Substation Engineering

Milav Dabgar

Outline

Definition and Purpose of Substations (Part 1)

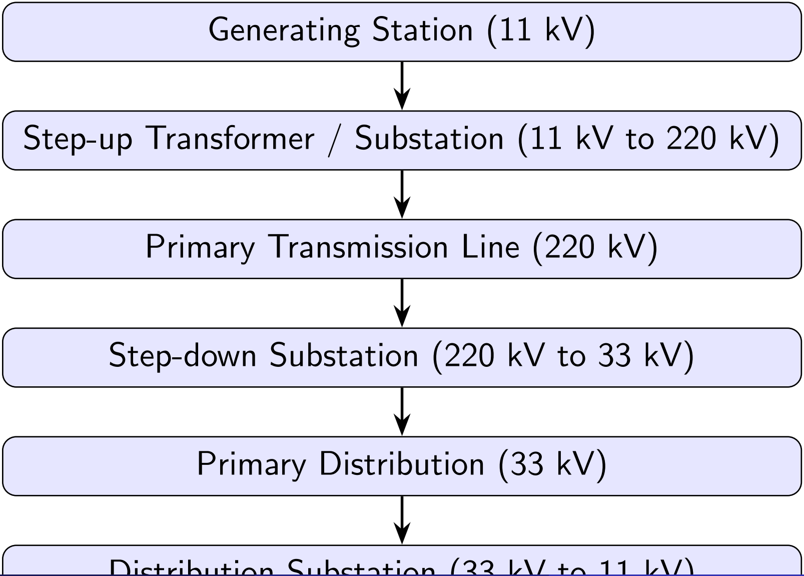
- Course: Substation Engineering (DI04009011)
- Unit 1: Introduction
- Lecture 1

Agenda

Overview of Electrical Power Systems

- Power systems consist of Generation, Transmission, and Distribution.
- Electricity is generated at relatively low voltages (11 kV - 25 kV).
- It is stepped up to high voltages (132 kV, 220 kV, 400 kV, 765 kV) for efficient long-distance transmission.
- It is stepped down again for distribution to consumers (33 kV, 11 kV, 415 V, 240 V).

Power System Network Diagram



What is a Substation?

- A substation is a critical node in the power grid.
- It serves as an intersection where power lines meet and voltage levels are changed.
- It houses transformers, switchgear, protective relays, and control equipment.
- Substations do not generate power; they route and condition it.

Formal Definition of an Electrical Substation

- An assembly of electrical apparatus such as transformers, switchgears, buses, etc.
- Situated in a specific location.
- Designed to change electrical characteristics (voltage, AC/DC, frequency).
- Used to switch power circuits on and off for grid management and maintenance.

Why Do We Need Substations?

- Generators cannot be connected directly to consumers.
- Long-distance transmission requires very high voltages to reduce losses.
- Consumers require low, safe voltages to operate appliances and machinery.
- Faults must be isolated to prevent whole-grid collapse.

Primary Purpose 1: Voltage Transformation

- The most recognizable function of a substation.
- Step-Up Substations: Increase voltage for transmission (e.g., 11 kV to 400 kV).
- Step-Down Substations: Decrease voltage for sub-transmission or distribution (e.g., 220 kV to 33 kV).
- Utilizes power transformers to perform this function efficiently.

Voltage Levels Table (Typical Indian Grid)

Grid Segment	Typical Voltage Levels
Generation	11 kV, 21 kV
Primary Transmission	400 kV, 765 kV
Secondary Transmission	132 kV, 220 kV
Primary Distribution	33 kV, 66 kV
Secondary Distribution	11 kV, 415 V, 240 V

Primary Purpose 2: Switching operations

- Substations provide the ability to switch equipment in and out of the system.
- Allows for routine maintenance without disrupting the entire grid.
- Facilitates load shedding or load transferring between different feeders.
- Done using Circuit Breakers and Isolators (Disconnectors).

Primary Purpose 3: Isolation of Faults

- Power systems are subject to faults (short circuits, lightning strikes).
- Substations contain protective relays that detect these abnormal conditions.
- Relays send signals to circuit breakers to open and isolate the faulty section.
- Protects expensive equipment (transformers) from catastrophic damage.
- Ensures stability of the remaining healthy grid.

Other Purposes: Power Factor Correction

- Industrial loads are highly inductive, causing poor power factor.
- Poor power factor reduces system capacity and increases losses.
- Substations may house Capacitor Banks or Synchronous Condensers.
- These devices inject reactive power to improve the power factor.

Other Purposes: Voltage Regulation

- Voltage drops along long transmission lines due to line impedance.
- Substations help regulate voltage to keep it within statutory limits.
- Accomplished using On-Load Tap Changers (OLTC) on transformers.
- Static VAR Compensators (SVC) are also used in modern substations.

Summary of Substation Purposes

- Voltage transformation (Step-up and Step-down).
- Switching for maintenance and load management.
- Protection and fault isolation.
- Power factor correction.
- Voltage regulation.

Definition and Purpose of Substations (Part 2)

- Course: Substation Engineering (DI04009011)
- Unit 1: Introduction
- Lecture 2

Recap of Primary Purposes

- Voltage Transformation (Transformers)
- Switching (Circuit Breakers and Isolators)
- Protection (Relays)
- Power Factor Correction
- Voltage Regulation

Purpose 4: Data Acquisition and Metering

- Substations serve as major data collection points.
- Voltage, current, real power (MW), and reactive power (MVAR) are continuously monitored.
- Energy meters record the power flowing through for billing and accounting.
- Instrument Transformers (CTs and PTs) scale down high values for measuring instruments.

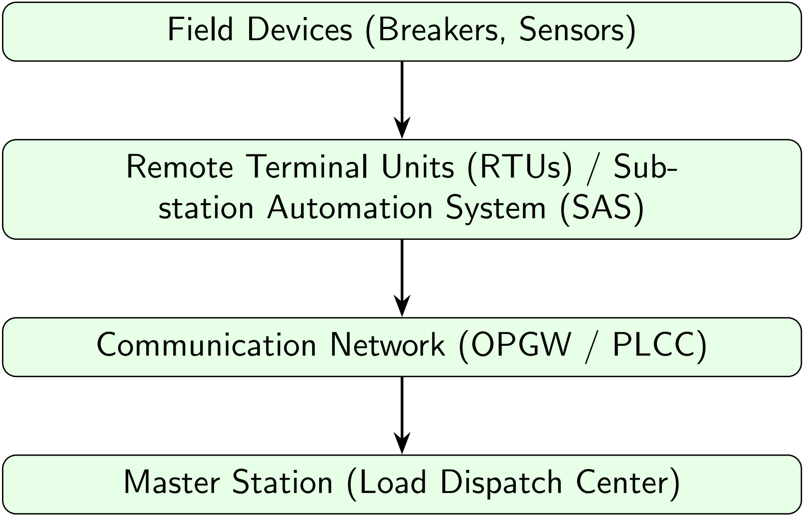
Instrument Transformers (CTs and PTs)

Current Transformer (CT)	**Potential Transformer (PT)**
Steps down high current (e.g., 1000A to 1A) for relays and meters.	Steps down high voltage (e.g., 220kV to 110V) for measurement.

Purpose 5: Communication Hub

- Substations communicate with the central Load Dispatch Center (LDC).
- Power Line Carrier Communication (PLCC) uses transmission lines for data transfer.
- Modern substations use Optical Ground Wire (OPGW) for high-speed fiber-optic communication.
- Transmits SCADA (Supervisory Control and Data Acquisition) data.

SCADA Integration



Purpose 6: Grid Synchronization

- Connecting two grids or bringing a generator online requires synchronization.
- Voltage magnitude, frequency, and phase angle must match exactly.
- Substations provide the point of connection and the synchronizing relays to perform this safely.
- Prevents massive electrical and mechanical shocks to the system.

Purpose 7: Load Shedding and Frequency Control

- When generation falls short of demand, grid frequency drops.
- To prevent a blackout, load must be temporarily disconnected (Load Shedding).
- Under-Frequency Relays (UFR) in substations detect this drop.
- They automatically trip specific distribution feeders to balance the grid.

Role of Substations in Smart Grids

- Transitioning from passive nodes to active, intelligent hubs.
- Integration of renewable energy sources (solar/wind farms).
- IEC 61850 standard for Substation Automation.
- Bi-directional power flow management.

IEC 61850 standard

- International standard for communication in electrical substations.
- Replaces hardwired connections with ethernet-based digital communications.
- Enables interoperability between equipment from different vendors.
- Features GOOSE (Generic Object Oriented Substation Event) messaging for fast protection.

Grid Stability and FACTS

- Flexible AC Transmission Systems (FACTS).
- Installed in key substations to enhance controllability and increase power transfer capability.
- Examples: STATCOM, SVC, TCSC.
- Provide fast-acting reactive power compensation.

Safety and Grounding

- Substations provide a safe environment for high-voltage operations.
- Extensive earth mat (grounding grid) installed below the substation.
- Ensures step and touch potentials remain within safe limits during a fault.
- Provides a low-resistance path for fault currents to earth.

Substation Security

- Physical Security: Fencing, lighting, cameras, access control.
- Cyber Security: Protecting SCADA and automation networks from hackers.
- Both are critical, as substations are vital national infrastructure.

Summary

- Substations are the brains and the brawn of the grid.
- They gather vital operational data and house communication links.
- They protect the grid from collapse via synchronization and load shedding.
- They are evolving rapidly to meet the demands of the Smart Grid.

