

Performance And Protection Analysis Of 400kv/200kv At Konetipuram Substation Under Normal And Fault Conditions

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Accepted 20-03-2026

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Abstract

This paper presents a comprehensive analysis of load flow and protection mechanisms in a 400 kV/220 kV extra high voltage (EHV) substation. Load flow studies are performed to evaluate steady-state system parameters such as bus voltage magnitudes, real and reactive power distribution, transmission losses, and equipment loading under normal operating conditions. The study provides insights into voltage regulation and system stability at high voltage levels.

Additionally, various fault conditions commonly encountered in substations—such as single line-to-ground, line-to-line, double line-to-ground, and three-phase faults—are examined. Internal faults in transformers and busbars are also discussed. The paper further explores protection schemes including distance protection, differential protection, overcurrent protection, earth fault protection, Buchholz relay operation, and busbar protection.

The process of fault detection, isolation, and system restoration is analyzed to ensure operational reliability. The study emphasizes the importance of coordinated protection systems and efficient fault management strategies for maintaining uninterrupted and secure power transmission.

Keywords: Load flow analysis, EHV substation, fault analysis, protection schemes, voltage stability, power system reliability

1. Introduction

Electrical power systems form the backbone of modern infrastructure, supplying energy to industrial, agricultural, commercial, and residential sectors. Substations are critical components within these systems, serving as nodes where voltage levels are transformed and power flow is regulated.

Extra high voltage substations, such as 400 kV/220 kV systems, are essential for efficient long-distance transmission. By operating at higher voltages, transmission losses are minimized and system efficiency is improved. The Konetipuram 400/220 kV substation represents a key element in the transmission network, linking generation sources with load centers while maintaining voltage stability and power quality.

Load flow analysis is a fundamental tool in power system engineering, used to determine steady-state operating conditions. It enables the calculation of bus voltages, phase angles, and power flows, thereby assisting in system planning, operation, and expansion. Proper analysis ensures that voltage levels remain within permissible limits and prevents overloading of transmission lines and transformers. Substations also incorporate various components such as transformers, busbars, circuit breakers, and isolators, each playing a vital role in system operation and safety. Faults in the system—whether

in transmission lines, transformers, or busbars—can disrupt power flow and damage equipment. Therefore, reliable protection schemes are essential to detect and isolate faults rapidly.

Modern substations increasingly rely on numerical relays and supervisory control and data acquisition (SCADA) systems to enhance monitoring, control, and automation. These technologies improve response time, reduce human intervention, and ensure efficient system management.

This study focuses on analyzing load flow characteristics and evaluating protection mechanisms to enhance the reliability and safety of EHV substations.

2. Literature Review

Several researchers have investigated different aspects of high-voltage substations and power system performance.

Uglešić et al. analyzed switching surges in transformers caused by sequential circuit breaker operations in a 400/110 kV substation. Their findings indicated that switching actions can generate significant overvoltages, potentially damaging transformer insulation and surge arresters. The study highlighted the need for proper coordination of protective devices.

Bhandari et al. examined the performance of 220 kV and 400 kV transmission lines using load flow analysis in ETAP software. Their results demonstrated that higher voltage transmission and optimal reactive power compensation significantly reduce power losses and improve voltage profiles.

Other studies have focused on numerical techniques for load flow analysis, particularly the Newton–Raphson method, which offers high accuracy and fast convergence for large-scale power systems. Efficient computational methods are essential for real-time and online system analysis.

Ivanković et al. explored modeling of 400 kV transmission networks using MATLAB and phasor measurement unit (PMU) data. Their work emphasized the importance of advanced monitoring and protection systems in detecting disturbances such as power swings and maintaining system stability.

These studies collectively underline the importance of accurate load flow analysis and robust protection schemes in ensuring reliable operation of high-voltage power systems

3 Load Flow Analysis and Results

3.1 Load Flow in 400 kV Feeders

The load flow data obtained from the 400 kV feeders represents the steady-state operating condition of the substation under different loading scenarios. The measured bus voltages remain close to the nominal value (around 400–409 kV), indicating a well-regulated voltage profile.

Feeders such as **Srisailam-I and Srisailam-II** show negative real power values, which indicates power import into the substation. These feeders act as receiving ends, supplying power to downstream loads. Similarly, **YTPS-I and YTPS-II** also operate as importing feeders under certain conditions.

On the other hand, feeders like **Yedula-II and ICT transformers (ICT-I and ICT-II)** exhibit positive real power values, indicating power export or transfer to lower voltage levels. The ICTs carry significant load, confirming their critical role in interconnecting 400 kV and 220 kV networks.

Reactive power flow varies across feeders. Negative reactive power indicates absorption (inductive behavior), while positive values indicate generation (capacitive support). The variation in reactive power reflects changing load conditions and the need for voltage control.

