1. Krzysztof KOGUT[1], 2. Krzysztof KASPRZYK[1], 3. Henryk BRZEZIŃSKI[1], 4. Renata KŁOŚ[1]

Sieć Badawcza Łukasiewicz - Instytut Elektrotechniki Centrum Badawcze Materiałów Elektrotechnicznych We Wrocławiu (1)
ORCID: 1. 0000-0002-9985-6815; 2. 0000-0001-8365-6838; 3. 0000-0002-5584-4433; 4. 000-0002-5917-8239;

doi:10.15199/48.2024.12.36

Alternative for SF_6 – review and Łukasiewicz – Institute of Electrical Engineering (Ł - IEL) approach to the subject

***Abstract**. The literature about the alternatives to SF_6 was reviewed. The mix of the insulating gases at the AC voltage (50 Hz) and lightning impulse voltage (LI) were tested. The results show that appropriately selected gas mixtures can increase the electrical strength by several percent compared to air. As a consequence, the distance between electrodes and the dimensions of the devices could be reduced. The gas mixture (B) has a higher strength than air under LI voltage at pressures up to 1 bar. The tests support the research for ecological alternatives to SF_6.*

Streszczenie.** W Ł - IEL dokonano przeglądu literatury dotyczącej alternatyw dla SF_6. Zbadano gazy izolacyjne przy napięciu przemiennym (50 Hz) i udarowym. Wyniki pokazują, że odpowiednio dobrane mieszaniny gazów mogą zwiększyć wytrzymałość elektryczną o kilkanaście procent w stosunku do powietrza, pozwalając na zmniejszenie odległości między elektrodami i gabarytów urządzeń. Mieszanina gazów (B) wykazuje wyższą wytrzymałość od powietrza przy napięciu udarowym przy ciśnieniach do 1 bara. Badania wspierają poszukiwanie ekologicznych alternatyw dla SF_6* ***(Alternatywy dla SF_6 – przegląd oraz podejście Łukasiewicz – Instytutu Elektrotechniki (Ł – IEL)).

Keywords: SF_6, gas insulation, Global Warming Potential, high voltage engineering.
Słowa kluczowe: SF_6, izolacja gazowa, Potencjał Tworzenia Efektu Cieplarnianego, inżynieria wysokich napięć.

Introduction

The National strategic goal and an important area of activity of Ł-IEL is to ensure the safe and failure free use of the power grid. The currently applied gas insulation based on sulphur hexafluoride (SF_6), recognized as a greenhouse gas, will be replaced by alternative gas mixtures with a neutral effect on the environment. It is a result of the changes in the European Commission regulations from 2023 and increased focus on climate protection [1].

The mentioned SF_6 gas is characterized by a high Global Warming Potential (GWP), which is 23.500.

It means that the emission of 1 kg of SF_6 into the atmosphere is equivalent to 23.5 tons of CO_2. Around 8.000 tons of SF_6 are produced every year, of which 80% is used by the power industry for arc extinguishing, cooling and insulation [2].

In Europe, SF_6 gas can be found in 10 of the 15 million switchgears in use: a total of 8.6 thousand tons, i.e. the equivalent of 196 million tons of CO_2.

According to BBC just one kilogram of SF_6 warms the Earth to the same extent as 24 people flying London to New York return [3].

For example, across the entire UK network of power lines and substations, there are around one million kilograms of SF_6 installed. A study from the University of Cardiff found that across all transmission and distribution networks, the amount used was increasing by 30-40 tons per year [3].

This rise was also reflected across Europe with total emissions from the 28 member states in 2017 equivalent to 6.73 million tons of CO_2. That's the same as the emissions from 1.3 million extra cars on the road for a year [3].

The most important means by which SF_6 gets into the atmosphere is from leaks in the electricity industry. [3].

On March 29, 2023, the European Commission voted on an amendment to the regulation on fluorinated greenhouse gases. The elimination of harmful SF_6 gas will take place in stages.

Annex IV, point 23 of the regulation of the European Parliament and of the Council on fluorinated greenhouse gases [4] determines the dates of prohibition for switchgears as follows:

- 1 January 2026 - medium voltage switchgear for primary and secondary distribution up to and including 24 kV.
- 1 January 2028 medium voltage switchgear for primary and secondary distribution from more than 24 kV and up to and including 52 kV.
- 1 January 2028 high voltage switchgear from 52 and up to and including 145 kV and up to 50 kA short circuit current with insulating or breaking medium using.
- 1 January 2031 high voltage switchgear of more than 145 kV or more than 50 kA short circuit current with insulating or breaking medium using.

