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Review and comparison of electro-insulation properties of vacuum and sulphur hexafluoride

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The paper specifies the results of the tests on electric strength of vacuum, sulphur hexafluoride (SF_6) and the insulation mineral oil under alternate voltage. The tests have been carried out for planar electrodes made of stainless steel or aluminum. It was found that 10^{-3} Pa vacuum, $3 \cdot 10^5$ Pa SF_6, and insulation mineral oil situated with equal inter-electrode gap equal to several millimeters, have approximately equal electric strength.
The degrees of influence of basic parameters of the insulation system on electric strength of SF_6 and vacuum are presented. Advantages and faults of vacuum, SF_6, and insulation mineral oil are mentioned, taking into account possible use of these media as a high-voltage insulation in various electric equipment. Mathematical processing of the test results was carried out with the use of the Statistica software [5].

KEYWORDS: high-voltage insulation, electric strength, vacuum, sulphur hexafluoride (SF_6), toxic byproducts

1. Introduction

The increase in of electric energy demand in large industrial and urban centers requires supplying the electric power networks with growing rated voltage. At the same time, the areas free of buildings, where the electric network equipment could be easily located, are more and more scarce. This, in turn, forces miniaturization of these devices.

Dimensions of electric power equipment are significantly affected by electric strength of the high-voltage insulation used in it. Hence, miniaturization forces searching and using more and more perfect media that are able to insulate the high voltage, to extinguish the electric arc and, at the same time, characterized by high electric strength. Such dielectrics like air and mineral oil commonly used before, are at present rather rare. They are usually replaced by sulphur hexafluoride (SF_6) or vacuum.

Vacuum enables free transmission of neutral or charged particles inserted in it. Moreover, it is distinguished by natural lack of electric charge. The first feature is used in electron and X-ray tubes, in particle separators and accelerators, and in electron microscopes. On the other hand, the natural lack of electric charge carriers is used in vacuum capacitors, cryogenic cables, and vacuum high-voltage circuit breakers. Sudden growth of the interest in vacuum used as a high-voltage insulation was observed in later part of last century and appeared to be a result of significant progress of the vacuum technology occurring at that time.

The sulphur hexafluoride (SF_6) was obtained for the first time in 1900 by H. Moissan and P. Lebeau [7] in France. Nevertheless, more comprehensive studies on electric properties of this material were undertook in 1939 by H. C. Pollock and F.S. Cooper [12]. These and further studies have shown that SF_6 is a chemically durable gas, even in conditions of electric discharge, while its electric strength is significantly higher than the one of air [9], [12], [17].

SF_6 is a colorless, odorless, incombustible gas. In normal conditions the SF_6 density amounts to 6.08 g/dcm^3. Hence, it is one of the heaviest known gases.

SF_6 is more and more commonly used in electrical engineering as an arc-extinguishing medium in HV circuit breakers and as a HV insulation medium in electrostatic generators, X-ray equipment, capacitors in the highest voltage measuring systems, electric-power cables, shielded HV switchgears, transformers (nonflammable, non-explosive). In the last three types of the equipment, particularly in the transformers, SF_6 is also used as a cooling agent.

2. Electric strength of vacuum and sulphur hexafluoride

Reduction of the gas pressure to the value at which the mean free paths of the gas particles and electrons exceed the inter-electrode gap precludes development of electron avalanches that initiate electric discharge in gases. For example, in the air of the temperature 297 K the mean free path of the electron and the particles (i.e. nitrogen and oxygen – the main air components) are equal to 1 cm at the pressures equal to 3.8 Pa and 0.67 Pa, respectively [10]. It means that the electron avalanche cannot arise, since almost each electron inserted into the inter-electrode gap is able to reach the anode without any collision.

In spite of this fact, the electric strength of such an insulation system has a finite value, since apart of the electron avalanche initiating the breakdown, there are other phenomena decisive in the discharge development [9], [10].

Fig. 1 [11] presents the results of electric strength tests carried out for alternate voltage and 60 Hz frequency (amplitude) in vacuum and SF_6, versus pressure under temperature 293 K. The considered insulation systems were provided with planar electrodes of 150 mm diameter, made of stainless steel, copper, or aluminum. The inter-electrode gap was equal to 5 mm. The systems were conditioned with multiple breakdowns.

