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METHODOLOGY FOR TESTING THE ELECTRIC STRENGTH OF VACUUM CHAMBERS DESIGNED FOR MODERN MEDIUM VOLTAGE SWITCHGEAR

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Abstract

The article presents methodology for testing the electric strength of vacuum chambers designed for modern medium voltage switchgear developed by the authors, using two innovative test stands designed and constructed by the research team above. Verification of the correctness of operation of the test stands, as well as the validity of the developed methodology was carried out by performing a series of tests. It was determined that below certain pressure values in the tested chamber (from about 5.0×10^0 Pa for station 1 and for about 4.0×10^{-1} Pa for station 2), the electric strength maintains a constant value, which guarantees stable operation of the vacuum chamber. The values of the total measurement uncertainty for the electric strength tests were also estimated.

Keywords: Vacuum interrupter, vacuum breakdown, electric strength, vacuum switchgear, measurement uncertainty.

1. Introduction

Supplying final customers with electricity of proper quality and uninterrupted access is currently an absolutely basic requirement. The quality of electricity directly depends on the quality of the components that are part of the power systems. Analyzing currently available sources on the technical condition of the power infrastructure, it can be stated with conviction that it is outdated and needs significant modernization. Regarding the continuity of electricity supply, specialized indicators have been introduced whose values are essentially determined by the failure of power networks, mainly medium voltage. Each of the Distribution System Operators faces the problem of obtaining the lowest possible values of power reliability indicators. These indicators include: SAIDI, SAIFI and MAIFI indexes [1–3].

One of the legal acts directly related to the topic of power grid reliability is the Regulation of the Minister of Economy dated May 5, 2007 on the detailed conditions of the operation of the power system. This document contains information on the obligation of Distribution System

Operators to make public on their websites the SAIDI, SAIFI (indicators designated separately for planned and unplanned interruptions) together with MAIFI [3]. Another document specifying detailed information on the mechanisms of calculation of the above-mentioned indicators and requirements, as well as penalties and bonuses for final results is specified in the Quality Regulation 2018-2025 [4] for Distribution System Operators.

Figure 1 shows the development of the planned and unplanned SAIDI index, taking into account the disastrous interruptions between 2016 and 2019. The storms that occurred in August and October 2017 confirmed everyone's belief that this type of event determines the total value of this indicator during the year. Analyzing the SAIDI indicators for planned interruptions, one can see that there was a clear downward trend in the years 2016-2019, however, it is far from the European average.

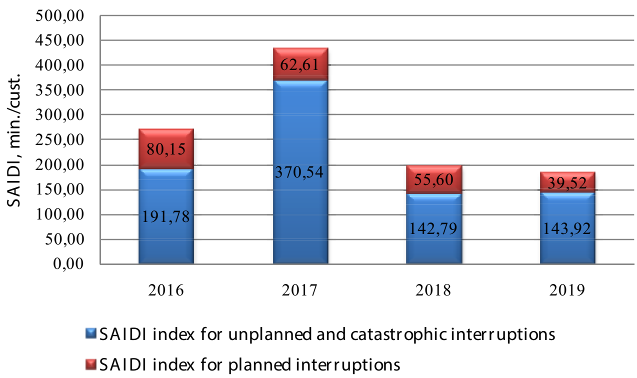

Fig. 1. SAIDI index in Poland in the years 2016-2019 (own elaboration, based on) [1, 2].

When analysing the reliability indicators of electricity supply in Poland, it is worth noting how they are shaped in other European countries. Fig. 2 shows the SAIDI indicator for unplanned and catastrophic interruptions in 2016 for selected European countries. These diagrams strengthen the belief that Poland is far behind the other European countries in terms of reliability indicators. Switzerland, Germany, Denmark, Luxembourg and the Netherlands are among the leaders in terms of the lowest unplanned and catastrophic SAIDI values. In 2016, each electricity customer in these countries was out of power for no more than 20 minutes. For comparison, in Poland this time was about 192 minutes.

The draft for the Polish Energy Policy until the year 2040 assumes that by 2025, energy supply quality indicators should reach the EU average and remain at the level of the EU average in subsequent years [6]. Reaching the values of SAIDI and SAIFI indicators at the level of the above-mentioned countries is certainly a great challenge for Polish DSOs, but it is also a motivation to take further actions that may improve the reliability of Polish power networks. Many research institutions and scientific entities are carrying out a number of advanced activities in this direction. An example is the research described in [7–9]. Cooperation between business and science can in the coming years prove a solution to the existing problems of power companies.

