Chapter 3

Applications of gaseous insulants

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3.1 Introduction

This chapter introduces the subject of gaseous insulation and provides information relating to the application of gaseous insulants to high voltage systems. It examines atmospheric air, compressed gases and illustrates how, by linking available experimental test data from such sources with a knowledge of the 'effectiveness' of various practical gas-gap clearances, the designer can achieve reliable insulation design. The chapter also briefly discusses the need for high voltage and extra high voltage (UHV) test areas or laboratories. Evidence is presented of how laboratory studies, on representative insulation systems and electrode arrangements, provide the designer with choices relating to electrical stresses, clearance levels, service performance and testing procedures. Gas insulated substations (GIS) using sulphur hexafluoride (SF_6) gaseous insulation have been used in transmission systems worldwide for more than 35 years. The service reliability of this class of equipment is of paramount importance. In addition, the chapter presents a large amount of experimental breakdown information on SF_6 and briefly reviews the application of field computation strategies in support of GIS and other equipment designs. Several of the major factors influencing the insulation design and in-service behaviour and reliability of SF_6 gaseous and epoxy resin support insulations, as used in GIS equipment, will also be considered.

Atmospheric air is the most abundant dielectric material which has played a vital role in providing a basic insulating function in almost all electrical components and equipment. However, because it has a comparatively low dielectric strength, large electrical clearances are required in air for high voltage applications such as overhead line bundle conductor or tower design or open-type EHV switchyards. Air clearances will be discussed in Section 3.2. Much research activity has taken place during the past 50 years to investigate compressed air and to develop other gases with even better characteristics than air. Some important characteristics of compressed gaseous insulation, including air, SF_6 and other gases, will be touched on in Sections 3.3 and 3.4 and considered further in Chapter 7.

As discussed elsewhere [1–5], the dielectric strength of air and other gaseous insulation is a function of gas density (δ). Advantage has been taken of this fact for many years in transmission switchgear, where high pressure gases have been used to provide essential insulation and arc interruption characteristics in heavy-duty interrupters. The concept of high pressure gaseous insulation has now been extended into combined metal-clad switchgear and connecting cables, termed gas insulated systems (GIS). Sometimes, gas insulated cables are referred to as gas insulated lines (GIL). Strategic aspects relating to gaseous insulation systems as used in GIS will be discussed in Section 3.4.

Since gas does not offer mechanical support for live conductors, switches, etc., it is used in combination with solid insulation. The gas/solid interface region must be looked at very carefully from an electrical design viewpoint, otherwise design weaknesses could result in problems in service, with the possibility of consequential breakdown or flashover of equipment. Even when the very best design principles have been adopted, breakdowns can still occur in air/solid interfaces under adverse environmental conditions such as pollution, fog, ice, snow or humidity. These aspects are outside the scope of this chapter and are dealt with elsewhere [5–8].

Whatever dielectric medium is used, be it solid, liquid or gas or combinations thereof, it is essential that careful consideration be given to the electrostatic field design of insulating components to produce compact, efficient, economic and reliable designs of high voltage equipment which will give long and trouble-free life in service. To this end, designers rely on analytical field analysis techniques to model electrostatic and other aspects of specific designs and, when appropriate, to optimise the shape and disposition of components. The general availability of commercial packages to carry out 'advanced' digital field techniques during the past 35 years has greatly assisted equipment designers.

Section 3.5 gives a brief indication of the purpose, scope and application of field analysis methods to provide valuable design information from extensive SF_6 gaseous insulation studies relating to simple electrode arrangements through to EHV equipment designs.

3.2 Atmospheric air clearances

3.2.1 Test areas

In dry, unpolluted areas, air clearances between live equipment and earth can be defined reliably. Legg [9] has described the minimum clearances necessary for high voltage test areas. The majority of high voltage tests on equipment are carried out indoors to avoid large variations in atmospheric conditions. When high voltage laboratories are constructed, the test voltages to be used are generally known and the physical size of the laboratory is determined by the dimensions of the voltage generating plant, the test objects and the clearances required to prevent flashover to the walls of the laboratory (see also Chapters 15–20). The flashover voltage of rod–rod and rod–plane gaps as a function of the gap spacing [9] is illustrated in Figure 3.1. From these graphs, the required dimensions of laboratories can be estimated. It will be noted that the lowest flashover voltages are experienced with positive switching surges and 50 Hz voltages, applied to rod–plane gaps. For this reason, the performance of a rod–plane gap under positive switching surges may be usefully taken as a datum (for required laboratory clearances) because all other combinations of gap geometry and voltage waveform produce higher flashover voltages. The sparkover of any gap is subject to statistical variation, and some knowledge of this is required before clearances can be estimated for a laboratory, etc. This essential consideration of statistical aspects also applies in day to day testing or measuring within laboratories (see Sections 3.3, 3.4). The breakdown voltages reproduced in Figures 3.1 and 3.2 relate to 50% flashover levels [9]. That is, if a large number of voltage tests at this level were applied to the gap, one-half of these tests would be expected to cause flashover. Breakdown to the walls of a laboratory or

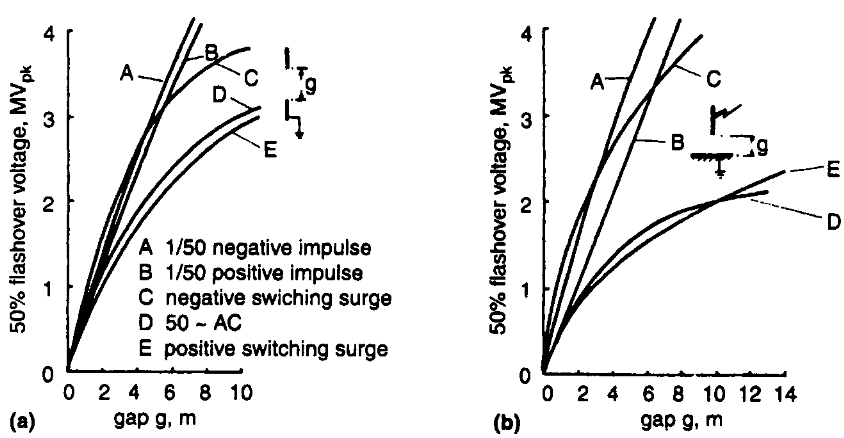


Figure 3.1 50% flashover voltage for **(a)** *rod–rod and* **(b)** *rod–plane gaps*

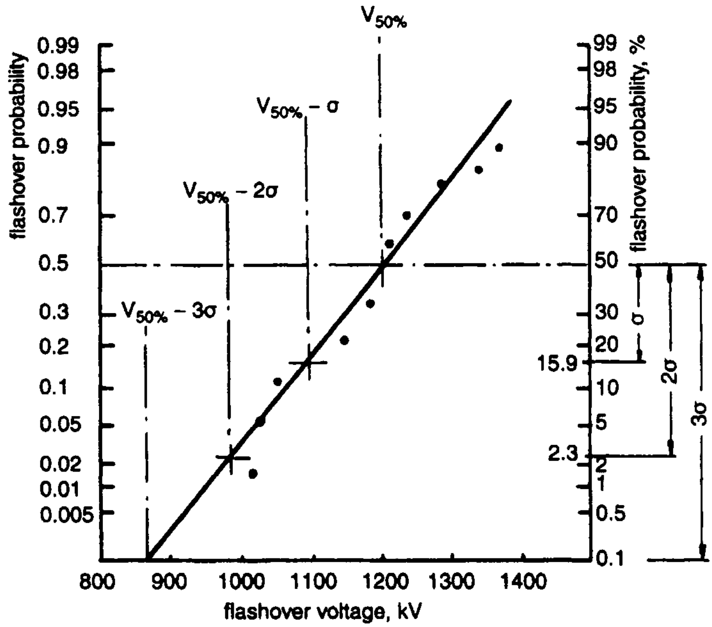


Figure 3.2 Illustrating probability of flashover

test-chamber must be avoided; therefore greater clearances than these are required.

In Figure 3.2, the 50% flashover voltage is 1200 kV for this particular gap. The voltage corresponding to the 16% probability line (1090 kV) is one standard deviation (σ) less than V_{50}, i.e. $V_{50} - \sigma$. The voltage corresponding to the 2% line is $V_{50} - 2\sigma$ (980 kV) and that to the 0.1% line is $V_{50} - 3\sigma$ (870 kV). In practice, one takes the withstand voltage of the gap as 2 or 3 standard deviations less than the 50% flashover voltage, i.e. $V_{50} - 2\sigma$ or $V_{50} - 3\sigma$. The withstand voltage of the gap represented by Figure 3.2 is therefore 980 or 870 kV. For 1/50 μs impulse waves, the standard deviation is of the order of 1 to 4%, the lower values occurring at the highest voltages, whereas for switching surges the standard deviation is of the order of 5–12% and increases with voltage. For 50 cycle voltages up to 1500 kV RMS, the standard deviation is approximately:

1.5 – 4%	for rod–plane gaps
0.5 – 2.5%	for rod–rod gaps
1.0 – 4%	for dry insulators
1.5 – 6%	for wet insulators.

