Dielectric Strength of Different Gases in GIS

Denis Denissov, Heinz Rebholz, Wolfgang Köhler, Stefan Tenbohlen
University of Stuttgart, IEH, Pfaffenwaldring 47, 70569 Stuttgart, Germany
E-mail: Denis.Denissov@ieh.uni-stuttgart.de

Abstract: SF_6 is a gas with excellent dielectric properties and is commonly used in gas-insulated equipment. However it has the high global warming potential. Thus, the development of new gases or gas mixtures for GIS, GIL is strongly desired. For dimensioning the gas insulated systems the support insulators (spacers) are of special interest. Contaminations on the insulator surface can cause field distortions and may lead to a significant reduction of the breakdown strength. To reduce the amount of used SF_6, the gases CO_2, N_2 and dry air are examined as possible substitutes for SF_6 at pressure range from 0.1 to 1 MPa. Their behaviour under AC and LI stresses is investigated. The study compares the breakdown characteristics of these gases and their mixtures in case of clean boundary surfaces as well as for the particle contaminated. A short introduction into the theory of gas discharge is given as well.

Key Words: dielectric strength, gas mixtures, GIS, spacers, particle contamination.

INTRODUCTION

Pure SF_6 has excellent insulating and arc-quenching properties. Therefore it remains the main HV insulation medium in gas-insulated equipment nowadays. However there are some serious concerns about its future employment from the ecological point of view. The global warming potential of SF_6 is considered to be at least 23.900 CO_2 equivalents [1]. So SF_6 has been classified on the Kyoto conference on climate change among the greenhouse gases. And its emission in the atmosphere ought to be reduced. Therefore one intensively looks for the possible environmentally friendly substitutes now. Many efforts have been taken to investigate the insulation properties of nitrogen and air under higher pressures. It is known, that pure nitrogen would end up in uneconomical designs of GIS/GIL to sustain the required insulation level. Using N2/SF6 mixtures, with a small amount of SF_6, the dielectric strength of N_2 can be significantly increased. Even now, N2/SF6 mixtures are used in GIL with up to 95% nitrogen. However, N2/SF6 mixtures are subjected to the heavy influence of conducting particles with increasing gas pressure, as well as with decreasing SF6 amount. Therefore the present study compares the breakdown characteristics of these gases and their mixtures in case of clean boundary surfaces as well as for the particle contaminated.

INTRINSIC STRENGTH OF GASEOUS DIELECTRICS

Under normal conditions, i.e. with no energy applied from outside, there are practically no free electrons to carry a charge in a gas. Only in the presence of a free electron, which is needed to produce an avalanche, the breakdown can succeed. Depending on the number of free electrons in the gas, after a certain voltage the sudden change of electric conductivity takes place. This drastic change of dielectric properties results in immediate drop of the applied voltage, which is called an electrical breakdown in a gas.

Besides the cosmic and the earth radiations a few more mechanisms can generate free electrons needed to build the avalanche. These are:

- field emission,
- photoelectronic emission,
- thermoemission.

An initial electron available in a gas volume is accelerated by electric field and travels his mean free path until the collision with a neutral molecule. Depending on the kinetic energy gained between collisions the electron can either be attached to the molecule or another free electron can be released. In pure SF_6 electron attachment leads to formation of stable negative ions, which in turn can recombine with existing positive ions (ion-ion-recombination). Electron detachment can be caused by one of the following processes:

- auto detachment,
- photo detachment,
- collision detachment.

In the presence of electric field the collision detachment or impact ionization plays the major role in generating free electrons [2].

Depending on the distribution of electric field in a discharge gap two different breakdown mechanisms can be distinguished, they are: streamer breakdown in case of uniform fields and streamer-leader breakdown in case of highly non-uniform fields.

