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The pre-insertion time for the closing resistors is determined by detailed network analysis, which takes into consideration all circuit parameters and point-on-wave switching techniques. In most cases the ideal pre-insertion time for optimum overvoltage control is in the region of 10 to 12 ms.

If we examine a circuit-breaker with closing resistors and compare it with the performance of a standard SF_6 circuit-breaker without closing resistors, we can see that resistors add complexity to the drive mechanism, increase the drive energy requirement of the circuit-breaker mechanism, reduce the reliability of the SF_6 circuit-breaker and increase the cost by 30 to 40%.

All the above complexities are introduced just for the duration of 12 ms while the circuit-breaker is closing, otherwise the closing resistors remain in the open position.

The author understands that several major utilities have experienced difficulties with failures of closing resistors on air-blast circuit-breakers and have had problems with the long term reliability of closing resistor drives. Some have already implemented alternative solutions for controlling the switching overvoltages on long lines, by applying metal-oxide surge arresters (at both line ends and in the middle of the line) [4] and by point-on-wave switching.

Surge arrester technology has undergone a radical change in the last ten years. The undoubted simplicity of the metal-oxide arrester, in which the overvoltage is controlled basically by the arrester's internal nonlinear resistance, was initially attractive but there were reservations about the ageing of the resistor 'blocks'. The technology has now advanced to such a stage and sufficient experience has been gained that the metal-oxide arrester is now fully accepted in the industry and is now applied in cases where overvoltage protection is required. This is evidenced by the fact that all manufacturers of surge arresters in the world have changed over completely to metal-oxide arresters. MOAs are tested to IEC 60099–1 and IEC 60099–4.

8.8.1 Main features of metal oxide surge arresters (MOA)

MOAs are continuous acting, their response time is short, they reduce switching overvoltages as voltages start to build up and, because there are no gaps in the assembly and no arc products, they have prolonged life.

Because of increased reliability and trouble-free service, experience of metal-oxide surge arresters (MOA) over the last ten years, the availability of low protective levels and high discharge energy capabilities of the resistor blocks, several utilities have started to replace the closing resistors with the simple and more economical MOA devices for controlling overvoltages during energising and de-energising of long lines. ABB have installed the first 550 kV GIS circuit-breakers without closing resistors in China. They have been in service for about two years without any trouble. The switching overvoltages at this installation are controlled by MOAs [4, 5].

8.9 Disconnector switching

Disconnectors in GIS installations are used mainly to isolate different sections of busbars either for operational reasons or for safety, during maintenance and refurbishment. They are also used for certain duties, such as load transfer from one busbar to another, off-load connection and disconnection of busbars and circuit-breakers. The switching duties imposed on disconnectors have caused difficulties on some GIS designs in service. These difficulties have resulted in dielectric failure to earth on GIS equipment or dielectric failures on power transformer windings.

At the 1982 Gas Discharge Conference, Yanabu *et al.* [6] highlighted the switching problems associated with slow moving contacts of a disconnector. Some utilities have observed bright glow on GIS flanges during the disconnector closing and opening operations and reported a few dielectric failures on GIS equipment. Since then, switchgear manufacturers and utilities have continued their investigations. IEC and CIGRE have also taken a very active interest to achieve a better understanding of the disconnector switching phenomena.

During the past ten years, the techniques for high frequency measurements have improved considerably. With the present sophisticated measuring and recording techniques, the very high frequency (VHF) transient voltages produced during the disconnector switching operations can now be very accurately recorded and analysed. They also help to explain the switching phenomena.

When the slow moving contacts of a disconnector close or open, hundreds of pre-strikes or re-strikes occur between the contacts. These restrikes generate steep-fronted (4–15 ns) voltage transients which last for several hundred milliseconds. The magnitude and frequency of the VHF transient voltages depend on:

- contact speed of the disconnector
- SF_6 gas pressure in the disconnector
- dielectric stresses on contact tips, stress shields and contact gap
- circuit parameters, voltage offset, polarity and trapped charge.

This subject has now been extensively discussed worldwide during the past ten years and the results of investigations have been reported in numerous publications (e.g. from IEE, IEEE, ISH, CIGRE).

The pre-strikes and re-strikes during the closing and opening operations of the disconnector generate very fast, increased voltage transients locally across the contact gap and to the earth, giving rise to transient ground potential rise (TGPR). The VHF transient voltages propagate on both sides of the disconnector as very fast travelling waves into the GIS installations, sometimes causing failure of GIS switchgear and the transformer.

