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Laboratory studies of the electrical strength of vacuums obtained on the basis of air, neon and helium

***Abstract**. The paper describes an innovative laboratory station based on a so-called demountable vacuum chamber and presents the results of electrical strength measurements using it. The pressure in the chamber was increased by injecting air, neon, and helium into it. It was found that the chamber with residual gases in the form of helium, in comparison with air and neon, retains its full insulating capacity over a much larger range of pressure values.*

***Streszczenie.** W artykule opisano innowacyjne stanowisko laboratoryjne oparte o tzw. rozbieralną komorę próżniową, a także przedstawiono wyniki pomiarów wytrzymałości elektrycznej z jego wykorzystaniem. Ciśnienie w komorze zwiększano poprzez dozowanie do jej wnętrza powietrza, neonu, oraz helu. Stwierdzono, że komora z gazami resztkowymi w postaci helu, w porównaniu do powietrza i neonu, zachowuje pełną zdolność izolacyjną w znacznie większym przedziale wartości ciśnienia. (**Badania laboratoryjne wytrzymałości elektrycznej próżni uzyskanej na bazie powietrza, neonu i helu**).*

Słowa kluczowe: komory próżniowe, próżniowa aparatura łączeniowa, wytrzymałość elektryczna, wskaźniki niezawodnościowe.
Keywords: vacuum interrupters, vacuum switchgear, electrical strength, reliability indicators.

Introduction

The use of vacuum technology takes place in many branches of industry and the economy. Over the past decades, vacuum has become established in the electrical industry as an insulating medium for switchgear and distribution equipment. In the 1980's, oil was the dominant insulating medium, with about 65% of newly designed medium voltage circuit breakers using oil. Currently, almost 100% of newly designed MV circuit breakers are based on vacuum insulation (Fig. 1) [1].

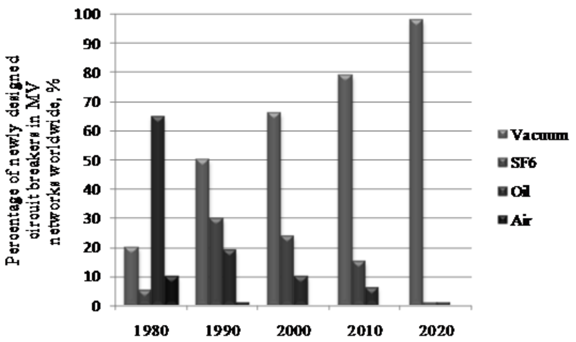

Fig.1. Circuit-breakers in MV networks from 1980 to 2020 by applied insulation medium [1]

In the Polish public power sector, the key fact is that reliability indicators have visibly improved in recent years. Both in the case of SAIDI and SAIFI, all DSOs in 2020 have achieved the minimum values of these parameters. Therefore, the SAIDI and SAIFI index for Poland (5 Distribution System Operators) was reduced [2]. In 2020, they amounted to 156,73 min/cust. and 2.55 interrup./cust., respectively (Fig. 2-3).

In order to continue the trend of reducing the values of reliability indices and improving the technical parameters of power infrastructure elements, it is crucial for the industry to cooperate with scientific institutions which have research laboratories enabling the development of new innovative technical solutions. One of such places is the Faculty Laboratory of Switchgear and Switching Devices of the Faculty of Electrical Engineering and Computer Science of Lublin University of Technology. It has at its disposal innovative laboratory workstations intended, among other things, for research on improving technical parameters of vacuum interrupters dedicated to modern switchgear. The research carried out in this unit perfectly coincides with the trends and directions of research carried out by the best scientific institutions [3-6].

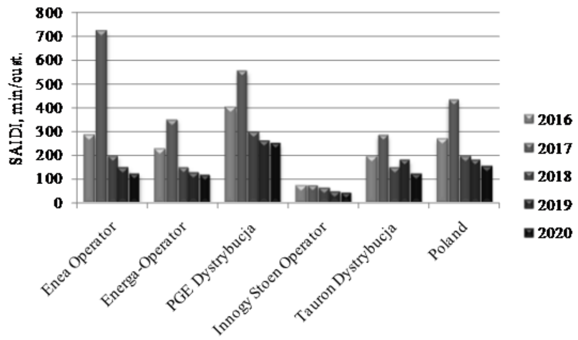

Fig.2. SAIDI index in 2016 - 2020 by Distribution System Operators in Poland [2]

