TITAN UNIVERSITY

An Overview of Gas-Insulated Substation

Section 1 Introduction

A gas-insulated substation (GIS) is a high-voltage substation where key conductive components are enclosed within a sealed environment. Instead of atmospheric air, the insulating medium used is sulfur hexafluoride (SF6) gas, which serves as a dielectric material. In contrast, an air-insulated substation (AIS) typically relies on atmospheric air for insulation and is almost always situated outdoors.

Origin

The development of gas-insulated substation (GIS) technology originated in Japan during the 1960s, driven by the urgent need to create substations with significantly smaller footprints. Over time, other countries gradually adopted GIS systems. Following approximately five years of testing and evaluation, the construction of GIS installations rose to around 20% of new substations in regions with limited space. However, in areas where space is abundant, the higher cost of GIS compared to air-insulated substations (AIS) has restricted its use to specific cases. In the United States, GIS accounts for only about 2 to 5% of new substation projects.

Space Efficiency of Gas-Insulated Substations

Gas-insulated substations (GIS) require significantly less clearance for phase-to-phase or phase-to-ground insulation compared to air-insulated substations (AIS). The overall space needed for a GIS installation is approximately one-tenth of what is required for a conventional AIS. Unlike AIS, which relies on several feet of air insulation to separate conductors, GIS uses sulfur hexafluoride (SF6) gas, which only requires a few inches for effective insulation. This compact design makes GIS an ideal choice for locations where real estate is limited or highly expensive.

EPS (Environmentally Resilient System)

Gas-insulated substation (GIS) technology is well-suited for extreme environments, such as arctic or desert regions, as it can be housed within a building that provides protection from harsh conditions. This setup safeguards system components from extreme temperatures, both hot and cold. Additionally, the electrical components in a GIS are enclosed within a Faraday cage, offering protection against potential lightning strikes.

Gas-Tight Modular Design

The live sections of a gas-insulated substation (GIS) are housed in individual gas-tight compartments, ensuring no gas transfer between adjacent modules and enabling independent gas monitoring for each section. To maintain the gas-tight integrity, O-rings are installed at the equipment and enclosure flanges.

A **gas monitoring system** is also in place, featuring an integrated alarm system along with automated tripping and lockout mechanisms. These activate if low pressure is detected due to gas leakage. This is crucial because a drop in the pressure of the dielectric SF6 gas directly reduces its insulating effectiveness.

1.1 Applications

High Voltage Applications

Gas-insulated technology becomes increasingly advantageous as voltage levels rise. For instance, a conventional 765kV substation requires a substantial amount of space. However, utilizing GIS for a substation of this voltage rating would significantly reduce the overall footprint.

Urban Applications

GIS technology is an excellent choice for installations in locations where real estate costs, aesthetics, and safety are key concerns. Acquiring land for a conventional air-insulated substation (AIS) in densely populated areas can be extremely expensive, politically challenging (especially if eminent domain is involved), or even unfeasible. For instance, constructing a high-voltage AIS in an urban setting like downtown New York City would be an exceptionally difficult task.

1.2 Hybrid GIS

A practical method for expanding an existing air-insulated substation (AIS) is through the use of mixed technology switchgear, also known as hybrid GIS. This solution is particularly effective when additional space is limited or unavailable for substation expansion. The design incorporates GIS components such as breakers, switches, and voltage/current transformers, while air-insulated conductors are used for interconnections between breaker positions and other equipment.

1.3 Indoor Installations

Building an indoor air-insulated substation is generally impractical and poses significant challenges for safe operation. In contrast, a gas-insulated substation (GIS) can be conveniently installed within an industrial building. It can seamlessly integrate into the facility's electrical infrastructure, enabling onsite voltage step-down as needed.

1.4 Foundation and Expansion Joints in GIS Systems

Gas-insulated substation (GIS) systems are typically mounted on a solid concrete pad or directly on the floor of their housing structure. Installation involves securing the GIS support frames to embedded steel plates or beams using bolts or welds, or by employing chemical drill anchors.

Expansion Joints

- **Expansion Drill Anchors:** These are not recommended for GIS installations, as the dynamic forces from circuit breaker operations can cause these anchors to loosen over time.
- **Bus Expansion Joints:** For larger GIS setups, bus expansion joints are often recommended. These joints are installed between different sections of the GIS to accommodate field adjustments during installation and to manage thermal expansion within the system.

1.5 Disadvantages of GIS Systems

There are several disadvantages to GIS systems. The disadvantages are outlined in the following list:

- The initial cost of a GIS system is higher compared to a conventional air-insulated substation (AIS).
- Transporting SF6 gas to the site can present logistical challenges.
- GIS substations are designed for indoor use, necessitating the construction of a separate building.
- Regular cleaning and maintenance are essential to prevent contamination from conductive particles.
- Contaminants such as particles or moisture inside the compartments can lead to flashovers.
- In the event of a fault, outages at GIS substations tend to be prolonged, and the resulting damage is typically severe.
- Gaining access to live components for maintenance is more difficult, and diagnosing issues often requires gas reclamation and disassembly of the modules.