Most switchgear manufacturers now have sufficient experience to incorporate design features which avoid failures on GIS equipment. The latest IEC standard provides further guidelines for testing and evaluating the switching performance of disconnectors.

In an installation where the high voltage side of the transformer is directly connected to the SF_6 metal-clad circuit-breaker by the GIS busbars and disconnectors, a surge arrester is normally connected near the transformer for protection against most of these overvoltages (Figure 8.10). However, even the present-day fast acting metal-oxide surge arresters (MOA) cannot cope with the VHF transient voltages generated by disconnector switching. They let these fast transients through to the high voltage windings of the transformer. The continuous overstressing of the transformer windings causes deterioration of the winding insulation. This ultimately can cause dielectric failure to earth inside the transformer tank with very severe consequences such as loss of the transformer, loss of supply and expensive repair.

Discussions with the manufacturers of surge arresters have confirmed that the present day metal-oxide surge arrester technology may not be able to provide adequate protection against these VHF transient voltages in the foreseeable future.

The switchgear manufacturers, on the other hand, have had sufficient experience with these switching processes to accurately measure the amplitude and the rate of rise and the durations of these VHF transient voltages. The author firmly believes that by careful design they will be able to dampen or eliminate altogether these overvoltages so that other switchgear equipment such as the transformer on the substation will not be damaged.

8.10 Ferroresonance

Ferroresonance is a well known phenomenon and it is defined in Chambers' dictionary as follows:

'A special case of paramagnetic resonance, exhibited by ferromagnetic materials. It is explained by simultaneous existence of two different pseudo-stable states for the magnetic material B-H curve each associated with a different magnetisation current for the material. Oscillation between these two states leads to large currents in associated circuitry.'

In a switchgear installation where electromagnetic voltage transformers are fitted, the ferroresonance can occur if the conditions are conducive.