Figure 1 shows that vacuum of the pressure 10^{-1} Pa to 10^{-4} Pa has, in substance, a constant electric strength. Moreover, the effect of electrode material type becomes visible. The best electric strength occurs in case of a system equipped with electrodes made of stainless steel, the one with aluminum electrodes is characterized by slightly worse electric strength, with the worst strength existing for copper electrodes. The insulation system with SF_6 reaches the electric strength level equal to the vacuum insulation system at the pressure of $2.5 \cdot 10^5$ Pa. Below this pressure value the electrode material type does not affect the electric strength of an SF_6 system.

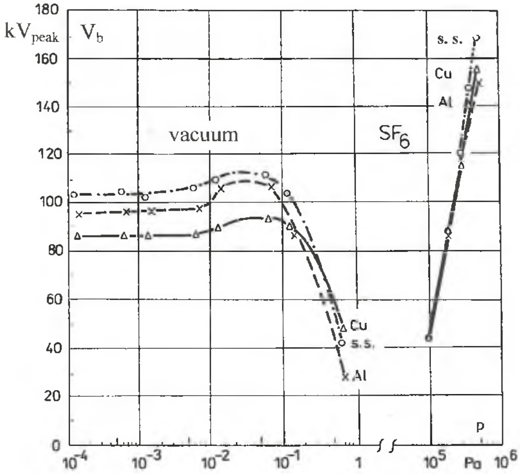

Fig. 1. Dependence of electric strength for alternate voltage and 60 Hz frequency (amplitude) in vacuum and SF_6, versus pressure under temperature 293 K; the considered insulation systems had planar electrodes made of stainless steel, copper, or aluminum, with inter-electrode gap equal to 5 mm [11]

The competitiveness of the electro-insulation properties of vacuum, SF_6, and, possibly, mineral oil (with the last being still an alternative for the insulation media) is important for a designer of electrical equipment.

Fig. 2 presents the measured relationships between the electric strength at alternate voltage and 50 Hz frequency (amplitude) in SF_6 of the pressures 10^5 Pa, $2 \cdot 10^5$ Pa, $3 \cdot 10^5$ Pa and $5 \cdot 10^5$ Pa, in vacuum of the pressure 10^{-3} Pa, and in mineral oil of good technical condition, versus the size of the inter-electrode gap. The examined insulation systems had planar electrodes of 50 mm diameter with rounded-off edges of Rogowski's profile, made of stainless steel or aluminum.

Fig. 2 shows that within the range of the experiment $3 \cdot 10^5$ Pa SF_6 has the electric strength approximating the strength of mineral oil and slightly less than electric strength of vacuum.

Taking into account competitiveness of these three insulation media and considering them as a high-voltage insulation used in a shielded switchgear, one may state that SF_6 is decidedly better material than mineral oil. It is, first of all, a consequence of fire and explosion hazards arising in case of the use of mineral oil. This situation forces construction of special emergency vessels able to contain the whole oil located in the device in case of possible leakage or break-down of the device. Moreover, the aging process of mineral oil requires periodic diagnostics of its condition and its possible regeneration.

Similar values of the electric strength of $3 \cdot 10^5$ Pa SF_6 and vacuum (Fig. 2) give evidence of approximate competitiveness of these two media used for high-voltage insulation purposes. Nevertheless, it should be noticed that casing of a device in which pressurized SF_6 is used as high-voltage insulation should mechanically withstand the pressure difference between SF_6 and Earth's atmosphere. For example, when the SF_6 pressure in the device is equal to $3 \cdot 10^5$ Pa, the pressure difference amounts to $2 \cdot 10^5$ Pa. On the other side, the casing of similar device equipped with vacuum insulation will be subjected only to atmospheric pressure applied to the casing from outside.

Taking into account possible occurrence of electric arc, in case of the device with SF_6 such an event is a source of a pressure wave. Therefore, the device casing must endure the additional mechanical stress and should be equipped with much stronger casing than the device with vacuum insulation.

