IEEE Transactions on Power Apparatus and Systems, Vol. PAS-97, no. 1, January/February 1978

DC DIELECTRIC STRENGTH OF A SF_6 GAS INSULATED SYSTEM

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ABSTRACT

The breakdown characteristics of gas insulated systems were investigated for DC and switching impulse voltage superposed upon DC of opposite polarity in laboratory - clean conditions. The breakdown voltage of a SF_6 gas gap for DC voltage is approximately 80 percent of that for AC crest value at pressure of 3.5kg/cm² abs., while an epoxy cast gap withstands the DC voltage by 1.7 times of the AC crest value. However, when the short epoxy cast gap is subjected to the combined voltage of DC and switching impulse of reverse polarity, the switching impulse breakdown voltage is strongly affected by the preset level of DC voltage. On the other hand, the superposed switching impulse breakdown voltages of conical insulators, for supporting a high voltage conductor in a cylindrical enclosure, are only slightly influenced by the DC voltage of reverse polarity. Therefore the combination of SF_6 gas and epoxy resin may be used effectively as an insulation system of the HVDC gas insulated substation.

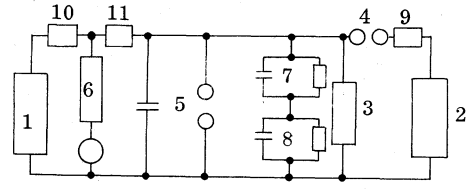
INTRODUCTION

Effects of conductive particles, electrode size, figure, surface conditions, etc on the DC dielectric breakdown characteristics of gas insulated systems have been investigated by some workers.(1)(2)(3) In judging whether a SF_6 gas insulated system is available for HVDC substation, the dielectric behaviors of gas insulated systems should be clarified against not only DC voltage, but also impulses superimposed upon the DC. Although the AC and impulse breakdown voltages of SF_6 gas insulated systems have been relatively well studied, the DC and the DC superposed with AC or impulse voltage are not fully investigated, especially for the case the insulating supports are contained. The authors' primary purpose of this investigation is to find the adequate insulation configurations for HVDC gas insulated substation. The second purpose is to make clear the breakdown characteristics of conical insulators in a coaxial cylinder gap against a surge stress superimposed on DC stress of reverse polarity. For these purposes, AC gas insulated systems of BIL 550 class were tested with various voltage waves. The dielectric strengths of coaxial cylinder and plane gaps were compared among DC, AC and lightning impulse and switching impulse voltages. Effect of electrode covering on the dielectric strength of the coaxial cylinder gap and plane electrode gap was investigated under the pressurized SF_6 gas atmosphere. The dielectric strengths of an epoxy cast model gap and a bus duct of BIL 550 for DC were compared with those of AC and impulse voltages. Also they were tested with combined voltages of DC and switching impulse.

TEST EQUIPMENT AND PROCEDURE

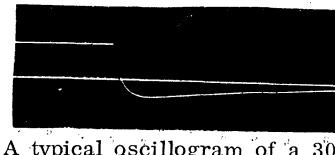
Test Equipment

The DC breakdown voltages of gas insulated systems are measured using a 2MV, 100mA silicon rectifier connected with a 750kV 10MVA testing transformer. An impulse voltage is superposed on DC as shown in Fig.1 (a). A typical superposed voltage is shown in Fig.1(b).



1 DC voltage source 400kV, 13mA
2 Impulse generator 3.6MV, 0.0147μF
3 Test specimen
4 Separate gap
5 Protective gap
6 Voltage divider 470MΩ
7 DC-1MHz voltage divider 100pF, 300MΩ
8 Low voltage arm 3μF, 10kΩ
9 Wave front resister 15kΩ
10&11 Current limiting resisters of 15&10kΩ

(a) Superposed voltage source



(b) A typical oscillogram of a 300×1400μs switching impulse voltage superposed on DC

Fig.1 Superposed voltage source and its output voltage wave

Test Objects

Four kinds of test objects, the electrode profiles of which are given in Fig.2(a), are illustrated in Fig. 2(b). The typical electrode configuration of a gas insulated substation is a coaxial cylinder gap, while insulation between contacts of an open disconnecting switch is a rod gap. A 80/200mm dia. coaxial cylinder gap is selected as an electrode assembly of the BIL 550 class bus bar.

F 77 130-8. A paper recommended and approved by the IEEE Switchgear Committee of the IEEE Power Engineering Society for presentation at the IEEE PES Winter Meeting, New York, N.Y., January 30-February 4, 1977. Manuscript submitted September 7, 1976; made available for printing December 17, 1976.

