Chapter 8

Switchgear design, development and service

S.M. Ghufran Ali

8.1 Introduction

This chapter describes the design, development and operation of switchgear [1–7]. It also describes how the development of generation and transmission has influenced switchgear evolution (Appendix). Factors which have contributed to the simplicity of design and increased the reliability of SF_6 switchgear are addressed and the important features of various manufacturers designs in first, second and third generation interrupters and improvements in circuit-breaker performance are highlighted. It also addresses issues associated with installation and on-site operations and monitoring.

8.1.1 SF_6 circuit-breakers

A circuit-breaker is a device which breaks or interrupts the flow of current in a circuit. It is used for controlling and protecting the distribution and transmission of electrical power. It is connected in series with the circuit it is expected to protect. It has to be capable of successfully:

- interrupting (i) any level of current passing through its contacts from a few amperes to its full short-circuit currents, both symmetrical and asymmetrical, at voltages specified in IEC 62271–100 and (ii) up to 25% of full short-circuit currents at twice the phase voltage
- closing up to full short-circuit making current (i.e. $2.5 \times I_{sym}$) at phase voltage and 25% of full making currents at twice the phase voltage
- switching (making or breaking) inductive, capacitive (line, cable or capacitor bank) and reactor currents without producing excessive overvoltages to avoid overstressing the dielectric withstand capabilities of a system

- performing opening and closing operations whenever required
- carrying the normal current assigned to it without overheating any joints or contacts.

This interrupting device becomes more complex as the short-circuit currents and voltages are increased and, at the same time, the fault clearance times are reduced to maintain maximum stability of the system.

A circuit-breaker has four main components: (i) interrupting medium (sulphur hexafluoride gas), (ii) interrupter, (iii) insulators and (iv) mechanism.

8.1.2 Sulphur hexafluoride

The pure SF_6 is odourless and nontoxic but will not support life. Being extremely heavy (4.7 times denser than air) it tends to accumulate in low areas and may cause drowning. It is a gas with unique features which are particularly suited to switchgear applications. Its high dielectric withstand characteristic is due to its high electron attachment coefficient. The alternating-voltage withstand performance of SF_6 gas at 0.9 bar(g) is comparable with that of insulating oil. SF_6 has the added advantage that its arc voltage characteristic is low, and hence the arc-energy removal requirements are low.

At temperatures above 1000 °C, SF_6 gas starts to fragment and at an arc-core temperature of about 20 000 °C, the process of dissociation, accelerates producing a number of constituent gases including S_2F_{10}, which is highly toxic (see Figures 7.10 and 8.1). However, these recombine very quickly as the temperature starts to fall and the dielectric strength of the gap recovers to its original level in microseconds. This allows several interruptions in quick succession.

The solid arc products consist mainly of metal-fluorides and sulphides with elemental sulphur, carbon and metal oxides. These are acidic and must not be inhaled. Metallic fluorides formed during the arcing do not harm the switchgear components provided the moisture in the interrupting chamber is absorbed by the molecular sieve. The dielectric integrity of the equipment is not impaired by the presence of these fluorides and sulphides.

8.2 Interrupter development

The key component in any circuit-breaker is the interrupter. Early EHV interrupters were two-pressure type, and these were superseded by the single-pressure puffer type in the early 1970s.

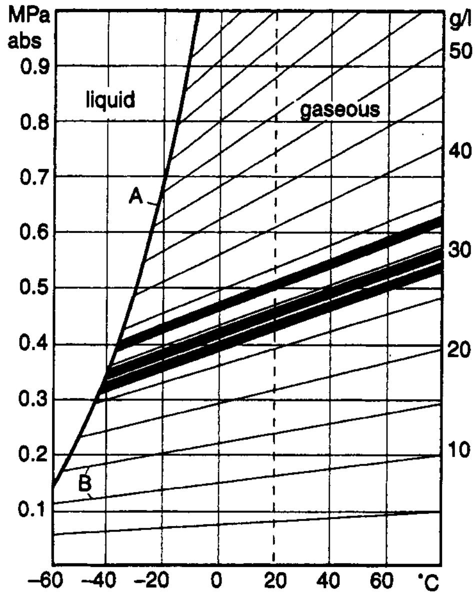


Figure 8.1 *Pressure-temperature diagram for SF_6 gas. A is the liquefaction line and B are density lines*

8.2.1 Two-pressure system

In the late 1960s and early 1970s, SF_6 EHV interrupters were based on the well-established two-pressure air-blast technology modified to give a closedloop for the exhaust gases. SF_6 gas at high pressure ($\approx$15 bars) was released by the blast valve through a nozzle to a low pressure reservoir instead of being exhausted to atmosphere. The gas was recycled through filters then compressed and stored in the high pressure reservoir for subsequent operations. Heaters were used to avoid liquefaction of the high pressure gas at low temperatures.

The relative cost and complexity of design led to the development of inherently simpler and more reliable single-pressure puffer type interrupters.

8.2.2 Single-pressure puffer type interrupters

8.2.2.1 First generation interrupters

The principle of a single-pressure puffer type interrupter is explained by the operation of universally known device – a 'cycle pump' – where air is compressed by the relative movement of a piston against a cylinder. In a puffer type interrupter, SF_6 gas in the chamber is compressed by the movement of the cylinder against the stationary piston. This high pressure gas is then directed across the arc in the downstream region through the converging/diverging nozzle to complete the arc-extinguishing process. The basic arrangement of the puffer type interrupters can be classified according to the flow of compressed SF_6 gas. These are generally known as mono, partial-duo and duo blast interrupters (Figures 8.2 and 8.3).

All types of interrupters are capable of high short-circuit current rating, but superior performance is generally achieved by either partial-duo or duo blast construction because most of the hot gases from the arc are directed away, giving the improved voltage recovery of the contact gap. Most of the puffer type interrupters have been developed for 50 to 63kA ratings, and some even for 80 and 100kA rating.

For a puffer type interrupter, retarding forces act on the piston surface as the contacts part. These forces are due to the total pressure-rise generated by compression and heating of SF_6 gas inside the interrupting chamber and are highest with maximum interrupting current and arc duration. Therefore, to provide consistent opening characteristics for all short-circuit currents up to 100% rating, high energy mechanisms are required.

8.2.2.2 Second generation interrupters

Worldwide development in the second generation interrupter concentrated on:

- rationalisation of designs
- improving the short-circuit rating of interrupters
- better understanding of the interruption techniques
- improving the life of arcing contacts
- reducing the ablation rate of nozzles by using different nozzle filling materials.

Most of the present day SF_6 circuit-breaker designs are virtually maintenance-free. This means that the arcing contacts and nozzles on the interrupters have been designed for long service life.

Most arcing contacts are fitted with copper-tungsten alloy tips. The erosion rate of these tips depends on the grain size of tungsten, the copper to tungsten ratio, cintering process and production techniques. The choice of the copper-tungsten alloy is therefore essential for both the erosion rate of the tips and the emission of copper vapour, which influences the recovery rate of the contact gap.