Types of Substations (Part 1)

- Course: Substation Engineering (DI04009011)
- Unit 1: Introduction
- Lecture 3

Agenda

- Basis of Classification
- Classification by Service Requirement
- Transformer Substations (Step-up, Step-down)
- Switching Substations
- Converting Substations
- Summary

Basis of Classification

- Substations can be classified in multiple ways:
- 1. According to Service Requirement (Function).
- 2. According to Constructional Features (Design/Location).
- 3. According to Operating Voltage.
- 4. According to Importance in the grid.

Classification by Service Requirement

- This classification focuses on the primary job the substation performs.
- Major Categories:
- - Transformer Substations
- - Switching Substations
- - Converting Substations
- - Power Factor Correction Substations

1. Transformer Substations

- The most common type of substation in the power system.
- Primary function: To transform voltage from one level to another.
- They utilize large power transformers.
- Can be further subdivided based on where they are in the grid.

Subtypes of Transformer Substations

- Step-Up Substation (at Generating Station)
- ↓
- Primary Grid Substation (Extra High Voltage to High Voltage)
- ↓
- Secondary Substation (High Voltage to Medium Voltage)
- ↓
- Distribution Substation (Medium Voltage to Low Voltage)

Step-Up Substations

- Located directly adjacent to power generating plants.
- Generation voltage (11kV - 25kV) is stepped up for transmission.
- Transmission voltages can be 132kV, 220kV, 400kV, or 765kV.
- Essential for reducing I^2R transmission losses.

Primary Grid Substations

- Located at the end of long Extra High Voltage (EHV) transmission lines.
- Steps down EHV (e.g., 400kV) to High Voltage (HV) (e.g., 220kV or 132kV).
- Supplies power to the secondary transmission network.
- Handles bulk power transfer for entire regions.

Secondary Substations

- Located closer to load centers (cities, industrial zones).
- Steps down HV (e.g., 132kV) to primary distribution voltages (33kV or 11kV).
- Lines originating here feed distribution substations.
- Often seen on the outskirts of towns or cities.

Distribution Substations

- Located very close to the end consumers.
- Steps down 33kV or 11kV to utilization voltages (415V 3-phase / 240V 1-phase).
- Feeds direct service lines to homes and small businesses.
- Small footprint, often pole-mounted or in small enclosures.

Comparison of Transformer Substations

Type	Input Voltage	Output Voltage	Location
Step-Up	11-25kV	132-765kV	Generating Station
Primary	400kV+	132-220kV	Regional Hubs
Secondary	132kV	33-11kV	City Outskirts
Distribution	11-33kV	415V/240V	Neighborhoods

2. Switching Substations

- DO NOT contain power transformers for voltage change.
- Input voltage equals Output voltage.
- Used strictly for switching operations in the network.
- Routes power, connects multiple transmission lines, and isolates faults.

3. Converting Substations

- Used to change AC to DC, or DC to AC, or change the frequency.
- Examples: HVDC (High Voltage Direct Current) converter stations.
- Traction Substations for railways (convert 3-phase AC to single-phase AC or DC).
- Requires heavy power electronic equipment (thyristors, IGBTs).

Summary

- Substations are classified primarily by their service requirements.
- Transformer substations change voltage levels and are found throughout the grid.
- Switching substations route power without changing voltage.
- Converting substations alter AC/DC state or frequency.

Types of Substations (Part 2)

- Course: Substation Engineering (DI04009011)
- Unit 1: Introduction
- Lecture 4

Classification by Constructional Features

- This classification focuses on how and where the equipment is installed.
- Main types:
- 1. Indoor Substations
- 2. Outdoor Substations
- 3. Underground Substations
- 4. Pole-Mounted Substations
- 5. Gas Insulated Substations (GIS)

1. Indoor Substations

- Equipment is installed inside a building.
- Generally restricted to lower voltages (up to 11kV or 33kV) due to clearance requirements.
- Used in heavily populated areas where space is limited.
- Used in industrial plants or areas with extreme weather/pollution.

Advantages and Disadvantages of Indoor Substations

Advantages	**Disadvantages**
- Protected from weather and atmospheric pollution. - Smaller land footprint. - Safer for the surrounding public.	- High civil construction cost. - Difficult to expand or upgrade later. - Clearance issues limit the maximum voltage.

2. Outdoor Substations

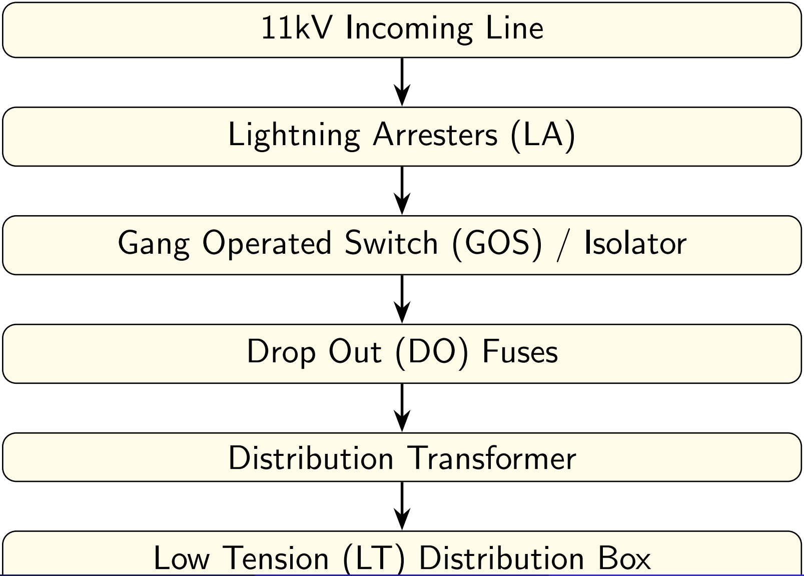
- Equipment is installed in open air.
- The most common type for voltages above 33kV (up to 765kV).
- Uses air as the primary insulation medium between phases and ground.
- Equipment is designed to withstand rain, wind, snow, and pollution.

Advantages and Disadvantages of Outdoor Substations

Advantages	**Disadvantages**
- Lower civil construction costs (no building needed).	- Requires a massive amount of land.
- Easy to expand and add new bays.	- Exposed to lightning, pollution, and severe weather.
- Easy visual inspection of equipment.	- Higher maintenance required for exposed contacts.

3. Pole-Mounted Substations

- A specific type of outdoor substation mounted on an H-pole or 4-pole structure.
- Used for distribution (e.g., 11kV to 415V).
- Transformer capacity is usually limited to 250kVA or 500kVA.
- Extremely cost-effective for local neighborhood distribution.


11kV Incoming Line
Lightning Arresters (LA)
Gang Operated Switch (GOS) / Isolator
Drop Out (DO) Fuses
Distribution Transformer
Low Tension (LT) Distribution Box

4. Underground Substations

- Constructed entirely below ground level.
- Used in extremely congested urban areas (mega-cities) where land cost is prohibitive.
- Major challenges include ventilation, cooling, and water ingress.
- Requires highly specialized, fire-resistant equipment.

5. Gas Insulated Substations (GIS)

- The modern revolution in substation design.
- All live components are enclosed in metal housings filled with SF_6 (Sulfur Hexafluoride) gas.
- SF_6 has extraordinary dielectric (insulating) properties compared to air.
- Allows phases to be placed very close together.

Why Choose GIS?

- Requires only 10% to 25% of the space of a conventional outdoor (AIS) substation.
- Highly reliable; components are completely sealed from pollution, dust, and wildlife.
- Minimal maintenance required over a 40-50 year lifespan.
- Significantly higher initial capital cost.

Air Insulated (AIS) vs. Gas Insulated (GIS)

Feature	AIS (Outdoor)	GIS (Indoor/Outdoor)
Insulating Medium	Atmospheric Air	SF6 Gas
Space Required	Very Large	Very Small (1/10th)
Initial Cost	Low	Very High
Maintenance	High (Regular cleaning)	Very Low (Sealed)
Reliability	Moderate (exposed to weather)	Very High

SF6 Gas Environmental Concerns

- SF6 is an extremely potent Greenhouse Gas (GHG).
- Global warming potential is 23,500 times that of CO2.
- Strict regulations govern its handling, leak detection, and disposal.
- Industry is actively researching SF6 alternatives (e.g., dry air, specialized gas mixtures).

Summary of Construction Types

- Outdoor Substations (AIS) remain the standard for high-voltage due to cost.
- Indoor and Underground Substations are utilized when space is restricted.
- Pole-Mounted units provide cheap, local distribution.
- GIS offers massive space savings and reliability through SF_6 technology.

Essential Features of Substations

- Course: Substation Engineering (DI04009011)
- Unit 1: Introduction
- Lecture 5

What are Essential Features?

- A substation involves huge capital investment.
- Errors in design can lead to massive financial loss or catastrophic blackouts.
- Essential features are the non-negotiable requirements that ensure the substation meets its operational goals.
- They dictate the overall design philosophy.

Core Essential Features

- 1. Location at the Center of Gravity of Load
- 2. Reliability of Supply (Security)
- 3. Ease of Maintenance
- 4. Provision for Future Expansion
- 5. Capital Cost Optimization
- 6. Safety and Clearances

1. Location at Center of Gravity of Load

- A distribution substation should ideally be located at the 'load center'.
- Reduces the length of the distribution network (feeders).
- Minimizes I^2R copper losses in the lines.
- Improves voltage regulation (less voltage drop at the far end).
- Often constrained by land availability in reality.