1.6 Disadvantages of Conventional AIS Systems

There are also numerous disadvantages to conventional AIS systems. The disadvantages are shown below:

- Equipment can deteriorate when exposed to environmental conditions such as varying temperatures and weather.
- The equipment is prone to contamination from airborne pollutants, such as particulate matter.
- Air-insulated substations require a large amount of land, which can be costly in densely populated urban areas, and may necessitate the use of eminent domain to acquire the land.
- In seismic areas, AIS systems are less stable and pose greater operational safety risks compared to GIS systems.
- Regular maintenance is required to keep the system in optimal working condition.
- In regions above 3,000 feet in elevation, special attention is needed due to the lower density of atmospheric air, which affects the dielectric properties.
- Due to the poor dielectric properties of air and factors like humidity, pollutants, salt, and moisture, AIS systems need more space for effective insulation.

1.7 SF6 Gas

A gas-insulated substation (GIS) utilizes sulfur hexafluoride (SF6) gas, a highly effective dielectric material, at moderate pressure to provide insulation between phase-to-phase and phase-to-ground. The high-voltage conductors, circuit breaker interrupters, switches, current transformers, and voltage transformers are fully enclosed within grounded metal housings, which are surrounded by pressurized SF6 gas for optimal insulation.

1.8 GIS Protection from Environmental Elements

In a gas-insulated substation (GIS), the system's active components are shielded from environmental factors such as exposure to atmospheric air, moisture, and particulate contamination. This protection leads to a more reliable system that demands less maintenance and boasts a longer service life, often exceeding 40 years, compared to its conventional air-insulated substation (AIS) counterpart.

Common Physical Configurations for GIS

For a single-line diagram, multiple physical arrangements can be implemented. When determining the optimal physical layout, factors such as the site's shape and the design of the connecting lines and cables should be taken into account.

Double Busbar Configuration

The double bus, single-break configuration is one of the most widely used designs for GIS. This approach is favored for its operational simplicity and high reliability. It also supports efficient protective relaying, offers excellent cost-effectiveness, and requires minimal space, making it an ideal choice for many applications.

1.9 Global Standards for GIS

International standards governing GIS are outlined in publications by CIGRE.

What is CIGRE?

According to its official website, CIGRE (the Council on Large Electric Systems) was established in 1921 as a global non-profit organization. It focuses on fostering collaboration among experts worldwide to share knowledge and work together to enhance the electric power systems of both the present and the future.

In addition to CIGRE, organizations such as the IEEE and the IEC have developed standards and technical guidelines addressing the design, testing, installation, and operation of GIS systems.

IEC Standards for GIS

The IEC (International Electrotechnical Commission) provides additional international standards relevant to GIS.

What is the IEC?

The International Electrotechnical Commission is a global organization responsible for developing and publishing standards for electrical, electronic, and related technologies. Its standards encompass a wide range of fields, including power generation, transmission, and distribution, as well as home appliances, office equipment, semiconductors, fiber optics, batteries, solar energy, nanotechnology, and marine energy, among others.

Key GIS Standard

IEC 62271-203 specifically addresses high-voltage switchgear and control gear. This part of the standard focuses on gas-insulated metal-enclosed switchgear designed for rated voltages exceeding 52 kV.

Section 2 Comparing the Economics of GIS and AIS

Cost Comparison Between GIS and AIS Equipment Costs

The cost of GIS equipment is typically higher than that of AIS. This is due to features such as the grounded metal enclosure, the inclusion of a Local Control Cabinet (LCC), and the extensive assembly completed at the factory.

Installation Costs

GIS systems are generally less costly to install compared to AIS. This is because most of the assembly is carried out in the factory, reducing on-site labor and complexity.

Site Development Costs

The site development costs for GIS are significantly lower than those for AIS. This is primarily due to the compact footprint required for GIS installations. The cost savings become more pronounced at higher system voltages, as high-voltage AIS installations demand larger areas to accommodate the extended insulating distances required by atmospheric air.

Cost Comparisons

Initial cost analyses of GIS suggested that the total installed cost of GIS would become comparable to that of AIS when substation voltage reached approximately 345 kV. Beyond this voltage threshold, GIS was considered the more cost-effective option compared to AIS.

However, recent studies indicate that advancements in technology and manufacturing processes have significantly lowered the costs of AIS. In contrast, GIS equipment has not experienced similar reductions in cost, maintaining a relatively stable price point.

Perception of GIS as Cost-Prohibitive

Despite being a long-established and highly reliable substation technology with minimal maintenance requirements, GIS is still often viewed as too expensive to implement. It is generally considered suitable only for specialized scenarios where space constraints are a critical factor in the decision-making process.

Digital Advancements Reducing GIS Assembly Size

The cost of GIS is gradually decreasing due to the integration of system functions across its components. For instance, the transition from analog to digital control systems in substations is replacing costly electromagnetic CTs and VTs with more affordable alternatives like optical VTs and Rogowski coil CTs.

These modern sensors are significantly smaller, enabling a reduction in the size of GIS assemblies. This compact design allows more GIS bays to be shipped fully assembled and turnkey, resulting in lower installation and site development costs. As a result, the benefits of GIS over AIS continue to grow.

2.1 SF6 – An Exceptional Dielectric Gas

What is SF6 (Sulfur Hexafluoride) Gas?

Sulfur hexafluoride (SF6) is a nonflammable, inert, and non-toxic gas composed of a sulfur atom surrounded by six tightly bonded fluorine atoms.

Due to its high electron affinity, SF6 is widely used as an insulating gas in high-voltage applications. It is approximately five times denser than atmospheric air at sea level and is colorless, odorless, and tasteless. SF6 is nearly insoluble in water, and like other gases, its solubility decreases as water temperature increases.

