REVIEW

SURFACE FLASHOVER OF SPACERS IN COMPRESSED GAS INSULATED SYSTEMS

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ABSTRACT

The spacer surface in a compressed gas insulated apparatus constitutes the weakest electrical location in the system. Discharges originating at the spacer-gas-electrode interface and the electric field distortion at the spacer surface may cause surface flashover. The presence of water vapor, conducting particles, and other contaminants may alter the flashover characteristics of the spacer. This paper reviews the various types of spacers used in gas-filled systems. The flashover performance of spacers under contaminated conditions is also evaluated. Further areas of work on the flashover of spacers are proposed in order to obtain a better understanding of the mechanism of flashover and towards the design of an efficient and reliable compressed gas insulated system.

1. INTRODUCTION

1.1 *Introduction*

The high voltage conductors in a compressed-gas insulated apparatus are supported by solid insulators called spacers. In general, the spacer-gas interface constitutes the weakest electrical location in the system. Microdischarges originating at the spacer surface due to high electric stresses can cause a surface flashover of the system. The presence of water-vapor, free and fixed conducting and non-conducting particles of various shapes and sizes, and decomposed gases resulting from arcing or discharges alters the flashover characteristics of the system. The performance of spacers in a contaminated environment also varies in different gases at various pressures.

Spacers are employed in bushings, circuit-breakers, sub-stations and compressed-gas-insulated transmission (CGIT) lines. The coaxial electrode geometry is widely used in these gas insulated systems. The maximum electric stress $\overline{E}_{max}$ acts at the inner conductor surface and is given by

$$|\overline{E}|_{max} = |\ \overline{E}\ (a)\ | = \frac{U}{a\ \ln(b/a)} \qquad (1)$$

where a is the radius of the inner conductor, b is the inner radius of the outer conductor, and U is the applied voltage.

The electric field is a minimum for the case when $b/a = e = 2.71$. Due to practical considerations, the ratio of the inner radius of the outer conductor to the radius of the inner conductor is varied between 2.5 and 3.0. In addition to coaxial geometries, other geometries tested in the laboratory are the plane-plane and the rod-plane configurations. These configurations are usefully employed to aid understanding the flashover mechanism in gases.

Various spacer profiles have been developed, using numerical field calculation techniques to reduce the electric stress acting along the spacer surface. These electric stresses can be reduced further by the use of a spacer material of low dielectric constant.

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A brief review of surface flashover was published by Cookson [1] in 1970. Since then, about 27 gas-insulated systems have been brought into commission and tests are being conducted into the 800 and 1200 kV prototype systems [2]. Flexible cables [3] as well as cables with semi-prefabricated units [4] are also being developed. This paper reviews the various types of spacers used in CGIT systems and their surface flashover performance especially in the presence of conducting particles.

1.2 *Gas Insulation and Spacer Geometries*

In recent years, SF_6 has been commonly used as gas insulation in CGIT systems. The SF_6 gas pressure normally used in these systems [5] is around 440 kPa. This is because a further increase in gas pressure causes a relatively small increase in the dielectric strength for a clean system. But for systems containing free and fixed conducting particles, an increase in the gas pressure above 440 kPa could also cause a reduction in the dielectric strength [3]. This reduction in the breakdown voltage depends on the location and size of the particle contaminant. In spite of the excellent electrical properties of SF_6, chemical stability and non-toxicity, it is sensitive to contamination, has a high boiling point, and is relatively expensive as compared to other common gases like N_2 and air. In search for an alternate gaseous dielectric for CGIT systems which has most of the advantages of SF_6 but fewer of the above-mentioned disadvantages, other gases like CCl_2F_2, C_4F_6, CF_3CN, etc. [6,7], and mixtures of SF_6 with these and other more common gases like N_2, air, CO_2 etc. have been investigated. This is discussed separately in a review on the subject [8]. It is anticipated that a 50% SF_6-air mixutre [3,9] at 540 kPa or a 50% SF_6-N_2 mixture [2,3,10,11] at 500 kPa will be used for 1200 kV systems. Circuit breakers containing 50% SF_6-N_2 mixtures have already been brought into commission [10]. These breakers offer advantages over those employing pure SF_6 in terms of the recovery voltage capabilities [12,13].

Using field calculation techniques [14], various spacer shapes have been developed in recent years. Cylindrical and corrugated-cylindrical shapes have also been tested frequently in the plane-plane and rod-plane geometries. For the coaxial-field geometry, the post-type spacer is normally used for the single-phase and three phase systems, while the disk-type spacer, the cone-type spacer and the multiblade-type spacers are used in the single-phase systems. Examples of some commonly used spacers are shown in Fig. 1. These spacers are separately discussed in Section 2.

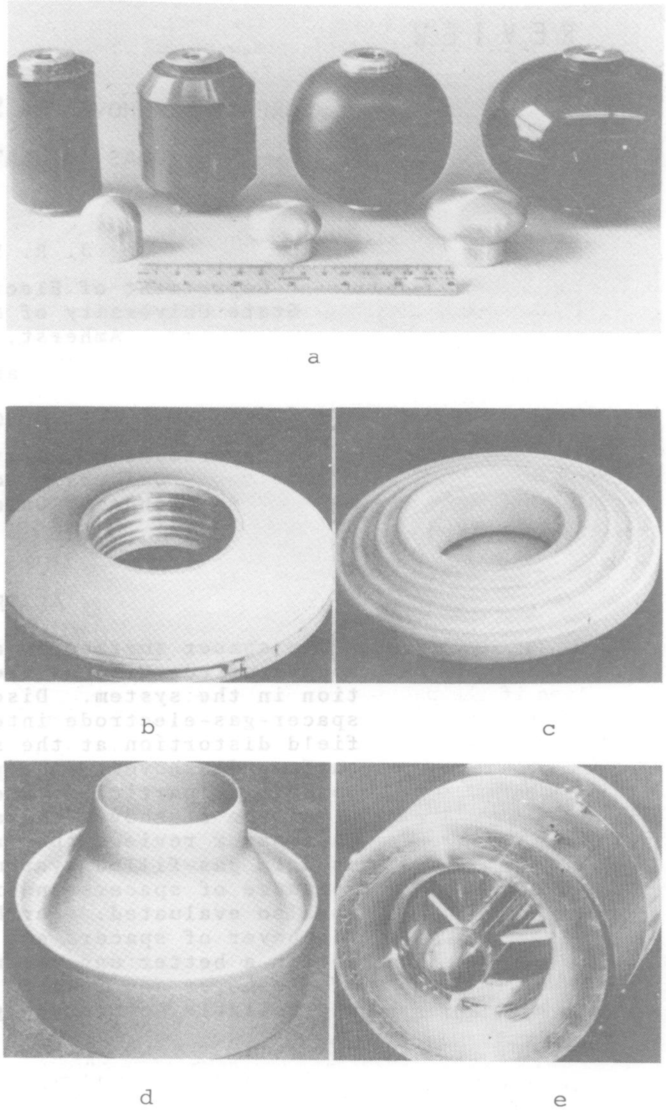


Fig. 1: Some commonly used spacers in compressed gas insulated systems. (a) Post-type spacers with insert shapes (b) Smooth disk-type (c) Corrugated disk-type (d) Cone-type (e) Trefoil-type.

1.3 *Spacer Material*

Various spacer materials have been tested and used in actual systems. These include porcelain [15-17], thermoplastics [15,18-27], and various epoxy resins [2-5,9-11,28-52].

The dielectric constant of the spacer material is an important property to be considered besides its dielectric strength, long life at power frequency, arc resistance, volume and surface resistances, performance at elevated temperatures, chemical stability in SF_6, and its mechanical strength.

The dielectric constant of the spacer material is important because spacers with a high dielectric constant having surface irregularities such as a depression may strongly distort the electric field acting on its surface [30]. A high dielectric constant also results in an increased local field at a particle on the spacer surface. Microdischarges can initiate at lower applied fields, reducing the breakdown voltage [18]. The electric field at the spacer-electrode interface is also high if a spacer material of a high dielectric constant is used.

