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DEVELOPMENT AND PILOT OPERATION OF A THREE-PHASE FULLY OPTICAL MEASURING VOLTAGE TRANSFORMER OF 220 kV WITH DIGITAL OUTPUT

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An electronic three-phase fully fiber-optic measuring voltage transformer (FOVT) of accuracy class 0.2 for a nominal voltage of 220 kV with a digital output for operation at power system facilities, including electrical substations, is described. The operation principle of the device is based on the use of a longitudinal linear electro-optical effect (Pockels effect) for measuring AC voltage. The fiber-optic measurement scheme based on low-coherent interferometry is connected via a fiber cable to an optical high-voltage primary converter (HVPC) with an electro-optical crystal placed in it; there are no additional voltage dividers inside. The digital signal processing unit (DPU) contains optical and electronic circuits for generating, detecting, and processing an electro-optical signal. FOVT has a digital interface that complies with the IEC 61950-9-2 LE standard, and can be used as a component for the Digital Substation and Smart Power Grid technologies. The design features of the HVPC and the DPU are described and the results of the metrological characteristics of FOVT-220, based on the data obtained during the certification and pilot operation at the 220 kV electrical substation, are presented.

Keywords: optical voltage transformer; Pockels effect; low-coherent interferometry; IEC 61950-9-2 LE; digital substation.

Optical digital voltage meters based on the use of the electro-optical effect in crystals in order to measure voltage have been actively developed for more than 20 years [1 – 3]. A large number of published papers both in Russian and foreign scientific and technical literature are devoted to the physical foundations of such meters [4, 5], optical modulation methods, mathematical algorithms for processing optical signals [1 – 3, 6 – 8], as well as experimental studies on optimizing the design of high-voltage sensitive elements and methods for increasing the temperature stability and accuracy of voltage measurements by optical methods [1 – 3, 6 – 9]. Leading Western manufacturers of electrical equipment, such as ABB, Siemens, GE, Arteche, Alstom, and NxtPhase, have been working in order to create fully optical digital voltage meters [10 – 13], but the authors do not know the off-the-shelf devices that exist to this date.

In Russia, according to the authors, since 2007 there has been experience in the commercial operation of optical voltage transformers with digital output based on the Pockels effect. The Russian company Professional Line LLC (ProLine) installed a number of measuring kits of optical current and voltage transformers of the Canadian company NxtPhase Corporation at power facilities [14 – 16]. Unfortunately, to this date, it was not possible to find relevant data on these meters and the results of their operation. The NxtPhase company ceased its activities due to bankruptcy.

Thus, according to the authors, at the time of writing the article on the Russian market there is no commercially available fully optical voltage meter for the 110 – 220 kV range with an accuracy class 0.2 corresponding to GOST R IEC 60044-7–2010 (Measuring transformers. Part 7. Electronic voltage transformers).

The objective of this paper is to present the results of the authors' work within the framework of a contract with FSK EES PJSC [17, 18] on the creation, certification, and pilot operation of a fully optical electronic transformer with a fiber output of accuracy class 0.2, designed for a nominal voltage of 220 kV (FOVT-220) with digital output, which fully corresponds to GOST R IEC 60044-7-2010. A patent of Russian Federation [19] was obtained for the design of an optical voltage meter and several papers were published in scientific journals [20 – 22]. At the time of writing this article, the

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three-phase measuring kit has been put into pilot operation and is undergoing long-term tests at the existing 220 kV electrical substation of FSK EÉS PJSC.