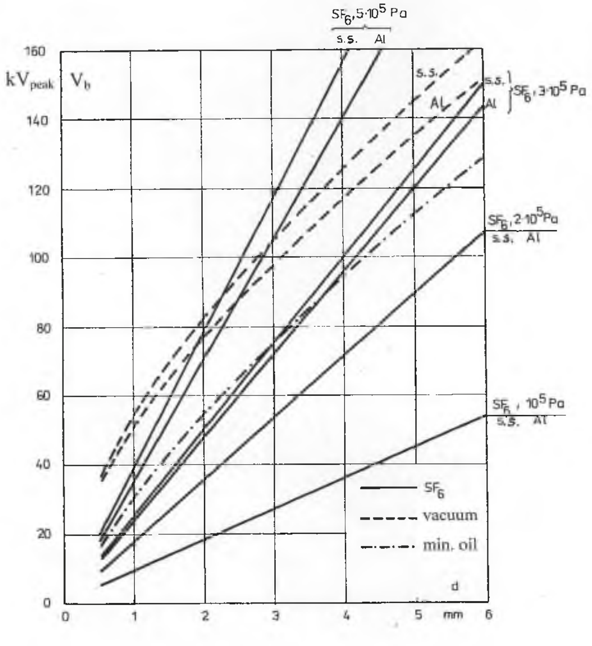

Fig. 2. Relationships between the electric strength at alternate voltage and 50 Hz frequency (amplitude) versus the size of the inter-electrode gap: SF_6 of the pressure values 10^5 Pa, $2 \cdot 10^5$ Pa, $3 \cdot 10^5$ Pa, and $5 \cdot 10^5$ Pa; vacuum of the pressure 10^{-3} Pa; mineral oil; the examined insulation systems had planar electrodes made of stainless steel or aluminum

In case of large devices equipped with vacuum insulation (as e.g. shielded switchgear) a problem of maintaining appropriate vacuum in them arises. In order to keep high electric strength, the pressure should be below 0.1 Pa (Fig. 1). The pressure inside the device gradually increases as a result of air penetration through the casing and gassing of the parts of the device. This process is particularly quick in case of large dimensions of the device. Finally, the pressure exceeds 0.1 Pa and the electric strength drops drastically. Therefore, in case of electric equipment of large dimensions, equipped with vacuum electro-insulation, a so-called dynamic vacuum is necessary, with permanent operation of vacuum pumps.

3. Summary

It was found, with the use of the Statistica software [5], that an insulation system with SF_6 is characterized by highly stable electric strength, as compared to a vacuum insulation system. The relative standard deviation of measured breakdown voltage values in the SF_6 insulation system usually did not exceed several percent, while the same parameter for the measurement carried out with a vacuum insulation system often exceeded a dozen percent. This is a result of small number of the factors significantly affecting electric strength of SF_6 as compared to the number of the factors influencing vacuum electric strength. These factors are specified in Table 1. Each factor is set together with approximate degree of its effect on electric strength of the system.

Table 1. Specification of basic factors of the insulation system affecting the electric strength (V_b) of SF_6 and vacuum, together with their degrees of influence. Degree of influence of a factor means that the factor may cause the following variations of the electric strength: small effect – electric strength variation V_b<10%, medium effect – electric strength variation V_b 10%...50%, large effect – electric strength variation V_b >50%

No	Type of the factor	Degree of influence of the factor on electric strength	
		SF_6	vacuum
1	Inter-electrode gap	large	large
2	Pressure	large	small up to 0.1 Pa, large above 0.1 Pa
3	Degree of macroscopic electric field inhomogeneity	large	large
4	Electrode material type	medium	medium
5	Purity of electrode surface and insulation medium	medium	large
6	Smoothness of electrode surface	medium	large
7	Area of electrode surface	medium	large
8	Method of conditioning	small	large

Electric strength of SF_6 is significantly affected only by three factors, i.e. the inter-electrode gap, gas pressure, and the degree of macroscopic electric field inhomogeneity. In case of vacuum insulation significant effects are additionally exerted by purity of vacuum and electrode surface, electrode surfaces smoothness, and the manner of conditioning.

Taking into account that deviation of a single operational parameter from its required value may lead to a flash-over, higher number of important factors affecting vacuum electric strength requires using more modern technology while constructing the high-voltage equipment with vacuum insulation.

On the other hand, the electro-insulation properties of vacuum are unrivalled taking into account the rate of recovery of electric strength of SF_6 and vacuum after occurrence of arc in these media. This is evident in Fig. 3 [1], where the after-arc electric strength of vacuum, SF_6, oxygen, and hydrogen are presented as functions of the time elapsing since extinction of the electric arc. It may be noticed that 10 μs after arc extinction the vacuum electric strength is restored up to 80 percent of its value before arc occurrence. In case of SF_6 the time of such a recovery is three times longer.