The surface and volume resistivity of the spacer is important because charges either originating from the spacer-electrode interface or introduced due to sparking or initiating from a particle on the spacer surface may accumulate on the spacer and enhance the electric field. A decrease in the surface resistivity facilitates the dissipation of any such trapped charges and thus reduces the enhancement of the local field [18].

Static charges also accumulate in the spacer material when stressed under direct voltages for an extended period of time [42]. This may cause enhanced electric fields at its surface. It is thus necessary for a spacer material to transmit or obstruct these charges so that the electric stress at its surface does not exceed the dielectric strength of the gas.

The arc-resistance performance of a spacer is important because under high energy discharges, the surface of spacer materials such as unfilled epoxy resins and Teflon(R) has been known to erode or carbonize [53-56]. Alumina-filled cycloaliphatic type and the Hydantoin type of epoxy resins have shown to have good resistance to carbonize under high energy sparks [55,57]. Alumina trihydrate (Al_2O_3 $3H_2O$) generally acts as a catalyst to react with the hydrocarbon fragments and conducting carbon formed under arcing to form carbon-monoxide and other volatile hydrocarbons and thus removes them. Wootten et al. [53] have developed a test method to determine the effect of high energy arcs on the flashover strength of spacers in compressed gases. This method has already proven its capability in the development of an epoxy resin that is extremely tract resistant [57].

Partial discharges cause deterioration of spacers made of synthetic material under high voltage stresses [58-60]. Even if the partial discharges are not detected during primary testing, they probably exist and lead to an accelerated failure of the spacer [60]. Differential expansion between the spacer material and the metal conductor also presents a problem, which can lead to internal cavities. It is therefore extremely important for a spacer material to be highly resistant to the effects of these discharges which may occur either on the surface of the spacer or within the internal gas cavities.

Porcelain has the disadvantage of being expensive and has a high dielectric constant. Teflon has a low dielectric constant but has poor arc resistance, especially when the discharge energy is sufficiently large. It is also relatively expensive. Polypropylene and polycarbonate are thermoplastics which deform at high temperatures and are also expensive. However, they may prove to be less expensive than cast epoxy if produced in large quantities. Cycloaliphatic epoxy resin in conjunction with alumina as filler has the advantage of high tracking resistance and can withstand temperatures of up to 105°C which is useful for thermal expansion matching with the aluminum conductor, but has the disadvantage of having a high dielectric constant and a short life to partial discharges in SF_6. Investigations for a suitable spacer material are still being conducted [44] and a spacer material (Hydantoin) has been developed and tested [2,3,10,57] which is relatively less expensive, has a low dielectric constant and a high operating temperature of up to 150°C. Hydantoin is being considered for possible use in flexible cables and the UHV systems. However, it has to be extensively tested in various gases under normal operating conditions.

Presently, epoxy resins are widely used as spacer material for the post-type, cone-type and disk-type of spacers while polycarbonate, polypropylene and Teflon are used for the miltiblade-type of spacer employed in flexible cables.

1.4 *Type of Voltage Applicati*

The performance of the spacer is different under direct, alternating and impulse voltages. Under direct steady-state voltages, the resistivity of the spacer material determines the field distribution, whilst under alternating and impulse voltages, the field distribution is capacitive [39]. The performance of spacers under various types of voltage application is especially different in a particle-contaminated environment. This is because the movement of free particles is different under the three types of voltage application [37]. Even in the case of fixed particles, the polarity and type of voltage will determine the flashover characteristics.

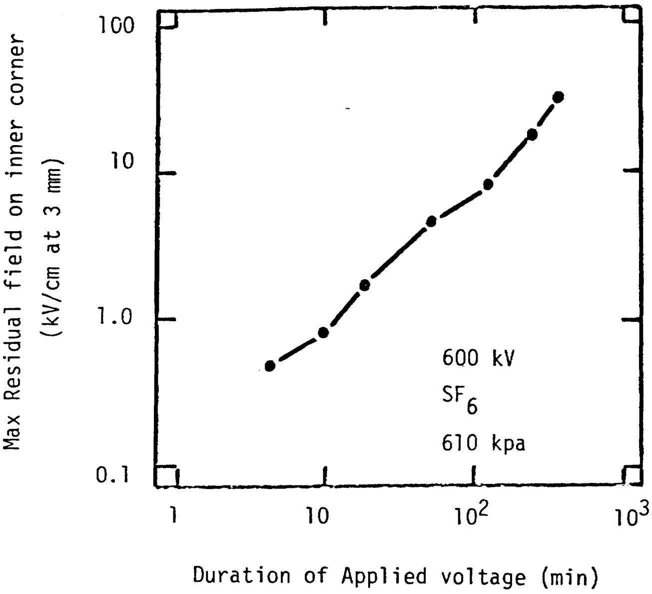


Fig. 2: Residual field due to volume charging on the surface of a post-type spacer subject to direct stresses [42].

Under direct voltages, the time constant of the redistribution of potential on the spacer surface is very large [39]. Volume charges may accumulate in the spacer when stressed under dc for extended periods of time. Fig. 2 shows [42] how the maximum residual field at the inner corner of a post-type spacer is varied with a constant 600 kV voltage applied from durations of 5 minutes to 3 hours in SF_6 at a pressure of 610 kPa. These results show that the amount of this "smooth charging" depends upon the length of time the field is maintained. It also depends on the magnitude of the applied voltage [42]. The field distribution in the vicinity of the spacer is modified and electrical breakdown in the surrounding gas may then result [42]. Charged spacers are also a problem, because they may attract the contaminating free particles present in the system, causing excessive stresses, or promote long-term failure by stress enhancement.

The breakdown voltages in the presence of a conducting particle on the spacer surface are generally lower under direct voltages as compared to alternating or impulse voltages under similar conditions. Sufficient investigations to determine the flashover capabilities of a spacer under direct voltages are therefore necessary. Spacer materials still have to be developed which are suitable for dc transmission systems.

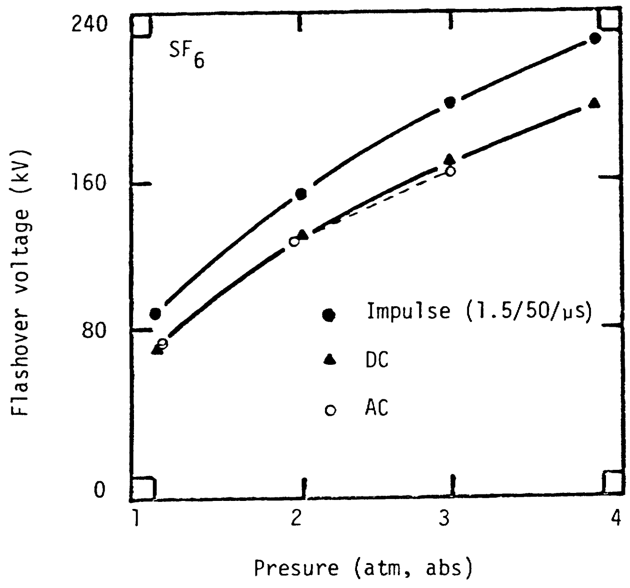


Fig. 3: The uniform field flashover voltages of a 10 mm cylindrical spacer under ac, dc and impulse voltages [39,51].

The direct flashover voltages of a clean cylindrical epoxy resin spacer in compressed SF_6 under a uniform field are shown [51] in Fig. 3. This was obtained with a rapidly applied voltage. A comparison of these results with those obtained by Nitta et al. [39] under alternating voltages shows a reasonably good agreement up to SF_6 gas pressures of about 3 atmospheres. One advantage of testing spacers under alternating voltages is that the volume charging of the spacer is quite negligible.

Under impulse voltages, the flashover voltages are usually higher as compared to those under direct or alternating voltages when tested under similar conditions. This is shown in Fig. 3 under conditions of a uniform field. In non-uniform fields, such as in a coaxial system, the performance under impulse voltages may vary depending on the polarity of the high voltage conductor, spacer shape, and the conditions investigated. For example, clean Trefoil-type of multiblade spacers [26] have a higher flashover voltage for positive polarity than for negative polarity. The same spacers under contaminated conditions have a lower breakdown voltage for positive polarity than for negative polarity.