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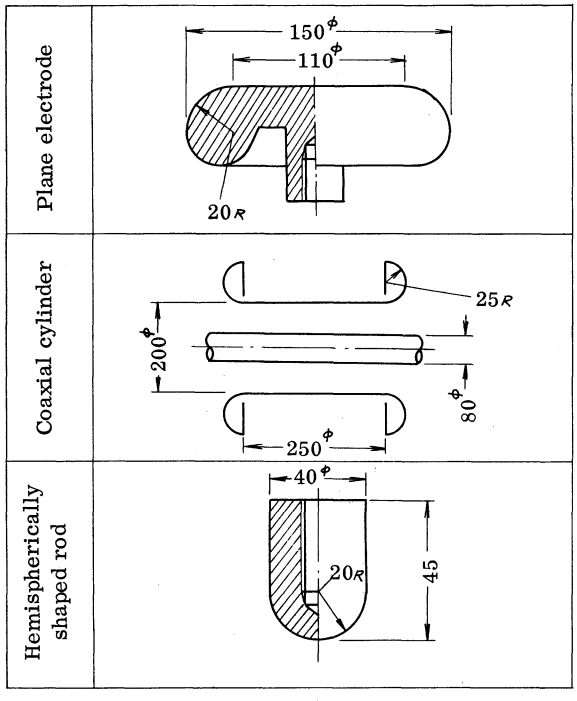


Fig2 (a) Electrode profiles

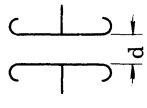
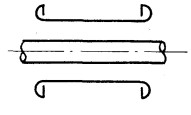
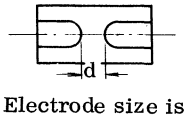
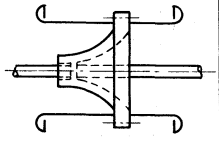
Type	Arrangements			Gap length
A	SF_6 gas gap	Plane to plane electrode	 Electrode size is shown in Fig2 (a)	Bare electrode d=5, 10, 12, 15, 20, 25, 30 mm
				2 or 3mm thick epoxy covering d=5,10,13,15,20,25mm
B	SF_6 gas gap	Coaxial cylinder	 Electrode size is shown in Fig2 (a)	Bare electrode 200φ outer diameter (80φ inner diameter)
				0.2mm covering of a high voltage conductor with doubly wound half lapped polyethylene terephthalate tape
C	Epoxy cast gap	Rod to rod	 Electrode size is shown in Fig2 (a)	Epoxy cast model gap d=2 and 3mm
D	Epoxy cast insulator	Conical insulator		Conical insulator for a BIL 550 class bus bar (200φ outer diameter 80φ inner diameter)

Fig2 (b) Electrode arrangement

A plane electrode gap of 150mm dia. is used in stead of a rod gap, to give more safety side results due to the larger highly-stressed area. The main dielectric components of the gas insulated substation are insulating rods for switchgear and conical insulators for supporting high voltage conductors. The two kinds of insulators illustrated in Fig.2(b) are selected for examining the dielectric behaviors against DC, AC, switching impulse, lightning impulse and superposed voltage stresses. The tested epoxy insulators are made of the same formation of cast resin as used for an AC gas insulated substation. The embedded electrodes are previously treated just like those in epoxy cast products. The tested epoxy cast insulators, therefore, do not indicate the dielectric strength in ideal conditions.

Test Procedure

Before experiment, the electrodes and the insulators were cleaned with dimethyl keton in laboratory - clean conditions and the test vessels were evacuated with a rotary vacuum pump to a pressure of less than 1mm Hg. SF_6 gas was directly fed from the supply cylinder into the test vessels. In making the breakdown tests on SF_6 gas gaps with DC voltage, the voltage was raised quickly to 50 per cent of the expected breakdown value and subsequently by steps of 10 per cent of the expected value with 1, 10, or 30 minute holding at each step until breakdown. The average 1 minute breakdown voltage was calculated from ten breakdown measurements. AC and impulse test procedures are the same as those described in the previously reported papers. (4)(5) The effect of electrode covering was confirmed with 30 minute DC withstand voltage. DC and AC V - T curves of epoxy model gaps were obtained in a time range from 0.5 to 300 minutes, using an automatic voltage control board, with which voltage step, voltage rising speed and voltage holding time can be preset. One and thirty minute DC dielectric strengths of conical insulators were investigated with the same test method as the one for SF_6 gas gaps. The superposed voltage tests were conducted with the test circuit given in Fig.1(a). One minute after the DC voltage stress had been previously applied, the 300/1400μsec switching impulse voltage of the reverse polarity was applied by steps of 5 per cent of an expected breakdown voltage, started from the 50 per cent of the expected breakdown value.

TEST RESULTS

Gas Gap

Coaxial cylinder gap : The DC breakdown voltage of a 80/200mm diameter coaxial cylinder gap of Fig.2(b) B related to DC application time and inside gas pressure is shown in Fig.3. The effect of voltage holding time is scarecely observed. Voltage polarity effect is prominent at the pressure above 1 kg/cm² abs. The positive DC breakdown occurs at slightly below the theoretical limiting breakdown voltage Ulim, while the negative breakdown occurs at much lower voltage than Ulim, especially at higher pressure. The negative DC breakdown voltage at 3.5 kg/cm² pressure is approximately 80 percent of the AC breakdown value. (4) Marked effect of electrode covering at negative polarity is found as given in Fig.4. In this case the inner conductor of 80mm diameter is insulated with doubly wound half lapped polyethylene terephthalate tape. The covering of

