

Development of the Experimental Stand for Studying and Testing Digital Protection Terminals

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Abstract. However, the approach to designing laboratory stands for training students and electrical personnel on the specifics of using digital protections in most cases has remained the same, which does not allow for fully realizing their potential. The purpose of the work is to improve the quality of the knowledge and practical skills received by students in the work with digital protection blocks. To achieve the goal, a specialized laboratory stand for testing digital security terminals has been developed. The stand consists of a mathematical model of the protected object, implemented in the form of a computer program and hardware, which allows real-time conversion of changes in model mode parameters into physical signals transmitted to the digital protection device. The stand provides the terminal feedback with the model, which makes it possible to study the protection behavior in the characteristic operating modes of the protected element. The protection of the "line-transformer" block using the Siprotec 4 7SJ6 Siemens terminal is considered. It is possible to calculate the protection operation parameters, configure the digital protection device, and also check the correct operation of the protections by automatically simulating normal and emergency operation modes of the protected object. The software and hardware of the stand makes it easy to expand its capabilities by adding new models of power system objects and other digital protection devices. The equipment used in the developed stand does not require significant capital investments, which makes this approach accessible to higher educational institutions. **Keywords:** digital security terminal, experimental stand, crate system, analog-to-digital converter; digital-to-analog converter.

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Dezvoltarea standului experimental pentru studierea și testarea terminalelor digitale de protecție

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Rezumat. Dezvoltarea tehnologiilor a contribuit la utilizarea pe scară largă a terminalelor digitale multifuncționale de protecție a reelelor la instalațiile de energie electrică. Cu toate acestea, abordarea proiectării standurilor pentru predarea studenților și personalului specificul utilizării protecțiilor digitale în majoritatea cazurilor a rămas aceeași, ceea ce nu le permite să-și dezvăluie pe deplin capacitățile largi. Scopul lucrării este de a îmbunătăți calitatea cunoștințelor și abilităților practice primite de studenți în lucrul cu blocuri de protecție digitală. Pentru a atinge scopul, a fost dezvoltat un banc de testare de laborator specializat pentru testarea unităților de protecție digitală. Urmând tendințele actuale, standul constă dintr-un model matematic al obiectului protejat implementat sub forma unui program de calculator și hardware, care permite conversia în timp real a modificărilor parametrilor modului model în semnale fizice, transmis către un dispozitiv digital real de securitate. Standul oferă un feedback al terminalului cu modelul, ceea ce face posibilă studierea comportamentului de protecție în modurile de funcționare caracteristice ale elementului protejat. Se are în vedere protecția unității „transformator de linie” folosind terminalul Siprotec 4 7RJ6 fabricat de Siemens. Este posibilă calcularea parametrilor de funcționare a protecției, configurarea dispozitivului digital de protecție folosind atât butoanele de control de pe panoul frontal, cât și software-ul specializat DIGSI 4, precum și verificarea funcționării corecte a protecțiilor prin simularea automată a modurilor normal și de urgență ale obiectului protejat. Software-ul și hardware-ul standului facilitează extinderea capacităților acestuia prin adăugarea de noi modele de obiecte ale sistemului de alimentare și alte dispozitive de protecție digitală.

Cuvinte-cheie: terminal de protecție digitală, stand experimental, convertor analog-digital; convertor digital-analogic.

**Разработка экспериментального стенда для изучения
и тестирования цифровых терминалов защиты**

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Аннотация. Благодаря развитию технологий на замену широко распространённым в электроэнергетике электромеханическим реле пришли многофункциональные цифровые терминалы релейной защиты. Однако подход к проектированию лабораторных стендов для обучения студентов и электротехнического персонала особенностям применения цифровых защит в большинстве случаев остался прежним, что не позволяет полноценно раскрыть их возможности. Целью работы является повышение уровня получаемых обучающимися современных знаний и практических навыков работы с цифровыми терминалами защит. Наиболее существенным результатом достижения цели является разработка специализированного лабораторного стенда для тестирования цифровых терминалов защиты. Следуя современным трендам, стенд состоит из математической модели объекта защиты, реализованной в виде алгоритма и программы для персонального компьютера, а также аппаратной части, позволяющей в режиме реального времени преобразовать изменение параметров режима модели в физические сигналы, передаваемые на реальное устройство цифровой защиты. Стенд обеспечивает обратную связь терминала с информационной моделью, что позволяет провести исследование поведения защит в характерных для защищаемого элемента режимах работы. Рассмотрена защита блока «линия-трансформатор» с использованием терминала Siprotec 4 7SJ6 производства фирмы Siemens. Значимыми результатами для обучающегося является возможность рассчитать параметры срабатывания защит, произвести настройку цифрового устройства защиты, используя как органы ручного управления на передней панели, так и специализированное программное обеспечение DIGSI 4, а также проверить правильность работы защит путём автоматического моделирования нормальных и аварийных режимов работы защищаемого объекта. Программное и техническое обеспечение стенда позволяет легко расширять его возможности путём добавления новых моделей объектов энергосистемы и других устройств цифровой защиты. Важным является, что применяемое в разработанном стенде оборудование не требует значительных капитальных вложений, что делает данный подход доступным для высших учебных заведений и позволяет получить изделие с оптимальным соотношением стоимость–возможности.