It is therefore very difficult to predict the performance of spacers under the type of voltage application, because the flashover will depend on the spacer shape, the voltage polarity, the type, size, and location of particle contamination and the stress level. Care should therefore be taken to identify the type of voltage used when evaluating the flashover performance of the spacers.

1.5 *Shielding Electrodes and Inserts*

The electric field in the vicinity of the spacer is controlled by the electrode geometry, the spacer profile, and the dielectric constant of the spacer material [30]. Significant field intensification can occur at the spacer-gas-electrode triple juntion if the cohesion between the spacer and the electrode is inadequate. This can lead to a reduction in the flashover voltage [17].

To avoid this, the most effective way is to provide the spacer with a shielding electrode. This shielding electrode works to reduce the electric field at the triple junction, as well as at the electrode and spacer surfaces. Menju et al. [29] found that with a smaller angle of inclination of the cone-type spacer, the potential gradient along the surface is reduced. However, it increases the maximum potential gradient on the high voltage conductor. A shielding electrode, when used, can reduce this high field on the conductor surface.

Metal inserts are also employed to modify the electric field at the spacer surface to a more favorable distribution [30]. However, they increase the electric stresses within the spacer, so that the breakdown strength of the spacer material may be exceeded by improper design. The insert and spacer material must also have thermo-mechanical compatibility and maintain intimate contact throughout the life of the spacer. This is to reduce the effect of partial discharges at the sapcer-electrode interface.

Shielding electrodes are normally used with the disk-type and cone-type spacers, whilst inserts are useful in reducing the electric stresses at the surface of the post-type spacer. However, multiblade-type spacers do not require the use of shielding electrodes or the inserts.

2. SPACER PROFILES

2.1 *Cylindrical Spacers*

The simplest spacer shape that has been tested is the cylindrical spacer [15,18-22,39,46-55,61]. For spacers of this geometry placed in uniform fields, the controlling factors for the flashover voltage are the degree of contact between the spacer and the electrode [1,17,18,21,62] and the surface condition of the spacer [39,51,63].

The electric field in a small gas gap due to imperfect contact between the spacer and the electrode is equal to the product of the average stress and the dielectric constant of the spacer material [21]. If the width of the gas gap is d_1, the length of the spacer is d_2, and the relative dielectric constant of the spacer material is ε_R, then the electric field E_g in the gas gap is given by

$$E_g = \frac{\varepsilon_R U}{d_2 + \varepsilon_R d_1} \simeq \varepsilon_R \frac{U}{d_2} \qquad \text{for } d_2 >> d_1 \qquad (2)$$

where U is the applied voltage and ε_R is small. Accordingly, corona starts in this gap at a relatively low voltage. The voltage V_i required to start discharges in the gas gap is given by [64]

$$V_i = V_d \left(1 + \frac{d_2}{\varepsilon_R d_1}\right)$$

where V_d is the sparking potential of the gas gap.

The electric field in the gas gap and the discharge inception voltage therefore depend on the dielectric constant of the spacer material, the degree of contact with the electrode, and the type and pressure of the gas insulation used [51]. For gas gaps less than 200 μm, a perfect contact between the spacer and the electrode is not considered to be essential [21]. For example, it is found that in N_2 at a pressure of 1.8 MPa, gaps of less than 80 μm do not influence the flashover voltage.

In a similar fashion, surface imperfections or voids can cause regions of higher electric stresses. Discharges originate at an imperfection, a conducting particle at the spacer surface, or at an imperfect contact at the spacer-electrode interface. These may easily develop into a streamer and trigger the breakdown of the main gap. On the other hand, the charged particles may also accumulate on the spacer surface and further enhance the local field and the ionization processes which could also lead to the development of the flashover channels.

Therefore, under uniform fields, the value of the flashover voltage along the spacer surface is lower than the corresponding breakdown value of the gas gap without the spacer. The spacer efficiency [46] is generally less than unity. However, a recent work by Gallagher and Pearlman [61] has reported spacer efficiencies greater than unity under uniform field. This discrepancy has to be clarified and therefore comparative studies under similar conditions are necessary.

Corrugated spacers have also been tested. Corrugations have been reported to both increase as well as decrease the flashover voltage [21,65-71]. The increase in the field strength between corrugations is by a factor of 2 rather than ε_R, as is in the case of a surface defect or void on the spacer surface [18]. Ikeda [72] reported that corrugations show satisfactory performance under contaminated conditions. Trump et al. [18] found that the advantages of using corrugations became considerable at higher pressures. Corrugations provided shielding effects against discharges emitted at the spacer-electrode interface and this more than compensated for the field distortion and increased field intensity caused by the corrugations. The final flashover was observed to glide over the tips of the corrugations. It has also been observed to follow the spacer surface [30]. The spark trajectory, therefore, depends on the spacer profile, the dielectric constant of the spacer material, the type and pressure of the gas used and the electric field. It usually appears preferable to terminate the spacer at the depression in the corrugated spacer, so that the nearest corrugation may act as a space charge shield. The use of a corrugated spacer is more advantageous if a spacer material of a low dielectric constant is used.

Cylindrical spacers have also been tested under non-uniform fields such as a rod-plane [22,46,52,73] and a rod-rod configuration [63]. The spacer efficiency was found to be greater than unity for certain regions of the gas pressure and type of gas used. This was ascribed to the obstruction in the corona-stabilization processes caused by the spacer bridging the non-uniformity [52]. However, further work in explaining the increase in the spacer efficiency is necessary towards a better understanding of the flashover phenomenon under non-uniform fields.

2.2 *Disk-Type Spacer*

Disk-type spacers have been frequently used in CGIT lines because of their simple geometry and because they occupy less space in the gas-insulated system as compared to the cone-type spacer [3,16,17,23-25,28,33,34, 41,43,74,76]. The variations in the disk-type spacer which have been used are the split disk [3], the doughnut-shaped [16], and the corrugated disk-type [23].

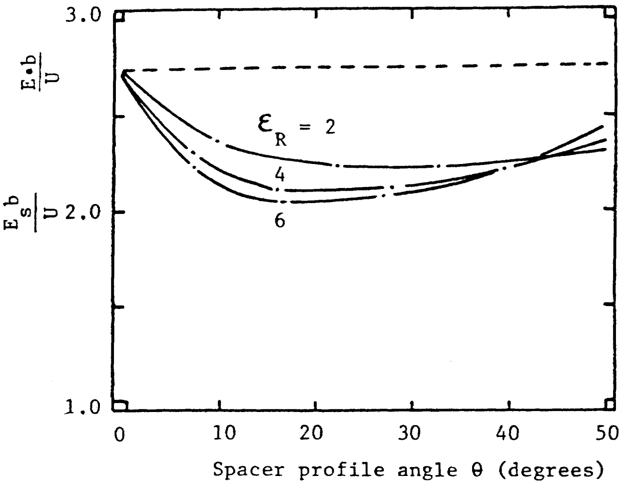


Fig. 4: The normalized electric field strength on the surface of a disk-type spacer as a function of the spacer profile angle θ. The values of the relative dielectric constants of the spacer material is given in the figure. E_s is the maximum field on the spacer surface near the inner electrode. E is the maximum field in the coaxial with the spacer. U is the applied voltage, a is the radius of the inner conductor, b is the radius of the outer conductor (a/b = 1/3) [25].

Optimal profiles for the disk-type spacers were determined by Takuma et al. [25]. The normalized electric stress as a function of the spacer profile angle θ is shown in Fig. 4 [25]. The spacer profile angle is the angle between the spacer surface and the direction of the electric field. It can be seen from the figure that the optimum spacer profile angles are 30°, 20°, and 20° when the dielectric constants of the spacer materials are 2, 4 and 6 respectively, and the ratio of the radius of the inner conductor *a* to the outer conductor *b* is *a/b* = 1/3. The maximum electric field strength in the presence of the spacer decreases to 70 to 80% of that of the coaxial system without the spacer or with a disk spacer of θ = 0°. The spacer profile angle also depends on the ratios of the radii *a/b*. θ is found to be larger for *a/b* = 1/4 and smaller for *a/b* = 1/2.

