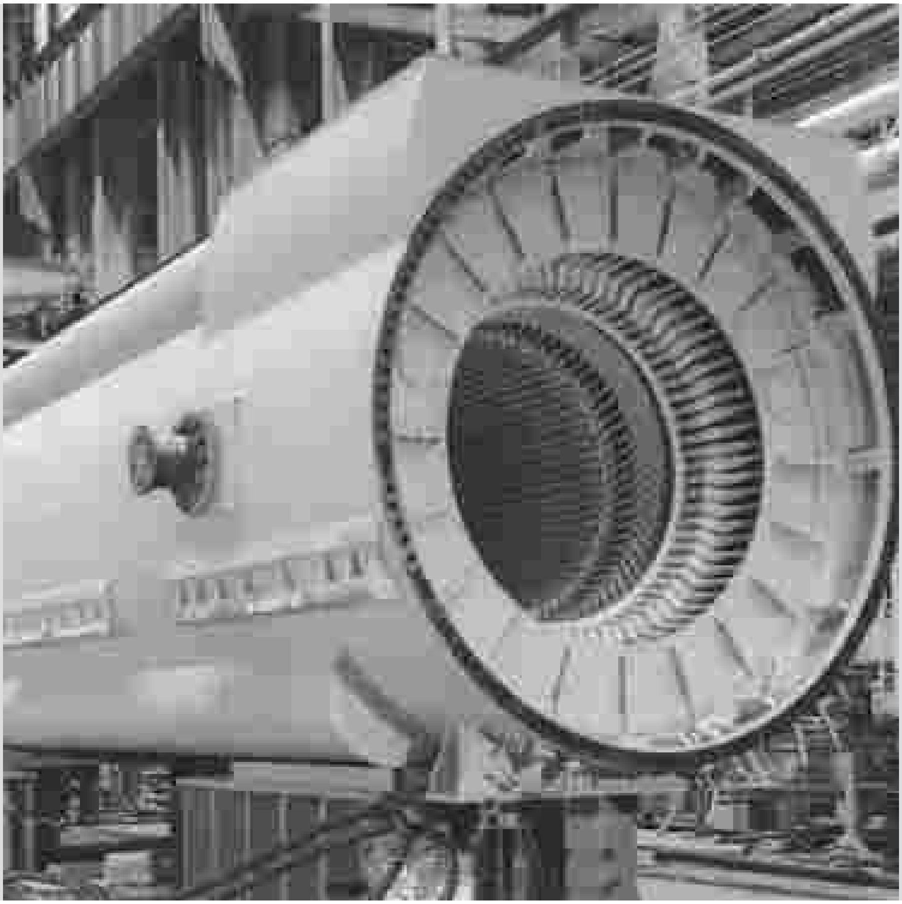
8 Symmetrical Components



Generator stator showing completed windings for a 757-MVA, 3600-RPM, 60-Hz synchronous generator (Courtesy of General Electric.)

The method of symmetrical components, first developed by C. L. Fortescue in 1918, is a powerful technique for analyzing unbalanced three-phase systems. Fortescue defined a linear transformation from phase components to a new set of components called *symmetrical components*. The advantage of this transformation is that for balanced three-phase networks the equivalent circuits obtained for the symmetrical components, called *sequence networks*, are separated into three uncoupled networks. Furthermore, for unbalanced three-phase systems, the three sequence networks are connected only at points of unbalance. As a result, sequence networks for many cases of unbalanced three-phase systems are relatively easy to analyze.

The symmetrical component method is basically a modeling technique that permits systematic analysis and design of three-phase systems. Decoupling a detailed three-phase network into three simpler sequence networks reveals complicated phenomena in more simplistic terms. Sequence network results then can be superposed to obtain three-phase network results. As an example, the application of symmetrical components to unsymmetrical short-circuit studies (see Chapter 9) is indispensable.

The objective of this chapter is to introduce the concept of symmetrical components in order to lay a foundation and provide a framework for later chapters covering both equipment models as well as power system analysis and design methods. Section 8.1 defines symmetrical components. In Sections 8.2 through 8.7, sequence networks of loads, series impedances, transmission lines, rotating machines, and transformers are presented. Complex power in sequence networks is presented in Section 8.8. Although Fortescue's original work is valid for polyphase systems with *n* phases, this chapter considers only three-phase systems.

CASE STUDY

The following case study traces the development of gas-insulated substations and switchgear (GIS) since GIS technology originated in 1936. GIS advantages include enhanced reliability, compact modular design, reduced maintenance and cost, prolonged life, and advanced monitoring capabilities. GIS circuit breakers are now available at voltages up to 1100 kV and interrupting currents up to 63 kA. Sulfur hexafluoride (SF_6) is the most commonly used gas for electrical insulation in GIS. This case study presents an overview of the environmental impacts of switchgear, where SF_6 as a greenhouse gas is an ongoing environmental concern [4].

Technological Progress in High-Voltage Gas-Insulated Substations

Ibrahim A. Metwally

In the last two decades, the evolutionary development of gas-insulated substations/switchgear (GIS) has resulted in higher integration of a number of new technologies to enhance performance and reliability by reducing defects, having more compact designs, and reducing maintenance intervals and costs. Incremental improvements are continuing in interrupter technology, such as self-extinguishing features at medium voltage (MV) and resistance interruption at extra- and

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ultra-high voltages (EHV and UHV). In addition, sulfur hexafluoride (SF_6) gas technology for circuit breakers, zinc oxide (ZnO) for arresters, radio communication for condition monitoring, and a choice of porcelain or polymer composite for the full range of equipment are also some of the technologies integrated or innovated by GIS manufacturers in recent years. Recently, ac GIS ratings have reached up to 1100-kV rated voltage and 50-kA_{rms} rated short-circuit breaking current. In addition, 1200-kV ac GIS are going to be visible very soon. Moreover, 500-kV dc GIS for dc transmission systems have become available.

