Possible High Pressure Nitrogen-Based Insulation for Compressed Gas Insulated Cables

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Abstract

Electricite' de France (EDF) is contemplating 420 kV compressed gas insulated cables (CGIC) as much as tens of kilometers long and environmentally acceptable. An extensive literature review is being made to determine as well as possible how to use nitrogen alone or with minimum SF_6 for insulation; the literature will probably not provide all information needed. Some measurements are also being made at EDF. Highlights are given here.

Introduction

Electricite' de France is considering CGIC up to tens of km long (though only about 32 km of CGIC over 100m exist now world-wide). They would be buried in a 420 kV network and have maximum phase diameter of about 0.7~0.8m. Insulation levels would be in accord with IEC values (for example, 630 kV power frequency, 1425 kV lightning impulse, and 1050 kV switching impulse.) Gas insulation would not be the usual SF_6. Many gases and mixtures have been studied, especially from 1975 to 1985; some perfluorocarbon and chlorofluorocarbon gases and mixtures are at least as good as SF_6 [1] but have undesirable chemical, toxicity, or decomposition properties; therefore N_2 alone or with minimum SF_6 is considered.

Theory of Breakdown

Breakdown is initiated by an avalanche evolving into a self-propagating streamer. Near the "critical field" (where $\bar{\alpha}=0$), in SF_6, $\bar{\alpha} = \beta E - \kappa p$. Nitrogen has no attachment, and its $\bar{\alpha} = \alpha = pAe^{-Bp/E}$. (E is field, p is pressure, and the constants are known.) The $\bar{\alpha}$ for a mixture is generally approximated by a linear combination of values for the constituents, weighted by respective partial pressures [2]. Our calculated $\bar{\alpha}$ for SF_6/N_2 mixtures agreed well with measured values [3].

The breakdown voltage for a mixture is found by solving simultaneously the following equations, using $\bar{\alpha}$ for the mixture. K is a parameter determined from breakdown measurements, x=0 on the initiating electrode point, and x_0 is where $\bar{\alpha}$ drops to zero.

$$\int_0^{x_0} \bar{\alpha}(x)\, dx = K, \qquad \bar{\alpha}(x_o) = 0$$

A microscopic surface protrusion can lower the streamer initiation voltage, especially at higher pressures. Larger values of Pedersen's figure of merit "M" [4] indicate less sensitivity to surface roughness; for N_2 it is larger than for SF_6, and that is reflected in mixtures.

A useful strategy is to combine gases with different mechanisms of free electron control over their full energy range [5]. Nitrogen slows free electrons, and SF_6 attaches free electrons well but only at low energies, making these gases a synergistic "team" [6].

The similarity principle can be used to compare breakdown in different size coaxial cables; for geometrically similar geometries, the product (Er) is a function of the product (nr) (E is field, r is a dimension, and n is gas molecule density.) Data here are presented as breakdown field vs. pressure to match the designer's view; that contains the complete information such as breakdown voltage, if desired.

Measurements at EDF

At Les Renardieres breakdown measurements have been made by one author (XW). They were made in a 1.56 m^3 vessel containing a 1m length of a coaxial configuration with diameters 185 and 400 mm. The conductor surface roughness is of typical GIS industrial type. In figures here, data from these measurements are designated by EDF-95.

Breakdown of Pure N_2

Breakdown of N_2 in coaxial systems has been measured [7], [8], [9], [10], [11]. Figure 1 gives the breakdown field for negative DC or crest AC measured in several cylindrical geometries as a function of pressure. In [11] the 6mm aluminum wires were significantly harmful. N_2 alone does not appear satisfactory.

There is not enough data on impulse breakdown in N_2 to confidently predict the impulse behavior of a reasonably sized CGIC. From data in [9], the impulse breakdown appears only marginally satisfactory.

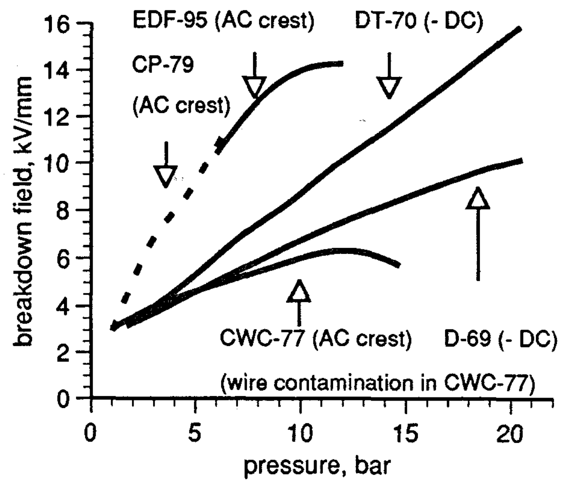

Figure 1. Breakdown field of N_2 measured in coaxial geometries. (Inner/outer diameters in mm are 185/400 for EDF-95, 89/226 for CP-79, 76/254 for DT-70 and D-69, and 76/250 for CWC-77.)