2. Reliability of Supply (Security)

- The grid must remain stable even if a component fails (N-1 Contingency).
- Substations must have redundant paths for power flow.
- If a transformer fails, another should be able to take the critical load.
- Achieved through complex busbar arrangements (e.g., Double Bus, Ring Main).

Busbar Arrangements and Reliability

Single Busbar: Cheap, but complete outage if the bus fails.

Double Busbar: More expensive, high reliability. Load can be shifted to the spare bus.

Ring Busbar: Excellent reliability, any breaker can be maintained without interrupting power.

3. Ease of Maintenance

- Substation equipment requires regular servicing (oil testing, contact cleaning).
- Layout must allow maintenance without shutting down the entire substation.
- Adequate spacing and bypass switches must be provided.
- Access roads must support heavy cranes for transformer removal.

4. Provision for Future Expansion

- Electrical demand inevitably grows over time.
- The initial design must leave physical space for extra transformers or line bays.
- Busbars should be designed so they can be easily extended.
- Control room panels must have spare slots.

5. Capital Cost Optimization

- Engineering is about balancing technical perfection with financial reality.
- Over-designing (too much redundancy) wastes public or company money.
- Under-designing leads to poor reliability and safety hazards.
- Selection of AIS vs. GIS, or Single vs. Double bus, depends heavily on cost-benefit analysis.

6. Safety and Clearances

- High voltage electricity can arc through the air.
- Statutory electrical clearances must be strictly maintained.
- Phase-to-Phase clearance: Distance between two live conductors.
- Phase-to-Earth clearance: Distance between live conductor and the ground/structures.

Statutory Clearances (Typical Values)

System Voltage	Phase to Earth (mm)	Phase to Phase (mm)
11 kV	178	229
33 kV	320	320
132 kV	1300	1300
220 kV	2100	2100
400 kV	3500	4000

Other Safety Features

- Substation Earthing System (Earth Mat) to control step and touch potentials.
- Lightning masts and shield wires for overvoltage protection.
- Gravel (crushed rock) spread across the yard to increase foot resistance and suppress weeds/fire.
- Fencing and interlocks to prevent unauthorized access.

Environmental and Aesthetic Considerations

- Noise mitigation: Transformers hum (magnetostriction), requiring sound barriers near residential areas.
- Oil spill containment: Pits under transformers to catch leaking oil, preventing ground contamination.
- Aesthetics: Using low-profile structures or enclosing the substation to blend with urban environments.

Summary

- A successful substation design balances cost with high reliability.
- It must be safely maintainable and expandable.
- Clearances and grounding ensure personnel safety.
- Environmental impact must be minimized.

Typical Layout of Substations

- Course: Substation Engineering
- Lecture 6: Typical Layout of Substations
- Unit 2: Substation Layout and Equipment

Agenda

- Introduction to Substation Layout
- Single Line Diagram (SLD)
- Major Switchyard Components
- Busbar Arrangements
- Electrical Clearances
- Control Room Layout

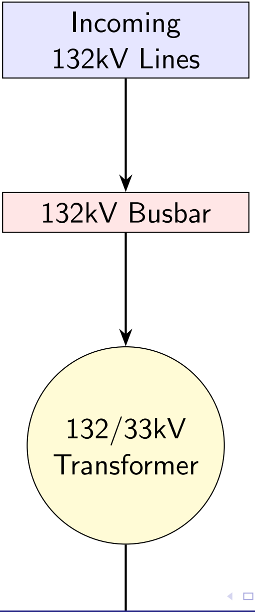
Introduction to Substation Layout

- A substation layout must ensure safe operation and maintenance.
- It provides a physical translation of the electrical circuit.
- Key goals include minimizing land use while maximizing reliability.
- Layouts must account for future expansion (additional bays).
- Separation of high voltage and low voltage zones is mandatory.

Single Line Diagram (SLD)

- The SLD represents the electrical connections of the substation in a simplified manner.
- Uses standardized symbols for components (CB, CT, PT, Isolator).
- Shows the sequence of equipment in a bay.
- Serves as the blueprint for creating the physical 3D layout.
- Essential for operational switching and interlocking logic.

SLD of a Typical 132/33kV Substation



Major Switchyard Components

- Lightning Arresters (LA): Placed at the line entry to protect against surges.
- Current & Potential Transformers (CT & PT): Used for metering and protection.
- Isolators (Disconnectors): Provide visible isolation for maintenance.
- Circuit Breakers (CB): Interrupt fault currents.
- Power Transformers: The heart of the substation for voltage stepping.

Layout Planning Criteria

- Topography and soil conditions of the site.
- Incoming line corridors and approach angles.
- Environmental conditions (pollution, altitude, seismic zone).
- Accessibility for heavy equipment transport (e.g., transformers).
- Statutory regulations and environmental clearances.

Typical Busbar Arrangements

- Single Bus Scheme: Simple, low cost, but low reliability (bus fault causes total outage).
- Main and Transfer Bus: Allows maintenance of bay circuit breaker without interrupting the feeder.
- Double Bus Double Breaker: Highly reliable, but very expensive; used in EHV stations.
- One and a Half Breaker Scheme: Best balance of reliability and cost for 400kV and above.
- Ring Main: Economical with high reliability, but limited expandability.

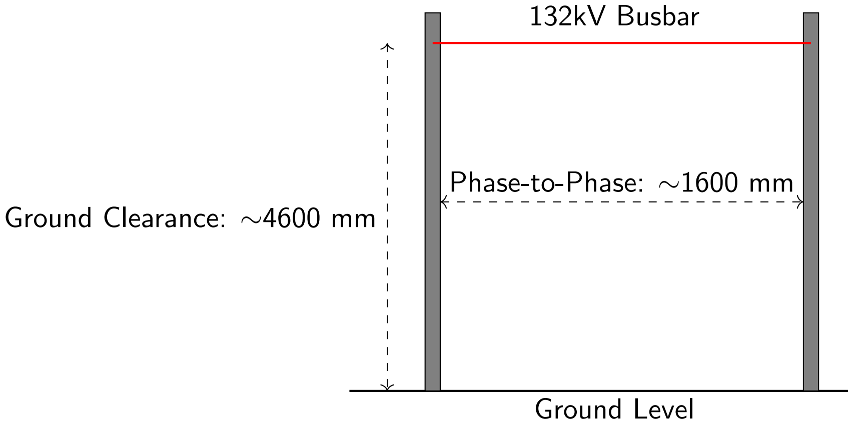
Comparison of Busbar Schemes

Scheme	Cost	Reliability	Footprint
Single Bus	Lowest Cost	Poor Reliability	Smallest Footprint
Main & Transfer	Medium Cost	Good Reliability	Medium Footprint
Double Bus	High Cost	Very Good Reliability	Large Footprint
One and a Half CB	Highest Cost	Excellent Reliability	Very Large Footprint

Electrical Clearances

- Clearances are minimum distances required to prevent electrical flashover in air.
- Phase-to-Earth Clearance: Distance from live part to grounded structure.
- Phase-to-Phase Clearance: Distance between two adjacent live phases.
- Sectional Clearance: Safe distance for a person to work on de-energized equipment near live parts.
- Ground Clearance: Minimum height of live parts above ground level.

Phase and Ground Clearances



Control Room Layout

- Usually located strategically to provide a clear view of the switchyard.
- Houses Control and Relay (C&R) panels, SCADA RTUs.
- Contains the AC and DC distribution boards (Battery banks).
- Requires cable trenches originating from the switchyard to enter the building.
- Air-conditioned environment to protect sensitive electronic relays.

Key Takeaways

- A Single Line Diagram is the foundational blueprint of any substation.
- Busbar arrangement choice dictates the cost, reliability, and physical footprint.
- Electrical clearances are mandatory for safety and preventing flashovers.
- Physical layout must account for heavy equipment access and maintenance space.

Next Lecture Preview

- Introduction to Power Transformers in Substations
- Core and Winding Construction
- Vector Groups and Tap Changers

Transformers (Part 1 of 2)

- Course: Substation Engineering
- Lecture 7: Transformers (Part 1 of 2)
- Unit 3: Substation Equipment

Agenda

- Introduction to Power Transformers
- Core and Winding Construction
- Transformer Vector Groups
- Tap Changing Mechanisms (OLTC)
- Cooling Methods
- Transformer Oil and Conservator

Introduction to Power Transformers

- Primary function: Step-up or step-down voltage levels.
- Operates on the principle of Faraday's Law of Electromagnetic Induction.
- Allows power transmission over long distances at high voltages (low current, low losses).
- Rated in MVA (Megavolt-Amperes) rather than MW.
- Highly efficient machines (often ¿99% efficiency).

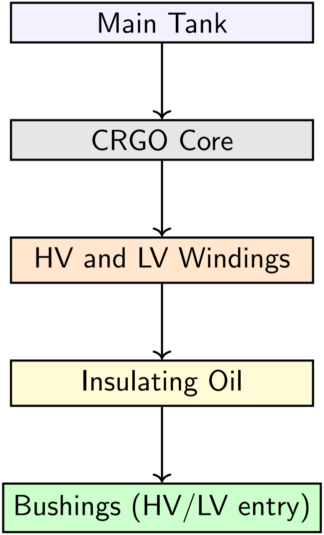
Role in Substations

- Transmission Substations: Step up voltage for grid transmission.
- Distribution Substations: Step down voltage for local distribution networks.
- Interconnecting Substations: Tie together grids operating at different voltage levels (e.g., 400kV to 220kV).
- Often use Auto-transformers for interconnecting closely matched voltage levels.