The application of optical voltage meters in high-voltage energy transmission systems has many advantages over the application of conventional inductive and capacitive voltage measuring transformers. The use of quartz optical fiber for transmitting the measured light signal to the crystal-transformer in the high-voltage sensor part and vice versa provides complete galvanic isolation of the high-voltage primary converter (HVPC) from the digital processing unit (DPU) located inside the control room, and also minimizes the effect of electromagnetic interference on the device. The main advantages of optical voltage meters include the following:

— full galvanic isolation both between high and low potentials of the meter, and between the HVPC and DPU;

— extremely fast response time to transition processes in the high-voltage line due to the optical nature of voltage conversion;

— resistance to resonance phenomena due to the complete absence of resistive or resistive-capacitive dividers inside the DPU and low-capacitance optical sensitive crystal;

— improved explosion safety due to the absence of oil and SF6 gas (even with catastrophic destruction of high-voltage isolation);

— linearity and wide dynamic range; FOVT provides the same accuracy in the voltage range from 0.2 to 1.5 times the nominal voltage;

— wide bandwidth up to the 100th harmonic of the measured frequency;

— the use of silicon compounds or special dielectric gels as a filling insulating medium corresponds to the Green-Energy concept (ecological safety and environmental friendliness) and allows minimizing leakages and ensuring stable performance and non-maintenance during the entire FOVT life;

— correspondence of the optical voltage meter to the innovative concept of electric power development: SmartGrid (or an intelligent energy system with an active adaptive circuit).

Optical Voltage Transformers Destignation. Fiber-optic voltage transformers with a digital output are designed for measuring and scale converting the high value of AC voltage of a commercial frequency of 50 Hz in circuits with an earthed neutral to a low value of AC voltage of a acommercial frequency of 50 Hz and generating signal of measurement data according to the IEC 61850-9-2:2011 standard in Russian (hereinafter IEC 61850-9-2 LE). The transfer of measurement results can be carried out to electric measuring devices, to systems for commercial accounting of electric energy, measuring devices (including devices measuring the electric power quality factors), and protection, automation, alarm and control devices. FOVT can be operated as a component of the Digital Substation and Smart Grid technologies.

Operation Principle of Electro-Optical Voltage Transformer. The principle of operation of the FOVT under consideration is based on the use of a linear electro-optical effect (Pockels effect) [4, 5]. FOVT measures the polarization ellipticity of the optical radiation transmitted through a crystal, which arises as a result of a change in the refractive index of optical normal waves under the influence of an electric field **E** applied to the crystal. The measured electric voltage U applied to the crystal is the integral of field **E** along the path of light inside the crystal (points 1 and 2, respectively, are the points of entry and exit of the optical beam from the crystal):

$$U = \int_1^2 \mathbf{E} d\mathbf{l}. \quad (1)$$

For electro-optical crystals of symmetry group 32, when optical radiation propagates along the X axis (second-order axis) of the crystal, the phase difference between the ordinary φ_o and the extraordinary φ_e waves after passing through the crystal is determined by the expression [21]

$$\varphi = \varphi_o - \varphi_e = \frac{2\pi}{\lambda} \frac{n_o^3 r_{11}}{2} \int_0^L E_x(x) dx = \frac{n_o^3 \pi r_{11}}{\lambda} U, \quad (2)$$

where U is the voltage applied to the end faces of the crystal; L is the length of the crystal along the X axis; E_x is the component of an external electric field along the X axis of the crystal; n_o is the refractive index of the ordinary (o) wave in the crystal in the absence of an external electric field; r_{11} is the component of the electro-optical crystal tensor; λ is the wavelength of light.

Thus, the measured electro-optical effect does not depend on the distribution of the electric field inside the sensor optical head (Pockels cell) and is completely determined by the voltage drop across the electro-optical crystal-transformer. As a result, the influence of the external environment on the device readings, typical for resistive and capacitive voltage dividers, is significantly reduced.

The electro-optical scheme of FOVT-220 is shown in Fig. 1. Radiation is sent to the optical sensing element through a fiber-optic cable. To measure the ellipticity of optical radiation arising in the crystal-transformer due to the electro-optical effect given in Eq. (2), the sensor uses the phase modulation method, in which the state of light polarization is transmitted through the optical fiber line [23].