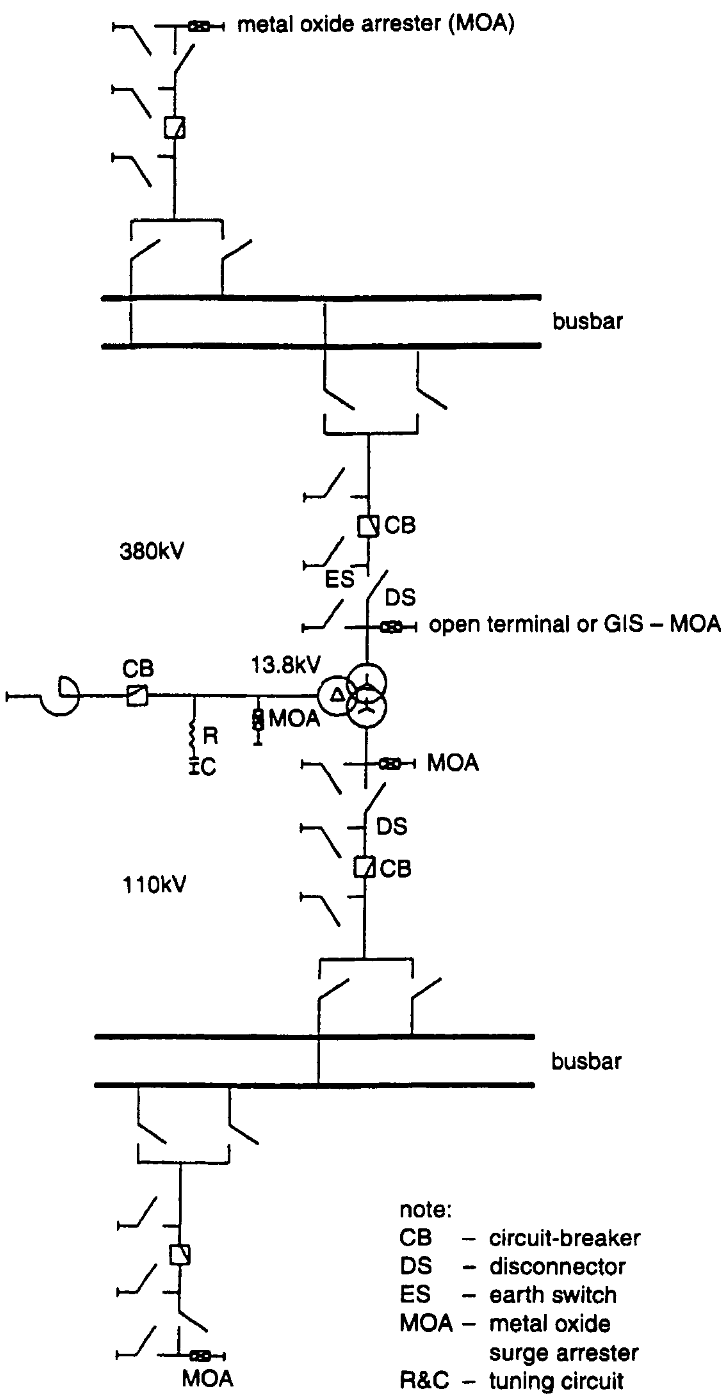

Figure 8.10 *Reactor switching by EHV and MV circuit-breakers*

Ferroresonance depends on the capacitive coupling between the unearthed, disconnected parts of the switchgear and the remainder of the plant. This happens when the sections of busbar fitted with voltage transformers are left energised through the grading capacitors of the open circuit-breaker; the value of the resultant voltages depends on the values of coupling capacitance and voltage transformer characteristics. The occurrence of ferroresonance is a statistical phenomenon which depends on the switching instants and the remanence effects of the voltage transformer.

The duration for which a voltage transformer may be left energised through the grading capacitors is critical. It is determined by the duty on the voltage transformer and the thermal capacity of its primary windings. In an ideal situation when a bus zone is de-energised, it should be immediately isolated and earthed. This may not always be possible in practice. Therefore, as soon as the switching sequence permits, the disconnectors nearest to the circuit-breaker should be opened and the earthing switches closed.

It is essential to analyse the network switching sequence to determine the optimised switching sequences which minimise the coupling effects and the maximum energising time for the VTs. It is recommended that ferroresonance damping devices must be fitted to the secondary windings of the VTs on a 'fit and forget basis' for safe operating of the system. The consequences of not carrying out the above recommendations could be quite serious. Several installations have experienced burnt out voltage transformers and flashovers on busbar insulating barriers.

8.11 System monitoring

8.11.1 Monitoring during installation and in service

The designs of EHV switchgear are becoming simpler and the number of interrupters per phase for the highest system voltages and fault currents (550 kV up to 63 kA) are getting fewer and fewer. There were six interrupters per phase for 420 kV in 1976 and only one in 1985/92. Consequently the reliability of present day SF_6 circuit-breakers has improved and they are now virtually maintenance-free.

Most SF_6 circuit-breakers are capable of interrupting 20 to 25 full short-circuit currents and of performing over 10 000 trouble free mechanical operations. This is the result of:

(a) improved arc interruption techniques employed in SF_6 gas and SF_6 gas-mixtures
(b) availability of low erosion rate nozzle materials
(c) reduced operating energies with low mechanical stresses on switchgear components

(d) computer-aided dielectric stress analysis techniques to optimise the shapes of the critical components and to obtain low dielectric stresses on contact tips, SF_6 gaps (across the contacts and to earth), stress shields, insulators and drive rods
(e) reduced number of moving parts and dynamic and static seals.

Therefore the practice of conventional regular maintenance will have to be re-examined. Because the present day SF_6 circuit-breakers can perform a large number of mechanical operations and have longer contact and nozzle service life, it is not necessary to open a GIS circuit-breaker every six months. Instead of regular maintenance, it is recommended that essential parameters listed below should be monitored, some continuously and others periodically, so that the assessment of switchgear condition can be made.

8.11.2 Continuous monitoring

The necessary parameters to be monitored by fibre-optic diagnostic techniques are:

- current
- voltage
- arcing time
- SF_6 gas pressure
- circuit-breaker contact travel characteristics.

Fibre-optic monitoring equipment has now been fully proven in service. It is stable over a long service period, robust, maintenance-free, easily installed and replaced and easily accessible. These measuring devices are now commercially available. They are accurate, reliable and reasonably priced. Fibre-optic instruments which can be used to see inside the circuit-breaker tank when the switchgear is live are also available.