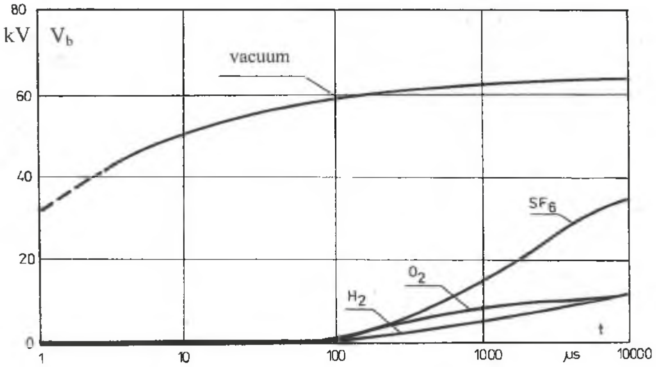

Fig. 3. Dependence of after-arc electric strength of vacuum, SF_6, oxygen, and hydrogen on the time elapsing since extinction of electric arc [1]

Among the faults of SF_6 one could mention its relatively high price and high condensation point equal to 243 K at $5 \cdot 10^5$ Pa. When the electric device operates under low temperature, the high condensation point of SF_6 may disable operation. Even partial SF_6 condensation causes reduction of pressure and gas density and, in consequence, worsens electric strength of the device.

These faults, i.e. high price and high condensation point, may be partially avoided using a mixture of SF_6 with other gases, e.g. nitrogen or helium, instead of pure SF_6. It was found that electric strength of a mixture including 20 percent SF_6 with nitrogen is only 25 percent lower than that of pure SF_6 [17].

With regard to health hazards and environmental issues, SF_6 itself is a relatively nontoxic and chemically inert gas. Due to its properties, it has been successfully used in medicine: for tamponade of retina in retinal detachment repair operations and as a contrast agent for ultrasound imaging [14], [15].

However, when electrical discharges occur within SF_6-filled equipment, toxic byproducts are produced. These byproducts may pose a threat to health of workers who come into contact with them [2], [16].

Byproducts that may be formed through arcing or other electrical discharges include HF, SF_4, SiF_4, S_2F_{10}, SO_2F_2, SO_2, SF_2, SOF_{10}, $S_2O_2F_{10}$, and H_2S, as well as a number of metal fluorides (e.g., CuF_2, AlF_3,WF_6, WO_3, FeF_3) [2].

According to the Hazardous Substances Databank, gaseous SF_6 byproducts such as SF_4, SiF_4, SO_2, SO_2F_2, and HF are extremely irritating to the eyes, nasal and pharyngeal mucosa. Due to their corrosive characteristics they may cause skin and eyes burns, nasal congestion, pulmonary edema, and bronchitis. Solid byproducts such as AlF_3 and CuF_2 dusts also irritate skin and eyes, nose, throat, and lungs when inhaled. If copper salts reach the gastrointestinal tract, they may act as irritants causing salivation, nausea, vomiting, gastric pain, hemorrhagic gastritis, and diarrhea [8], [16].

Safety precautions for SF_6 byproducts are often addressed in SF_6 handling procedures for gas-insulated electrical equipment. They include the requirement for the worker to wear protective clothing and approved respirator when the presence of byproducts is suspected (e.g., when the SF_6-filled breakers are exposed to a severe arc for an abnormal period of time due to improper operation of the breaker) [16].

As far as environmental protection is concerned, SF_6 is a potent greenhouse gas, since it is an efficient absorber of infrared radiation. The relative contribution of SF_6 to global warming is estimated at the present time to be only 0.01%, and contrary to other environmental pollutants, SF_6 does not contribute to stratospheric ozone depletion. However, the atmospheric lifetime of SF_6 is estimated to range between 800 and 3200 years. Because SF_6 is extensively used, concerns have been raised about its long-term environmental effects. If production and leak rates of SF_6 are maintained at current level, it is expected that in 100 years, its contribution to global warming could be 0.1%.

It must be remembered that, without disposal methods that destroy SF_6, all of the SF_6 that has been produced eventually gets to the atmosphere.