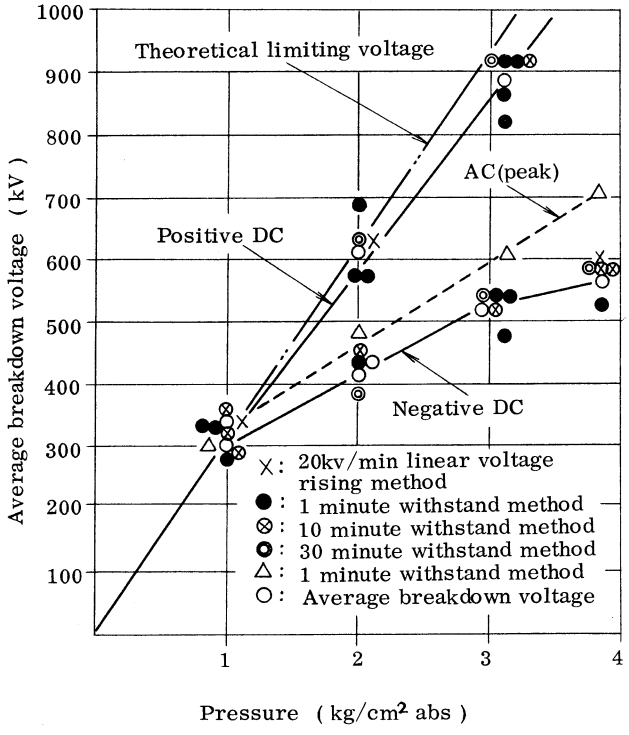


Fig. 3 Breakdown voltage of a 80/200mm diameter coaxial cylinder gap v.s. gas pressure and voltage application

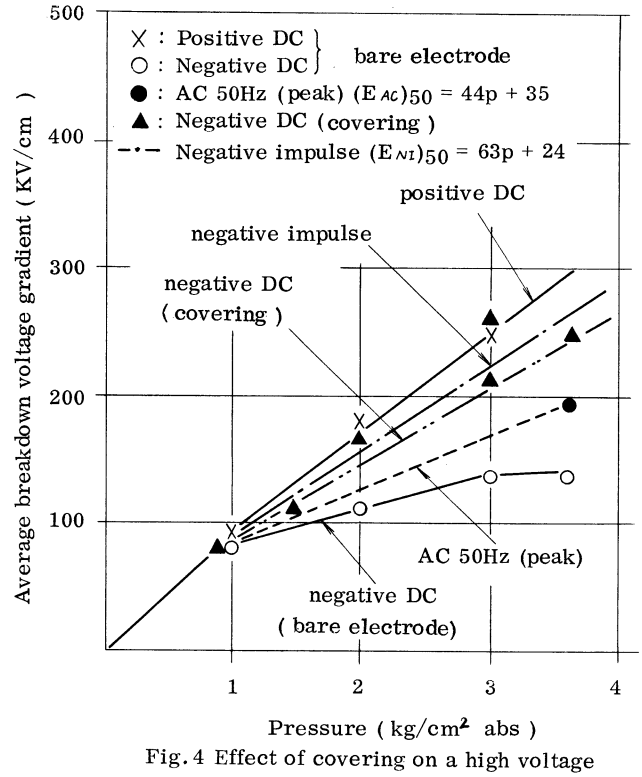


Fig. 4 Effect of covering on a high voltage conductor of 80 mm diameter

an inner conductor of bus bar raises DC breakdown stress nearly up to the level of the negative impulse breakdown stress.

Plane to plane gap : The DC breakdown voltage of 150 mm diameter plane electrode gap is shown in Fig. 5(a), in comparison with the AC. No remarkable difference is observed between both polarities of DC voltage. The AC breakdown voltage is almost the same as the value expected from the breakdown voltage of 430mm diameter plane gap.(4) The DC breakdown voltage at 3.5kg/cm² abs. is about 80 percent of the AC breakdown value, similar to the case of a coaxial cylinder gap. The covering on the negative electrode increases remarkably breakdown voltage.

Insulator

Epoxy cast model gap

V - T curve : Fig. 6 shows the V - T curves for both DC and AC voltages, giving two straight lines for both on a logarithmic paper, i. e.,

$$U(t) = U(1) \cdot t^{-\frac{1}{16}} \quad (kV)$$

here U(t) : average t minute breakdown voltage
U(1) : average 1 minute breakdown voltage
$U_{DC}(1)$ = 300 kV
$U_{AC}(1)$ = 175 kV crest

The inclinations of both DC and AC V - T curves seem to be the same. Additionally, the average impulse breakdown voltage is nearly equal to the DC 30 second breakdown voltage.