Core and Winding Construction

- Core: Made of CRGO (Cold Rolled Grain Oriented) silicon steel to minimize eddy currents and hysteresis losses.
- Core Type vs. Shell Type construction.
- Windings: Usually electrolytic copper, insulated with kraft paper.
- LV winding is placed closer to the core, HV winding placed outside to reduce insulation requirement to the core.
- Spacers and barriers ensure cooling ducts for oil flow.

Internal Structure of a Power Transformer



Transformer Vector Groups

- Indicates the phase angle difference between HV and LV windings.
- Standardized using a clock-face notation (e.g., Dyn11).
- D = Delta (HV), y = Star (LV), n = neutral brought out.
- 11 indicates LV leads HV by 30 degrees (clock position 11).
- Crucial for parallel operation; transformers must have compatible vector groups.

Tap Changing Mechanisms

- Used to regulate the output voltage by varying the number of turns in a winding.
- Usually provided on the HV winding (lower current, easier to switch).
- Off-Circuit Tap Changer (OCTC): Can only be operated when transformer is de-energized.
- On-Load Tap Changer (OLTC): Allows tap changing without interrupting the load.
- OLTC requires complex diverter switches and transition resistors.

Cooling Methods

- Transformers generate heat due to copper and iron losses.
- ONAN (Oil Natural Air Natural): Natural convection of oil and air.
- ONAF (Oil Natural Air Forced): Fans blow air across radiators.
- OFAF (Oil Forced Air Forced): Pumps force oil flow, fans force air.
- ODAF (Oil Directed Air Forced): Oil pumped directly into winding ducts.

Comparison of Cooling Classes

Class	Characteristics
ONAN	Base rating, no moving parts, low maintenance
ONAF	$\sim$125% of base rating, requires fans, medium maintenance
OFAF	$\sim$133%+ of base rating, requires pumps and fans, high maintenance
ODWF	Used in hydro plants, very high cooling efficiency

Transformer Oil Properties

- Mineral oil serves dual purposes: Insulation and Cooling.
- High Dielectric Strength (BDV) to prevent internal arcing.
- Low Viscosity to allow free convection and heat transfer.
- High Flash Point to prevent fire hazards.
- Must be free of moisture; even ppm levels of water drastically reduce BDV.

Conservator and Breather System

- Conservator Tank: Allows for expansion and contraction of oil with temperature changes.
- Prevents the main tank from rupturing due to pressure.
- Silica Gel Breather: Attached to the conservator. As oil cools and contracts, air is drawn in.
- Silica gel absorbs moisture from the incoming air.
- Color change (Blue to Pink) indicates silica gel is saturated.

Key Takeaways

- Power transformers step voltages up/down via magnetic induction with high efficiency.
- Vector groups determine phase shifts and are critical for parallel operation.
- OLTC allows voltage regulation under load.
- Oil serves for both insulation and cooling; the conservator manages volume changes.

Next Lecture Preview

- Transformer Protection Systems
- Buchholz Relay operation
- Differential Protection
- Testing and Maintenance Practices

Transformers (Part 2 of 2)

- Course: Substation Engineering
- Lecture 8: Transformers (Part 2 of 2)
- Unit 3: Substation Equipment

Agenda

- Importance of Transformer Protection
- Buchholz Relay Operation
- Pressure Relief Valve (PRV)
- Differential Protection
- Temperature Indicators (WTI & OTI)
- Testing and Dissolved Gas Analysis (DGA)

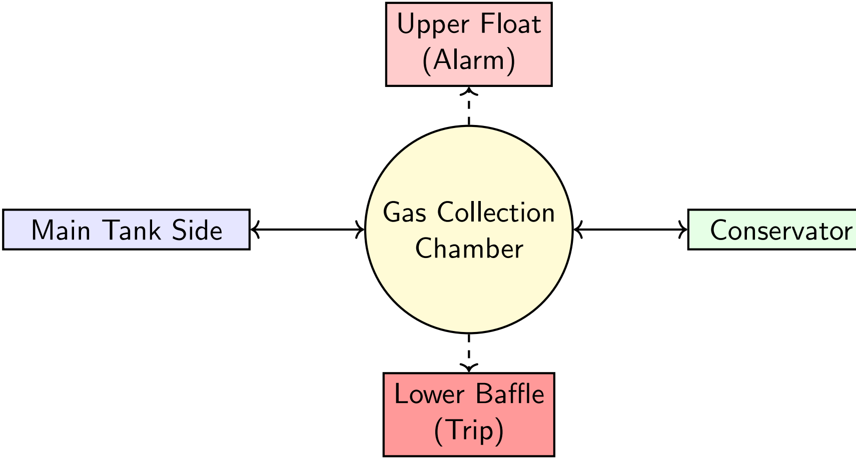
Importance of Transformer Protection

- Transformers are the most expensive assets in a substation.
- Internal faults (e.g., inter-turn short circuits) can lead to catastrophic explosions.
- Protection must be fast to limit damage and secure the grid.
- Involves both Mechanical protections (built onto the transformer) and Electrical protections (relays in control room).

Buchholz Relay Operation

- Gas and oil actuated mechanical relay.
- Installed in the pipe between the main tank and the conservator.
- Minor faults: Generate slow gas bubbles. Gas collects at the top, displacing oil, causing upper float to drop and trigger an ALARM.
- Major faults: Severe arcing causes massive oil surge. Surge pushes the lower flap, triggering a TRIP to the circuit breakers.

Buchholz Relay Mechanism



Pressure Relief Valve (PRV)

- The last line of mechanical defense against explosions.
- Mounted on top of the main tank.
- Spring-loaded diaphragm that pops open when internal pressure exceeds a safe limit.
- Instantly vents oil and gas to the atmosphere, preventing tank rupture.
- Fitted with micro-switches to send a TRIP signal.

Differential Protection Scheme

- Primary electrical protection for the transformer.
- Principle: Current entering the transformer must equal current leaving (adjusted for turns ratio).
- Current Transformers (CTs) on HV and LV sides continuously compare currents.
- If a difference (spill current) is detected, it indicates an internal fault.
- Instantly trips both HV and LV circuit breakers.

Temperature Indicators (WTI & OTI)

- Oil Temperature Indicator (OTI): Measures top oil temperature using a bulb thermometer.
- Winding Temperature Indicator (WTI): Simulates winding hot-spot temperature using a thermal image technique (combines oil temp + load current from a CT).
- Both provide ALARM and TRIP contacts.
- Also used to automatically switch on cooling fans and pumps (ONAF/OFAF).

Transformer Testing (Routine and Type)

- Type Tests: Done on one prototype to verify design (e.g., Lightning Impulse test, Temperature rise test).
- Routine Tests: Done on every unit manufactured.
- Winding Resistance Measurement.
- Insulation Resistance (Megger) and PI.
- Turns Ratio and Vector Group verification.

Factory Acceptance Tests (FAT)

Test	Purpose
Winding Resistance	Detect loose connections or broken strands
Turns Ratio	Verify core and winding turns, OLTC function
Insulation Resistance	Check health of paper and oil insulation
Impulse Test	Verify capability to withstand lightning strikes

Dissolved Gas Analysis (DGA)

- The most powerful predictive maintenance tool.
- Similar to a blood test for a transformer.
- Faults (arcing, overheating) break down oil and paper, creating specific gases.
- Gases dissolve in the oil. Oil samples are analyzed in a lab via Gas Chromatography.
- Key gases: Hydrogen (Arcing), Ethylene (Overheating oil), Carbon Monoxide (Overheating paper).

Maintenance and Oil Filtration

- Periodic checks of silica gel breather.
- Checking for oil leaks at gaskets and valves.
- Cleaning of bushings to prevent external flashovers.
- Oil filtration/centrifuging: Used to remove moisture, dirt, and dissolved gases from oil.
- Prolongs the life of both the oil and the solid insulation.

Key Takeaways

- Buchholz relay detects internal gas generation and oil surges.
- Differential protection provides high-speed electrical fault clearance.
- DGA is a vital predictive tool for assessing internal health.
- Regular maintenance ensures the transformer reaches its design lifespan.

Next Lecture Preview

- Introduction to Isolators (Disconnectors)
- Isolators vs Circuit Breakers
- Construction and Types of Isolators

Isolators (Part 1 of 2)

- Course: Substation Engineering
- Lecture 9: Isolators (Part 1 of 2)
- Unit 4: Switchgear Equipment

Agenda

- What is an Isolator?
- Isolator vs. Circuit Breaker
- Need for Isolation in Substations
- Types of Isolators (Construction based)
- Horizontal Break Isolators
- Pantograph Isolators
- Earth Switches

What is an Isolator?

- An isolator is a mechanical switching device.
- Primary function: To provide a VISIBLE break in an electrical circuit.
- Used to safely isolate a section of a substation for maintenance.
- Operates under 'No Load' conditions only.
- It is not designed to break fault currents or even normal load currents.

Isolator vs. Circuit Breaker

- Circuit Breaker (CB): Designed to make and break circuits under normal load AND fault conditions (short circuits). Contains an arc quenching medium.
- Isolator: Designed to open or close only when there is negligible current. Has no arc quenching medium.
- Sequence of operation: CB opens first, then Isolator opens. Isolator closes first, then CB closes.
- Operating an isolator on load will result in a massive, uncontrolled arc.