Most of the currently used insulation media in medium voltage overhead power devices are based on sulphur hexafluoride (SF6). The gas is odorless, colorless, non-toxic and non-flammable under normal conditions. It belongs to the so-called fluorinated greenhouse gases that increase the atmosphere temperature. SF6 gas is the most powerful greenhouse gas classified so far. The

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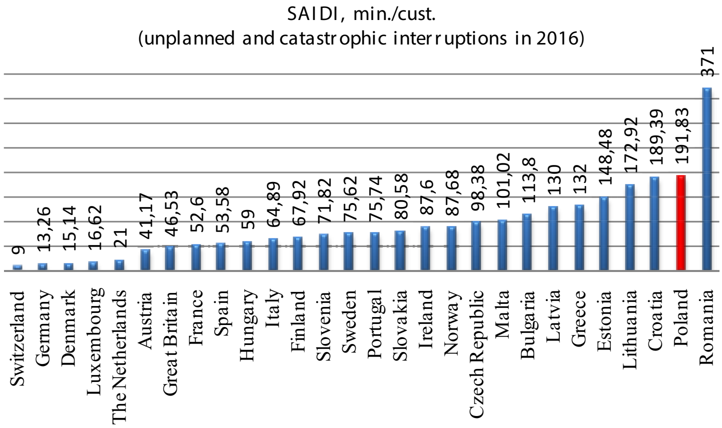

Fig. 2. SAIDI index for unplanned interruptions in 2016 for European countries [5].

parameter known as global warming potential (GWP) for sulphur hexafluoride is 22.200 which means that 1 kg of SF6 is equivalent to 22 200 kg of carbon dioxide.

Many global organizations and institutions have turned their attention to the harmfulness of sulphur hexafluoride [10–12]. In 1987, the Montreal Protocol was signed, the aim of which is to prevent the formation of an ozone hole, and to limit the use of substances that damage the ozone layer. A similar idea is taken up by another document, the Kyoto Protocol, in force since 2005. Environmental protection is also the subject of discussions in the European Union's committees. The regulation concerning fluorinated greenhouse gases assumes the reduction of emissions of these gases in EU countries by about 73% by 2030 and by about 75% by 2050 in relation to 1990.

Vacuum technology is an alternative to the harmful gas SF6, the use of which in electrical engineering has been known practically since the beginning of electricity [13]. Vacuum, as an insulating and extinguishing medium used in switchgear, has displaced other centres of operation, thus the vast majority of medium voltage switches and disconnectors currently produced are devices with vacuum chambers [14–17]. The advantage of this technology over other solutions results from its extraordinary properties such as environmental neutrality, high switching durability, any working position of the device, quick recovery of electric strength or lack of explosion and fire hazard [13]. A significant number of installed devices with vacuum chambers are directly connected with the necessity to diagnose them in terms of vacuum condition. A number of existing diagnostic methods are used for this purpose to assess the correct operation of vacuum extinguishing chambers. These methods have been described in detail in the papers [18–24]. Unfortunately, due to the fact that these methods cannot be applied during the operation of a given device, their application requires a number of activities such as disassembly, work in laboratory conditions and reassembly, which directly affects the increase in reliability indicators.

Due to the requirements and limitations above, there is a legitimate need to develop new devices with better operational parameters and free from harmful SF6. The response to this demand is the EKTOS switch disconnector, which is the final result of the project entitled: *Development and implementation for the production of an innovative overhead vacuum switch disconnector dedicated to intelligent medium voltage networks* implemented by the Lublin University of Technology in consortium with the company EKTO from Białystok as part of the activities supported by the National Center for Research and Development.

The motivation to undertake research related to vacuum chambers was, inter alia, growing demand for electricity and requirements for the reliability of electricity supply, which is directly related to the need to improve the rated parameters of vacuum chambers with their simultaneous miniaturization. These include rated current, breaking current, cut-off current, and dielectric strength. Additionally, there is a strong need to develop a method of continuous (online) diagnostics of the vacuum level in extinguishing chambers.

Two original test stands as described later on can be used for this purpose. One of them creates the possibility of testing the vacuum chambers currently used in electric switchgear, as well as their diagnostics in terms of the state of vacuum. The other, enables a number of innovative research processes to be carried out that give a chance of developing new solutions for modern power equipment on a global scale.

2. The authors' laboratory stands for testing vacuum extinguishing chambers

The first of the author' test stands consists of a specialist mobile construction, in which it is possible to mount the vacuum chamber to be tested, as well as to connect the power supply and load the stand with power cables terminated with angular connector heads. The possibility of precise adjustment of the specified inter-contact distance is ensured by installing an extraction screw with a 1 mm pitch thread. In order to even out the distribution of electromagnetic field inside the stand, screens made of copper pipes and stainless-steel balls were mounted. The test object in the above-described station are disconnector vacuum chambers, designed to connect the current circuits of overhead medium voltage power networks.