Dielectric strength for superposed voltage stress : 3mm epoxy cast model gaps are stressed with the DC voltage superposed with a 300/1400μ sec switching impulse

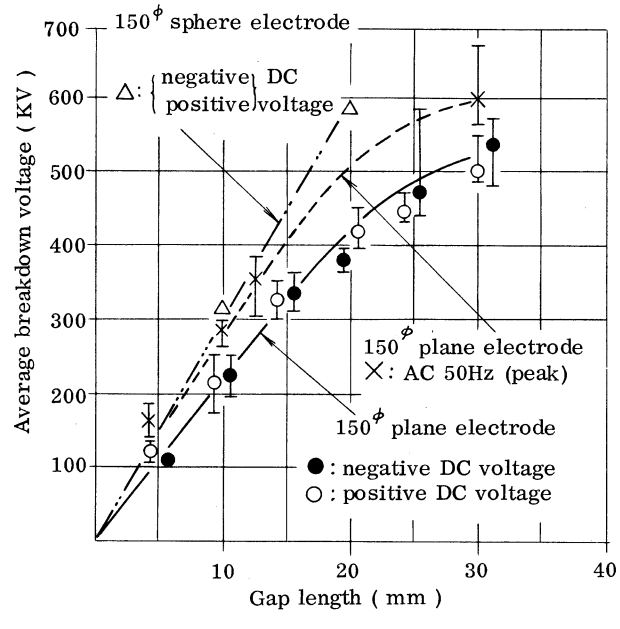


Fig. 5 (a) Breakdown voltages of 150mmφ plane to plane and 150mmφ sphere to sphere as a function of gap length.

voltage. This breakdown voltage is strongly effected between each other as shown in Fig. 7. The relation is shown by the following equation.

$$U_{SI} = -\frac{7}{8} \cdot U_{DC} + 440 \quad (kV)$$

where U_{DC} : prestressed DC voltage
U_{SI} : switching impulse breakdown voltage

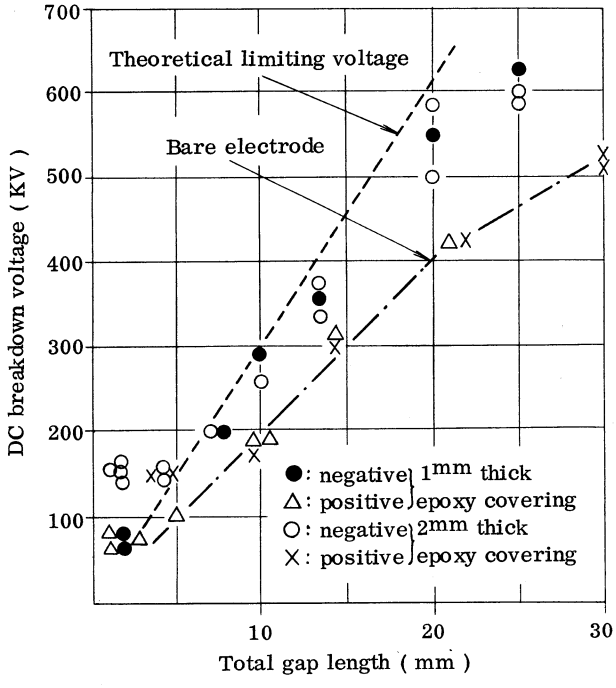


Fig. 5(b) DC breakdown voltage of epoxy-covered plane electrode gap.

Conical insulator

DC dielectric strength : The breakdown characteristics of conical insulators are tested at 3.5kg/cm^2 abs. for DC, lightning impulse, switching impulse and AC voltage. The results are given in Table 1. The negative DC breakdown voltage of conical insulators is unexpectedly higher than that of the coaxial cylinder gap alone by about 10 percent, while the positive DC breakdown voltage is lower than that of the coaxial cylinder gap alone by about 15 percent. Breakdown of a conical insulator starts from the highly stressed region. (5)(7) It is noticeable that the negative DC average breakdown voltage is nearly equal to the AC crest and the switching impulse voltages.

Dielectric strength for superposed voltage stress : The conical insulator of Fig. 2(b) is tested with the DC voltage superposed with a switching impulse voltage of reverse polarity. The influence of prestressed DC voltage and gas pressure on switching impulse breakdown voltages is investigated. The test results are given in Fig. 8. As shown in this figure, the DC prestressed voltage has no effect on the switching impulse breakdown voltage when the pressure is low as 1kg/cm^2 abs.. The relatively high DC prestressed voltage reduces the switching impulse breakdown voltage when the pressure is high as 3.5 kg/cm^2 abs.. However, the influence of the prestressed DC voltage on the switching impulse breakdown voltage is not so remarkable as for the epoxy cast model gaps. The prestressed DC 300kV voltage, both positive and negative, only reduces the switching impulse breakdown voltage by 15 to 20 percent.