Vandermeeren [77] showed that an optimal disk-type spacer performs better than a spacer of other geometries such as cone-type spacer. For this optimal type, a spacer material with a high dielectric constant could also be used without any significant reduction in the breakdown voltage.

Clean disk spacers have a higher flashover voltage on positive impulse than on negative polarity, but for contaminated spacers, the positive impulse flashover voltage is reduced much more than the negative breakdown voltage [24]. However, in the presence of contamination, corrugated disk spacers show a more consistent performance than that of a smooth disk, particularly for impulse voltages. Under alternating voltages, the flashover level is reduced by 20% as compared to impulse levels [23].

Eteiba et al. [76] found that a fixed wire shaped conducting particle near the central conductor and oriented radially along the disk spacer interface was most effective in reducing the flashover voltage under impulse voltages. This was because the effective gap between the electrodes was considerably reduced.

Disk-type spacers are especially necessary for gap-stop joints in a CGIT line [77]. The split-disk spacers are under consideration for use in the flexible gas cables which are presently under developemtn [2,3].

2.3 *Post-Type Spacers*

The post-type spacer was introduced by Cooke and Trump [30] because of its basic simplicity in design and economy, especially at UHV for CGIT lines. Because of the large size of the UHV system, the use of post-type spacers offers a considerable economic saving over the more massive disk or cone-type spacers [79]. Various combinations of inserts and spacer shapes are used as shown in Fig. 1. The inserts help to reduce the electric stresses at the spacer-electrode interface. The flashover characteristics of such spacers could be further improved by small changes in the spacer shape near the spacer-electrode interface [74, 79].

Another advantage of using post-type spacers is that under contaminated conditions, less attachment area is exposed to the particles compared to the disk-type or cone-type of spacer, and therefore the probability for conducting particles to hop onto the spacer and cause flashover is also reduced.

Investigations by Cooke et al. [30] on the corrugated post-type spacers showed that under direct voltages, the corrugations reduced the performance of spacers in compressed gases, but Cronin and Perry [23,80] performing similar tests under ac showed that corrugated spacers performed better under contaminated conditions. Cooke [37] found that even under direct voltages in the presence of contamination, the systems performance could be relatively improved by employing post-type spacers. He concluded that an increase in the path length did not necessarily increase the contaminated spacers strength. Spacer surface profile should be such as to avoid high stress regions where an elongated particle can reside.

Johnson et al. [81] found that corrugated post-type spacers of a high dielectric constant reduced the flashover voltage by 20%, and so the use of a material with a low dielectric constant should help to reduce the electric field distortion produced by the corrugations.

Tripost-type of spacers with a low dielectric constant are planned to be used in a prototype 1200 kV system [2]. Currently, they are used in the single-phase and three-phase CGIT lines [3]. The post-type spacers are also being considered for use in CGIT lines employing semi-prefabricated units [4].

2.4 *Cone-Type Spacers*

Cone-type spacers have been frequently used in single phase CGIT lines and are useful especially as gas-stop joints [2,3,4,29,82]. One of the disadvantages of employing cone-type spacers is that they occupy more space as compared to the disk-type or the post-type spacer.

Menju et al. [29] calculated the electric field and potential distribution around a cone-type spacer and found the optimum profile for the spacer. Fig. 5 shows [29] the maximum potential gradients as a function of the angle of inclination which the spacer surface makes with the high voltage conductor. If the angle of inclination is small, the potential gradients along the surface of the cone-type spacer becomes lower. However, the choice of a small angle of inclination results in a higher maximum potential gradient on the high tension inner conductor. Hence, a compromise is necessary to obtain lower stresses on both the surface of the spacer and the inner conductor. Good results have been obtained by equating the maximum resultant spacer field with the conductor field [30, 83]. An angle of inclination of 45° appears to be optimum to use in CGIT lines [29]. The breakdown characteristics of the cone-type spacer tested in SF_6 at 360 kPa for dc, ac, lightning and switching impulse voltages are given in Table 1 [36]. It is noticeable that the negative dc average breakdown voltage is nearly equal to the ac crest and the switching impulse values. For this reason, the cone-type spacers could be considered for use in dc transmission systems.

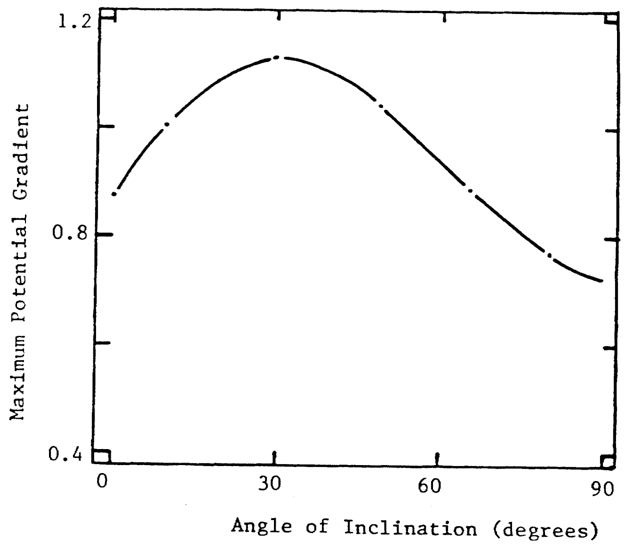


Fig. 5: Maximum potential gradient on the surface of the inner electrode as a function of the angle of the inclination of a cone-type spacer [29].

Cone-type spacers are also more capable of withstanding contamination than disk-type spacers [29]. Under contaminated conditions, they give a higher flashover voltage on positive impulse than on negative impulse. The convex side of the spacer is more affected by the conducting particles of the contamination than the concave side [23].

Corrugated cone-type spacers have been successfully employed in a 420 kV bus at Wehr, West Germany [82] and are also amongst those recommended for use in cables with semiprefabricated units [4].

2.5 *Multiblade-Type Spacer*

Multiblade-type spacers were first proposed by Hampton et al. [26] using 2, 3, or 4 blades for use in flexible cables or those employing stranded conductors [4]. The conductor is replaced by 2 or more separate subconductors and the spacer protrudes between them. The sub-conductors are at the same potential.

TABLE 1

Breakdown voltage of a cone-type spacer at 360 kPa pressure of SF_6 for dc, lightning impulse switching impulse and ac voltages [36]

Polarity	DC		Lightning Impulse		Switching Impulse		AC (peak)		DC Gas Gap
	Breakdown Voltage (%)	Average Breakdown (%)	Breakdown Voltage (%)	Average Breakdown (%)	Breakdown Voltage (%)	Average Breakdown (%)	Breakdown Voltage (%)	Average Breakdown (%)	Average Breakdown (%)
Positive			98						
	112		102		98				
	98	102	102	102	98	101	88		119
	98		104		95		89	89	
Negative	84		98		87				
	84		101		75				
	84	85	98	100	95	87	89		77
	87		102		80				
			101						

Fig. 6 shows [26] that the maximum surface stresses for 2, 3, or 4 bladed spacers are approximately 50, 60, and 65% of that for a plain disk-spacer. Another advantage of this spacer is that the field at the conductor-space interface makes the breakdown voltage independent of the small gaps between the spacer and the conductor. Banford [27] showed that a three-bladed spacer (Tre-foil) relatively gave a good performance under contaminated conditions.

The multiblade spacers will be used for the flexible CGIT line presently under development in Europe [3,26].

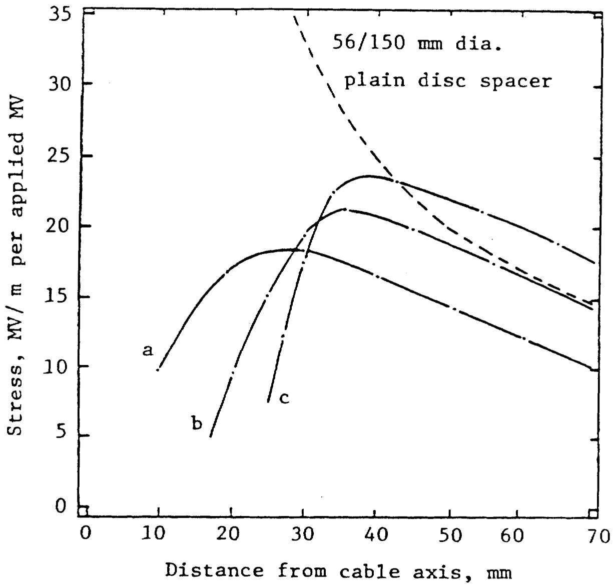


Fig. 6: Stress distribution on a multiblade-type spacer (a: 2 blades, b: 3 blades, c: 4 blades). Sheath diameter = 150 mm, subconductor diameter = 32 mm [26].

