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CALIBRATION OF EXPERIMENTAL INSTALLATION FOR MEASURING PARTIAL DISCHARGES IN LOW CAPACITANCE INSULATION SAMPLES

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Purpose. The method for calibrating an experimental installation for studying the patterns of partial discharges arising in samples of paper insulation having low capacitance was developed. **Methodology.** In order to verify the proposed method, a physical experiment was carried out in a high-voltage laboratory to measure partial discharge parameters using a digital oscilloscope. Free software for circuit simulation was used to create high-pass filter schematics. **Results.** The task of calibrating the systems for measuring partial discharges of low capacitance insulation samples (for example, ranging from 1 pF to 5 pF) is characterized by high complexity, because the calibration capacitor must have a capacitance an order of magnitude smaller than the capacitance of the test sample (from 0.1 pF to 0.5 pF, accordingly), which sometimes cannot be achieved practically. Moreover, in such case the stray capacitance will obviously be of the same order as the capacitance of calibration capacitor, or even greater. In such cases traditional calibration circuits where calibration generator is connected in parallel with the test object cannot be applied. **Originality**. Alternate calibration circuit was proposed, implemented and tested in the work, where the calibration generator is connected in series with test object. **Practical value**. Studies of the proposed calibration method have shown that it can be used quite effectively in cases when test object have low capacitance. The results of recording the calibration pulses showed that they can be reliably recorded and measured with a minimum error (oscilloscope error), and errors associated with parasitic parameters of the recording circuit are automatically taken into account when calibrating by this method and do not require additional adjustments. **Conclusions**. There is a possibility to increase the sensitivity of the measuring circuit to 0.05 pC/V, primarily by increasing the gain of the oscilloscope at least 100 times without repeating the calibration procedure. This will make it possible to study insulation samples of fairly high quality in which the level of partial discharges is much lower than in those samples used in this work. The experimental installation can be used to analyze different ways of modeling partial discharges on a personal computer and comparing their results with a real experiment. References 15, figures 12.

Key words: partial discharge, calibration procedure, calibration generator, high-pass filter.

КАЛІБРУВАННЯ ЕКСПЕРИМЕНТАЛЬНОЇ УСТАНОВКИ ДЛЯ ВИМІРЮВАННЯ ЧАСТКОВИХ РОЗРЯДІВ У ЗРАЗКАХ ІЗОЛЯЦІЇ З МАЛОЮ ЄМНІСТЮ

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Розроблено методику калібрування експериментальної установки для дослідження закономірностей часткових розрядів, що виникають у зразках паперової ізоляції з малою ємністю. З метою перевірки пропонованої методики проведено натурний експеримент у високовольтній лабораторії із застосуванням цифрового осцилографа для вимірювання параметрів часткового розряду. Для розробки схеми фільтра високих частот було використано безкоштовне програмне забезпечення для схемо технічного моделювання. Задача калібрування систем для вимірювання часткових розрядів зразків ізоляції з малою ємністю (наприклад, в діапазоні від 1 пФ до 5 пФ) характеризується високою складністю, оскільки калібрувальний конденсатор повинен мати ємність на порядок меншу за ємність досліджуваного зразка (відповідно, від 0,1 пФ до 0,5 пФ), чого на практиці іноді неможливо досягти. Більше того, необхідно враховувати, що за таких умов порядок значень паразитної ємності буде таким же, що і для ємності калібрувального конденсатора, або навіть більшим. З цієї причини для таких систем неможна застосовувати традиційні схеми калібрування, коли калібрувальний генератор підключений паралельно об'єкту випробування. В даній роботі була запропонована, реалізована та апробована альтернативна схема калібрування, відповідно до якої калібрувальний генератор з'єднаний послідовно з об'єктом випробування. Дослідження запропонованого способу калібрування показали, що його можна досить ефективно використовувати у випадках, коли досліджуваний зразок має малу ємність. Результати реєстрації калібрувальних імпульсів показали, що їх можна надійно зареєструвати та виміряти з мінімальною похибкою (похибка осцилографа), а похибки, пов'язані з паразитними параметрами схеми реєстрації, автоматично враховуються при калібруванні цим методом і не потребують додаткових коригувань результатів. Існує можливість підвищити чутливість вимірювальної схеми до 0,05 пКл/В, в першу чергу, шляхом збільшення коефіцієнта підсилення осцилографа щонайменше в 100 разів без повторення процедури калібрування. Це надасть змогу досліджувати зразки ізоляції досить високої якості, які характеризуються суттєво нижчим рівнем часткових розрядів, ніж у зразків, використаних у цій роботі. Експериментальна установка може бути застосована з метою аналізу різних способів моделювання часткових розрядів на персональному комп'ютері та порівняння їх результатів з реальним експериментом.

