SUBSTATION INSULATION

Substations are comprised of an array of equipment used for the purposes of providing flexibility for interconnections between transmission lines, transformers, generating equipment, and loads. The equipment normally used in substations includes transformers (both power transformers and instrumentation transformers used for system protection, monitoring, and control), circuit breakers, disconnect switches, bus conductors, and surge protection equipment. All of these devices and apparatus use nonconducting materials to provide electrical isolation between all parts of the equipment operating at different voltages. These materials and combinations thereof are the substation insulation, which is the subject of this article. The provision of isolation between energized parts is a simple concept but is, in practice, complicated by the need to achieve overall system design optimization and accommodate the range of electrical stresses, material characteristics, mechanical duties, and environmental stresses.

Insulation materials include solids, liquids, and gases. In substations, dielectric liquids like mineral oil and other synthetic fluids are used in transformers and circuit breakers. Air is the most common form of gas insulation, which, used in conjunction with selected solid insulation materials (e.g., porcelain and epoxy/fiberglass/polymeric insulators), makes up the most common form of insulation system used in substations. In urban areas where space available for substations is limited and costly, compact gas-insulated substations are employed. Equipment in these substations, including bus, circuit breakers, instrument transformers, and disconnect switches, are enclosed in grounded metal structures. The energized components are supported internally with solid insulating spacers made out of reinforced polymers, and they are insulated with pressurized sulfur hexafluoride (SF_6) gas.

The insulation systems in substations are designed to operate satisfactorily for many years without problems. This requires that the insulation system must withstand a wide range of electrical stresses imposed by the power system and the environment. The applied voltage, the material properties, and the geometrical design of the substation and its equipment determine electric field stresses. The applied voltages cover a wide range of magnitudes and durations as illustrated in Fig. 1. Normal system operation requires substation

J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*.

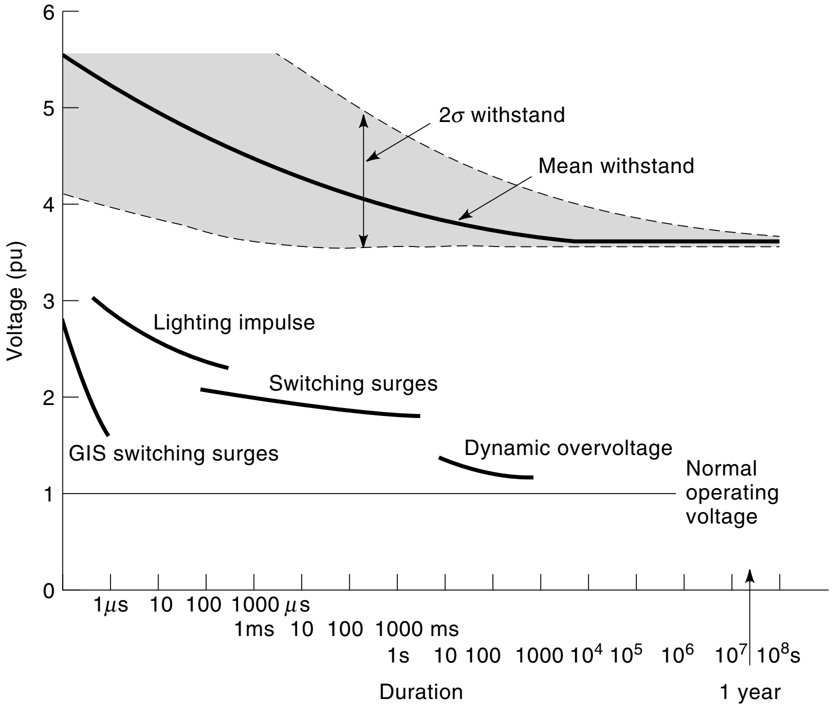

Figure 1. Voltage–time curves of applied voltage typical in substation environments and typical withstand strength for coordinated operation.

insulation to withstand power frequency voltages indefinitely over a range typically ± 10% of nominal system voltage. Voltage profiles over a power system depend on many factors, including primarily reactive power management and system design factors. Loss reduction and other system requirements typically result in system voltages near the maximum end of the system design range in many situations.

Under abnormal system operation when system disturbances (e.g., generator trips, load rejections, or line trips) occur, significant dynamic overvoltages are generated. These dynamic overvoltages are typically power-frequency overvoltages, which persist for small fractions of a second to a few seconds as determined by power flow control systems and/or system stabilizers. Also associated with many system disturbances are switching surges or transients which are generated by circuit breakers opening or closing to clear faults and to restore potential to transmission lines or other system elements. Switching transients are frequently in the range of 2 per unit (pu) magnitude, with front times in the microsecond range and durations in the range of hundreds of microseconds. The magnitude and duration of switching transients are dependent on system design, lengths of lines, and use of surge-limiting reclosing devices.

Lastly, substation insulation is required to withstand the stresses imposed by environmental phenomena including lightning. Lightning may strike directly or remotely but will result in conducted lightning surges appearing at the substation terminals. Lightning activity varies considerably depending on geographic location and, therefore, system requirements for lightning withstand vary. Lightning phenomena also depend on natural effects which result in lightning stroke currents with varying magnitudes. The voltages which result depend on transmission line surge impedances, grounding system impedance, and so on. Lightning-generated surge magnitudes for close-in strikes can be in the range of 3 pu with risetimes in the range of a microseconds and durations in the range of a few tens of microseconds.

Designers have the option to consider application of surge-limiting or protective devices. These devices are described elsewhere in this encyclopedia; however, the decision to apply surge protection depends on a number of technical and economic considerations. These include the cost of optional surge protective devices versus the cost of purchasing more or less surge withstand capability in substation equipment and the cost of more or less insulation for line and substation insulation systems.

Stresses imposed by type, factory, and system testing, by power system disturbances, by switching surges, and by lightning must be withstood with a comfortable margin. The margin is achieved through a careful insulation system design using advanced knowledge of insulating material capabilities and advanced analytical techniques. In practice, margins between stress levels and withstand capability are fairly wide for two reasons. Perfectly manufactured and maintained insulating materials and systems are not, as yet, a totally dependable reality; and secondly, some allowance is usually made for loss of insulation strength resulting from normal long-term material aging. In the case of imperfect insulation systems, solids are typically cast, filled materials (epoxies and other plastics) which are prone to void and metallic inclusion defects. Conductors can have sharp burrs or protrusions which create localized stress enhancements. Contamination in the form of metal filings, dirt, cleaning rags, and even insects and other vermin can be found in gas- and liquid-filled equipment. Lastly, environmental factors such as ice, snow, and airborne pollution can significantly degrade the performance of conventional air-insulated systems. Aging processes are typically accelerated by defects in solid and liquid insulation, by electrochemical processes in insulating gases, and by atmospheric and pollution effects in air-insulated equipment. Long-term aging processes include failure mechanisms associated with conventional material aging, thermal aging, electrochemical aging in GIS, cement growth aging in porcelain insulating components, and so on.

Mechanical stresses are caused by normal and abnormal operations in the power system and by environmental effects. Environmental stresses include (a) loadings from wind, ice, and combinations thereof (galloping conductors and the resulting insulation loading, aeolean vibration), (b) earthquakes, and (c) vandalism. Mechanical stresses imposed by the power system itself on insulation systems are associated with maintenance operations and with systemic stresses including short-circuit loading (bundle dynamic loading on insulator strings or cantilever loading of posts in rigid bus systems). Lastly, thermomechanical loading needs to be considered to accommodate thermal expansion of bus sections to (a) prevent overloading the insulating supports and (b) ensure that differential expansion of bonded metallic and insulating materials is not the source of short- or long-term problems.

Exposed air-insulated conventional substations must continue to perform reliably in spite of adverse environmental conditions. Industrial and atmospheric pollution, moisture, salt, ice, and low/high temperature operation are all issues which need to be considered in a practical substation insulation design. Designers of insulation systems have several choices in dealing with such situations. Conventional porcelain insulation is likely to have the lowest initial capital cost; but in adverse conditions, some form of contamination monitoring program will be needed and cumulative maintenance costs for monitoring and washing can be substantial. Resistive glazed porcelain insulators will exhibit significantly better performance under polluted conditions, but they are more costly to purchase. Composite or nonceramic insulation systems are a relatively new and attractive technology; although still under development in the area of station post insulators, nonceramic insulators are gaining in practical use. Materials used in such insulation systems offer the potential for relatively maintenance-free operation under adverse contamination conditions.