The nozzle is the most important component of a puffer type interrupter. The interruption characteristic of an interrupter is governed by nozzle geometry, shape, size and nozzle material.

In the western world, at present there are only nine EHV circuit-breaker manufacturers – ABB, AEG, GEC-Alsthom (now Alstom),

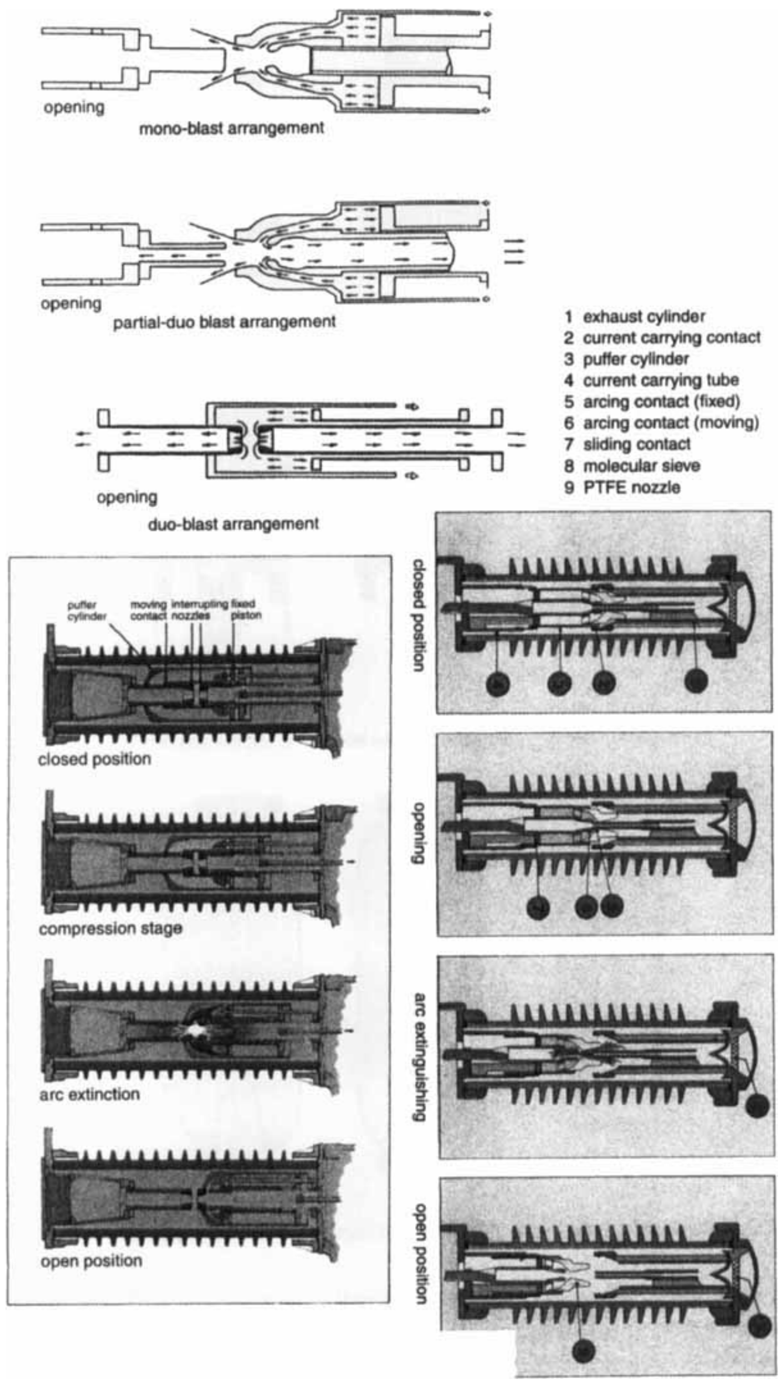


Figure 8.2 Principles of SF_6 puffer type interrupters

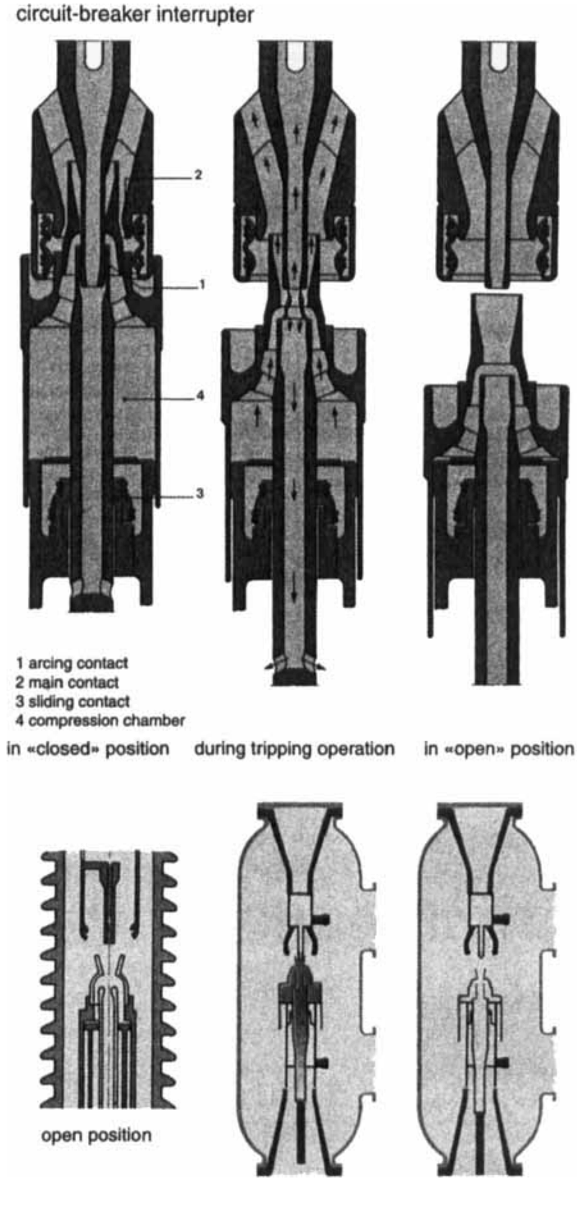


Figure 8.3 First and second generation interrupter circuit-breakers

Hitachi, Merlin Gerin, Mitsubishi, Reyrolle, Siemens and Toshiba. The nozzles on these circuit-breakers can be classified into two categories – long and short. There is no evidence available to show that at 550 kV the dielectric performance of the long-nozzle is superior to that of short-nozzle, since most of the designs have achieved 50/63kA ratings at

420/550 kV. It is, however, very clear that the rate of nozzle ablation very much depends on the choice of material, which could be either pure (virgin) PTFE or filled PTFE.