In response to these challenges, scientists and engineers around the world are working hard to develop alternative solutions that are both effective and environmentally friendly.

One of the leading research centres in this area is the Łukasiewicz – Institute of Electrical Engineering (Ł-IEL), which focuses on identifying and implementing new insulation technologies.

In this paper the review of available alternatives to SF_6, discussing their properties, advantages and potential limitations is presented.

Moreover, the approach and achievements of the Łukasiewicz – Institute of Electrical Engineering in the context of developing and testing innovative solutions reducing the impact on the natural environment and improving the safety and reliability of power systems are presented.

Global trends

A comprehensive review of literature shows that research has been conducted for many years on insulating gases alternative to SF_6 or modifying its composition [5-10].
Over the last 5-7 years, the number of published papers on the mentioned topics has increased significantly.
It is due to noticeable upcoming changes in regulations and pressure to increase environmental safety.

The European Commission's recommendation of March 29, 2023, for withdrawal the SF_6 over the next few years forces us to look for and use alternatives.

The investigation of the publications related to the power industry creates a few main research directions.

Currently, the leading directions are primarily [11, 12, 13]:

A) synthetic gases with good electrical strength but not fully known impact on the environment and still high GWP coefficient,

B) the use of vacuum and dry air, but problems with maintaining tightness and cleanliness along with high electrical strength,

C) a mixture of generally available gases with a strength higher than air and increasingly similar to SF_6 but with a GWP coefficient 23,500 times lower.

Substitutes for SF_6, that have a lower environmental impact and have compatible dielectric properties including good current interrupting are looking around the world [13, 14].

The main factors that influence the high electrical strength of gas insulation include electronegativity, high density, high thermal conductivity, non-flammability, and the ability to recombination.

The electronegativity of the gas ensures that it can effectively capture free electrons, which reduces the risk of developing electric discharges. The high density of the gas increases its insulating properties, which indirectly results from the Paschen law [15].

Gases with a higher density have a larger number of molecules per unit volume improves their insulating properties. High thermal conductivity is a key feature because it enables the effective dissipation of heat generated by the flow of current during the operation of power equipment under standard operating conditions, which prevents overheating and insulation damage.

Another significant factor in the selection of the insulating medium is the non-flammability of the gas. It minimizes the risk of fire in the event of electrical discharges and allows for more efficient and faster extinguishing of the electric arc during the operation of many devices. In addition, attention should be paid to the parameter of recombination ability. It means the gas can quickly combine positive and negative ions, which helps maintain its insulating properties.

A looking for new, alternative solutions should focus on meeting all the mentioned properties as much as possible.

The currently used solutions are not able to fully meet the assumptions of the European Commission regulation and other parameters specified in the applicable subject standards.

All alternatives should be relatively simple technologically and enable manufacturers to maintain the equipment design without costly technological changes. The electrical strength of SF_6 is approximately three times greater than air and is difficult to obtain without chemical gas synthesis. However, the current design and used pressures in power equipment guarantee dimensional margins due to oversizing.

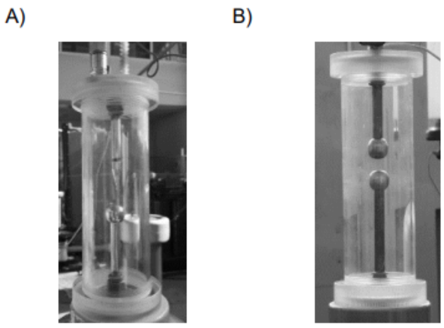


Fig.1. The electrodes system used for the tests. A – needle – sphere electrodes system, B – sphere – sphere electrodes system

Research methods

Research methods of the tests conducted by Ł – IEL are based on the use of several types of electrodes simulating different distributions of electric field intensity (Fig. 1).

The first one is a heterogeneous system modelled by using needle-sphere electrodes. The gap between the electrodes was 15 mm. The small radius of the needle electrode causes a local increase in the electric field intensity.