3.2 Load Flow in 220 kV Feeders (Day-wise Analysis)

Day 1 Analysis

The 220 kV system operates with bus voltages around 218 kV, showing minimal deviation from rated values.

- Feeders such as **DMPNT and SSM** show negative real power, indicating load demand (power import).

- **KMP-I and KMP-II** act as exporting feeders, supplying power to adjacent regions.
- **KLKY feeders** demonstrate high power export, contributing significantly to system load sharing.
- **ICT transformers** carry the highest current (>400 A), confirming their major role in power transfer. Reactive power analysis reveals that some feeders (e.g., **MDGL-I**) consume large reactive power, indicating inductive loads.

Day 2 Analysis

On Day 2, slight variations in voltage (around 216–218 kV) are observed, but the system remains within acceptable limits.

- Increase in real power transfer through ICTs (≈ 170 MW) indicates higher system loading.
- Exporting feeders maintain consistent contribution, while importing feeders show moderate variation.
- Reactive power distribution remains balanced, ensuring voltage stability.

Day 3 Analysis

Day 3 data shows higher fluctuations in power flow:

- Significant increase in export through **Yedula-II** and ICTs
- Higher reactive power demand in some feeders, indicating stressed operating conditions
- Despite fluctuations, voltage levels remain within permissible limits, demonstrating system robustness

3.3 Power Balance and Stability Analysis

Real Power Balance

Across all observed days:

- Total real power import \approx Total real power export
 - Example (Day 1):
 - Import ≈ 370 MW
 - Export ≈ 382 MW
- This near equality indicates that generation and load demand are properly balanced, with minimal transmission losses.

Reactive Power Balance

Reactive power also shows close balance:

- Example (Day 1):
 - Import ≈ 189 MVAR
 - Export ≈ 208 MVAR
- This balance is essential for maintaining voltage stability and avoiding voltage collapse.

System Stability

The overall system demonstrates:

- Stable voltage profile
 - Balanced real and reactive power
 - No significant overloading
- Hence, the substation is operating under **theoretically stable steady-state conditions.**

3.4 Theoretical Calculations

Case 1: 400 kV Feeder (Srisailam-I)

Given:

- Real Power (P) = -103 MW
- Reactive Power (Q) = -73 MVAR

Apparent Power (S):

$$S = P^2 + Q^2 \Rightarrow S = \sqrt{P^2 + Q^2}$$

$$S = (-103)^2 + (-73)^2 = 10609 + 5329 \Rightarrow S = \sqrt{10609 + 5329}$$

$$S = 15938 \approx 126.2 \text{ MVA} \Rightarrow S = \sqrt{15938} \approx 126.2 \text{ MVA}$$

Power Factor (PF):

$$PF = \frac{P}{S} = \frac{103}{126.2} \approx 0.82$$

Case 2: 220 kV Feeder (DMPNT)

Given:

- Real Power (P) = -74 MW
- Reactive Power (Q) = -9 MVAR

Apparent Power (S):

$$S = (-74)^2 + (-9)^2 \Rightarrow S = \sqrt{(-74)^2 + (-9)^2}$$

$$S = 5476 + 81 = 5557 \Rightarrow S = \sqrt{5476 + 81} = \sqrt{5557}$$

$$S \approx 74.5 \text{ MVA (corrected)} \Rightarrow S \approx 74.5 \text{ MVA (corrected)}$$

Power Factor (PF):

$$PF = \frac{P}{S} = \frac{74}{74.5} \approx 0.99$$

(Note: Your earlier value 80.5 MVA was slightly incorrect—this corrected version improves accuracy for publication.)

3.5 Key Observations

- Voltage levels are well maintained in both 400 kV and 220 kV systems
- ICT transformers carry the highest load and are critical components
- Both importing and exporting feeders maintain system balance
- Reactive power management plays a key role in voltage stability
- The system operates under stable steady-state conditions across all days

4. PROTECTIVE DEVICES OF SUBSTATION



Fig:4.1: LIGHTNING ARRESTER

A lightning arrester in a 400kV/220kV substation is a protective device used to safeguard costly equipment such as power transformers, circuit breakers, current transformers, voltage transformers, and busbars from high-voltage surges caused by lightning strokes and switching operations. In Extra High Voltage substations, overhead transmission lines are directly exposed to atmospheric conditions, making them highly vulnerable to lightning strikes. When lightning strikes a transmission line or nearby structure, a high surge voltage travels along the line toward the substation. If not controlled, this surge can damage insulation and cause equipment failure.

A lightning arrester, also called a surge arrester, is connected between the line and earth near the equipment to provide a low-impedance path for surge currents to safely flow into the ground. Under normal operating conditions, the arrester behaves like an insulator and does not conduct current. However, during overvoltage conditions, it becomes conductive and diverts the surge energy to the earthing system, thereby limiting the voltage to a safe level known as the protective level.

Modern 400kV/220kV substations use metal oxide lightning arresters (ZnO type) without spark gaps, which offer fast response time, high energy absorption capability, and better reliability compared to older silicon carbide types.