Substation design involves many interacting factors for which economic trade-offs need to be made. For example, conventional air-insulated rigid bus design requires designers to follow an iterative manual approach (1) or to use an optimization techniques to formulate the constrained multi-factor nonlinear design problem (2). Insulation coordination and determination of the basic insulation impulse level (BIL) require a number of risk-weighted decisions to be made, all of which have significant economic and reliability consequences. Insulation systems are one of the major critical elements in the design of substations, but their design must be integrated with all aspects of substation design.

In this article, the most important aspects of many of the topics introduced above will be described in greater detail. Two major types of substation design are in common use. Therefore the remainder of this article treats insulation systems under the headings of "Open Air-Insulation Systems" and "Enclosed Gas-Insulation Systems."

OPEN AIR-INSULATION SYSTEMS

Conventional air-insulated substations (AIS) represent a large majority of installed high-voltage substations. They have been the installation of choice since the advent of high-voltage power transmission and distribution systems. They range in voltage from distribution levels to 765 kV systems. The external insulation generally utilized in these outdoor substations takes the form of insulators (posts, suspension, and pin type) and housings. These types of apparatus are generally broken into classifications based on manufacturing and materials. These two broad categories are ceramic and polymeric. Ceramic insulators include those constructed from porcelain and glass. Polymeric insulators, often referred to as nonceramic insulators, are made up of various designs, usually incorporating fiberglass strength members encapsulated in rubber housings which afford protection to the fiberglass core from electrical stresses and moisture. This article provides a brief introduction into the area of conventional substation insulation. The initial section explains the importance of environmental conditions as related to insulator performance. This is followed by (a) a brief history of the development of both ceramic and nonceramic insulators, (b) a synopsis of their performance with respect to environmental conditions and contamination, (c) aging mechanisms and failure modes, and (d) factory and type testing and specifications.

Operation in a Contaminated Environment

The environment in which an insulator is installed can have significant impact on the unit's performance. When insulators are situated in areas where they are exposed to contamination, their performance can deteriorate significantly. This is likely the single greatest challenge encountered in the design and operation of substation insulation. In order to provide some insight into the subject, this section describes the contamination flashover process and gives a synopsis of the remedies used to solve contamination related operating problems.

The process of contamination flashover is described in detail in the literature (3). For introductory purposes the phenomenon can be described as follows. When installed in a contaminated environment, insulator surfaces become coated over time with whatever airborne contaminants are present. This coating can take the form of deposition of dry contaminants such as road salt or industrial pollution, or it can be deposited in a wet form, as is the case with units installed in coastal areas. The presence of dry contamination deposits does not generally affect the performance of the insulators. This is because most of the contaminants do not form a continuous conductive layer on the insulator surface. However, when the insulator is wetted due to condensation, fog, or light drizzle, its electrical integrity can be compromised if the contamination contains soluble electrolytes. This occurs because upon wetting of an insulator surface that is contaminated with soluble pollution, a conductive solution is formed over the insulator surface. When this happens, the surface resistance of the insulator is greatly reduced, and significant current can flow across the energized insulator to ground. Such current flow results in heating of the conductive solution covering the insulator surface. Since the amount of contamination deposited naturally on the insulator surface is not uniform, the surface resistivity of the electrolyte solution is not uniform, and therefore the current density over the insulator surface is also not uniform. This uneven current density causes localized heating at points on the insulator surface. As the current continues to flow, the insulator surface begins to dry in certain areas. As these areas dry, the current flowing in them is transferred to other areas in parallel with the dry spots. This results in localized increases in current density, and the associated increased heating eventually leads to the formation of more dry areas. As the process continues, dry bands, which block current flow, form on the insulator surface. When these dry bands form, the entire voltage impressed across the insulator appears across the dry bands. Since these dry bands are too narrow to withstand the voltage across them, arcing occurs and the dry bands undergo flashover and increase in size. Once dry band arcing is initiated, two outcomes are possible. The insulator can become sufficiently dried so as to prevent complete flashover, or the dry band arcs can increase in size until complete flashover of the unit occurs. The flashover/withstand outcome is statistically based, and it is dependent on the effectiveness of the wetting action and the contamination severity. The mechanism is similar for coastal areas where salt storms can occur with direct impingement of saline solution on the insulator surface.

Visual observation of surface contamination is not a reliable indicator of problem severity. For example, pollution in the form of salt sufficient to cause flashover can go visually unnoticed on an insulator surface. Conversely, the integrity of insulators that are completely blackened by contaminants can be unaffected. The key to the severity of pollution on insulators lies in the conductivity of the liquid layer formed during wetting. A standard measure of this conductivity is equivalent salt deposit density (ESDD). The ESDD of an insulator surface is obtained by wiping the unit down and dissolving the gathered contaminants in distilled water. Once the contaminants have dissolved, the conductivity of the water sample is measured. This measure is expressed in the equivalent amount of salt (in mg/cm^2) that will result in the same conductivity when salt is dissolved in the same amount of distilled water. ESDD is utilized as a critical design parameter when insulators are installed in contaminated environments. It is used to determine the leakage distance required for the insulator to perform adequately in a given environment. The ESDD values encountered in service have been slotted into ranges that vary in environmental conditions ranging from pristine to heavily contaminated. Table 1 presents a chart based on IEC Publication 815 (4) illustrating the relation between contamination severity, measured ESDD levels, and recommended leakage distance.

Mitigation of Contamination Flashover. There are a number of mechanisms used to reduce or eliminate the possibility of contamination flashover of ceramic insulators. These include:

- Use of insulators with optimized shapes
- Periodic cleaning
- Grease coating
- RTV coating
- Resistive glaze
- Polymer replacement

Use of Insulators with Optimized Shapes. The shape and leakage distance of insulators can be varied to address environmental conditions. Generally the shapes are aerodynamically optimized to gather as little pollution as possible and to enhance self-cleaning through wind and rain. Standardized variation in shape parameters has been developed for service areas characterized by different environmental contamination processes. Special designs of varying shed profiles, diameters, spacings, leakage distance, and so on, are available.

Table 1. IEC 815 Contamination Severity Table

Pollution Level (Max. ESDD)	Examples of Typical Environments	Min. Leakage Distance
I—Light (0.06 mg/cm^2)	Areas without industries and low density of houses equipped with heating plants Areas with low density of industries or houses but subjected to frequent winds and/or rainfall. Agricultural areas (use of fertilizers can lead to a higher pollution level). Mountainous areas. **Note:** All these areas shall be situated at least 10 km to 20 km from the sea and shall now be exposed to winds directly from the sea.	16 mm/kV
II—Medium (0.20 mg/cm^2)	Areas with industries not producing particularly polluting smoke and/or with average density of houses equipped with heating plants. Areas with high density of houses and/or industries but subjected to frequent winds and/or rainfall. Areas exposed to wind from the sea but not too close to the coast (at least several km distant).	20 mm/kV
III—Heavy (0.60 mg/cm^2)	Areas with high density of industries and suburbs of large cities with high density of heating plants producing pollution. Areas close to the sea or in any case exposed to relatively strong winds from the sea.	25 mm/kV
IV—Very Heavy (>0.60 mg/cm^2)	Areas generally of moderate extent, subjected to conductive dusts and to industrial smoke producing particularly thick conductive deposits. Areas generally of moderate extent, very close to the coast and exposed to sea-spray or to very strong and polluting wind from the sea. Desert areas, characterized by no rain for long periods, exposed to strong winds carrying sand and salt, and subjected to regular condensation.	31 mm/kV

Note. This table is based on ceramic and glass insulators (Ref. IEC 815). Its use for composite insulators is still to be verified.

Periodic Cleaning. In many installations, either a high-pressure water system or corn-and-CO_2-pellet blasting is utilized to periodically clean surface contaminants off insulators. Of these, high-pressure water cleaning is predominant and by far the cheapest. Corn-and-CO_2-pellet blasting is far more effective for cleaning cementatious like deposits that are difficult to remove. These procedures are generally applied on a repetitive basis linked to the pollution composition, severity, and deposition mechanism.

Grease Coating. Coating of insulator surfaces with petroleum gels or hydrocarbon greases is utilized in areas of heavy contamination. These coatings produce hydrophobic surfaces and a surface layer capable of encapsulating the contaminants. The former characteristic is covered in the section on nonceramic insulators, while the latter prevents the contaminants from going into solution upon initiation of the surface wetting mechanism. This approach has proven effective and has been in use for many years. As with washing, this is a maintenance-based solution, which must be periodically repeated. Usually the old grease is removed before new grease can be applied. In most instances, both the application of the new and removal of the old grease are manual operations. The process is slow and requires circuit outages.