SF6 Gas Pressure

SF6 gas is contained in GIS systems at pressures ranging from 400 to 600 kPa absolute. This pressure is optimal for preventing the gas from condensing into a liquid under the lowest temperatures the equipment might encounter.

In SF6, the speed of sound propagation is approximately one-third that of air at atmospheric pressure. As a result, the sound produced during arc interruption is quieter in SF6 than in air.

Dielectric Strength: SF6 Gas vs Air

At 0.1 MPa (1 atm or atmospheric pressure), SF6 has a dielectric strength that is three times greater than that of air. As the pressure within a GIS enclosure rises, the dielectric strength of the SF6 gas also increases due to the higher gas density.

At the pressures typically found inside GIS enclosures, the dielectric strength of SF6 can significantly exceed that of atmospheric air.

Arc-Interrupting Capability of SF6 Gas

SF6 is approximately 100 times more effective at interrupting arcs than air. It has become the preferred medium for arc interruption in high-voltage circuit breakers, replacing traditional insulating materials such as oil and air.

Reactive Decomposition Byproducts

Certain reactive decomposition byproducts can form when sulfur and fluorine ions interact with trace amounts of moisture, air, and other contaminants in the system environment. The quantities of these byproducts are usually very small. To mitigate this, molecular sieve absorbents within the GIS enclosure help to remove these reactive byproducts gradually over time.

Section 3 Toxic Breakdown Gases from SF6

HF (Hydrofluoric Acid)

Hydrofluoric acid (HF) is a toxic byproduct of SF6 decomposition. It is generally a gas with a boiling point of around 19°C. Exposure symptoms may not appear immediately, and due to its high reactivity, HF has a short half-life.

SO2 (Sulfur Dioxide)

Sulfur dioxide (SO2) is another toxic decomposition product of SF6, typically found as a gas with a boiling point of approximately -10°C.

SOF2 (Thionyl Fluoride)

Thionyl fluoride (SOF2) is a toxic gas produced from SF6 breakdown. When exposed to moisture, SOF2 decomposes into SO2 and HF over time. It is colorless with a strong odor like rotten eggs and condenses at around -43°C.

Gas Storage

SF6 gas is commonly supplied in 50 kg cylinders, stored in a liquid state under a pressure of about 6000 kPa.

Gas Handling Systems

Gas handling systems include equipment like filters, compressors, and vacuum pumps, which are readily available on the market.

International standards outline the recommended practices and safety measures for handling SF6 gas, prioritizing the safety of personnel.

SF6 as a Greenhouse Gas

SF6 is a potent greenhouse gas that can significantly contribute to global warming. During an international treaty conference in Kyoto, Japan in 1997, SF6 was identified as one of the six greenhouse gases whose emissions should be reduced.

Half-Life of SF6

Although SF6 represents a relatively small proportion of total greenhouse gas emissions, it has an exceptionally long atmospheric lifespan. Its half-life is estimated to be around 3,200 years. As a result, even small amounts of SF6 released into the atmosphere have a lasting, cumulative impact, unlike other greenhouse gases that dissipate more quickly.

Gas Recycling

To prevent gas leakage in a GIS system, SF6 is fully contained within sealed enclosures, enabling its complete reclamation and recycling.

By adhering to current international guidelines for the use of SF6 in electrical equipment, the contribution of SF6 to global warming can be limited to less than 0.1% over a 100-year period, if GIS personnel strictly follow these guidelines.

Gas Emissions Reduction Measures

The emission rates of SF6 gas from high-voltage electrical equipment have decreased over time, largely due to improved handling and recycling practices adopted by utilities.

Field inspections of GIS systems in operation for several years have demonstrated that the leak rate can be as low as 0.1% per year, provided that handling and recycling standards are updated and followed.

Section 4 Contaminants and Oxidation in SF6 Gas

Moisture Condensation

The SF6 gas within the enclosures must maintain a low moisture level to avoid condensation on the surfaces of the epoxy support insulators. Moisture accumulation on these surfaces can lead to dielectric breakdown.

The use of absorbents inside the enclosures helps lower moisture content in the gas, although over time, moisture can gradually escape from the internal surfaces and solid dielectric materials.

Condensation as Ice and Gas Dew Points

When moisture condenses into ice, it does not impact the breakdown voltage.

To prevent such issues, gas dew points should be kept below around –10°C. Moreover, moisture levels are typically kept under 1000 ppmv, which is achievable with proper gas handling practices.

Small Conducting Particles

Small conductive particles, typically in the millimeter size range, can significantly reduce the dielectric strength of SF6 gas. This effect becomes more pronounced as the pressure exceeds 600 kPa absolute.

Dielectric Breakdown

These conductive particles are influenced by the electrical field within the gas. Dielectric breakdown can occur when the particles are drawn to areas with higher field strength inside the equipment or accumulate along the surface of solid epoxy support insulators. Therefore, maintaining a clean environment in the GIS assembly is essential for optimal operation.

Section 5 Detecting and Removing Particles from the Enclosure

Detection: During both factory and field power frequency high voltage tests, contaminating particles can be identified as they are carried by the electric field. This leads to small electric discharges and acoustic signals.

Removal: Once these particles are detected, they can be eliminated by opening the equipment. Some GIS systems are designed with internal "particle traps" that capture the particles before they settle in areas where they could potentially cause breakdowns. Additionally, most GIS assemblies are shaped to create low electric field regions where particles can accumulate without causing damage.

Section 6 Contaminants in Reused SF6 Gas

Reactive liquids, like oil, and solid contaminants in used SF6 can be easily removed through filtration. However, inert gaseous contaminants, such as oxygen and nitrogen, are more challenging to eliminate.