Ключевые слова: цифровой терминал защиты, экспериментальный стенд, крейтовая система, аналого-цифровой преобразователь; цифро-аналоговый преобразователь.

INTRODUCTION

The knowledge of specialists to correctly calculate the parameters of protective relaying and automatics (PRA) to adjust the PRA devices increases the operation reliability and safety of the electric equipment service. It is therefore important still at the stage of study at a higher school not only to obtain theoretic knowledge but also practical skills of work with a modern equipment. To achieve this goal the laboratory stands are used.

Nowadays, microprocess protections are used mostly in the energy system. Functionality is their major advantage. A single device can fulfil the functions of the current, voltage, frequency, time relays and be integrated into the SCADA system (Supervisory Control And Data Acquisition); microprocess protections take a lesser place, they are characterized by a high flexibility and accuracy in measurements, automatic registering of emergency modes with their subsequent analysis [1, 2].

The devices of protective relaying are meant for protect various elements of the electric supply system, like the electric supply lines, motors, transformers, etc. Therefore, one possibility of a

modern laboratory stand the simulation of operation of these elements, which is achieved using the mathematic modeling.

Analysis of existing solutions

At CIS countries high schools, during the fulfilment of the laboratory works by the students, the outdated laboratory stands are used the ones primarily obtained in the 60th--80th years of the 20th century, or those manufactured by students or teachers using the equipment of electromagnetic or induction types, which ceased being used at plants [3, 4, 5, 6]. The latter fact interferes with the students' obtaining modern knowledges and competencies necessary for the work. Often, at a separate stand only one laboratory work is being fulfilled, which requires using rooms with large areas.

Modern industrial samples of the educational PRA stand [7, 8] are presented by constructions with several relays and a mimic diagram. Such kind of a scheme is shown in Fig. 1. These stands are multifunctional. A student is supposed to perform the work in two steps: first, calculation-theoretical, where he in the process of preparation to fulfil the task calculates the protection parameters

and, secondly, is a practical stage, which includes adjusting the stand for the work, for the protection of the necessary parameters of response and checking the correction of its work. The stand is applied with the instructional guidelines for the performance of possible laboratory works.



Fig. 1. NTTS-10.66 laboratory stand “Protection relaying in electric-supply systems”.

To be able to work with the microprocess terminals is an important skill for the modern specialist. This is why the educational stands that use the microprocess relay protection must be pointed out separately [9, 10]. The protection of this kind can be set far more parameters than, e.g., in electromechanical relays. The example of such a stand is shown in Fig. 2.

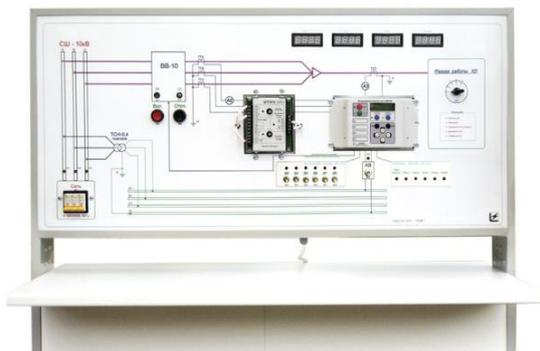


Fig. 2. NTTS-10.10.3 laboratory stand “Protection relaying and automation MP500”.

The above constructions of stands make it possible to learn how to use the equipment and check the correction of its operation. However, because of the construction peculiarities, it is impossible to reveal all resources of the microprocess terminals, as well as to ensure a sufficient flexibility during their modernization.

There are also virtual laboratory stands being developed using special software [11, 12, 13] such as MATLAB, LabView, Multisim, etc. The example of the virtual laboratory stand is shown in Fig. 3.