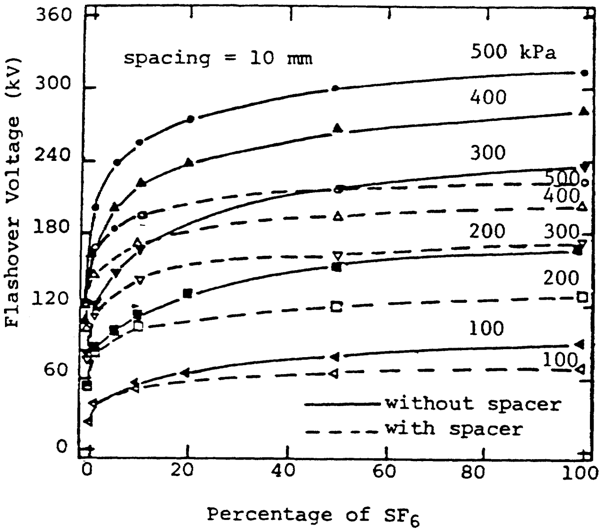


Fig. 7: Direct flashover voltages for a 10 mm cylindrical spacer in SF_6-N_2 gas mixtures in a uniform field [46].

3. GASES IN CGIT SYSTEMS

Flashover investigations have been carried out in the common gases like CO_2 [19], air [22,25], and N_2 [15,18-21,84,85]. Spacers have also been tested in electronegative gases like CCl_2F_2 [15-17] and in SF_6-gas mixtures [46-52,76,86]. However, most of the work in the references is confined to pure SF_6.

SF_6-gas mixtures have been widely investigated for use in CGIT lines because they offer certain advantages over pure SF_6. This can be found by referring to a review on the subject [8]. SF_6-N_2 and SF_6-air gas mixtures are anticipated to be used for the 1200 kV system [2,3]. However, most of the surface flashover work in gas mixtures reported in the literature has been done by the authors [46-52].

Fig. 7 shows [46] the surface flashover voltages of a cylindrical epoxy resin spacer in SF_6-N_2 gas mixtures in a uniform field. It can be seen that the addition of small amounts of SF_6 to N_2 can greatly increase the breakdown voltage both in the absence and presence of the spacer. However, with larger contents of SF_6 in SF_6-N_2 mixture and at higher pressures, the surface flashover voltage in the presence of the spacer is much lower than the breakdown voltage without the spacer. In the presence of the spacer, the breakdown voltage of a 50% SF_6-N_2 mixture is about 90% that of pure SF_6. These results are significant in the sense that 50% SF_6-N_2 mixtures can be used instead of pure SF_6 in systems employing spacers without much deterioration in their withstand ability.

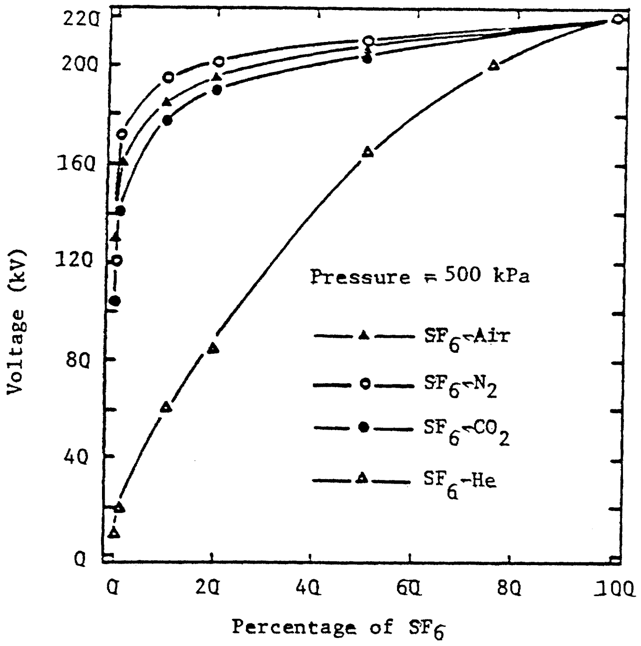


Fig. 8: Direct flashover voltages for a 10 mm cylindrical spacer in SF_6-gas mixtures in a uniform field [49].

The comparison of the surface flashover voltages of various SF_6-gas mixtures in the presence of a spacer is shown [49] in Fig. 8. It can be seen taht SF_6-N_2 gas mixtures show superior surface flashover performance as compared to SF_6-air, SF_6-CO_2 or SF_6-He mixtures. Although SF_6-He gas mixtures have been reported to tolerate best the presence of free conducting particles [87], they have the lowest dielectric strength as compared to other SF_6-gas mixtures for the same amount of SF_6 in the gas mixture.

4. CONTAMINATION IN CGIT SYSTEMS

The contamination in a gas-insulated system may consist of free and fixed conducting particles, nonconducting particles, water vapor, and the decomposed by-products due to arcing along the spacer gas-electrode interface.

In systems without spacers, the dielectric strength is not affected by conducting particles unless they are large enough (>30 μm) to distort the field [32]. However, systems with spacers are more sensitive to contamination [39].

An important problem with spacers arises when conducting particles lie on the spacer surface and reduce the dielectric strength of the system. This happens under direct, alternating as well as impulse voltages. It is very difficult to predict the magnitude of this reduction as it depends on the stress level, the distribution on the spacer surface, particle shape and size, and particle location. Performance can be impaired severely especially if the particle is large enought or if small particles accumulate on or near the spacer surface.

4.1 *Free-Conducting Particles*

In the absence of the spacer, the free particles become charged and oscillate between the electrodes under the influence of the applied field. As a charged particle approaches an electrode, it loses its charge to the electrode through a gas microdischarge. One theory of breakdown is that this particle-electrode microdischarge generates region of high space charge to trigger the breakdown of the main gas gap [85].

Another theory holds that when a charged particle approaches a critically small distance from the oppositely charged electrode, the condition for the breakdown of this microgap may be satisfied, leading to a microdischarge. Such a discharge short circuits the microgap almost instantly and brings the particle to the electrode potential. The particle then acts as an extended protrusion in the main gas gap. Depending on the particle and gap dimensions and the gas pressure, the stress in the remaining gap may be sufficient for a critical avalanche and streamer formation leading to a breakdown [88].

However, in the presence of the spacer and under direct voltages the particles lift off the enclosure at very low stresses and proceed with high velocity to impact on the conductor and the spacer. Under positive polarity of the inner conductor in a coaxial system, the particles tend to accumulate on the spacer surface while under the negative polarity, they favor the conductor [11].

Corrugated spacers give a relatively better flashover performance in contaminated conditions as compared to spacers without corrugations. Fig. 9 gives the minimum spacer breakdown strength with four different types of post-spacers under direct voltages [37]. Gas gap breakdown and surface flashover voltages without contamination are shown as the dashed lines. When 6.4 mm long aluminum wire particles were added, the surface flashover occurred over a broad range of voltages. The two spacers shown on the left in the Figure generally failed at lower voltages than the two spacers shown on the right.

With the Trefoil spacer and direct applied voltages, the spherical particles moved back and forth between charged electrodes, picking up a charge by contact at one electrode and transferring it to the other electrode and receiving an opposite charge [27].

Bouncing particles could readily move to and stay on the post-type spacer under direct voltages [37]. This behavior was more notable in the presence of residual charges and voltage gradients on the spacer surface. Fireflies [37,85] were frequently seen approaching the vicinity of the spacer and then moving away without touching or hopping onto the spacer surface. Particles which eventually move to more sensitive areas such as high-field regions on the electrode or spacer surfaces may ultimately reduce the insulation strength of the system. On the other hand, movement of a particle to a less sensitive region could also result in an improved insulating strength.