GIS Construction

GIS is commonly used to designate gas-insulated, metal-clad electrical switchgear. GIS includes air entrance bushings, power cable connections, transformer connections, busbars, circuit breakers (CB), bus and cable isolators, earthing switches, current and voltage transformers "measuring devices" (CT and VT), and surge arresters. Figure 1 illustrates a single-line diagram and components of GIS. Many new SF_6-to-air bushings are now composed of composite construction, consisting of a fiberglass/epoxy inner cylinder that contains the SF_6 gas and provides structural strength. The external weather shed is made of silicone rubber.

SF_6 is the most common gas used for electrical insulation; its pressure values range from 0.29 MPa to 0.51 MPa (at 20 °C). Recently, SF_6 has been replaced with the 95% mixture of nitrogen (N_2) and 5% of SF_6 at 1.3 MPa pressure, or with a 90% mixture of N_2 and 10% of SF_6 at 0.94 MPa pressure, as well as with a 80% mixture of N_2 and 20% of SF_6 at 0.71 MPa pressure. The latter corresponds to the 0.4 MPa pressure when pure SF_6 is used.

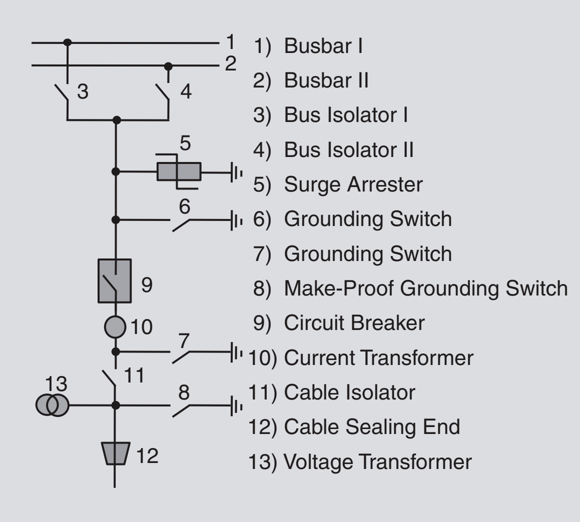

Figure 1 Single-line diagram and components of GIS

Today, the environmental consideration related to the "greenhouse" effect grows, especially for using SF_6 and its mixtures in the compressed-gas electric power apparatus. SF_6 gas is one of the strongest manmade "greenhouse" gases; its global warming potential is estimated to be approximately 25,000 times larger than that of carbon dioxide (CO_2) gas. At equal gas pressure, SF_6/N_2 mixtures are less sensitive to insulation defects than undiluted SF_6. The recent trend is to use ultra-diluted SF_6/N_2 gas mixtures with SF_6 content # 1%.

Typically, solid insulators are required to provide support to stressed conductors in such systems. Solid insulating spacers represent the weakest points in these systems. Several troubles and system outages have been reported worldwide due to spacer failures. Normally, pure SF_6 or SF_6/N_2 mixtures at high pressures are used as an insulating medium. Complete failure or partial discharge may occur on the spacer surfaces, but they rarely occur at the highly pressurized gas unless there are solid conducting particles in the gas, as will be discussed later.

Spacers used in GIS are usually made of epoxy or cast resin. These spacers fundamentally are divided into two types according to their shapes, namely, discs and cones. The presence of spacers results in complex dielectric field distribution. It often intensifies the electric field, particularly on the spacer surface. The insulation ability of SF_6 is highly sensitive to the maximum electric field, and furthermore, the insulation strength along a spacer surface is usually lower than that in the gas space. Due to the previously mentioned spacer troubles, they should be precisely designed to realize a quasi-uniform electric field distribution along their surfaces. In addition, functionally graded materials (FGM) find extensive application in the insulation system such as GIS. FGM consist of materials of different permittivities (dielectric constants), i.e., with a spatial distribution of permittivity. This new spacer material can be optimized to control the electric field along the spacer surface, especially at the triple junction "gas/spacer/enclosure."

Advantages

Gas-insulated systems, such as gas-insulated lines and switchgear (GIL and GIS), are widely used in the electric power industry for transmitting and controlling bulk power, respectively. The concept of SF_6 HV GIS has proved itself in several thousands of installations worldwide. It offers the following outstanding advantages:

- Minimal space requirements, where the availability and price of land play an important part in selecting the type of switchgear to be used. It resolves the problems that arise in large towns, industrial conurbations, mountainous regions with narrow valleys, and underground power stations.
- Full protection against contact with live parts because the metal enclosure affords maximum safety for personnel under all operating and fault conditions.

- Protection against pollution due to the fact that the metal enclosure fully protects the switchgear internal components against environmental pollutants such as salt deposits in coastal regions, industrial vapors, and precipitates, as well as sandstorms. The compact switchgear can be installed in buildings of uncomplicated design in order to minimize the cost of cleaning and inspection and to make necessary repairs independent of weather conditions.
- Free choice of installation site that leads to potential savings for the expensive grading and foundation work, e.g., in permafrost zones, and short delivery and erection times for indoor switchgear installation regardless of the weather conditions.
- Protection of the environment because of its very flexible modular system that can meet all requirements of configuration given by network design and operating conditions.
- Longevity means an expected lifetime of at least 50 years and being maintenance-free for more than 20 years.

History and Technological Progress

Historically, air-insulated substations (AISs) were the only available technology until 1936. However, this resulted in a number of difficulties, namely, (1) pollution in desert areas or in close proximity to industrial or coastal areas, (2) insufficient space for AIS when constructing new substations/extensions (e.g., inside cities), and (3) restrictions by planning laws that only permit AIS substations where there is “no demonstrable alternative.”