They are characterized by small dimensions, high operational reliability, arc insulation from the environment, quiet operation, any operating position and resistance to vibration and shock. They are made of movable and fixed contacts, made of copper-filtered tungsten (W-Cu) in a ratio of 70% tungsten to 30% copper. The movement of the movable contact is enabled by elastic bellows. There is also a metal condensation screen in the chamber, which protects the chamber casing from conductive particles which, when deposited on it, could cause deterioration of its parameters.

The special design of the tested chambers offers the possibility of repeated gas filling due to their unsealing and adaptation to connecting a set of vacuum pumps. In addition, for the purposes of scientific research, the vacuum chamber with modified elements was manufactured, in which the condensation screen was removed and the stationary pole was extended. This results in the ability to observe physical phenomena occurring between the chamber contacts, including electric breakdowns and the arc ignition process. The construction of the second test stand is based on the so-called demountable vacuum chamber whose main element is the discharge chamber, inside which there is a contact system terminated with contact strips made of copper-filtered tungsten (70% W, 30% Cu).

The construction of the chamber has been designed in a way that allows free access to its internal part, and thus changing the contact strips. This allows to examine the dependence of electric strength on the type of materials from which the contacts of the tested chamber are made. Thanks to the sight glasses mounted in the test stand, it is possible to precisely observe the phenomena occurring inside the chamber. The adjustment of the inter-contact distance was accomplished by integrating the movable contact assembly with a drive with a pneumatic linear actuator and a linear displacement sensor. The set value of the inter-contact distance is displayed on an LCD display attached to the structure. The operation of the drive is carried out with buttons on the operator panel or by remote control ensuring isolation of the stand from the operator performing the measurement.

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The main element of the test set supplying the above-mentioned test stands is a high voltage transformer cooperating with a modern, programmable control panel, which greatly facilitates the performance of tests. An additional capacitive divider, made on the basis of selected low-loss polypropylene capacitors ensures precise voltage measurement. The control panel is equipped with a brush voltage regulator along with the drive. The control part is a SIMATIC S7 1200 PLC controller and a dedicated measuring module. The technical parameters are presented in Table 1 and the test stands are shown in Fig. 3.

Table 1. Rated parameters of the test set.

Power transformer LV/MV		**Voltage divider**		**Control panel**	
Supply voltage	230 V	Supply voltage	50 kV	Supply voltage	230 V
Rated power	2.5 kVA	Capacity	190 pF	Rated power	6 kVA
Output voltage	50 kV/25 kV	Transmission	412.5	Output voltage	0–250 V

Fig. 3. Test stands for testing vacuum chamber (a – No. 1, b – No. 2).

To ensure adequate pressure inside the tested vacuum chambers, a vacuum set consisting of a turbomolecular and rotary vacuum pump, cooperating with a dedicated vacuum meter and a set of specialized gauges is used. The above-mentioned system works with a capacity of 90 l/s, thanks to which it is possible to test chambers at the pressure used in the switchgear currently available on the market.

What is more, it is possible to introduce a mixture of various types of noble gases (helium, argon, neon) into the contact gap space of the chamber in order to study their effect on the electric strength of the tested system and the arc ignition process. A technical gas set is used for this purpose, with devices enabling connection and dosing of a given amount. The block diagram of the system for testing electric strength using the described test stands is shown in Fig. 4, while the electric diagram is shown in Fig. 5.