Pure PTFE is white in colour and is most commonly used because of its reasonable price. The rate of ablation of pure PTFE is relatively high and very much depends on grain size, moulding or compacting pressure, cintering procedure and quality of machining and surface finish. It has also been observed that the radiated arc energy penetrates deep in the body, producing carbon molecules. To overcome this, some manufacturers use coloured PTFE which absorbs the radiated arc energy on the surface and prevents deep penetration.

To ensure consistent performance with reduced rate of ablation and long life, most manufacturers use filled PTFE for high short-circuit currents interruption (in the region of 63 kA and above).

There are three types of filling: boron nitride (cream colour), molybdenum (blue colour) and aluminium oxide (white).

Since the ablation rate of the filled nozzles is low, the change in nozzle throat diameter after about 20 full short-circuit interruptions is normally very small. The pressure rise characteristic of the interruption hardly changes and therefore the performance of the interrupter remains consistent, giving a long, satisfactory service life.

Filled PTFE material is slightly more expensive than pure PTFE, but its consistent performance and extra-long life justifies its use on high current interrupters. Some examples of PTFE nozzles are shown in Figure 8.4.

8.3 Arc interruption

8.3.1 Fault current

Present day transmission circuit-breaker designs are based on single-pressure puffer type SF_6 interrupters. The gas flow is produced by the self-generated pressure difference across the nozzle, either by the movement of the cylinder against the stationary piston, or by the simultaneous movement of both the piston and cylinder. The magnitude and the rate of rise of the no-load pressure rise depends on the interrupter design parameters. These are: diameter of the cylinder, nozzle geometry, throat area, swept volume and opening speed.

During fault current interruption, an arc is drawn between the moving and fixed arcing contacts or between the two fixed arcing contacts. The throat area of the nozzle is partially or completely choked by the diameter of the arc, while the arc energy heats up the SF_6 gas in the interrupting chamber, thus causing a substantial pressure rise (Figure 8.5).

The total pressure rise inside the interrupting chamber consists of the

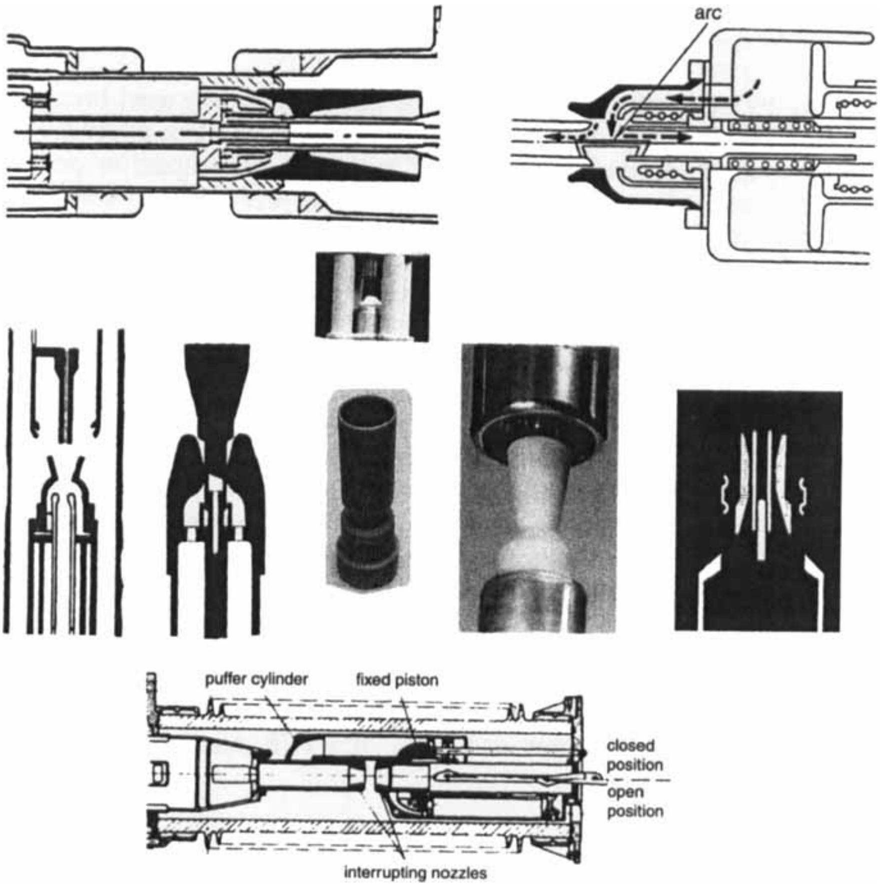


Figure 8.4 Examples of PTFE nozzles

no-load pressure-rise and the arcing pressure rises which produce a considerable pressure difference between the upstream and downstream regions of the nozzle. This pressure difference causes a sonic flow of relatively cold SF_6 gas across the arc. This fast movement of SF_6 gas makes the arc unstable and removes heat energy and in the process cools the arc.

If the rate of recovery of the contact gap at the instant of current zero is faster than the rate of rise of the recovery voltage (RRRV), the interruption is successful in the thermal region (i.e. first 4–8 μs of the recovery phase), followed by successful recovery voltage withstand in the dielectric region (above 50 μs) and then full dielectric withstand of the AC recovery voltage. This whole process is known as successful fault current interruption.

If, however, the RRRV is faster than the recovery of the gap, then failure occurs either in the thermal region, or in the dielectric region after clearing the thermal region.

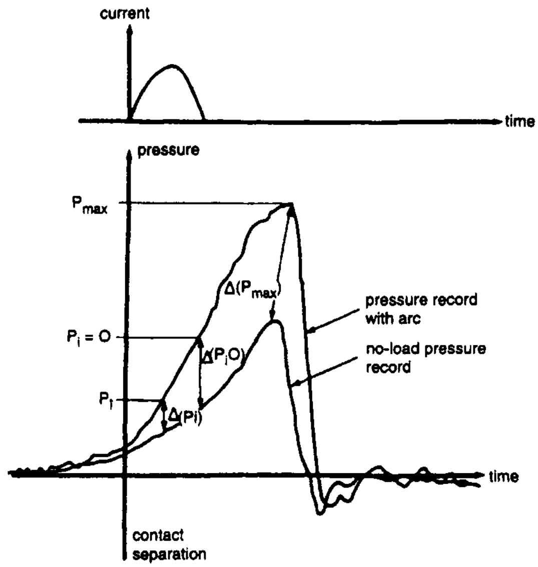


Figure 8.5 Pressure-rise characteristic in a puffer type interrupter

Over the past 30 years, researchers worldwide have carried out very useful work which has brought better understanding of the physical processes associated with the arc interruption at and near current zero. Computer models and programmes have been developed which can accurately predict the performance of an interrupter at, and near, current zero. However, in a real interrupter the recovery process in the dielectric region (i.e. above 50 μs) is very complex, since it is influenced by many factors. These include contact and nozzle shapes, arc energy, gas flow, rate and nature of ablation of nozzle material, rate and amount of metal vapour present in the contact gap, dielectric stress of the gap, dielectric stress on the contact tips and the proximity effect of the interrupter housing.