Ключові слова: частковий розряд, процедура калібрування, калібрувальний генератор, фільтр високих частот.

PROBLEM STATEMENT. When designing and developing insulation for high-voltage equipment, it is necessary to consider all the factors affecting the reliability of insulation over a significant period of operation. One of the factors that can significantly reduce the service life of insulation is the occurrence of partial discharges. Electrical discharges in solid and liquid insulation, not leading to overlap or breakdown of interelectrode gaps are classified as partial discharges. In addition, electrical discharges propagating along the surface of solid insulation located in a gaseous or liquid medium are also classified as partial discharges. Such discharges are classified as surface partial discharges. According to [1], a partial discharge is a localized electrical discharge that bridges only a portion of the insulation in an electrical insulation system. The conditions for the occurrence of partial discharges depend on the design of the insulating elements, the distribution of the electric field in which insulating elements are located, the properties of the insulating material, technologies used in manufacturing the insulating material, and so on. Partial discharges usually do not lead to an immediate electrical breakdown of the insulation, but can cause local destruction of the dielectric material. Under certain conditions, when partial discharges exist for a long time, they can lead to a reduction in dielectric strength of the insulation structure as a whole, and can cause damage to power equipment.

Partial discharge measurement is a reliable method for diagnosing the insulation condition of high-voltage electrical equipment at alternating current (AC) voltage. Since in the 20th century, AC predominated in power generation, power supply and power consumption systems, methods for diagnosing the insulation condition of electrical equipment based on the measurement of partial discharges were also developed for AC voltage [2]. The increased interest in high-voltage direct current (HVDC) transmission systems has also led to the challenge of measuring and interpreting partial discharges at direct current (DC) voltage [3, 4]. For example, partial discharges pose a threat to oil-paper insulation of HVDC converter transformers [5, 6] and HVDC cable systems [7].

Currently, such methods for detecting partial discharges are known and used [8–10]: electrical detection, ultra-high frequency detection; acoustic detection, chemical detection and optical detection method. Electrical detection or electrical pulse detection is still the most widely used of the above methods in practice [2]. This method is widely used by laboratories, as well as by high-voltage equipment manufacturers when monitoring the insulation quality of manufactured equipment, primarily when testing power and instrument transformers, current limiting reactors and cables. For many years, this method has been used for diagnostic examinations of high-voltage equipment under operating conditions.

To study the characteristics of insulating materials for the conditions of partial discharges occurring, their qualitative and quantitative characteristics, experimental installations and information-measuring systems are used. The test circuits and measuring systems depend on the test object, its operating conditions and the purpose of the research. The high-voltage equipment with oil-paper insulation is most sensitive to the formation of partial discharges. In this paper, to study the patterns of partial discharges arising in samples of high-voltage insulation, in particular, electrical cardboard (of different origin, thickness, moisture) or polymer and glass materials, an experimental installation is used, which design was described in [11, 12].

A feature of studies of partial discharges in insulating materials is the small size of the samples and electrode systems, which leads to a low capacitance of the tested insulation and makes it difficult to determine the quantitative indicators of partial discharges using the well-known methods recommended in [1].

The aim of the work is to develop a method for calibrating an experimental installation for studying the patterns of partial discharges arising in samples of paper insulation having low capacitance.

MATERIAL AND RESULTS. A review [2] shows that almost all modern systems for measuring partial discharges by electrical detection method use two main types of circuits for detecting partial discharges: straight detection circuit and balanced detection circuit. To study partial discharges at different forms of applied voltage, a special experimental installation was assembled in the high-voltage laboratory, which corresponds to the straight detection circuit. Photograph of high-voltage components of the experimental installation is shown in Fig. 1.

Figure 1 – A photograph of high-voltage part of experimental installation

All components which correspond to a straight detection method can be seen in photo above: step-up voltage transformer, coupling capacitor; partial discharge test object, shielded high-pass filter, kilovoltmeter and connecting wires. This experimental installation is described in [11, 12] and therefore will not be considered in detail here. The electrical detection method requires the contact of measuring instruments with the test object. The method is sensitive to various kinds of interference and requires the use of a set of measures to protect against them, for example, the use of corona-free wires, special filters, shielding and measuring instruments with processing the results using special software. As a metering instrument a digital oscilloscope [13] was used. The oscilloscope was connected to a laptop via a

USB interface. Photograph of low voltage components of the experimental installation is shown in Fig. 2.