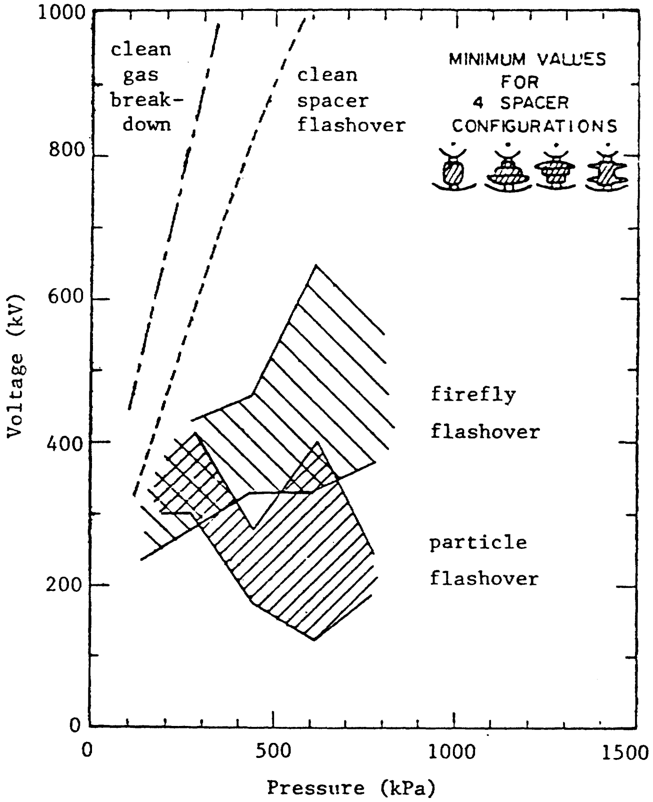


Fig. 9: Direct flashover voltages for four types of post-spacers with 6.4 mm wire particle contamination in SF_6 [37].

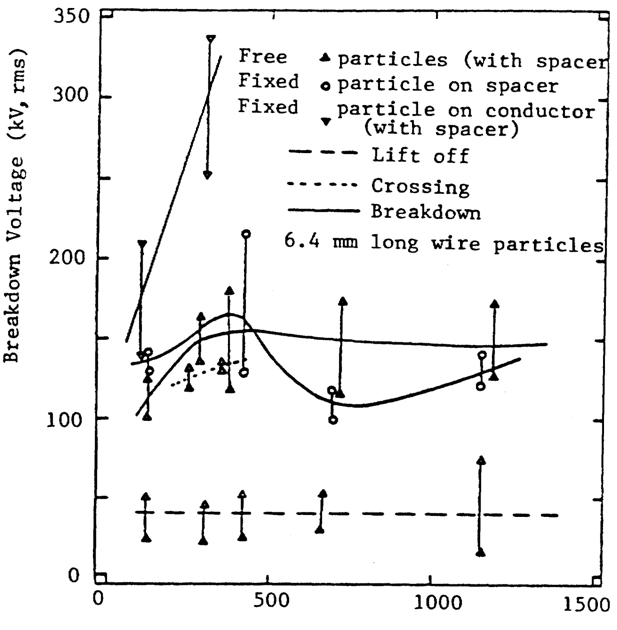


Fig. 10: Lift-off and crossing voltages for free particles and breakdown voltages for free and fixed particles in a SF_6-filled 76/250 mm coaxial system with a post-type spacer [9].

Flashover characteristics of a spacer very much depend on the site where the contaminating particles are located. For example, in a cone-type spacer, the convex side is more affected by contamination than the concave side [23].

Under direct voltages, insulating coatings on the electrodes do not prevent the conducting particles from moving from their initial position to either electrode [32]. But once there, they would remain stationary. This is because the particles cannot discharge at the insulated electrode and receive its charge of oppostie sign to drive it across the spacer surface.

Under alternating voltages and in the absence of the spacer, the crossing of the particle over to the opposite electrode is the criterion for gas breakdown. However, with spacers, the particle crossing criterion is not conclusive for breakdown. Voltage levels corresponding to the particle motion onto the spacer are important [35]. The particle may be deposited on its surface and remain there even if the voltage is raised. With several free particles in the system, usually the first particle depositing on the spacer surface is observed to cause a flashover. The minimum alternating breakdown voltage levels in such cases of a post-type spacer are within 10% of the direct breakdown voltages [5].

Figure 10 gives the lift-off, crossing and breakdown voltages [9] for 6.4 mm long, aluminum wire-shaped particles which are free to move in a coaxial system, as well as for particles fixed onto a post-type spacer and on the inner electrode. It can be seen that at SF_6 gas pressures below 500 kPa, the alternating breakdown voltages are the lowest for free particles as compared to fixed particles on the spacer or the electrode surface.

Kuwahara [32] showed that a small amount ($\sim$350 mg) of fine metallic powder ($<$ 30 µm) had little effect on the alternating breakdown voltage in a coaxial system without a spacer. However, Nitta [39] found them harmful to flashover along the surface of a cone-type spacer. Fig. 11 gives [39] the effect of the amount of copper powder on the alternating breakdown voltage of two systems, with and without the spacer. Under alternating voltages, they tend to form a bridge along the spacer surface thus reducing the breakdown voltage.

Banford [27] observing the movement of spherical particles on the surfaceof a Trefoil spacer under alternating voltages found them oscillating at a given spot on the spacer surface and adapting a random walk over the spacer blade, ending up at the electrode. With several particles oscillating furiously, they could collide with each other and end up in a trap ensuring a clean-up of the system. However, copper filings, after achieving a particular distribution on the spacer surface, would remain stationary.

Under impulse voltages, the spherical particles on a Trefoil spacer moved vigorously and a complete clean-up of the spacer was achieved. A certain degree of movement was also achieved with copper filings [27].

4.2 *Fixed Conducting Particles*

Fixed conducting particles may either be located on the spacer surface or may constitute an electrode protrusion. Breakdown is usually caused by field enhancement. The effect of a fixed conducting particle on the surface of a post-type spacer was shown in Fig. 10. Tests with the 6.4 mm long fixed particles for a 75 mm/250 mm coaxial geometry in the high-field region on a post-type spacer show that direct flashover voltages in SF_6 are up to 30% lower than the corresponding minimum alternating breakdown values at a pressure of 440 kPa. Under alternating voltages, the minimum flashover values are the same as those in the case of the free particles [5].

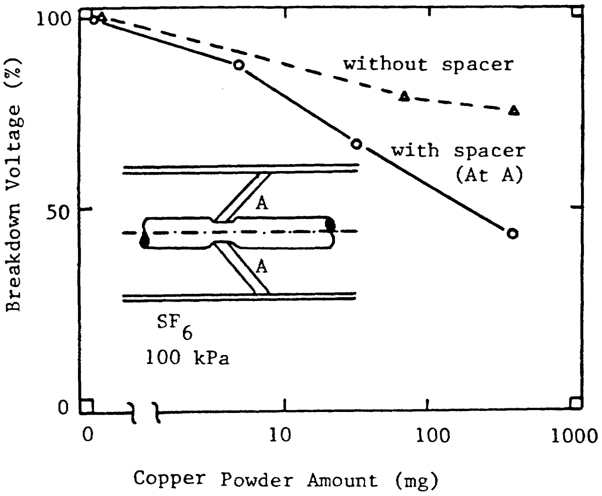


Fig. 11: Effect of amount of fine copper powder (< 30 μm diameter) on the alternating breakdown voltages of a coaxial system with a cone-type spacer [39].

The length of the fixed particle on the spacer surface has a profound effect on the flashover voltage. Fig. 12 [34] shows the effect of the length of fixed particles on the flashover voltage of disk-type spacers under alternating and impulse voltages at various locations on the spacer surface. The breakdown voltages are the lowest when the particle is fixed midway on the spacer surface between the electrodes. Under direct voltages, the values are substantially lower than those in the case of alternating voltages.