Having established the withstand voltage for various gaps – or conversely the gap required to withstand the various test voltages – the dimensions of a laboratory can be estimated. Even clearances based on $V_{50} - 3\sigma$ are often increased for two reasons. First, the walls of the laboratory can influence the flashover voltage and invalidate the test. Second, clearances are required for radio interference or partial discharge measurements. During partial discharge tests, one may be looking for very small internal discharges (often as small as 1 pC) in the test object so that spurious discharges from the circuit (busbars, transformers, etc.) must be an order smaller. If the clearances are too small, even though they are adequate to prevent flashover, then small discharges may flow to the walls of the laboratory, thereby preventing accurate measurements. Test area dimensions are given in Table 3.1. For very high voltage test equipment (>3 MV), it may be uneconomic to build an enclosure with adequate clearances and the test equipment can be moved and used outdoors.

Ryan and Whiskard [10] describe the design, planning and supervision of the construction of a new UHV testing laboratory (see Figure 3.3). The main purpose of this laboratory was to provide a major facility in the UK for the development of switchgear rated up to 765 kV. The authors report on some of the dielectric research undertaken to achieve this position. Following the opening of the laboratory in 1970, these workers were closely connected with the development of new ranges of open-terminal and metal-clad SF_6 switchgear, rated up to 550 kV and for fault current levels up to 63 kA (see Chapter 8). These switchgear design activities were supported by extensive dielectric research studies, which enabled the major factors influencing the insulation integrity of practical equipment to be determined. Much of this work has been extensively reported in the literature.

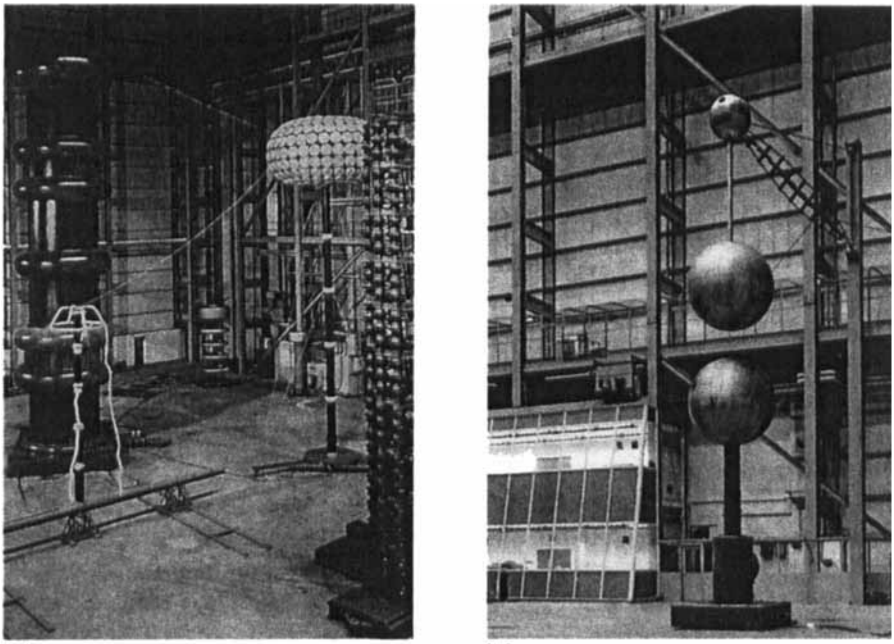
Ryan and Whiskard [10] outlines:

(a) the criteria used in designing the UHV laboratory, and presents a critical appraisal of the facilities during the first 15 years of its operational life [for information, now BSTS Clothier Laboratory]

Table 3.1 Approximate dimensions of test hall for 50 Hz 3-phase tests [9]

Transformer voltage rating	HT to earth clearance, *X*				Nominal test room dimensions in feet			Diameter of discharge free busbars	
	Minimum practical		Discharge free at full voltage						
(kV RMS)	(ft)	(m)	(ft)	(m)	L	W	H	(in)	(cm)
100	1.3	0.4	2	0.6	15	10	10	2	5
250	3	0.9	5	1.5	20	15	15	4	10
500	7	2.1	10	3	40	25	20	8	20
800	13	3.9	20	6	50	40	35	12	30
1000	19	5.8	25	7.6	75	55	50	15	40

L = length; W = width; H = height



(a) (b)

Figure 3.3 Major items of laboratory equipment [10]
(a) *View of 2 MV transformer, 4 MV impulse generator and UHV divider and test object in test hall*
(b) *View of 2 MV sphere-gaps, control room and galleries*

(b) some significant laboratory activities, including examples of studies on various switchgear and nonswitchgear components for systems up to 765 kV, all having been subjected to rigorous dielectric proving tests
(c) the use of specific high voltage test procedures (e.g. climatic, artificial rainfall and mixed voltage testing, together with important technical factors which have influenced the dielectric design of apparatus.

Chapters 15–18, respectively, by E. Gockenbach discuss basic measuring techniques, basic testing techniques, partial discharge measuring techniques and digital measuring techniques. In Chapter 19, R.C. Hughes considers the strategically important topic of traceable measurements in high voltage tests. These two workers have been extremely active in strategic developments within IEC/CIGRE in these sectors in recent years. The reader should be aware that modern UHV laboratories exist in several countries, including Brazil, Canada, France, Germany, Italy, Japan, UK and USA. Numerous 'quality' technical papers have been presented by experts from these organisations (see IEC/CIGRE/IEEE/ IEE Publications).

3.2.2 Sphere gaps

A convenient use of airgaps is as a calibration for high voltages. It is useful in that no voltage dividers or electronic equipment is required (which can malfunction), but suffers from lack of accuracy, ± 3% (this covers the whole range of voltage). Spark gaps are recognised in IEC52, 1960. The sphere gap is accurate and reproducible over its range, which extends to gaps equal to 0.5 × sphere diameter, after which it loses accuracy due to field distortion. It is also necessary to take account of humidity, temperature and pressure, all of which affect the breakdown voltage. The sphere gap records peak voltage and can therefore be used for AC or impulse voltages with only slight variations for positive or negative pulses. For very fast impulses (< 10 μs), it is necessary to irradiate the gap with a radioactive source in one sphere (or use a UV source) to provide the necessary initiating electrons.

Modern EHV and UHV laboratories are capable of measuring voltages to high accuracy (see Chapter 15), being equipped with precision voltage dividers, used in conjunction with the 'latest' digital measuring techniques incorporating sophisticated software support. However, in industrial laboratory test facilities, it is still common for sphere gaps to be used (e.g. Figure 3.3(b)) to calibrate another measuring system because it can be easily verified by the inspectors. The revision document of IEC 52, 1960 is currently under consideration by the National Committees. No change has been made to the extensive tabulated values of 'sparking voltage against gap', since existing values are considered to constitute 'a consensus standard of measurement' which has been unchanged for 75 years.

Sphere gap sparking voltages given in the tables can be considered to have uncertainties of ±3% for a 95% confidence level. A spark gap can be regarded as 'fit-for-purpose' provided its flashover performance characteristic 'conforms', i.e. to be less than a specified value. Otherwise, a high value of σ (obtained in a test series) indicates something is wrong (e.g. dirt, dust, insufficient source of ionising ions) while a sufficiently low value of σ indicates that particular sphere gap is acceptable for calibration use.

3.2.3 Spark gaps

Spark gaps are used for protection of equipment against high voltage surges, for all voltage ranges, the advantage being that the dielectric is recoverable. Historically, spark gaps range from the common GPO arrester, having low pressure N_2 in a ceramic body, with voltage ratings of 150–1000 V and current ratings of 10^3 amp.s, to low pressure gas or vacuum 'bottles' with voltage ratings of 1 to 50 kV and current ratings of 50 kA for railway equipment protection, for example. The simplest and most common spark gap is the rod-gap, used on outdoor equipment such as transformers, substations and bushings. Its characteristics are well documented (e.g. Figure 3.4); its simplicity is offset by a variable breakdown voltage with respect to time and polarity. Special designs with improved characteristics have been developed recently for EHV and UHV systems. For equipment protected by a rod-gap, it is important to know its 'breakdown voltage against time' characteristic relative to that of the equipment being protected to ensure that the rod-gap operates first, under all surge conditions. Such protection is known as insulation co-ordination, as covered by IEC Technical Committee 28 and discussed in Chapter 2 (e.g. see also Figures 3.5 and 3.6).