DISCUSSION OF RESULTS

Gas Gaps

The negative DC breakdown voltage gradient of the coaxial cylinder gap at 3.5kg/cm^2 pressure is approximately 150kV/cm according to the data in Fig. 4. This voltage gradient is nearly 50 percent of the limiting breakdown voltage gradient. In this case, the total area exposed to the high field is nearly 0.15m^2. On the other hand, the breakdown voltage gradient of a 150mm diameter plane gap is 210kV/cm, whose exposed stressed area is 0.015m^2. This corresponds to 70 percent of the limiting value. This area effect is in a good agreement with the data given in the literature. (1) Such a breakdown far below the limiting value, as given above, is said to originate from the cathode surface microstructure and or from free particles attached on or moving near

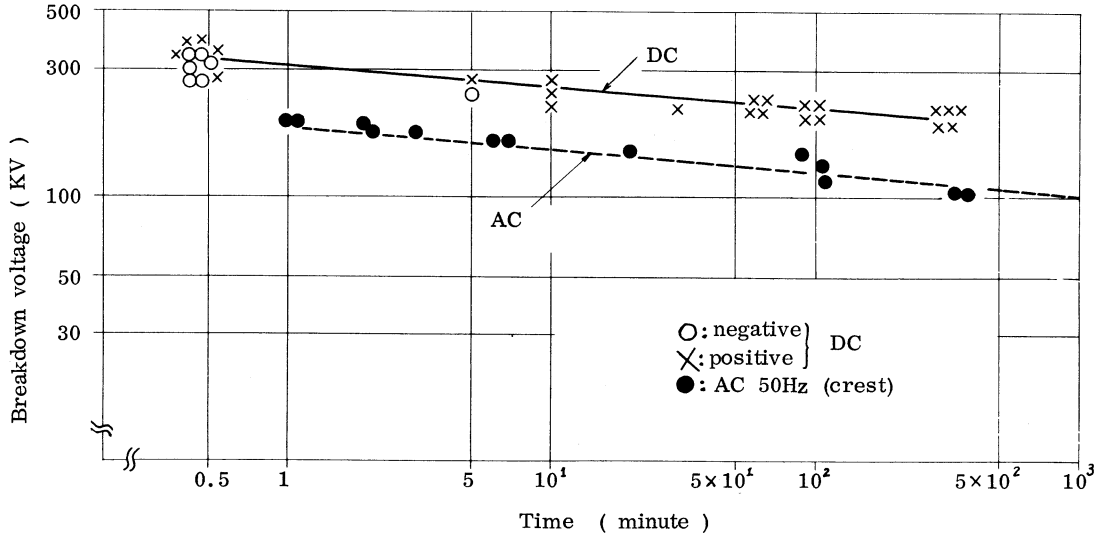


Fig. 6 The V-T curves for DC and AC voltage of epoxy cast model gap (d = 2 mm)

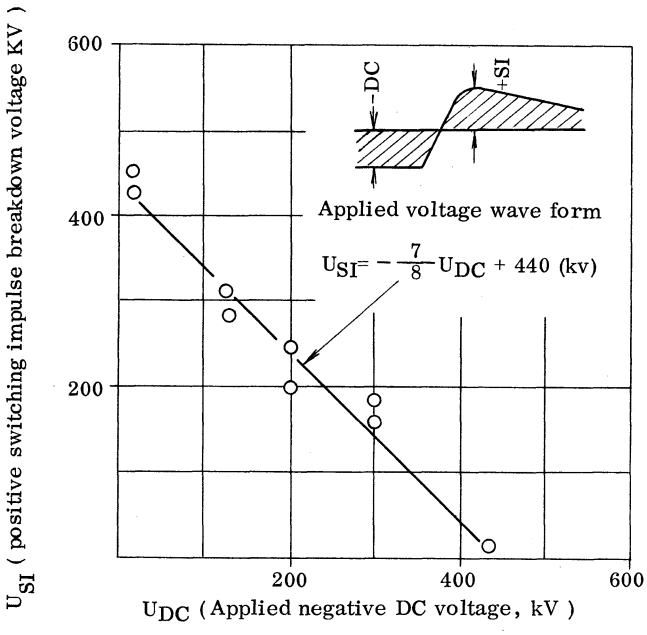


Fig. 7 Switching impulse breakdown voltages of epoxy cast gaps with the superposed voltage of DC and Switching impulse

the electrode surface. The reduction of the breakdown voltage may be caused mainly by cathode micro-irregularities, since the negative breakdown voltage can be raised remarkably by the cathode covering, as shown in Fig.4 and 5(b).

Covering effect : The covering on a highly stressed negative electrode has notable effect on increase in the breakdown voltage, as shown in Fig.4 and 5(b), while the covering on a positive electrode is not effective as in Fig.5(b). Even if both positive and negative electrodes are equally stressed, increase in the withstand voltage can be expected, so long as a cathode is insulated with solid dielectrics. This may be because the covering makes microscopically irregular cathode surface relatively smooth and prevents electron emission, which plays a main role in gas discharge.

Insulators

Epoxy cast model gap : It is quite interesting that the inclinations of AC and DC V - T curves are almost the same as shown in Fig.6. In the tested range of these V - T curves, the inside high field intensity seems to start the breakdown. From these curves, the life of epoxy casting can be estimated for both DC and AC voltages. Breakdown of an epoxy cast model gap against a superimposed voltage stress is very similar to that of a plastic cable, that is, so-called homo space charge seems to be formed in the vicinity of the electrodes stressed by DC. Thus the epoxy casting near the electrode surface is highly stressed and lead to the ultimate breakdown, when the switching impulse voltage of opposite polarity is superposed to the prestressed DC voltage.