The dielectric aspect of interruption is not yet fully resolved and to the author's knowledge accurate prediction is not possible at present.

8.3.2 Capacitive and inductive current switching

When a puffer type interrupter switches small inductive (transformer and reactor) or capacitive (line, cable, capacitor bank) currents, it relies entirely on its no-load pressure rise characteristic, since there is practically no contribution of pressure from these small load current arcs.

The magnitude of the no-load pressure rise and the gas flow across the nozzles determines whether the current is interrupted at, before (on falling-current) or after (on rising-current) current zero.

If the current is interrupted at current zero, the interruption is normal and the transient recovery voltages are within the specified values.

However, when premature interruption occurs due to current chopping the interruption is abnormal – it causes high frequency reignitions and overvoltages. If the interrupter chops the peak current, the voltage doubles instantaneously. If this process is repeated several times due to high frequency reignitions, the voltage doubling continues with rapid escalation of voltages (Figure 8.6). When these overvoltages exceed the specified dielectric strength for the switchgear, the interrupter and/or other parts of the switchgear may be damaged.

The phenomena of chopping and reignition is attributed to the design of an interrupter. Most of the EHV interrupters are designed to cope with high fault currents, up to 63 kA in the UK and up to 80 kA in some other countries. If a design is concentrated only on performance of high currents with high, no-load pressure rise in the interrupting chamber, it will be too efficient for small current and will try to interrupt before its natural current zero. This efficiency sometimes works against it and produces the phenomenon of current chopping and reignitions with adverse consequences.

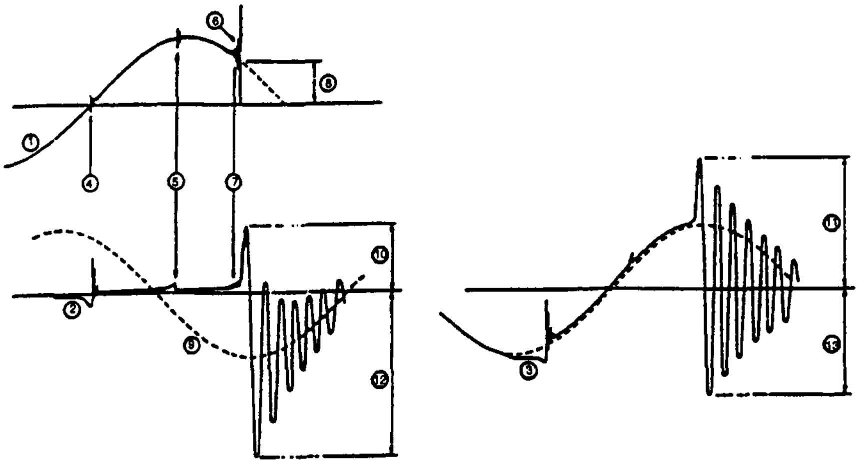
The interrupter design should therefore incorporate features which cope equally well with small as well as high currents (i.e. softer interruption). It is sometimes desirable to have a softer interrupter to give satisfactory performance for all conditions.

8.3.3 Reactor switching

In a high voltage system, reactors are used for system VAr compensation. These are connected either directly onto the high voltage system with EHV circuit-breakers, or to the low voltage delta, tertiary windings of the auto-transformer (at 12 or 33 kV) by MV circuit-breakers. The shunt reactors are frequently switched at least two to three times per day. The SF_6 circuit-breakers for this duty are expected to carry out about 5000 satisfactory switching operations on one set of contacts and nozzles.

Service experience worldwide has shown that this switching duty can cause difficulty for some circuit-breaker designs which were earlier tested satisfactorily, on available standard circuits at the major testing stations. It is generally acknowledged that those circuits did not truly represent the site conditions.

The mechanism of reactor current interruption, the phenomena of current chopping and multiple reignitions, and the generation of high frequency oscillatory overvoltages are well understood. It has been established that the high frequency oscillations are governed by the electrical circuit in a given system, configuration and the interrupter design (i.e. load side capacitance, load side inductance, inductance of the busbars, value of parallel capacitance across the interrupter (including the grading capacitance), inductance of the loop formed by the grading capacitors, and no-load pressure rise characteristic of the interrupter).



Chopping phenomena in a single-phase circuit

1 current to interrupt
2 voltage across circuit-breaker
3 voltage across inductive load
4 failed interruption due to reignition (short contact distance)
5 influence of arc voltage
6 current instability oscillation leading to current chopping
7 arc voltage oscillation
8 effective chopping level
9 main power frequency voltage
10 suppression peak, first voltage maximum across circuit-breaker
11 first voltage maximum across inductive load
12 recovery voltage peak, second voltage maximum across circuit-breaker
13 second voltage maximum across inductive load

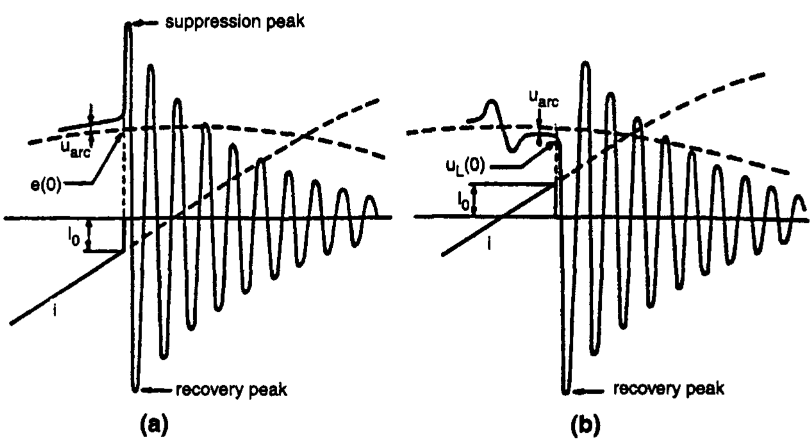


Figure 8.6 *Overvoltages from inductive current chopping and reignitions. Lower diagrams show current chopping* **(a)** *before and* **(b)** *after natural current zero*

Since one or all the above parameters could be variable, the issue becomes extremely complex. IEC Subcommittee, CIGRE Working Groups and ANSI have examined various aspects to produce universally acceptable switching test guidelines and a test circuit. The most recent IEC Document IEC 61233 – gives a circuit for testing and application guide for assessing the general performance of a circuit-breaker.

Until IEC provides a final solution, it is recommended that site measurements and system studies should be carried out to ensure that as realistic a circuit as possible is used for testing a circuit-breaker on that site. In addition, where possible 'R' and 'C' damping circuits and metal-oxide surge arresters should be used to ensure safe operation. Failing that, there could be very costly and serious consequences for the users. Some examples are described below.