Many workers have derived empirical relationships to correlate breakdown voltage with gap spacing for rod–plane gaps [1]. For example, Ryan and Whiskard, working in the laboratory [10], reconfirmed results of earlier Russian workers by studying the 50 Hz breakdown characteristic of three rod–plane electrode systems [i.e. (i) a 1.27 cm square cut rod, (ii) a 0.2 cm diameter hemispherically ended rod and (iii) a 0.5 cm diameter

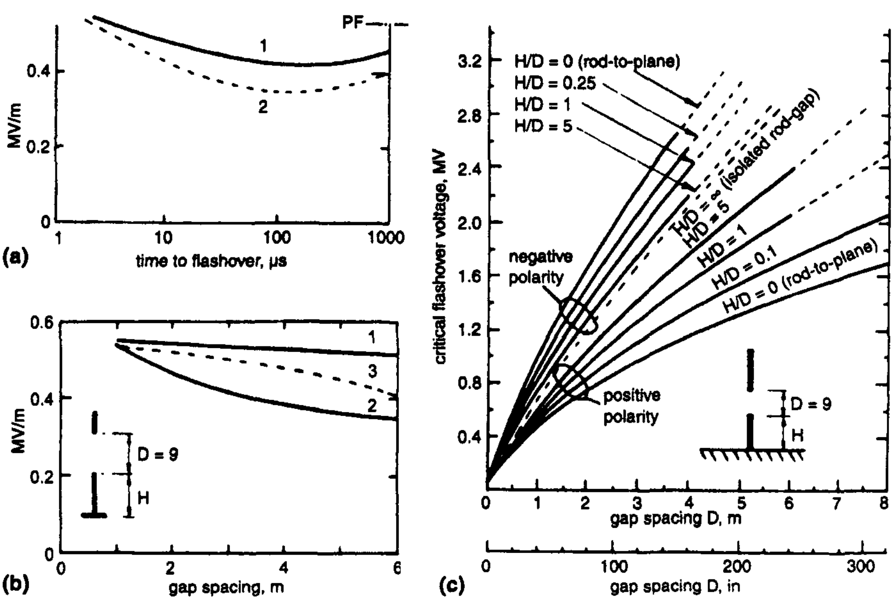


Figure 3.4 *Rod-gap characteristics [11]*

(a) *Typical relationships for critical flashover voltage per metre as a function of time to flashover (3 m gap): 1 Rod-rod gap; 2 conductor–plane gap; PF = power frequency CFO*

(b) *Typical relationships for flashover voltage per metre as a function of gap spacing: 1 1.2/50 μs impulse; 2 200/2000 μs impulse (rod-rod,* H/D = *1.0, positive dry); 3 power frequency*

(c) *Switching surge flashover strength of rod–rod and rod–plane gaps (courtesy Edison Electric Institute); wave fronts of 100–200 μs; vapour pressure = 12.5 mean Hg*

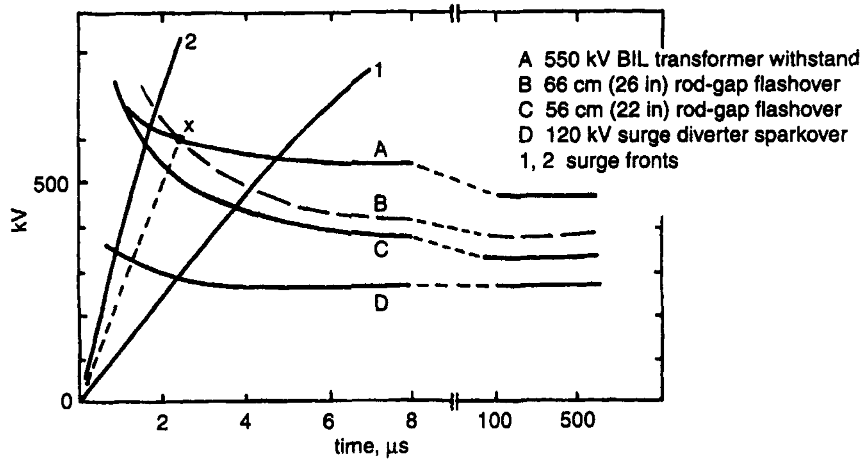


Figure 3.5 Transformer protection by rod-gap and surge arrester [11]

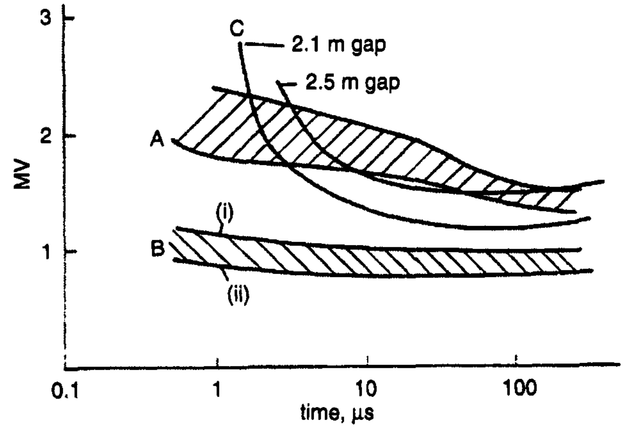


Figure 3.6 Insulation co-ordination diagram [10]
A Typical V/t characteristics of 420 kV GIS
B Representative characteristics of 396 kV ZnO arrester
C Lower limit curve of a line gap for specific gap settings
(i) Upper limit 40 kA amplitude
(ii) Lower limit 3 kA amplitude

sphere]. It was originally established by Tikhodeyev and Tushnov (1958) – see [1], p. 617 – that the breakdown voltage (V_s) could be predicted, to within 1%, for airgaps with ($1 \leq g \leq 9$) m, using an expression of the form

$$V_s = 0.0798 + 0.4779\,g - 0.0334\,g^2 + 0.0007\,g^3 \quad \mathrm{MV_{pk}}$$

where g is the gap in metres. A simpler equation ($V_s = 1.62\,g^{1/3} - 1.1$), was found to be accurate to ± 5%. Ryan and Powell found that, for rod–plane gaps in the range 1–5 m, the measured 50 Hz breakdown voltages lay within 3.5% of the values given by the large equation above when (i) the end of the rod was square cut and within 3% when it was hemispherically terminated (ii). The corresponding results with electrode system (iii) gave breakdown results some several percentage points higher than those given by the above equation. It is worth emphasising that, although the form of the rod termination had little effect on the breakdown voltage, the three electrode systems exhibited widely different values of corona onset voltage [1].

The role of rod-gaps and surge-arresters, widely used as overvoltage protective devices, is summarised elsewhere [11]. Voltage–time 'withstand' characteristics exist for different types of insulation when subjected to various types of overvoltage. The various time regions refer to particular types or shapes of test voltage. The 'withstand' levels used for self-restoring insulation are at a suitably chosen level below the 'V_{50}/time' characteristic (a selected multiple of σ below), while characteristics for 'non-self-restoring' insulation are obtained from withstand characteristics corresponding to the specified test voltages for the various categories of test voltage. The example reported by Diesendorf [11], reproduced in Figure 3.5, illustrates that protection can be achieved in any time region in which the protective characteristic lies below the withstand characteristics of the insulation concerned. The 120 kV surge arrester (curve D) protects the transformer over the entire time-range, whereas the 26 inch (660 mm) rod-gap (B) protects the transformer only against surges with front slopes less than OX. Steeper surges would cause the insulation to breakdown before the rod-gap could operate. To achieve reliable protection, comprehensive test data must exist both for the protective devices and the insulation components of any system [12].

Figure 3.6 provides further results from extensive insulation co-ordination studies [10, 13], on this occasion for 420 kV GIS assemblies; V/t characteristics for GIS and for corresponding 396 kV (rated) ZnO arresters and standard line-gaps are compared. This investigation looked into the strategic question of insulation co-ordination for GIS. Zinc oxide (ZnO) arresters are now used worldwide to provide robust protection to modern transmission systems [14]. It is also interesting to observe in passing the remarkable expansion of the application of metal oxide arresters to overhead lines at lower system voltages in recent years. The voltage class of these applications ranges from several kilovolts to EHV/UHV voltage.