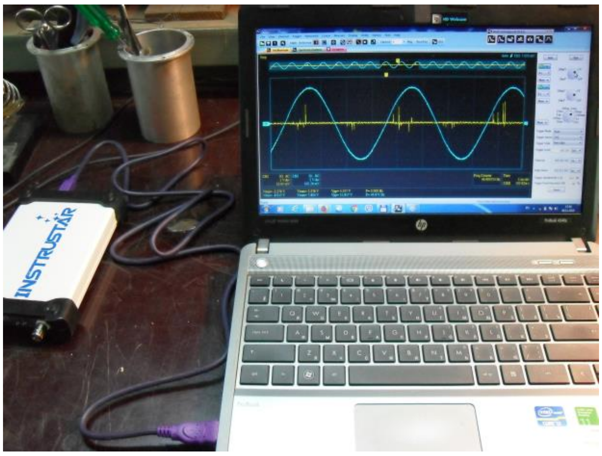

Figure 2 – A photograph of low-voltage part (metering instrument) of experimental installation

The main circuits of installations for studying the partial discharges and measurement methods are recommended in standards and technical literature [1, 2]. A partial discharge is a localized discharge that can partially bridge the insulation between two electrodes of different potentials. In most cases, partial discharges are the result of local concentrations of electric field intensity and are manifested in the form of current pulses lasting no longer than 1 μs, which occur inside the test object. The current pulse caused by a partial discharge, falling on a special detector, is converted into a signal of current or voltage proportional to the charge of the pulse at its input. But the charge that occurs in the discharge zone cannot be measured directly. For the characteristics of partial discharges, the concept of apparent charge q_0 is used, i.e. such a charge, which when instantaneously injected into the interelectrode system of the studied insulation sample causes the same voltage change at its electrodes (and hence on measuring devices) as the real discharge. Apparent charge is measured in coulombs (C).

In order to be sure that there is a certain relationship between the measured value of the apparent charge of partial discharge and the actual charge of partial discharge in the object of study, the partial discharge measuring circuit must be calibrated.

The calibration of the measuring system is performed in order to determine the scale factor k, which unequivocally connects the magnitude of the apparent charge with the reaction of the measuring system to its occurrence. In [1] the following calibration circuits are recommended, which differ only in the place of connection of the measuring system – in series with the coupling capacitor (refer to Fig. 3), or in series with the test object (refer to Fig. 4).

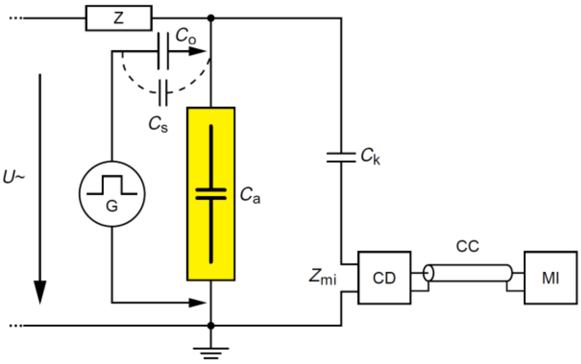

Figure 3 – Calibration circuit when coupling device is connected in series with the coupling capacitor

In Fig. 3: *U*~ is high-voltage power supply; *G* is step voltage generator; C_0 is calibration capacitor; Z_{mi} is input impedance of measuring system; *CC* is connecting cable; C_a is test object; C_k is coupling capacitor; *CD* is coupling device (usually includes a signal amplifier); C_s is stray capacitance; *MI* is measuring instrument (usually an oscilloscope); *Z* is filter (usually a high-pass filter).

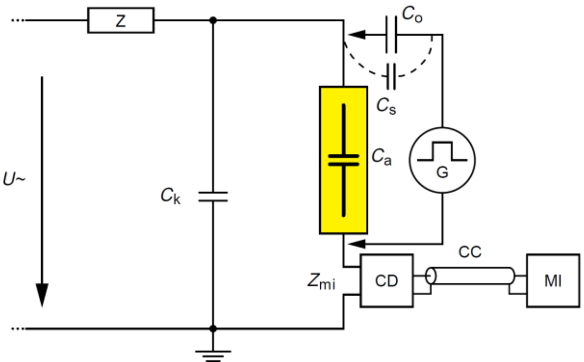

Figure 4 – Calibration circuit when coupling device is connected in series with the test object

In Fig. 4, the same designations are used as in Fig. 3. The calibration of the measuring system is performed by applying short-duration current pulses with a rise time of not less than 60 ns from the generator *G* through the calibration capacitor C_0 with known value of apparent charge q_0 to the pins of the test object. Here the known value of apparent charge is given by (1).

$$q_0 = U_0 C_0 . \quad (1)$$

In expression (1) U_0 is output voltage of step voltage generator *G*.