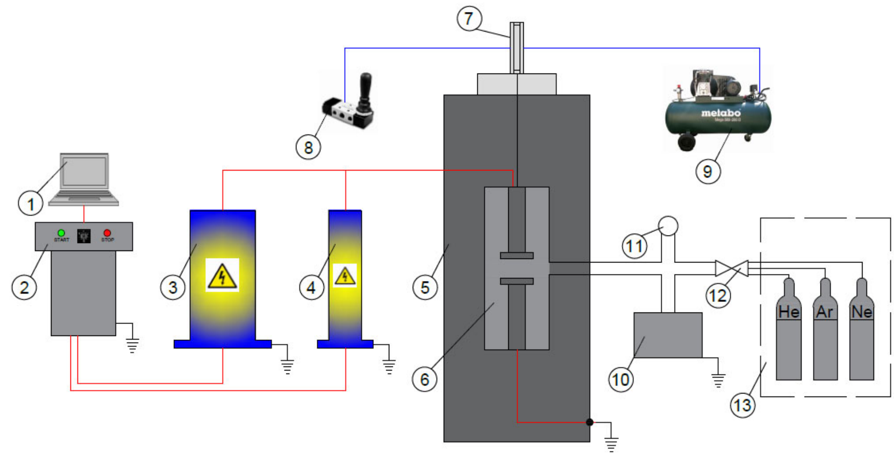

Fig. 4. Block diagram of the system for testing the electric strength of vacuum chambers (1 – computer, 2 – control panel, 3 – power transformer, 4 – capacitive divider, 5 – test stand (No. 1 or No. 2), 6 – contact system, 7 – pneumatic actuator, 8 – pneumatic manual valve, 9 – compressor, 10 – set of vacuum pumps, 11 – vacuum gauge, 12 – manual vacuum valve, 13 – technical gas set).

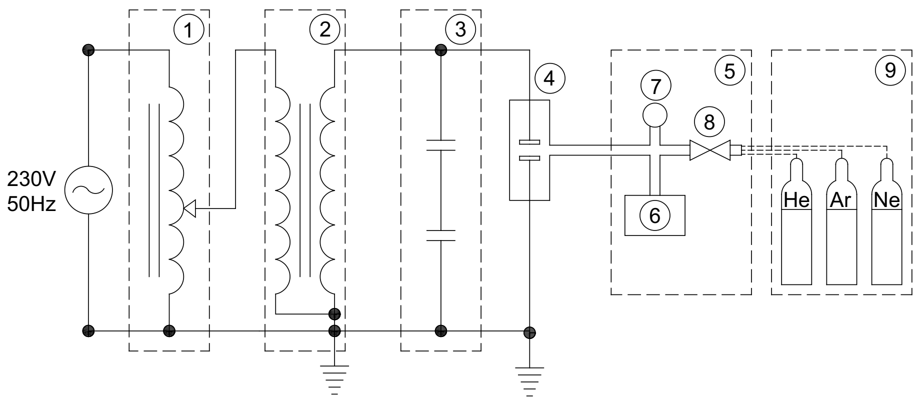

Fig. 5. Electric diagram of the system for testing the electric strength of vacuum chambers (1 – control panel, 2 – power transformer, 3 – capacitive divider, 4 – tested vacuum chamber, 5 – vacuum system, 6 – set of vacuum pumps, 7 – vacuum gauge, 8 – manual vacuum valve, 9 – technical gas set).

3. Research methodology

With all the necessary electric connections made, the desired contact distance in the currently used test stand, and the appropriate pressure inside the vacuum chamber obtained, the determination of the test configuration in automatic mode was begun. Next the value of the test voltage, test time, rate of voltage build-up and maximum leakage current were set. Then the test was started, during which it was possible to preview the current values of the voltage and output current on the HV side, as well as preview the course of the voltage in time a the graph generated by the program. The system automatically increased the voltage applied to the test stand until there was an electric surge between the chamber contacts. The recorded value of the breakthrough voltage was used for further analysis by the authors of the test.

Using the above-described laboratory stands, number 1 with a special vacuum chamber installed and stand number 2 with the so-called demountable chamber the electric strength of contact systems was tested for contact gap distances in the range from 1 mm to 5 mm with a pitch of 0.1 mm and pressure inside the chambers in the range from 4.0×10^{-4} Pa to 1.2×10^3 Pa.

4. Verification of the correct operation of stands and the developed test methodology

First of all, verification of the correct operation of laboratory stand No. 1 was carried out. For this purpose, a special vacuum chamber was installed and breakdown voltage was measured for inter-contact distances in the range of 1÷5 mm and the pressure inside the chamber in the range $4.0 \times 10^{-4} \div 1.2 \times 10^3$ Pa. Figure 6 shows the dependence of the breakdown voltage of the tested chamber as a function of the inter-contact distance for selected pressure values.

Analyzing the obtained characteristics, it can be observed that in the pressure range between $8.0 \times 10^{-4} \div 5.3 \times 10^{-1}$ Pa, the value of the breakdown voltage increases with the increase in the inter-contact distance and this parameter has the main impact on the voltage values at which the breakdown occurred between the chamber contacts. When the pressure inside the tested vacuum chamber increases, it can be observed that the characteristics approach the horizontal course, at which the breakdown voltage is only influenced by the pressure inside the chamber. This phenomenon occurs for pressures above 6.7×10^0 Pa.

Figure 7 shows the dependence of the breakdown voltage as a function of pressure inside the tested chamber. Considering the above dependences, first of all, it should be noted that below the pressure of about 5.0×10^0 Pa, the breakdown voltage for each of the set inter-contact distances remains at constant values. This corresponds to the linear characteristics from Figure 6.