The radiation from a broadband source, a superluminescent diode (SLD), passes through the circulator and the polarizer and then through the polarization modulator, which is made in the form of an anisotropic fiber coil wound on a piezoceramic cylinder, and enters the optical head (Pockels cell). It is an optical system with crystals, a lens, a reflecting mirror and a Faraday rotator. 45° splicing of the fiber between the polarizer and the modulator provides the same

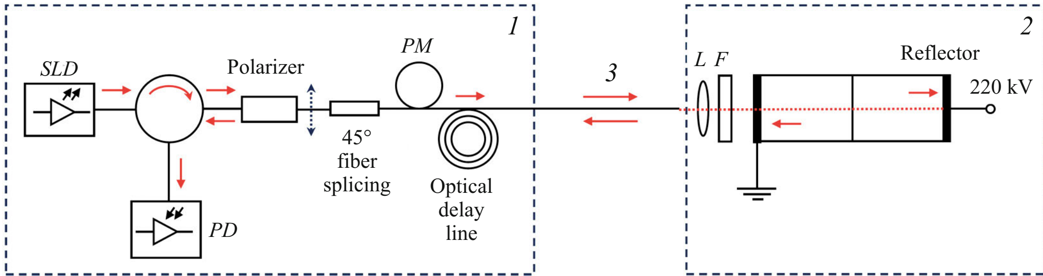

Fig. 1. Electro-optical scheme of the fiber-optic voltage transformer and the sensing element: *1*, digital processing unit; *2*, high-voltage primary converter; *3*, fiber-optic cable; SLD is the superluminescent diode (or other broadband radiation source compatible with single-mode optical fibers); 45° is the splicing of anisotropic fibers with the orientation of the anisotropy axes of the fibers being welded at an angle of 45 degrees to each other; *L* is the lens; *F* is the 45° Faraday rotator; *PD* is the photodetector; *U* is the voltage applied to the optical sensing element; *PM* is the phase modulator.

power supply for both polarization modes of the fiber by the radiation emerging from the polarizer.

Passing through the modulator, the delay line and the optical fiber cable between the receiving module and the optical head, the radiation exits the fiber, passes through the lens *L*, which forms the optical beam, the 45° Faraday rotator *F*, and electro-optical crystals; then it is reflected from the reflector and it returns to the circulator, which directs the radiation coming from the side of the polarizer to the photodetector PD.

When voltage is applied to the crystal-transformer (sensor), between the polarization modes, an additional uncompensated delay appears at the output of the fiber line. In this case, the polarization of the reflected radiation at the output of the fiber line is converted from the linear to elliptical. Ellipticity is determined by the value of the voltage applied to the electro-optical crystal in accordance with Eq. (2). In order to exclude the influence of optical losses in the sensor on the measurement results, a phase type of the sensor, in which the state of light polarization is transmitted through the optical fiber line, is implemented. This necessitates the application of a polarization-preserving optical fiber of the PANDA type.

The optical measuring voltage transformer FOVT-220 structurally consists of two main parts (Fig. 2): a high-voltage primary converter (HVPC) with an optical sensor inside and an electro-optical digital processing unit (DPU).

The high-voltage primary converter is made in the form of a supporting insulating column, consisting of a cored fiberglass pipe, covered with an external silicone shell, with upper and lower aluminum flanges (Fig. 3*a*). The column is mounted on a steel base-stand, treated with an anticorrosion coating. The polymer outer cover itself is not subject to corrosion. Inside it there is a structure with an optical sensing element fixed between two high-voltage electrodes. All nominal voltage of 220 kV drops directly on the crystal. One end of the crystal is under the voltage of 220 kV, the other is grounded.

The uniqueness of the design of the developed FOVT-220 lies in the complete absence of any capacitive or

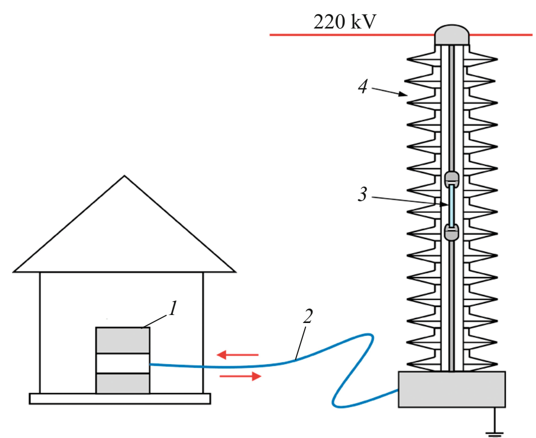

Fig. 2. Structure of the optical measuring voltage transformer FOVT-220 with a fiber output: *1*, digital processing unit; *2*, fiber-optic cable (up to 1000 m); *3*, optical sensing element; *4*, high-voltage primary converter.