RTV Coating. Room-temperature vulcanizing (RTV) silicone coatings are being applied with increasing frequency on both substation and line insulators. RTV coatings are applied over porcelain insulators and bushings to provide hydrophobic surfaces (described in detail in the section on nonceramic insulators). Current information based on service experience and laboratory testing shows that these coatings perform well and will last for a number of years. The lifetime depends upon the coating composition, the application thickness, and of course the pollution severity. RTV coatings are popular in that they represent a longer-term solution, which does not require replacement of the insulators. They can be applied over existing insulators after adequate cleaning. A further advantage is that they can be applied to insulators on live circuits. Their mechanism of resistance to contamination flashover is based on surface hydrophobicity maintenance and contamination encapsulation. These processes are similar to those described in subsequent sections dealing with polymer insulators. As is the case with nonceramic insulators, RTV coatings can rapidly deteriorate in the presence of electrical discharges, so care must be taken at higher voltage levels to ensure that coated insulators are free of corona.

Resistive Glaze Insulators. In areas of heavy contamination, resistive glaze insulators are often used to alleviate contamination flashover. Resistive glaze insulators utilize a specialized glaze, which is partially conductive. The glaze is formulated so as to provide steady-state power frequency current flow along the insulator surface. Its use results in a uniform electric field distribution and surface heating. Both of these contribute to superior contamination performance. Surface heating inhibits wetting through condensation and aids in the drying process, while the more uniform electric field distribution acts to control dry band flashover. The conduction current of the glaze is generally designed to be approximately 1 mA and results in an insulator surface that is several degrees warmer than the ambient surroundings.

The improvement in contamination flashover performance through the use of resistive glaze was first demonstrated in the 1940s (5). Since that time, resistive glaze insulators have met with mixed success when applied in service. The technology has been commercially available since the 1950s. The 1970s saw production of both suspension and post-type resistive glaze insulators. While they both provided excellent contamination flashover resistance, they suffered from glaze corrosion at the junction point where electrical contact was made between the metal portions of the insulator and the glaze. The problem was particularly severe in the case of suspension units where there is a high current density at the glaze/pin junction. The glaze corrosion resulted in a break in the conductive path between the insulator's line and ground end. This prevented the flow of resistive current and thereby eliminated the improvement in contamination performance. Manufacture of resistive glaze suspension insulators was halted after several years, but application of the technology to the production of post insulators and bushings continued. Over the years, the corrosion problem on post insulators has been studied and performance improved. Currently, resistive glaze post insulators and bushings are successfully utilized in many installations worldwide where the environmental conditions are severe (6). Recently, there has been renewed interest in resistive glaze suspension insulators. The process utilized in producing these units has undergone significant improvement, and work performed by manufacturers suggests that the problems associated with severe glaze corrosion have been successfully addressed (7).

Use of Nonceramic Insulators. Use of nonceramic insulators as a solution to contamination flashover problems has been growing since the early 1980s. Their application for this purpose and a number of others is given in the section on nonceramic insulators.

Ceramic Insulation

Insulators made of ceramic materials include those made from porcelain and glass. Their initial use precedes the construction of power systems. They were first introduced as components in telegraph networks in the late 1800s. There are a number of basic designs for ceramic insulators. Porcelain is used for the production of cap and pin suspension units, solid- and hollow-core posts, pin-type, multiple-cone, and long-rod insulators, and bushing housings. Glass, on the other hand, is used only for cap and pin suspension and multiple-cone posts. Typical designs for these types of insulators are shown in Fig. 2.

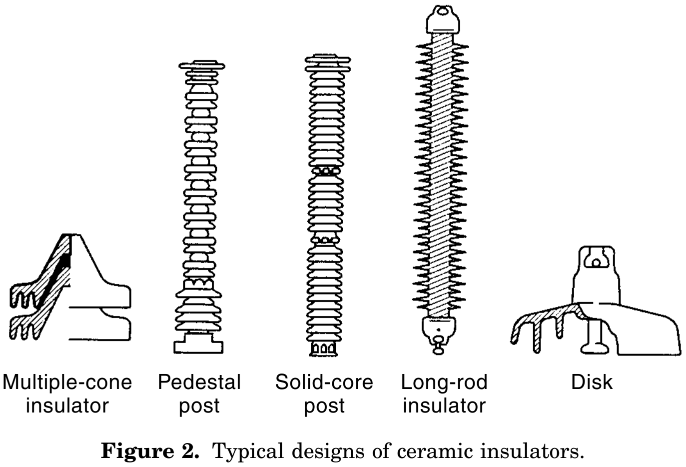

Figure 2. Typical designs of ceramic insulators.

Porcelain and glass insulators are well established as might be expected based on their long history of use. Currently, these types of insulators comprise by far the majority of in-service units. Continuous improvements in design and manufacturing processes have resulted in insulators, which are both reliable and long-lasting. Porcelain units are coated with a glaze to impart strength to the surface. Today's glass insulators are predominantly manufactured from thermally toughened glass, which prevents crack formation. Both of the materials have inert surfaces, which show very good resistance to surface arcing, and both are extremely strong in compression.

The manufacturing process for electrical porcelain is complex and involves numerous steps. With glass insulators, the manufacturing process is less complex, but still requires tight control. Failures of porcelain and glass insulators can usually be traced back to the manufacture, material, or application of the units. If adequate caution and control in these areas is not maintained, the likelihood of an inferior product increases. However, as previously mentioned, when well made, both porcelain and glass insulators are highly reliable. The majority of bushings and lightning arresters installed in today's substations are contained within porcelain housings. Porcelain housings are in essence hollow-core post insulators.

Polymeric Insulators

Polymeric or nonceramic insulators were first introduced in 1959. They were made from epoxy; and when used outdoors or in contaminated environments, they were susceptible to problems associated with UV degradation, tracking, and erosion. Various manufacturers through the 1960s and 1970s produced nonceramic insulators (NCIs). Those early designs were primarily of the suspension/dead-end and post type. Certain fundamental aspects of the early designs formed the basis of today's production units. They utilized a pultruded fiberglass core as the strength member. The fiberglass core was afforded protection against the environment through encapsulation in a rubber housing. The mechanical connections at the insulator ends were made using a variety of means. Some designs used glued fittings, others had wedge-type attachments, and still others utilized crimping. In all cases, metal end fittings were attached to the fiberglass rod to give the insulator the mechanical strength the applications required.

Early advocates of NCIs claimed that they afforded an up to 90% weight reduction when compared to their ceramic equivalents. NCIs are better in terms of safety when used for bushings. They also had superior resistance to seismic events and shock loads such as those to which insulators are exposed when conductor or hardware failure occurs on adjacent spans. Another area in which they showed promise was their ability to withstand vandalism. Significant portions of ceramic insulator failures are due to vandalism involving shooting. When a bullet hits a ceramic unit, it breaks or shatters. NCIs do not fail immediately when shot because their components are not brittle. There are instances reported where NCIs have remained in service without problems for many years after being shot. A final advantage claimed by manufacturers and users of early NCIs was that they could be designed with extremely high leakage lengths. This allowed relatively easy optimization of designs to differing environmental conditions.

Early experience with NCIs was confined to short lines and trouble spots. The trouble spots were generally associated with areas of environmental contamination or gunshot damage. The initial experience with these applications proved somewhat disappointing. A host of problems not previously experienced with ceramic units were encountered. Amongst these were tracking and erosion, chalking and crazing, hardware separation, corona splitting, and water penetration. Many of these were associated with the use of inappropriate housing materials and manufacturing techniques, poor-quality fiberglass rods, modular sheds, and poor sealing between the rod, housing, and end fittings. These operating problems resulted in a significant number of outages and line drops. Based on the initial field performance, NCIs saw limited use and therefore limited production.

By the 1980s the technology had evolved sufficiently to address the concerns generated through the early field experience. Understanding of the early failure mechanisms combined with improvements in materials and manufacturing technology resulted in the development of the NCIs available today. Generally, today's NCIs are characterized by one-piece shed or housing structures. This one-piece external housing is obtained through single-stage molding or post assembly vulcanization. Tracking and erosion performance has improved markedly. Most industry standards include tracking and erosion tests, and most of the insulators in production today utilize a track-free high-temperature vulcanized elastomer housing. The importance of sealing the exterior of the insulator against moisture has been well recognized, and it is addressed in most current designs. Present experience with these insulators is beginning to indicate a failure rate approaching that of ceramic units.

Today NCIs are utilized as standard products in many of the world's power delivery systems. Their main areas of application include distribution and transmission systems rated up to 345 kV. There is limited use above 345 kV all the way up to 765 kV.