In order for the calibration procedure to be considered valid, it is necessary to ensure the following ratio (2) between the capacitance of calibration capacitor and the capacitance of the test object.

$$C_0 < 0.1 C_a . \quad (2)$$

However, due to the fact that the capacitance of the insulation sample used to study the characteristics of partial discharges is in the range from 1 to 5 pF, the above requirement for the calibration capacitor C_0, which have a capacitance of 0.1 pF to 0.5 pF, cannot be achieved practically. Moreover, the stray capacitance C_s will obviously be of the same order as the capacitance C_0, or even greater. Under these conditions, the calibration of the measuring system using the circuits shown in Fig. 3 or Fig. 4 cannot be performed. Taking into account the above, another calibration circuit was proposed, implemented and tested in the work. In above two circuits (in Fig. 3 and Fig. 4) calibration generator was connected in parallel with the test object. In the new circuit shown in Fig. 5, the calibration generator is connected in series with test object.

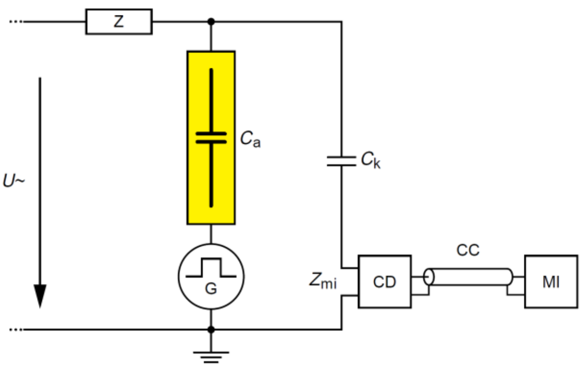

Figure 5 – Calibration circuit when the calibration generator is connected in series with test object

Calibration was performed on the experimental installation described in [11, 12]. The circuit is based on condition of connecting the step voltage generator *G* in series with the test object C_a. At such connection all parasitic parameters of the test circuit are considered automatically, in contrast to circuits in Fig. 3 and Fig. 4, where such parasitic parameters had to be taken into account separately when performing calibration.

In addition, there is no need for a calibration capacitor with strict requirements for its capacitance. When a pulse is applied from the calibration generator *G* to the object of research C_a, the corresponding charge is injected, which is defined by (3).

$$q_0 = C_a U_0 . \quad (3)$$

In expression (3) U_0 is output voltage of step voltage generator *G*; C_a is a capacitance of the insulation sample. As a result, a pulse proportional to the input charge will be received at the output of the measuring system. If one determine the ratio of the amplitude of the signal received on the measuring instrument to the input charge q_0, one obtain the calibration factor *k*. The coefficient *k* is then used to determine the magnitude of the charge of the partial discharge in the tested samples of high-voltage insulation, which are used in the research.

To attenuate the voltage with a frequency of 50 Hz, a high-pass filter with a damping factor at a frequency of 50 Hz not less than 80 dB was developed. In addition to pulses from partial discharges, a test voltage with a frequency of 50 Hz is also present on the loading element (coupling device). The amplitude of this signal is much, 10^3-10^4 times greater than the amplitude of the pulses of partial discharges. Thus, the test voltage signal creates interference that prevents the registration of pulses of partial discharges. To attenuate this signal, high-pass filters are used [14]. The technical literature provides the basic requirements for such filters, but specific designs and values of their elements are not given, believing that in each study, researchers independently calculate and make such a filter based on the capabilities and needs of a particular test installation. Among the available passive filter schemes, the 4th and 3rd order Butterworth and Chebyshev filters were considered in the paper. The calculation of filters was performed using free circuit simulation program Micro-Cap 12 [15]. This software includes a built-in filter design program which directly creates filter schematics.

The Butterworth filter feature is that its amplitude-frequency characteristic (frequency response) in the bandwidth is as smooth as possible in contrast to the Chebyshev filter, which in the bandwidth allows nonlinearity of the frequency response up to 3 dB.