If GIS and AIS are compared in the need of space for the same function, the space reduction by using GIS is in the ratio of 1:5. That means less than 20% of the space of AISs is needed to install a GIS. In 2007, more than 20,000 bays in over 2000 substations are installed worldwide, in all kinds of environmental conditions and with the whole spectrum of voltage and current ratings.

Following the invention of SF_6 gas in 1900, the applications of this gas have significantly advanced since 1940. Alternating current (ac) GIS technology originated in 1936, when a Freon-GIS assembly, rated at 33 kV, was demonstrated in the United States. Later, in the mid-1950s, the excellent insulating and arc-extinguishing properties of SF_6 gas were recognized. By the mid-1960s, GIS was sufficiently well-developed to be commercially viable and appealing to a broader market. Over time, progressive innovative steps have allowed manufacturers to develop a range of GIS voltage ratings of 550 kV in 1976, 800 kV in 1979, and recently up to 1100 kV as shown in Figure 2 for the ac systems. The use of 1100-kV ac transmission lines, (i.e., doubling the voltage from

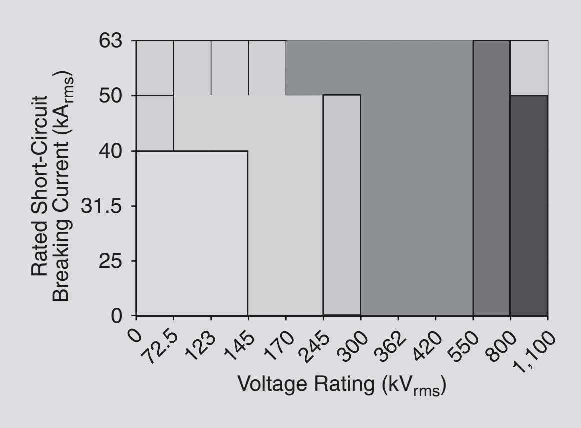

Figure 2 Rated short-circuit breaking current of ac GIS for a wide voltage range

the traditional level of 550 kV) reduces the transmission losses by a factor of four, which is a significant savings of energy. Moreover, the 1200-kV ac GIS are going to be seen very soon.

Recent trends in power transmission and distribution technologies involve high-voltage direct-current (HVDC) installations in the electric system. This improves the overall system reliability and achieves economical benefits. Direct current (dc) GIS are considered integral parts of these installations. Therefore, there has been a resurgence of interest in HVDC SF_6 equipment in recent years. Recently, 500-kV dc GIS for dc transmission systems have become available in Japan.

The phenomenon of accumulated charges on a solid insulator surface is one of the critical parameters at the insulation design stage even for both ac and dc all gas-insulated equipment (e.g., GIS and GIL). There are three kinds of electric charging mechanisms: volume conduction, surface conduction, and electric field emission. These mechanisms are characterized in terms of the time constant, applied voltage, and charge distribution. The behavior of metallic particles left on the enclosure is one of the largest differences. Also, degradation of metal-oxide arrester blocks under dc stress is of significant importance.

Figure 3 illustrates the percentage evolution and development of different types of HV substations in the market from 1960 to 2020. Highly integrated switchgear (HIS) is a compact switchgear solution for a rated voltage of up to 550 kV. HIS is mainly used for renewal or expansion of air-insulated outdoor and indoor substations, particularly if the operator wants to carry out modifications while the switchgear is in service. With the HIS solution, the circuit-breakers, disconnectors, earthing switches, and transformers are accommodated in compressed

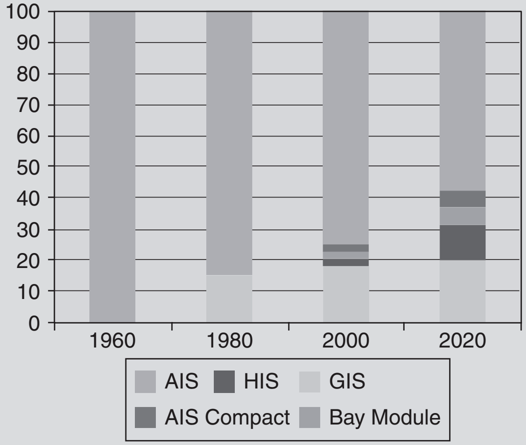

Figure 3 Percentage evolution and development of HV substations in the market

gas-tight enclosures and at a minimum number of independent gas compartments. This makes the switchgear extremely compact. The modularity and flexibility of today's switchgear allows designing highly optimized GIS using a reduced minimum number of junction elements (elbows and cross junctions, among others). This concept allows delivering subtransmission and distribution substations made of one or two shipping units only, fully assembled and tested in factory. This will result in quasielimination of the site assembly and tests, which is a real benefit of the customer's project management. These optimized GIS can shorten the time needed from ordering to commissioning to about 44% (i.e., by about 5–6 months). It is worth mentioning that the recent size of building, space requirement, and packing volume have been reduced for the 145 kV GIS, to be less than 20%, 15%, and 25% of those in 1968, respectively.

Gas-insulated modules have recently been seen at all voltage levels up to 550 kV, as an intermediary between GIS and AIS. They are suitable for the following categories of applications: standardization and optimization of new substation and/or extensions in large networks, reconstruction or refurbishment of AIS with operational constraints and/or space limitations, and the extension of AIS with space limitations. Therefore, the market of these applications will most likely increase as shown in Figure 3.

Recently, disconnecting circuit breaker technology, which integrates the disconnecting function into the circuit breaker and eliminates the need for two separate free-standing disconnectors, has led to shrinking footprint, equipment, and construction costs, and increases availability. The solution makes it possible—for the first time—to build compact EHV AIS substations and load hubs close to large cities and urban areas, where high land prices and space restrictions usually prohibit the construction of large AIS.