Difference Summary

Feature	Circuit Breaker (CB)	Isolator
Breaking Capacity	High (Fault currents)	Zero (No load only)
Arc Quenching	Yes (SF6, Vacuum, Oil)	No (Air)
Speed of operation	Milliseconds	Seconds (Motor/Manual)
Purpose	Protection and switching	Safety and isolation

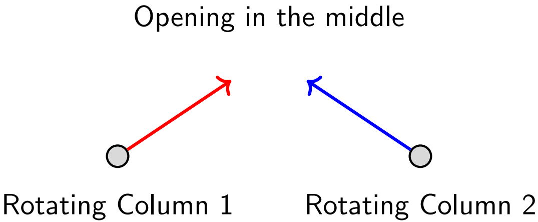
Types of Isolators (By Construction)

- Isolators are classified by how their moving contacts open.
- Horizontal Double Break (HDB)
- Horizontal Center Break (HCB)
- Vertical Break
- Pantograph / Semi-Pantograph
- Selection depends on voltage level, space availability, and busbar arrangement.

Horizontal Double Break (HDB) Isolator

- Features three insulator columns per phase.
- The middle insulator column rotates.
- A single contact blade is mounted on the rotating middle column.
- When it rotates 90 degrees, it breaks contact at both ends simultaneously.
- Very common in older layouts and up to 220kV.

Horizontal Center Break (HCB) Isolator



Vertical Break Isolator

- The contact arm swings upwards in a vertical plane.
- Used when horizontal phase-to-phase clearance is tight.
- Requires less ground footprint.
- Common in EHV (Extra High Voltage) yards where phase spacing is critical.
- The blade must be balanced with counterweights or springs.

Pantograph Type Isolator

- Operates vertically like a scissor lift.
- Connects a lower busbar to an upper busbar.
- Extremely space-efficient; minimizes substation footprint.
- Highly complex mechanical linkages.
- Used primarily in 400kV and 800kV substations.

Isolator Operating Mechanisms

- Manual Operation: Done via a mechanical handle and operating pipe. Common for lower voltages (up to 33kV) or as a backup.
- Motor Operated Mechanism (MOM): Uses an electric motor (usually DC) to drive the gear assembly.
- MOM box is mounted at the base of the isolator structure.
- Allows remote operation from the control room.

Earth Switches (Earthing Blades)

- Often integrated with the main isolator structure.
- Function: To ground the isolated section of the line.
- Discharges trapped charges and capacitive voltages to ground safely.
- Strict mechanical interlocking ensures the Earth Switch can ONLY close when the main Isolator is OPEN.
- Closing an earth switch on a live line causes a dead short circuit.

Key Takeaways

- Isolators provide a visible safety break for maintenance.
- They MUST NOT be operated on load.
- Different designs (Center break, Vertical, Pantograph) cater to different layout constraints.
- Earth switches discharge trapped capacitive currents.

Next Lecture Preview

- Ratings and Specifications of Isolators
- Interlocking Schemes (Breaker - Isolator - Earth Switch)
- Arcing Horns
- Testing and Maintenance of Isolators

Isolators (Part 2 of 2)

- Course: Substation Engineering
- Lecture 10: Isolators (Part 2 of 2)
- Unit 4: Switchgear Equipment

Agenda

- Electrical Ratings of Isolators
- Arcing Horns
- Interlocking Logic (CB, Isolator, Earth Switch)
- Installation and Alignment
- Testing Procedures (CRM, IR)
- Maintenance and Troubleshooting

Electrical Ratings of Isolators

- Rated Voltage (kV): Maximum system voltage it can withstand (e.g., 145kV for a 132kV system).
- Rated Normal Current (A): Continuous current the contacts can carry without overheating (e.g., 1250A, 2000A).
- Rated Short-Time Withstand Current (kA): Ability to withstand mechanical and thermal stress of a short circuit for 1 to 3 seconds.
- Lightning Impulse Withstand Voltage (kVp): Ability to withstand transient overvoltages.

Short Time Withstand Current

- During a short circuit, immense electro-dynamic forces try to push the isolator contacts apart.
- Contacts are designed with 'reverse loop' designs to use electromagnetic forces to grip tighter during a fault.
- Rated in kA for 1 or 3 seconds (e.g., 40kA for 3s).
- Failing this rating leads to contact separation, severe arcing, and destruction of the switch.

Arcing Horns

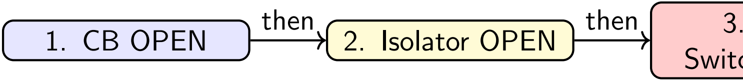
- Small metallic extensions attached to the main contacts of the isolator.
- Purpose: When the isolator opens, a small charging or magnetizing current may cause a minor arc.
- The arc is forced to strike on the arcing horns rather than the main silver-plated contacts.
- Protects the main contacts from pitting and erosion.
- Arcing horns make contact first while closing, and break contact last while opening.

Need for Interlocking

- Human error in substation switching can be fatal.
- Opening an isolator on load causes a massive explosion.
- Closing an earth switch on a live line causes a dead short circuit.
- Interlocking systems FORCE the operator to follow the correct switching sequence.
- Can be Mechanical (castell keys) or Electrical (relay logic).

Typical Interlocking Logic

To OPEN / Isolate:



Electrical vs. Mechanical Interlocking

- Electrical: Uses auxiliary contacts of the CB to cut power to the Isolator motor. Standard for modern remote operations.
- Mechanical: Uses captive keys. To operate the isolator manually, a key must be retrieved from the CB panel (only releasable when CB is open).
- Mechanical interlocking is fail-safe, even if DC power is lost.

Installation and Alignment

- Isolators require precise civil foundations to ensure they are perfectly level.
- Misalignment causes the male/female contacts to clash or fail to fully engage.
- Operating pipes must be plumb; torque must be evenly distributed.
- Frequent cause of failure is poor initial alignment causing mechanical binding.

Testing of Isolators

Test	Check for
Contact Resistance (CRM)	High resistance causing overheating
Insulation Resistance (IR)	Degraded porcelain insulators
Timing and Travel	Smooth operation, alignment issues
High Voltage (Dielectric)	Ability to withstand rated voltage

Contact Resistance Measurement (CRM)

- Also known as the 'Ductor Test'.
- Injects a high DC current (usually 100A) across the closed contacts.
- Measures the millivolt drop to calculate resistance in micro-ohms.
- High micro-ohm readings indicate loose contacts, loss of spring pressure, or oxidation.
- Prevents thermal runaway and melting of contacts.

Routine Maintenance

- Cleaning of male and female contacts with solvent.
- Application of conductive grease to prevent oxidation and ensure smooth sliding.
- Inspection of springs for loss of tension.
- Checking tightness of terminal connectors using thermo-vision cameras.
- Lubrication of bearings and gears in the MOM box.

Key Takeaways

- Isolators must withstand short-circuit forces without opening.
- Strict interlocking logic (CB -¿ Isolator -¿ Earth Switch) prevents fatal errors.
- Arcing horns protect main contacts from pitting.
- CRM testing is vital to prevent contact overheating.

Next Lecture Preview

- Introduction to Circuit Breakers
- Arc Interruption Principles
- SF6 and Vacuum Circuit Breakers

Busbars in Substations

- Substation Engineering (DI04009011)
- Lecture 11: Busbars (Part 1 of 2)
- Functions, Materials, and Basic Configurations

Agenda

- Introduction to Busbars
- Functions of a Busbar System
- Busbar Materials (Copper vs. Aluminum)
- Types of Busbar Profiles
- Basic Busbar Configurations
- Single Busbar System
- Double Busbar System

What is a Busbar?

- A busbar is a metallic strip or bar that conducts electricity within a switchboard, distribution board, substation, or other electrical apparatus.
- It serves as a common connection point for multiple incoming and outgoing circuits.
- Derived from the Latin word 'omnibus', meaning 'for all' (a common collector).
- They carry large currents and are uninsulated in outdoor switchyards, supported by insulators.

Primary Functions

- Collects electrical power from incoming feeders.
- Distributes electrical power to outgoing feeders.
- Provides flexibility in routing power during maintenance or faults.
- Acts as a rigid or flexible structural element capable of withstanding electromagnetic forces during short circuits.

Busbar Materials

- Copper (Cu): Traditionally used due to high electrical conductivity and superior mechanical strength.
- Aluminum (Al): Currently the most common material for outdoor substations due to lower cost and lighter weight.
- Silver (Ag): Used for contact plating to reduce contact resistance, but not for the main busbar.
- Galvanized Steel: Sometimes used for very high voltage, low current applications or as a reinforcing core.

Copper vs. Aluminum Properties

Property	Copper	Aluminum
Conductivity	100% (IACS reference)	$\sim$ 61% (IACS)
Density (g/cm^3)	8.96 (Heavy)	2.70 (Light)
Tensile Strength	High	Moderate
Cost	High	Low
Corrosion Resistance	Very Good	Good (forms protective oxide layer)

Types of Busbar Profiles

- Flat Strips: Common in indoor panels; easy to connect and bend.
- Tubular (Hollow Cylinder): Standard for high voltage outdoor substations; excellent rigidity and reduced corona loss.
- Solid Round: Used for lower currents; heavy and prone to skin effect at larger diameters.
- Stranded Flexible Cables: Used in 'strain' bus systems, suspended between gantry towers like transmission lines.

Skin Effect and Corona in Busbars

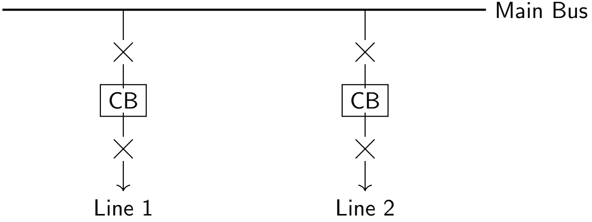
- Skin Effect: Alternating current tends to flow near the surface of the conductor. A hollow tube uses material efficiently.
- Corona Discharge: High electric field at sharp edges ionizes the surrounding air.
- Round and tubular profiles eliminate sharp edges, mitigating corona loss and audible noise at EHV (Extra High Voltage) levels.
- Spacing: Adequate clearance between phases is critical to prevent flashovers.