The filters were calculated based on a load resistance of 500 Ohms, the value of which was chosen as a compromise. If the resistance is less than 100 ohms, the characteristics of the filter can be achieved by simpler means, but the signal amplitude at such a load will be too small and requires more amplification by the amplifier. A large resistance, more than 1000 Ohms, will give a sufficiently large signal of the partial discharge pulse, but the required characteristics of the filter can be obtained due to the significant inductances.

During the filter designing the following parameters were selected: passband ripple was 3.0103 dB; passband frequency was 1000 Hz; stopband attenuation was 20 dB; stopband frequency was 500 Hz.

An example of the obtained amplitude-frequency characteristic for the 4th order Butterworth filter is shown in Fig. 6.

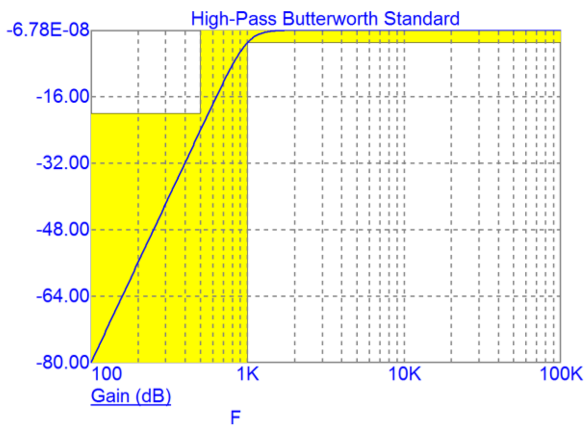

Figure 6 – Amplitude-frequency characteristic of the Butterworth filter of the 4th order

An example of the obtained amplitude-frequency characteristic for the 3rd order Chebyshev filter is shown in Fig. 7.

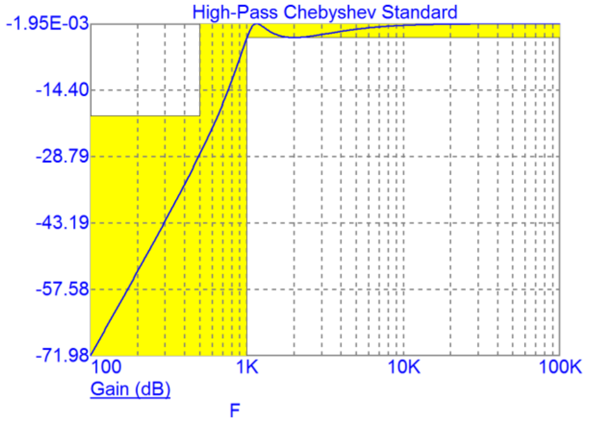

Figure 7 – Amplitude-frequency characteristic of the Chebyshev filter of the 3rd order

Circuit implementation of the Butterworth filter is shown in Fig. 8.

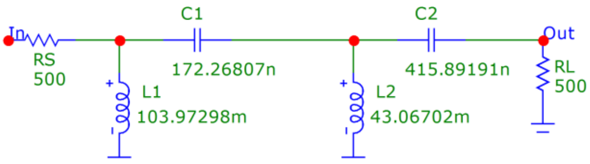

Figure 8 – Schematic diagram of the Butterworth filter of the 4th order

In its turn, circuit implementation of the Chebyshev filter is shown in Fig. 9.

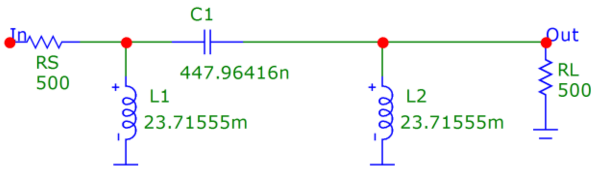

Figure 9 – Schematic diagram of the Chebyshev filter of the 3rd order

Analysis of the calculations showed that the Chebyshev filter, having a nonlinearity of the amplitude-frequency characteristic in the bandwidth of 3 dB, creates attenuation at a frequency of 100 Hz at 72 dB, while the Butterworth filter at the same frequency has attenuation at 80 dB and uniform (without attenuation) amplitude-frequency characteristic in the bandwidth. Therefore, the schematic diagram of the 4th order Butterworth filter was chosen for implementation in the experimental installation.

During operation the high-pass filter showed high characteristics. This filter transmits high frequencies of the input signal (pulses of partial discharges), while suppressing the low frequencies of the signal (voltage with a frequency of 50 Hz) as it shown in Fig. 10. The electrical method of detecting partial discharges is sensitive to all kinds of interference, so in order to protect against them, the filter was placed inside the shield.