Transmission system growth may lead to higher requirements with regard to short-circuit current and/or nominal current ratings after the initial GIS installation. An upgrade of busbars, circuit breakers, and metering transformers may have to be investigated. Upgrades may also consist of an addition of isolated earthing switches for offline monitoring, voltage indicators, and partial discharge sensors. The planning for an extension or upgrade option should begin during the initial GIS design stage.

In some designs of bay module type used for GIS extensions and upgrades, the following elements are integrated into one bay: circuit breakers, bus disconnectors, earthing switches, voltage transformers, current transformers, outgoing feeder disconnectors with earthing switches, and surge arresters. In addition, the circuit breaker is integrated with current transformers, and disconnector contacts are directly mounted on circuit breaker. The key benefits of this compact design are: space-saving by optimized system design, modularity and flexibility for application in all possible substation designs, low overall height, optimized maintenance management, reduction in life cycle cost, and short on-site erection due to prefabricated and type-tested modules.

New Development Trends

Increased equipment loading and an inability to build new or expand conventional stations to accommodate additional loads has lowered the relative GIS costs compared with those of AIS. Manufacturing improvements have lowered the real GIS costs as well. Changes in the utility business environment and ownership have led to a greater acceptance of these changes. The above factors will increase the market share of GIS. This is expected even without further GIS technical improvements.

The evolutionary development of GIS has resulted in higher integration, reduced opportunity for defects, and more compact designs. Incremental improvements are continuing in interrupter technology, such as self-extinguishing features at MV and resistance interruption at EHV and UHV.

The latest GIS technological achievement is in the 1100-kV AC GIS. The 1100 kV system has the following features: multi-bundle conductors, larger line-charging capacity (approximately four times as large as that of the 550 kV system), larger power plants that are located relatively close to the UHV system, and large-capacity transformers (3000 MVA/bank) that interconnect the UHV system with the 550 kV system. To reduce corona noise, multibundle "eight" conductors with a large diameter are employed, which leads to a decrease in the line surge impedances and an increase in the time constant of dc component associated with fault current. In addition, the use of large power generators and large capacity power transformers lead to larger reactance-to-resistance ratio and contribute to an increase of the dc time constant in the fault currents. Consequently, the rate of decrease of current (*di*/*dt*) around current zero is taken as 28 A/ s, which is equivalent to 63 kA_{rms} with 10% component. As a result, the rated short-circuit breaking current, which is the highest short-circuit current that a circuit breaker is capable of breaking at the instant of contact separation in kA_{rms}, is taken as 50 kA_{rms} (see Figure 2).

Generally, there are two main problems for network expansion in the 550 kV to transfer power from remote plants:

- It is very difficult to secure multiple power transmission routes, which enable sufficient power transmission from remote power plants, thus, the construction of the 1100-kV transmission lines with a capability three to four times greater than that of 550-kV transmission lines.
- Short-circuit current in the 550-kV network will increase above the expected level (63 kA_{rms}).

Highly sophisticated system design technologies are necessary to deal with the following technical issues of the 1100-kV transmission system:

- Solutions for network problems and technology, such as secondary arc extinction. Secondary arc extinction is a serious concern in UHV systems and needs to be addressed at the design stage of such projects. Mitigation measures, such as neutral reactors, special switching schemes of shunt reactors, and high-speed grounding switches, have to be studied.
- Insulation coordination issues, such as overvoltages on transmission lines and in substations, can be effectively controlled by high-performance, heavy-duty surge arresters. Therefore, these arresters are selected with an individual energy rating of ù 55 MJ. These metal-oxide surge arresters are a key technology for 1100-kV insulation coordination, where their I-V characteristics become more flat (i.e., higher energy aborption capability). Lightning overvoltages dominate the nonself-restoring internal insulation design of substation equipment; it is important to suppress lightning overvoltages effectively by arranging metal-oxide surge arresters at adequate locations, such as at line entrances, busbars, transformers, and also within GIS. To control switching overvoltages below the ground fault overvoltage level, the closing/opening resistor can be employed as shown in Figure 4, where the total length and

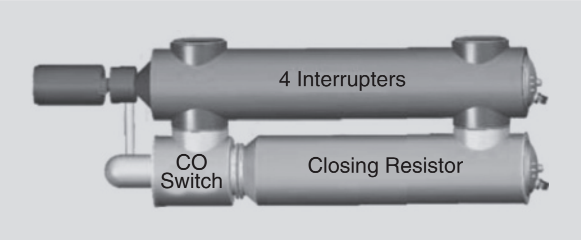

Figure 4 Four-interrupter and closing resistor and its close/open (CO) switch unit of the 1100-kV gas circuit breaker

the height of the 4-interrupter/closing resistor and its close/open (CO) switch unit are 10 m and 3.8 m, respectively.

For MV networks, on the other hand, the interrupting chamber of the self-extinguishing CB is divided into two main compartments at the same pressure of about 0.51 MPa during the closed condition. During opening, the gas pressure increases by heat generated in the arc, then the gas blasts from one arc compartment to the other one. By applying an external magnetic field, one arc rotates around the contact periphery and cools, and no pitting of contacts occurs.

Life Cycle Assessment

The switchgear only makes a minor contribution to the total global warming potential of a representative urban distribution grid. On the contrary, other grid components such as cables and transformers play the decisive role—regardless of whether AIS or GIS technology is used. Figure 5 shows an overview of the percentage environmental impact categories that were examined in a study at switchgear level. It is based on a representative mix of all switchgear types in the MV range. Clear advantages for GIS compared to AIS are also shown in regard to global warming potential, except the SF_6 emission as was explained earlier.

It is worth mentioning that the contributions to global warming potential of an urban power distribution grid is 92% from grid components, such as cables and lines, and 8% from switchgear, where the latter can be divided as 7% from switchgear in ring-main units and only 1% from switchgear of substation transformers.