Oxygen and Nitrogen: These gases can enter during regular gas handling or inadvertently, such as when the air is not fully evacuated from the equipment before the SF6 is introduced.

Required Gas Purity: Fortunately, international standards specify that SF6 purity only needs to be above 98%. As a result, a simple field test using commercially available SF6 purity meters can verify whether the used SF6 is suitable for reuse.

Recycling SF6

In cases of significant gas contamination, SF6 manufacturers can reclaim the contaminated gas, process it, and essentially restore it to a new SF6 product.

Permanent Disposal of SF6: While not yet widely practiced, when SF6 reaches the end of its life cycle, it can be incinerated with materials that allow it to be transformed into environmentally safe gypsum.

SF6 Emissions Reduction Initiatives

The US EPA runs a voluntary program to track and reduce SF6 emissions within the electric utility sector. This initiative offers guidance on methods for reducing emissions and recognizes utilities that implement effective SF6 reduction strategies.

Other regional authorities have taken similar approaches, with some considering stricter measures such as banning or taxing the use of SF6 in electrical equipment.

Safer Alternatives to SF6

While alternative gases for medium voltage electrical equipment exist, no practical substitutes have been identified for high-voltage applications, despite extensive research. These alternatives often present drawbacks that outweigh their potential benefits, such as reduced greenhouse gas impact. Consequently, SF6 will remain the preferred choice for GIS in power system fault interruption and switching tasks.

An alternative gas mixture being used in gas-insulated transmission lines (GIL) for extended bus runs without arcing is a combination of SF6 and nitrogen. This mixture helps reduce the overall amount of SF6 in the enclosure.

Section 7 GIS System Enclosure Modules

7.1 Categories of Equipment Modules

GIS systems are built using standardized equipment modules, which include:

- Circuit breakers
- Current transformers
- Voltage transformers
- Disconnect and grounding switches
- Interconnecting bus
- Surge arresters
- Connections to the broader electric power network

Single-Phase vs. Three-Phase Enclosures

For systems up to approximately 170 kV, all three phases are typically integrated into a single enclosure.

For systems above 170 kV, the three-phase enclosure becomes impractically large, leading to the adoption of a "single-phase enclosure" design.

There are no significant performance differences between three-phase and single-phase enclosures in GIS systems, and some manufacturers use single-phase enclosures across all voltage levels.

Joining and Sealing of Enclosure Modules

GIS enclosure modules are connected using bolted flanges that feature an "O"-ring sealing system to ensure a tight seal.

The conductors are linked with a sliding plug-in contact to connect the conductor sections.

Internal Support Insulators in GIS Modules

The components inside the GIS are supported by cast epoxy insulators, which create a gas barrier between different parts of the system or have holes cast in the epoxy to allow gas flow from one side to the other.

These insulators are made from carefully cast epoxy resin to prevent voids or cracks during the curing process. The material is specially formulated and shaped to optimize electric field distribution, enhance mechanical strength, resist surface electric discharge, and ensure ease of manufacturing and assembly.

Epoxy Support Insulators

Cast epoxy support insulators come in various types, such as post, disk, and cone.

Integrity testing involves a high-voltage power frequency withstand test, paired with sensitive partial discharge monitoring. The goal is to keep the electric field stress inside the cast epoxy insulator below a specified level to prevent aging of the solid dielectric material.

Electrical stress limits on the cast epoxy support insulator are not a critical constraint, as the GIS dimensions are primarily determined by the lightning impulse withstand level of the gas gap and the conductor's required diameter to carry load currents up to several thousand amps. This results in sufficient space between the conductor and the enclosure to ensure low electrical stress on the support insulators.

Metal Used in GIS Enclosures

Enclosures are typically made from cast or welded aluminum, although steel is also commonly used. Steel enclosures require painting on both the interior and exterior to prevent rusting. In contrast, aluminum enclosures do not need painting but may be painted for easier cleaning, aesthetic purposes, or to improve heat transfer to the surrounding environment.

The choice between aluminum and steel depends on cost differences and the continuous current requirements. For continuous currents above 2000 amps, steel enclosures need non-magnetic inserts made from stainless steel. Alternatively, the enclosure material may be switched to stainless steel or aluminum to accommodate the current.

Grounding Individual Enclosures

Each metal enclosure section within the GIS modules is electrically connected. This can be done in one of two ways:

1. The flange joints of the enclosure provide a direct electrical contact.
2. External shunts are bolted to the flanges or to grounding pads on the enclosure for connection.

Grounding of Single and Three Phase Enclosures

Previously, single-phase GIS enclosures were single-point grounded to prevent the flow of circulating currents within the enclosures. However, the current practice involves multi-point grounding, even though it may result in some electrical losses due to circulating currents.

For single-phase GIS enclosures, the three enclosures should be bonded together at both ends to promote circulating currents. These currents help cancel the magnetic field that would otherwise be generated outside the enclosure due to the conductor current.

In three-phase GIS enclosures, eddy currents are present within the enclosure, but circulating currents do not occur. These enclosures also require multi-point grounding. With multiple grounding points and numerous parallel paths for current to flow from an internal fault to the substation ground grid, it is easier to maintain the safe touch and step voltages as specified in IEEE 80.

Pressure Vessel Specifications

The specifications for pressurized vessels in GIS enclosures are defined by GIS standards. The design, manufacturing, and testing processes adhere to the pressure vessel standards of the country where the equipment is produced.