These arresters are installed at the line entrance of the substation, near transformer terminals, and sometimes on both high-voltage and low-voltage sides of power transformers for complete protection. The rating of a lightning arrester is selected based on system voltage, maximum continuous operating voltage, discharge current capacity, and insulation coordination requirements. Proper earthing is essential for effective operation, as poor grounding reduces the arrester's performance.

Regular inspection, leakage current monitoring, and thermal scanning are carried out to ensure healthy operation. Thus, lightning arresters play a critical role in protecting 400kV/220kV substations from transient over voltages, improving equipment life, enhancing system reliability, and ensuring continuous and safe power transmission. Additionally, lightning arresters in 400kV/220kV substations are designed to withstand very high discharge currents, typically in the range of 10kA to 40kA, depending on system requirements.

They are coordinated with the insulation level of transformers and switchgear to ensure proper protection margin. Periodic testing such as insulation resistance measurement and leakage current analysis helps in assessing their condition and preventing unexpected failures.

FIG:4.2: CAPACITIVE VOLTAGE TRANSFORMER

A Capacitor Voltage Transformer (CVT), also called a Capacitive Voltage Transformer, is an instrument transformer used in 400kV/220kV substations to step down very high transmission line voltages to a measurable and standardized low value (generally 110V or 63.5V) for metering, protection, and control purposes. In Extra High Voltage substations, direct measurement of voltage is not possible due to insulation and safety limitations, so CVTs are used to provide an accurate scaled-down voltage signal to protective relays, energy meters, synchronizing panels, and SCADA systems. A CVT mainly consists of a capacitor divider unit, an electromagnetic unit (intermediate transformer), and a tuning reactor.

The capacitor divider is connected between the line and ground and divides the high voltage into a lower intermediate voltage. This intermediate voltage is then fed to the electromagnetic transformer, which further steps it down to a standard secondary voltage suitable for instruments. The tuning reactor is used to compensate for frequency errors and to improve voltage regulation and accuracy. In addition to voltage measurement, CVTs are also used for Power Line Carrier Communication (PLCC), where high-frequency communication signals are coupled onto transmission lines for protection signaling and communication between substations.

In 400kV/220kV substations, CVTs are preferred instead of conventional Potential Transformers (PTs) mainly due to economic and practical reasons. At very high voltages like 400kV, a conventional electromagnetic PT would require very high insulation levels, large core size, and heavy winding,



making it bulky, expensive, and difficult to install. The insulation cost increases rapidly with voltage level in PTs. In contrast, CVTs use a capacitor voltage divider, which is more economical and lighter for EHV applications. They provide adequate accuracy for protection and metering while being cost-effective for high-voltage systems.



Additionally, CVTs serve dual purposes by supporting carrier communication, which normal PTs cannot provide. Therefore, in 400kV/220kV substations, CVTs are widely used because they are more economical, compact, multifunctional, and suitable for Extra High Voltage transmission systems while ensuring reliable voltage measurement and protection operation.

CVTs in 400kV/220kV substations must maintain high accuracy for both protection and metering applications, typically conforming to standard accuracy classes such as 0.2, 0.5, or 3P for protection. They are designed to withstand switching surges, lightning impulses, and system over voltages. Proper installation, periodic oil level inspection, capacitance measurement, and tan delta testing are essential to ensure long-term reliability and stable performance in EHV systems.

FIG:4.3: ISOLATORS

An isolator, also known as a disconnecter, is a mechanical switching device used in 400kV/220kV substations to isolate a particular section of the

power system for maintenance or safety purposes. Unlike circuit breakers, isolators are not designed to interrupt load current or fault current; they are operated only after the circuit breaker has opened the circuit. In Extra High Voltage substations, isolators are installed on both sides of circuit breakers, transformers, busbars, and transmission lines to provide visible isolation, ensuring that equipment is completely disconnected from the energized system before maintenance work is carried out.

The main function of an isolator is to provide a clear and visible air gap between live and disconnected parts, which enhances safety for operating and maintenance personnel.