8.11.3 Periodic monitoring

During the assembly and installation of GIS switchgear on site, care must be taken to ensure that all joints are correctly tightened, all loose particles are removed and all gas chambers are properly cleaned. After assembly, a UHF partial discharge technique may be used to ensure that the whole GIS installation is free from loose particles. This technique has been very successfully used to locate loose particles within a few hundred millimetres (Reyrolle and Strathclyde University who developed the technique have published several papers on this subject). The other techniques of partial discharge measurement have been evaluated by CIGRE WG 15–03 (CIGRE paper 15/23–01, 1992 Paris). These are not discussed here.

The advantage of this technique is that measurements can be made at a relatively low voltage level without overstressing the switchgear insulation. Once the installation is found to be free of any loose particles, it can be safely energised. After the energisation of GIS substation, there is, in the author's view, no need for continuous partial discharge monitoring. Several GIS installations in this country and abroad have been continuously energised for 10 to 15 years without ultra high frequency partial discharge (UHF-PD) monitoring devices and have given trouble-free service. The long term reliability of these sophisticated monitoring devices is still to be proven. However, a periodic check, say every two years, can be made so that the signature prints of the spectrum of discharges can be compared with those obtained just before energisation, and any deterioration in the dielectric integrity of the GIS installation can be detected.

8.12 Insulation co-ordination

To ensure the safety and reliability of a GIS open-terminal or a hybrid switchgear installation, it is necessary to carry out proper insulation co-ordination of switchgear equipment and complete installation, so that the switchgear assembly shall be able to withstand all overvoltages imposed on the system during its service (e.g. see Chapters 2 and 3). The possible sources of overvoltages are:

- atmospheric overvoltages – caused by direct lightning strikes and back-flash
- transient overvoltages – caused by inductive (reactor), capacitive (line, cable) loads and out-of-phase switching
- temporary overvoltages – caused by the resonance of the network and power transformer windings and by ferroresonance in electromagnetic VTs.

The choice of insulation level of equipment is very critical. The design of switchgear should ensure that flashover cannot occur across the open contact gaps with impulse or other overvoltages on one terminal, and the out-of-phase AC peak voltage on the other terminal (i.e. the gap sees the sum of the two overvoltage peaks). The design should be complemented by detailed system studies of the switchgear installation to optimise the switching sequence and the number and locations of suitable metal-oxide surge arresters.

8.13 Conclusions

Modern SF_6 circuit-breakers are simple, reliable and virtually maintenance-free, and some designs have now achieved ratings up to

63 kA at 522 kV with one break per phase. Circuit-breaker designs with third generation SF_6 interrupters have reduced the driving energy by 50 to 60% and have brought increased reliability and further reduction in costs.

Reactor switching causes difficulty for some circuit-breaker designs. Until a realistic test circuit is available to verify the performance of the circuit-breaker, for reactor switching duties it is recommended that metal-oxide surge arresters and R-C tuning circuits (where possible) should be used for added safety.

Owing to increased reliability, high energy discharge capability and trouble-free service over a decade, metal-oxide surge arresters are extensively used for insulation co-ordination on the substation and gradually replacing the closing resistors for switching EHV transmission lines [4, 5]. On GIS installations, where electromagnetic voltage transformers are used, ferroresonance can occur and some protection is afforded by fitting ferroresonance damping devices to the secondary windings of the voltage transformers.

8.14 Acknowledgments

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8.16 Appendix

Since the 1830s, electricity has been used commercially in the telegraph industry, and many firms in the UK, Europe and America supplied various types of low voltage equipment to suit.

In Germany, Siemens & Halke was the largest company which became interested in higher voltage technology. The others which followed were Allgemeine Elektrische Gesellschaft (AEG), established in 1883 as Deutsche Edison Gesellschaft, Schuckert & Co. and the Union Company. In Switzerland, the leading companies were Oerlikon (1882) and Brown Boveri (1891), and in Sweden, ASEA (1883).

The use of alternating current started in lighting plant at the end of the 1880s. Edison, among others, was opposed to the use of alternating current, which at the time was considered hazardous. Crompton was one of the leading advocates of direct current, while Ferranti supported the cause of alternating current. However, the research continued and engineers in different countries had a breakthrough almost at the same time in the use of polyphase alternating current. Later, great progress was made in this technology, in particular with the invention of the transformer and alternating current (AC) motor.