3.2.4 Overhead lines and conductor bundles

Various classifications of dielectric stress may be encountered during the operation of any equipment ranging from (i) sustained normal power frequency voltages, (ii) temporary overvoltages, (iii) switching overvoltages to (iv) lightning overvoltages. These are represented in the laboratory, for test purposes, by standard test waves: power frequency, switching impulse and lightning voltages. The strength of external insulation is dependent on geometric factors, on air density, temperature, humidity (appropriate correction factors are available), precipitation and contamination (due to natural or industrial pollution). The presence of ice and snow can influence the flashover performance of outdoor insulators (see Reports of CIGRE Task Force 33.04.09 [7, 8]. Ice and snow accretions can present serious problems in many cold regions of the world; there is well documented evidence that the number of single phase-faults increases substantially during cold precipitation and after accretion when followed by a rise in air temperature. Further research is required to provide a better understanding of such flashover events.

Before effective insulation co-ordination can be achieved, a large amount of experimental test data is required on arrangements such as support insulators (various shapes), rod–plane gaps (for protective purposes), rod–plane, ring–plane gaps, etc. which approximate to practical conditions (e.g. air insulator strings for transmission lines (vertical, horizontal, vee-strings, disc, longrod, fog-type, etc.). A variety of typical characteristics for various arrangements have been summarised and presented by Diesendorf [11, 12]. Examples are reproduced in Figure 3.7.

The mean breakdown stress, i.e. V/g, in large practical gaps (Figure 3.4), is typically 500 V/mm, somewhat reduced from the 2 kV/mm in

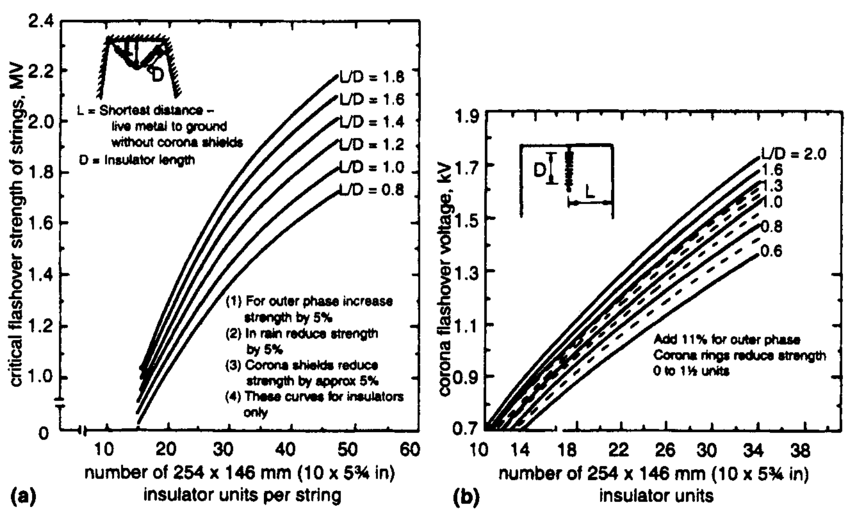


Figure 3.7 Switching surge characteristics of string insulators
(a) *Flashover strength;* **(b)** *along tangent strings*
See EHV transmission line reference book, Edison Electric Inst., New York, 1968

sphere gaps. This can decrease even further in wet weather, such that breakdown of air under lightning conditions can occur at stresses as low as 20 V/mm. In overhead line design [11], it is necessary to design conductor bundles such that the stress at the surface of the bundle is less than that to initiate corona, otherwise radio noise would be generated and losses and corrosion would increase. An indication of surface stress levels of various UHV conductor bundle designs are given in Figure 3.8. Special problems to be overcome before effective overvoltage protection can be achieved in practice are considered elsewhere [11].

It should be noted that, during the IEE School on High Voltage Engineering and Testing, a visit is normally made to the Clothier UHV Laboratory (now part of the British Short Circuit Testing Station, Hebburn) to witness examples of pre-breakdown discharge activities in large practical gaps, for AC, DC and impulse voltages (see also Chapter 20). This workshop complements lectures by Messrs. Hughes, Gockenbach and Allen and is relevant to material covered in Chapters 15–20.

3.2.5 Guidelines for live working

Live working [15] allows necessary maintenance and repairs to be performed on high voltage systems without the necessity for interruption of the power supply to customer(s). To achieve effective live working, safety of workers and total reliability of the operation is vital. To this end, 'safe working distances', i.e. the air insulation distances to be maintained in the various 'working configurations' in order that the risk of occurrence

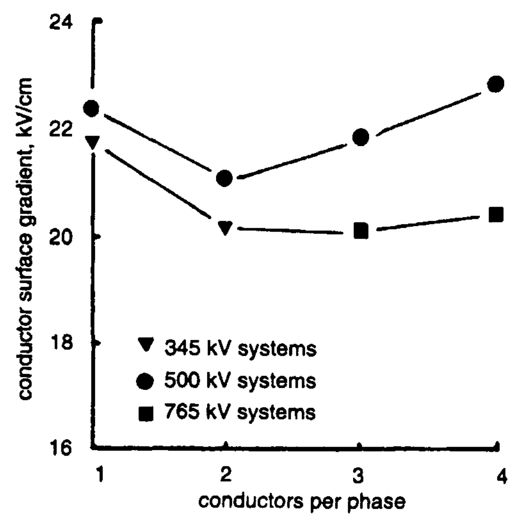


Figure 3.8 Typical surface gradients on overhead transmission line conductors
See EHV transmission line reference book, Edison Electric Inst., New York, 1968

of flashovers, which (i) could possibly be harmful to all personnel working nearby and (ii) could cause disturbances to the system, are sufficiently low.

Safe working distances can be determined by applying the principles of insulation co-ordination which is based on [15] three main elements:

(i) knowledge of stresses which occur at worksite
(ii) knowledge of the electrical strength of the work site insulation when subjected to such stresses
(iii) assessment of the probability of occurrence of insulation failures in the situation under consideration of stresses and strength.

A recent CIGRE Brochure, summarised in [15], deals with the insulation in live working and also addresses special considerations, namely safety aspects related to the exposure of workers to electric and magnetic fields. It provides:

(a) a general subject overview
(b) a discussion on voltage stresses at the work site and the effect of the adoption of overvoltage limiting measures and devices
(c) dielectric withstand characteristics of the work site insulation, starting from the reference conditions and addressing the influence of conducting bodies at floating potentials of damaged insulators and insulating tools and of atmospheric conditions and altitude
(d) procedure for evaluation of the risk of failure during live working and for the assessment of working distances (case study examples are given of application)
(e) assessment of minimum working distances as from viewpoint of exposure of workers to electric and magnetic fields [EMF].

In live working, the main concern is the performance under transient overvoltages. These activities are usually restricted to periods of 'good' weather. Consequently, lightning overvoltages are generally not important, and there is normally little risk of power frequency pollution flashover [15].

3.3 Other gases

The availability and characteristics of air makes it the most used gaseous insulant. In enclosed equipment, e.g. heavy duty gas blast circuit-breakers, by using air at high gas pressures, the dielectric performance, etc. could be greatly enhanced. However, because of limitations, gases other than air have been considered. The most popular of these has been sulphur hexaflouride gas (SF_6), which has dielectric strength about twice as good as air and also offers excellent thermal and arc interruption characteristics (see Chapter 7). Despite this, the search continues for other gases with improved characteristics.

There has been considerable research activity (for example, see

Reference 16) to find alternative gases and gas mixtures, which may have comparable breakdown strengths as SF_6 (see Figures 3.9, 3.10) but can offer technical, environmental and economic advantages. Binary mixtures with inexpensive gases like N_2, air, CO_2 and N_2O have been under continuous investigation to arrive at efficient and economical mixtures and obtain a better understanding of the dielectric processes involved. The mixture of SF_6 and N_2 is the only mixture to achieve significant commercial application in switchgear, mainly to overcome problems associated with low ambient temperature conditions (in Canada, for example).