The overvoltages produced by chopping and high frequency reignition can result in the following:

(i) For extra high voltage circuit-breakers:

- tracking on the nozzle surface and nozzle puncturing
- dielectric failure on switchgear
- flashover inside the circuit-breaker causing explosion in open terminal circuit-breakers and severe damage.

(ii) High voltage circuit-breakers:

- catastrophic damage to circuit-breakers
- resonance between the high frequency overvoltages and transformer windings, possibly causing damage to the tertiary windings, loss of transformer and loss of supply.

8.3.4 Arc interruption: gas mixtures

Pure SF_6 gas is very efficiently used in the present day commercial circuit-breakers to interrupt high currents up to 63 and 80 kA. It is, however, an expensive gas and, at common operating pressures of 6 bar(g), it starts to condense at – 20 °C and in its pure form it is not suitable for operation at lower ambient temperatures. When the ambient temperature becomes too low (i.e. – 50 to – 60 °C) the gas starts to liquefy and the interrupter contains a mixture of SF_6 gas, liquid droplets and fine mist. This mixture affects the gas flow conditions in the nozzle and transfer of thermal energy from the arc, thus impeding the performance of the breaker.

The need for more efficient and economical transmission switchgear which can operate satisfactorily at temperatures down to – 50 °C in Canada, Scandanavian countries and Russia has stimulated the search for new gases and gas-mixtures, as a potential replacement for pure SF_6 gas in puffer type circuit-breakers. Extensive research in the USA, Japan and Europe has confirmed that at present no single gas tested is found to be superior to pure SF_6 gas in all aspects of dielectric withstand capability and arc interruption.

Several gas mixtures have been studied with the objective of exploiting the properties of the component gases so that they could be used effectively in switchgear. A survey of some of the published work on various gas mixtures has shown that the performance of several gas mixtures appears very promising.

One such mixture is SF_6/nitrogen (N_2). Its dielectric strength at about 15% increased pressure equals that of pure SF_6 gas at normal pressure. The mixture is less sensitive to strong localised electric fields and can be operated at higher pressures up to 6 bar or at lower temperatures down to −50 °C, with potential cost savings of up to 35%. While the dielectric strength of the clean SF_6/N_2 gas mixture is extremely encouraging, its interrupting performance does not compare favourably with pure SF_6 gas. The short-circuit rating of an SF_6/N_2 circuit-breaker at −50 °C is normally degraded by one level of the IEC standard rating (i.e. a 50 kA circuit-breaker is generally used for 40 kA rating).

Work is in progress worldwide to find a suitable mixture which can be used efficiently down to −50 °C ambient temperature without penalising its short-circuit or dielectric performance. I understand that some manufacturers have achieved this and hopefully soon the breakers with such gas mixtures will be commercially available.

8.4 Third generation interrupters

Puffer type interrupters require drive mechanisms to provide energy for moving the cylinder of the interrupter at relatively high speeds of 6 to 9 m/s. The fast movement of the cylinder compresses the SF_6 gas. The high pressure rise upstream of the nozzle due to compression and arc heating of the gas is required for quenching the longest possible arcs associated with both the single-phase to earth fault and the last phase to clear condition of the three-phase fault. This results in very complex and powerful drives which exert high reaction forces on dashpots, seals, joints, structures and foundation, and affects the reliability and cost of a circuit-breaker. The experience over the last 15 years has shown that the majority of failures on site are mechanical. Therefore switchgear manufacturers have concentrated their efforts on producing simple interrupting devices and reliable and economical mechanisms. To achieve this, they have addressed the fundamental issue of reducing the retarding forces on the drive mechanisms during an opening stroke. This work has led to the development of third generation interrupters which have the following improved design features and economies compared with first and second generation interrupters:

(a) 10 to 20% reduction in energy has been achieved by optimising the puffer type interrupter designs, which ensures that the maximum arc duration for the highest current does not exceed 21 ms.

(b) 50 to 60% reduction in drive energy has been achieved by skilfully utilising the arc energy to heat the SF_6 gas, thus generating sufficient high pressure to quench the arc and assist the mechanism during the opening stroke.

At least two switchgear manufacturers have successfully used this principle to produce low energy circuit-breakers (Figure 8.7). The design criteria depend on optimising the volumes of the two chambers of the interrupter:

(a) the expansion chamber, to provide the necessary quenching pressure by heating the gas with arc energy
(b) the puffer chamber, to provide sufficient gas pressure for clearing the small inductive, capacitive and normal load currents.

The optimum sizes of these chambers are determined by detailed computer studies of the arc input and output energies, temperature profiles, gas flow, the quenching and total pressures.

The main advantages of this design concept are as follows:

(a) softer interruption producing low overvoltages for switching small inductive and capacitive currents
(b) low energy mechanisms, lighter moving parts, simpler damping devices and reduced loads on foundation and other switchgear components
(c) long service life, at least 10 000 trouble free operations
(d) increased reliability and low cost circuit-breakers.

8.5 Dielectric design and insulators

On EHV circuit-breakers for voltages up to 550 kV, the number of interrupters per phase has decreased from six to one. Therefore the dielectric performance has become extremely important. To optimise the designs, it is essential to carry out detailed stress analysis studies for all critical components, using sophisticated computer programmes and CAD systems.

Most of the major manufacturers have developed their own computer programmes, and their designs are based on stress levels from past experience. These CAD techniques are used to optimise the shapes of stress shields, contacts and insulators. They also optimise stress levels on stress shields, gaps, grading capacitors (if any), support insulators and drive rods.

In addition to the proper stressing of components, it is extremely important to choose the correct insulating material, since the presence of the degradation products inside the circuit-breaker can damage the silica