resistive-capacitive dividers in the composition of the high-voltage primary converter. This feature allows avoiding the operation disadvantages typical for traditional voltage dividers.

To implement the direct application of high voltage to a sensitive crystal without high-voltage breakdown, a special form and fastenings of high-voltage electrodes were developed, distributions of electric field strengths in critical places, selection of a dielectric compound, and many other solutions for achieving stability under high voltage were optimized.

The shape and dimensions of high-voltage electrodes were developed after mathematical simulation and optimization in order to achieve the maximum uniformity of the electric field strength distribution and to minimize its peak values.

The entire remaining free internal volume of the HVPC is filled with dielectric compound that meets the requirements for high-voltage isolation of this type of high-voltage equipment. The use of the compound as a dielectric insulat-

Fig. 3. Layout of a high-voltage primary converter with an optical sensor inside (*a*) and an electro-optical digital processing unit (*b*) in a 19-inch rack.

ing medium was due to the requirements of the performance specification (PS) for reasons of non-maintenance, explosion and fire safety, as well as environmental friendliness. One HVPC is intended to connect to one phase of an electric power line.

Optical radiation generation, detection and mathematical processing of the optical signal are carried out in the electro-optical DPU (Fig. 3*b*). It consists of a fiber-optic conversion circuit, a digital system for receiving, processing and analyzing data, a digital data generation system in the IEC 61850-9-2 LE format, and an analog output data generation system 1 V/$\sqrt{3}$ 0.1 A.

After detecting the radiation returned to the DPU by the sensing element and mathematically processing the detected optical signal, the instantaneous voltage value is calculated and transmitted digitally to the secondary equipment: fiscal metering devices, telemetry devices, electric power quality control devices, relay protection and automation. In the DPU an external GPS/GLONASS synchronization signal (1PPS or IEE 1588-2) is received and a digital signal of three voltage phases is transmitted via the digital interface IEC 61850-9-2 LE via an optical connecting cable connected to an optical connector of ST type.

The data transmitted via the digital interface corresponds to the international standards IEC 61850-9-2 LE and IEC 61869. The electro-optical DPU supports the ability to connect to both digital and analog monitoring and control systems. To ensure the possibility of incorporating FOVT-220 into the online operation monitoring system, the device has a special RS-232/485 port for reading diagnostic data (also available to the operator on the device display). The diagnostic port operates only in the data reading mode and does not have the ability to change the device settings.

TABLE 1. Metrological and Technical Characteristics of FOVT-220

Characteristic	Required value
Requirements for the main parameters	
Nominal circuit voltage, kV	220/$\sqrt{3}$
Accuracy class according to GOST R IEC 60044-7-2010	0.2
(with a distortion factor of the sinusoidal curve of not more than 30%), %	3
Frequency transmission range in the presence of harmonics in the measured signal, Hz	40 – 2500
Nominal frequency of the measured circuit voltage, Hz	50
Service life, years	30
Operating environment requirements	
Operating temperature range, °C:	
for HVPC	From –60 to +60
for DPU	From –5 to +40
Fouling factor of the outer isolation	I; II; III; IV
Static mechanical load, N	Up to 1000
Installation height above sea level, m	Up to 1000
Digital interface of the meter	
Output sampling frequency according to IEC 61850-9-2, number of samples per second	4000, 12,800
Number of simultaneously transmitted output streams according to IEC 61850-9-2 with different sampling frequencies	2
Time synchronization input type	1PPS optical (fall/front) 1PPS electric (fall/front) IEE1588v2
Frequency holding period in the absence of external synchronization, sec, not less than	20
DPU power voltage of, V	220 ± 44 AC or DC
DPU power consumption, W, no more than	300
Electrical isolation requirements	
Withstand voltage of full lightning impulses relative to the ground and between phases of the internal and external isolation, kV	950
The voltage of the chopped lightning impulses relative to the ground and between phases, kV	1100
One-minute alternating withstand voltage of the internal and external isolation in the dry state and in the rain, kV	395