Environmental constraints are now assuming greater significance and

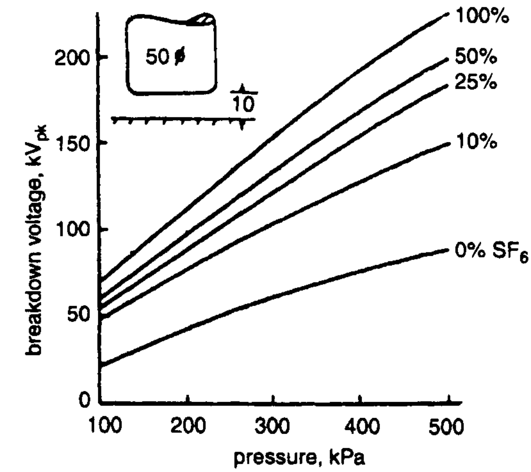


Figure 3.9 Uniform-field breakdown voltages for SF_6 – air mixtures

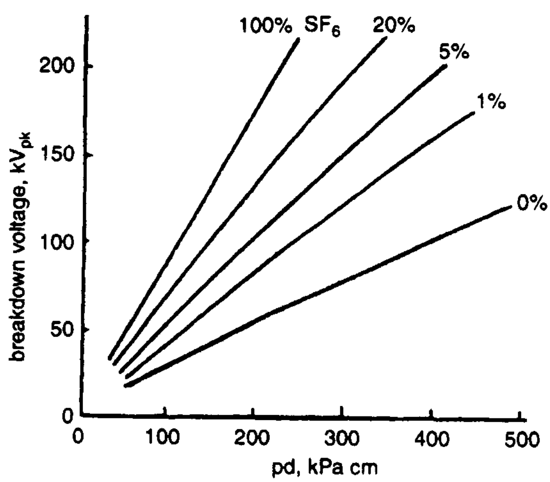


Figure 3.10 Paschen curves for SF_6–N_2 mixtures at 20 °C (50 Hz)

these have resulted in great attention being necessary for packaging, transport and reclaiming of used SF_6 and renewed interest in the choice of N_2/SF_6 mixtures for gas insulated systems. The attraction of such mixtures is that N_2 gas predominates, enabling the amount of SF_6 used to be kept to a minimum. Much work was carried out in the 1970s and 1980s by switchgear manufacturers, universities and others, and dielectric characteristics were obtained for a wide range of electrode configurations, some similar to those shown in Figures 3.9–3.11. These studies revealed that the dielectric withstand characteristics of N_2 increases rapidly with only a small percentage of SF_6 present. The commercial and environmental implications are that N_2/SF_6 mixtures with < 20% SF_6 can achieve a 'significant' dielectric withstand performance for a greatly reduced SF_6 gas requirement (see also 'Guide for SF_6 mixtures', CIGRE Report 163, August 2000, by Working Group 23.02; Task Force 01).

In the present extremely environmentally conscious climate (e.g.

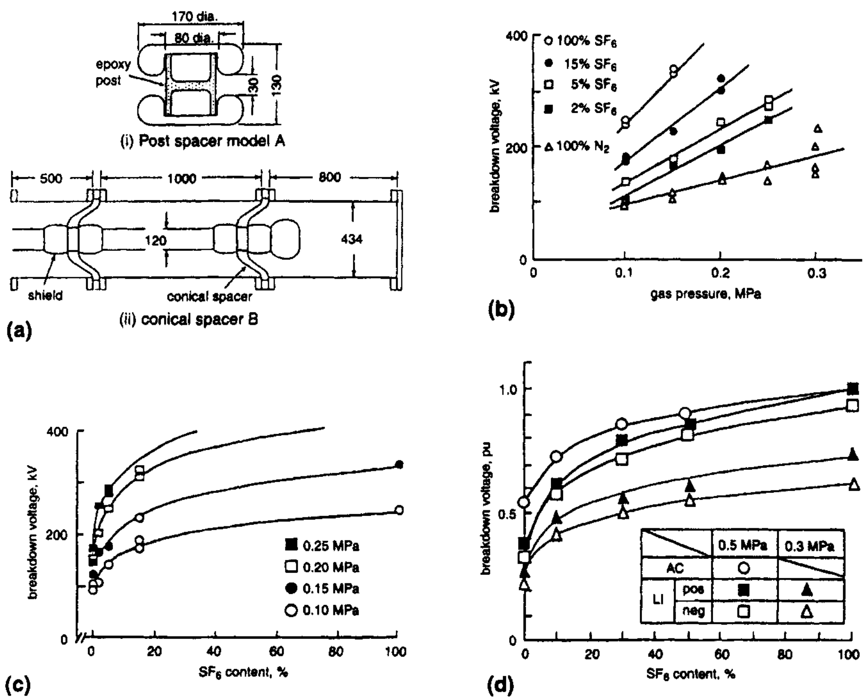


Figure 3.11 Further breakdown characteristics in N_2–SF_6 mixtures [29]

(a) *Spacers*
(b) *Pressure dependency of surface breakdown voltages of post spacer model A under clean condition; neg. LI, SF_6/N_2 mixed gas*
(c) *Dependence of negative LI surface breakdown voltages on SF_6 content under clean condition; post spacer model A, SF_6/N_2 mixed gas*
(d) *Dependence of breakdown voltages of conical spacer B on SF_6 content under clean condition in SF_6/N_2 mixed gas*

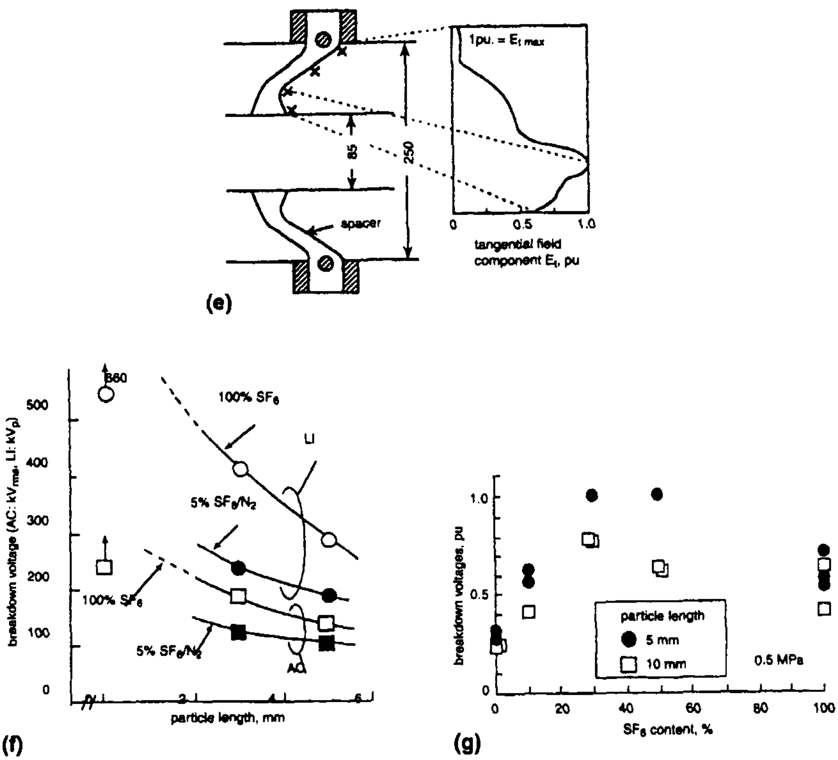


Figure 3.11 Further breakdown characteristics in N_2–SF_6 mixtures [29]

(e) *Conical spacer model C; × = attached particles*
(f) *Particle-initiated breakdown voltages of conical spacer C at 0.4 MPa*
(g) *Particle-initiated AC breakdown voltages of conical spacer B in SF_6/N_2 mixed gas*

concern regarding the depletion of Earth-shielding ozone by chlorofluorocarbons (CFCs) and the resulting large 'ozone hole' having opened up over Antarctica covering up to 11 million square miles), a major reduction of SF_6 gas requirement for large substations appears attractive to many people and this could well provide the 'incentive' for a strategic re-evaluation (see Figure 3.11) of N_2/SF_6 mixtures for gas insulated substations (GIS). Similarly, present day difficulties during planning/commissioning of certain new overhead line(s), due partly to delays caused by consideration of a plethora of 'alleged' environmental concerns raised by small protest groups, has resulted in serious consideration being given to the adoption of an alternative line technology, the so-called gas insulated line (GIL) approach. N_2/SF_6 gas mixtures have again been suggested and evaluation studies are currently being carried out by EDF and others in Europe.

Ternary gaseous dielectrics have been extensively investigated, such as $N_2 + SF_6$ or $CHF_3 + SF_6$, in conjunction with perfluorocarbons. Fluorocarbons, when mixed with SF_6, may exhibit interesting synergistic effects which at present are not fully explained. A variety of gaseous insulating systems has been investigated (see CIGRE Report 163, referred to above), comprising multi-component gas mixtures carefully selected on the basis of physicochemical knowledge, especially on the interactions of low energy electrons with atoms and molecules. Much valuable research work in this field has been carried out by a group, led for many years by L.G. Christophorou, at Oak Ridge National Laboratory, Knoxville, TN, USA.