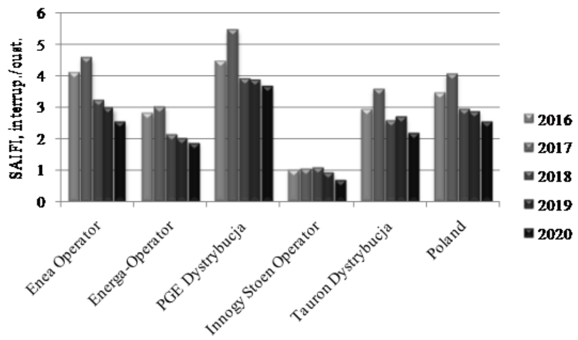

Fig.3. SAIFI from 2016 to 2020 by Distribution System Operators in Poland [2]

Laboratory bench

The test bench for consists of four main components [7-10]. It is a high-voltage test set with nominal voltage of 110 kV, demountable vacuum discharge chamber with contact gap control system, vacuum kit with technical gases and system for photographic recording of arc processes.

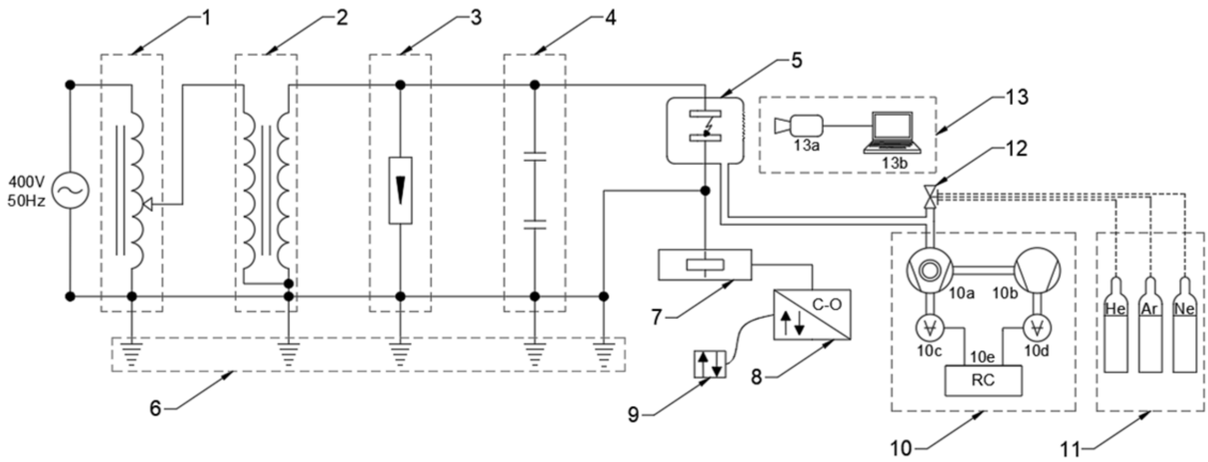

Fig.4. Schematic of the system designed to test and record arc processes in a demountable vacuum chamber: 1 - control system, 2 - test transformer, 3 - surge arrester, 4 - capacitive divider, 5 - demountable vacuum chamber, 6 - dedicated grounding, 7 - electromagnetic drive, 8 - control panel, 9 – contact gap adjustment, 10 - vacuum set (a - turbomolecular vacuum pump, b - pre-pump, c, d - vacuum gauge, e - pressure regulator), 11 - technical gas kit, 12 - vacuum hand valve, 13 - system for photographic recording of arc processes (a - ultra high-speed camera, b - computer unit with dedicated software)

A schematic diagram of the laboratory test stand used to conduct the tests described in this paper is shown in Figure 4. The test set consists of a regulating autotransformer, a test transformer rated 110 kV, a surge arrester that performs protective functions, and a capacitive measuring divider. The test set is controlled by a control panel, which is used to set the measurement parameters and to start the test.

The main element of the laboratory stand is the discharge chamber with the contact system mounted inside. It was made in a "dismountable" way, with the possibility of changing the type of contact pads, and also equipped with a glass sight-glass allowing observation of its interior during the experiments. One of the poles of the chamber, which is the stationary pole, is connected to high voltage, while the lower (moving) pole is effectively grounded. The adjustment of the contact gap is carried out using a motor drive, while the open-close operation was realized by adapting the electromagnetic drive from a medium voltage circuit breaker to the bench.