The transmission and reception of optical radiation from the DPU to the sensing element inside the HVPC is carried out via a fiber-optic cable for a distance of 20 to 1000 m, which allows placing the DPU at a distance from the high-voltage switchgear in a location with the required operating conditions. The isolation and mechanical characteristics of the fiber-optic cable connecting the HVPC and DPU comply

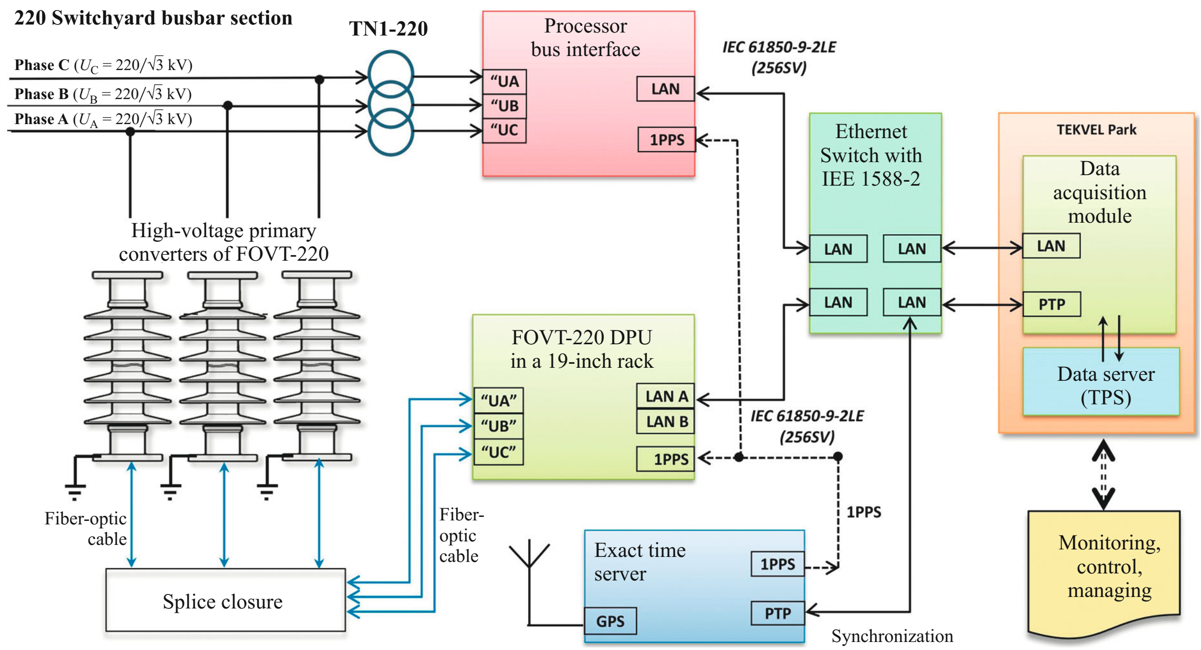

Fig. 4. The schematic structure of the set of technical means for FOVT-220 PO organizing.

with the requirements and standards for outdoor installation at electric power facilities.

Metrological Testing and Measuring Instrument Certification of FOVT-220. Metrological testing in order to certify the type of measuring instrument (MI) was carried out in accordance with the performance specification for FOVT-220 of FSK EÉS PJSC by specialists of FSUE VNIIMS. During the tests, the metrological characteristics of the optical transformer, such as the value of the relative measurement error and phase error in the HVPC temperature range from –60 to +60°C, were investigated. The DPU was separately tested for electromagnetic compatibility and insensitivity to electromagnetic interference. As a result of FOVT-220 testing, the specialists of VNIIMS of the Federal Agency for Technical Regulation and Metrology issued a certificate confirming the measuring instrument type and developed techniques and recommendations on the features of testing and verifying fully optical voltage transformers with digital output.