3.4 Switchgear and GIS

3.4.1 Introduction

High voltage switchgear, which forms an integral part of any substation (i.e. switching station), is essentially a combination of switching and measuring devices [2, 17]. The switches (circuit-breakers), connect and disconnect the circuits and the measuring devices (instrument transformers), monitor the system and detect faults. Particular care must be given to the selection of switchgear since security of power supply is dependent on their reliability. The reliability of any circuit-breaker depends on insulation security, circuit-breaking capability, mechanical design and current carrying capacity. Considering modern switchgear practice, circuit-breakers can be broadly classified according to the insulating medium used for arc-extinction: bulk-oil; air-break; SF_6 gas; small oil-volume; air-blast; vacuum.

Several types exist for indoor or outdoor service conditions. There are established relationships between types of switchgear selected and the design of the system, Briefly, until about 1980: (i) for voltages up to 11 kV, most circuit-breakers were of the oil-break type, or of the air-break type, using air at atmospheric pressure; (ii) from 11 to 66 kV, oil circuit-breakers were mainly used while, at 132 and 275 kV, the market was shared by oil interrupters (both bulk-oil and small oil-volume) and gas blast circuit-breakers.

Recent developments have seen a move towards 'oil-free' devices and the increased demand for vacuum and 'rotating-arc' SF_6 circuit-breakers for distribution systems and the increased use of SF_6 circuit-breakers for system voltages 66 kV/132 kV, up to and beyond 565 kV. However, it should be appreciated that (i) modular 'small-oil-volume' designs proved to be popular for all but the highest ratings [2] and that earlier generation of 420 kV air-blast circuit-breaker designs, originally developed in the 1960s, are likely to remain in service in the UK grid for at least the first 20 years of this new millenium. Later chapters will discuss transmission and distribution switchgear, substation design, condition monitoring techniques together with the timely and topical themes of 'life management' of network assets and 'working systems harder' [18, 19].

Historically, it is worth noting that, in the 1960s, the second generation air-blast transmission circuit-breakers for 420 kV had six breaks per phase [2]. As stated in the previous paragraph, many of these designs are still in service in the UK grid. The prediction that such interrupters would develop to higher rating was not fulfilled and the recent trend has been towards compact SF_6 switchgear. By incremental research, it has been possible to develop SF_6 dead-tank circuit-breakers for 550 kV, 63 kA rating, with only two breaks per phase [20, 21]. Recent developments are discussed in Chapters 7–11.

3.4.2 Arc extinction media

The basic construction of any circuit-breaker entails the separation of contacts in an insulating 'fluid'. The insulating 'fluid' which fills the circuit-breaker chamber must fulfill a dual function. First, it must extinguish the arc drawn between the contacts when the circuit-breaker opens, and second, it must provide adequate, and totally reliable, electrical insulation between the contacts and from each contact to earth.

Selection of arc extinction 'fluid' is dependent on the rating and type of circuit-breaker. The insulating media commonly used for circuit-breakers are:

air	(at atmospheric pressure)
oil	(which produces hydrogen for arc-extinction)
compressed air	(at pressure 7 MPa)
sulphur hexafluoride, SF_6	(at pressure < 0.85 MPa)
vacuum.	

The principle of circuit interruption techniques and their application in circuit-breakers, either of single or multiple break design, is described in Chapters 7–11 and elsewhere [2, 20, 21]. However, it is appropriate to comment briefly here on interruption techniques, relevant to SF_6 circuit-breakers, to illustrate basic principles relevant to the application of gaseous/solid insulation systems. The complex discharge products of SF_6 are discussed in Chapters 7–10. Earlier studies have described extensive research and development [2] on interrupter nozzle performance, relevant to the design of air blast interrupters. Table 3.2 provides a convenient summary of single or double pressure SF_6 interrupter processes [4] together with a brief explanation of live-tank and dead-tank design philosophies.

Table 3.2 SF_6 circuit-breaker concepts [4]

Single or double-pressure

The flow of SF_6 gas necessary for circuit-breaking may be produced in either of two ways. In both cases, however, the actual process of current interruption is similar, i.e. the arc is established through a nozzle by the separation of the contacts and/or gas flow and is subjected to an 'axial' gas blast which abstracts energy from the arc, resulting in extinction at a current zero.

The gas flow may be achieved by the use of a two-pressure system (Figure A) whereby the operation of a blast valve allows gas to flow from a high pressure reservoir through a nozzle into a low pressure reservoir. The alternative is a single-pressure system (Figure B) where compression of the gas is caused by movement of a cylinder over a fixed piston (or vice versa). In this system, commonly called the 'puffer' (Figure C), the moving contact system and cylinder are usually joined together so that the movement of only a single component is necessary for arc initiation and interruption.

The single-pressure system is inherently less complicated than the double-pressure, which requires two separate gas reservoirs with associated seals, a compressor and gas-handling system, and heaters to prevent liquefaction at low temperatures. Furthermore, in the double-pressure system there is the necessity of synchronising the blast-valve and the contact driving systems.

Very high unit interrupting ratings can now be achieved with both systems,

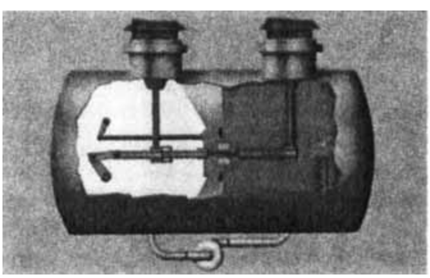


Figure A Double-pressure system

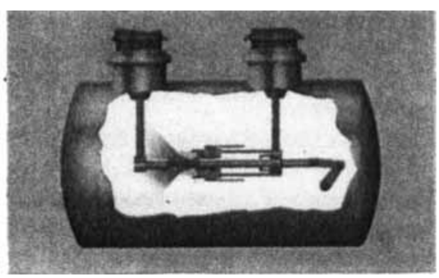


Figure B Single-pressure system

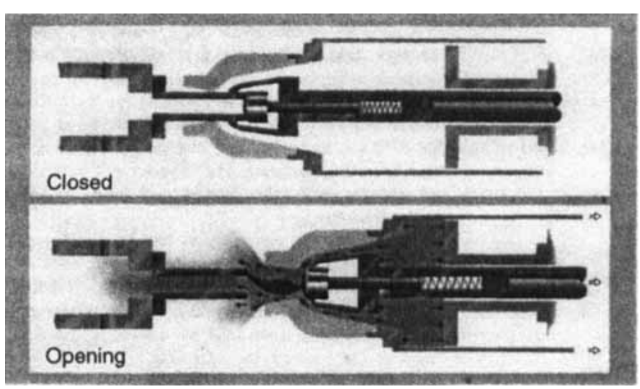


Figure C Single-pressure puffer system

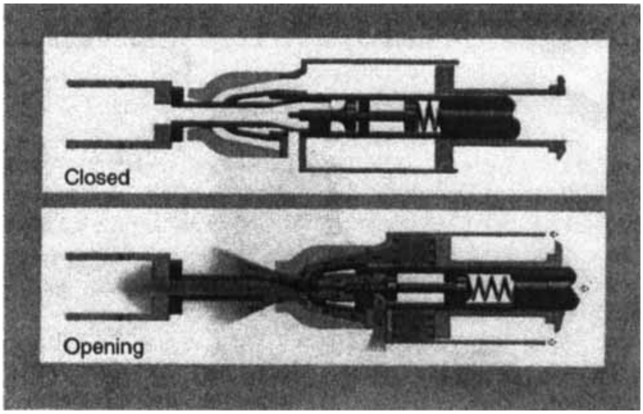


Figure D Partial duo-blast puffer system

though the high performance single-pressure system requires a more powerful operating mechanism to ensure a sufficiently high velocity for the contact/cylinder arrangement. This, however, is easily obtainable with either pneumatic or hydraulic power units, and at the lower performance levels, spring opening mechanisms also offer a practical alternative

Initially the performance limitations of the single-pressure system meant that earlier types of circuit-breaker incorporated double-pressure interrupters; but the continuing development of the single-pressure puffer interrupter has led to designs which are capable of the highest ratings. It seems likely, therefore, that such interrupter systems will be the basis of most future EHV circuit-breakers. They will also find wider application in the high voltage distribution field.

In any axial gas blast interrupter, the unit performance may be significantly improved by using a dual-blast construction in which the arc is drawn through two nozzles. In this construction, the gas now is towards both arc roots, and metal vapour from the contacts is not blown into the arc column. In the partial duo-blast construction (Figure D) one of these nozzles has a smaller diameter, which reduces the amount of gas passed through the nozzles and hence also the mechanical energy input without a significant reduction in performance compared to the full duo-nozzle construction. The Reyrolle puffer interrupters incorporate partial duo-blast constructions.