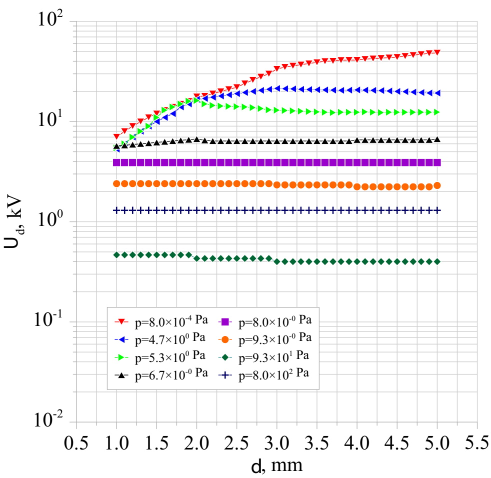

Fig. 6. The dependence of the breakdown voltage U_d on the inter-contact distances d for selected values of pressure p in the vacuum chamber specially designed.

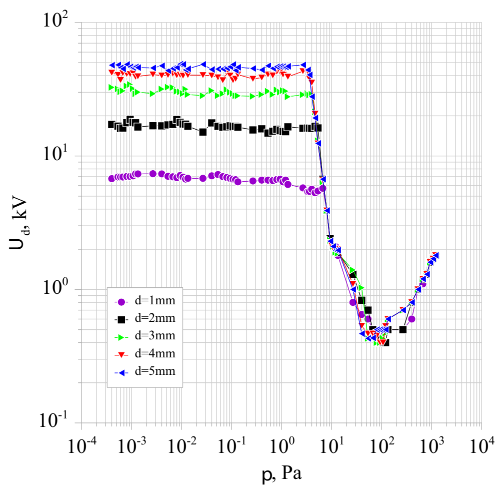

Fig. 7. The dependence of the breakdown voltage U_d on the pressure p for selected inter-contact distances d in the vacuum chamber specially designed.

Ensuring appropriate pressure inside the vacuum chamber guarantees a high and stable value of its electric strength, and thus failure-free operation of electric equipment, which is implemented by manufacturers of vacuum chambers used in modern medium voltage switchgear.

With an increase in pressure above 5.0×10^0 Pa, a sharp decrease in breakdown voltage is visible until reaching a minimum value of approx. 0.4 kV for pressures in the range of $8.0 \times 10^1 \div 1.2 \times 10^2$ Pa. Along with the mentioned decrease in strength, emerging glow discharge was observed. Further aeration of the chamber's inter-contact space results in an increase in electric strength.

Similar measurements were carried out using test stand No. 2, based on a demountable vacuum chamber. The values of breakdown voltages inside the chamber were measured for inter-contact distances from 2 mm to 5 mm, for a pressure range of $4.0 \times 10^{-4} \div 4.4 \times 10^2$ Pa. Figure 8 shows the values of the measured breakdown voltages as a function of inter-contact distances for selected pressure values.

For pressures in the range of $4.0 \times 10^{-4} \div 3.0 \times 10^{-1}$ Pa, the breakdown voltage is mainly affected by the inter-contact distance. With further aeration of the chamber, this situation changes in favour of the pressure value, which has been observed from about 4.5×10^{-1} Pa. A similar phenomenon occurred during measurements with the previous test stand.

Figure 9 presents the dependence of the breakdown voltage U_d as a function of pressure inside the demountable chamber for the tested inter-contact distances d. Analyzing the dependences presented above, similar graphs can be observed as for stand No. 1 (Fig. 7). For pressures below about 4.0×10^{-1} Pa, constant breakdown voltages occur.

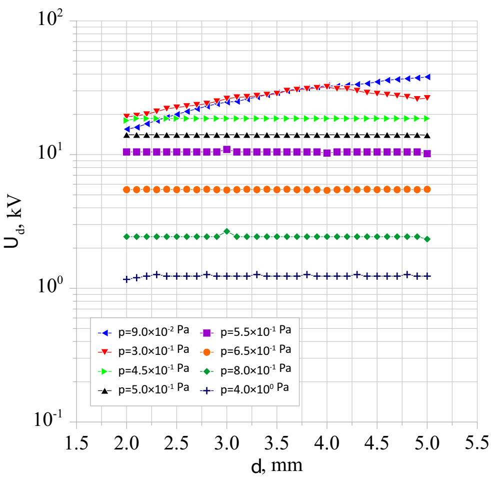

Fig. 8. The dependence of the breakdown voltage U_d on the inter-contact distances d for selected values of pressure p in the demountable vacuum chamber.