This subsequently led to the concept of the present day transmission system, in which electric power at high voltage and low current was transmitted to another place at a distance and transformed back to a reasonable voltage and distributed for local consumption (i.e. generation at one point and consumption some distance away).

The first successful long distance transmission of electrical power employing three-phase alternating current was from Lauffen hydroelectric station. The Lauffen Frankfurt transmission line in Germany, 175 km long, transmitting at 15 kV, 40 Hz with an overall efficiency of 75%, was inaugurated on 24 August 1891.

Other important dates on the transmission calendar worldwide [7] are:

1911 : 110 kV transmission line – Lauchhammer, Riesa (Germany)
1929 : 220 kV transmission line – Brauweiler, Hoheneck (Germany)
1932 : 287 kV transmission line – Boulder Dam, Los Angeles (USA)
1952 : 380 kV transmission line – Harspranget, Halsberg (Sweden)
1965 : 735 kV transmission line – Manicouagan, Montreal (Canada)
1985 : 1200 kV transmission line – Ekibastuz, Kokchetau (USSR).

The main reason for using ever higher voltages was economy of transmission.

In the UK electrical industry, Merz and McLellan's contribution stretches back to 1889 when they were the consulting engineers to the North Eastern Electric Company, the pioneer in its field of generation and distribution. This company was regarded as a model of an efficient private utility not only in the UK but throughout the world.

The foresight of Charles Merz brought about fundamental developments in electrical power supply in the North East, elsewhere in Britain, its overseas dominions and in the USA. He was instrumental in establishing the first 20 kV integrated transmission system of the North East in 1907 and the standardising of the British Supply frequency at 50 Hz instead of 24 and 40 Hz used in different parts of the country.

In 1907 Merz predicted a saving of 55 million tons of coal each year if UK power supply was operated and managed as an integrated whole. In 1924, he proposed the establishment of a super-tension transmission network for linking up the existing supply areas and developing new ones and to allow interchange of power at one frequency, similar to those already existing at that time in the USA, Canada, Sweden, Japan, France, Germany and the North East coast of England.

Merz's suggested form of super-tension network was endorsed by the similar IEE proposal 28 years later for the British 275 kV supergrid. His dream became a reality when on 1 April 1948 the British Electricity Authority (BEA), the largest utility in the western world, was created. In 1954 it became the Central Electricity Authority (CEA) in Britain and at the same time came the formation of South of Scotland Electricity Board (SSEB). In 1957 Merz's vision was completed by the formation of the Central Electricity Generating Board (CEGB), with the 400 kV interconnected supergrid in the UK.

From 1890 to 1960, the transmission voltages increased from 2 kV to 400 kV. Important dates in UK transmission [7] are:

1890 – 2.0 kV
1905 – 5.5 kV
1907 – 20 kV
1924 – 60 kV
1926 – 132 kV
1953 – 275 kV
1963 – 400 kV

The switchgear industry worldwide has kept pace with the increasing demands of both currents and voltages during this period, by developing reliable switchgear for controlling and protecting the electrical networks.