In 400kV/220kV substations, different types of isolators are used, such as single break, double break, center break, and pantograph type isolators, depending on the voltage level and substation layout. Double break isolators are commonly used at 400kV because they provide better voltage distribution and compact design, while pantograph isolators are often used in busbar arrangements where vertical space is limited. Many isolators are also provided with an earthing switch, which is used to discharge trapped charges and ensure complete safety. Isolators can be manually operated or motor-operated, and they are interlocked with circuit breakers to prevent operation under load conditions. Although isolators do not have arc-quenching mechanisms, they are essential components in substation switching schemes such as single bus, double bus, breaker-and-a-half, and ring bus systems. Proper maintenance, lubrication of moving parts, contact inspection, and alignment checks are necessary to ensure reliable operation. Thus, isolators play a crucial role in ensuring operational flexibility, equipment protection, and safety in 400kV/220kV substations. CVTs in 400kV/220kV substations must maintain high accuracy for both protection and metering applications, typically conforming to standard accuracy classes such as 0.2, 0.5, or 3P for protection. They are designed to withstand switching surges, lightning impulses, and system over voltages. Proper installation, periodic oil level inspection, capacitance measurement, and tan delta testing are essential to ensure long-term reliability and stable performance in EHV systems. In a 400kV/220kV substation, isolators are not rated by power (MVA) but by voltage level and current carrying capacity. For 400kV systems, isolators typically have current ratings of 2000A, 2500A, or 3150A, depending on the transmission line or transformer capacity. For 220kV systems, common ratings are 1250A, 1600A, 2000A, or 2500A. They are also designed to withstand short-circuit currents of about 31.5kA or 40kA for 1 to 3 seconds. The

exact capacity depends on the substation design and load requirements.



FIG:4.4: RELAYS

Relays are very important protective devices used in a 400 kV substation to detect faults and isolate the faulty section quickly. They continuously monitor electrical parameters such as current, voltage, frequency, and impedance. When abnormal conditions like short circuits, overloads, or earth faults occur, the relay sends a trip signal to the circuit breaker to disconnect the faulty part of the system. This helps protect expensive equipment like transformers, transmission lines, and generators, and also ensures the stability and reliability of the power system.

In a 400 kV substation, several types of protective relays are used depending on the equipment and protection requirements. Distance relays are commonly used for transmission line protection, as they measure impedance to determine the location of faults on the line. Differential relays are used to protect transformers and busbars by comparing the current entering and leaving the equipment. If there is a difference beyond a set limit, the relay operates and trips the circuit breaker. Overcurrent relays and earth fault relays are also used as backup protection to detect excessive current and ground faults.

Modern 400 kV substations mostly use numerical relays, which are microprocessor-based devices. These relays provide faster operation, higher accuracy, self-diagnostics, event recording, and communication with control systems. They can perform multiple protection functions in a single unit, making the protection system more reliable and efficient. Thus, relays play a critical role in ensuring safe operation and protection of high-voltage substations.



FIG:4.5: WAVE TRAP

A wave trap is an important device used in 400 kV substations for communication and protection purposes. It is also called a line trap. A wave trap is installed in series with the transmission line, usually between the busbar and the transmission line, to block high-frequency communication signals from entering unwanted parts of the power system while allowing normal power frequency (50 Hz) current to pass through.

The main function of a wave trap is to confine high-frequency carrier signals used in Power Line Carrier Communication (PLCC) to a particular transmission line. In PLCC systems, high-frequency signals are transmitted along power lines for purposes such as telecommunication, tele-protection, and control signals between substations.



FIG:4.6: CURRENT TRANSFORMER

A Current Transformer (CT) in a 400kV/220kV substation is an instrument transformer used to step down very high line currents to a safe and measurable value (usually 1A or 5A) for metering, protection, and control applications. In Extra High Voltage substations, transmission lines and power transformers carry very large currents that cannot be directly connected to measuring instruments or protective relays due to insulation and safety limitations. The CT is connected in series with the transmission line and produces a secondary current

proportional to the primary current based on its transformation ratio. This scaled-down current is supplied to energy meters, ammeters, differential relays, distance relays, overcurrent relays, and busbar protection schemes.



In 400kV/220kV substations, CTs are generally oil-filled or SF₆ insulated outdoor type, designed to withstand high insulation levels and short-circuit currents. The capacity or rating of a CT is defined by its primary current rating, secondary current rating, burden capacity (in VA), and accuracy class. Typical primary current ratings in a 400kV yard range from 800A, 1000A, 1250A, 1600A, 2000A, up to 3150A depending on the transmission line or transformer capacity. The secondary rating is commonly 1A or 5A. The burden capacity may range from 15VA to 60VA or higher, depending on the connected devices. For protection purposes, CTs are designed with high accuracy under fault conditions and may have accuracy for differential protection. They are also designed to withstand high short-circuit currents, sometimes up to 31.5kA or 40kA for 1 second, depending on system fault level. Proper polarity marking, earthing of secondary winding, and avoiding open-circuiting the secondary are essential for safe operation. Regular testing such as ratio test, insulation resistance test, and knee point voltage test ensures reliable performance.

FIG:4.7: CIRCUIT BREAKER

A Circuit Breaker (CB) in a 400kV/220kV substation is a critical protective switching device used to interrupt normal load currents and fault currents under abnormal conditions such as short circuits, overloads, or equipment failures. In Extra High Voltage substations, SF₆ (Sulphur Hexafluoride) circuit breakers are commonly used because of their excellent arc-quenching properties, high dielectric strength, and fast operation. The main function of a CB is to detect fault signals from protective relays and quickly isolate the faulty section of the power system to prevent equipment

damage and maintain system stability. When a fault occurs, the relay sends a trip signal to the breaker, which opens its contacts and extinguishes the arc formed during current interruption using SF₆ gas insulation.

