modeling (wrong choice of method for solving differential equations, excessively large integration step, errors in the initial conditions and so forth). Processes in the physical model naturally occur in real time, allowing it to be connected directly to the tested equipment. Accordingly, the use of physical models for investigation tests of a breadboard of smart relay protection for electrical networks is the optimal solution.

The disadvantage of the physical model is the large weight and dimensions which however, is not so critical for fixed installations. In addition, the parameters of the model elements can be varied in a relatively small range and the list of items is limited by a manufacturer's

Fig. 5: The appearance of the electrical system model EE2-RZAES-S-K

nomenclature. The last two disadvantages are eliminated partly or fully by the development of own elements of the physical model for a particular research problem.

Physical models of electrical networks that can be used for research projects are presented on the Russian market by products of "GalSen" and "Uchtekh-Profi" companies. As an example, Fig. 5 shows a model of the electric system EE2-RZAES-S-K manufactured by "GalSen" company allowing to carry out various studies in the field of relay protection and automation of power systems. In addition to standard models designed for use in the learning process for a variety of engineering disciplines, manufacturing of physical models to order with an arbitrary configuration and a list of equipment is possible.

Creation of a physical model of an electric network is also possible with the use of foreign-made equipment, for example, Lucas-Nulle company's products. However, the cost of this solution gets higher and the questions of creation of an individual physical model for a specific research task become much more difficult so that, it is advisable to use products of the specified Russian manufacturers.

When conducting investigation tests of a breadboard of smart relay protection for electrical networks, its analog input circuit should be connected to the secondary winding of current and voltage measuring transformers that are a part of the physical model of the electrical network. The breadboard digital inputs should be connected to the signals positions of the model breakers and digital outputs to breaker control circuits. Thus, the breadboard will be able to analyze the operating parameters of the model network, take into account the real state of breakers (that is, to analyze the network topology) and in case of emergencies to send a command to switch off the damaged equipment, thereby completely simulating real work of relay protection and automation devices. By creating the conditions that match to a given emergency situation at various points in the network, it is possible to check the operation of all relay protection algorithms embedded into the breadboard, the protection sensitivity, as well as to verify whether the selectivity of the protective actions is ensured. Fixing the analog current and voltage signals as well as digital signals using a digital oscilloscope will make it possible to register the parameters of the transitional mode and determine the performance of relay protection, then comparing the response time to the requirements of technical specifications. A breadboard response time can also be determined using an electronic stopwatch operated according to output discrete signals from the breadboard; for example, for this purpose IVPR-203M or similar devices can be used.

Thus, the physical model of the electrical network with connected instrumentation makes it possible to carry out all the necessary investigation tests of the developed breadboard of electrical network smart relay protection.

CONCLUSION

The number of analog and digital inputs in existing equipment for testing and adjustment of relay protection and automation devices (RETOM, “Neptun”, MICRON, Omicron, DRTS) allows in turn to check and calibrate the analog inputs of the developed relay protection breadboard and check the operation of the simplest security algorithms. Features of the hardware are not enough for a comprehensive breadboard verification taking into account the operation control of the digital inputs and outputs. Obtaining the required number of analog and digital signals for all inputs of the relay protection breadboard is possible with the full simulation of the electrical network. Two methods of implementation of the electrical network model were considered: mathematical and physical modeling. It is shown that simulation of the electrical network in the real-time software and hardware complexes allows for check of relay protection and automation in HIL cycle, enables to test operation of the device in all situations and typical operating modes. Physical modeling of the network is more clear, free from inaccuracy and errors of mathematical modeling, easy to implement in real-time and the cost of the physical model is lower than the real-time systems such as RTDS or eMEGAsim. Therefore, the use of a physical model for the investigation tests of a breadboard of electrical network smart relay protection is the best option. It is shown that the features of the physical network model combined with instrumentation is sufficient to conduct all the necessary investigation tests of a smart relay protection breadboard.

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