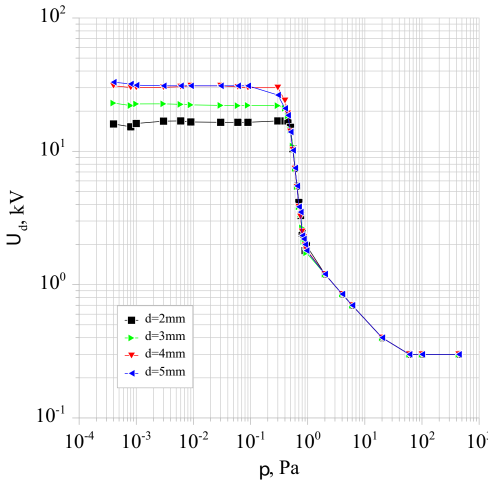

Fig. 9. The dependence between breakdown voltage U_d and pressure p for selected inter-contact distances d of the demountable vacuum chamber.

With further increase of pressure inside the chamber, there is a sharp drop in the breakdown voltage at which glow discharges were also observed. The smallest recorded breakdown voltage was about 0.3 kV.

5. Measurement uncertainty analysis of the developed research methodology

Based on the measurements carried out, static measurement uncertainty (type A) related to the series of measurements and type B uncertainty were calculated which is based on the scientific judgment of the experimenter using all information about the measurement and sources of its

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uncertainty. The methodology and results of voltage and current calibration performed by the manufacturer of the test set as described before are presented.

Type A evaluations of measurement uncertainty is calculated when the performed tests consist in carrying out a specific number of measurements and then calculating the arithmetic mean, which is taken as the final result [25–27]. Direct type A measurement uncertainty for jump voltage $u_A(U_d)$ measurements is equal to the standard deviation of the mean (1):

$$u_A(U_d) = \sqrt{\frac{1}{n(n-1)} \sum_{i=1}^{n} \left(U_{di} - \overline{U_d}\right)^2}\,, \tag{1}$$

where: U_{di} – jump voltage for the i-th measurement; $\overline{U_d}$ – average jump voltage for n measurements; n – number of measurements taken.

For the calculation of type B measurement uncertainty, we use information about the measuring instruments used in the tests. We define this uncertainty with the following expression (2):

$$u_B(U_d) = \frac{\Delta x}{\sqrt{3}}\,. \tag{2}$$

The calibration uncertainty Δx is determined on the basis of technical data of the measuring instrument (3). In the case of tests carried out with the use of the above-described stands, the calibration uncertainty is mainly influenced by the measured value of the flash-over voltage U_d, as well as the measuring range z:

$$\Delta x = c_1 x + c_2 z\,. \tag{3}$$

The c_1 and c_2 coefficients were specified by the manufacturer of the measuring instrument installed in the control panel. They are respectively: $c_1 = 0.05\%$ and $c_2 = 0.01\%$. The total measurement uncertainty is calculated as follows (4):

$$u(U_d) = \sqrt{u_A^2(U_d) + u_B^2(U_d)}\,. \tag{4}$$

Measurement uncertainty of type A was calculated for a series of 10 measurements of breakdown voltage for an inter-contact distance of 4 mm, made using two test stands described above. Analogous calculations were made in order to calculate type B uncertainty. Then, the total value of the measurement uncertainty was calculated for test stands No. 1 and No. 2. Figures 10 and 11 show the dependences of the measured values of breakdown voltage and total uncertainty as a function of pressure for the test stand with a special-design chamber and the test stand based on a demountable vacuum chamber.

For flash-over voltage measurements in a special version of the vacuum chamber, in the pressure range $4.0 \times 10^{-4} \div 8.0 \times 10^{-2}$ Pa, the total uncertainty was approx. 1 kV, which is, respectively, approx. 2.5% of the measured value of the breakdown voltage. When the pressure was increased to 8.0×10^{0} Pa, the calculated value of the total uncertainty was from 3% to 5% of the measured value. For pressures from 8.0×10^{0} Pa to 1.2×10^{3} Pa, the values of the total measurement uncertainty increased intensively. It is worth noting, however, that type B measurement uncertainty has the biggest influence on the total value of the measurement uncertainty.