Breakdown in uniform fields

At exceeding the gas-specified critical field strength the attachment-detachment processes reach a point from which the ionization dominates (effective ionization coefficient $\alpha_{eff} > 0$). Now the electron avalanches can shape, and the number of charge carriers grows exponentially. When the ion concentration at the head of the avalanche exceeded 10^8 a steep rise in current, known as a streamer, happened and breakdown of the gap in uniform filed followed [3]. On account of the electron-to-ion mass ratio the electrons travel faster to anode and leave slow ions at the place of their formation. That leads to the alteration of field in the gap and yields in further excitation processes at avalanche's head. When the streamer reached the opposite electrode it was heated instantaneous and thermally ionized. Finally the streamer breakdown occurs by means of this highly conductive "kanal".

Breakdown in highly non-uniform fields

For non-uniform fields with a negative impurity or an electrode additionally the electron production by means of the field emission from metallic surface must be taken into account [4]. Since the critical field strength in the gap is confined by the divergent field characteristic there is no more prerequisite to further constant grow of the avalanche. So the pure streamer breakdown is prevented. On the contrary the combined discharge mechanism consisting of the streamer and a consequent leader is involved here. A slightly conductive streamer region turns into a dissociated, highly conductive leader (precursor mechanism). This effect reveals especially under transient voltage stresses. In the case of slowly changing stresses like operation AC voltage the corona stabilization effect prevails.

Influence of gas pressure on breakdown process

The decisive impact on formation of initial electrons has a mean free path, an imaginary average distance between collisions. The higher is the density of a gas, the shorter mean free path is. So in the same field at high pressures the electron gains less kinetic energy between collisions; that leads to the increase of dielectric strength. The surface roughness of electrodes acts in the opposite way, so that at the pressure range between 0,7-0,9 MPa no more linear increase of breakdown voltage is possible.

Flashover along the boundary gas/solid body

In order to achieve a satisfactory dielectric strength in GIS, the surfaces of support insulators (spacers) have to be correspondingly dimensioned. Spacers usually represent critical weak points within the whole insulation and may reduce the reliability of the GIS. In GIS with its moving contacts the appearance of metallic particles is inevitable. Conductive particles produce plenty of charge carriers by means of the intensive partial discharge activity. New particles will lie on the spacer's surface along the field lines and further distort an applied field. Due to considerably higher dielectric constant of a spacer material in comparison to one of insulated gas the field strength rises locally on the surface already when the particle only approaches to the spacer. The reason for that is so called proximity effect. It becomes evident that due to the surface contamination field distortions can appear and badly reduce the dielectric strength of the whole arrangement [5].

EXPERIMENT DETAILS

Test setup

A modified part of a commercial 420kV GIS was used as a test chamber, inside of which the experimental electrodes arrangement was installed. This arrangement contains two aluminium plates as HV and ground electrodes (1,2) as shown in Fig.1. It can host up to 12 spacers (5) shielded by specially shaped electrodes (3,4). Each test spacer can be selected pushing out a pneumatic controlled piston (7). A cylindrical solid insulator of 25 mm diameter and 45 mm height is employed as a spacer model. It is made of epoxy resin filled with aluminium oxide (Al_2O_3). To simulate the possible particle contamination (6) in GIS a 4 mm long NiCr-wire (Ø 0,2 mm) is attached to the surface with silicon in the middle of the spacer. The test chamber can be filled with a gas at the pressures up to 1,4 MPa. In the present work the pressure range between 0,1-10 MPa is investigated.

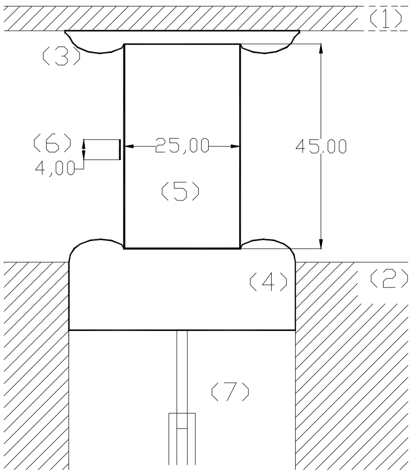

Fig. 1 Test setup with model spacer
1. HV electrode; 2. grounded electrode; 3, 4. specially shaped electrodes; 5. model spacer; 6. particle; 7. piston.