The second one is a sphere-sphere electrode system simulates a more uniform field distribution. The sphere diameter was 20 mm. The gap between electrodes was 12 mm. The electrode spacing determines the field strength.

High voltage tests were carried out using 50 Hz alternating voltage systems and a Haefely 700 kV, 35 kJ, lightning impulse voltage (LI) generator in Marx configuration, with the HiAS 743 recording and analysis system [16].

The measurement systems used for the tests are presented in Figure 2. In the case of lightning impulse voltage, the “up and down” method was used, according to PN - EN 60060-1:2011. Hundreds of measurements were conducted to determine the 50% flashover.

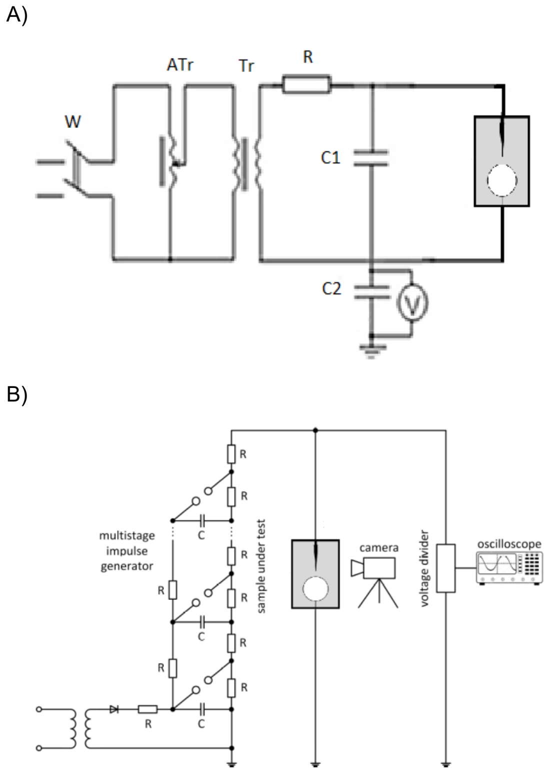


Fig.2. Measurement systems, A – alternating voltage tests system, 50 Hz, B – lightning impulse voltage test system

Results

Mixtures of generally available gases with different percentages (ratios) were used for the tests. Two mixtures were selected, defined as “A” and “B”, the results of which were the most interesting compared with the air, which was the reference gas. The gas mixtures consisted of a maximum of 4 components.

Due to cooperation with companies from the electrical industry, the detailed composition of gas mixtures cannot be fully presented.

Tests of the flashover voltage of gases in sphere-sphere and needle-sphere electrode systems at an alternating voltage of 50 Hz and lightning impulse voltage were conducted.

The results of the flashover voltage of the tested gas mixtures in the needle-sphere electrode system at an alternating voltage 50 Hz are presented below (Fig. 3).

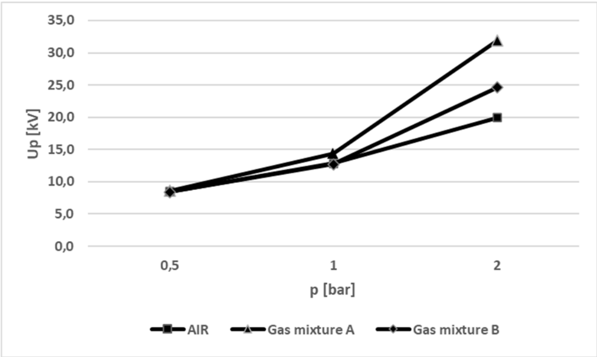


Fig.3. Flashover voltage of the tested gas mixtures in the needle-sphere electrode system at an alternating voltage 50 Hz

The results of the needle-sphere electrode system are extremely interesting. The measurements were repeated three times, cleaning the electrode surfaces after each attempt.

The electrical strength of the "B" and "A" gas mixture was much higher than that of air, especially at a pressure of 2 bar. Gas mixture "A" had an electric strength higher than air by approx. 60%, and gas mixture B by approx. 23%. The significant differences were not noticed at lower pressures. It may be due to the lower measurement voltage. However, in the case of mixture "A" at a pressure of 1 bar, the electrical strength of the system was higher than that of air by approximately 11%. This is an incredibly interesting issue because such large increases have not been recorded with the sphere electrode system.