Current Designs. As previously mentioned, manufacture of NCIs has matured over the last 30 years. Methods of production that have been proven to result in functionally acceptable insulators have been standardized. These critical design and manufacturing aspects focus on shed and housing material, integrity of fiberglass strength member, and methods of sealing against moisture and of attaching end fittings.

Shed Material. In today's manufacture of NCIs, the most commonly used shed and housing materials are hydrocarbon and silicone elastomers. The hydrocarbon elastomers include ethylene-propylene rubbers (EPRs) such as ethylene-propylene monomer, ethylene-propylene diene monomer, and a copolymer of ethylene-propylene and silicone. The silicone elastomers include both high-temperature and room-temperature vulcanizing materials. Both these families of materials utilize aluminatrihydrate as a filler which enhances the materials' tracking performance. The silicone and hydrocarbon elastomer housing materials have been developed to the stage where the tracking and ultraviolet degradation encountered with older designs are no longer a concern. Both materials are utilized on distribution and transmission systems (8). The EPR materials have shown good performance in clean environments, whereas the silicone-based materials function well in both clean and contaminated applications. One of the key characteristics affecting the contamination performance of NCIs is surface hydrophobicity. Hydrophobicity is a characteristic which can (for insulation application) be simply and effectively defined as the ability of a surface to bead water which is deposited on it. As previously explained in the section on environmental and contamination performance, contamination flashover of external insulation involves dry band arcing which develops due to heating and evaporation of electrically continuous liquid paths formed from the dissolution of surface contaminants in a layer of moisture present on the insulator surface. When a surface has a high degree of hydrophobicity, water deposited on it forms individual beads or droplets. This droplet formation inhibits the creation of leakage currents and the associated dry band arcing process. Simply put, an insulator with a highly hydrophobic surface will be characterized by significantly better contamination flashover performance than an identical one with a nonhydrophobic surface. Most polymer insulator housings are hydrophobic when the insulators are first installed. Exposure to surface discharges, corona, and certain chemicals (including water) reduces the hydrophobicity of polymer surfaces. With EPR-based housings, exposure to the operating environment results in the reduction and eventual permanent elimination of surface hydrophobicity. This is one of the more significant differences between the two housing materials. Unlike the EPR compounds, silicone housings have the ability to recover a highly hydrophobic surface state after it has been lost. In the silicone materials used, high- and low-molecular-weight chains constantly break down and recombine. The material's initial hydrophobic state is due to the presence of the low-molecular-weight oils on the surface. The process of losing hydrophobicity involves the removal of these oils. In service, this occurs primarily through exposure to surface arcing which can be present when the insulators are applied in areas of severe contamination. Typically even under extremely severe conditions, the duration of conditions that cause surface arcing is limited to tens of hours. When the arcing abates, the surface again becomes coated with the low-molecular-weight oil and the hydrophobicity is regained. This process of hydrophobicity regeneration takes somewhere between several hours and several days. The number of times that the process can repeat is not known; but given the thickness of the bulk material used in NCIs, it is expected that the process can go on for the expected life of the insulators.

Fiberglass Core. The mechanical strength of NCIs is provided through the use of a fiberglass core. For strain, dead-end, and solid-core post designs, this fiberglass rod is generally manufactured using a pultrusion process. These pultruded rods contain axially aligned electrical grade glass fibres in a resin matrix. Two types of resin are in common use. Epoxy resin is generally believed to give better performance, while polyester resin is a lower-cost alternative. Potential problems associated with these types of pultruded rod include (a) axial cracking due to poor handling or manufacturing procedures and (b) stress corrosion cracking otherwise termed brittle fracture. Brittle fracture is a process which culminates in the physical parting of the insulator and is therefore of significant concern. It is not fully understood and is currently the focus of a significant amount of research.

End-Fitting Attachment and Moisture Ingress. Since their inception, several methods of attaching end fittings to solid-core NCIs have been utilized. Some of the original designs had end fittings that were glued, while others utilized a wedge method of connection. The end fitting fills two very important requirements of an NCI. First, it has to be able to support mechanical loading of the insulator with no slippage. Second, it must be designed so as to ensure that moisture cannot penetrate to the fiberglass core through the interface that exists where the end fitting is joined to the insulator. The importance of the first function is obvious; however, if long-term performance is to be achieved, the second requirement is just as critical, if not more so. Most of the end fittings used in today's designs are either swaged or crimped. This type of connection has proven to give best performance from both the strength and the sealing aspects. Moisture sealing is achieved in three ways: (a) RTV or some other sealant is applied over the end-fitting–housing interface, (b) the end fitting is installed using an interference or friction fit over the housing, or (c) the housing material can be extruded over a portion of the end fitting during the molding phase of the manufacturing process. The last of these is the most effective, and the first has proven least reliable in preventing moisture ingress.

Hollow-Core NCIs. Hollow-core NCIs (HCNCIs) are made of fiberglass filament tubes impregnated with epoxy resin. The housing is then generally extruded over the fiberglass tube. This extrusion process can result in the manufacture of the weathersheds, or, alternatively, the weathersheds can be fitted over the housing and vulcanized. In substations they are utilized primarily as housings for lightning arresters, transformers, circuit breakers, and wall bushings. There are also some applications where they are used as station post insulators for supporting buswork, switches, and other electrical equipment. When compared to conventional ceramic bushings and insulators, they offer several advantages. Amongst these are: light weight, superior contamination performance, and increased reliability under earthquake conditions. For bushings, their use represents an important safety enhancement. As with their porcelain counterparts, internal faults can lead to pressure rises that result in rupture. When this occurs in a properly designed HCNCI, the explosion associated with the same occurrence in a porcelain housing is avoided because the housing does not shatter and present a safety hazard. HCNCIs are also seeing applications as station post insulators. Here they are used because of their earthquake damage resistance, contamination performance, and light weight. The greater mechanical flexibility of an NCI compared to a similar size porcelain needs to be considered. This feature can be exploited fully by incorporating the NCI mechanical characteristics at the substation design stage.

Testing and Specifications

All insulators are tested according to standard procedures outlined in various national and international publications. Porcelain and glass insulators are mechanically and electrically proof tested prior to shipment. In the case of NCIs, prior to leaving the factory each production piece is subject to mechanical but not to electrical proof testing. The primary reason for this difference is that porcelain and glass units are generally made of a number of smaller units in series. For example, a 230 kV station post would generally comprise two smaller posts bolted together to give the clearances required for 230 kV. This allows for piecewise testing of individual components. With NCIs a 500 kV insulator is manufactured as a single piece. Performing electrical tests on each unit would require significant time and investment in a sizable high-voltage test facility. In addition to mechanical and electrical proof tests, the raw materials used in production of ceramic, glass, and polymer insulators are tested as a control on the production process.

With regard to qualification and application testing, the most widely used standards are those issued by IEC, ANSI, IEEE, CSA, and CEA (9–13) Porcelain, glass, and polymeric insulators are subjected to both electrical and mechanical tests. Depending upon the type of insulator, the electrical tests include wet and dry power frequency flashover, lightning impulse flashover, steep front impulse flashover, power arc, and RIV/corona tests. Mechanical tests include tension, thermal mechanical cycling, torsion, cantilever, and electrical–mechanical testing. Contamination performance tests are also performed on these insulators in accordance with the descriptions given in subsequent sections.

A good source of information on the similarities and differences between ceramic and polymer insulators is available in the form of application guides issued by the IEEE (14,15). These contain up to date information regarding the use and service experience of NCIs. The material is of a general tutorial nature and is geared to an audience considering the use of NCIs but not having an intimate knowledge of their functional characteristics.

Contamination tests are described in both IEC and IEEE standards (16,17). At the current time, two test methods, both developed for ceramic and glass insulators, are recognized. These methods and variations upon them are also being applied to NCIs; and at the same time, other tests to characterize the operation of a polymer insulator in a contaminated environment are being developed.