A vacuum set consisting of two pumps, a rotary pre-pump and a turbomolecular pump, is used to ensure the specified vacuum inside the discharge chamber. Pressure measurement is carried out using two vacuum gauges connected to a pressure regulator. Selected technical gases are connected to the station. Their dosing to the system is possible through a vacuum, precise manual valve.

An ultra-fast camera controlled by a computer with specialized software installed was used for photographic recording of arc processes occurring inside the discharge chamber.

Analysis of laboratory test results

Breakdown voltages were measured for a vacuum obtained with air, neon, and helium, for four contact gaps: d_1 = 0,7 mm, d_2 = 0,9 mm, d_3 = 1,7 mm, and d_4 = 2,3 mm. The initial pressure value was $p = 3\times10^{-3}$ Pa, while the pressure at which the minimum of the electrical strength value was reached was taken as the final value. This value was 4,0 Pa for air, 3,0 Pa for neon and 7,0 Pa for helium.

Figures 5 - 7 show the dependence of the breakdown voltage U_d as a function of the pressure p for the contact gaps d_1 – d_4.

Two characteristic intervals of the obtained characteristics were observed. In the first one, the electrical strength does not change its values significantly.

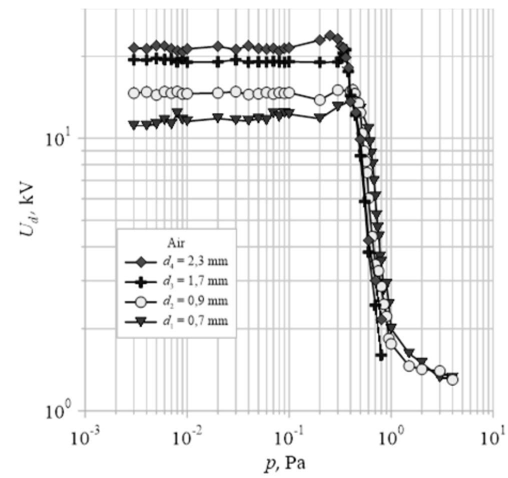

Fig.5. Dependence of the breakdown voltage U_d as a function of pressure p for a vacuum chamber filled with air

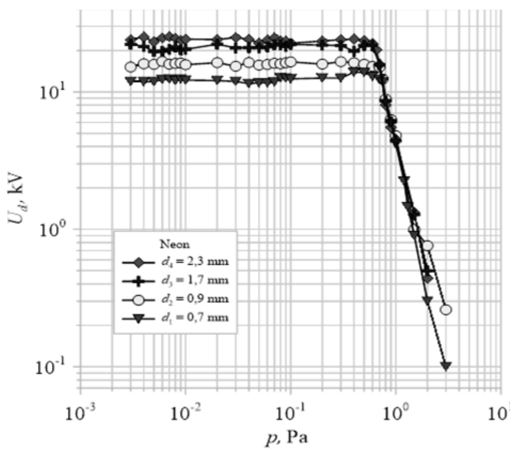

Fig.6. Dependence of the breakdown voltage U_d as a function of pressure p for a vacuum chamber filled with neon

Comparing this part of the characteristics for all analyzed insulating media, it can be concluded that the type of residual gases in this pressure interval does not have a significant influence on the cell breakdown voltages. The small differences may be due to inaccuracies in setting the contact gaps for successive test trials. The value of this voltage was about 12 kV for contact gap d_1, about 15 kV for d_2, about 20 kV for d_3 and about 22 kV for d_4. The electrical strength remained constant over the pressure range from 3×10^{-3} Pa to a value of 3×10^{-1} Pa for the air-filled chamber, 6×10^{-1} Pa for the neon-filled chamber, and 2×10^{0} Pa for the helium-filled chamber. It should also be noted that as the contact gap in this range increases, the breakdown voltage value increases. When the above pressures are exceeded, the electrical strength of the system decreases rapidly, which is the second characteristic interval of this graph. Figures 8 and 9 compare the breakdown voltages for two selected values of contact gaps: d_2 = 0,9 mm and d_4 = 2,3 mm, juxtaposing all tested insulating gases on one characteristic.