Busbar Arrangement Criteria

- Selecting a busbar arrangement depends on several factors:
- System Voltage and Capacity.
- Reliability and Continuity of Supply (Can a fault shut down the whole station?).
- Flexibility for Maintenance (Can breakers be isolated without losing load?).
- Initial Cost and Available Space.
- Simplicity of Protection Schemes.

Single Busbar System

- The simplest and least expensive configuration.
- All incoming lines and outgoing loads are connected to a single, continuous busbar.
- Each line has one circuit breaker and two isolators.
- Requires minimal space and is easy to operate.

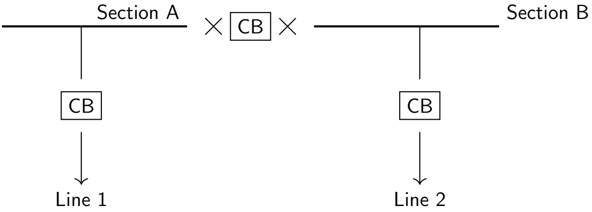


Single Busbar System: Disadvantages

- Low Reliability: A fault on the busbar causes a complete station outage.
- Difficult Maintenance: To clean or maintain the busbar, the entire substation must be de-energized.
- Breaker Maintenance: If a circuit breaker fails or needs maintenance, its associated line must be shut down.
- Usage: Typically limited to small, low-voltage distribution substations.

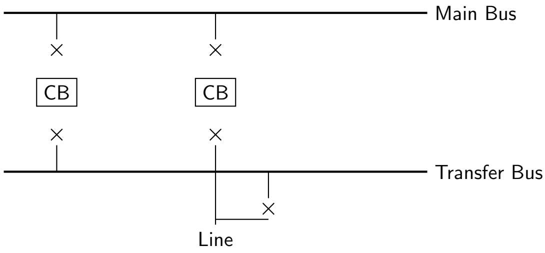
Single Busbar System with Sectionalization

- The main bus is divided into sections by a bus-coupler breaker and isolators.
- If a fault occurs on one section, only half the substation is lost.
- Allows maintenance on one bus section while the other remains active.
- Improves reliability over a plain single bus with minimal extra cost.



Main and Transfer Bus System

- Consists of a 'Main' busbar and an auxiliary 'Transfer' busbar.
- Includes a special 'Bus Coupler' breaker connecting the two buses.
- Allows any line breaker to be taken out of service for maintenance while keeping the line active.
- The line is temporarily routed through the Transfer Bus and protected by the Bus Coupler breaker.



Operation of Main and Transfer Bus

- To maintain Feeder 1's breaker:
- 1. Close the Bus Coupler breaker (energizes the Transfer Bus).
- 2. Close Feeder 1's isolator to the Transfer Bus.
- 3. Open Feeder 1's main circuit breaker.
- Feeder 1 is now supplied via the Transfer Bus and protected by the Bus Coupler breaker.
- Drawback: A fault on the Main Bus still causes a total outage.

Summary of Basic Configurations

- Busbars act as the main electrical junction in a substation.
- Aluminum is the preferred material for outdoor high-voltage busbars.
- Tubular shapes are favored to mitigate corona and skin effect.
- Single Bus: Cheap but unreliable.
- Sectionalized Bus: Better reliability for minimal cost.
- Main & Transfer Bus: Allows breaker maintenance without losing the load.

Advanced Busbar Configurations

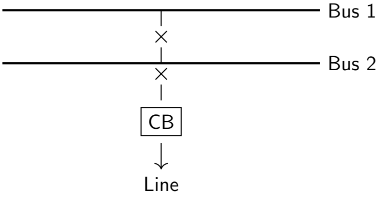
- Substation Engineering (DI04009011)
- Lecture 12: Busbars (Part 2 of 2)
- High-Reliability Systems for Transmission Substations

Agenda

- Recap of Reliability Challenges
- Double Busbar Single Breaker System
- Double Busbar Double Breaker System
- One-and-a-Half Breaker System
- Ring Bus (Mesh) System
- Comparison and Selection Guidelines

Double Busbar Single Breaker System

- Consists of two identical main busbars (Bus 1 and Bus 2).
- Each incoming/outgoing circuit is equipped with one circuit breaker but can be connected to EITHER Bus 1 or Bus 2 via isolators.
- A Bus Coupler breaker connects Bus 1 and Bus 2.
- Provides excellent flexibility: circuits can be divided between the two buses.

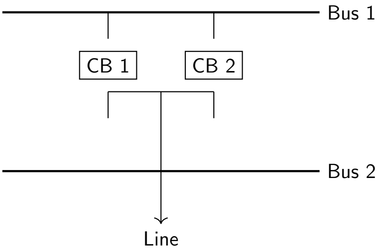


Double Bus Single Breaker: Operation

- Bus Maintenance: To maintain Bus 1, all circuits are transferred to Bus 2 without interrupting supply.
- Fault Isolation: A fault on one bus does not cause a total station outage.
- Limitation: Breaker maintenance still requires the connected line to be taken out of service, UNLESS a transfer bus is also added (Double Main & Transfer).
- Complex interlocking is required to prevent selecting both buses simultaneously under load without the bus coupler closed.

Double Bus Double Breaker System

- Two main buses, and TWO circuit breakers per circuit.
- Highest possible reliability: each circuit is permanently connected to both Bus 1 and Bus 2.
- Any bus can be cleared for maintenance at any time.
- Any circuit breaker can be maintained without taking the line out of service.

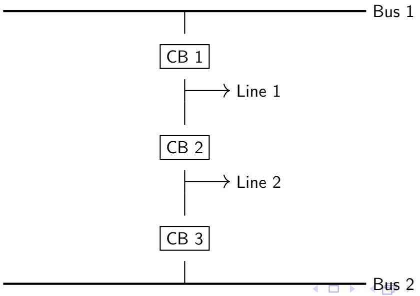


Double Bus Double Breaker: Pros & Cons

- Advantages:
- - Unmatched reliability and flexibility.
- - No interruption for bus or breaker faults/maintenance.
- - Simple protection relaying schemes.
- Disadvantages:
- - Extremely expensive (requires twice the number of circuit breakers).
- - Requires a massive amount of physical space in the switchyard.

One-and-a-Half Breaker System

- The industry standard for Extra High Voltage (EHV - 400kV and above).
- Two main buses. Three circuit breakers are used to protect two circuits.
- Therefore, there are 1.5 breakers per circuit (3 breakers / 2 circuits).
- The three breakers are connected in series between Bus 1 and Bus 2, forming a 'diameter'.



Operation of One-and-a-Half Breaker

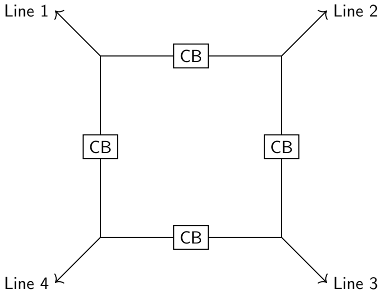
- Normal Operation: All three breakers are closed. Both buses are energized.
- Breaker Maintenance: Any single breaker can be opened for maintenance without interrupting either circuit.
- Bus Fault: If Bus 1 faults, the breakers connected to it trip. Power continues to flow to both circuits via Bus 2 and the middle 'tie' breaker.

Why 1.5 Breaker is Preferred

- Cost-effective high reliability: Saves one breaker per two circuits compared to Double Breaker.
- Highly resilient: A fault on a bus AND a simultaneous breaker failure still might not drop the load.
- Easy addition of new circuits: Just add another 'diameter'.
- Drawback: Complex protection relaying, especially for the middle 'tie' breaker which must protect either Line 1 or Line 2 depending on the fault location.

Ring Bus (Mesh) System

- Breakers are arranged in a closed ring or loop.
- Circuits tap off between the breakers.
- Number of breakers equals the number of circuits (1 breaker per circuit).
- Power can flow in both directions around the ring.



Ring Bus: Advantages and Limitations

- Advantages:
- - Low cost (one breaker per circuit).
- - Any breaker can be maintained without losing a circuit.
- - High reliability against bus faults (there is no 'main bus', just the interconnections).
- Limitations:
- - If one breaker is out for maintenance, the ring is 'open'. A subsequent fault splits the station in two.
- - Difficult to expand beyond 6 circuits without compromising reliability.

Comparison of Busbar Schemes

Scheme	Breakers/Circuit	Reliability	Cost	Maintenance Flexibility
Single Bus	1	Low	Lowest	Poor
Main & Transfer	$1 + 1$ (Coupler)	Moderate	Low	Good (Breaker only)
Ring Bus	1	High	Moderate	Good
1.5 Breaker	1.5	Very High	High	Excellent
Double Breaker	2	Highest	Highest	Excellent

Selection Guidelines by Voltage

- 11kV / 33kV: Single Busbar or Single Busbar with Sectionalization. Cost is the primary driver.
- 66kV / 132kV: Main and Transfer Bus, or Double Bus Single Breaker. Balance of cost and maintenance needs.
- 220kV / 400kV / 765kV: One-and-a-Half Breaker or Ring Bus. Reliability is paramount to prevent grid collapse.