In 400kV substations, circuit breakers are typically rated at 400kV with current ratings of 2000A, 2500A, 3150A, or even 4000A depending on system load capacity. For 220kV substations, common current ratings are 1250A, 1600A, 2000A, and 2500A. The breaking capacity (short-circuit breaking current) is usually 31.5kA, 40kA, or sometimes 50kA for 3 seconds, depending on the system fault level. The making capacity is generally 2.5 times the breaking current to handle peak short-circuit currents. Circuit breakers may be of live tank or dead tank type, and they are equipped with operating mechanisms such as spring-operated or hydraulic mechanisms for quick action. Proper maintenance, including gas pressure monitoring, contact wear inspection, timing tests, and insulation tests, is essential to ensure reliable performance.

Thus, circuit breakers are vital components in 400kV/220kV substations, ensuring safe interruption of faults, protection of expensive equipment, and continuity of power supply. circuit breakers in 400kV/220kV substations are designed for high-speed operation, typically clearing faults within 3 to 5 cycles to maintain system stability. They are integrated with auto-reclosing schemes for transmission lines to restore supply after temporary faults. Continuous monitoring of SF₆ gas pressure and operating mechanism ensures safe and reliable performance.

Furthermore, circuit breakers at 400kV/220kV levels are equipped with trip coils, closing coils, and auxiliary contacts for proper control and indication. They operate in coordination with protection relays, SCADA, and auto-reclose systems. Routine tests such as contact resistance measurement, timing analysis, and insulation checks ensure dependable fault interruption and long service life.



FIG:4.8: TIED BREAKER

In a 400kV substation, a tie breaker is part of the one-and-a-half breaker scheme, also called the breaker-and-a-half arrangement, which is commonly used in Extra High Voltage systems to provide high reliability and operational flexibility. In this scheme, three circuit breakers are used for two transmission lines or circuits, meaning each circuit is connected between two breakers, and one breaker is shared between adjacent circuits. Because three breakers are used to protect two circuits, it averages to one and a half breakers per circuit, which is why it is called the one-and-a-half breaker scheme.

The middle breaker that is shared between two circuits is often referred to as the tie breaker. This arrangement ensures that if one breaker fails or is taken out for maintenance, both circuits are not completely interrupted, thereby improving continuity of supply. It also allows isolation of any bus section without shutting down the entire substation.

This scheme is mainly used in 400kV substations because at such high voltage levels, power transfer capacity is very large and reliability requirements are extremely high. A simple single-bus or double-bus scheme may not provide sufficient security, and breaker failure could lead to major outages. Although the one-and-a-half breaker scheme is more expensive due to the additional circuit breaker and complex protection system, it is justified at 400kV because of the high power handling, system stability considerations, and the importance of uninterrupted transmission. In contrast, 220kV substations often use double bus or bus coupler schemes since the power level and reliability requirements are comparatively lower.

Thus, the tie breaker in a 400kV substation enhances system flexibility, fault isolation capability, and operational reliability, making it suitable for critical Extra High Voltage transmission networks. the tie breaker in a 400kV one-and-a-half breaker scheme improves system stability during contingencies and



reduces the risk of complete bus failure. It allows



independent operation of each circuit while sharing protection responsibilities. Advanced relay coordination and breaker failure protection are incorporated to ensure quick isolation and uninterrupted power transmission.

FIG:4.11: CORONA RING

A corona ring, also known as a grading ring, is a metallic circular ring installed on high-voltage equipment such as transformer bushings, circuit breakers, CVTs, lightning arresters, and insulators in 400kV/220kV substations to control electric field distribution and reduce corona discharge. In Extra High Voltage systems, the electric field intensity at sharp edges or terminals becomes very high, which can ionize the surrounding air and produce corona. Corona results in power loss, audible noise, radio interference, ozone formation, and gradual insulation deterioration. To prevent this, corona rings are installed at the high-voltage terminal ends of equipment. The ring increases the effective radius of the conductor and distributes the electric field uniformly around the surface, thereby reducing electric stress concentration.

In 400kV substations, corona rings are especially important because the operating voltage is very high and the risk of corona discharge is significant. At 220kV level, corona rings may also be used, but they are more critical at 400kV due to higher electric field strength. The ring is typically made of aluminum or galvanized steel and is firmly connected to the high-voltage terminal. Proper design ensures smooth surface finish to avoid sharp points that could intensify electric stress.

Corona rings improve insulation life, reduce electromagnetic interference, enhance system reliability, and maintain voltage performance. Regular inspection is necessary to ensure mechanical tightness and absence of corrosion. Thus, corona rings play a vital role in maintaining electrical stress control and ensuring safe and

efficient operation of 400kV/220kV substation equipment.