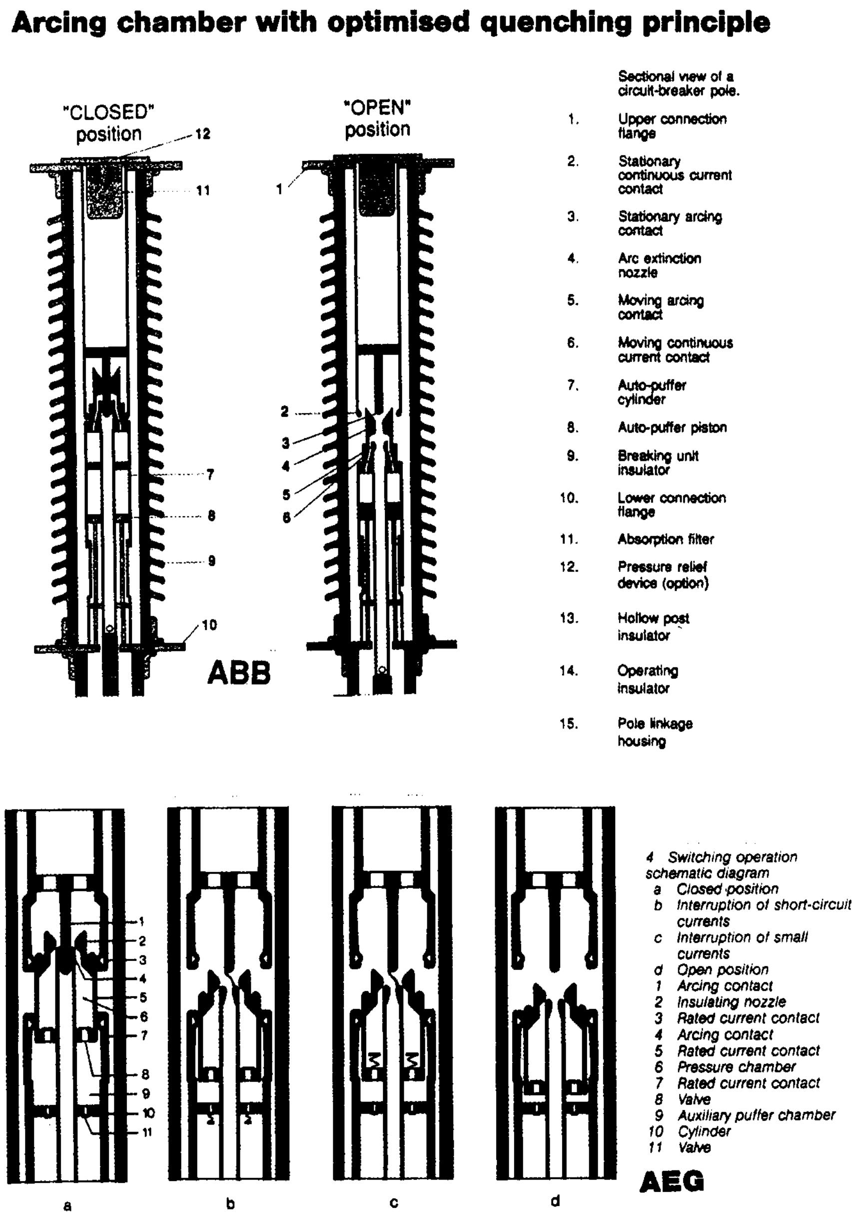


Figure 8.7 Third generation interrupter circuit-breakers

base insulators. Long term resistance of insulating material to SF_6 degradation products is essential and most manufacturers have chosen alumina-filled cast resin insulators or the designs which prevent direct contact of degradation products with the surface of silica base insulators. Field computation relating to switchgear design has been covered elsewhere in detail [1].

8.6 Mechanism

The operating mechanism is a very important component of a circuit-breaker. When it operates, it changes the circuit-breaker from a perfect conductor to a perfect insulator within a few milliseconds. A failure of the mechanism could have very serious consequences. It is therefore essential that the mechanism should be extremely reliable and consistent in performance for all operating conditions.

The circuit-breaker may have one or three mechanisms, depending on the operational requirements – either single-phase or three-phase reclosing. The mechanisms fitted to the circuit-breakers are hydraulic, pneumatic or spring, or their combination. The circuit-breaker mechanisms used by manufacturers are grouped as follows:

Pneumatic	Close	and	Pneumatic	Open
Hydraulic	Close	and	Hydraulic	Open
Spring (motor charged)	Close	and	Spring	Open
Hydraulic	Close	and	Spring	Open
Pneumatic	Close	and	Spring	Open

The number of operating sequences and the consistency of closing and opening characteristics generally determines the performance of the mechanism. Although IEC 62271–100 type tests require only 2000 satisfactory operations to prove its performance, the present tendency is to carry out 5000 extended trouble-free operations tests to demonstrate the compatibility of these mechanisms with the SF_6 circuit-breakers, which are virtually maintenance-free.

The task of the third generation SF_6 circuit-breakers, which are fitted with low energy mechanism and lightweight moving parts, becomes much easier. They satisfactorily perform 10 000 trouble-free operations without any stresses and excessive wear and tear on the moving and fixed parts of the breaker.

8.7 SF_6 live- and dead-tank circuit-breakers

In live-tank (AIS) circuit-breakers the interrupters are housed in porcelain insulators. The interrupter heads are live and mounted on support insulators on top of a steel structure to conform with the safety clearances (Figures 8.8*a* and *b*). In dead-tank circuit-breakers the interrupters are housed in an earthed metal tank, usually of aluminium, mild or stainless steel, depending on the current rating. The GIS circuit-breakers could be of either vertical or horizontal configuration. Four switchgear manufacturers in the world produce horizontal EHV circuit-breakers, while the rest have vertical designs (Figures 8.9*a* and *b*).

The live-tank circuit-breakers are generally used in open-terminal outdoor substations (Figures 8.8*a* and *b*), while the dead-tank circuit-breakers are used in GIS indoor and outdoor substations (Figures 8.9*a* and *b*). Both types of circuit-breakers have been developed for ratings up to 63 kA at 525 kV and have given satisfactory service all over the world during the past two decades. The choice of the type of circuit-breaker, however, depends on many factors. Some of these are:

- cost of the switchgear
- atmospheric pollution
- potential environmental restrictions
- price and availability of the land
- individual preference
- security against third party damage.

In locations where the price of land is high (i.e. in the centre of cities) the GIS option becomes very attractive because it drastically reduces the overall dimensions of a substation. For example, at 420 kV, the ratio of land required for a GIS installation to that necessary for an open-terminal substation is about 1:8.

8.7.1 Basic GIS substation design

GIS substations are of two types – outdoor and indoor. The basic design of both indoor and outdoor switchgear is the same but the switchgear for outdoor substations requires additional weather-proofing to suit climatic conditions. Both substation types have been in service throughout the world over the last two decades and have given satisfactory performance.

In Japan, most SF_6 GIS installations are located outdoors without a protective building and have been in service since 1969. In the UK, GEC and Reyrolle SF_6 GIS installations have been in use outdoors since 1976, notably at Neepsend (1976) and Littlebrook (1979). To the author's knowledge there have been no major failures in either country.

