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Gas substitutes of SF_6 for voltage testing of medium voltage equipment

Streszczenie. *(**Gazy zastępcze do SF_6 dla prób napięciowych urządzeń średnich napięć**). Wobec konieczności ograniczenia stosowania SF_6 ze względu na jego szkodliwe oddziaływanie na środowisko, istnieje potrzeba zastąpienia go innym medium izolacyjnym w próbach napięciowych urządzeń średnich napięć. Przedstawiono badania laboratoryjne z zastosowaniem sprężonego powietrza w próbach napięciowych z równoczesnym pomiarem wyładowań niezupełnych.*

***Abstract**. The paper refers to the problem of reducing industry application of SF_6 gas, especially as an insulating medium in high voltage tests. The laboratory experiments have been focused on compressed atmospheric air substituting SF_6 in HV manufacturing tests. The results of voltage tests of insulators combined with partial discharge measurements are shown.*

Słowa kluczowe: sześciofluorek siarki (SF_6), gazy izolacyjne, próby napięciowe, wyładowania niezupełne
Keywords: sulphur hexafluoride (SF_6), voltage testing, insulating gases, medium voltage equipment, partial discharges.

Introduction

Environmentally friendly testing of medium voltage (MV) equipment after manufacturing process seems to be nowadays very actual topic. SF_6 gas is widely used in electric power due to its excellent dielectric and arc-quenching properties. It is also used for testing of MV components. However, it belongs to greenhouse gases which usage should be reduced according to Kyoto protocol. According to CIGRE [1,2,4] SF_6 can decompose into by-products when exposed to different types of electric discharges. Today ABB Calor Emag has pledged themselves to apply SF_6 in a closed loop to avoid any contribution to the greenhouse effect. Many attempts have been made to find an alternative insulating gas in view of the environmental compunction with SF_6 (e.g. leakage, recycling) [3,6,7,9] Especially it was expected that SF_6 mixtures as well as nitrogen gas is useful for reducing the amount of SF_6. This approach might be promising in applications where SF_6 is used as an insulating medium in high voltage applications. However for high volume production testing of MV equipment it was expected to have a SF_6-free medium. The compressed nitrogen and compressed air have been considered. This paper presents study on selection of proper gaseous medium with regard to physical parameters like pressure and required sensitivity for successful partial discharge (PD) measurement.

Insulating properties of compressed gases

Following insulating mediums might be considered as a replacement for SF_6 in order to realize testing with no environmental impact:

- vacuum,
- compressed nitrogen,
- compressed "Hydrocarbons free" air (CO-1ppm, CO_2-10ppm, NOx-0.1ppm, humidity<5ppm, hydrocarbons < 0.1ppm),
- compressed atmospheric air,
- compressed ”dry” atmospheric air,
- SF_6 mixtures.

The SF_6 comparing to environmentally friendly gases manifests high breakdown strength, what made it attractive in low-pressure applications e.g. the relative breakdown strength of some gases (air assumed 1) is:

- SF_6 ~ 2,3 - 2,5
- N_2 ~ 1,15
- CO_2 ~ 0,95

Vacuum based testing has shown two main obstacles:

- complicated procedure to obtain vacuum, low vacuum would be needed for 85kV test, long preparation time, influence of humidity,
- big volume of chamber needed to evacuate.

Current trends in application of *SF_6 mixtures* (like SF_6/N_2) are twofold [e.g. 5,8,9]:

- *High SF_6 content:* 20-50% SF_6 in N_2. N_2 content results in 10-15% reduction of dielectric strength of mixture comparing to pure SF_6,
- *Low SF_6 content:* 0,1-10% SF_6 in N_2 mainly recommended as a extinguishing medium of switchgears.

SF_6 mixtures (like SF_6/N_2) were not considered as the main goal was to eliminate SF_6 completely from MV tests. Additionally, it might be a problem providing high volume mixtures of those gases with repetitive content for testing in industrial environment.

Compressed nitrogen (N_2) has many useful properties such as: no contribution to the greenhouse effect, no toxic decomposition products, low cost, non-flammable, simple handling, long life time. Due to lower dielectric properties of N_2 at low pressure comparing to SF_6 in order to avoid flashover the higher pressure will be required. It is also known from literature, that breakdown probability is influenced by number of tests without exchanging gas in the chamber. The breakdown voltage of SF_6 and N_2 in non-uniform electric filed as a function of pressure is shown in Figure 1.