5. TRANSFORMER IN SUBSTATION

FIG:5.1: INTERCONNECTING TRANSFORMER

An Interconnecting Transformer (ICT) in a 400kV substation is a high-capacity power transformer used to interconnect two different voltage levels, typically 400kV and 220kV, to facilitate efficient power transfer between transmission networks. It is mainly used to step down voltage from 400kV to 220kV or sometimes step up from 220kV to 400kV depending on system requirements. ICTs in 400kV substations are generally auto-transformers because both voltage levels are part of the transmission system and share a common neutral point. The auto-transformer design reduces copper usage, size, cost, and losses compared to a conventional two-winding power transformer of the same rating. These transformers are designed for very high power capacities, typically ranging from 315 MVA, 500 MVA, 630 MVA, up to 1000 MVA, depending on grid demand. They are equipped with OLTC (On Load Tap Changer) for voltage regulation and advanced cooling systems such as ONAN, ONAF, or OFAF to handle heavy loads. ICTs are essential in 400kV substations because they enable bulk power transfer between EHV and HV networks while maintaining voltage stability and system reliability.

An ICT is preferred in 400kV substations instead of a conventional two-winding power transformer mainly because of efficiency and economic advantages. In transmission-level interconnection, the voltage ratio between 400kV and 220kV is not very large, so an auto-transformer is more suitable. It provides better voltage regulation, lower impedance, reduced losses, and higher efficiency. Additionally, ICTs allow smooth power flow between interconnected grids, supporting load sharing and system stability. While a standard power transformer is typically used for stepping down to distribution levels (like 220kV to 132kV or lower), an ICT is specifically designed for high-capacity interconnection between major transmission voltage levels. Thus, in 400kV substations, ICTs are used because they are more economical, compact, efficient, and suitable for bulk power transfer between Extra High Voltage networks.

In a 400kV substation, the Interconnecting Transformer (ICT) is one of the most important and costly pieces of equipment because it handles bulk power transfer between major transmission voltage levels such as 400kV and 220kV. ICTs are generally three-phase auto-transformers designed to operate continuously under heavy load conditions. Since both 400kV and 220kV belong to the transmission

network, the auto-transformer construction is preferred as it uses a common winding for both primary and secondary sides, reducing copper usage, size, weight, and overall losses.

The power rating of ICTs in 400kV substations typically ranges from 315 MVA, 500 MVA, 630 MVA, up to 1000 MVA depending on grid demand and system design.

Additionally, interconnected transformers improve the overall reliability and operational flexibility of the substation, making maintenance easier and ensuring uninterrupted power supply under both normal and contingency conditions.



FIG:5.2: BUSHINGS

Bushings in a 400kV substation are high-voltage insulating devices used to safely pass electrical conductors through grounded barriers such as transformer tanks, circuit breaker enclosures, or walls without causing electrical breakdown. In Extra High Voltage systems like 400kV, bushings are critical components because they must withstand very high operating voltages, lightning impulses, switching surges, and environmental stresses.

They are commonly used in power transformers, interconnecting transformers (ICTs), circuit breakers, and shunt reactors. The most widely used type in 400kV substations is the condenser (capacitive graded) bushing, which contains layers of insulating paper and conductive foils arranged to control the electric field distribution evenly across the insulation. This grading prevents excessive electric stress at any single point and improves reliability.

400kV bushings are usually oil-impregnated paper (OIP) type or resin-impregnated paper (RIP) type, enclosed in porcelain or polymer insulators to provide external insulation and mechanical strength. They are designed with high Basic Insulation Level (BIL) to withstand lightning impulse voltages. The current carrying capacity of bushings depends on transformer rating and may range from 1000A to 3150A or more. Proper sealing is essential to prevent moisture entry, which can reduce insulation strength. Regular maintenance includes insulation resistance testing, capacitance and tan delta (power factor) testing, oil level inspection (for OIP type),



FIG:5.3: BREATHER

and thermal scanning to detect overheating. Any failure in a 400kV bushing can cause severe damage to transformers and lead to major outages. Therefore, bushings are designed with high insulation strength, proper grading, and robust construction to ensure safe and reliable operation in Extra High Voltage substations.

A breather in a 400kV substation is a protective device fitted to power transformers and interconnecting transformers (ICTs) to prevent moisture from entering the transformer oil during breathing action. In large 400kV transformers, a conservator tank is provided to accommodate expansion and contraction of insulating oil due to temperature changes. When the oil expands, air is pushed out, and when it cools, air is drawn into the

conservator. This process is called breathing. If moist atmospheric air directly enters the transformer, it can reduce the dielectric strength of the oil and damage insulation. Therefore, a breather is installed between the conservator tank and the atmosphere.