Recently in the UK, there has been a trend in favour of indoor GIS substations for technical and environmental reasons. SF_6 GIS equipment requires clean, dry and particle free assembly for safe operation. The assembly and dismantling of outdoor GIS equipment in the UK has been carried out in the past under a portable tent, and internal drying of the GIS chambers has been achieved by circulating dry nitrogen. This

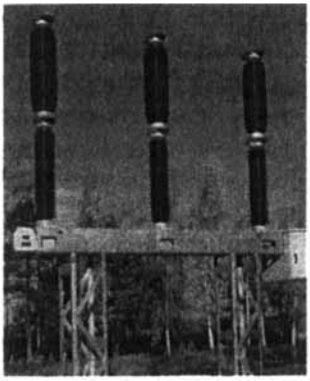
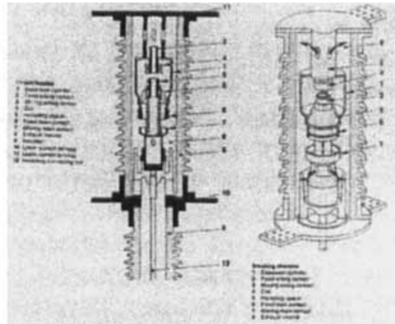
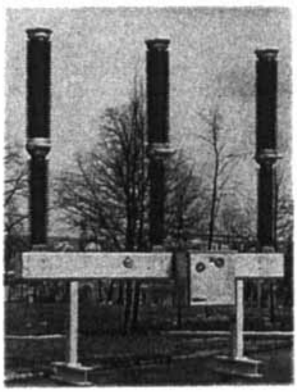


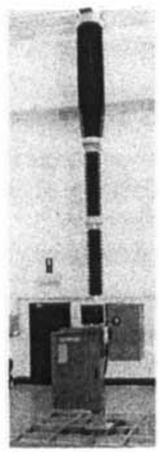
ABB 145/170 kV



MERLIN GERIN 145 kV

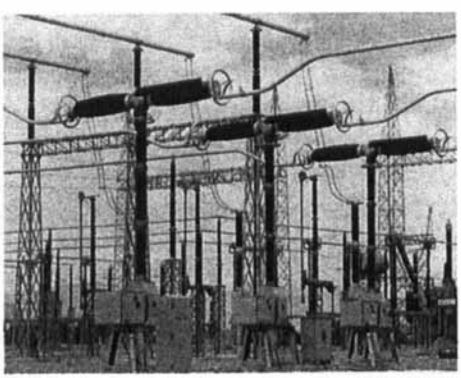


ALSTOM 145 kV

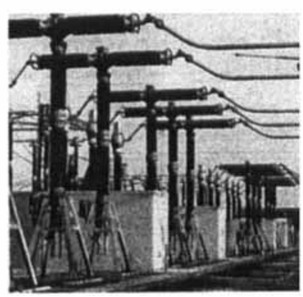


SIEMENS 300 kV

REYROLLE 300 kV



ALSTOM 300 kV



REYROLLE 420/525 kV

Figure 8.8a Examples of SF_6 live tank (AIS) circuit-breaker installations

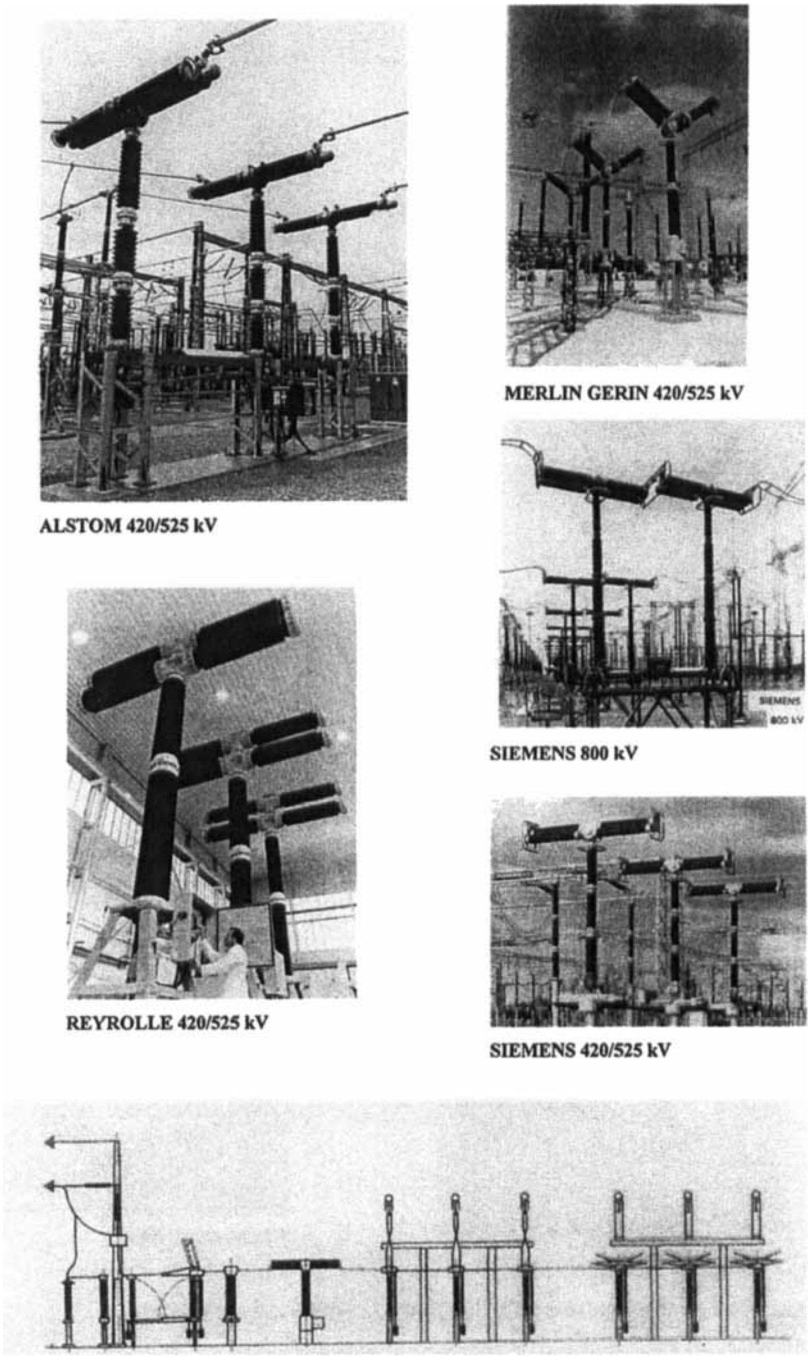


Figure 8.8b Examples of SF_6 live tank (AIS) circuit-breaker installations

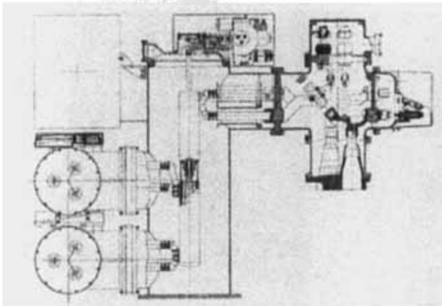


ABB 123 kV

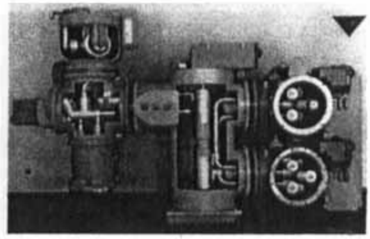


ABB 145/170 kV

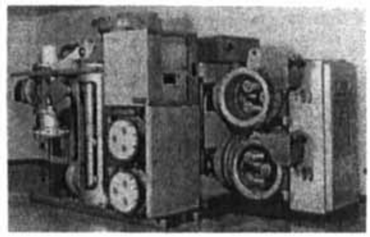
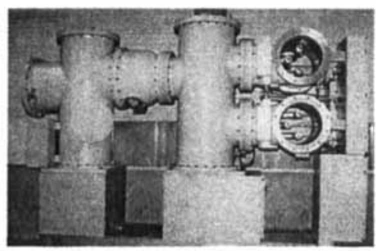
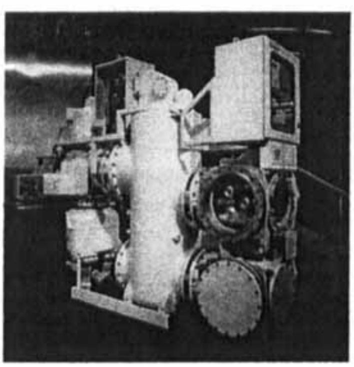