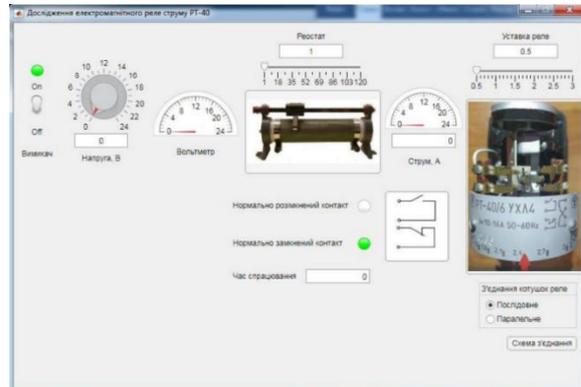


Fig. 3. Example of virtual laboratory stand for protection relaying and automation.

They are characterized by a high flexibility and possibilities to model various equipment paying only once for the software and a personal computer (PC).

The students work with files of the ready-assembled models of corresponding stands for each laboratory work. These stands gain from the economic view point and the quantity of laboratory works, which can be modeled, however in this case the students fail to obtain the working skills using a real equipment.

The combination of the above approaches are the education stands, where, first, the development and testing are performed of the computer model of power-system in the program, and then, using the devices for terminal operation testing, the real currents or voltages are supplied onto the device examined. For this, special program modules are used, which can be obtained coming with the testing device for checking the operation of terminals. The ‘RL-model’ is the example of such a model that can be obtained coming with a PETOM-61 device. It can simulate various kinds of short-circuits (SC), synchronous running and swaying, phase-failure (without SC), load step-like change. This module allows watching out for the process, which is preset in the RM-model and yield to PETOM the calculated currents, voltages and fix the states of digital inputs on the oscillogram [14]. The RL-model program window is shown in Fig. 4.

The program module ‘Generator of sequences’ allows creating several banks with possible transitions between them, which allows modeling more complicated states of a system, reveal not

only emergency, but pre- and after-emergency modes, the modes of transition of a single-phase into a two-phase SC and etc. This program module makes it possible to model the modes, close to real, because using the parameter setting of higher harmonics, it is possible to obtain the signal distortion. Thus, the microprocessor terminal potential can be disclosed more extensively, and the students can get the operation skills with real equipment.

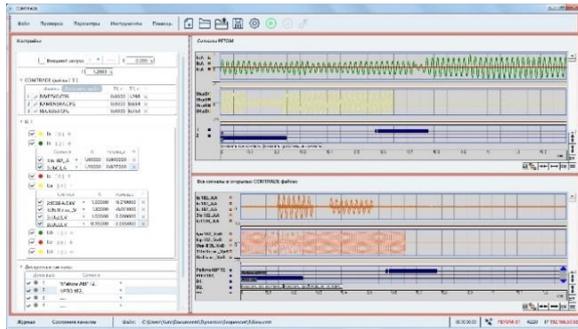


Fig. 4. Program window of RL-model.

To test the operability of protective relay devices without taking into account the reaction of the power system, tests can be carried out in an open circuit mode using hardware and software testing complexes (HSTC). An example of such a complex based on the Omicron SMS 356 device is shown in Figure 5.



Fig. 5. Apparatus-program test complex based on device CMC 356 of OMICRON company.

To test the relay protection devices in an open cycle the results of the autonomous modeling are preserved in a unified format of digital oscillograms COMTRADE and further they are formed into the analogue signals, using the DPTC, which are supplied to the inputs of the tested device in the real time mode.

The DPTC includes the PC, in which the energy-system model is realized or the generalized electric energy object (GEO) and software, monitoring the testing device and the modes of per-

forming the test. As the test devices, the micro-process device-program diagnostic complexes can be used, such as NPP ‘Dinamika’ of ‘PETOM’ type produced by OMICRON (based on CMC 356) (Fig. 5) or similar complexes of other producers [15].

A more effective method used for the development, testing and optimization of the secondary electric equipment, as well for the study of the modes of the energy system functioning during the transition or emergency modes, is a digital modeling of the energy system in real time with a physical connection of the relay protection systems to the model [16, 17].

A modern trend is the use of simulators RTDS (Real Time Digital Simulator) that allows combining real devices with a virtual model of environment of their operation and performing complex testing the PRA devices a valid feed-back and reaction on their state change [18, 19, 20]. These simulators can update the output data in the real-time mode, which means that all calculations necessary for the modeling of the circuit with the use of the Dommel algorithm [21], are fulfilled in real time, equal to or lesser than the time step of the modeling. Using the RTDS, it is possible to study the energy systems in static and dynamic modes, as well as to test the protection relaying devices, to create the solutions for improving the electric energy quality, to educate and train a personnel, etc. The RTDC example is shown in Fig. 6 [16].



Fig. 6. Apparatus-program test complex RTDS.