Since the pressures in GIS enclosures are relatively low and GIS is classified as electrical equipment, third-party inspections and code stamping of the GIS enclosures are not required.

Rupture Discs

Rupture discs are often employed as a safety measure in pressure vessels. However, the pressure increases resulting from internal fault arcs within a typical GIS compartment are usually predictable and gradual. As a result, the protective system will interrupt the fault before the pressure reaches dangerous levels.

Inspections of Internal Components

Typically, periodic inspections or maintenance of GIS internal components are not necessary. The following conditions should be met:

- **Dry Inert Gas Environment**: The interior of the enclosure is maintained in a dry, inert gas atmosphere, which is not subject to aging.
- **UV Exposure**: Moreover, there is no exposure to sunlight or the harmful effects of UV radiation on any internal materials.
- **Module Seal Durability**: The O-ring seals within the modules are generally in excellent condition due to the use of a double-seal system, where the outer seal protects the inner one.

Protection of Outdoor Enclosures

GIS equipment remains unaffected by aging, regardless of whether it is installed indoors or outdoors. For outdoor GIS systems, specific measures are necessary to provide protection from corrosion, extreme ambient temperatures, and solar UV radiation.

Pre-assembled GIS Modules

GIS modules are usually transported in the largest possible assembly size that allows for convenient transport, clearance, and maneuvering. Lower voltage units are often delivered with two or more circuit breaker positions fully assembled. These modules are connected using bolted flanged enclosure joints and conductor contacts, allowing for a relatively quick assembly process.

Section 8 Conductors in a GIS System

High-voltage conductors in GIS systems are predominantly made of aluminum, although copper is sometimes preferred for higher continuous current capacities. The surfaces that conduct the electrical current are typically silver-plated to enhance performance. To connect conductor sections, bolted joints and sliding electrical contacts are commonly used.

Electrical Contacts in GIS Systems

Sliding contact elements in GIS systems come in various designs, but typically, they feature numerous individually sprung, silver-plated copper contact fingers working in parallel. To prevent wear and particle generation over time, contact lubricants are applied to maintain smooth operation and protect the sliding surfaces.

Use of Sliding Conductor Contacts to Improve Module Assembly

Sliding conductor contacts simplify the assembly of GIS modules by allowing for easy movement of the conductors. This flexibility helps accommodate the differential thermal expansion between the conductor and the enclosure. These contact assemblies are also employed in circuit breakers and switchgear to transfer current from the moving contacts to the stationary ones.

Section 9 Circuit Breakers and Transformers Used in GIS System

9.1 Circuit Breakers

Both AIS (Air Insulated Switchgear) and GIS (Gas Insulated Switchgear) systems utilize similar dead tank SF6 puffer circuit breakers. However, in GIS systems, the configuration differs slightly. Rather than using SF6-to-air bushings that are mounted on the circuit breaker enclosure, the GIS circuit breaker is directly connected to the adjacent GIS module. This design enhances compactness and simplifies the integration of components within the GIS system.

Current Transformers for GIS Applications

Current transformers are devices used in substations to convert high currents from the conductor into standardized, measurable values for metering, measuring, and protection purposes.

Installation Location: In GIS systems, inductive-ring type current transformers are typically used, and they can be installed either inside or outside the GIS enclosure.

Metering and Protection: These functions are carried out on the secondary winding side of the transformer, while the GIS conductor serves as the single-turn primary for the current transformer unit.

Considerations for Current Transformers

When current transformers (CTs) are installed inside the enclosure, they need to be shielded from the electric field generated by the high-voltage conductor. If not, high transient voltages may appear on the secondary winding due to capacitive coupling.

For CTs mounted outside the enclosure, the enclosure must have an insulating joint, and enclosure currents should be shunted around the CT.

Both of these types of GIS construction are commonly used in practice.

Digital Output Signals from CTs - Analog Relays

Advanced CTs have been designed to reduce space and GIS costs by eliminating the magnetic core or Rogowski coil. These CT units output low-level signals that can be immediately converted by a device mounted on the enclosure into a digital signal. Once digital, the signal can be transmitted over long distances using wire or fiber optic cabling to control or protective relays.

However, a challenge is that many protective relays used by utilities do not accept digital input directly, even though the relay may convert the conventional analog signal to digital before processing.

Voltage Transformers (VTs)

In GIS applications, Voltage Transformers (VTs) are typically inductive with an iron core. The VT is often a sealed unit equipped with a gas barrier insulator.

Installation Option 1: The VT is designed to be easily removable, allowing the GIS system to undergo high voltage testing without damaging the unit.

Installation Option 2: The VT is equipped with a disconnect switch or a removable conductor link.

The primary winding is supported by an insulating plastic film that is immersed in SF6.

To prevent capacitive coupling of transient voltages, the VT should include an electric field shield between the primary and secondary windings.

Voltage Sensors

Advanced voltage sensors utilize a capacitive coupling cylinder between the conductor and enclosure.

Advantages:

- Reduced size and cost compared to traditional voltage sensors.
- These capacitive sensors do not require disconnection during the high-voltage withstand test, which simplifies the process.

The output signal from the voltage sensor is low-level, allowing it to be immediately converted into a digital signal. However, this digital signal faces the same limitations as the advanced CT output signal, especially concerning protective relaying and system compatibility.