Conical insulator : All high tension cylindrical conductors of a SF_6 gas insulated substation are insulated with epoxy insulators and gas gaps in series against the enclosures. To know how this system behaves to the superposed impulse voltage is very interesting and important, because the HVDC SF_6 gas insulated system will often be exposed to such stresses. The test results in Fig.8 might indicate the following facts : The switching impulse breakdown voltages are, but not so strongly, affected by gas pressure. This may be because at higher pressure more space charges, which enhance the electric field, are formed by conductive particles or irregular electrode surfaces. Namely when the gas pressure is relatively low and thus the mean free path length for gas molecules is greater than the intensified field region in

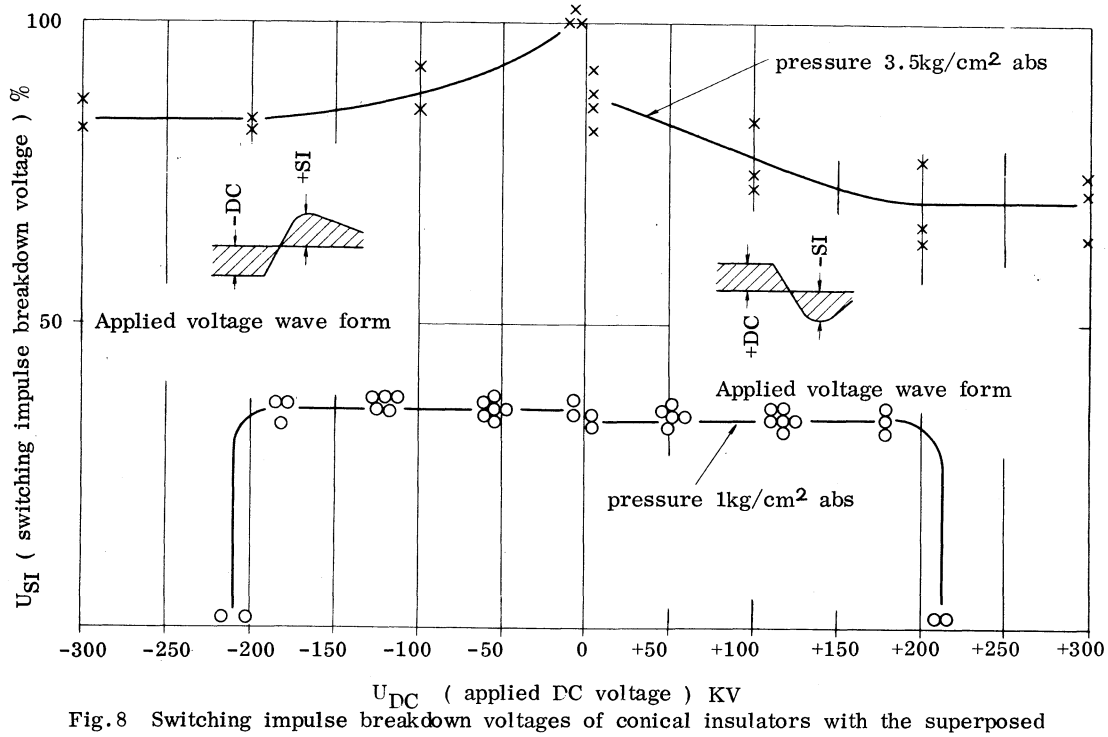


Fig. 8 Switching impulse breakdown voltages of conical insulators with the superposed voltage of DC and Switching impulse.

Table 1. Breakdown voltages of conical insulators at 3.5kg/cm² abs. pressure of for DC, lightning impulse, switching impulse and AC voltages.

Polarity	DC		Lightning impulse		Switching impulse		AC (peak)		DCgasgap
	Break - down voltage (%)	Average breakdown voltage (%)	Break-down voltage(%)	Average breakdown voltage (%)	Break-down voltage(%)	Average breakdown voltage(%)	Break-down voltage(%)	Average breakdown voltage(%)	Average breakdown voltage(%)
Positive	112 98 98	102	98 102 102 104	102	98 98 95	101	88 89 89	89	119
Negative	84 84 84 87	85	98 101 98 102 101	100	87 75 95 80	87			77

the vicinity of the micro-irregular surface of electrodes or conductive particles, space charge is not formed, because collisions do not occur within the region. However as more molecules occupy the small intensified region at higher pressures, some ionization can take place even in the localized region and space charges are generated. Space charges produced in such processes may affect more or less the successive switching impulse breakdown. Now assumed that 125kV DC gas insulated system under transmitting DC power be stressed by a switching im - pulse, the switching impulse breakdown voltage only decreases at either polarity by about 12 per cent, as shown in Fig. 8. Therefore, the dielectric test with superposed voltage wave seems to be unnecessary, since such a small reduction can be solved through an appropriate selection of design stress.