The total measurement uncertainty for the stand with a demountable chamber in the pressure range $4.0 \times 10^{-4} \div 3.0 \times 10^{-1}$ Pa was approx. 0.8 kV, which corresponds to approx. 2.5% of the measured value of the breakdown voltage. Above the pressure of 3.0×10^{-1} Pa, the total uncertainty

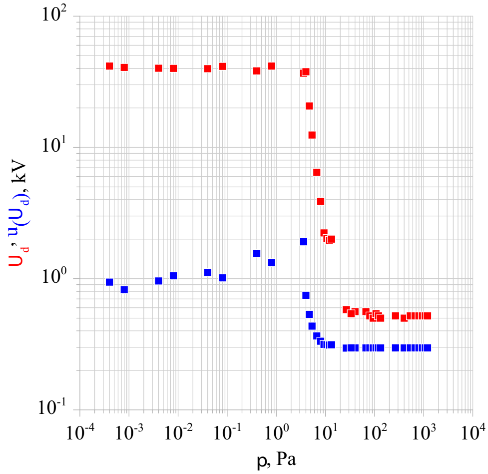

Fig. 10. The dependence of mean values of breakdown voltages and total measurement uncertainty as a function of pressure in the chamber specially designed for the inter-contact distance d = 4 mm.

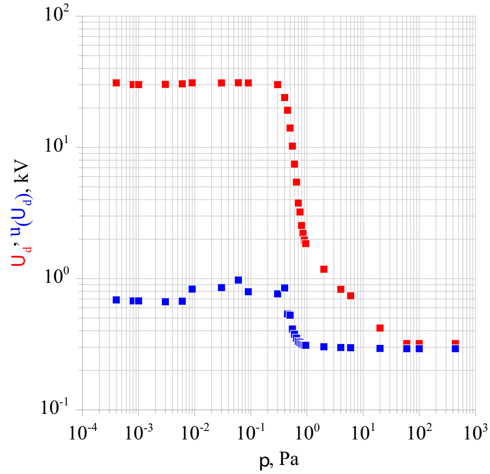

Fig. 11. The dependence of mean values of breakdown voltages and total measurement uncertainty as a function of pressure in the demountable chamber for inter-contact distance d = 4 mm.

value increased with the decrease of the breakdown voltage value. In this case, a similar situation occurred as in the case of the stand No. 1. The main influence on the total uncertainty was exerted by type B uncertainty. One of the solutions that can reduce the value of type B uncertainty in both cases is reducing the measuring range in certain pressure ranges which is possible with the use of the control panel.

6. Voltage and current calibration of the test set

According to the PE EN-60060 standard, the maximum error of the measured system must be less than 3% of the value on the standard, after taking into account the measurement uncertainty. The measurement class of the standards used during the test was intentionally decreased to a level of 1%. Therefore, the actual measurement uncertainty values are lower than those given in the tables below. The total measurement uncertainty of the system is given as the expanded uncertainty, with a normal distribution with a 95% confidence level and a coverage factor k = 2. The calculation results are summarized in Tables 3 and 4.

The following dependences were used in the calculations (5,6,7):

$$\delta = X_{\mathrm{OB}} - X_{\mathrm{standard}}\,, \tag{5}$$

$$\delta_{\%} = \frac{X_{\mathrm{OB}} - X_{\mathrm{standard}}}{X_{\mathrm{standard}}} \times 100\%\,, \tag{6}$$

$$\overline{X} = 2 \times \sqrt{\delta^2 + \overline{x}^2_{\mathrm{standard}} + \left(\frac{l.s.d.}{\sqrt{3} \times 2}\right)^2}\,, \tag{7}$$

where: δ – absolute error (scalar), $\delta_{\%}$ – relative error, $\overline{x}_{\mathrm{standard}}$ – measurement uncertainty of the reference standard, l.s.d. – the least significant digit, X_{OB} – voltage/current value on the tested object, X_{standard} – voltage/current value on the reference standard,

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Table 2. Measurement and calculation results during voltage calibration.

Voltage on the tested object	**Voltage reference standard**	**Absolute error**	**Relative error**	**Total measurement uncertainty**	**Total measurement uncertainty (percentage)**
U_{OB} [kV]	$U_{standard}$ [kV]	δ [kV]	$\delta_{\%}$ %	$\overline{U}$ [kV]	$\overline{U}_{\%}$ [%]
5.1	5.1	0.0	0.00	0.08	1.51
10.1	10.1	0.0	0.00	0.12	1.15
15.0	15.1	–0.1	–0.66	0.26	1.70
20.0	20.1	–0.1	–0.50	0.29	1.44
25.0	25.1	–0.1	–0.40	0.33	1.30
30.1	30.2	–0.1	–0.33	0.37	1.21
35.0	35.2	–0.2	–0.57	0.54	1.52
40.0	40.2	–0.2	–0.50	0.57	1.42
45.0	45.3	–0.3	–0.66	0.75	1.66
50.0	50.3	–0.3	–0.60	0.79	1.56

Table 3. Measurement and calculation results during current calibration.