Pfeiffer and Völker [63] recorded the luminous phenomenon originating from a fixed particle on the spacer surface using a highly sensitive image intensifier. They found that a conducting particle at the spacer surface had a similar effect as a protrusion on the electrode surface. The discharge developed in the same manner as in a field distorted gas gap, and so the reduced electrical strength could be satisfactorily explained by this field distortion.

When the fixed particle constitutes an electrode protrusion, the breakdown voltages are substantially reduced in the absence of the spacer due to field enhancement. However, when a spacer is closely located, the breakdown voltage of this field-distorted gap is found to increase [48,50]. Fig. 13 shows the influence on the direct flashover voltages of a 1 mm protrusion on the surface of a plane electrode in various SF_6-N_2 gas mixtures as the distance between the protrusion and the cylindrical spacer is varied [48]. The authors ascribed the increase in the breakdown voltage to the reduction in the electric field at the tip of the protrusion as the distance between the protrusion and the spacer surface is reduced. Similar results were obtained for gas pressures up to 500 kPa, for both the polarities of the electrode protrusion in the presence of corona stabilized breakdown. Comparative studies are not available in the literature and further work would help in explaining the reported results.

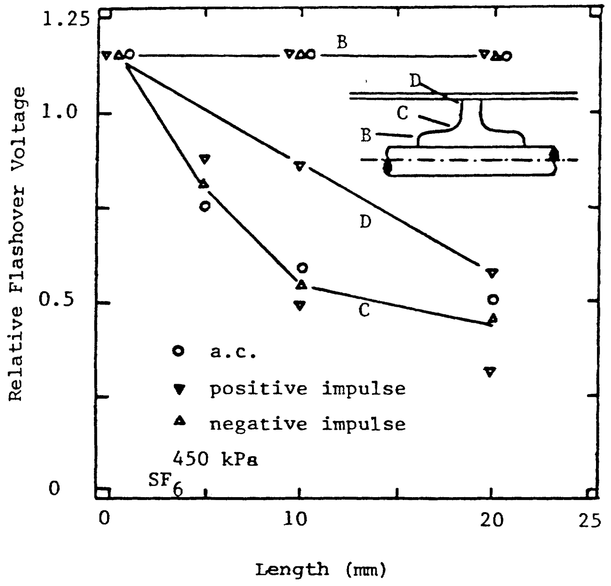


Fig. 12: Influence of the length of a copper wire on the flashover voltage of a disk-type spacer [34].

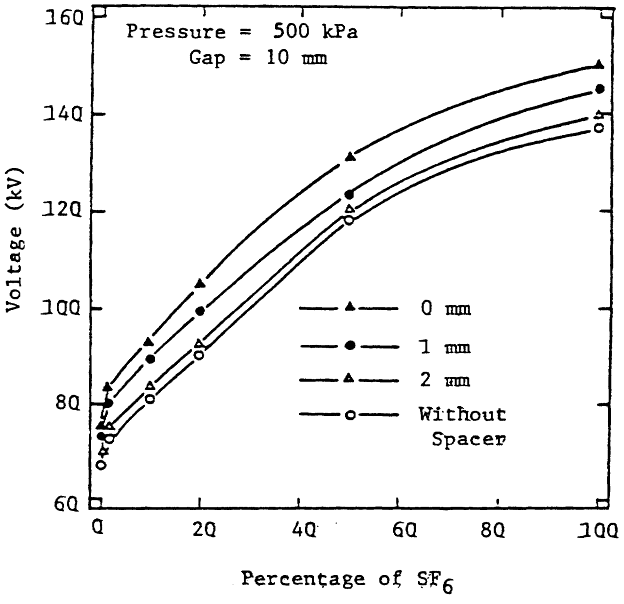
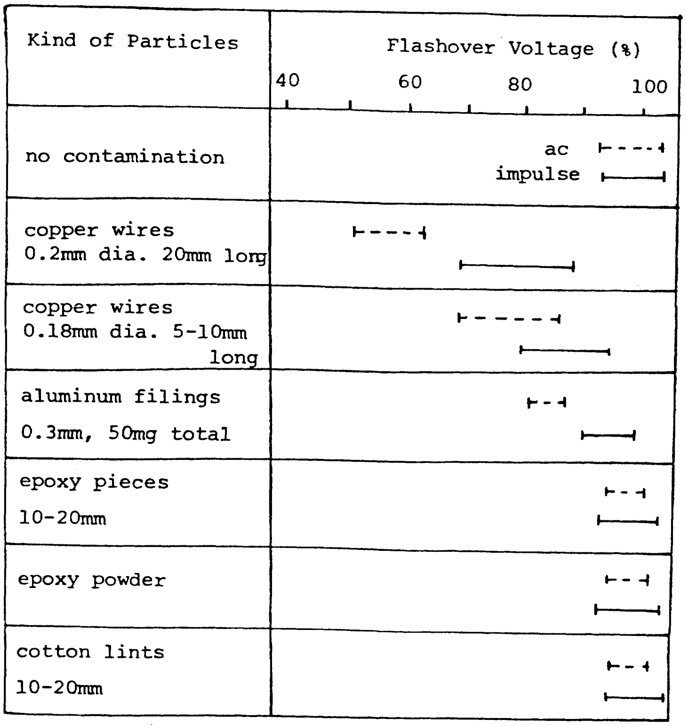


Fig. 13: Direct flashover voltages for a cylindrical spacer in SF_6-N_2 gas mixtures with a 1 mm protrusion on the negative plane electrode (Distance of the protrusion from the spacer surface is given in the figure) [48].

Under long term dc application, volume charges on a clean epoxy post-type spacer accumulate at a moderate rate, distribute uniformly, and are of the same polarity as that of the inner conductor in a coaxial system [42]. However, this charge accumulation is different in the presence of a fixed conducting particle on the spacer surface. Not only are there sharp peaks in charge intensity, corresponding to the particle position, but their polarity is also reversed. Steady and decaying currents are usually observed in the case of elongated fixed particles which eventually lead to breakdown [37].

TABLE 2

Effects of various kinds of particles on the flashover voltage of practical spacers at 300 kPa pressure of SF_6 [39]



4.3 *Non-Conducting Particles*

Nitta [39] showed that under similar conditions, the effect of insulating particles in reducing the flashover voltage of a coaxial spacer is less compared to that of conducting particles. These results are given in Table 2 [39]. When insulated fibers were used in the presence of a Trefoil spacer, no reduction in the flashover voltage and no movement of the fibers were observed under alternating voltages [27]. Under direct voltages, these fibers stuck to the spacer surface and did not move even when the applied voltage was incresed to breakdown. The spacer had to be wiped clean to remove them. Similarly, under impulse voltages, no movement of these particles was observed. However, insulating fibers in combination with fine conducting power can impair-the flashover performance [37].

4.4 *Water Vapor*

The presence of moisture is found responsible for a marked decrease in the flashover voltage of spacers [89,90]. However, Nitta [39] reported that the presence of moisture scarcely influences the breakdown voltage or the surface flashover voltage in SF_6, as long as no condensation takes place and the moisture remains completely in gaseous phase. If the spacer surface gets wet by the condensation of moisture, the flashover voltage decreases considerably. In practice, even if the surface of the spacer is dry initially, moisture can condense on it due to temporal changes in the ambient temperature and therefore the system will be liable to a drop in the flashover voltage [91-93].

Fig. 14 gives the effect of the surface temperature on the alternating flashover voltage of cylindrical spacers having various contents of moisture [39]. When the temperature is lower than 0° C, the flashover is almost equal to that in the dry condition. This shows that the water frosted on the spacer surface does not impair the flashover performance. The flashover voltage decreases when the ice melts as the temperature rises. Further temperature rise increases the flashover voltage towards the dry condition level because of the evaporation of the condensed water.