AC Breakdown for SF_6/N_2 Mixtures

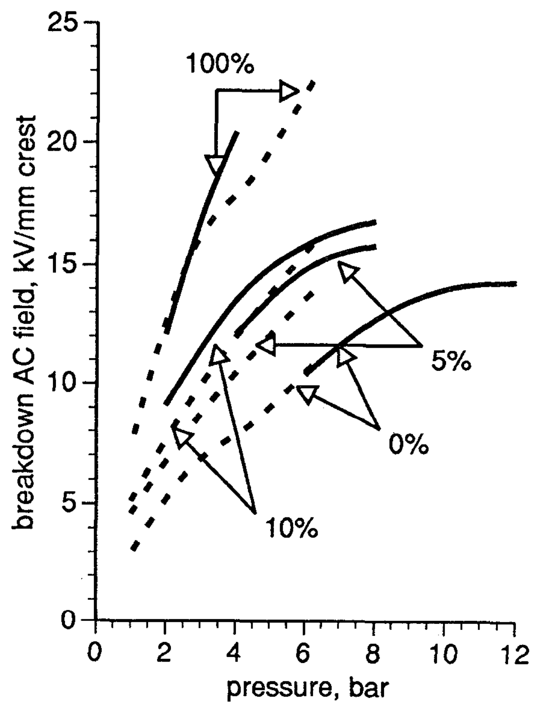

Figure 2. Measured breakdown fields in coaxial cables of diameters 185/400 mm (EDF-95, solid curves), and 89/226 mm (Cookson & Pedersen, 1979, dashed curves). The % SF_6 in mixtures with N_2 is indicated.

Our calculated breakdown voltages for N_2/SF_6 mixtures agreed well with measured values in uniform field small gaps and in cylindrical geometry, as well as with other calculations [12]. The measured values of breakdown voltages of N_2/SF_6 mixtures in large coaxial geometry [9] agreed with values calculated here at 1 bar, but at higher pressures they were significantly less, possibly because of surface roughness or particles. In figure 2 reasonable agreement is found for measured breakdown fields in coaxial cables for various mixtures and pressures, from EDF-95 and CP-79.

Surface Roughness Effects

With the field near a hemispherical protrusion [13] we calculated the breakdown of N_2/SF_6 mixtures with surface roughness in a coaxial geometry, as shown in figure 3. Each mixture has a critical protrusion size below which the roughness has no effect, that critical size being smaller as the proportion of SF_6 increases.

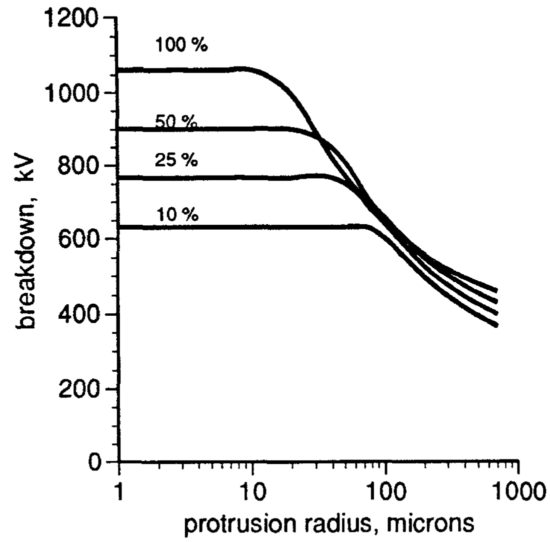

Figure 3. Calculated breakdown voltages in 35/110 mm diameters coaxial line with various size hemispherical protrusions at 3 bar total. The % given indicates the portion that is SF_6 in a mixture with N_2.

Impulse Breakdown of SF_6/N_2 Mixtures

Lightning and switching surge breakdown for SF_6/N_2 mixtures in a 89/226 mm (diameters) coaxial geometry was measured in [9]. Relatively small additions of SF_6 to N_2 gave large improvements. Figure 4 shows reasonable agreement for measured breakdown fields for various mixtures and pressures in coaxial cables, from EDF-95 and CP-79.