Live or dead tank

The SF_6 interrupter can be incorporated in either live-tank or dead-tank circuit-breakers (Figure E). The type chosen will depend on economics and/or the type of application; for example, the dead-tank construction (in which all interrupters are enclosed within an earthed pressure vessel) is essential for use in complete metal-clad installations, although the same breaker may be used with terminal bushings in open-type layouts. In assessing relative economics of live and dead-tank constructions, the cost of any associated current transformers should be considered. Accommodation for current transformers is, of course, integral in the dead-tank circuit-breaker, but separate post-type units are usually necessary with the live-tank design for outdoor installations. With indoor installations the current transformers may be accommodated in the through-wall bushings or cable-sealing ends.

Generally it might be expected that at the lower end of the voltage/current scale, where only one or two series breaks per phase are required, i.e. up to 420 kV the live-tank construction is probably more economical; but at higher voltages with three or four (or more) series breaks, the dead-tank construction tends to have an economic advantage because of the reduced amount of external insulation.

It is worthwhile noting that dead-tank circuit-breakers are inherently more suitable for areas subject to earthquakes.

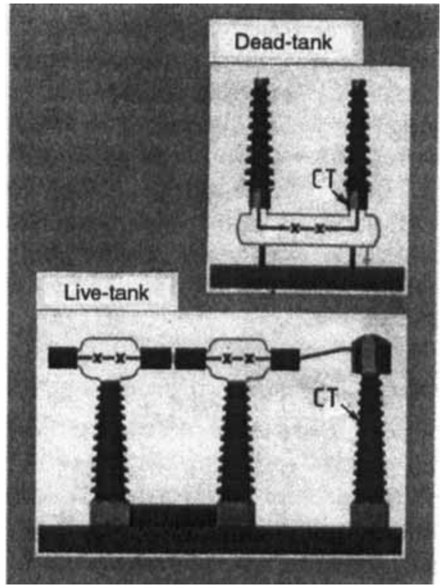


Figure E Live- and dead-tank circuit-breakers

(Courtesy NEI Reyrolle Ltd)

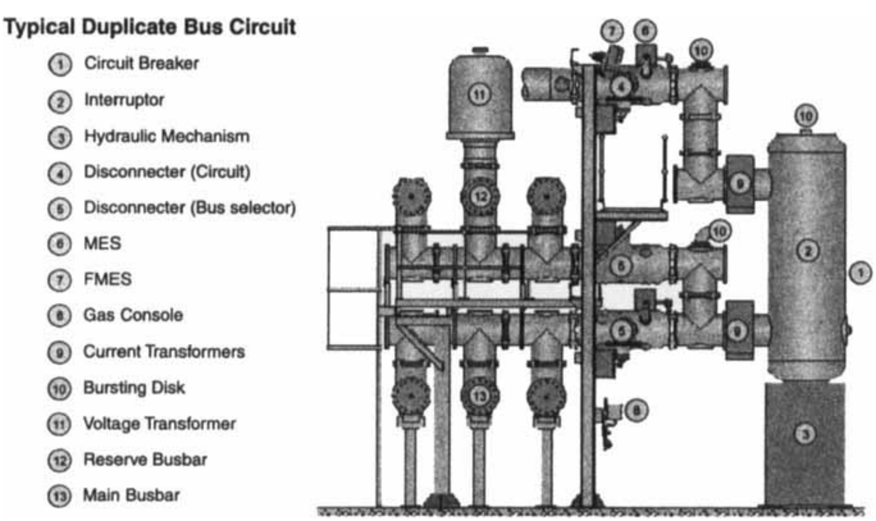


Figure 3.12 Sectional view through a typical 420/550 kV GIS duplicate busbar circuit (Courtesy VA Tech Reyrolle)

3.4.3 General dielectric considerations

Because of the widespread use of SF_6 insulated GIS (see Figures 3.12 and 3.13), it is appropriate to touch briefly on some general points relating to the dielectric performance of gas-gaps and gas/solid insulation interfaces in SF_6 under clean and contaminated conditions. The literature on this subject is vast, and extensive bibliographies exist (References 13, 23–28, for example), listing some important papers which can be arbitrarily grouped into topic areas: particulate contamination and detection, diagnostic techniques, operating experience, breakdown studies, internal-arcing, spacer experience and dielectric discharge performance.

3.4.3.1 Dielectric withstand capabilities, gas-gap data

Figure 3.14 shows a selection of typical SF_6 breakdown characteristics for the electrode systems illustrated in Table 3.3 [13]. From the vast amount of breakdown data accrued, the limits of lightning and switching impulse withstand gradient performance for a family of large practical GIS gas-gap type configurations were produced and are illustrated in Figure 3.15 for SF_6 pressures in the range $(0.1 < p < 0.6)$ MPa.

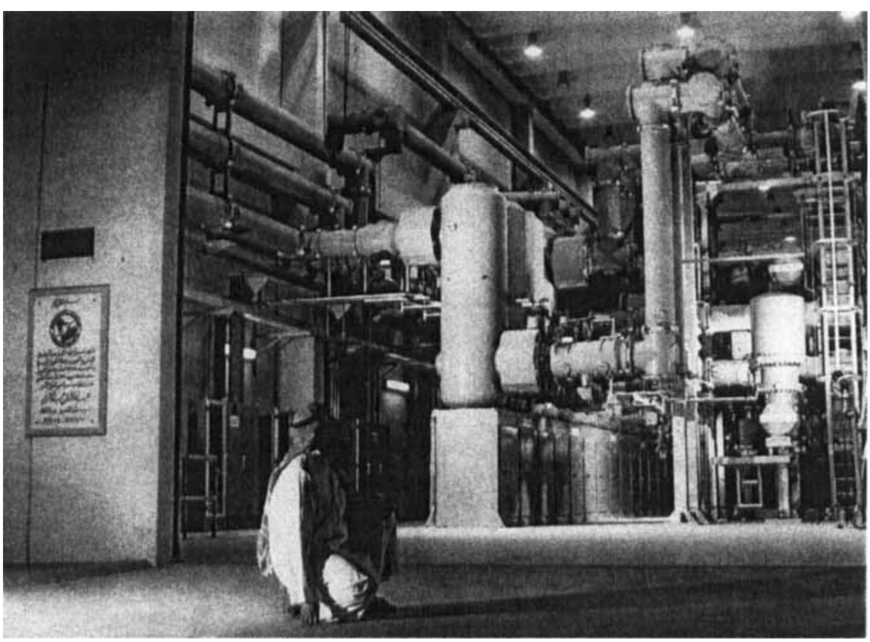


Figure 3.13 Example of 420 kV GIS equipment on a recent substation project in the Middle East (Courtesy VA Tech Reyrolle)

Waveshape	Electrode systems	Waveshape	Electrode systems
1 LI +ve	J	7 SWI +ve	E
2 LI −ve	J	8 SWI −ve	E
3 LI +ve	A	9 LI +ve	C
4 LI −ve	A	10 LI −ve	C
5 LI +ve	E	11 AC 50 Hz	I,G,H
6 LI −ve	E	12 LI −ve	I,G,H

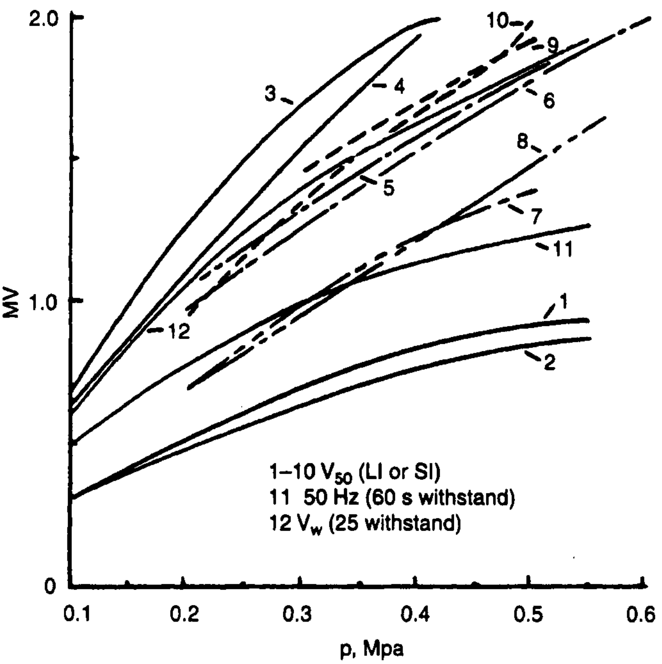
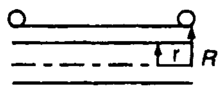
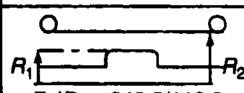
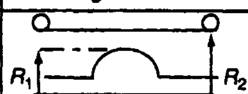
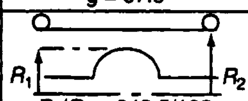
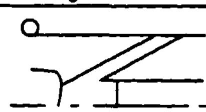
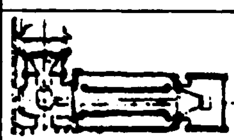
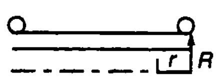
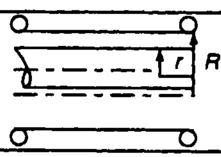


Figure 3.14 Example of SF_6 breakdown characteristics [13]

Experimental determination of critical breakdown (E_{50}) and highest withstand (E_w) gradient values were obtained using similar test techniques to those adopted previously [13] (i.e. $E = V/\eta g$; see Section 3.5.2). It should be emphasised that these curves present typical design type gradient relationships and encompass the results obtained for a large family of coaxial cylinder and perturbed electrode configurations for gas-gaps in the range $50 < g < 180$ mm. Theoretical breakdown gradient levels are also given in Figure 3.15(a–d); it is readily apparent that practical results deviate from theory as SF_6 gas pressure increases [13]. A corresponding withstand curve for 50 Hz conditions is also shown in both Figures 3.14 and 3.15.