GIS Failures

GIS have been in operation for more than 35 years, and they have shown a high level of reliability with extremely low failure rates. This is the result of quality assurance during the design and manufacturing processes as well as during the erection and on-site commissioning. However, the return of experiences has shown that some of the in-service failures are related to defects in the insulation system.

The main components involved in failures of 300–500 kV GIS are

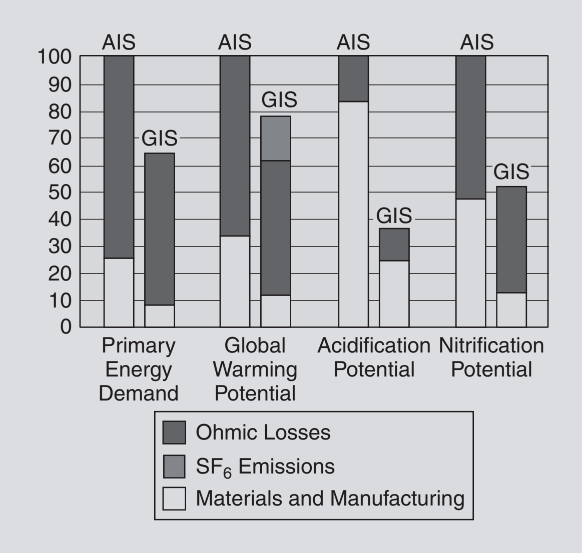

Figure 5 Environmental impact of AIS and GIS

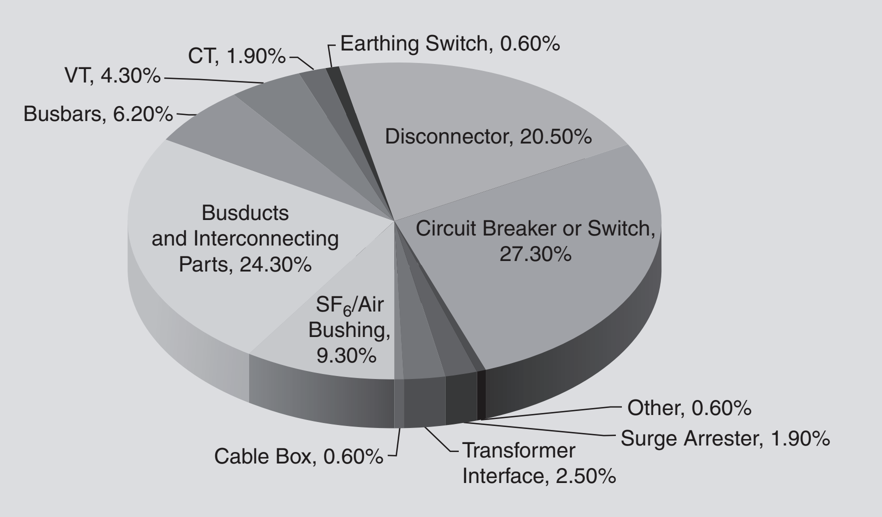

Figure 6 Main components involved in failures of 300–500 kV GIS

given in Figure 6, where the major components that cause failures by about 72% are circuit breakers (CB), disconnectors, and bus ducts and interconnecting parts. Major failure of GIS is a collapse of one of its major components or elements, which causes the lack of one or more of its

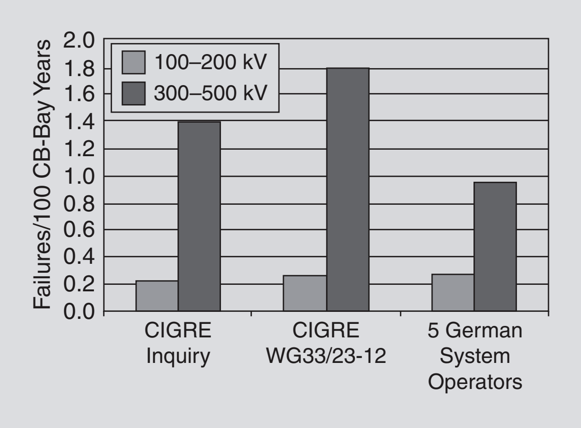

Figure 7 Rates of dielectric failures in GIS

fundamental functions. A major failure will result in an immediate change in the system operating conditions. The major failure rate is equal to the number of major failures divided by the sum of circuit-breaker bays, multiplied by the number of in-service years. The dielectric failure rates presented in Figure 7 are taken from different sources. In range 1 (from 100 kV to 200 kV), the failure rate is in good correspondence and amounts to be about 0.25 failures per 100 CB-bay years. In range 2 (from 300 kV to 500 kV), the failure rate is significantly higher due to the higher electric field strength. The deviations are between 0.95 and 1.8 failures per 100 CB-bay years.

When analyzing the failure causes, it must be stated that a lot of failures do not occur in GIS of modern design (e.g., insufficient insulation coordination of disconnectors and earthing switches or imperfections in solid material). Furthermore, a reduction of teething faults is likely due to the application of advanced testing methods. Therefore, a target failure rate of 0.1 failures per 100 CB-bay years should be achievable, where about 61% of the failures could have been detected and classified by monitoring and diagnostic systems, respectively.

Origin of PD in GIS

Partial discharges (PD) are electrical discharges that do not completely bridge between the electrodes. Although PD magnitudes are usually small, they cause progressive deterioration and may lead to ultimate failure. It is essential to detect their presence in a nondestructive controlled test. There are two types of the fine contaminants in both GIS and GIL systems: either insulating or metallic particles. The former has a relatively innocuous effect, while the latter drastically reduces the corona onset and breakdown voltages of the system.

GIS equipment is made compact; hence the working field strength within the equipment increases and becomes very sensitive to field perturbations due to defects. PD in compressed SF_6 GIS arise from protrusions, free conducting particles, floating components, and bulk insulation defects, such as voids and delaminations. PD resulting from the third and the fourth sources will, in turn, lead to failure of the GIS. In the case of a floating component (one not bonded to the conductor or sheath), the discharge magnitude is normally sufficient to decompose SF_6 in quantities.