Summary

- Advanced busbar systems use multiple breakers and buses to provide redundancy.
- Double Bus Double Breaker is the most reliable but most expensive.
- One-and-a-Half Breaker is the preferred standard for extra-high voltage transmission.
- Ring Bus offers great reliability for a small number of circuits at lower cost.
- Selection depends entirely on the criticality of the load and the voltage level.

Auto-Reclosers in Power Systems

- Substation Engineering (DI04009011)
- Lecture 13: Auto-Reclosers (Part 1 of 2)
- Principles and Fault Characteristics

Agenda

- Nature of Power System Faults
- Transient vs. Permanent Faults
- What is an Auto-Recloser?
- Why use Auto-Reclosers?
- The Operating Sequence
- Key Terminology
- Dead Time and Reclaim Time

The Nature of Faults on Overhead Lines

- Overhead lines are exposed to the environment (weather, trees, animals).
- Studies show that 80% to 90% of faults on overhead networks are TRANSIENT.
- Transient faults disappear quickly if the line is temporarily de-energized.
- Only 10% to 20% of faults are PERMANENT, requiring physical repair.

Examples of Transient Faults

- Lightning strikes causing a temporary arc across an insulator.
- A bird or squirrel bridging the gap between a phase and ground, which is then vaporized or falls away.
- Wind blowing branches into a line, which then swing clear.
- Ice loading causing lines to gallop and briefly touch.

Examples of Permanent Faults

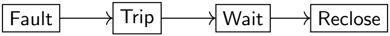
- A broken conductor falling to the ground (downed line).
- A tree falling entirely across the lines and remaining there.
- A shattered insulator.
- A vehicle crashing into and breaking a utility pole.

The Problem with Manual Restoration

- Historically, if a line tripped, it locked out.
- A crew had to be dispatched to patrol the line, which could take hours.
- If they found it was just a transient fault (like a lightning strike), they would just close the breaker.
- Result: Hours of power outage for customers due to a fault that lasted milliseconds.

What is an Auto-Recloser?

- A self-contained device with the necessary intelligence to sense overcurrents, time and interrupt fault currents, and automatically re-energize the line.
- If a fault is detected, it trips (opens).
- It waits a brief moment to allow the transient fault arc to clear (de-ionize).
- It then automatically re-closes.
- If the fault is gone, power is restored instantly. If not, it tries again or locks out.



Benefits of Auto-Reclosing

- Drastically reduces outage duration for customers (SAIDI improvement).
- Maintains system stability on transmission networks by quickly restoring parallel paths.
- Reduces operational costs by minimizing unnecessary line patrols.
- Allows for unmanned operation of remote substations.

The Reclosing Sequence

- A typical recloser is programmed for multiple 'shots' (attempts) before it locks out.
- Example sequence: Trip → 1st Reclose → Trip → 2nd Reclose → Trip → Lockout.
- Fast Trips: The first trip is usually very fast to clear temporary faults quickly before damage occurs.
- Delayed Trips: Subsequent trips are delayed to allow downstream fuses to blow if the fault is permanent and localized.

Key Terminology: Dead Time

- Dead Time (or Reclosing Time): The duration between the clearing of the fault (breaker open) and the reclosing of the breaker contacts.
- Purpose: Must be long enough to allow the arc path at the fault location to de-ionize.
- If Dead Time is too short: The arc will re-strike immediately upon reclosing.
- If Dead Time is too long: Motors stall, and system stability is compromised.

Key Terminology: Reclaim Time

- Reclaim Time (or Reset Time): The time following a successful reclose before the recloser resets its internal counter back to zero.
- Purpose: To distinguish between a single permanent fault and a series of independent transient faults.
- If another fault occurs BEFORE the reclaim time expires, the recloser considers it part of the same sequence.
- If another fault occurs AFTER the reclaim time expires, it treats it as a brand new fault.

Key Terminology: Lockout

- Lockout: The final state of a recloser after it has exhausted all programmed reclosing attempts.
- The breaker remains permanently open.
- Signifies that the fault is highly likely to be permanent.
- Requires human intervention (local or remote SCADA) to reset and close the breaker.

Single-Phase vs. Three-Phase Reclosing

Feature	Single-Phase Reclosing	Three-Phase Reclosing
Fault Type	Used for Single Line-to-Ground faults.	Used for all faults (multi-phase).
Breaker Mechanism	Each phase operates independently.	All three phases trip and close together.
System Stability	Better (2 phases still transmit power).	Worse (all power flow stops).
Complexity	High (complex relays and mechanisms).	Lower.
Application	EHV Transmission Lines.	Distribution and Sub-transmission.

Summary

- 80-90% of overhead line faults are transient and clear themselves if briefly de-energized.
- Auto-reclosers automatically trip and reclose to restore power after transient faults.
- Dead Time is the wait period to allow the arc to clear.
- Reclaim Time is the wait period to reset the sequence counter.
- Lockout occurs when all attempts fail, indicating a permanent fault.

Auto-Recloser Coordination

- Substation Engineering (DI04009011)
- Lecture 14: Auto-Reclosers (Part 2 of 2)
- Coordination Strategies and Network Application

Agenda

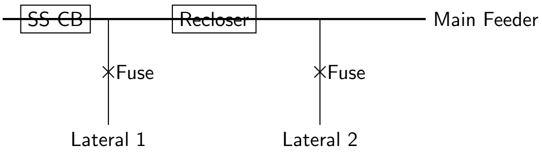
- What is Protection Coordination?
- Distribution Network Layout
- Time-Current Curves (TCC)
- Recloser-Fuse Coordination
- Strategy 1: Fuse Saving Scheme
- Strategy 2: Fuse Blowing Scheme
- Comparison of Schemes

What is Protection Coordination?

- Coordination is the process of selecting protective devices and their settings so that only the faulted part of the system is disconnected.
- Goal: Minimize the number of customers affected by a fault.
- Principle: The protective device CLOSEST to the fault should operate FIRST.
- If the closest device fails, the upstream device should act as a backup.

Typical Distribution Network Layout

- Substation Breaker: Protects the entire feeder.
- Main Feeder Recloser: Installed along the main line to segment it.
- Lateral Fuses: Installed where small lateral branches tap off the main feeder.
- Most faults occur on the lateral branches (due to trees, animals in residential areas).



Time-Current Curves (TCC)

- A TCC is a log-log graph showing the time it takes for a device to operate at various fault currents.
- X-axis: Current (Amps).
- Y-axis: Time (Seconds).
- Reclosers have adjustable TCCs (Fast curves and Slow/Delayed curves).
- Fuses have fixed TCCs (Minimum Melting Curve and Total Clearing Curve).

Recloser Operating Characteristics

- A typical recloser sequence uses a combination of Fast and Slow operations.
- Example Sequence: 2 Fast Trips, followed by 2 Slow (Delayed) Trips.
- Fast Curve (e.g., 'A' curve): Trips almost instantaneously. Intent is to clear transient faults BEFORE a downstream fuse can begin to melt.
- Slow Curve (e.g., 'C' curve): Trips with a time delay. Intent is to give a downstream fuse enough time to blow if the fault is permanent.

Fuse Saving Scheme: Concept

- Objective: Prevent lateral fuses from blowing during transient faults.
- How it works:
- 1. Fault occurs on lateral branch.
- 2. Recloser 'Fast Curve' operates FASTER than the fuse's minimum melting time.
- 3. Recloser trips, arc clears, recloser closes.
- 4. If fault was transient, the line is restored and the fuse is SAVED.

Fuse Saving Scheme: Permanent Faults

- What if the fault is permanent?
- 1. Recloser does its fast trips (e.g., 2 times). The fault remains.
- 2. Recloser switches to its 'Slow Curve'.
- 3. Recloser stays closed long enough for the fault current to melt and blow the lateral fuse.
- 4. Fuse clears the faulted lateral branch.
- 5. Main feeder remains energized.

Pros and Cons of Fuse Saving

Pros	Cons
Saves truck rolls for transient lateral faults.	Every customer on the main feeder experiences a momentary blink during the fast trips.
Excellent SAIDI (duration) metrics.	Poor MAIFI (momentary interruption) metrics.
Reduces permanent outage costs.	Power quality complaints from sensitive commercial loads (blinking clocks, computer reboots).

Fuse Blowing Scheme: Concept

- Objective: Never blink the main feeder for a fault on a lateral branch.
- How it works:
- 1. All recloser operations are set on a 'Slow Curve'.
- 2. If a fault occurs on a lateral branch, the fuse ALWAYS blows before the recloser can trip.
- 3. The recloser does nothing for lateral faults. It only acts on main line faults.

Pros and Cons of Fuse Blowing

Pros	Cons
Perfect power quality for main feeder customers (no blinks).	EVERY lateral fault (even transient) causes a permanent outage for that branch.
Excellent MAIFI metrics.	Poor SAIDI metrics.
Simpler coordination logic.	High maintenance costs (many truck rolls to replace blown fuses).

Hybrid Schemes

- Modern digital relays allow for adaptive or hybrid schemes.
- Weather-dependent: Use Fuse Saving during a lightning storm (high transients), switch to Fuse Blowing on a clear day.
- Load-dependent: If a critical customer (hospital, data center) is on the main line, use Fuse Blowing.
- Trip-saving (Trip-to-Save): Recloser trips fast once. If fault persists, it stays closed and lets the fuse blow.

Summary

- Coordination ensures only the faulted section is isolated.
- Reclosers use Fast and Slow Time-Current Curves to coordinate with fuses.
- Fuse Saving uses fast trips to clear transients without blowing fuses (causes blinks).
- Fuse Blowing forces the fuse to clear all lateral faults (prevents blinks, increases outages).
- The choice of scheme depends on utility goals: minimizing outages vs. maximizing power quality.