To provide a better understanding of statistical variations possible with 50 Hz dielectric breakdown characteristics, relating to practical GIS

Table 3.3 Electrode systems [13]

Electrode system	Description	Shape	Size (mm)	HV electrode material
A,B,C	Concentric/ eccentric cylinders		R/r = 190/70 $S = 0$, $g = 120$ $S = 20$, $g = 100$ $S = 30$, $g = 90$	Aluminium
D	Perturbed cylinders	 $R_2/R_1 = 242.5/112.5$ $g = 130$	——	Stainless steel
E	Perturbed cylinders	 $R_2/R_1 = 317.5/250$ $g = 67.5$	——	Brass
F	Perturbed cylinders	 $R_2/R_1 = 242.5/125$ $g = 117.5$	——	Copper
G	Support* barrier		——	——
H	GIS RIG		$g \approx 160$	——
I	Concentric† cylinders		$R = 224$ $r = 64$ $g = 160$	Aluminium
J	Eccentric cylinders		$R = 285$ $r = 31.5$ $g = 40$	Aluminium

* various resin formulations have been studied, including, silica, alumina, bauxite and dolomite filled systems

† Using corrugated outer cylinder

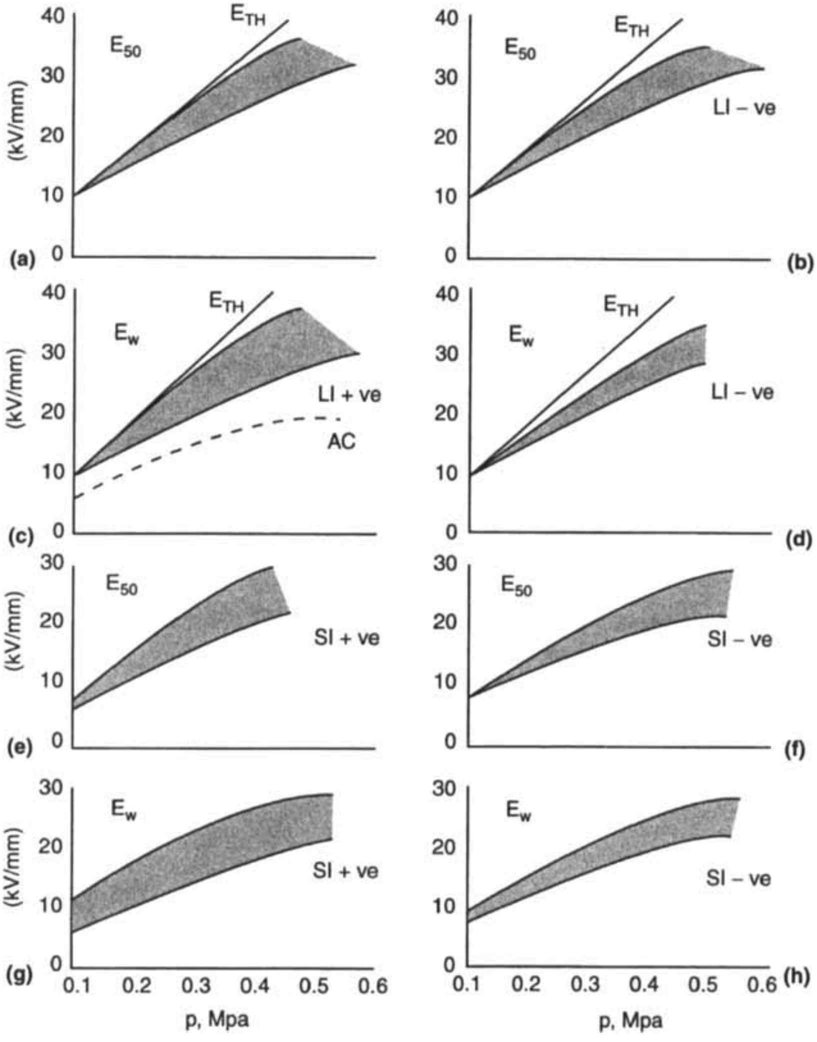


Figure 3.15 *Typical limits of 50% breakdown gradient (E_{50}) and critical withstand gradient (E_w) on SF_6 pressure for large coaxial and perturbed cylindrical electrode systems under clean conditions [13]*
Curves
(a), (b), (c), (d): *Lightning impulse (LI) waveshape (1.2/50 μs)*
(e), (f), (g), (h): *Switching impulse (SI) waveshape (250/2500 μs)*
– – – – *also shown in curve* c, *the lower limiting 50 Hz withstand characteristic (E_w)*
E_{50} data: curves a, b, e and f; E_w data: curves c, d, g and h

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type assemblies, it is relevant to consider the following results [13]. Figures 3.16–3.18 show the variation in individual short-term 50 Hz breakdown performance, with repeated sparking, for large perturbed and unperturbed cylindrical electrode systems. For comparison, the

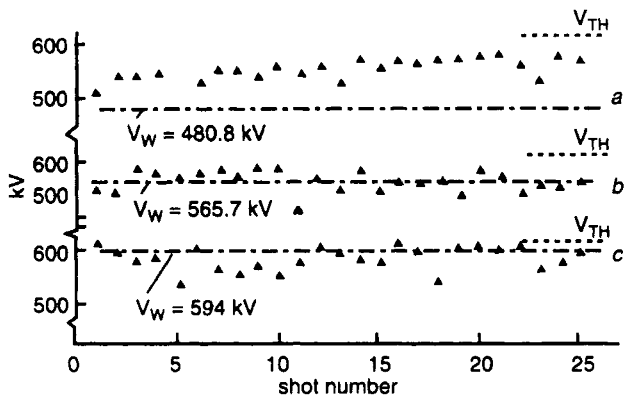

Figure 3.16 *Sequence of 50 Hz breakdown levels in SF_6 for concentric cylinders - electrode system A (SF_6 pressure: 0.1 MPa)*

- – – V_{TH} *Theoretical breakdown level (621.6 kV)*
- * *(based on $(E/p)_{lim}$ = 89 kV mm^{-1} MPa^{-1}*
- ▲ *individual spark breakdown*
- *p *'PIP' - partial (incomplete) breakdown*
- V_w *maximum (1 min) withstand level, established immediately prior to test runs a, b or c, respectively*

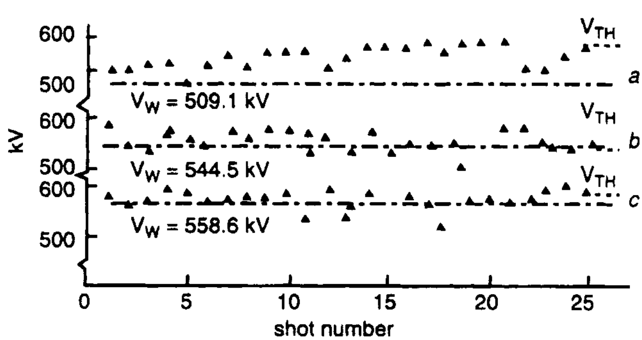

Figure 3.17 *Sequence of 50 Hz breakdown levels in SF_6 for perturbed electrode system F (SF_6 pressure: 0.1 MPa)*

- – – V_{TH} *Theoretical breakdown level (574 kV)*
- * *(based on $(E/p)_{lim}$ = 89 kV mm^{-1} MPa^{-1}*
- ▲ *individual spark breakdown*
- *p *'PIP' partial (incomplete) breakdown*
- V_w *maximum (1 min) withstand level, established immediately prior to test runs a, b or c, respectively*