Section 10 Switching and Arrester Devices in GIS Systems

Disconnect Switches

A disconnect switch consists of a moving contact that opens or closes the gap between stationary contacts. The switch is activated by an insulating operating rod, which is moved by a sealed shaft running through the enclosure wall.

The stationary contacts are equipped with shields to ensure proper electric field distribution and prevent excessive surface electrical stress.

The operating velocity of the moving contacts in a disconnect switch is slower compared to a circuit breaker. Disconnect switches are designed to interrupt only low levels of capacitive or small inductive currents.

Fast-acting Disconnect
For transformer magnetizing current interruption duty, the disconnect switch is equipped with a fast-acting spring operating mechanism.

Load Break Disconnect Switches
Historically, load break disconnect switches were used in GIS systems. However, with advancements in circuit breaker technology and cost reductions, it has become more practical to use circuit breakers instead of load break disconnect switches.

Combination Disconnect-Earthing Switch

The design of the combined disconnector/earthing switch allows for space-saving with three positions:

1. Disconnector closed; earthing switch open
2. Disconnector open, earthing switch open
3. Disconnector open, earthing switch closed

A motor-operated actuator drives the combined disconnector/earthing switch, and interlocking mechanisms between the disconnector and earthing switch ensure safe operation. When used as a busbar disconnecting switch, the unit can be connected to the busbar with a compensator to minimize mechanical stress from tolerances and thermal expansion. A fast disconnect option can be selected when used as a feeder disconnecting switch to break bus-transfer current.

Ground Switches

Ground switches feature a moving contact that opens or closes the gap between the high-voltage conductor and the enclosure.

Sliding Contacts: These contacts are electric-field shielded and integrated at both the enclosure and the conductor.

Maintenance Ground Switch: This type is operated either manually or by motor drive and can close or open within several seconds. When fully closed, it is capable of carrying the rated short-circuit current for the specified duration (1 or 3 seconds) without sustaining damage.

Fast-Acting Ground Switch

A fast-acting ground switch is equipped with a high-speed drive, typically a spring mechanism, and contact materials designed to resist arcing. It can be closed twice onto an energized conductor without causing significant damage to itself or surrounding components.

Installation Location: Fast-acting ground switches are commonly installed at the connection point between the GIS and the rest of the electric power network. This placement ensures the switch can handle situations where the connected line is energized and effectively manages the discharge of a trapped charge.

Testing with the Use of Shunt

Ground switches are typically equipped with an insulating mount or bushing for the ground connection.

Normal Operations: During standard operation, the insulating element is bypassed using a bolted shunt that connects to the GIS enclosure.

Installation or Maintenance: When the ground switch is closed, the shunt can be removed, allowing the ground switch to serve as a connection between the test equipment and the GIS conductor.

Voltage and Current Testing: This setup enables the testing of the internal GIS components without the need to remove SF6 gas or open the enclosure. A common test involves measuring contact resistance using two ground switches.

Surge Arresters

Cable and direct transformer connections within a GIS system are not prone to lightning strikes. Since GIS conductors are enclosed in a grounded metal housing, the only path for lightning impulse voltages to enter and potentially cause damage is through the connection between the GIS and the external electrical system.

As a result, the primary areas of concern for protection are the SF6-to-air bushing connections and transformers.

The zinc oxide type surge arrester is ideal for use in an SF6 environment. These arresters are supported by an insulating cylinder within the GIS enclosure section, ensuring effective protection.

Air-Insulated Surge Arresters vs. Gas-Insulated Surge Arresters
Air-insulated surge arresters, when used in parallel with SF6-to-air bushings, typically provide sufficient protection for GIS systems against lightning impulse voltages at a much lower cost compared to SF6-insulated arresters.

In air-insulated systems (AIS), the withstand voltage for switching surges is considerably lower than for lightning impulses. This is because the longer duration of the switching surge allows time for the discharge to bridge the longer insulating distances in air.

In contrast, GIS systems feature short insulation distances that can be bridged quickly by the short time-span of a lightning impulse. The longer duration of a switching surge does not significantly reduce the breakdown voltage in GIS systems.

Insulation coordination studies often indicate that surge arresters are not necessary in a GIS. However, many users prefer specifying surge arresters for transformers and cable connections as a more conservative safety measure.

Section 11 Connections in GIS Systems

Interconnecting Buswork in GIS Systems

When GIS modules are not directly connected, an SF6 bus system is used. This system has an inner conductor surrounded by an outer enclosure. The components needed for the connection include support insulators, sliding electrical contacts, and flanged enclosure joints, which are like those in the GIS modules.

Typically, the length of a bus section is limited to 6 meters due to the span between conductor contacts and support insulators. However, specialized bus designs, such as those used in Gas-Insulated Transmission Lines (GIL), can have sections up to 20 meters long. These designs are applied in both GIS systems and separate transmission lines.

SF6-to-air bushings

SF6-to-air bushings are designed with a hollow insulating cylinder attached to a flange at the end of a GIS enclosure. This cylinder is pressurized with SF6 gas on the interior, while the outer surface is exposed to atmospheric air. The conductor runs through the center of the cylinder and extends to a metal end plate, which is bolted to an air-insulated conductor. The SF6 gas inside the bushing typically maintains the same pressure as the rest of the GIS system.

SF6-to-air bushings are equipped with moisture and contaminant shields or sheds on the outside, improving performance in wet or contaminated conditions. Internal metal shields are used to control electric-field distribution, while higher voltage bushings may also feature external shields for additional protection. Historically, the insulating cylinder was made from porcelain, but modern bushings now typically use a composite material, such as a fiberglass epoxy inner cylinder with an external weather shed made of silicone rubber. This composite design provides better contamination resistance and is safer than porcelain, as it is less likely to fracture.