Generating and measuring test stresses

The overall test system is schematically shown in Fig.2. Voltage stresses can be produced either by a GIS encapsulated HV test transformer (380 V/510 kV, 50 Hz), or by an eight-stage Marx' impulse generator with standardized LI stress of 1,2/50 µs up to 800 kV. The impulse voltage was normally increased from approximately 50% of the expected flashover voltage in 10% steps until flashover occurred. The AC voltage was raised with a rate of 6 kV/s. To prevent multiple breakdowns during the AC test a protective relaying turns off the voltage on primary side of the transformer immediately after succeeded breakdown. Transient LI stresses are measured by means of a capacitive HV divider and AC voltages using a capacitive filter on the primary side.

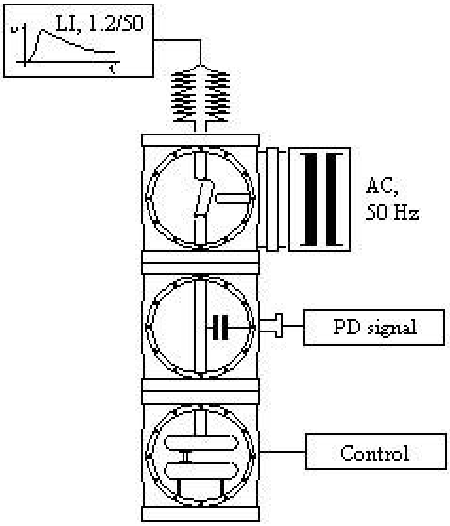

Fig.2 Test setup

Field distribution along the spacer

Field configuration impacts significantly on the gas discharge process. A simulation shown in Fig.3 demonstrates the referenced potential distribution along the spacer model.

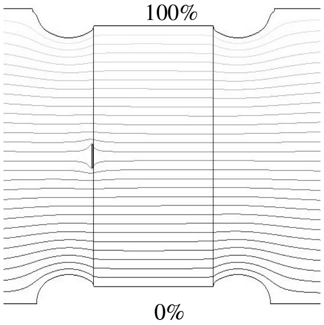

Fig.3. Potential distribution along the spacer

Hereinafter we will characterize the electric strength of a gas by its flashover field strength. So one can easily compare the measurements with the results of other experiments on a similar geometry. The flashover field strength E_F can be calculated from the measured flashover voltage U_F using a constant factor k_F:

$$E_F = k_F \times U_F . \tag{1}$$

The geometry-dependant factor k_F for the arrangement described above was found to be 0,224 cm^{-1}[6]. Local field distortions brought with a particle contamination are not considered in k_F.

Influence of surface roughness

Local rise of the field stress cased by the surface roughness of the electrodes can result in essential reduction of the streamer breakdown voltage. This field rise cannot be found analytically, so only evaluation of its influence can be done. In the test arrangement the electrodes with the average roughness height of 1,2 µm are employed, i.e. no impact on breakdown behaviour is expected [7].

To keep the roughness height below 10 µm during the experiments the electrodes was regularly polished.
During the LI stress some tracks of the breakdown occasionally remain on the electrode surface as a result of a particle burnout. A typical picture is shown in Fig.4. Various tracks of previous tests have to be cleared to avoid additional PD sources. Thus, the independency of single tests is provided.

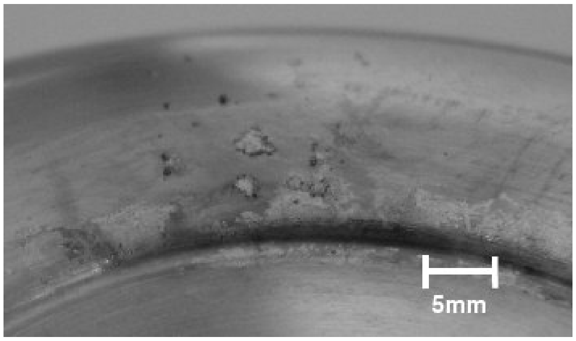

Fig.4 Breakdown tracks on the electrode

RESULTS AND DISCUSSION

Test realization

To determine the mean flashover voltage $U_{F,m}$ and the correspondent field strength $E_{F,m}$ a series of 12 separate spacer models was stressed per each test case. All values of flashover field strengths are referenced to the calculated peak values of applied voltages with the inherent confidence interval of 95% according to normal distribution. Gas pressures marked on the graphs below correspond to absolute pressures in MPa.