The device being tested accepts the modeling complex as a real medium and reacts on the processes that are very close to real, receiving an immediate response of the virtual power system being modeled on the impact produced. Due to this, the possibility appears to test the PRA device together with the model of the object protected, on which it will be mounted [22].

Recently, energy companies of many countries use the RTDS simulators more extensively. Over the past twenty years, the real time modeling ceased being the experimental technology to fulfill only the testing projects. It has become an everyday tool used for solving the most different practical problems by the energy companies [23, 24].

Real-time simulators enable the energy companies to reduce supplier risk during equipment installations, manufacturers to conduct comprehensive factory acceptance testing of devices, research institutes to test new algorithms and approaches throughout the development process, and consultants to provide greater depth of analysis than is possible with other tools.

The main RTDS simulators' advantages, the possibility of including the real equipment into the model of the power system being examined should be used.

The aim of the work

The aim of the work is to enhance the quality of the knowledge obtained and practical skills of work with protection digital terminals of the high schools' students and the production electrotechnical personnel, using the original affordable approach, based on modern tendencies, during the development of the experimental stands for the digital protection testing.

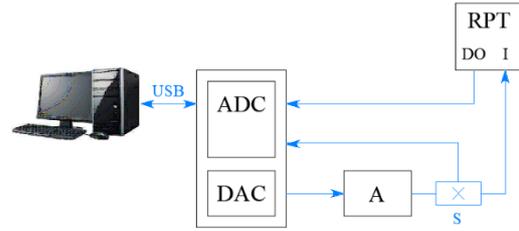
Experimental stand description

Regardless of the obvious advantages of the RTDS stimulators, their application in most project, science-research and educational organizations is problematic owing to their excessive cost.

A more available method for the stand realization to test the protection relaying terminals (PRT), a PC use is, combined with the analogue to digital and digital to analogue converters. A simplified structural scheme of this solution is shown in Fig. 7.

In the PC, the model of a protection element of the energy system is created, which allows obtaining current instantaneous values in the element phases in normal and emergency modes. The presence of the PRT reaction on the modeling modes and its velocity allow estimating of being correct or incorrect of the protection operation.

The calculation results of the of instantaneous current values in the model using an ADC and a signal amplifier are transmitted to the current inputs of the protective relays (I).



ADC – analog to digital converter; DAC – digital to analog converter; A – signal amplifier; S – Hall sensors; PRT – protection relaying terminal.

Fig. 7. Stand structural scheme.

The protection response is recorded using a signal from a configured discrete output of the unit (DO), which is transmitted to the ADC. The ADC also receives data from the measuring transducer (D), which monitors the instantaneous values of the current flowing through the protective relays.

The LTR11 and LTR34 boards of the LTR crate system by L-Card were used as ADC and DAC in this setup. LTR34 is a 16-bit, 8-channel DAC with a resolution of 16 bits, while LTR11 is a 14-bit, 32-channel ADC with a maximum sampling rate of 400.0 kHz. The crate is connected to a PC via a USB interface. The manufacturer provides libraries for accessing device functions in the C++ programming language.

The model used in the developed setup, described as an example, represents a section of a system consisting of a cable line (W) and a step-down transformer (T). The schematic diagram of the model is shown in Fig. 8.

Instantaneous current values in the phases can be calculated based on the previously calculated values of normal and emergency mode currents according to the expressions:

$$\begin{aligned}
 i_{L1} &= \sqrt{2}I_{L1}(\sin \omega t), \\
 i_{L2} &= \sqrt{2}I_{L2}\left(\sin \omega t - \frac{2\pi}{3}\right), \\
 i_{L3} &= \sqrt{2}I_{L3}\left(\sin \omega t + \frac{2\pi}{3}\right),
 \end{aligned}
 \tag{1}$$

where $i_{L1(L2,L3)}$ – instantaneous current values in the phases, A; $I_{L1(L2,L3)}$ – RMS current values, A; ω – angle frequency, corresponding to industrial frequency 50 Hz; t – current time, s.

In the same figure to the right of the diagram, the element parameters are shown for one of the task options. Based on this data, a student will be able to calculate the protection parameters.