ABB 123 - 145/170 kV


ABB 123 kV


ALSTOM 145 kV


SIEMENS 145/170 kV

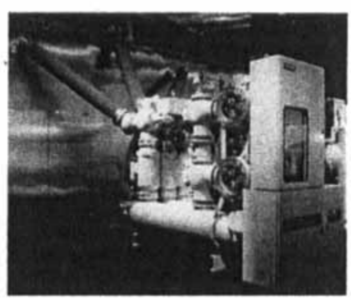

SIEMENS 145/170 kV

Figure 8.9a Examples of SF_6 dead tank (GIS) circuit-breakers

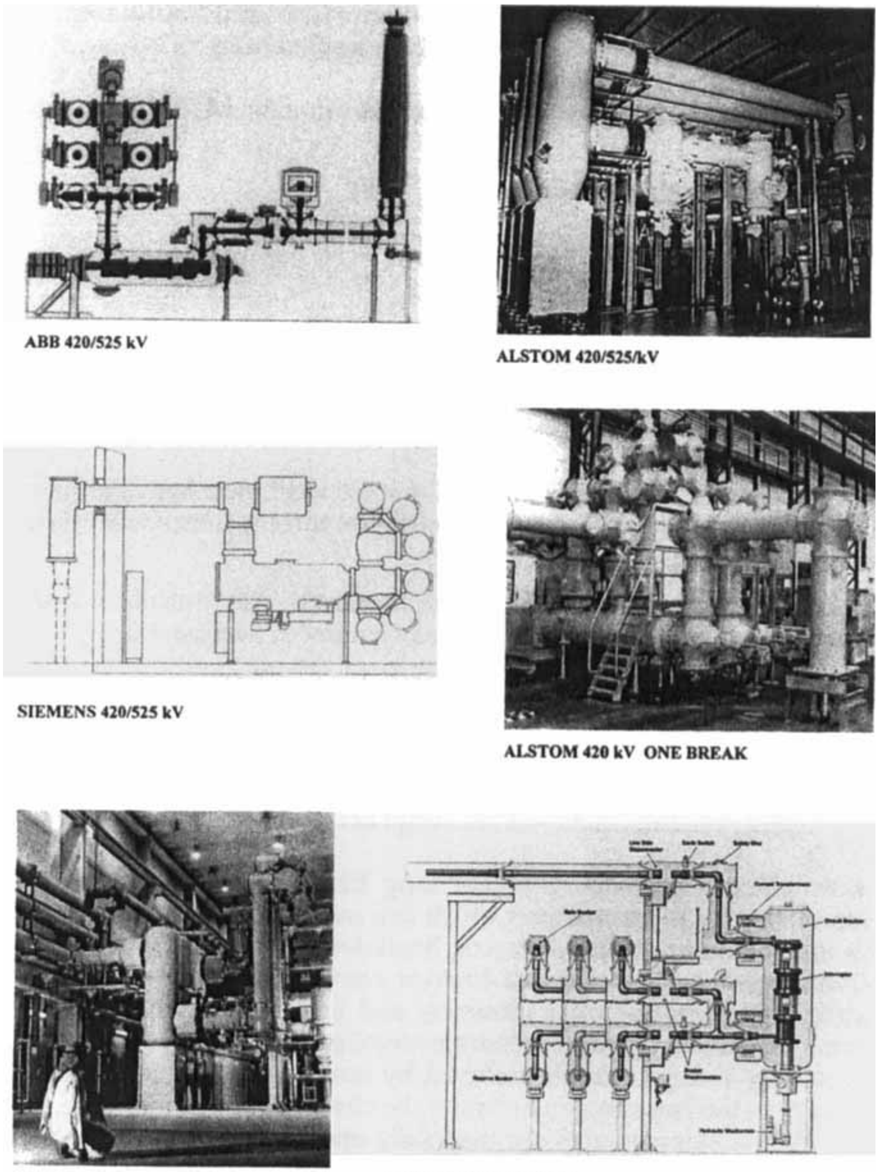


Figure 8.9b Examples of SF_6 dead tank (GIS) circuit-breaker installations

process can take some days. Therefore it has become usual practice in the UK to install GIS substations indoors in purpose-built buildings so that assembly, installation and maintenance can be undertaken in controlled conditions.

Since a GIS installation consists of an assembly of pipework and steel

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structures, it is usually regarded as unattractive and unsuitable for environmentally sensitive locations. The visual impact is reduced by housing the GIS in a building.

The switchgear equipment used at open terminal and GIS substations includes:

- circuit-breaker (already discussed in detail)
- disconnector*
- switch disconnector*
- earth switch*
- current transformer*
- voltage transformer*
- closing resistors*
- surge arresters*
- busbars*

The basic designs and operations of these devices* have been discussed elsewhere in detail [2, 3] but the following important issues will be discussed here with case examples:

(a) closing resistors/metal-oxide surge arresters – to control overvoltages on long line switching (see also Chapter 2, Section 2.5)
(b) disconnector switching
(c) ferroresonance
(d) monitoring on site.

8.8 Closing resistors/metal-oxide surge arresters

The switching and re-energising of long EHV transmission lines can generate very high overvoltages which can overstress equipment insulation and sometimes cause dielectric breakdown. The magnitude of the overvoltages depends on circuit-breaker characteristics, circuit-breaker grading capacitors, circuit parameters and line lengths. The system is normally protected against excessive overvoltages by damping the transient recovery voltage. This is achieved by inserting a specified value of resistance in the line circuit just before the electrical contact is made. For safety, the resistor contacts are then fully open before the travel of the circuit-breaker main contacts is complete. These precise movements are achieved by mounting the closing resistors on the interrupter assembly in parallel with the main contacts. The moving contacts of the closing resistors are directly connected to the main drive of the interrupters, so that the relative movements can be accurately set. Since the pre-insertion time of the resistor before the main contact touch is very critical, the mechanical drive has to be very precise and positive. The closing resistor drive thus becomes complex, requiring high energy operating mechanisms for the circuit-breaker.