Flashover field strength under AC stress

Flashover field strengths (with no contamination) in the following insulated gases: N_2, CO_2 and compressed air vs. gas pressure are shown in Fig.5. Electric strength of the arrangement rises steadily with increasing pressure.
Carbon dioxide and compressed air shows nearly no difference in their electric strengths. Nitrogen on the contrary stays far below them over the whole pressure range.

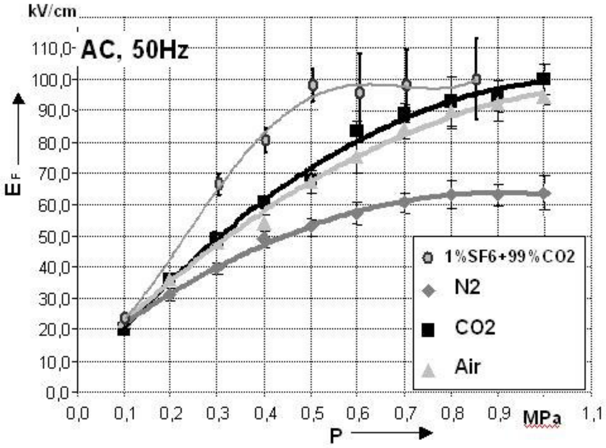

Fig.5 Flashover field strength vs. pressure for N_2, CO_2 and compressed air (no particle contamination)

In the case with the metal particle contamination a significant reduction of breakdown voltage (up to 50%) can be observed in the Fig.6. The extent of reduction depends in general on the voltage type and on the field distribution in the gap [8].

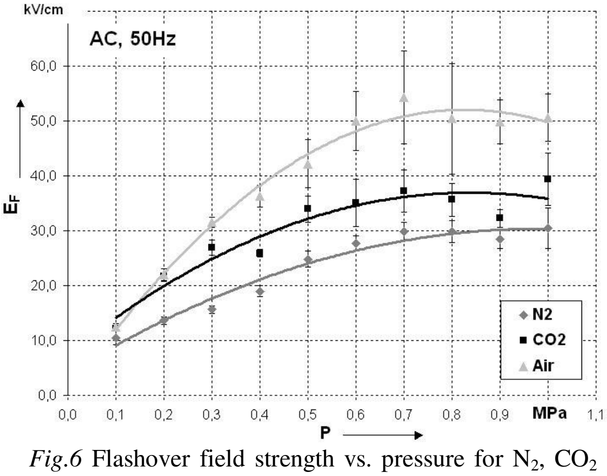

Fig.6 Flashover field strength vs. pressure for N_2, CO_2 and compressed air (with particle contamination)

From direct comparison of Fig.5 and 6 follows that CO_2 demonstrates the highest reduction of the electric strength in slightly non-uniform fields. Moreover the curves for CO_2 and for the air in distorted fields do not rise anymore after 0,6 MPa, which is a consequence of a stabilization corona.

Flashover field strength under LI stress

During the LI stress with positive polarity a surface charge accumulates on the particle contaminated spacer surface, once the PD-inception voltage exceeded and no breakdown occurred.