Figures 4 and 5 show the 50% flashover voltage of gas mixtures in the needle-sphere (Fig. 1A) and sphere-sphere (Fig. 1B) electrode system at lightning impulse voltage.

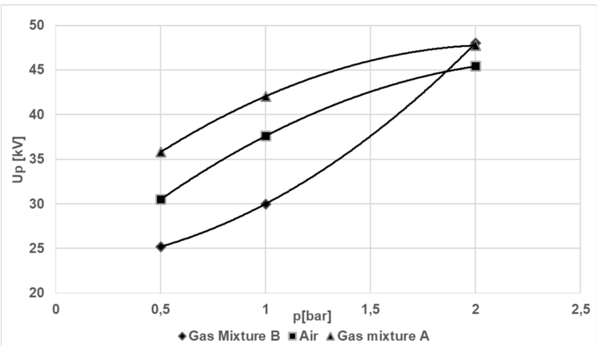
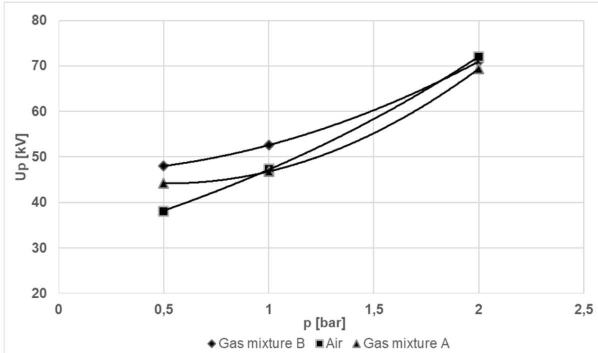


Fig.4. 50% flashover voltage of gas mixtures in the needle-sphere electrode system at lightning impulse voltage

Measurements at impulse voltage with positive polarization in the needle-sphere electrode system showed significant differences in the electric strength of insulating systems. The flashover voltage for the gas mixture "A" at a pressure of 0.5 bar was up to 17% higher compared to air. A similar situation was observed at the pressure of 1 bar. The flashover voltage was approximately 12% higher than air.

In the sphere electrode system, the biggest differences in electric strength were observed for pressures of 0.5 bar and 1 bar. In the case of a pressure of 0.5 bar, both mixtures "A" and "B" have a higher withstand voltage than air. For mixture "B" it was approximately 25% more than air, while for mixture "A" this value was higher by approximately 15%. At a pressure of 1 bar, only mixture "A" showed a much higher electrical strength compared to air, amounting to approximately 10%. Figure 6 shows the discharges recorded during lightning impulse voltage tests for various gas mixtures.



Rys.5. 50% flashover voltage of gas mixtures in the sphere-sphere electrode system at lightning impulse voltage

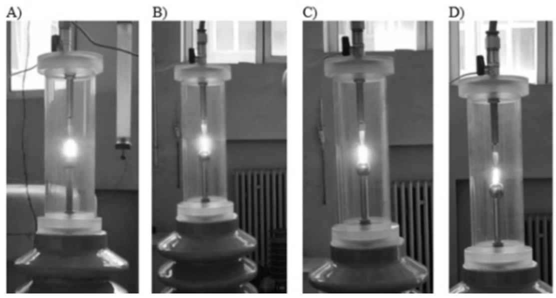


Fig.6. The discharges recorded during the lightning impulse voltage test. A - Mixture B, the pressure of 1 bar, the measure after few tests, the system with the residue on the electrodes; B – Mixture B, the pressure of 1 bar, the measure on the polished electrodes; C – Mixture A, the pressure of 0,5 bar; D – Air at the pressure of 1 bar

Visible differences in the colour and intensity of the discharge channel were observed. It may result from the used gases or electrode materials (brass). The used pressure was also an important parameter influenced by the width of the discharge channel.

The literature reports on SF_6 gas testing in similar measurement systems were analysed. There were not many publications that examined the sphere-sphere and needle-sphere electrode systems. Hence, the needle-plate, and sphere-plate electrode systems were selected for comparison.

Interesting results were obtained by Sadaoui and Beroual [17]. In the sphere (10 mm diameter and 10 mm gap) - plate system, the SF_6 gas at a pressure of 1 bar was characterized by a strength of 70 kV at a lightning voltage of positive polarity and approx. 100 kV at a pressure of 2 bar.