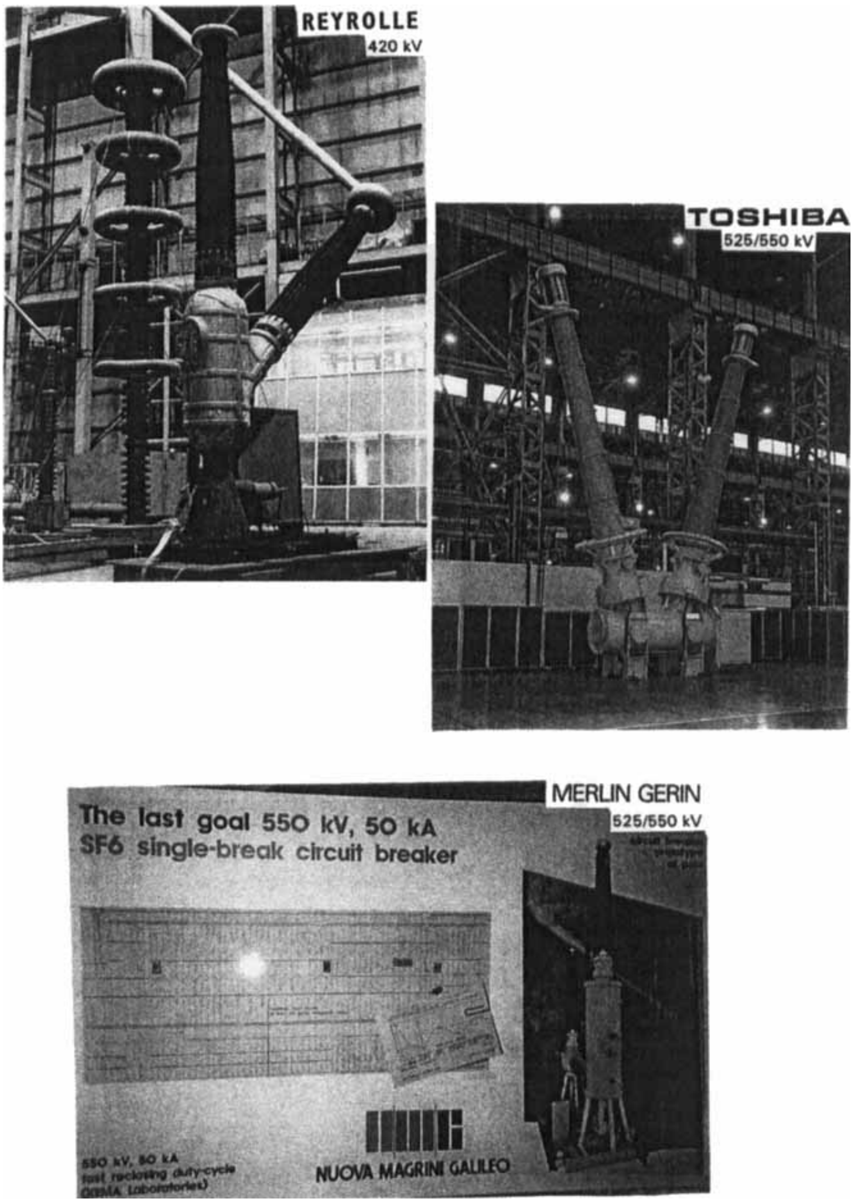

Figure 8.11 One-break 420/550 kV SF_6 circuit-breakers (1985–1992)

Merz once again played an important role in bringing Parson, Clothier and Reyrolle together on Tyneside who jointly brought about the electrical revolution in alternating current (a.c.) generation, transmission and control. Merz, Clothier and Reyrolle pioneered the concept of bulk oil, compound filled switchgear in UK and jointly developed the first iron-clad switchgear. This was a bulk-oil double plain-break, metal clad, 5.5 kV circuit breaker with compound filled busbars in 1905. This brought new standards of safety to the high voltage distribution system. With continuous improvement in switchgear technology and the efficient use of SF_6 gas, the ultimate goal in circuit breaker design has now been achieved in the development of one-break 420 kV (Ali *et al.*, 1984 [2, 3] Figure 8.11) and 550 kV (Suzuki *et al.*, 1992, [4]) circuit breakers.

8.16.1 SF_6 circuit breakers in the UK

Early transmission in the UK at 132 kV employed bulk-oil circuit breakers in open-terminal substations but from the mid-1940s air-blast breakers were made in increasing numbers, particularly driven by the establishment of the 275 kV super-grid system. The earliest 420 kV open-terminal circuit breakers in the UK were first commissioned in the early 1960s and had twelve series air-blast interrupters per phase. SF_6 insulated current transformers were produced over the range 145 kV to 420 kV in 1950s.

Following the development and validation of synthetic testing techniques, the recovery voltages available for tests were no longer governed by the maximum direct output of the short-circuit testing stations. This allowed the development of interrupter units with higher breaking capacity. In 1971 two-cycle 420 kV 35 GVA air-blast breakers with six series breaks per phase were installed by GEC and Reyrolle.

SF_6 open-terminal circuit-breakers appeared in Europe from the mid-1960s onwards and the first SF_6 GIS installations were commissioned in Europe in the late 1960s. In the early to mid-1970s in the UK, 300 kV GIS installations were supplied to CEGB by both GEC and Reyrolle followed by 420 kV GIS substations towards the end of that decade.

The first high power SF_6 interrupters utilised air-blast technology, modified to give a closed two-pressure system. The relatively high cost and complex mechanisms of the system led to the development of single-pressure puffer type interrupters which were first applied in EHV circuit breakers in the early 1970s for both open terminal and GIS installations.