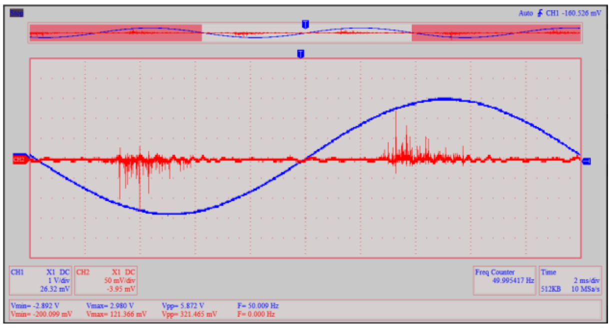

Figure 10 – Example of partial discharge pulses with attenuated 50 Hz voltage signal (red curve)

In Fig. 10 red color shows the registered pulses of partial discharges, and blue color shows the sinusoidal voltage applied to the cardboard.

An experimental study of the capabilities of the developed circuit showed that the use of a passive high-pass filter in combination with the amplifier UZ-29 provided a fairly high sensitivity for measuring partial discharges (0.1-0.5 pC) in combination with a high level of resistance to electromagnetic interference under conditions of high-voltage laboratory.

The results of calibration of the circuit for measurement of partial discharges arising in a sample of electrical cardboard with a thickness of 2 mm are shown in Fig. 11 and Fig 12.

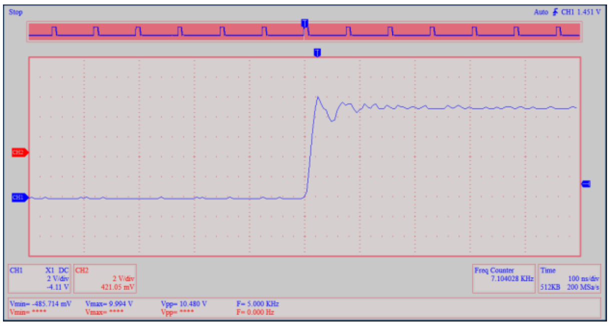

Figure 11 – Front of calibration pulse

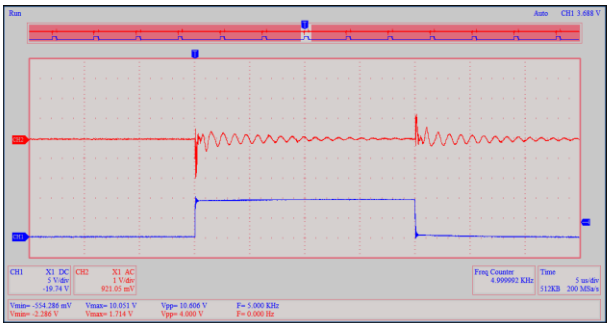

Figure 12 – The result of registration of the calibration pulse by the measuring circuit (circuit reaction)

Fig. 11 shows an oscillogram of a calibration pulse with an amplitude of 10 V, the pulse front is approximately 10 ns, which satisfies the requirements of the international standard [1].

Since the capacitance of the insulation sample in this electrode system $C_a \approx 1$ pF, the amplitude of the calibration pulse $U_0 = 10$ V, then the injected charge is:

$$q_0 = C_a U_0 = 1 \cdot 10 = 10 \text{ pC}. \qquad (4)$$

For this charge value (4), the reaction of the measuring circuit was 2 V. Thus, the calibration factor in this experiment is k = 5 pC/V.

CONCLUSIONS. Studies of the proposed method of calibration of the installation for measuring the characteristics of partial discharges have shown that it can be used quite effectively in cases where the test object at the time of calibration can be disconnected from the grounded electrode. The results of recording the calibration pulses showed that they can be reliably recorded and measured with a minimum error (oscilloscope error), and errors associated with parasitic parameters of the recording circuit are automatically taken into account when calibrating by this method and do not require additional adjustments.

In addition, it should be noted that there is a possibility to increase the sensitivity of the measuring circuit to 0.05 pC/V, primarily by increasing the gain of the oscilloscope at least 100 times (up to 10 mV per division, in comparison with 1 V per division used in Fig. 12) without repeating the calibration procedure of the circuit. This will make it possible to study insulation samples of fairly high quality in which the level of partial discharges is much lower than in those samples used in this work. The experimental installation can be used to analyze different ways of modeling partial discharges on a personal computer and comparing their results with a real experiment.

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