Comparing these values with the electric strengths of the tested gas mixtures obtained by Ł - IEL, it can be concluded, that it is approximately 60% at a pressure of 1 bar and approximately 70% at a pressure of 2 bar about SF_6.

These comparative values should not be treated as fully reliable because the dimensions of the electrodes in the tests of both scientific institutions were slightly different.

However, the presented values show the direction of work as prospective.

In the case of the needle-plate electrode system, the strength of SF_6 at a positive impulse voltage determined by F. Sadaoui and A. Beroual was approximately 65 kV and 80 kV, respectively.

Similar results were presented by Bok-Hee Lee et al. [18] and Beroual and Coulibaly [19]. Bok-Hee Lee obtained electric strengths at a similar level in the system of plate electrodes with a needle-shaped protrusion, while Beroual and Coulibaly declared that SF_6 at a pressure of 1 bar and an impulse voltage of positive polarity was characterized by an electric strength of 100 kV in the sphere electrode system.

Comparing the results in the sphere-sphere electrode system obtained by Ł-IEL and by Beroual and Coulibaly, it can be concluded that the electric strength of the gas mixture "B" is approximately 53% of the strength of SF_6. It is an excellent result compared to the strength of air in an identical system (approximately 30% of the strength of SF_6). The results of electric strength presented by Ł-IEL, in relation to SF_6, should be taken with a few percent uncertain as a result of differences in the electrode systems presented in the literature, including diameters and gap.

Conclusion

An analysis of the global trends in the looking for alternative gases to SF_6 was carried out at the Łukasiewicz – Institute of Electrical Engineering. Additionally, initial tests were performed with mixtures of generally available gases, using alternating voltage with a power frequency 50 Hz and lightning impulse voltage. The research included a sphere electrodes and a needle-sphere electrode system with small gaps between them.

The results of the needle-sphere electrode system are extremely interesting. The electrical strength of the "B" and "A" gas mixture was much higher than that of air, especially at a pressure of 2 bar.

The "up-and-down" measuring method for lightning impulse voltages allowed for the determination of 50% of the flashover voltage. A comparison of test results for the prepared mixtures in relation to air shows, that there is a theoretical chance to increase the electrical strength by several percent.

It suggests the possibility of reducing the distance between the electrodes, and this in turn allows for reducing the dimensions of power equipment or maintaining the current design. At pressures up to 1 bar, the electric strength of the prepared gas mixture "B" is higher than air. The results suggest that is possible to reduce the working pressure by approximately 10%.

However, these are approximate calculations. It may affect the thickness of the wall of the chamber and the limitation of materials. The results of this research constitute a valuable contribution to the looking for ecological alternatives to SF_6, showing both the potential and challenges of the introduction of new insulating gases into power systems. Further research will focus on optimizing these solutions to ensure their reliability and effectiveness in real operating conditions.

***Authors**: dr inż. Krzysztof Kogut, Sieć Badawcza Łukasiewicz – Instytut Elektrotechniki, CME Grupa Badawcza Technologii Wytwarzania Materiałów, ul. M. Skłodowskiej – Curie 55/61, 50-369 Wrocław, E-mail: krzysztof.kogut@iel.lukasiewicz.gov.pl; dr inż. Krzysztof Kasprzyk, Sieć Badawcza Łukasiewicz – Instytut Elektrotechniki, CME Grupa Badawcza Technologii Wytwarzania Materiałów, ul. M. Skłodowskiej – Curie 55/61, 50-369 Wrocław, E-mail: krzysztof.kasprzyk@iel.lukasiewicz.gov.pl;*
mgr inż. Henryk Brzeziński, Sieć Badawcza Łukasiewicz – Instytut Elektrotechniki, CME Grupa Badawcza Materiałów Kompozytowych i Recyklingu, ul. M. Skłodowskiej – Curie 55/61, 50-369 Wrocław, E-mail: henryk.brzezinski@iel.lukasiewicz.gov.pl; Renata Kłoś, Sieć Badawcza Łukasiewicz – Instytut Elektrotechniki, CME Grupa Badawcza Technologii Wytwarzania Materiałów, ul. M. Skłodowskiej – Curie 55/61, 50-369 Wrocław, E-mail: renata.klos@iel.lukasiewicz.gov.pl;