The breather mainly contains silica gel crystals, which act as a drying agent to absorb moisture from the incoming air. Silica gel is usually blue in color when dry and turns pink when it absorbs moisture, indicating that it needs replacement or regeneration. The breather also contains an oil seal (oil cup) at the bottom, which prevents direct contact of outside air with silica gel and stops dust or insects from entering. In 400kV substations, maintaining dry insulation is very important because high voltage equipment is highly sensitive to moisture contamination. Regular inspection of silica gel condition, oil level in the oil cup, and proper sealing ensures effective operation. Thus, the breather plays



a crucial role in protecting expensive 400kV transformers by maintaining oil quality, preventing insulation failure, and ensuring long and reliable service life.

In a 400kV substation, the breather is specially designed to handle large volumes of air because high-capacity transformers such as 315 MVA, 500 MVA, or 630 MVA ICTs experience significant oil expansion and contraction. The size of the breather depends on transformer oil capacity and breathing rate. A properly selected breather ensures efficient moisture absorption even during rapid temperature changes.

The breather, which contains a moisture-absorbing material like silica gel, removes moisture and dust from the incoming air before it enters the transformer. This prevents contamination of the transformer oil, which could otherwise reduce insulation strength and lead to faults. By keeping the internal environment dry and clean, the breather plays an important role in improving the efficiency, reliability, and lifespan of the transformer.

FIG:5.4: EARTH PIT

An earth pit in a 400kV/220kV substation is a crucial component of the grounding (earthing) system used to safely dissipate fault currents, lightning surges, and leakage currents into the ground. In Extra High Voltage substations, the magnitude of fault current can be extremely high, sometimes reaching 31.5kA or 40kA, and without a proper earthing system, it can cause serious damage to equipment and pose danger to personnel. The earth pit provides a low-resistance path for these currents to flow safely into the soil, thereby maintaining the equipment body and structural parts at earth potential and preventing electric shock hazards. It also ensures proper operation of protective devices such as relays and lightning arresters by stabilizing system voltage during fault conditions.

An earth pit generally consists of an earth electrode buried vertically in the ground, connected to the substation earthing grid through a conductor. The commonly used electrode materials are copper rods, galvanized iron (GI) rods, copper plates, or GI plates, selected based on soil conditions and corrosion resistance requirements. Around the electrode, layers of charcoal and salt are traditionally used to reduce earth resistance by improving soil conductivity and retaining moisture. In modern substations, bentonite compound is often used instead of charcoal and salt for better and long-lasting conductivity. The earthing grid in a 400kV/220kV substation is made of buried GI strips or copper conductors interconnected in a mesh pattern covering the entire switchyard area. The earth resistance is maintained typically below 1 ohm to ensure effective grounding. Regular testing using an earth resistance tester is conducted to monitor performance. Thus, the earth pit is an essential safety and protection system in 400kV/220kV substations, ensuring safe dissipation of high fault currents, protection of equipment, and safety of operating personnel. In a 400kV/220kV substation, the earth pit is part of a comprehensive earthing system that includes an extensive underground earth mat or grid spread across the entire switchyard. This grid connects all metallic structures, equipment frames, transformer neutrals, lightning arresters, circuit breakers, isolators, control panels, and fencing to ensure uniform earth potential throughout

the substation area. This minimizes step potential and touch potential, which are critical safety



concerns during fault conditions. Step potential refers to the voltage difference between two points on the ground surface, while touch potential refers to the voltage difference between grounded equipment and the earth surface.

FIG:5.5: BUCHHOLZ RELAY

A Buchholz relay is a gas-operated protective device used in 400kV substations to protect oil-immersed power transformers and interconnecting transformers (ICTs) from internal faults. It is specifically installed in the pipe connecting the main transformer tank to the conservator tank. Since 400kV transformers are very high-capacity units such as 315 MVA, 500 MVA, or higher, their protection is extremely important due to their cost and critical role in power transmission. The Buchholz relay operates on the principle that internal faults inside a transformer, such as insulation failure, short-circuited windings, core faults, or overheating, produce gases due to decomposition of transformer oil. These gases accumulate in the relay chamber.

The relay contains two floats and mercury switches (or magnetic switches in modern types). During minor internal faults, gas slowly accumulates in the relay, causing the upper float to drop and activate an alarm signal. In case of a severe fault, such as a major winding short circuit, a sudden surge of oil flows toward the conservator, which tilts the lower float and operates the trip circuit breaker to isolate the transformer immediately. Thus, it provides both alarm and trip functions. The Buchholz relay is only

used in oil-filled transformers with conservator tanks and is not applicable to sealed or dry-type transformers. Regular maintenance includes gas collection testing and checking the relay mechanism. Therefore, in 400kV substations, the Buchholz relay is an essential protective device that detects internal transformer faults at an early stage, prevents major damage, and ensures safe and reliable transformer operation.

In a 400kV substation, the Buchholz relay plays a very important role in transformer protection because transformers at this level handle very high power and are extremely costly. Even a small internal fault, if not detected early, can develop into a major failure. The Buchholz relay helps in early detection of incipient faults such as insulation deterioration, hot spots in windings, loose connections, core heating, and partial discharge. These minor faults generate small amounts of gas inside the transformer oil, which gradually accumulates in the relay chamber and gives an alarm signal before the fault becomes severe.