Atmospheric air is most natural insulating gas-mixture, composed of nitrogen and oxygen in volume proportion 78% to 21% respectively. The remaining 1% is formed by noble gases, steam, carbon dioxide, etc. The electric strength of air depends on: geometric configuration of electrodes (shapes, radius of curvature), humidity of gas, parameters of applied voltage.

Compressed atmospheric air possesses several key advantages as it is easy to obtain, neutral gas and cheap installation as well as easy filling and emptying procedure necessary for fast production testing is required. Thus, the most attractive seemed to be utilisation of compressed atmospheric air as an insulating medium for MV testing in discrete manufacturing production and most of tests presented in this paper have been focused on this medium. Special attention was paid to determine the relationship between flashover and gas pressure.

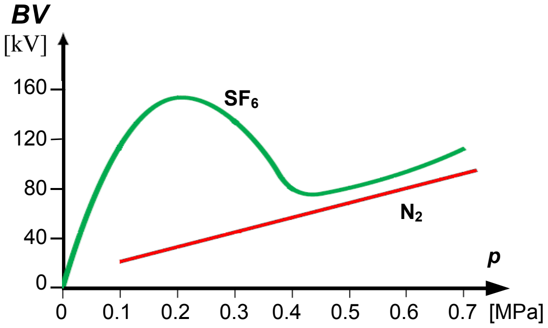

Fig. 1. Breakdown voltage (BV) of SF_6 and N_2 in non-uniform electric field [6]

Discharges in compressed gas

It is known, that in certain range of gas pressure the breakdown properties of the gas can be improved, increasing the gas pressure [e.g. 10, 11]. Thus, this paper is focused on compressed atmospheric air, as a most natural insulating gas-mixture. The advantages, which yield pressurised-air based test system, are low cost, speed - faster test cycle, environmentally friendly medium, regeneration of dielectric properties.

The higher breakdown voltage of air and other gases can be achieved at higher pressure. The breakdown voltage increases linearly with pressure in uniform electric field up to about 1,5 MPa and above that level the curves saturate. In non-uniform field this characteristic depends strongly on electrode configurations. The problem is even more complicated when voltage test of insulators is combined with PD measurement. The conditions for flashover in air depend then on the properties of solid dielectric and surface conditions. In such case, the crucial is electric field distribution in air (usually non-uniform).

Application of compressed air as insulating medium in high voltage testing requires thus determination of the relationship between breakdown voltage and pressure. The breakdown voltage below the critical pressure is influenced by the processes as: ionization by collision, photoionization and electron attachment. The breakdown in air can occur when the size of a single electron avalanche reaches a critical value. The size of the avalanche is determined by the total number of electrons $N_e(x)$ existing at its head, when the avalanche takes place at a distance x from the starting point. The size of the avalanche depends on the ionization coefficient α and the attachment coefficient η. Their values depend thus on the ratio E/p (E - electric field, p-pressure) [13]:

(1) $$\alpha = p \cdot f(E/p)$$

According to Raether [13] the size of avalanches is equal:

(2) $$N_e(x) = \exp\int_0^x (\alpha - \eta)dx$$

and the breakdown criterion is:

(3) $$\int_0^{x_{cr}} (\alpha - \eta)dx = \ln(N_{cr})$$

where x_{cr} is the critical avalanche length and N_{cr} is the critical number of electrons in the avalanche.

(4) $$N_{cr} = e^{\alpha(p)\cdot x_{cr}(p)}$$

The linear relationship between voltage breakdown and pressure is valid approximately up to 1,5 MPa in the uniform field. The breakdown voltage above the critical value decreases slower than linearly. It is caused by deformation of electric field by space charges, electron emission from cathode as well as deformation of the field distribution by surface charges on the solid dielectric surface. The positive ions formed during ionization in surroundings of the electrode of higher curvature are building-up positive space charge, causing its local elongation, and facilitation in discharge development. At higher pressure, due to attenuation of diffusion processes, the local charge density can be significant.

In a non-uniform field there is a well-known rule for determination of breakdown voltage Up in air at normal pressure. In arrangement with one electrode grounded it can be calculated from a form: Up=14+3.16a [kV], where *a* - distance in cm. In order to compare electric withstands of compressed gases, a test has been performed in rod-plate arrangement in a pressure chamber. Rod represents a high voltage electrode whereas plane has been grounded. Before the test, the chamber was evacuated and then the corresponding gas was filled. Distance between rod-plate was 72mm, which corresponds to the height of tested insulators. The comparison of flashover voltages in non-uniform electric field, as a function of pressure for different insulating mediums (N_2, atmospheric air, dry atmospheric air, hydrocarbons free) is presented in Fig.2.