The software of the FOVT-220 DPU is built-in and represents a set of microprograms designed to ensure the device normal functioning, interface control, etc. The influence of the software was taken into account when normalizing the metrological and technical characteristics of the devices.

Table 1 shows the main metrological and technical characteristics of the device.

Preliminary testing and calibration of the FOVT-220 optical meter was carried out in the high-voltage laboratory of the company. The measuring equipment included: a high-voltage test installation UIV-230 (TestSet, Russia), a reference high-voltage capacitive voltage converter PVE-330 of accuracy class 0.05 (NPP Mars-Energo, Russia) and a testing vector comparing installation UPVK-ME 61850 (NPP Mars-Energo, Russia). It is designed for calibration and verification of measuring converters (MC) or electronic voltage or current transformers, the output signals of which are represented by a digital stream in the format of the IEC 61850-9-2 LE standard, or in the format of the IEEE-488.2 standard, by comparing them with the analog output signals of the reference voltage MC.

Pilot Operation (PO) of FOVT-220. The three-phase measuring kit FOVT-220 was installed at the 220 kV electric substation of FSK EÉS PJSC for the PO in order to ascertain the long-term operational characteristics of the device. During the PO, it is supposed to obtain data on the draft of the measurement accuracy, its dependence on the ambient temperature, and the influence of the impact of external natural factors (precipitation, solar radiation, pollution, icing) on the accuracy and stability of measurements. The schematic structure of the set of technical means for FOVT-220 PO organizing is shown in Fig. 4.

The FOVT-220 measuring HVPCs were installed on metal support trusses 3.5 m high and connected to the high-voltage 220 kV switchyard busbar section of the substation via a hardware connector on the upper flange of the HVPC (Fig. 5).

Each HVPC is connected by a separate fiber cable to a splice closure located away from high-voltage devices for safety and installation convenience. In the splice closure, optical light guiding cores of three cables from HVPC were spliced into the corresponding cores of one cable; then the optical signal via one multicore fiber cable installed outdoors enters the equipment room, where it is connected to the DPU.

Fig. 5. General view of the HVPC installed at the 220 kV switchyard during the PO at the 220 kV substation of FSK EÉS PJSC.

In parallel with FOVT-220, high voltage is supplied to TN1-220 (capacitive measuring voltage transformer ARTECHE DFK-245 manufactured by Electrotechnica Arteche Hermanos S.L. of accuracy class 0.2). The three-phase measuring TN1-220 is connected in the equipment room to the ENMU process bus interface of Energoservice, which performs analog-to-digital signals conversion and the delivery of digitized data in the form of sampled values (SV256) to an Ethernet network by broadcast streams according to IEC 61850-9-2 LE.

The streams of sampled values from different connections should be synchronized; therefore, ENMU and DPU receive 1PPS synchronization signals from the exact time server. Further, digital streams through the Ethernet switch with the support of the PTP synchronization protocol are analyzed and saved in the Tekvel Park control system of the Tekvel company. Tekvel Park has a modular structure that includes modules for the stream data acquisition and processing (LVB) and a server for storing, processing and visualizing data (TPS) with remote user workstations. Users connect to the server through a secure connection.

Structurally, the entire hardware of DPU is located in a ground-type network 19-inch rack. The values of the measured voltage from both transformers were analyzed by a comparison program, and the result of the relative error of the voltage measurement for all three phases between the reference and the tested transformers was recorded as a series of files.