Treeing is a failure process in solid dielectrics, which, once initiated, will normally proceed to a failure through the bulk of dielectric. The most important defects are shown in Figure 8. Typical defects may result from errors in manufacturing, shipping, and assembly, including loose or electrically floating corona shields, undetected scratches, and poor electrical contacts.

Figure 9 illustrates the contribution of each of these defects and

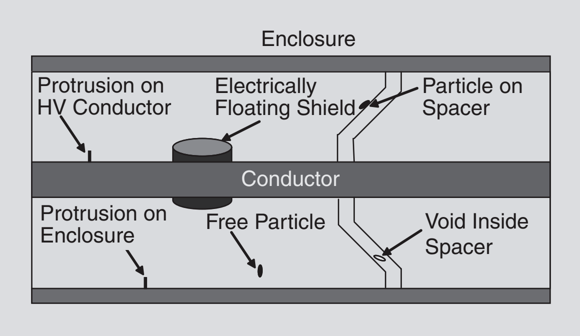

Figure 8 Possible defects in the insulation system of GIS

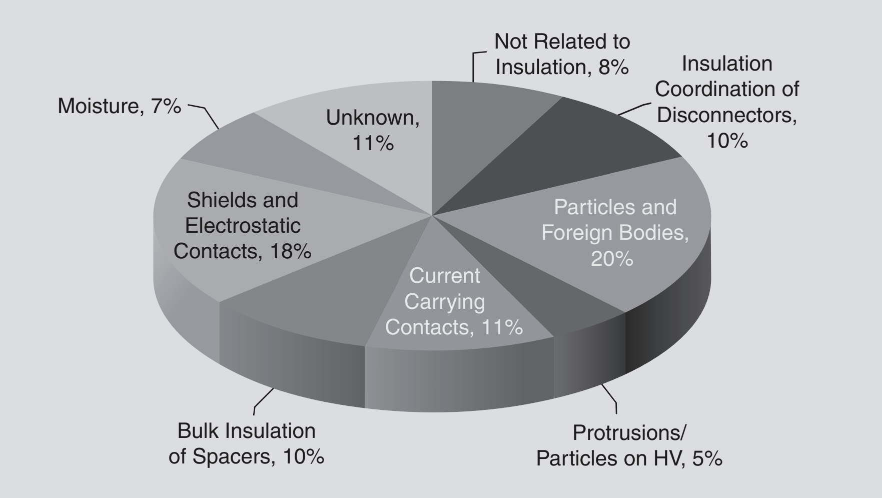

Figure 9 Main failure causes in GIS

other sources in the failure of GIS. It can be seen from Figure 9 that the defects shown in Figure 8 represent about 53% of the total main failure causes in GIS. A protrusion from live or grounded parts creates a local field enhancement. Such defects have little influence on the ac withstand level because the voltage varies slowly and the corona at the tip will have time to build up a space charge that shields the tip. Under switching and lightning surges, however, there is not enough time to build up such space charges. Consequently, the basic lightning impulse withstand level (BIL) will be drastically reduced. Usually, protrusions exceeding 1 mm are considered harmful.

Free moving particles have little impact on the BIL, while the ac withstand level can be significantly reduced. This reduction depends on their shape and position; the longer they are and the closer they get to the HV conductor, the more dangerous they become. If they move onto a spacer, they become even more dangerous. A particle on a spacer may, with time, lead to deterioration of the spacer surface. Under typical conditions for GIS, particles have inception electric fields of several kV/mm and true charges of several 10 pC to 100 pC. Wire particles approximately correspond to the type of particles encountered in practice.

Voids and defects inside spacers could create discharges once the initiation voltage is exceeded. Usually, such voids are found during quality control in the factory. A defect within a spacer will give rise to discharges, electrical trees, and eventually lead to breakdown. Since the sound absorption in epoxy is very high, the chance to detect them with acoustic measurement is small.

A floating component is a conducting element that is not bonded to, or in electrical contact with, the conductor or sheath. Generally, floating components should not be present in GIS. The most common types of components that may become floating are spacer inserts or field-grading shields at either the conductor or the sheath "enclosure." If a field-grading shield becomes mechanically loose, it may become electrically floating. A floating shield adjacent to an electrode could give rise to large discharges between the shield and the electrode, which can eventually lead to failure.

Floating components normally cause PD with magnitudes in the range of 10^4 to 10^6 pC/pulse with repetition rates of 120 to several thousand discharges per second, in multiples of 120 Hz (for 60 Hz power frequency). An electrically floating shield takes a potential, which is determined by the relationship between its capacitance to the conductor versus that to ground, which exceeds the insulation level to the conductor or to ground, and the capacitance will then discharge. Such discharges tend to be repetitive with a charge transfer in the range of nC to μC. The discharge pattern is usually regular and with PD magnitude larger than that for a void in an insulator.

PD Mitigation Methods

If the effects of defects/contaminants are mitigated or controlled, then improvement in the reliability of SF_6 GIS could be achieved. Moreover, this could lead to higher working stresses for future compressed gas apparatus, and consequently to a considerable reduction in SF_6 GIS size and cost. Some techniques that are used for the mitigation and control of particle contaminations in GIS are particle traps, dielectric coating of the electrodes, and the use of SF_6 gas mixtures.