One important feature of the Buchholz relay is the gas sampling valve provided at the top. When an alarm occurs, the collected gas can be extracted and analyzed. The type and composition of gas (such as hydrogen, methane, acetylene, etc.) help in identifying the nature of the internal fault. This analysis supports preventive maintenance and avoids unexpected transformer breakdown.



FIG:5.6: EARTHING RODS

Earthing in a 400kV/220kV substation is a fundamental safety and protection system designed to provide a low-resistance path for fault currents, lightning surges, and leakage currents to safely dissipate into the ground. In Extra High Voltage substations, fault current levels can be extremely high, often reaching 31.5kA or 40kA, and without an effective earthing system, these currents can cause severe equipment damage, fire hazards, and

life-threatening electric shocks. The earthing system consists of a buried earth mat or grid made of galvanized iron (GI) strips or copper conductors laid in a mesh pattern beneath the entire switchyard. All metallic parts of equipment such as transformers, circuit breakers, isolators, lightning arresters, structures, control panels, and fencing are connected to this grid to maintain them at earth potential.

The main objectives of earthing are to ensure personnel safety by reducing step potential and touch potential during fault conditions, to provide a stable reference point for system voltage, and to ensure proper operation of protective relays and circuit breakers.

It also helps in dissipating lightning currents effectively through lightning arresters. Earth electrodes such as GI rods, copper rods, or plates are driven deep into the soil and connected to the earthing grid to achieve low earth resistance, typically below 1 ohm in EHV substations. Materials like charcoal, salt, or bentonite are used around electrodes to improve soil conductivity. Regular testing of earth resistance and inspection of connections are necessary to maintain system effectiveness.

Earthing rods in a 400 kV substation are essential components of the grounding system that provide a low-resistance path for fault and lightning currents to safely flow into the earth. They help in protecting costly equipment such as transformers and circuit breakers by preventing overvoltages and diverting excess current away from them. Earthing rods also ensure the safety of personnel by maintaining touch and step voltages within safe limits, thereby reducing the risk of electric shock.



FIG:5.7: REACTOR IN 400KV

In a 400 kV substation, a reactor is an important device used to control voltage and manage reactive power in the power system. Long high-voltage transmission lines generate excess capacitive reactive power, especially during light load conditions. This can cause a rise in voltage known as the Ferranti effect. To control this voltage rise and maintain the system voltage within safe limits, reactors are installed in the substation. A reactor works as an inductive device that absorbs excess reactive power from the transmission line.

Reactors operate on the principle of inductance. When current flows through the reactor coil, it creates inductive reactance that opposes the capacitive effect of the transmission line. By absorbing reactive power, the reactor helps maintain proper voltage levels, improves voltage regulation, and protects electrical equipment from overvoltage conditions. Because of these advantages, reactors are widely used in extra high voltage systems such as 220 kV and 400 kV substations.

The most commonly used type in a 400 kV substation is the shunt reactor, which is connected between the transmission line or bus bar and the ground through circuit breakers and isolators. The rating of reactors is generally expressed in MVAR, such as 50 MVAR, 63 MVAR, or 80 MVAR depending on system requirements.

There are mainly two types of reactors used in 400 kV substations: shunt reactors and series reactors. Shunt reactors are connected in parallel with transmission lines or busbars and are primarily used for voltage control by absorbing reactive power. Series reactors, on the other hand, are connected in series with the line and are used to limit short-circuit currents during fault conditions. Among these, shunt reactors are more commonly used in high-voltage substations.

6. CONCLUSION

The project on the performance and protection analysis of a 400 kV/220 kV substation under normal and fault conditions concludes that efficient operation of a high-voltage substation depends on proper coordination between system components, accurate load flow management, and reliable protection schemes. From the analysis, it is observed that under normal operating conditions, the substation maintains a balance between real and reactive power, ensuring stable voltage profiles and efficient power transfer. However, during fault conditions, there is a significant disturbance in voltage, current, and power flow, which can lead to equipment damage if not controlled promptly.

The study highlights the importance of protective devices such as relays, circuit breakers and current transformers in detecting and isolating faults quickly. The use of components like reactors, wave traps, and proper earthing systems further enhances

system stability by controlling over voltages, limiting fault currents and ensuring safe dissipation of fault energy. Load flow analysis also plays a key role in identifying power import and export conditions, helping in optimal operation and planning of the substation.

Overall, the project demonstrates that a well-designed protection system combined with effective monitoring and control techniques ensures the reliability, safety, and continuity of power supply in a 400 kV/220 kV substation. It emphasizes the need for regular maintenance, advanced protection schemes, and modern automation to handle increasing power demand and complex fault scenarios, thereby improving the overall efficiency and stability of the power system.

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