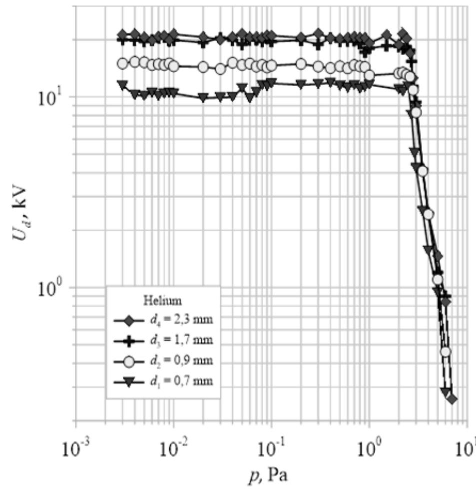

Fig.7. Dependence of the breakdown voltage U_d as a function of pressure p for a vacuum chamber filled with helium

Analyzing the above figures, note the well-defined differences in the pressure intervals at which the system insulated with the selected residual gas maintained its full insulating capacity. For all contact gaps tested, the insulating capability of the system was lost first for the air-filled chamber, then for the neon-filled chamber, and finally for the helium-filled chamber.

Figure 10 compares the breakdown voltage characteristics as a function of pressure for a contact gap of d_2 = 0,9 mm for a chamber with residual gases in the form of air and helium.

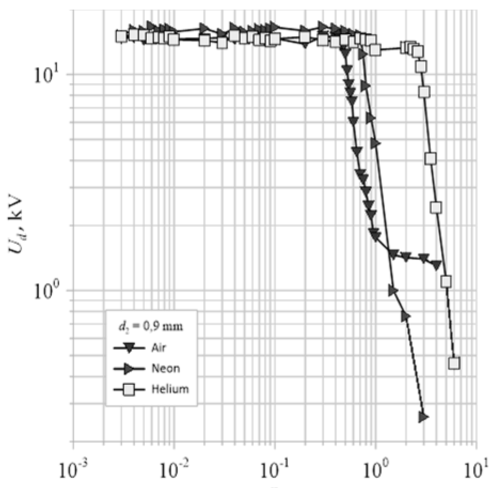

Fig.8. Comparison of the breakdown voltage U_d as a function of pressure p for a vacuum chamber filled with air, neon and helium, for a contact gap d_2 = 0,9 mm

A reference pressure of p_{ref} = 1,0 Pa was chosen and the corresponding breakdown voltages were read, which are summarized in Table 1. While for the air residual gas discharge chamber, the insulating capacity was lost, for the helium residual gas chamber, it was maintained at a constant, safe level.

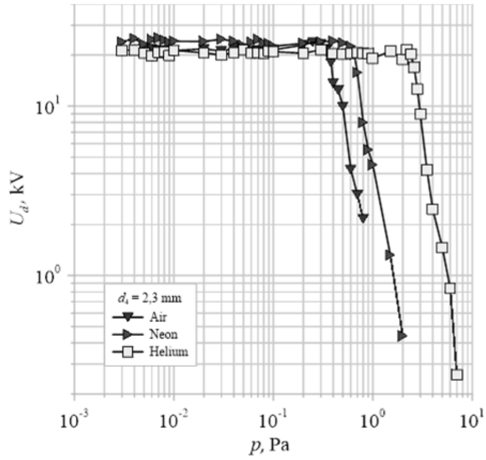

Fig.9. Comparison of the breakdown voltage U_d as a function of pressure p for a vacuum chamber filled with air, neon and helium, for a contact gap d_4 = 2,3 mm

Table 1. U_d breakdown voltage values for reference pressure p_{ref}

Residual gas type	
Air	Helium
p_{ref} = 1,0 x 10^0 Pa	
$U_{d(Air)}$ = 1,90 kV	$U_{d(He)}$ = 15,00 kV

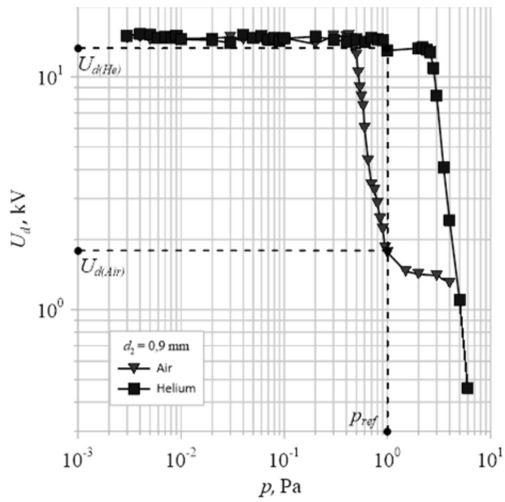

Fig.10. Comparison of the breakdown voltage U_d as a function of pressure p for a vacuum chamber filled with air and helium, for the contact gap d_2 = 0,9 mm