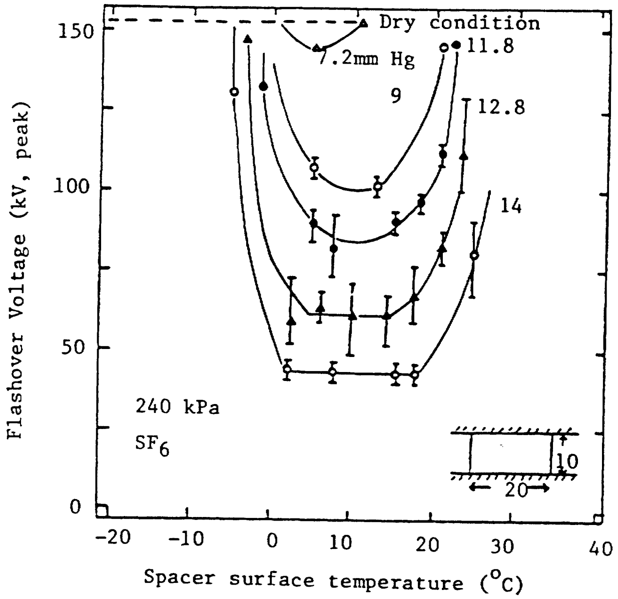


Fig. 14: Alternating flashover voltages as a function of spacer surface temperature with various water contents in SF_6 (the water pressures in mm of Hg are given in the figure) [39].

4.5 *Decomposed Gases*

Arcing in SF_6 produces various decomposed products such as F_2, S_2F_{10}, SF_4, S_2F_2, etc. Of these, SF_4 is the major product of decomposition [94,95] in SF_6. However, this gas is likely to react with the moisture content in SF_6 and the SiO_2 of the silica-filled epoxy spacer (if it exists), and the resulting gases such as SOF_2, SO_2F_2, SiF_4, and HF are formed [96-100].

One major effect of these reactions is a considerable decrease in the surface resistance of silica-filled epoxy resin spacer [77]. The alumina-filled spacers remain unaffected even in the wet condition. This decrease in the surface resistance may cause a nonuniform field distribution across the spacer surface and initiate partial discharges across resistive layers. These discharges could develop into a flashover on the spacer surface. Tracking has occurred under 10 kV direct voltage in silica-filled epoxy resin spacer in SF_6 at 500 kPa containing 3% by volume of SF_4 and 1000 ppm of H_2O. The normal withstand voltage of this spacer [39] was 150 kV.

The formation of free carbon takes place in decomposed by-products of CCl_2F_2, CO_2, and the fluorocarbon bases which form a conducting layer on the spacer surface thus impairing their performance [3,11]. This decomposition of gases may be caused by arcing or by corona discharges from a conducting particle in the system. These discharges cause a deterioration of the spacer material at the same time [101]. Arcs on the aluminum conductors result in an exothermic reaction in systems involving aluminum conductor-epoxy spacer [10]. Some of the gaseous by-products are toxic [102]. All these may impair the surface properties of the spacer. No flashover investigations have been reported so far under these conditions.

5. CONCLUSION

The spacer-gas-electrode interface forms the weakest location in a compressed gas insulated system. Microdischarges originating at the triple junction or at the spacer surface due to high electric stresses can either develop into a streamer and lead to a flashover or can cause an accumulation of charged particles on the spacer surface. These charges further enhance the electric field, and the stresses may exceed the dielectric strength of the gas insulation and cause a breakdown.

Shielding electrodes and inserts are successfully used to reduce the electric field at the triple junction. However, they increase the electric stresses in the spacer material, so that the breakdown strength of the spacer material may be exceeded by improper design.

The surface flashover voltage is therefore a function of the degree of contact of the spacer with the electrode, the dielectric constant of the spacer material, the shape of the spacer, the electrode geometry and the type and pressure of gas insulation used.

The performance of a spacer is different under dc, ac, and impulse voltages. Under dc, the resistivity of the spacer material determines the field distribution while under ac and impulse voltages, the distribution is capacitive. When stressed under dc for extended periods of time, volume charges accumulate in the spacer. The electric field distribution in the vicinity of the spacer is then modified and electric breakdown of the surrounding gas may result.

Contamination in the form of free and fixed conducting particles can greatly alter the flashover characteristics of the spacer. However, it is very difficult to predict the reduction in the breakdown voltage as it depends on the stress level, the size and location of the particles, the shape of the spacer, the gas insulation and the type of voltage used. Free conducting particles form the most serious type of contamination which can impair the flashover performance. The presence of these particles in the presence of a spacer can be more damaging than for the gas gap alone. With the particles, the flashover voltages are lower under dc operation than under ac or impulse conditions.

The presence of water vapor and decomposed gases influence the surface properties of the spacer material. This is true especially when silica is used as a filler in the epoxy resin spacers. Tracking may also occur on the surface of the spacer at extremely low stresses. The surface flashover voltage under these circumstances is then greatly reduced.

The various types of spacers used in CGIT lines include disk-type, cone-type, post-type, and multiblade-type for single phase lines, post-type for three-phase lines, and the multiblade type for flexible cables. Corrugated cone-, disk-, and post-type spacers, especially of a low dielectric constant material, perform relatively well under contaminated conditions.

The cycloaliphatic type of epoxy resin is the most commonly used spacer material for cone-type, disk-type, and post-type spacers while thermoplastics such as Teflon, polypropylene, and polycarbonate are used in multiblade type spacers. Hydantoin type of epoxy resin has recently been developed and tested; it shows promisign results for use as a spacer material.

The more important spacer material properties to be considered are its high surface resistance to erode or carbonize under arcing and its low dielectric constant. Other equally important properties of a spacer are its high dielectric strength, long life at power frequency, chemical stability in SF_6, mechanical strength and performance at elevated temperatures.

The post-type spacer appears to be the most suitable spacer that can be used for single-phase as well as three-phase systems. The inserts help to reduce the electric stresses at the triple-junction and so the flashover voltage along the spacer surface is greater than the breakdown voltage of the gas without the spacer in the pressure range of interest. In the presence of particle contaminants, a minimum area is exposed to the particles for attachment, and so this spacer performs relatively better than the other types of spacers. The use of corrugations and a spacer material of a low dielectric constant would be of further advantage in the performance of this spacer. Another advantage of this spacer is that it helps to reduce the overall cost of a large UHV system due to its small dimensions as compared to the cone and disk-type of spacers.

The cone and disk type of spacers are relatively more sensitive to particles than the post-type of spacer. Although their casting and installation is simple, they are large compared to post-type spacers, and this adds to the cost of manufacturing the spacers. Shielding electrodes are also required to reduce the electrical stresses acting on the spacer surface. Optimal profiles of these spacers may help to reduce these stresses. These types of spacers are especially useful as gas-stop joints and in gas-insulated cables with semi-prefabricated units.

The multiblade type of spacers are used in flexible cables and show a good performance when a spacer material of low dielectric constant is used. Corrugating the spacer shape may further aid their performance under contaminated conditions.

Future systems include the flexible compressed gas insulated cables of large power handling capability, cables with semi-prefabricated units, cables with bundled subconductors, the 800 and 1200 kV single and three phase lines, and dc transmission systems. Mixtures of SF_6 with air or N_2 have been recommended for use in 1200 kV transmission systems. SF_6-N_2 and SF_6-He gas mixtures show promising results for use in high voltage circuit breakers.

Detailed investigations are necessary to explain precisely the prebreakdown and breakdown mechanism of spacers in compressed gases. Extensive work must also be carried out to determine the spacer flashover performance in SF_6-N_2, SF_6-air, SF_6-CO_2, SF_6-He, and other gases and gas mixtures which are being investigated as replacement gases for SF_6. This must be done especially in the presence of free and fixed conducting particles under alternating and direct voltages to evaluate the reduced performance. The performance of corrugated spacers having a low dielectric constant also needs to be evaluated under these conditions.

The influence of decomposed byproducts of the gas insulation on the spacer, spacer material and the conductor especially in the presence of water vapor must be evaluated to determine the deteriorated flashover performance.

Volume charging of the spacers under direct voltages applied for an extended period poses a serious threat to the performance of spacers. Extensive work is necessary in this area to clear the way for future compressed gas dc transmission systems.

Spacer materials of low dielectric constant and resistance to track or erode under arcing, besides having other required properties, are being developed and have to be fully tested before justifying their use in compressed gas insulated systems.

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