11.1 Power Cable Connections - Cable Termination Kit

The power cabling connections in a GIS system use a cable termination kit, which creates a physical barrier between the cable dielectric and the SF6 gas inside the GIS. The kit ensures proper electric-field distribution at the cable's end. Since the cable termination is immersed in SF6 gas, the length is short, eliminating the need for sheds. The cable conductor connections are either bolted or compression-type, attaching to the end plate or cylinder of the cable termination kit.

Power Cable Connections – Testing Port

On the gas side, a removable link or plug-in contact is used to transfer current from the cable to the GIS conductor.

Testing: For high-voltage testing of either the GIS or the cable, the cable is disconnected from the GIS by removing the conductor link or plug-in contact.

Testing Access Port: Located on the GIS enclosure near the cable termination, this port allows for attaching a test bushing.

Plug-in Cable Termination Kit

Plug-in termination kits are available for solid dielectric power cables with system voltages up to 170 kV.

This type of connection allows one section of the plug-in termination to be installed during the manufacturing process, enabling the GIS cable termination compartment to be factory-sealed and tested before delivery.

In the field, the power cable with the mating terminator section is installed and plugged into the factory-installed termination part on the GIS.

For power cables that are stiff, difficult to bend, or may be direct-buried, a disconnect link is still required in the GIS termination closure.

SF6 to Oil Connections

To connect a GIS conductor directly to a transformer, a special SF6-to-oil bushing is required, which mounts on the transformer.

- **Transformer Side**: The bushing connection is immersed in oil at the end where the transformer's high-voltage leads are connected.
- **SF6 Gas Side**: Features a removable link or sliding contact for connecting to the GIS conductor. The bushing can be either an oil-paper condenser type or a solid insulation type.

Since SF6 leakage into transformer oil must be prevented, most bushings have a center section that allows any SF6 leaks to disperse into the atmosphere rather than contaminating the transformer.

For testing, the SF6 end of the bushing is disconnected from the GIS conductor after accessing it through an opening in the enclosure. The enclosure of the transformer can also be used to attach a test bushing.

Section 12 The GIS Control System

12.1 Local Control Cabinet (LCC)

A local control cabinet (LCC) is typically provided for each circuit breaker position when wiring the GIS back to the substation control room. Shielded multi-conductor control cables are used for the control and power wires, which include operating mechanisms, alarms, heaters, auxiliary switches, CTs, and VTs. These cables run between the GIS equipment modules and the LCC.

Inside the LCC Unit

The LCC unit includes a mimic diagram that represents the part of the GIS being controlled, along with terminals for all GIS wiring. Integrated into the mimic diagram are control switches and position indicators for the circuit breakers and switches. Additionally, the LCC typically provides annunciation for alarms, electrical interlocking, and other control functions. Although the LCC is not an essential component of the GIS, it is a widely established and popular feature in most GIS systems.

Very Fast Transient Voltages

Switching and circuit breaker operations in a GIS generate surge voltages internally, characterized by a very fast rise time in the nanosecond range and peak voltage levels of around 2 per unit. These very fast transient voltages do not pose a problem within the GIS, as the surge duration is extremely short, much shorter than that of lightning impulse voltages. However, an issue may arise when some of these very fast transient voltages escape the GIS through locations where the metal enclosure has a discontinuity, such as at insulating enclosure joints for external CTs or at SF6-to-air bushings.

Transient Voltages in Control Wiring

Transient ground rise voltages on the outside of the enclosure may cause minor sparking across the insulating enclosure joint or with adjacent grounded components. While this may appear concerning, the shock potential is very low and not harmful. However, if these very fast transient voltages penetrate the control wiring, they can lead to operational errors in control devices, with solid-state controls being particularly vulnerable.

Shielding and Grounding: To address this issue, proper shielding and grounding of the control wires are essential. In a GIS, the control cable shield should be grounded at both the equipment and LCC ends, either using coaxial ground bushings or short connections to the cabinet walls where the control cable enters the cabinet.

Section 13 Gas Monitoring and Leak Detection

Gas Monitoring System

The insulation and interruption capabilities of SF6 gas depend on maintaining a specific gas density, determined by design tests. Since SF6 gas pressure varies with temperature, a temperature-compensated pressure switch, either mechanical or electronic, is used to monitor the equivalent gas density effectively.

Allowable Gas Density Loss

GIS enclosures are initially filled with SF_6 gas to a density significantly above the minimum required for full dielectric and interrupting performance. This design ensures that the GIS can tolerate a 5–20% reduction in gas density before its performance is negatively impacted.

Section 14 Density and Pressure Alarms

Density Alarms

Density alarms alert operators when gas leakage reduces the enclosure's gas density to the minimum acceptable level. These alarms can automatically trigger circuit breakers and switches, placing the GIS system into a pre-established safety state to mitigate risks.

Pressure as a Trigger

Although monitoring gas density ensures precise system operation, measuring pressure is simpler and more common. Gas monitoring systems can be configured to track internal pressure instead of density. Advanced pressure gauges can also measure the rate of gas leakage, though these gauges are significantly more expensive than mechanical, temperature-compensated pressure switches.

Gas Compartments and Zones

GIS (Gas-Insulated Switchgear) systems are divided into separate compartments using gas barrier insulators to facilitate gas handling. Due to the arcing that occurs within a circuit breaker compartment, it is typically assigned an independent gas compartment.