REFERENCES

[1] Regulation on fluorinated gases – P9_TA (2023)0092 (2023), (europa.eu)
[2] Polski Przemysł – Ekologiczny rozdział energii, Green Switching, 50 (2012), Green Switching
[3] BBC Climate change: Electrical industry's 'dirty secret' boosts warming (2019), (bbc.com)
[4] Report - A9-0048/2023 (2023), (Regulation, Annex IV)
[5] Owens J. G., Greenhouse Gas Emission Reductions from Electric Power Equipment through Use of Sustainable Alternatives to SF_6, *3M Electronics Materials Solutions Division. 3M Company*. 3M Science. Applied to Life. (2018)
[6] Wang Y., Huang D., Liu J., Zhang Y. and Zeng L., Alternative Environmentally Friendly Insulating Gases for SF_6, *Processes* 7 (2019), 216
[7] Dincer M.S., Tezcan S.S., Duzkaya H., Dincer S., Synergism analysis in dielectric strenght of CO_2+N_2+O_2 ternary mixtures, *Aleksandria Engineering Journal* (2022) 61, 3747-3756
[8] Nechmi H., Beroual A., Girodet A.,Vinson P., Fluoronitriles/CO_2 gas mixture as promising substitute to SF_6 for insulation in high voltage applications, *IEEE Trans.on Dielectrics and Electr. Insulation*, 23, (2016), No.5, 2587–2593
[9] Haddad A., Turri R., Manganella A., Eco-Friendly alternatives to replace SF_6 in high voltage gas – insulated transmission lines: a comparative study, Università degli Studi di Padova. A.A. 2019/2020, (2020)
[10] Rakowska A., Siodła K., Sześciofluorek siarki a ochrona środowiska, *Przegląd Elektrotechniczny,* ISSN 0033-2097, 98 (2022), nr 10, 240-243
[11] Owen J., Xiao A., Bonk J. et al., Recent Development of Two Alternative Gases to SF_6 for High Voltage Electrical Power Applications, *Energies, 14* (2021), No. 16, 5051
[12] Rokunohe T., et al, Development of 72 kV high pressure air-insulated GIS with vacuum circuit breaker, *IEEJ Trans. PE*, Vol. 125 (2005), No.12, 1270-1277
[13] Bellofatto L., Sigismondi P., SF_6 FREE Alternative – Study of Ternary Mix Natural Gas for Electrical Insulation Purpose, 2023 PCIC Energy Europe (PCIC Energy), Milan, Italy, (2023), 1-7
[14] Okabe S., GoshimaH., Tanimura A., Tsuru S.,Yaegashi Y., Fundamental Insulation Characteristic of High-Pressure CO_2 Gas under Actual Equipment Conditions, *IEEE Trans. on Dielectrics and Elect. Insulation* 15 (2008), No. 4, 1023-1030
[15] Khalaf M., Sabri M.J., Majeed M. A., Jasim H. E., Effect of the Longitudinal Magnetic Field on the Electrical Breakdown in Argon and Nitrogen Plasma Discharges, *World Scientific News*, WSN 55 (2016), 114-125
[16] Kogut K., Bolesław Mazurek B., Zboromirska – Wnukiewicz B., Kasprzyk K., Wytrzymałość elektryczna izolatora rurowego o modyfikowanej powierzchni, *Przegląd Elektrotechniczny* ISSN 0033-2097, 92 (2016), nr 10, 163 – 166;
[17] Sadaoui F., Beroual A., Influence of polarity on breakdown voltage of gases in divergent electric field under lightning impulse voltages, *International Conference on High Voltage Engineering and Application*, Shanghai, China, (2012), 496-499
[18] Lee B. H., Baek Y. H., Choi H. S., Oh S. K., Impulse breakdown characteristics of the plane-to-plane electrode system with a needle-shaped protrusion in SF_6, *Current Applied Physics*, 7 (2007), No. 3, 289-295
[19] Beroual A., Coulibaly M-L., Experimental investigation of breakdown voltage of CO_2, N_2 and SF_6 gases, and CO_2-SF_6 and N_2-SF_6 mixtures under different voltage waveforms, *2016 IEEE International Power Modulator and High Voltage Conference (IPMHVC),* San Francisco, USA, (2016), 292-295