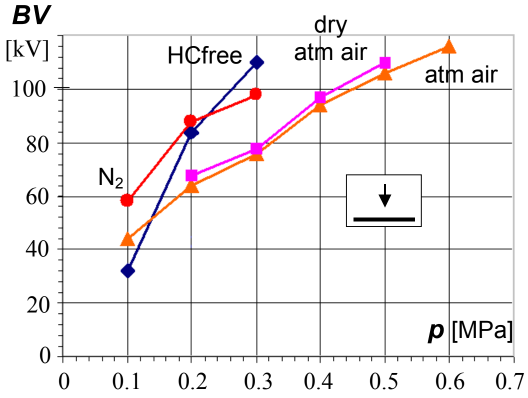

Fig. 2. Breakdown voltage (*BV*) versus pressure for different gases in rod-plate arrangement (d =72mm)

Measuring method and experimental setup

Actually the aim of the high voltage testing is to check the margin of electric strength of the equipment being tested. The goal of the measurements was to perform combined high voltage test and simultaneously partial discharge measurement, being one of the main tests of medium and high voltage insulation properties. It is very important to eliminate the surface and corona discharges and identify the internal partial discharges in solid dielectric with required sensitivity. In order to assess the application of compressed air in those tests the laboratory measurements on model electrode arrangements have been performed. Two cases have been considered: the first one in the rod-plate arrangement for the discharges in inhomogeneous electric field and the latter one with solid dielectric corresponding to supporting insulator. All experiments were performed in a high-pressure gas chamber. The samples and model of support insulator were placed in the chamber between electrodes. The pressure in the tank has been adjusted using compressor and manometer. The pressure was varied between atmospheric 0.1 MPa and 0.7 MPa, while most of the tests were performed at 0.5 MPa. Before running a test with a gas different than atmospheric air, the chamber was evacuated with a vacuum pump and then the gas was filled up. The tank was filled either by means of compressor in case of atmospheric air or from the containers in case of nitrogen/hydrocarbon free air.

The high voltage electrode in the tank was connected through the resistor to a PD-free transformer TP110 as shown in Fig. 3. For partial discharge detection the wideband current transformer was used. The main advantages of such coupling is: galvanic isolation of detection circuits from the high voltage side and cut-off of power frequency 50 Hz signal in the detection circuits as a low cut-off frequency of the CT was 10 kHz. The measuring signal was connected through protection unit, high frequency amplifier to a digital oscilloscope and PD analyzer. Both, the scope and phase-resolved acquisition system were connected to the host computer via GPIB interface. The PDs were visualized either as an accumulated pattern on the scope or on the phase-resolved plane where *x*-axis corresponds to phase of the test voltage, *y*-axis to apparent charge and colour (*z*-axis) represents the number of occurrence.

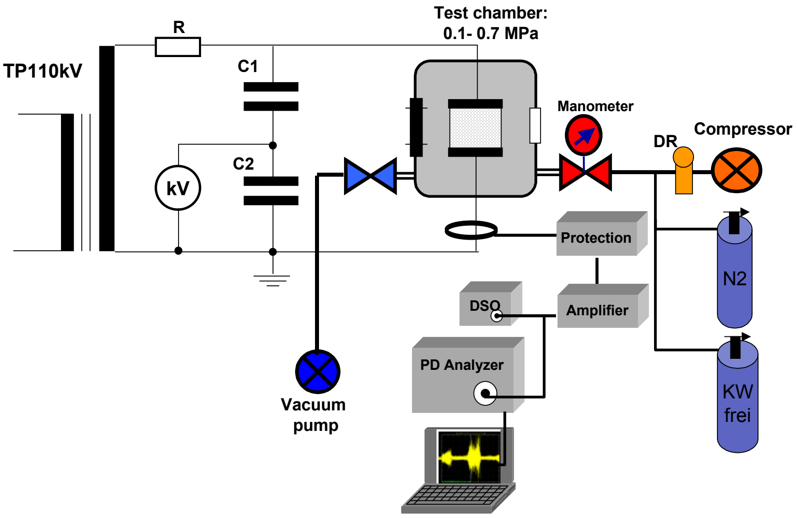

Fig. 3. Experimental setup

Measurement results

Voltage test.

The high voltage withstand measurements have been focused on compressed atmospheric air as potentially best-suited medium for industrial environment. The model of support insulator has been subjected to AC stress while controlling an air pressure in the test tank. The goal of this test was to determine the gas parameters during a test in order to avoid a flashover.