Figure 6 shows the voltage oscillograms for three phases during the FOVT-220 PO. The upper oscillogram corresponds to the phases of the nominal voltage measured by FOVT-220, the lower one corresponds to the phases of the nominal voltage measured by the reference comparison transformer ARTECHE DFK-245. Visually, the oscillograms from the reference transformer are harmoniously distorted. The measured harmonic distortion factor (HDF) for FOVT-220 was 0.58 and for ARTECHE HDF = 2.43. The developed optical measuring transformer demonstrates a multiple advantage in the transmission of spectral components of the initial voltage. It is worth noting that at the calibration stage in the laboratory of the company the HDFs of FOVT-220 and PVE-330 coincided with an accuracy of tenths.

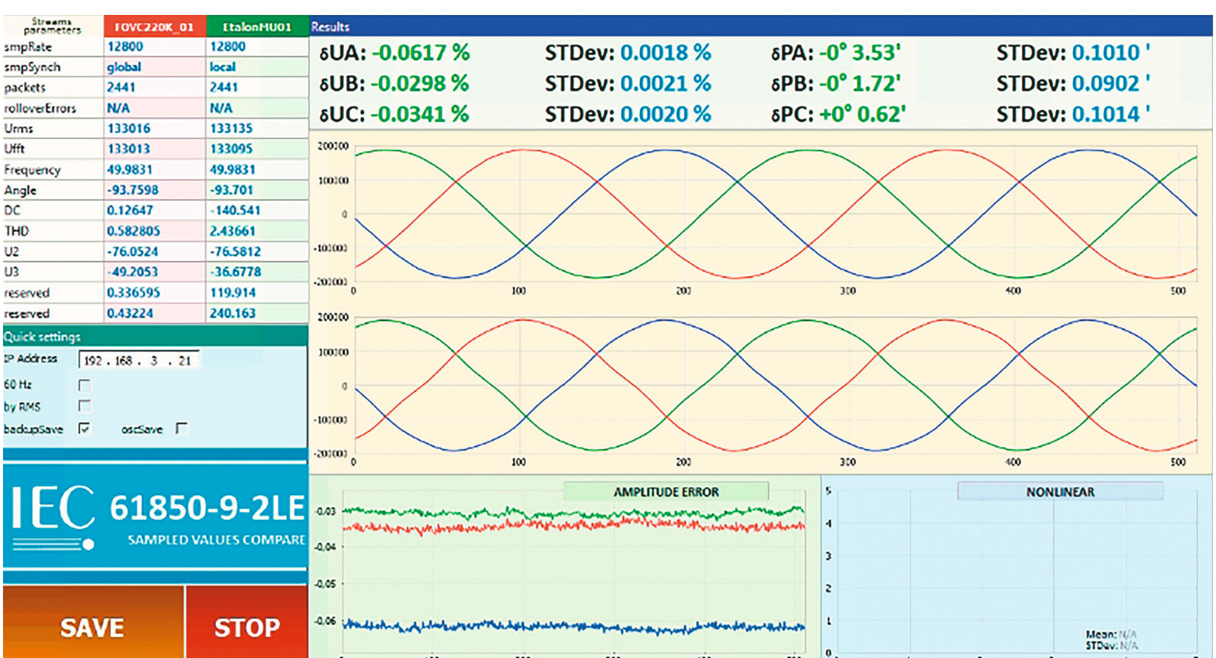

Fig. 6. Voltage oscillograms obtained using FOVT-220 (top) and a comparison transformer ARTECHE DFK-245 (bottom) in the PO process at 220 kV substation (fragment of the metrological program interface).