Gas Handling Systems

These systems can process and store up to 1000 kg of SF_6 at a time. However, this is often impractical due to the time required for the process. As a solution, larger compartments are subdivided into smaller sections, each containing a few hundred kg of SF_6.

Bypass Piping for Interconnected Sub-Compartments

To optimize gas monitoring, small compartments can be interconnected via external bypass piping, forming a larger gas zone for density monitoring.

Connecting Multiple Gas Compartments

Pros:

- Easier leak detection when alarms are linked to smaller gas zones.
- Larger gas zones allow more time to replenish SF6 between the first and second alarms for the same size leak.

Cons:

- Faults in one compartment may lead to contamination in adjacent compartments.
- Greater SF6 loss can occur before a gas-loss alarm is triggered.

Section 15 Testing and Installation

General Test Requirements

- Testing for circuit breakers, CTs, VTs, and surge arresters is not GIS-specific.

Representative GIS Assemblies

- Design tests ensure that GIS components (excluding the circuit breaker) can withstand:
  - Lightning impulse voltage
  - Switching impulse voltage
  - Power frequency overvoltage
  - Continuous current
  - Short-circuit current

Test Standards

- Define test levels and procedures for proper testing compliance.

Factory Production Tests

- Conducted on fully assembled GIS, including the circuit breaker, covering:
  - Power frequency withstand voltage
  - Conductor circuit resistance
  - Leak checks
  - Operational checks
  - CT polarity verification

Other Component Testing

- Support insulators, VTs, and CTs undergo specific tests before GIS assembly.
- Field tests repeat factory tests to ensure reliability.

- Cleanliness checks of the GIS interior, specifically regarding contaminating conducting components.
- Checking interlocks is another critical testing procedure.
- Additional field tests, such as a surge voltage test, may be required if the GIS is a critical component of the electric power grid.

Air Evacuation and Gas Filling

- Air evacuation is necessary for opened gas compartments before sealing the system and filling it with SF6 gas.
- Control system wiring is completed before conducting appropriate field tests.

Installation Timeline

- High-voltage GIS units, shipped as separate modules, require approximately two weeks per circuit breaker position for installation and testing.
- Lower voltage systems, shipped as pre-assembled bays with factory wiring, can be installed much faster.

Operational Procedures for a GIS

The operational procedures of a GIS such as providing systems monitoring, control, and protection of the power is the like that of an AIS, except that internal faults are not self-clearing, so reclosing should not be used for faults internal to the GIS.

Disconnect and Ground Switch Operations

Special care and attention are required when operating disconnect and ground switches. Improper operation can lead to severe internal faults.

Potential Faults Due to Improper Operation

If a disconnect or ground switch is opened under load or closed into load/fault current, arcing between moving and stationary contacts can cause:

- Phase-to-phase fault in a three-phase enclosure GIS
- Phase-to-ground fault in a single-phase enclosure GIS

Consequences

- Severe internal damage to the GIS
    - Unlike AIS switches, GIS switches are difficult and time-consuming to replace.

Pressure Rise Due to Internal Faults

During a fault condition, the internal pressure in the GIS gas compartment rises as the arc heats the gas.

Extreme Cases & Risks

- A rupture disk may activate, or in severe cases, the enclosure may burn through.
- This could lead to the release of hot, decomposed SF6 gas, posing a serious burn injury risk to nearby personnel.

Safety Interlocks

Secure interlocks are in place to protect the GIS system and personnel:

- The circuit breaker must be open before an associated disconnect switch can be opened or closed.
- The disconnect switch must be open before the associated ground switch can be closed or opened.

Operational Wear on Internal Parts

- GIS internal parts are well-protected within the metal enclosure, preventing aging over time.
- Due to proper material selection and lubrication, switch contacts experience minimal wear.

Contacts and Nozzles

- Arcing contacts of the circuit breaker and the Teflon nozzle of the interrupter are the only components that show wear.
- Wear is proportional to the number of operations and the magnitude of load/fault currents interrupted.

Durability & Maintenance

Modern circuit breakers can handle thousands of load current interruptions and tens of full-rated fault current interruptions before requiring inspection or replacement.

Section 16 Inspections

Inspecting Circuit Breakers

Most circuit breakers do not require frequent internal inspections, except for special-use applications like pumped storage plants.

Similarly, most GIS systems will never need to be opened for maintenance.

Maintenance & Repairs

Circuit breakers experiencing frequent tripping should be checked and repaired after 6,000 mechanical operations.

Interrupters should undergo overhaul after interrupting 20 short-circuit events at up to 40kA.

Performance & Reliability

- Operational experience indicates that this maintenance schedule exceeds performance requirements, ensuring long-term reliability.

Section 17 Replacing Faulty GIS Systems

Faulty Designs & Reasons for Replacement

In isolated cases, earlier GIS installations required replacement due to:

- Inherent design failures
- Persistent corrosion and sealing issues, leading to SF_6 leakage

Most older GIS designs are no longer in use or being manufactured, and some manufacturers have ceased operations.

Replacement Process

- If space allows, a new GIS or AIS is built adjacent to the existing GIS, and connections are gradually transferred.

- If space is limited, the GIS is replaced section by section, using custom-designed temporary interface bus sections to connect the old and new systems.

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This concludes our course on "An Overview of Gas Insulated Substations". You may now proceed to the final exam located on the course page. Thank you for taking this course with Online-PDH!