In-Service Inspection and Failure Modes

Substation insulators are often periodically inspected to ensure their continued integrity. For regular porcelain, this includes visual inspection; and in the case of suspension units, it includes an in-service electrical test. For glass, monitoring usually comprises only a visual inspection. These simple actions are usually sufficient to detect any impending problems with ceramic or glass insulators. In-service monitoring of NCIs presents a greater challenge. Methods such as infrared thermography, radio noise detection, corona observation, and electric field monitoring have proven somewhat effective as diagnostic tools for assessing the in-service condition of NCIs. The differences in approaches to NCI and ceramic/glass monitoring are due to the different failure mechanisms characterizing each type of insulator. Damage to ceramic insulators is generally noticeable due to surface cracks. In suspension units, there can be hidden electrical punctures through the insulator in the area between the cap and the pin. These are not visually detectable, but can be detected using a simple field instrument. With glass insulators, any significant physical damage usually results in destruction of the shed because the units are made of tempered glass. With NCIs the insulator can be seriously damaged inside with no indication on its exterior. The mode of failure predominant with NCIs involves mechanical or electrical failure due to rod breakage and/or surface or internal tracking. Because of this, monitoring of NCIs is more complex than monitoring ceramic or glass insulators. Up-to-date information on different approaches to the monitoring of NCIs in-service is summarized in Ref. 18.

Mechanical Characteristics and Dynamic Loading Effects

Substations must be designed to withstand system disturbances and the complete range of environmental phenomena. System disturbances include failures of the insulation system design in one form or another which result in short circuits. The fault currents supplied to the short circuit will flow in the substation bus system and interact following Faraday's law, producing significant forces between the bus conductors. The bus conductors respond dynamically and impose loadings on the insulation system, which supports the bus conductors. For suspension bus systems, interphase forces cause the bus conductors to swing ("skipping rope-like"), which results in (a) reduction of the interphase clearances as illustrated in Fig. 3 and (b) dynamic loads on the suspension insulators. For example, under severe conditions, the phase conductors can swing 180° from their rest position and drop vertically, which imposes large shock axial loading on the insulators. In addition, two- or three-conductor bundles systems are commonly employed in suspension bus systems in order to satisfy bus ampacity requirements. Under short-circuit conditions, such bundles collapse inwardly because the conductors in the bundle are accelerated very rapidly toward each other. The effect is referred to as bundle pinch or bundle collapse, and it results in very large axial dynamic loading on the suspension insulators, which support the bus systems (19,20).

For rigid bus systems, interphase forces cause bus systems to oscillate dynamically. The displacement of such bus systems are not usually significant in comparison with static interphase clearances; however, the bus forces load the post in-

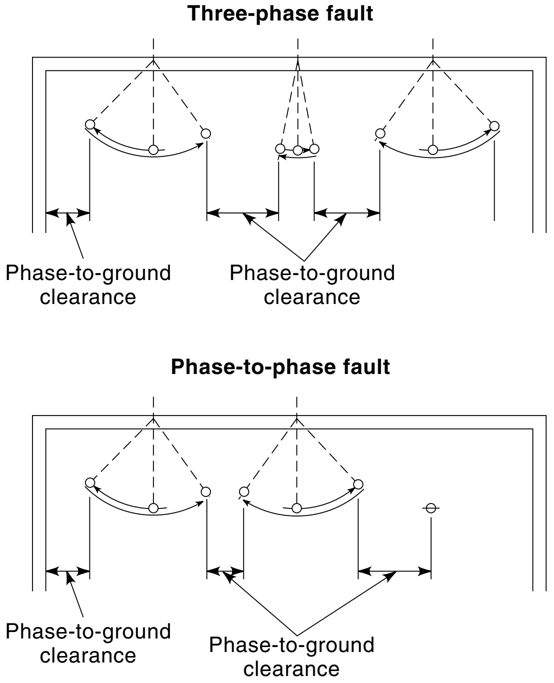

Figure 3. Cross-sectional view of suspension bus, with short-circuit-induced displacements. The reduced phase-to-phase and phase-to-ground clearances must be taken into account in the design of substation bus systems and connections to equipment.

sulators in cantilever fashion. Bus design processes typically optimize the mechanical design in such a way that interphase spacing, bus span between supports, and the resulting loading under maximum short-circuit conditions are balanced (21).

Environmental loading varies significantly depending on geographical location. Wind loading produces transverse loading, which must be coordinated with other simultaneous loads. In addition, wind loading can induce aeolean vibration of bus systems; this produces dynamic loadings, which also must be coordinated with simultaneous loadings. In many jurisdictions, earthquake events must be considered. In these locations, special seismic requirements are specified for switchgear and bus systems, and full-scale seismic dynamic testing is frequently required.

Air Clearances

Multiphase short-circuit currents generate interphase forces which result in phase conductor displacements. In rigid bus systems, the resulting displacements are relatively minor and do not significantly reduce the phase-to-phase clearance. However, for flexible bus systems the phase displacements can be very significant depending on the bus configuration, the short-circuit current magnitude and duration. The mechanics of the phenomenon are well-described in the literature (19,20). The ability of buses to operate successfully following short circuits is an important factor for substation and system reliability. Secondary bus faults can also have a severe effect on power system operations and stability. For line entrance buses the impact of secondary faults may be relatively small; however, for main bus sections the impact would likely be severe.

As described above, significant phase displacements occur under short-circuit conditions which temporarily reduce the phase-to-phase clearance and which, in locations in proximity to grounded structures, temporarily reduce the phase-to ground clearance. The dynamics of such displacements and means for calculating them have been described in the literature, and minimum allowable clearances have been recommended (22–24). Because the statistical coincidence of bus conductors being in the minimum clearance position at exactly the instant a high value switching or lightning surge is present, IEC and others have suggested that probabilistic design approaches may be suitable (22,24). Advanced methods such as these are expensive and complicated and have been of primary interest in cases where existing substations were being considered for uprating to accommodate higher short-circuit currents. However, in such cases, advanced analysis has shown that significant savings can be achieved (25).

ENCLOSED GAS-INSULATION SYSTEMS

IEEE Std C37.122-1993 (26) defines a gas-insulated substation (GIS) as “a compact, multicomponent assembly, enclosed in a grounded metallic housing in which the primary insulation medium is a compressed gas, and which normally consists of buses, switchgear and associated equipment.” GISs have been in use for many years worldwide, especially at the lower voltage classes. A photograph of a typical GIS installation is shown in Fig. 4. The technology has also found use for gas-insulated lines (GIL). The factors that led to the initial interest and popularity of this technology included the promise of high reliability, low maintenance, and compact size. The reduced land requirements (10% to 20% of that of an equivalent conventional, air-insulated installation) made the technology especially attractive for urban areas. Reduced maintenance requirements made it suitable for remote, unattended installations. The encapsulation of all high-voltage parts isolated the insulating materials from environmental influences and made a GIS suitable for regions with heavy salt contamination (e.g., coastal areas), high altitudes, and areas of high precipitation. In recent years, the technology has been extended to higher-voltage classes. A GIS at 550 kV, for instance, was first introduced in the late 1970s. However, GIS application at higher voltage levels was accompanied by a number of problems and resulted in dielectric failures and costly outages (27). Many of these problems can be attributed to those of a developing technology and have prompted active research programs by manufacturers, universities, and utilities. The combined research efforts have, in general, allowed for better specifications, testing, and design evaluation, resulting in a modern GIS which is more reliable and more trouble-free.

Insulation Systems Used in GIS

A GIS houses the high-voltage components within a metallic enclosure. The conductor and enclosure are usually configured in a coaxial arrangement with a single-phase conductor housed within its own enclosure. However, at lower voltages, three-phase enclosure systems have also become popular, and some installations will use a combination of the three-phase enclosure and single-phase enclosure designs. The main insulating material used in GIS is a compressed gas, which fills the space between the conductor(s) and enclosure. The conductors themselves are supported by solid insulating spacers made of a mineral-filled epoxy compound. These spacers can be of a disk or conical shape, or in some cases it can be of a “post” design (Fig. 5). In certain applications, such as for support members and drive rods in GIS switchgear, fabric-reinforced epoxy insulators are also used.

GIS enclosures are usually fabricated of an aluminum alloy, although some installations use steel enclosures. In most designs, the enclosure sections are bolted or welded to

Figure 4. A typical 230 kV gas-insulated substation. (Photograph courtesy of Ontario Hydro.)