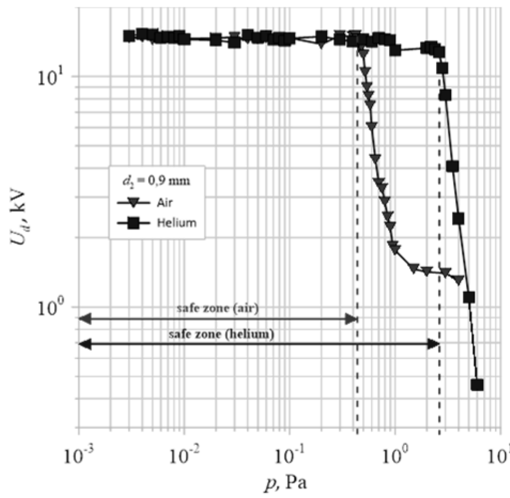

Fig.11. Comparison of safety zones for air-filled and helium-filled vacuum chamber, for contact gap d_2 = 0,9 mm

Based on the above analysis, it can be concluded that the isolation system with vacuum obtained on the basis of helium generates a much larger safe zone, characterized by a maximum electrical strength, depending on the contact gap of the electrodes of the isolation system. The range of safe zones in the selected example is shown in Figure 11.

Summary

Based on the results of measurements of the electrical strength of a vacuum chamber with residual gases in the form of air, neon, and helium described in this paper, the authors have developed a method for increasing the rated operating pressure of a vacuum interrupter by using a helium-based vacuum as an insulating medium. Currently manufactured vacuum interrupters dedicated to electric power switching apparatus operate at a rated pressure of 10^{-3} Pa or less. By increasing the rated operating pressure to 10^{0} Pa by injecting helium inside, the full insulating capacity of the system is maintained. In this way, it is possible to reduce the probability of potential leakage of the vacuum interrupters installed in a given apparatus (e.g. in a disconnector or circuit breaker).

The final effect of the solutions proposed by the authors may be the improvement of the technical parameters of the vacuum switchgear and the reduction of the possibility of interruptions in the supply of electricity to end users, thus further reducing the reliability indices.

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REFERENCES

[1] Slade P. G., The Vacuum Interrupter Theory, Design, and Application, *CRC Press*, 2021
[2] Power engineering, distribution and transmission, *Polish Power Transmission and Distribution Associaton's Report*, Poznań, 2021
[3] Lee W.-Y., Jun J.-U., Oh H.-S., Park J.-K., Oh Y.-H., Song K.-D., Jang H.-J., Comparison of the Interrupting Capability of Gas Circuit Breaker According to SF_6, g^3, and CO_2/O_2 Mixture, *Energies*, 13 (2020), 6388
[4] Stoczko Sz., Szewczyk M., Pochanke Z., Chmielak W., Experimental study on field emission current in vacuum interrupter at functional limit of vacuum pressure, *Electric Power Systems Research*, 191 (2021), 106860
[5] Li S., Geng Y., Liu Z., Wang J., "V" shape curves of physical parameters of field emitters versus applied voltage toward breakdown in vacuum, *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 25, 2008, 749-755
[6] Gortschakow S., Franke S., Methling R., Gonzalez D., Lawall A., Taylor E.D., Graskowski F., Properties of Vacuum Arcs Generated by Switching RMF Contacts at Different Ignition Positions, *Energies*, 13 (2020), 5596
[7] Węgierek P., Lech M., Kozak C., Pastuszak J., Methodology for testing the electric strength of vacuum chambers designed for modern medium voltage switchgear, *Metrol. Meas. Syst.*, 27 (2020), 687-700
[8] Lech M., Węgierek P., Breakdown Initiation and Electrical Strength of a Vacuum Insulating System in the Environment of Selected Noble Gases at AC Voltage, *Energies*, 15 (2022), 1154
[9] Węgierek P., Lech M., Test stand for testing and diagnostics of medium voltage vacuum interrupters, *Przegląd Elektrotechniczny*, 97 (2021), nr 2, 176-179
[10] Lech M., Disassemblable vacuum interrupter as an innovative test stand designed for research on improving the operational parameters of power switching apparatus, *Informatyka. Automatyka, Pomiary w Gospodarce i Ochronie Środowiska – IAPGOS*, 3/2020, 66–69