GIS systems are typically conditioned before service by raising the voltage in discrete steps so as to move particles over a period of time into particle traps, but additional particles may be generated due to the switching operation of circuit breakers and conductor movement under load cycling. Particles adhering to the support insulators can result in significant reduction in the impulse flashover voltage of the system. In order to prevent the particles from interacting with solid support insulators, electrostatic particle drivers and traps are used. In ac GIS, the particle traps are usually fixed around, or near to, the insulators, which represent low-field areas, to prevent the attachment of the particles on the insulators and so reduce the chance of particle-initiated breakdowns associated with the insulators. In dc GIS, the bus consists of three regions, namely, a spacer region where an electric shield is installed at the triple junction, a particle scavenging region where both the particle driver and the particle trap exist, and a non-levitating region where the electrodes are coated. In such dc GIS, a shield ring “field-well ring” is placed at the end of the particle driver for two purposes: (1) to reduce the electric field and assist the particle trapping and (2) to prevent the firefly phenomenon, where the particle sometimes stays very close to the HV conductor under negative polarity.

Dielectric coatings of conductors in GIS systems improve the dielectric strength. This is due to coating over the conductor roughness and decreasing the high local field; coating resistance reduces the development of pre-discharges in the gas, and significance reduction in the particle charge during impacts and a consequent increase in the lifting field. However, coating the conductor can also create problems. If the coating is damaged, it could create particles. The coating lowers the particle mobility and thus, makes more difficult the use of particle traps. By increasing the lift-off voltage, it can be more dangerous because the particles can then lift off and induce direct breakdown without previous warning or possibility of PD detection “spring effect.”

SF_6-N_2 is often considered to be the best substitute for SF_6 in both GIS and GIL because of the following reasons:

- N_2 is a cheap gas, and its dielectric strength in a uniform field is higher than that of gas mixtures of SF_6 with most common gases.

- It avoids SF_6 liquefaction at low ambient temperatures.
- It reduces the quantity of SF_6 and hence reduces environmental impact.
- At equal gas pressure, SF_6-N_2 mixtures are less sensitive to insulation defects than undiluted SF_6.

The effective ionization coefficient (a) for the SF_6-N_2 mixture decreases with the ratio of N_2/SF_6. In addition, the PD magnitude for fixed protrusions increases with gas pressure, where pure SF_6 gives the greatest increase. For free moving particles, the PD magnitude is independent of both the type and pressure of the gas.

Generally, the field strength near the triple junction can be reduced by devising the spacer shape such that an obtuse angle exists at each spacer-electrode interface, as well as by electrode-inserted spacers. In addition, FGM has recently been introduced, as was discussed earlier. Furthermore, the conducting particles can be effectively trapped and prevented from reaching the HV conductor by electrode-inserted rib spacers or trap-rib spacers with dielectric coating of the earthed enclosure.

Partial Discharge Monitoring Systems

Ultra-high frequency (UHF) technique can be applied for PD measurement in GIS, either using internal or external UHF couplers. The internally fitted UHF couplers have some limitations, such as the risk of breakdown (if they are not positioned in the hatchcover, where the field is very low), a large number of sensors is required to detect PD for a GIS (e.g., from six to nine per three-phase bay), and possible focusing of the UHF signal because the enclosure may act as a reflector. External UHF couplers also have some limitations, such as some loss of sensitivity as they may contain internal protection circuitry or preamplifiers that prevent pulse injection during the sensitivity verification test. However, external UHF couplers have many advantages such as: sensors are movable, the UHF technique is applicable to GIS having dielectric windows, it is a cost-effective method, and it offers a more effective and flexible PD location system.

The acoustic emission (AE) technique offers several advantages: movable sensors, good sensitivity, immunity to external noise, defects may be localized and recognized, and risk assessment based on source characterization. Its disadvantages are the high attenuation and, for some cast enclosures and defects in cast epoxy (e.g., voids) attenuation may be significant, requiring too many sensors. Therefore, the UHF technique has many characteristics that make it advantageous over that of the AE.

The world's first GIS online partial discharge monitoring (PDM) system was introduced in 1993, and they are now installed worldwide at voltages of 230–800 kV. Today, different PDM systems are available and utilize the same principle of UHF technology. Based on practical experiences with actual monitoring and diagnostic systems, the GIS system's reliability can be improved with exploitation of service life. The cost benefits of using PDM systems can be deduced from the dramatic reduction in failure rates when comparing the in-service failure statistics with and without using such systems.

A PDM system normally operates as a "black box" that captures UHF signals and submits warning and alarm signals to the substation control system only in the case of in-service relevant PD activity. Therefore, the most important PDM system features are the applied noise suppression techniques and the efficiency of the PD identification algorithms.

Today, the suppression of noise and other background signals like radar or mobile phone signals is realized by combined hardware and software filters. Actual PD identification algorithms are based on phase-resolved pulse sequence analysis. The applied redundant diagnosis systems (RDS) with hierarchical or hybrid structures consist of PD feature extraction and defect classification in combination with a proper reference data base to identify the type and nature of the insulation defect. The results from such RDS can have an accuracy of correct identification in the range of over 95%. Only a very small number of captured PD data sets are classified as unknown defect or identified in a wrong way.

Conclusion

GIS are widely used in the electric power industry as a key element for controlling bulk power from MV to UHV range. SF_6 and SF_6/N_2 mixture HV GIS have proved themselves in several thousands of installations worldwide because of their many outstanding advantages.

Epoxy or cast-resin solid insulators are used as spacers in GIS. They represent the weakest points in GIS systems as the electric field on their surfaces is higher than that in the gas space.

Historically, AIS were the only available technology until 1936, and it will continue to share more than 60% in the coming decade with the introduction of compact AIS and HIS types.

Highly optimized GIS, using a minimum number of junction elements (elbows and cross junctions), allows delivering much smaller subtransmission and distribution substations fully assembled and tested in factory (i.e., shortening the time to commissioning).

AC GIS rated 1100 kV and short-circuit breaking current of 50 kA_{rms} is the latest GIS technological achievement. The 1200-kV ac GIS are going to be visible very soon. DC GIS rated 500 kV for HVDC transmission systems have become available, too.