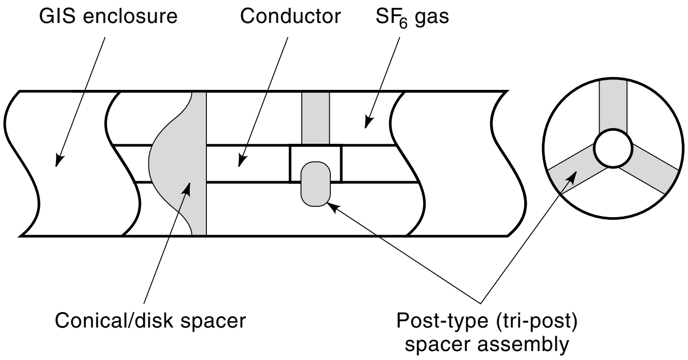

Figure 5. Typical spacer arrangements found in a gas-insulated substation.

the adjacent enclosures to form an electrically continuous sheath. Some designs have used electrically isolated, individually grounded enclosure sections (to limit enclosure currents and associated losses). The spacers used to support the high-voltage conductor are often used as "gas barriers" to compartmentalize the GIS into several gas sections to facilitate maintenance and gas handling. In these cases, the spacer is an integral part of the mechanical design at flanges and system seals. Enclosure dimensions vary according to the application and manufacturers' designs but typically, a 550 kV GIS bus has an enclosure diameter in the 500 mm to 600 mm range. Enclosure diameter is one of the factors that determine electrical insulation stress for both the gas and solid insulation systems and is factored into overall design.

Most GISs use compressed sulfur hexafluoride (SF_6) as the insulating gas. SF_6 is highly electronegative (i.e., readily "captures" electrons) and is therefore an excellent electrical insulator as well as an excellent interrupting medium in SF_6 circuit breakers. Typically, the SF_6 used in GIS is pressurized to about 4 atm to 5 atm, although some circuit breakers use higher pressures in the range of 7 atm for interrupting performance considerations. The maximum usable gas pressure is often determined by the low-temperature specification for the equipment. At low temperatures, high-pressure SF_6 can liquefy resulting in a loss of gas density and insulation capability. In some extremely cold climates, SF_6/N_2 mixtures are sometimes used to avoid the liquefaction problem but maintain a certain level of insulation capability. In some applications without switching components (such as in long lengths of gas-insulated transmission lines), pure N_2-insulated systems were considered in view of the rising costs of SF_6 gas and increasing environmental concerns over the inadvertent release of SF_6 into the atmosphere. Initial prototypes and installations use a small percentage ($\sim$10%) of SF_6 in N_2.

Dielectric Problems in GIS. The compact nature of a GIS inevitably results in higher overall electrical stresses as compared to insulation systems used in conventional substations. While a considerable (theoretical) dielectric margin is still maintained in overall designs, insulation and system defects limit the overall dielectric performance as they do in most insulation systems. However, a GIS, with its higher stresses, is particularly sensitive to defects which are not always easily avoided or detected. GIS components are manufactured and assembled in near "clean-room" conditions, but the minute defects and contaminants that might be introduced may escape detection and cause dielectric problems. Furthermore, many of these defects may be "harmless" under steady-state conditions but significantly weaken insulation performance under transient stresses. Laboratory experiments have shown that some defects can withstand power frequency stresses well in excess of operating levels but may cause failure at levels lower than operating levels when impulse voltages are applied (28,29).

The operation of a GIS switchgear, as a result of the compact dimensions of the equipment and the characteristics of the insulating gas, will also generate extremely high-frequency-content transients (risetimes in the range of nanoseconds). These "very fast transients" (VFTs) have resulted in a number of operational problems and have also resulted in a new class of electrical stresses which is part of the "normal" operating conditions of the GIS. Of course, many of the minute defects in the GIS are extremely sensitive to these VFTs, and VFTs had been blamed for a number of failures in the past.

The proper insulation performance of the GIS depends not only on proper design but also on defect control in manufacture, assembly, and operation. For these reasons, much emphasis has been placed with respect to (a) manufacturing and assembly quality control and (b) methods for testing and diagnostic condition monitoring. There are many causes for GIS insulation failure, including the following:

Free Conducting Particles. Free-moving metallic particles can be found within the GIS enclosure, usually introduced inadvertently during assembly but sometimes self-generated by moving parts within switchgear components. This is by far the most common form of defect found in GIS.

Fixed Metallic Defects. This class of abnormalities includes metallic burrs, protrusions, and other defects on the conductors.

Defects in Solid Insulating Components. Solid insulators may contain voids, contaminants, and other defects not detected by manufacturing quality control.

Solid Insulator Surface Contamination. The surfaces of insulators may be degraded by external influences, such as assembly-introduced contaminants (metallic and nonmetallic) and self-generated corrosive by-products resulting from other defects such as partial discharges resulting from loose corona shields and other cases of poor electrical contact.

Inadequate Designs. Some components (e.g., disconnectors, gas-to-air bushings, etc.) may not have been properly designed for all operational conditions within a GIS. Although there have been a number of failures attributed to inadequate designs, these are almost exclusively with the earliest generation designs.

Gaseous Insulation Systems in GIS. The primary gaseous insulation used in a GIS system is pressurized sulfur hexafluoride (SF_6). SF_6 is a man-made gas with numerous commercial and industrial applications, only one of which is its application as a insulating and interrupting medium in power equipment. As a result of its commercial importance, the gas has been extensively studied (30).

In its normal state, SF_6 is chemically inert, nontoxic, nonflammable, and stable. Its strong affinity for electrons (i.e., the SF_6 molecules readily attach electrons to form negative SF_6 ions—"electronegativity") gives the gas its high dielectric strength. In addition, its good heat transfer characteristics, along with its ability to recombine quickly after being disassociated in electrical arcing and electrical discharge, make the gas an excellent arc-interrupting medium and it is used extensively in both GIS circuit breakers and conventional stations.

In recent years, much attention has been placed on the use of SF_6 gas. SF_6 gas is an efficient absorber of infrared radiation and has been identified as being a strong greenhouse gas (although not an ozone depleting gas). Recently, SF_6 has been getting attention by worldwide environmental agencies. However, best estimates indicate that, despite its high capacity to act as a greenhouse gas, the overall contribution to global warming is extremely small given the production and usage patterns today (31). Nonetheless, these environmental concerns combined with the increasing cost of gas manufacture have led to voluntary guidelines within the electrical utility sector concerning the use of SF_6 gas including recovery techniques, inventory control, and recycling and reusing techniques (32).

The other major issue surrounding the use of SF_6 in power systems is the toxic decomposition by-products. SF_6, when involved in electrical discharge or arcing (especially under uncontrolled conditions such as in the case of insulation failure), will generate highly toxic by-products, which not only damage other GIS components but also pose a health risk to persons working with the GIS, such as the repair crew (33). Considerable effort has been placed into understanding the chemistry of SF_6 decomposition by-products, measuring by-product formation rates under common conditions, and developing safe work practices to deal with these issues.

The primary by-products include gaseous by-products (mostly SOF_2 and SO_2F_2) but may also include a number of trace gases, such as S_2F_{10}, in specific circumstances. Solid arcing by-products, such as aluminum fluoride, are also normally formed in reaction with the metallic components of the GIS. The solid by-products are found as a very fine powder, which is a respiratory irritant in itself, but may also be a carrier for the toxic gaseous species adsorbed on the surface of the solid particles. Typically, decomposed SF_6 from a GIS has a pungent, “rotten egg” odor.

In general, respiratory protection from gaseous and solid by-products is recommended during GIS maintenance and by-product handling. The procedures “published elsewhere (34)” discuss the various levels of respiratory protection ranging from full-face gas mask with supplied air respirator to half-face gas mask with combination organic vapor-acid gas chemical cartridge. Contaminated SF_6 gas should be treated before reuse or disposed. Common scrubber materials such as 13× molecular sieve are adequate for the removal of the arced gas after a major fault.

Another aspect of the SF_6 by-products is the effect of by-products on the dielectric and mechanical integrity of the GIS. Evidence from actual GIS and laboratory experiments indicates that epoxy spacers with silica fillers are especially susceptible to attack by arc by-products, which can severely degrade the dielectric integrity of the spacer (35). The attack is associated with visible changes on the surface, lowering of the impulse withstand strength, and a corresponding drop in the direct current (dc) surface resistivity. The attack mechanism is by hydrofluoric acid (HF) by diffusion through the epoxy to the filler site. HF is a common by-product generated in secondary reactions of the primary gaseous by-products with moisture. The reuse of insulating materials, which have been exposed to arced gas, should be undertaken with caution.

Solid Insulation Systems in GIS. Insulators for HV gas-insulated switchgear must be designed and manufactured to withstand the special electrical, mechanical, thermal, and chemical stresses experienced in service and during maintenance (36). Materials that meet these requirements include epoxy resins with finely ground mineral fillers. Several types of fillers are in common use, such as alumina, dolomite, silica, aluminum trihydrate, and their mixtures. Some GIS insulators, such as operating rods and support cylinders for circuit breakers, may also contain fibrous reinforcements. The standard manufacturing process for epoxy insulators is casting at elevated temperatures. The casting ingredients—resin, hardener, and fillers—are mixed and degassed under vacuum, poured into a preheated mold, and cured at elevated temperature. After demolding, the insulator is normally post-cured to reach its final properties.