CONCLUSION

The dielectric strength of a gas insulated system in laboratory-clean conditions was minutely investigated against DC and superposed voltage stresses. From these experimental results the following conclusions are deduced.

(1) The DC dielectric strength of the SF_6 gas gaps is approximately 80 percent of the AC one at 3.5kg/cm² abs. pressure.

(2) The covering on the negative electrode with dielectrics is effective as has been reported by the litera - ture.[1]

(3) The short duration DC dielectric strength of the epoxy cast model gap is nearly the same as the impulse dielectric strength. The inclination of the DC V - T curve is almost the same as that of AC V - T curve.

(4) The transient wave dielectric strength of the short epoxy cast gap seems strongly influenced by the homo charge generated by the DC prestressed voltage, while that of the combined insulation with epoxy and gas gap in series such as a conical insulator is less affected by the DC prestressed voltage.

(5) Accordingly, the dielectric test with superposed impulse voltage seems unnecessary.

(6) The polarity reversal test seems unnecessary also, since the DC operating stress is very low.

(7) It should be carefully investigated whether the conical insulator is also suitable for the HVDC gas insulated system.

(8) In addition to these conclusions, the influence of free particles on the DC dielectric strength of the insulator seems to require further study.

ACKNOWLEDGEMENT

Authors wish to express their deep appreciation to the management of Tokyo Shibaura Electric Co., Ltd. for permitting them to submit their paper.

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Discussion

S. A. Boggs (Ontario Hydro, Toronto, Canada): The authors are congratulated on their extensive research into SF_6-insulated dc apparatus. We would appreciate the authors' comments on the following:

As the authors point out, there are very significant differences between the field gradings of solid dielectrics under ac and dc potentials. In ac SF_6-insulated systems, it is common to design the epoxy insulators so that the potential is more uniformly graded along the insulator than in the gas so that breakdowns will occur in the gas rather than along the insulator. For the case of dc, the grading of common insulating materials depends on the volume and surface resistivity and is likely to be highly nonuniform. This may lead to significant corona at the spacer and to corona stabilization. This could explain the greater strength of the spacers than the gas which was noted by the authors. Did the authors note corona at the spacers? One would think that spacers designed for use in dc systems would be designed to have controlled resistivity. Have the authors given thought to the paper design of spacers for dc systems?

The difference between the ac crest and the dc breakdown of the epoxy-filled gaps is surprisingly small. Other literature/1/ suggests that for other dielectrics it may be very much greater. In view of the presentation of results for 30-second breakdown, one wonders if the authors imposed the dc potential as a step function. If so, the primary damage may have occurred due to that impulse rather than the subsequent dc.

Surface coating in SF_6-insulated systems presents a very complicated problem. The authors note that they are working under laboratory clean conditions, but one must wonder how many particles in the 100 μm radius range remained in their system. The potentials at 350 kPa at which their system was failing for negative dc were such as would levitate spherical particles in this size range and whisker-like particles very much shorter. The activity of such particles is well known and should give rise to large corona pulses, optical and acoustic activity. Was any such activity observed? The conductor coatings would, of course, limit the transfer of charge to such particles and the creation of space charge which allows them to oscillate at the conductor. However, every particle which approaches the conductor is likely to discharge through the coating. If no effective means of trapping particles is present, the effect of the coating may not be permanent. Finally, any breakdown will, as noted, puncture the coating. The usefulness of conductor coatings is therefore suspect.

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Manuscript received February 17, 1977.

M. Abdel-Salam (Faculty of Engineering, Assuit University, Assuit, Egypt) and Kh. Ali (Ministry of Irrigation, Cairo, Egypt): The authors should be commended for their experimental estimation of dc dielectric strength in SF_6 gas-insulated system.

For the completeness of the information reported in this paper, we would like the authors to give comments of the following:

1) Berg and Works[1] previously analysed the effect of positive impulses superimposed on positive dc voltage and found that the impulse ratio in SF_6 may be as low as one half. Would the authors give an explanation why their study was restricted to superimpose impulses to dc bias voltage of reverse polarity? Are the authors recommend the testing of CGI systems by superimposing impulse on dc bias voltage having either the same or reverse polarity?

2) What will be the effect of impulse superimposition on dc bias voltages of the same and reverse polarity if the dimensions of the gap or the gas pressure yields for the breakdown to take place unpreceded by corona.

3) The dimensions of the rods used in the epoxy cast gap need to be stated.

4) It is very helpful to include also in Figs. 3 & 4 the positive impulse breakdown voltages. Hence, what is the corresponding positive impulse ratio?

5) The method by which the theoretical limiting voltage of Fig. 3 was estimated needs some clarification.

6) In Fig. 5a, one curve indicates the positive and negative dc breakdown voltages, and second indicates the 50 Hz peak AC breakdown voltage. The third curve may appear to express the theoretical limiting breakdown voltage. The author's hint in this regard is appreciated.

7) Are the authors aim to denote the dc 30 second breakdown voltage mentioned in the text as the short duration dc dielectric strength in conclusion 3.