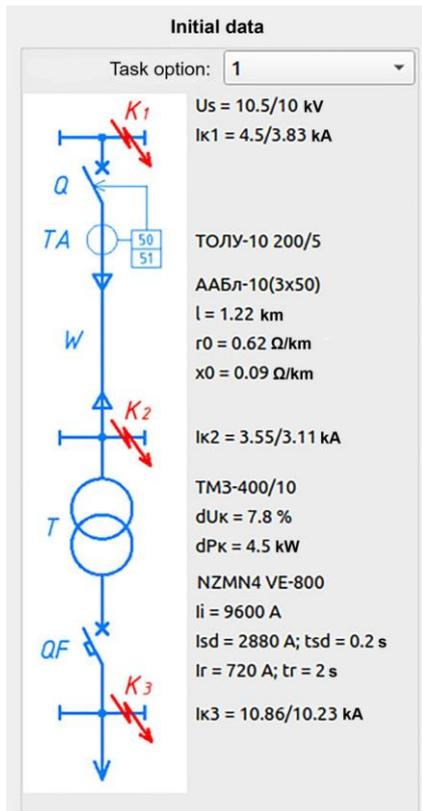


Fig. 8. Design scheme and parameter elements.

A two-stage current protection is applied as protection for these elements: short-circuit protection (ANSI code 50) and short-circuit protection with independent time delay (ANSI code 51) [25].

To check the accuracy of the protection trip parameters calculation and terminal setting, characteristic modes are simulated that allow assessing its sensitivity and selectivity. Each mode is divided into several stages of a certain duration.

The self-start load mode is designed to check for excessive protection tripping. The mode consists of 3 stages: 1) normal operation (phase currents equal to the nominal current of the automatic breaker *QF*, taking into account its connection to the side of the *T* transformer's LV; duration – 0.5 s); 2) remote three-phase short circuit in the 0.38 kV network (phase currents in the network are two times higher than the setting of the breaker's *QF* pickup current *I_{sd}*, the duration is determined by the time of the breaker's trip, taking into account its protective characteristic determined by the setting *t_r*); 3) normal operation (analogous to stage 1, the duration is determined taking into account the acceptable display of time-grid values on mode parameter change graphs and is less than 0.5 s). In the self-start mode, no protection tripping should be observed.

The minimum single-phase short circuit mode in phase "L1" at point *K₃* is designed to check the

sensitivity and trip time of the second stage of the current protection. The mode consists of two stages: 1) normal operation (currents and duration are similar to the previous mode); 2) short circuit in point *K₃* (currents in the phases correspond to a single-phase short circuit on the side of the power transformer's MV with consideration of its change in phase and magnitude when transitioning to the LV side; the duration is determined by the setting of the *QF* relay's *t_{sd}* and taking into account the selectivity stage of *dt = 0.5 s*). In this mode, the second stage of protection should trip within the time interval of *t_{sd}...t_{sd} + dt*.

The minimum two-phase short circuit mode in phases "L2" and "L3" at point *K₂* is designed to check the sensitivity and trip time of the first stage of the current protection. The mode consists of two stages: 1) normal operation (the current and duration are similar to the previous mode); 2) a short circuit at point *K₂* (the current in the phases corresponds to a two-phase short circuit on the high voltage side of the power transformer; the duration is 0.2 s). In this mode, the first stage of protection should trip in the time interval of 0.04 ... 0.2 s.

For clarity, table 1 shows the correct reaction of the protections for the modeled mode. The "+" sign corresponds to the trip of the protection, "-" to the non-trip.

Table 1

Correct reaction of protection stages			
№	Mode	50	51
1	Selfstart	-	-
2	SC in <i>K₃</i>	-	+
3	SC in <i>K₂</i>	+	-

The considered protections are implemented using the Siemens Siprotec 4 7SJ6 digital relay for protection of connections 6-35 kV.

The student can adjust the trigger parameters of the protections either through buttons on the device's front panel or with the help of specialized software DIGSI 4.

The VAC90.4 hi-fi amplifier (Fig. 9) is used as a signal amplifier from the DAC to transmit it to the current inputs of the relay, with a maximum output power of 2x300 W at a 4 Ohm load. To increase the current level to 150 A, taking into account the maximum multiplication of current transformers, matching transformers T1, T2 with transformation ratios 30/1 are used. Resistors R1, R2 (0.5 Ohm) are used to limit the current spikes of the transformers in the transition mode. Hall

sensors ACS758KCB-150B-PFF-T are used to measure the current supplied to the PRT input.