In the early days of the GIS, solid epoxy casting systems based on silica flour fillers were in common use. However, extensive corrosion was found in circuit breakers on insulator surfaces due to the reaction of silica with SF_6 arcing byproducts, such as hydrogen fluoride (as discussed previously). Today, corrosion-resistant filler materials like alumina or dolomite (calcium-magnesium carbonate) are used in circuit breakers. In GIS buses, where arcing is not likely to take place, some manufacturers continue to use silica-containing fillers.

Bulk failure of the solid dielectric in GIS spacers is relatively rare, amounting to 10% to 20% of failures (36,37). GIS spacers fail through an electrical treeing mechanism; these can develop over time from minute voids and contaminants in spacers in spite of rigorous factory testing and field testing. Solid dielectrics are known to exhibit intrinsic breakdown strengths in excess of 1 MV_{rms}/mm, but they are susceptible to aging even though GIS epoxy spacers operate at much lower stresses. Indeed, early experience with designs operating with maximum stresses near 10 kV_{rms}/mm revealed failures by electrical treeing after about 5 years of service. Typical design stresses range from 2.0 kV_{rms}/mm to 4.1 kV_{rms}/mm, depending on the voltage class (38), though higher stress designs (5 kV_{rms}/mm to 6 kV_{rms}/mm) have been attempted. There is a great incentive to operate insulators at the highest possible stresses to maintain compact designs and reduce manufacturing costs. However, there is also clear evidence that reliability in the higher-voltage classes is much worse than that in the lower-voltage classes (27,37). In addition to increases in operating stress, the difficulties in the manufacture of substantially larger castings increase the probability of marginally defective spacers, heightening the likelihood of treeing failures.

Factory testing of epoxy spacers is intended to eliminate potentially defective spacers. At present, most epoxy GIS insulators are routinely factory tested using a combination of high alternating current (ac) potentials and a partial discharge (PD) test. Most factory PD tests, which are conventionally performed with a large coupling capacitor and a narrowband, integrating detector, have a noise-limited sensitivity in the range of 2 pC to 5 pC (35). This is also the typical acceptance level for GIS spacers, for all voltage classes. High test voltages are felt necessary to ensure that marginal defects can be successfully detected with the PD test, while the short time of the test is believed to contribute little to the aging of the insulator. However, the response from the two types of defects will be vastly different during this test. In the case of voids and delaminations, PDs will be detectable, within limitations, at the outset of the test. By contrast, sharp metallic protrusions and contaminants may exhibit a "silent" initiation phase, thereby escaping detection. Furthermore, the concern has been expressed that a short application of high voltage could result in the formation of electrical trees at contaminants that, once initiated, will eventually lead to premature failure. In many cases, PDs associated with the early phases of electrical trees are a few picocoulombs or less and may not be detected with equipment in present use.

Some very specialized test techniques have been proposed which expose the insulator to ionizing radiation during electrical tests (39). The radiation (usually X rays) is intended to initiate PDs in extremely small void defects in the insulation to allow these defects to be detected. Frequently, these defects may not discharge adequately during the short duration of a test, thereby escaping detection. Such methods, in combination with advanced high-sensitivity measurement techniques, have much greater ability to detect minor defects, which may still cause premature failure. However, this type of testing has been restricted to development tests and type tests on new products.

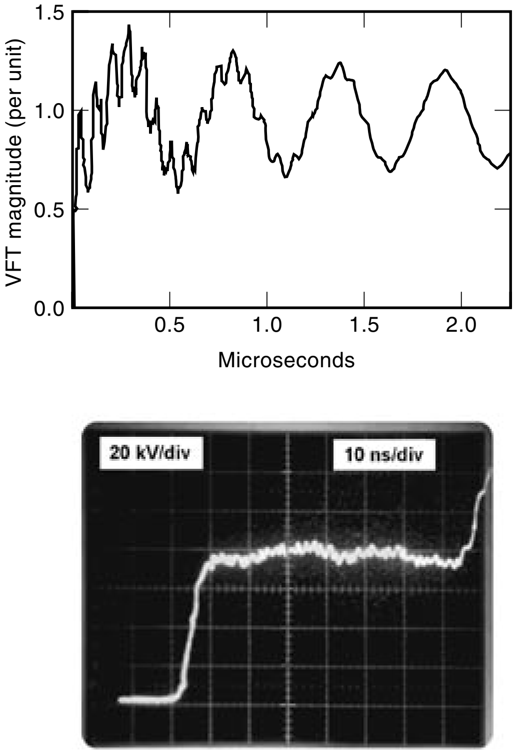

Figure 6. Very fast transient (VFT) waveforms in a gas-insulated substation. The top figure is typical of the overall waveshape. The lower figure shows the leading edge and the initial risetime typical for VFT. The lower figure was measured in an actual gas-insulated substation using a 1 GHz bandwidth real-time oscilloscope.

Insulation Stress in GIS

Electrical Stresses. A GIS, like any element in a power system, must be designed to withstand (a) all stresses which may be applied under normal system operations and (b) all stresses applied under any design-specific abnormal or environmentally induced stresses. Electric field stresses are determined by the applied voltage and by the material properties and geometrical design of the GIS. Many of the applied voltages, which stress the GIS, are the same as for stations of conventional design and insulation. These stresses include normal system voltage, temporary dynamic overvoltages (at the power frequency), switching surges, and lightning surges. Any differences in these stresses as compared to conventional stresses can be attributed to the influence of the GIS itself as a circuit component on the power system. That is, the higher capacitance of GIS will influence the electrical stresses applied to it.

The GIS must be designed to withstand all of the external stresses described above which may appear at the equipment terminals. However, a GIS has the capability to generate its own unique switching surge phenomena, described above as very fast transients or VFTs. VFTs, especially those generated by disconnectors in a GIS, has been extensively reported in the literature (29,40,41). A typical VFT waveform is illustrated in Fig. 6. These transients have components with frequencies one to two orders of magnitude higher than "conventional" power system transients and, as a result, VFTs impose an unconventional stress on many GIS components and influence station design, operation, and maintenance.

VFTs occur as a result of the relatively small dielectric clearances in a GIS. Voltage collapse (breakdown), such as between contacts of a disconnector during operation, occurs rapidly, in the range of a few nanoseconds (40). This rapid voltage collapse results in nanosecond-risetime traveling wave transients which propagate throughout the GIS and to externally connected apparatus. The propagation of such transients occurs with little loss or distortion as the coaxial nature of the GIS forms an excellent high-frequency distribution network. Understanding VFT behavior requires that the GIS be treated as a network of transmission line-modeled components. Transient overvoltage waveforms at a given location within the GIS equipment are generated as a result of the superposition of the various reflections of the initial traveling wave generated by the breakdown. As a result, waveshapes and magnitudes can differ significantly at locations only a few meters apart. Normally, measurements of VFTs can only be done with specialized sensors and instrumentation with at least 100 MHz bandwidth (42). Since an appropriate sensor cannot easily be placed at points of interest within a fully enclosed GIS, VFT characterization studies usually involve a combination of calculations and verifying measurements. The other aspect, which needs to be considered, is the characteristics of the disconnector itself. Each intercontact arc will generate a VFT surge. However, during a single operation, several tens to hundreds of individual VFT surges of varying magnitudes can be generated. Techniques for characterizing disconnectors are discussed in the literature (43).

VFT generated within the GIS propagate to external system components through gas-to-air bushings, cable interfaces, and so on. VFTs can propagate externally on "grounded" components such as the GIS enclosure. These transients manifest themselves as transient enclosure voltages (TEVs) which can result in several tens of kilovolts of short-lived (duration in the range of a few milliseconds) voltages on grounded components (29,44). TEVs raise concerns over personnel safety and can also cause interference and disrupt low-voltage auxiliary wiring and control circuits. While no one has been seriously injured as a direct result of TEVs, special precautions are normally taken to avoid indirect consequences such as startling an unsuspecting worker in a precarious location. The interference issue is addressed through good electromagnetic compatibility (EMC) practice and is described elsewhere (45).

The direct effect of VFTs on external apparatus has also been the subject of some concern. Although the VFT waveform will be distorted as it propagates into attached apparatus, the overall rate-of-rise of such stresses are still significant and has been suspected (if not proven) in several transformer failures worldwide (46). This is a matter requiring further study.