8) Conclusions 5 and 6 are only confined to the case of conical insulators.

9) We have developed a mathematical model II for computing the positive dc breakdown voltage of SF_6 gaps in divergent fields. The criterion obtained for breakdown voltage was formulated in the following equation:

$$\int_{0}^{x_{cc}} (\alpha - \eta)\, dx = Z \frac{r_c}{x_c}$$

where r_c is the radius of conductor in corona, x_c is the length of the enhancement zone around the hv conductor and Z is a constant whose value only depends on the gap geometry being 50 for coaxial cylinders and 150 for concentric spheres as well as rod-to-plane gaps. Applying this criterion to the case of coaxial cylinders given in the paper under discussion predicts positive dc breakdown voltages in agreement with present experimental values.

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Manuscript received March 2, 1977.

S. Menju and K. Takahashi: The authors appreciate the interest and comments of the discussors. At first the authors would like to give the following comments concerning the specific points made by Mr. S. A. Boggs.

(1) As the discussor points out, DC voltage distribution in gas and solid gap in series or along an insulator in gas admits of discussions.

The data concerning the DC breakdown of gas and solid gap in series and gas solid interface indicate that both the DC voltage distributions seem to be almost the same as the AC, since the breakdown voltages of gas and solid gap in series are increasing with gas gap spacing, as shown in Fig. 5 (b) and the negative breakdown voltages of conical insulators are almost the same as the AC ones, as given in Table 1.

The discussor suggests that corona at the spacers and corona stabilization which take place due to inhomogenity in resistivity of spacers, could cause the increase in the DC breakdown values. The authors, on the other hand, think that space charges could be formed by some conductive particles and accumulated on the spacers rather homogeneously. This would cause the increase in the DC breakdown voltages, since our molding technology is high enough to get the homogeneous volume and surface resistivity although macroscopically and hence local field intensification at the spacer could not be formed.

(2) Not only for AC but also for DC, mitigation of electric field along the insulator surface in the most important to get the spacer which has excellent insulating capability even under the moderate contaminated conditions. From this part of view, conical insulators are considered as one of the best spacers.

(3) The tested epoxy insulators are made of the same formation of cast resin as used for AC GIS. The embedded electrodes are previously treated just like those in epoxy cast products. The tested epoxy cast gaps, therefore, have not only good insulating capability, but also excellent thermal and mechanical capability. Namely the ideal dielectric strength of epoxy can not be realized, due to the compromise among them.

(4) The authors fully agree with Mr. Boggs' comment relating to surface coating in SF_6 insulated systems. But the authors consider that there exist some possibilities to use surface coating in GIS, in case that GIS is assembled in highly dust-controlled room or in case that free conductive particles are effectively trapped.

The following comments are concerning the points made by Mr. M. Abdel-Salam and Mr. Kh. Ali.

Manuscript received April 26, 1977.

(1) Berg and Works investigated the effect of space charge on electric breakdown of SF6 in needle to plane gap. In their investigation corona is present already at the lower DC voltage stress due to the extremely nonuniform field. Space charges made by corona strongly influence the successive impulse breakdown voltage. On the other hand, in slightly nonuniform fields, such as in a coaxial cylinder field, positive impulse superimposed on positive DC voltage is considered to be nearly equal to the breakdown value by positive impulse alone, since DC voltage stress at lower level can not form space charge. Positive impulse stress superimposed on negative DC would rather be more severe for insulators, because the voltage swings from minus DC to plus impulse. As concluded in the paper, the authors recommend to conduct only the DC and impulse testing of GIS systems independently.

(2) If DC bias voltage stress is low, no marked effect on impulse breakdown is found in nearly uniform field, but small quantity of free conductive particles may exist in gaps which are assembled in laboratory clean conditions of floating dusts $\leqslant 0.12 mg/m^3$. Such particles would form some space charges, which may be accumulated on the insulator surface. This would affect the impulse breakdown voltage to some extent.

(3) The dimension of the embedded electrode used in the epoxy-filled gap is given in Fig. 2 (a).

(4) Positive impulse breakdown voltage can be calculated by the critical breakdown stress of (Ecrit) $PI = 78\ P + 11$ kV/cm ($1 \leqslant P \leqslant 4$ kg/cm^2 abs). (1)

(5) The theoretical limiting voltage is calculated by the limiting value of breakdown gradient $E_{lim} = 86.1 \cdot P$ kV/cm (P : kg/cm^2), below which no sparking should be possible, neglecting the avalanche length.

(6) Please see the revised caption for Fig. 5(a).

(7) Yes, the authors do.

(8) They would be applied not only to the case of conical insulators but also to the case of post and disc type, because DC operating stress is much lower than the breakdown voltage stress.

(9) A mathematical model proposed by the discussors is very interesting and the authors expect that the more details will be published.

REFERENCE

[1] Kawaguchi, Sakata and Menju: Dielectric Breakdown of Sulphur Hexafluoride in Nearly Uniform Fields, IEEE PAS Volume PAS-90 No. 3, May/June 1971.