International Council on Large Electric Systems recommends that at the end of life of SF_6 equipment, the gas will either have to be recycled, or reduced to environmentally compatible end products [2]. SF_6 can be destroyed by thermal decomposition (>1100°C). In this process the constituents of SF_6 (i.e. sulfur and fluorine) are converted into the naturally occurring materials $CaSO_4$ (gypsum) and CaF_2 (fluorspar) by reacting with $CaCO_3$ (calcite) [2], [6].

It is widely accepted that SF6, when properly managed, does not represent a greater danger for the users than the other materials used in other types of electric devices irrespective they are vacuum-insulated, air-insulated or oil-insulated. Proper handling procedures and innovative designs of gas-insulated constructions minimize leaks to the atmosphere and health hazards.

Procedures for safe handling of SF_6 are available from a number of authorities [3], [4], [6], [13] and from manufacturers. Polish regulations [13] are a direct translation of International Electrotechnical Commission's Technical Raport [4].

References

[1] Cobine J. D., Research and development leading to the high power vacuum interrupter, IEEE Transaction, 1963, v. PAS-82, p. 201.

[2] Dervos C.T., Vassiliou P., Sulfur hexafluoride (SF_6): global environmental effects and toxic byproduct formation, Journal of the Air & Waste Management Association, 2000, v. 50, p. 137.

[3] International Council on Large Electric Systems. SF_6 Recycling Guide, Publication number 117, Task Force 23. 10. 01, August 1997.

[4] International Electrotechnical Commission, Technical Raport − Type 2, IEC 1634: 1995, High-voltage switchgear and controlgear − Use and handing of sulphur hexafluoride (SF_6) in high-voltage switchgear and controlgear.

[5] Lesińska E., Statistica Pl, StatSoft Polska, Kraków 1997 (in Polish).

[6] Mauthe G. at al., SF_6 and the global atmosphere, Electra, 1996, v. 164, p. 121.

[7] Moissan H., Lebeau P., Sur un nouvean corps gazeux: le perfluorure de soufre SF_6, Comptes Ren-clus Hebdomadires des Séances de l´Académie de Sciences, 1900, v. 130, p. 865 (in French).

[8] National Library of Medicine, Hazardous Substances Databank, 2001, available at http://toxnet.nlm.nih.gov/.

[9] Opydo W., Properties of gas and vacuum high-voltage insulation systems, Wydawnictwo Politechniki Poznańskiej, Poznań 2008 (in Polish).

[10] Opydo W., Ranachowski J., Electrical properties of vacuum insulation systems under a. c. voltage, Wydawnictwo Naukowe PWN, Poznan-Warsaw, Poland 1993 (in Polish).

[11] Opydo W., Opydo J., Comparision of elektro-insulating properties of vacuum and sulphur hexafluoride, Archiwum Elektrotechniki, 1994, v. 43, p. 403 (in Polish).

[12] Pollock H. C., Cooper F. S., The effect of pressure on the positive point-to-plane ischarge SO_2, SF_6, CCl_2F_2, Ar, He, and H_2. Phys. Rev., 1939, v. 56, p. 170.

[13] Polski Komitet Normalizacyjny, Polska Norma PN-E-06115, Wysokonapięciowa aparatura rozdzielcza i sterownicza − Użytkowanie i postępowanie z sześciofluorkiem siarki (SF_6) w wysokonapięciowej aparaturze rozdzielczej i sterowniczej (in Polish).

[14] Ryan S.J., Schachat A.P., Retina, Elsevier Mosby, Philadelphia, PA, 2005.

[15] Schneider M., Arditi M., Barrau M.B., Brochot J., Broillet A., Ventrone R., Yan F., BR1: a new ultrasonographic contrast agent based on sulfur hexafluoride-filled microbubbles, Invest Radiol, 1995, v. 30, p. 451.

[16] The U.S. Environmental Protection Agency, Byproducts of sulfur hexafluoride (SF_6) use in the electric power industry, Washington, DC, 2002, available at: http://www.epa.gov/electricpower-sf6/documents/sf6_byproducts.pdf.

[17] Wieland A., Gasdurchlagmechanismen in elektronegtiven Gasen (SF_6) und in Gasgemischen, Elektrotechnischen Zeituschrift, 1973, v. A. 94, p. 370 (in German).