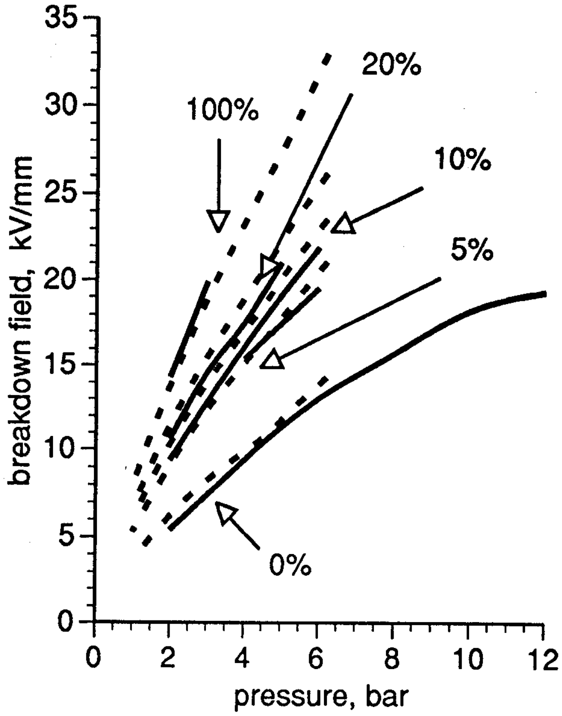

Figure 4. Measured breakdown fields with negative lightning impulses for coaxial cables with diameters 185/400 mm (EDF-95, solid curves) and 89/226 mm (CP-79, dashed curves.) Each arrow indicates the % SF_6 in a mixture with N_2, for one solid curve and one dashed curve.

Spacers for Conductor Support

Spacers (generally made of vacuum cast epoxies) in several forms are used to support the conductor, and can be the weakest part of the insulation. Flashover along a clean spacer generally begins in the "triple junction" where the spacer meets an electrode and there is an unavoidable gas gap electrically in series between the spacer and electrode. The field in the triple junction can be reduced by one or more of at least five means: (1) a concave "pocket" in the electrode for the end of the spacer, (2) a metal insert in the spacer contacting the electrode, (3) a conducting coating on the spacer where it contacts the electrode, (4) shielding rings on the spacer and connected to each electrode [14], and (5) material with a lower dielectric constant.

The flashover voltage of a clean spacer can be as high as that of the empty gas gap. Conducting particles are harmful (more with AC than with impulse) when fixed to the spacer. A ribbed surface on the spacer can reduce particle effects, but its non-uniform fields lower the flashover voltage in clean conditions. The breakdown along spacers with DC stress is different from that with AC because of charging and field distributions.

Spacers Subjected to AC Voltage

Relevant work on spacers in N_2/SF_6 mixtures was done by Blankenburg [15], who measured 50 Hz flashover voltages of an unfilled epoxy resin spacer between Rogowski electrodes separated by 14 mm. Pressures varied between 0.5 and 3 bar. Artificial voids were created by removing the epoxy from part of the spacer in contact with one electrode.

With pure SF_6 and no artificial voids the addition of the spacer reduced the flashover voltage only 5 to 10%. With pure nitrogen there was no effect from a spacer without artificial voids, the results agreeing with the corresponding CIGRE Paschen curve for the gap without spacer [16].

For a relatively "large" artificial void of 0.2 mm, Blankenburg's measured inception voltages are given in figure 5 with our calculated values. They agree well at lower pressures; measured values fall below calculated ones at higher pressures, especially at higher concentrations of SF_6.

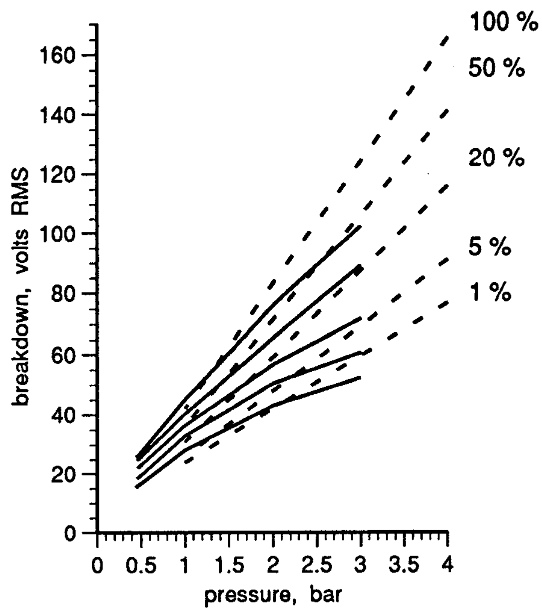

Figure 5. Measured [15] (solid curves) and calculated (this project, dashed curves) breakdown voltages for a spacer (with a void) in a 14mm gap. The % values refer to the portion of SF_6 in a mixture with N_2.

Particle Effects on Spacers

A study was made in [17] of a conducting particle on an epoxy spacer in N_2/SF_6 for AC and negative lightning stress of a coaxial system (diameters 2.54/7.0 cm) at pressures of 1 to 4 bar. The particle was a 0.8 mm diameter wire, 2 mm long. With AC a particle near the inner conductor reduced the breakdown voltage about a factor of 2 at lower pressures and 3 at higher pressure, but the 50%/50% mixture was almost as good as pure SF_6; for impulses the particle harm was similar but not quite so bad as with AC. The particle increased the impulse ratio from the range of 1.25 to about 1.5.

Spacer Behavior under Impulse Voltage Stress

In [18] the impulse breakdown of the mixture of 10% SF_6/40% N_2/50% Ar was studied with epoxy spacers.

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