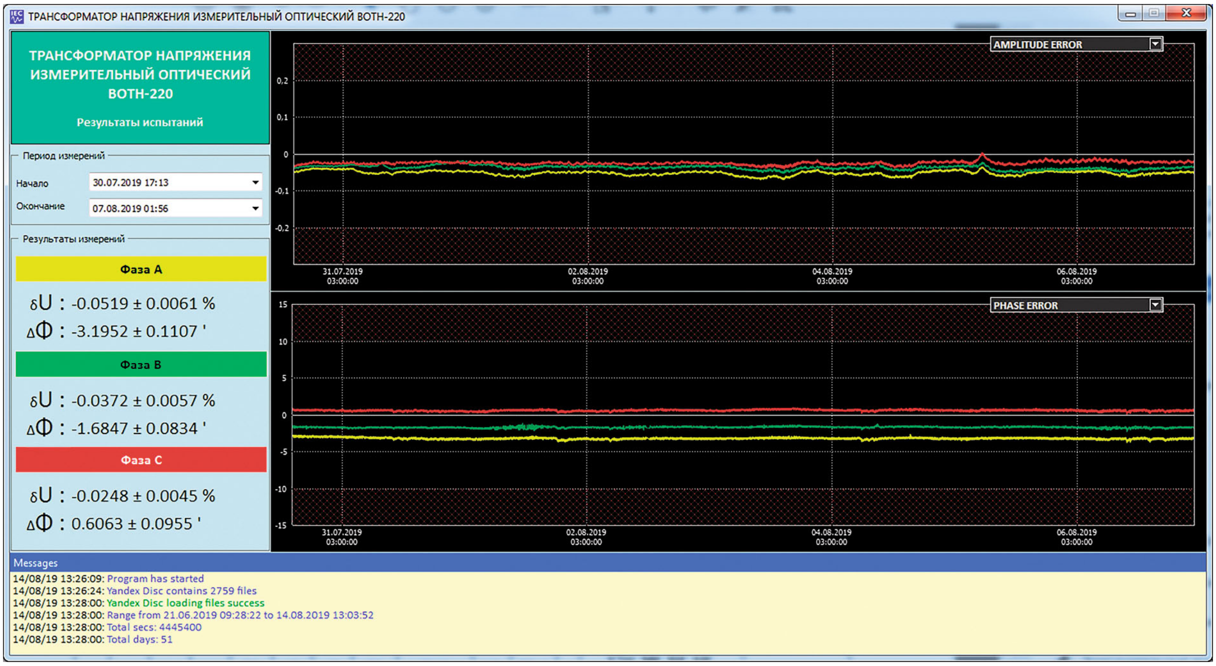

Fig. 7. Graph of the long-term value of the voltage measurement error between FOVT-220 and the comparison transformer ARTECHE DFK-245 in the PO process at 220 kV substation (fragment of the comparison program interface).

At the time of writing the article, FOVT-220 has been in the PO for more than six months. During this time, the maximum value of the relative measurement error did not exceed 0.1%, and the average value was 0.04 – 0.07% (Fig. 7). The PO program prescribes the location of FOVT-220 at the substation for one year with periodic on-site metrological measurements of the error value by the specialists of FSUE VNIIMS.

During the FOVT tests in the high-voltage laboratory of IQ Systems Ltd., at a constant indoor temperature of 23 ± 3°C, the optical voltage transformer provided a stable value of the relative measurement error for a long time. The root-mean-square error was less than 0.01%. Such a small value, together with the indicated advantages of the new technology, opens up possibilities for using an optical voltage transformer based on the Pockels effect as a metrological measuring instrument for Calibration and Certification Agencies.

CONCLUSIONS

A three-phase fully optical measuring voltage transformer FOVT-220 based on the Pokels effect of accuracy class 0.2 for a nominal voltage of 220 kV with a digital output of IEC 61950-9-2 LE standard has been developed. The device was certified for the measuring instrument type at the FSUE VNIIMS and has been approved for PO at the facility of FSK EÉS PJSC, i.e. the 220 kV electrical substation. During the certification tests of FOVT-220, the requirements stated in the performance specification were confirmed, as well as the requirements of GOST R IEC 60044-7-2010 (Measuring transformers. Part 7. Electronic voltage transformers). During the PO at the 220 kV electrical substation, the maximum value of the relative measurement error did not exceed 0.1%, and the average value was 0.04 – 0.07%. FOVT can potentially be applied at energy system facilities as a component of the Digital Substation and Smart Grid technologies. Providing a constant indoor temperature of 23 ± 3°C, the optical voltage transformer can be used as a metrological measuring standard for voltage of 110 – 220 kV with accuracy class 0.01.

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