The maximum test voltage was assumed 85 kV$_{rms}$. However, in order to verify a breakdown characteristic of a gas versus pressure with a margin, some tests were performed up to 110kV. The temperature during measurements was 18-21°C, while humidity 60-70%. The atmospheric air breakdown voltage characteristic versus pressure in the range 0,1-0,5 MPa is shown in table 1.

The obtained results show that for compressed atmospheric air already at the pressure 0,2 MPa the breakdown voltage is 98 kV and exceeds with a margin the required level of 85 kV.

Table 1. The atmospheric air *BV* vs. pressure

Support insulator - compressed atmospheric air	
Pressure [MPa]	**Breakdown voltage [kV]**
0,1	78
0,2	98
0,3	108
0,4	>120
0,5	>120

Partial discharge measurements.

After the manufacturing process the quality assessment of the insulators in routine tests is evaluated using measurements of partial discharges. In order to optimise the process the combined high voltage and PD test is performed simultaneously in compressed atmospheric air. The main focus was paid to achieve the required sensitivity, distinguish the internal discharges occurring in the solid insulation from external ones (outside and inside the test tank like corona) as well as disturbances. The phase-resolved results are presented in form of accumulated pattern, superimposed on one period of test voltage. Partial discharge measurements performed on support insulator in compressed atmospheric air at a pressure 0.5 MPa are presented in Fig 4. The surface discharges and corona has been suppressed. There are shown internal PD registered at 60, 70, and 90 kV. No flashover was observed up to 120 kV.

Discrimination of PD forms

Performing PD analysis, important is proper interpretation and classification of discharge forms. Especially measuring internal discharges in solid insulation, one can expect additional corona in gas and surface discharges, which might coexist [12]. In such a case the latter one may manifest even much higher amplitude than the internal discharges embedded in solid material. Thus, just a measurement of a total discharge magnitude may lead sometimes to wrong conclusions. To properly classify discharge types very useful is a PD measurement performed on phase-resolved plane, where accumulated PD pulses are displayed according to their magnitude and phase location over certain number of test voltage periods. Examples of such measurements performed on support insulator by means of PD analyzer, are presented in Fig. 5. Those results were obtained at 0,3 MPa while surface discharges and corona was not fully suppressed. In a first case (Fig. 5a) the surface discharges are overlapping the internal discharges in solid insulation. In Fig. 5b are shown internal discharges superimposed with external corona. However, there is still possible a clear discrimination of those forms of discharges. In the third case presented in Fig. 5c, internal discharges are covered by external surface discharges. Also in this case phase-resolved acquisition allows for proper PD identification.

Conclusions

In this paper selection of proper insulating medium substituting SF_6 in MV manufacturing test was discussed. Different alternatives for SF_6 based testing have been considered. SF_6 mixtures (like SF_6/N_2) were not considered as the aim was to eliminate SF_6 completely from MV tests. Replacing SF_6 in tests of MV equipment will allow for saving on recycling and cost of SF_6 as well as will eliminate environmental impact.

After preliminary comparative tests the main focus was paid on a compressed atmospheric air in the range of pressure 0.1-0.6 MPa. Pressurised-air based test system represents several key advantages like: neutral gas and environmentally friendly, easy to obtain and cheap installation as well as easy filling and deflating procedure necessary for fast production testing. In addition, important is regeneration of dielectric properties after flashover. It seems to be recommended to run industrial test at a pressure about 0.3-0.5 MPa. In frame of this paper the MV insulator was subjected to high voltage and PD test.

Wide band current transformer put on the grounding wire picked up the PD signal. For support insulator (busbar socket) tested at 0.5 MPa the flashover occurs above 120 kV (for 0.3 MPa at 108kV).

It was shown that the required sensitivity was achieved. However, performing PD measurements it is important to distinguish between internal discharges in solid insulation and external surface discharges or corona, which may occur in gas.

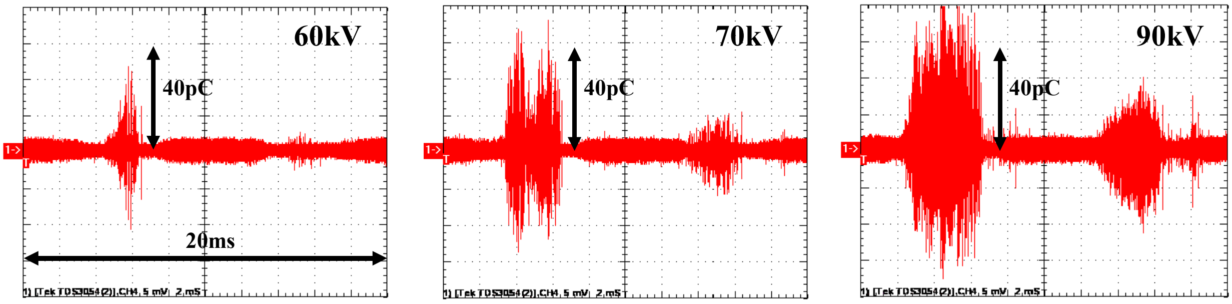

Fig. 4. Oscillograms of partial discharges registered in support insulator at 0,5 MPa