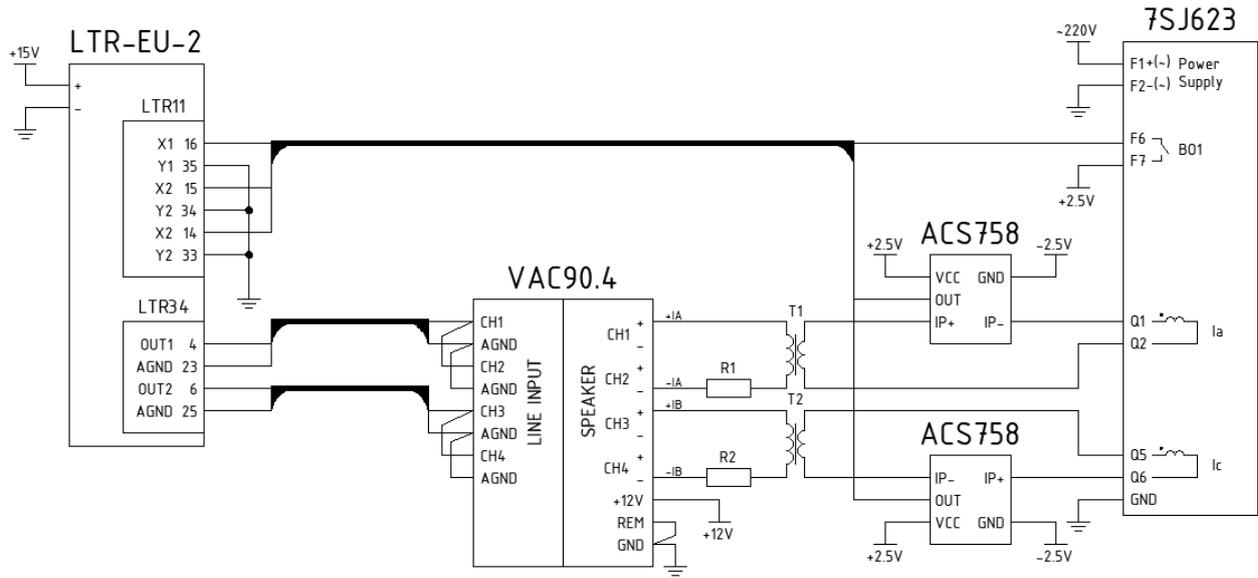
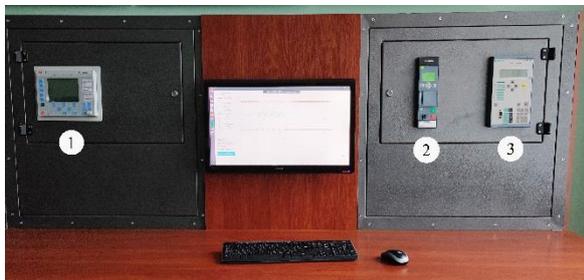


Fig. 9. Simplified principal scheme of stand.

The system model is implemented on a PC as a C++ language program using the cross-platform visual component library Qt in the Qt Creator development environment. The program allows for automatic sequential modeling of the previously considered modes of operation for a given user-defined variant number. During the modeling process, the program checks the proper functioning of the protections and outputs the corresponding service messages. For clarity, in real-time mode, the changes in primary and secondary currents in the "L1" and "L3" phases are displayed, as well as the state of the RPT output configured to close the contact when the current protections are triggered.

A workstation has been organized for working with the stand, presented in Fig. 10.



1 – REF630; 2 – Siprotec Compact 7SK80; 3 – Siprotec 4 7SJ6.

Fig. 10. General view of the stand.

At present, the following digital protection and automation devices have been integrated into the stand construction: Siprotec 4 7SJ6 – protection

for connections 6-35 kV (Siemens, Germany); Siprotec Compact 7SK80 – motor protection (Siemens, Germany); REF630 – protection for connections 6-35 kV (ABB, Switzerland). The possibility of integrating RPT of other types is provided.

The selection of the device under test is performed by the operator using a PC connected to the LTR system via USB interface.

Procedure for working with the test stand

Based on the data provided by the program, in accordance with the selected task option, the student selects the parameters for triggering a two-stage current protection with an independent triggering characteristic, which is installed on high-voltage switch Q (Fig. 8). The protection should also be checked for sensitivity and selectivity.

The calculation procedure for the described example is as follows.

Determination of the triggering parameters of the trip (first stage) [26]. To ensure selective work with the automatic switch QF, the trip triggering current is adjusted from the maximum short-circuit current on the low-voltage busbars of the substation transformer according to the following condition:

$$I_{sz}^I \geq K_{otl} \frac{I_{K2,max}^{(3)}}{K_T}, \quad (2)$$

where K_T is the transformation coefficient of the transformer T ; $I_{sc.max}^{(3)}$ is the maximum short-circuit current on the low voltage busbars of the transformer substation, A.

The sensitivity check of the trip is performed using the following formula:

$$K_f \geq \frac{K_{sch}^{(2)} I_{K2.min}^{(2)}}{K_{sch}^{(3)} I_{sz}^I}, \quad (3)$$

где $K_{sch}^{(2)}, K_{sch}^{(3)}$ – the coefficients of the schemes, for two-phase and three-phase short circuits respectively.