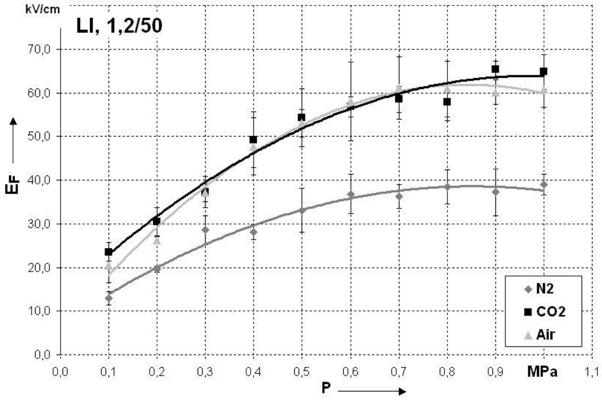

Fig.7 Flashover field strength vs. pressure for N_2, CO_2 and compressed air (with particle contamination)

The results for this case shown in Fig. 7 prove again the similarity in CO_2 and air flashover behavior. However there is some increase in the flashover strength due to existent surface charge. Further investigations on this point are necessary.

Electric strength of SF_6/N_2-mixtures

The electric strength of SF_6/N_2 mixture where SF_6 takes 5% of the volume is shown in Fig.8.

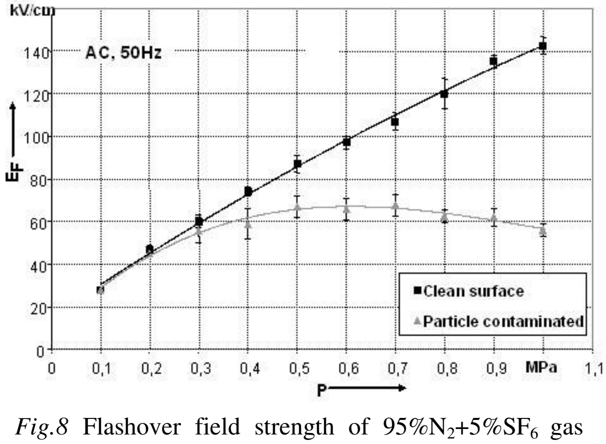

Fig.8 Flashover field strength of 95%N_2+5%SF_6 gas mixture vs. absolute pressure [9]

It can be seen that the SF_6-contained gas mixtures experience essential reduction of their electric strength in the presence of particle contamination. The SF_6/N_2-

mixture demonstrates more than 50% decay of its dielectric properties under AC voltage stress at higher pressures.

Compressed air and CO_2 vs. $5\%SF_6+95\%N_2$ and $1\%SF_6+99\%\ CO_2$ mixtures

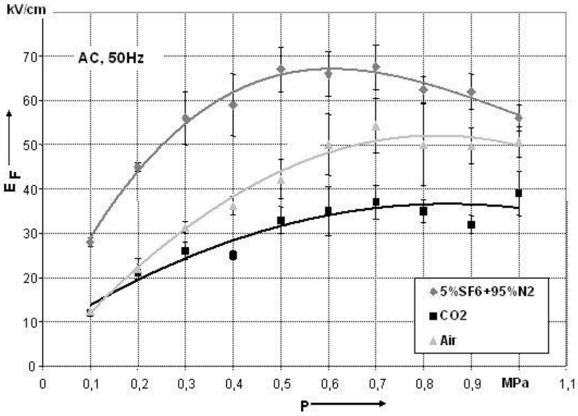

Fig.9 Flashover field strengths in compressed air, CO_2 and $5\%SF_6+95\%N_2$ under AC stress with particle contamination vs. pressure

CONCLUSIONS

The presented tests in different gaseous dielectrics determine the flashover field strength of the given arrangement. As anticipated the flashover voltage along clean surface of spacers generally increases with rising gas pressure.

Among all tested gases CO_2 revealed the highest sensitivity to particle contamination. In case of positive lightning impulse voltage stress CO_2 and the air show few differences in dielectric behaviour over the whole pressure range.

Pure nitrogen has the lowest electric strength among considered gases. The strong reduction of its dielectric properties comparing to the air, which contains about 80% of nitrogen, has to be examined further. Adding a little amount of SF_6 to these gases results in a noticeable increase of the breakdown field strength.

If the employment of the pure SF_6 insulation and its mixtures will be legally forbidden in the future, compressed air or carbon dioxide insulations present themselves as possible substitutes. However higher pressures together with an increased impact of the contamination on the insulation performance has to be overcome in the design of future apparatuses.

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