TEV is also responsible for random sparking between various metallic parts of the station (such as between GIS enclosures and support structures). Measures taken to prevent nuisance sparks often eliminate the symptom, but not the existence, of TEV. Sparking is common across insulated flanges, such as are found at some current transformers and at GIS–cable interfaces (to permit galvanic corrosion protection schemes of pipe-type cables). In most cases, sparking across insulating flanges is of little concern, because very little energy is dissipated in the sparks. However, in the case of a line-to-ground fault in the GIS, substantial power frequency fault current can flow through the ionized channel of high-frequency sparks across insulating flanges of cable interfaces, resulting in substantial damage to the flange and possibly the rupture of the oil seals of the cable (47).

Electrical breakdown processes in gases are extensively covered in the literature (48–50). Breakdown initiation and discharge channel growth are driven by electronic avalanche processes. Free electrons initiate the processes. Because of the electronegativity of the SF_6 gas, free electrons are not in very great supply. Free electrons are created by cosmic radiation but are rapidly attached to gas molecules. To initiate a breakdown avalanche, there must be a coincidence in time of a free electron in a highly (electrical) stressed volume of gas. This volume must be stressed sufficiently to accelerate the free electron enough to release two or more electrons when it collides with another gas molecule. These are then accelerated, collide with other molecules, and release even more electrons, and so on, creating an electron "avalanche." If the avalanche grows to a "critical" size, complete breakdown of the insulation between the system electrodes can result. In solids, the processes are similar but are limited to smaller microvoids, cracks, or within the solid materials. In this case, the breakdown process is typically slower because the avalanches are terminated at an early stage by collision processes in the solid materials. Ultimately, these processes in the solids do progressive damage, which creates tree-like breakdown channels in the solid, eventually leading to complete failure over periods of time ranging from months to years.

Thermomechanical Stresses. As with any compact electrical equipment using a variety of different materials, thermomechanical stresses must be factored into GIS design. Well-known Joule heating occurs when current flows in conductors, and it must be routinely considered in the design of equipment. The heating is a concern for two primary reasons: (a) from the perspective of thermal expansion, which needs to be carefully considered when insulating materials are bonded to conductors, and (b) from the perspective of the mechanical behavior of insulating materials as a function of temperature.

Concerns about differential thermal expansion are typically addressed through the use of filler materials in solid insulation components, which bring the coefficients of thermal expansion of bonded materials into close agreement. Allowance for chemical and/or mechanical bonding at insulator–metal interfaces involves trade-offs between (a) the stress enhancements which can be tolerated from roughened electrodes and (b) the mechanical strength requirements imposed by the differential expansions (longitudinally and radially) of the bus conductors and the insulating materials.

Concerns about maximum operating temperatures of materials arise because designs are optimized, typically, at high temperatures. As a result the insulating material's mechanical properties as a function of temperature are a critical design constraint. If such constraints are violated, insulating materials typically soften and thus yield irreversibly under mechanical stress. Failure may not result immediately, but if the temperature limits are routinely exceeded, failure ultimately results from the reduced clearances between energized parts. In addition, concerns about temperature may be raised in the context of long-term aging processes. Arrhenius-type aging models are typically used to estimate loss of equipment life caused by short-term overloading (high temperature) (36).

Insulation Coordination and Protection

In most cases, the same principles for insulation coordination are applied to a GIS as they are for conventional stations. That is, the equipment electrical withstand capability and protection levels are designed according to standard stresses as defined in standards. In most cases, lightning stresses are thought to be most onerous, and the lightning-impulse withstand level (LIWL) is used for insulation coordination purposes. LIWL is the insulation level of the equipment when subjected to a standard "lightning impulse," which is defined in standards as having a double exponential shape with a rise and fall time of 1.2 ms and 50 ms, respectively. The term LIWL is common in international literature and standards (i.e., IEC), but North American standards have also used the term BIL (basic insulation level). The two terms are practically equivalent. GIS equipment insulation capability is also defined by its withstand to standard "switching surge" waveforms (switching impulse withstand level SIWL) and its withstand to power frequency (50/60 Hz) voltages for a 1 min duration [power frequency withstand level (PFWL)].

All GIS components are tested at an advanced design stage ("type" tests) to ensure the ability of a given design to meet all of the required insulation withstand levels. Although these tests ensure the soundness of the fundamental design, in practice the insulation performance of the GIS is often dictated by the presence of defects within the system introduced during shipping and/or assembly. As indicated earlier, these defects may cause insulation failure in practice, especially under VFT stress. VFTs, although relatively low in magnitude, are generated in great numbers during normal operation. Consequently, the insulation must respect not only the fast, nanosecond risetimes of these transients but also the high number of transient stresses experienced during normal operation. This poses two problems for insulation coordination. Firstly, since, as indicated earlier, the V–T characteristic of GIS with defects is such that the insulation failure can occur at lower levels with fast risetime surges as compared to "slower" ones, onsite insulation testing with power frequency waveforms or "slow" impulses do not necessarily detect the defects in question (28,51). Secondly, the sheer number of VFT which can occur normally suggest that defects with even low breakdown probabilities must also be detected.

One approach, which has been used to address these problems, is to install equipment with intentionally large dielectric margins. Researchers will often show declining GIS insulation performance (i.e., failure rate) for a lower ratio of LIWL to rated operating voltage, as is normally found in the higher-voltage classes (28). For these reasons, some utilities have, at additional expense, specified higher LIWL levels for the equipment they purchase. For example, in the 550 kV voltage class, which has historically some of the highest failure rates, an LIWL of 1800 kV has been adopted by some over the 1425 kV or 1550 kV levels in the standards. In these cases, the LIWL is used as a rough measure of relative internal electrical stress. However, one should be careful in using this type of analysis since LIWL is not a measure of how highly stressed the equipment is but rather an almost arbitrary "label" placed on the equipment reflecting the customer's requirements and agreed-to test levels. For instance, within the realities of manufacturing and pricing strategies, it is not unusual to find identical equipment sold to two separate customers with different insulation ratings. Details of insulation levels are often determined by specific application requirements. However, users should be aware of, and understand, design trade-offs and their implications.

The concern over insulation levels has largely been the result of high failure rates with early designs used at the highest voltage levels (27). GIS at lower voltages (230 kV and below) have operated reliably. Many of the insulation problems, which afflicted these early, high-voltage installations, have been studied and are now understood. Modern GIS designs promise much higher reliability through, among other things, careful design of electrical stresses and through defect control. Some of these advances have also come in improved techniques for on-site testing of GIS and in diagnostics and monitoring technology for detecting those defects which escape detection by other means. Although there is no question of the technical advances, there are varying strategies for how these technologies are best implemented. Consequently, there is still much controversy in attempts to define standards for such testing. Most variations in test approach consider (a) the cost–benefit issues as well as trade-offs between high test levels and potentially damaging equipment and (b) the introduction of diagnostic techniques to improve the efficacy of high voltage tests. Normally, a high ac voltage is applied as a minimum on-site test, but in some cases the ac voltage is varied according to a complex pattern to "condition" the GIS and in other cases the impulse voltages are applied on-site (52).

Diagnostic Techniques. Diagnostic and monitoring techniques are often used to improve the insulation performance of the GIS (53). As indicated above, diagnostics are often used to improve the quality of on-site testing. Monitoring systems are also available which apply some of these techniques on a continuous basis looking for signs of deterioration.

Diagnostics can be as simple as analyzing the SF_6 gas for trace quantities of decomposition by-products as an early indication of a developing problem. In many cases the relative concentration of the various by-product species may yield clues concerning the nature of the defect. Acoustic techniques are also in common use. These include the use of simple ultrasonic detectors or specialized acoustic emission (AE) sensors intended to detect abnormal discharges, PDs or free-moving metallic particles by monitoring for sounds generated by these defects (54). Electrical techniques are also used, but these usually require some special sensor installed in the GIS. Many of these electrical techniques measure in the 1000 MHz range to isolate signals from interference from corona on connected overhead lines and various forms of communication broadcasts (55).

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GARY FORD
JOHN KUFFEL
NOBORU FUJIMOTO
Ontario Hydro Technologies

SUBSTATION INSULATION. See SUBSTATION INSULATION.

SUBSTATION LOAD. See POWER STATION LOAD.

SUBSTATION POWER, MODELING. See POWER SUBSTATION MODELING.

SUBSTATION, RECTIFIER. See RECTIFYING CIRCUITS; RECTIFIER SUBSTATIONS.

SUBSTATIONS. See TRANSFORMER SUBSTATIONS.

SUDDEN CARDIAC DEATH. See DEFIBRILLATORS.

SUMMATION, ADDERS. See SUMMING CIRCUITS.