In the next step, the trip current of the maximum current protection (MCP) (second stage) is determined. Taking into account the spread of breaker parameters (25%), non-excited devices (5%), relay errors (5%) and current transformers (10%) the trip current of the protection is determined by the formula:

$$0.85 I_{sz}^{II} \geq 1.3 \frac{I_{sd.QF}}{K_T}. \quad (4)$$

Further, sensitivity testing of the overcurrent relay is carried out.

$$K_f \geq \frac{K_{sch}^{(1)} I_{K3.min}^{(1)}}{K_{sch}^{(3)} I_{sz}^{II} K_T}, \quad (5)$$

where $K_{sch}^{(1)}$ is the scheme coefficient for a single-phase short circuit.

The operation time of the overcurrent relay is determined using the formula:

$$t_{sz}^{II} \geq t_{sd.QF} + \Delta t, \quad (6)$$

where $t_{sd.QF}$ is the setting of the operation time of the automatic circuit breaker QF; Δt is the selectivity level.

The results of the calculations, as well as the current transformer transformation ratio, are entered into the protective relay inputs either directly from the terminal or using specialized software provided by the protective relay manufacturer (DIGSI 4).

To start the testing mode in the software, click on the corresponding button located in the lower left corner of the main program window.

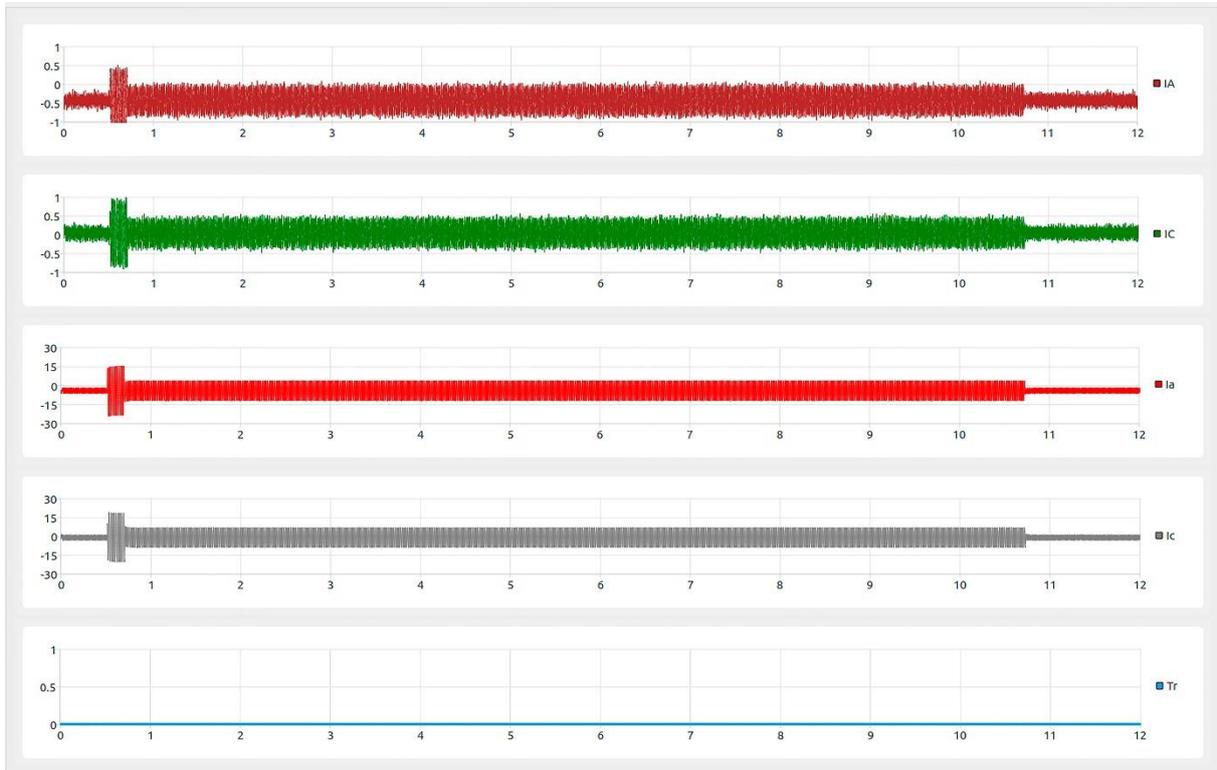


Fig. 11. Example of obtained results after starting modeling of self-starting mode.