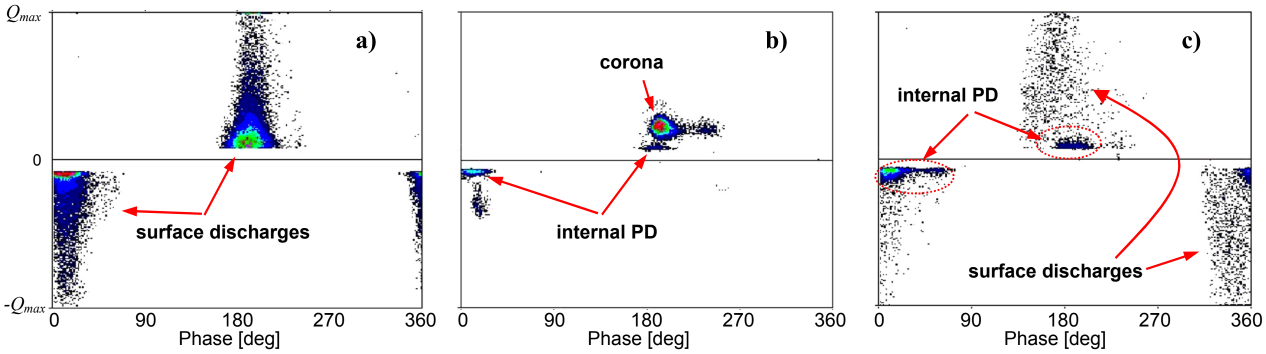

Fig. 5. Different forms of partial discharges:
a) surface discharges, b) internal discharges and corona, c) internal and surface discharges

REFERENCES

[1] O'Connell P. et. al., SF_6 in the electric industry, Status 2000, Paper of CIGRE WG 23.02, *ELECTRA*, No 200, pp. 16-25, 2002.

[2] Byproducts of Sulfur Hexafluoride (SF_6) - use in the electric power industry, *US Environmental Protection Agency, ICF Consulting*, 2002.

[3] Gacek Z., Rusek T., Chosen gas-mixture in high voltage engineering, *Proc. of III Int. Symp. NEET'2003*, pp. 74-77, Zakopane, Poland, 2003

[4] Ciok Z., Gazy zastępcze do SF_6 – mieszaniny gazowe, *EUI'03, Przegląd Elektrotechniczny – Konferencje*, 1'2003, pp. 31-35

[5] Hayakawa N., Hatta K., Okabe S., Okubo H., Partial discharge characteristics leading to breakdown in electronegative gases, *Proc. of the 13th ISH* Delft, 2003.

[6] Koch D., SF_6 properties and use in MV switchgears, *Merlin-Gerin, Schneider Electric "Cahier Technique"*, no 188, 2003.

[7] N_2/SF_6 mixtures for gas insulated systems, D1-201, Task Force D1.03.10, CIGRE session 2004.

[8] Słowikowski J., U progu zastosowania mieszanin N_2/SF_6 w urządzeniach rozdzielczych, *Proc. VIII Symp. EUI'01*, pp. 399-404, Zakopane, Poland, 2001

[9] Pfeiffer W., Schoen D., Requirements for gaseous insulation for application in GITL considering N_2, N_2O and CO_2 with low content SF_6, *Conf. Rec. 2004 IEEE ISEI*, pp. 536-539, Indianapolis, USA 2004.

[10] Kuffel E., Zaengl W.S., Kuffel J., High voltage engineering - Fundamentals, 2nd ed., *Newness Press*, 2000

[11] Abdel-Salam M., Stanek K., On the calculation of breakdown voltages for uniform fields in compressed air and SF_6, *IEEE Trans. on Indust. Appl.*, vol. 24, No. 6, 1988.

[12] Florkowska B., Florkowski M., Zydroń P., Localisation and identification of corona forms based on phased-resolved images, *Measurement Science and Technology*, Institute of Physics Publishing, No 12, 2001, pp.1304-1310.

[13] Raether H., Electron avalanches and breakdown in gases, *Butterworth*, London, 1964.

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