Voltage on the tested object	**Voltage reference standard**	**Absolute error**	**Relative error**	**Total measurement uncertainty**	**Total measurement uncertainty (percentage)**
I_{OB} [mA]	$I_{standard}$ [mA]	δ [mA]	$\delta_{\%}$ [%]	$\overline{I}$ [mA]	$\overline{I}_{\%}$ [%]
5.0	5.02	–0.02	–0.40	0.09	1.72
10.1	10.12	–0.02	–0.20	0.12	1.22
15.5	15.56	–0.06	–0.39	0.20	1.32
20.2	20.23	–0.03	–0.15	0.22	1.08
25.5	25.65	–0.15	–0.58	0.40	1.56
30.1	30.25	–0.15	–0.50	0.43	1.42

On the basis of the results presented in Tables 2 and 3, the relations between the voltage value on the standard and the total measurement uncertainty of the voltage as a function of voltage value on the tested object (Fig. 12) as well as the relations between the current value on the standard and the total measurement uncertainty of the current as a function of current value on the tested object (Fig. 13) were generated.

The total measurement uncertainty, both for voltage and current measurements, did not exceed 3%, so the final assessment based on the PE EN-60060 standard is positive.

The research stands presented in this article are innovative solutions allowing, among others for testing of the electric strength of the inter-contact space, which can be used to diagnose the efficiency of vacuum chambers dedicated to medium voltage switchgear. The special design of the tested vacuum chambers, as well as the availability of a test stand based on the so-called demountable vacuum chamber, allow testing of the impact of a number of parameters (including the inter-contact distance, pressure inside the chamber, the content of the electronegative gas mixture in the chamber, type of load, type of contacts and their structure), both on the values of dielectric strength of the chambers as well as on the parameters related to the process of formation,

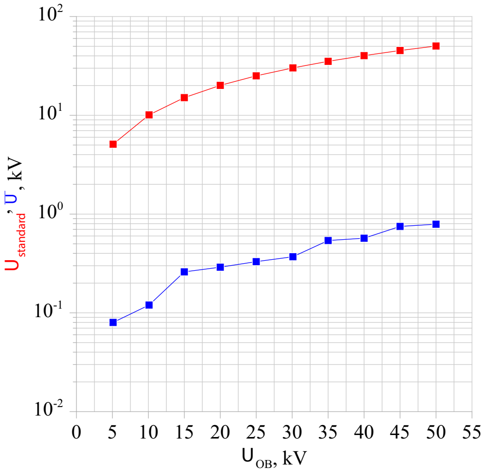

Fig. 12. The dependence of the voltage value on the standard and the total measurement uncertainty of the voltage as a function of the voltage value on the tested object.

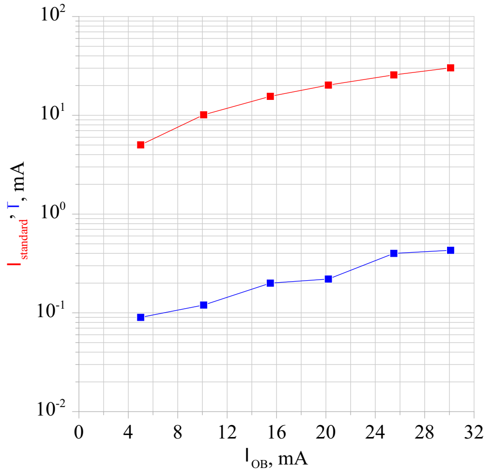

Fig. 13. The dependence of the current value on the standard and the total measurement uncertainty of the current as a function of the current value on the tested object.

burning and extinguishing of an electric arc in a vacuum which will be carried out in subsequent stages of research and development work conducted by the authors of the article.

Analyzing the obtained results of measurements of electric strength, it can be stated that the developed methodology of tests carried out using designed and constructed test stands is correct and provides correct information on the phenomena occurring during electric discharge in a vacuum. In addition, the test set used to power the described stations meets the requirements of calibration standards, which was confirmed by laboratory tests and subsequent calculations. The measurement uncertainty determined on the basis of target measurements reached unsatisfactory values in certain ranges. To eliminate this phenomenon, in the near future work will be undertaken to improve the grounding condition of the test stands, using innovative equipment designed for this purpose, as well as further modifications of the stands, in order to improve the distribution of the electromagnetic field and thus eliminate partial discharges. A significant dispersion of the results obtained in certain ranges may also indicate that the conditioning process of the tested vacuum chambers has not been fully completed. A separate issue is also taking into account the vacuum losses in the section between the vacuum pump and the test chambers or installing an additional vacuum gauge near the test objects, which is also in the nearest future plans of the research team.

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