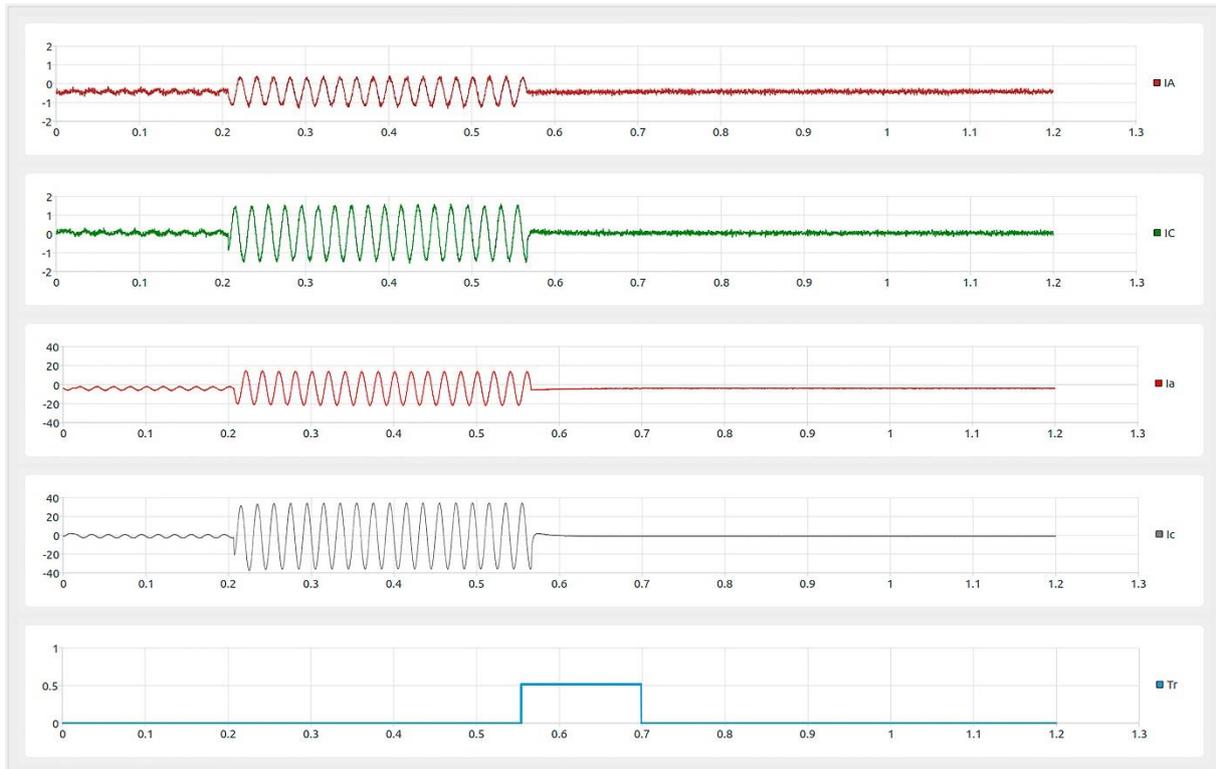


Fig. 12. Example of obtained results after starting modeling of SC mode in point K_3 .

For clarity, the testing results display curves of instantaneous values of primary and secondary currents in phases "L1" and "L3", as well as the status of the output terminal configured to close the trip circuit when the current protection is activated. Examples of the results display are shown in Figs. 11 and 12.

In case of incorrect operation of the protection, the simulation process is stopped and an error message with comments is displayed, allowing the user to identify and fix the cause of the malfunction.

CONCLUSIONS

The developed universal experimental stand allows testing real microprocessor-based protection relaying terminals in laboratory conditions, taking into account the specifics of the protected element. The testing is carried out by supplying the studied device with analog and digital signals corresponding to characteristic normal and emergency operating modes of protection objects. Due to the implementation of feedback, the stand allows for the automation of the protection testing process in typical operating modes of the object.

The stand allows for the acquisition of skills not only in calculating the triggering parameters of specific protection elements, but also in practical skills of setting up digital protection terminals

using specialized software, such as DIGSI from Siemens, SFT2841 from Schneider Electric, Connectivity Package from ABB, as well as using a modern human-machine interface (HMI).

The developed stand provides convenience in operation due to the use of a built-in database of element parameters (cable lines, transformers, etc.). The listed features of the stand allow it to be used not only in laboratory work, but also for improving the qualifications of electrical personnel.

The equipment used in the stand is more affordable compared to analogues, which allows for its widespread use in higher education institutions.

The software and equipment used make it easy to expand the capabilities of the stand by adding protection blocks from other manufacturers who can implement more complex protections (such as distance or differential), as well as creating new software models of protection objects (such as high-voltage asynchronous and synchronous electric motors, generators, three-winding transformers, power transmission lines, etc.).

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