Circuit breakers, disconnectors, bus ducts, and interconnecting parts are the major components that cause failures by about 72% in GIS. Generally, the higher the operating voltage of GIS, the higher is the failure rate due to the higher electric field strength.

A target failure rate of 0.1 failures per 100 CB-bay years should be achievable, in particular by means of monitoring and diagnostic systems, as about 61% of the failures could have been detected.

PD in compressed SF_6 GIS arise from protrusions, free conducting particles, floating components, and bulk insulation defects (voids). These defects represent about 53% of the total main failure causes in GIS.

Some techniques used for the mitigation and control of particle contaminations in GIS are particle traps, dielectric coating of the electrodes, the use of SF_6 gas mixtures, and the use of FGM as solid spacers for optimizing its profile.

The ultra-high frequency and acoustic emission techniques can be used for GIS PD monitoring system, where the former has many advantageous characteristics over the latter. A dramatic reduction in failure rates can be achieved when using such systems.

Further Reading

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8.1 DEFINITION OF SYMMETRICAL COMPONENTS

Assume that a set of three-phase voltages designated V_a, V_b, and V_c is given. In accordance with Fortescue, these phase voltages are resolved into the following three sets of sequence components:

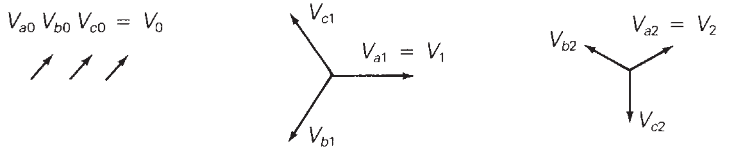
1. *Zero-sequence* components, consisting of three phasors with equal magnitudes and with zero phase displacement, as shown in Figure 8.1(a)
2. *Positive-sequence* components, consisting of three phasors with equal magnitudes, 1 120° phase displacement, and positive sequence, as in Figure 8.1(b)
3. *Negative-sequence* components, consisting of three phasors with equal magnitudes, 1 120° phase displacement, and negative sequence, as in Figure 8.1(c)

The zero-, positive-, and negative-sequence components of phase *a*, which are V_{a0}, V_{a1}, and V_{a2}, respectively, are presented in this section. For simplicity, drop the subscript *a* and denote these sequence components as V_0, V_1, and V_2. They are defined by the following transformation:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \; 5 \; \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} \tag{8.1.1}$$

where

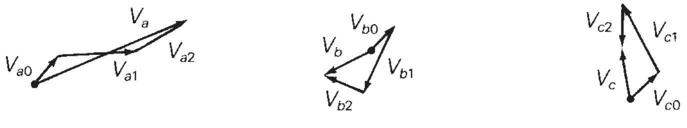
$$a \; 5 \; 1\underline{/1208} \; 5 \; \frac{2 1}{2} \; 1 \; j\frac{\sqrt{3}}{2} \tag{8.1.2}$$



(a) Zero-sequence components

(b) Positive-sequence components

(c) Negative-sequence components



Phase *a*

Phase *b*

Phase *c*

FIGURE 8.1

Resolving phase voltages into three sets of sequence components

$a^4 \; 5 \; a \; 5 \; 1\underline{/1208}$

$a^2 \; 5 \, 1\underline{/2408}$

$a^3 \; 5 \, 1\underline{/08}$

$1 \; 1 \; a \; 1 \; a^2 \; 5 \; 0$

$1 \; 2 \; a \; 5 \; \sqrt{3}\underline{/2\,308}$

$1 \; 2 \; a^2 \; 5 \; \sqrt{3}\underline{/1\,308}$

$a^2 \; 2 \; a \; 5 \; \sqrt{3}\underline{/2708}$

$ja \; 5 \, 1\underline{/2108}$

$1 \; 1 \; a \; 5 \;\; 2\,a^2 \; 5 \; 1\underline{/608}$

$1 \; 1 \; a^2 \; 5 \;\; 2\,a \; 5 \; 1\underline{/2\,608}$

$a \; 1 \; a^2 \; 5 \;\; 2\,1 \; 5 \; 1\underline{/1808}$

TABLE 8.1

Common identities involving $a \; 5 \; 1\underline{/1208}$

Writing (8.1.1) as three separate equations:

$$V_a \; 5 \; V_0 \; 1 \; V_1 \; 1 \; V_2 \qquad (8.1.3)$$

$$V_b \; 5 \; V_0 \; 1 \; a^2V_1 \; 1 \; aV_2 \qquad (8.1.4)$$

$$V_c \; 5 \; V_0 \; 1 \; aV_1 \; 1 \; a^2V \qquad (8.1.5)$$

In (8.1.2), *a* is a complex number with unit magnitude and a 1208 phase angle. When any phasor is multiplied by *a*, that phasor rotates by 120° (counterclockwise). Similarly, when any phasor is multiplied by $a^2 \; 5 \; (1\underline{/1208})\;(1\underline{/1208}) \; 5 \; 1\underline{/2408}$, the phasor rotates by 2408. Table 8.1 lists some common identities involving *a*.

The complex number *a* is similar to the well-known complex number $j \; 5 \; \sqrt{2\,1} \; 5 \; 1\underline{/908}$, Thus, the only difference between *j* and *a* is that the angle of *j* is 908, and that of *a* is 1208.

Equation (8.1.1) can be rewritten more compactly using matrix notation. Define the following vectors $\boldsymbol{V}_\text{P}$ and $\boldsymbol{V}_\text{S}$, and matrix $\boldsymbol{A}$:

$$\boldsymbol{V}_\text{P} \; 5 \; \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \qquad (8.1.6)$$

$$\boldsymbol{V}_\text{S} \; 5 \; \begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} \qquad (8.1.7)$$

$$\boldsymbol{A} \; 5 \; \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \qquad (8.1.8)$$