Surge Arrestors in Power Systems

- Substation Engineering (DI04009011)
- Lecture 15: Surge Arrestors (Part 1 of 2)
- Overvoltages and Basic Principles

Agenda

- What is an Overvoltage?
- Causes of Overvoltages
- Lightning Surges (External)
- Switching Surges (Internal)
- The Role of a Surge Arrestor
- Operating Principle
- The Ideal Surge Arrestor

What is an Overvoltage?

- An overvoltage is any voltage condition exceeding the normal operating limits of a power system.
- They manifest as 'transient surges'—rapid spikes in voltage that last for microseconds or milliseconds.
- These high voltages can break down the insulation of expensive equipment like transformers, leading to catastrophic failure.
- They are broadly classified into External and Internal overvoltages.

External Overvoltages: Lightning

- Caused by atmospheric electrical discharges (Lightning).
- Direct Strike: Lightning hits the phase conductor directly. Causes massive voltage spikes (millions of volts).
- Indirect Strike: Lightning hits nearby ground or structures. Electromagnetic induction creates a surge on the line.
- Characteristics: Extremely high magnitude, extremely fast rise time (measured in microseconds, e.g., 1.2/50 μs wave).

Internal Overvoltages: Switching Surges

- Caused by changes in the operating state of the power network.
- Examples:
- \- Opening or closing circuit breakers.
- \- Energizing or de-energizing long transmission lines or capacitor banks.
- \- Earth faults on one phase causing voltage to rise on healthy phases.
- Characteristics: Lower magnitude than lightning, but longer duration (slower rise time, e.g., 250/2500 μs wave).

Impact of Overvoltages on Equipment

- Insulation Breakdown: The primary mode of failure. Solid, liquid, or gaseous insulation is punctured.
- Transformer Damage: Surges can cause internal winding flashovers, destroying the transformer.
- Bushing Flashovers: Arcs jumping across the external porcelain insulators of equipment.
- Without protection, the grid would be destroyed during every thunderstorm.

What is a Surge Arrestor?

- A surge arrestor (or lightning arrestor) is a protective device connected in parallel with the equipment it protects (usually from phase to ground).
- Under normal operating voltage, it acts as an OPEN circuit (an insulator).
- When an overvoltage surge arrives, it instantly becomes a SHORT circuit (a conductor).
- It safely shunts the high-voltage surge energy to ground, protecting the equipment behind it.

Operating Principle

- Surge arrestors rely on highly NON-LINEAR resistive materials.
- Non-linear means its electrical resistance changes drastically depending on the voltage applied.
- Low Voltage (Normal Operation) $\rightarrow$ High Resistance (Stops current flow to ground).
- High Voltage (Surge Condition) $\rightarrow$ Low Resistance (Allows surge current to flow to ground).
- Once the surge passes and voltage normalizes, it instantly reverts to high resistance.

The Concept of 'Follow Current'

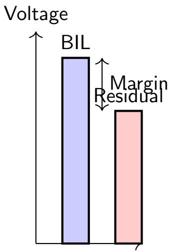
- When an arrestor conducts a surge to ground, the normal system AC voltage tries to 'follow' the surge current down the same path.
- This is called 'Power Frequency Follow Current'.
- If the arrestor cannot stop this follow current, it creates a permanent line-to-ground fault, tripping the system breaker.
- A critical function of an arrestor is to quickly extinguish this follow current and seal itself off.

Characteristics of an Ideal Surge Arrestor

- 1. Draw zero current during normal system operating voltage.
- 2. React instantaneously to overvoltages (zero delay).
- 3. Provide a very low impedance path to ground during a surge to limit the voltage on the equipment.
- 4. Safely absorb or dissipate the massive thermal energy of the surge.
- 5. Completely suppress power frequency follow current immediately after the surge passes.

Protective Margin

- The arrestor determines the maximum voltage the equipment will ever 'see'. This is called the 'Residual Voltage'.
- Equipment has a 'Basic Insulation Level' (BIL) - the maximum voltage it can withstand without damage.
- Protective Margin = BIL - Residual Voltage.
- A proper design ensures a large protective margin (typically 20% or more).



Location of Surge Arrestors

- Location is critical. A surge arrestor must be placed as CLOSE as electrically possible to the equipment it is protecting.
- Most commonly mounted directly adjacent to power transformer bushings.
- Also placed at line entrances (where overhead lines enter the substation) to catch surges before they travel through the busbars.
- Lead lengths (connecting cables to the arrestor and to ground) must be kept as short and straight as possible.

Summary

- Overvoltages come from lightning (external) or switching operations (internal).
- Surge arrestors act as pressure relief valves, shunting high voltages to ground.
- They rely on non-linear materials to act as insulators at normal voltage and conductors at high voltage.
- An ideal arrestor reacts instantly, handles massive energy, and stops follow current.
- They must be located as close as possible to the protected equipment.

Surge Arrestors (Part 2 of 2)

- Advanced Surge Protection
- Metal Oxide Varistors (MOV)
- Selection, Testing, and Maintenance

Agenda

- Recap: SiC vs MOV Technologies
- Metal Oxide Varistors (MOV) Basics
- Gapless Design and V-I Characteristics
- Key Ratings and Selection Criteria
- Installation Practices
- Testing, Monitoring, and Failure Modes

Recap: SiC vs MOV Arresters

- Silicon Carbide (SiC) arresters require series spark gaps to prevent continuous current flow at normal voltages
- SiC blocks have a relatively low non-linear index
- Metal Oxide Varistors (MOV) have highly non-linear characteristics
- MOV arresters eliminate the need for series spark gaps
- MOV arresters provide faster response times to steep-front surges

Metal Oxide Varistors (MOV) Basics

- Primary material is Zinc Oxide (ZnO) with small amounts of other metal oxides (Bismuth, Cobalt, Manganese)
- The microstructure consists of conductive ZnO grains surrounded by highly resistive grain boundaries
- Acts as an excellent insulator at normal power frequency voltages
- Transitions to a highly conductive state during overvoltage events
- Provides seamless transition back to insulating state once the surge passes

Gapless Design and Advantages

- No Spark Gaps: Eliminates problems of gap pitting, moisture ingress, and delayed spark-over
- Continuous Protection: The arrester is permanently connected and responds instantaneously
- Higher Energy Absorption: ZnO blocks can absorb significantly more thermal energy than SiC
- Compact Size: Simplifies substation layout and reduces overall equipment footprint
- Better Pollution Performance: Especially true for polymer-housed ZnO arresters

V-I Characteristics of ZnO

- Pre-breakdown region: Very low leakage current (mostly capacitive) at normal voltage
- ↓
- Knee point: The voltage at which the transition occurs
- ↓
- Breakdown/Operating region: Current increases by orders of magnitude for a small increase in voltage
- ↓
- High-current region: Resistance is minimal, discharging the surge energy to the ground

Comparison of Surge Arrester Types

Feature	SiC Arrester	ZnO (MOV) Arrester
Series Gaps	Required	Not Required (Gapless)
Non-linearity	Moderate	Extremely High
Response Time	Slower (due to gap spark-over)	Instantaneous
Leakage Current	Zero (blocked by gap)	Very small (continuous)
Energy Handling	Lower	Higher

Key Ratings of Surge Arresters

- Rated Voltage (Ur): Maximum permissible 10-second power frequency overvoltage
- Maximum Continuous Operating Voltage (MCOV or Uc): The max power frequency voltage the arrester can withstand continuously
- Nominal Discharge Current (In): Peak value of standard lightning impulse (8/20 micro-seconds) used for classification
- Energy Rating (kJ/kV): Capability to dissipate surge energy without thermal runaway

MCOV and Rated Voltage

- MCOV is arguably the most critical parameter for gapless arresters
- MCOV must be strictly greater than the maximum continuous phase-to-ground voltage of the system
- Temporary Overvoltages (TOV) dictate the Rated Voltage (Ur)
- Selection requires balancing protection margin (lower rating) with thermal stability (higher rating)

Arrester Selection Criteria

- Determine the maximum continuous system voltage (to set MCOV)
- Determine maximum Temporary Overvoltage (TOV) magnitude and duration (to set Ur)
- Select the required discharge current class (e.g., 10kA for most transmission systems)
- Calculate the Required Protection Level (LIPL and SIPL) and compare against equipment BIL and BSL
- Ensure adequate protective margin (typically greater than 20% for lightning impulses)

Installation and Location

- Location: Should be located as close as possible to the equipment being protected (typically power transformers)
- Lead Lengths: Keep connecting leads to the line and ground as short and straight as possible
- Inductive Voltage Drop: $L(di/dt)$ in long leads can add significantly to the residual voltage, reducing the protection margin
- Clearances: Ensure adequate phase-to-phase and phase-to-ground clearances

Testing of Surge Arresters

- Routine Tests: Reference voltage test, residual voltage test, partial discharge test
- Type Tests: Operating duty test, TOV test, short-circuit test, weather aging tests
- Field Tests: Insulation resistance (Megger), Third harmonic leakage current measurement
- Thermal Imaging: Infrared thermography to detect localized heating indicating block degradation

Condition Monitoring: Leakage Current

- Gapless arresters conduct a continuous, very small leakage current (usually ¡ 1mA)
- This current has capacitive and resistive components
- Resistive leakage current increases as the ZnO blocks age or absorb moisture
- Third Harmonic Measurement: Used to isolate and measure the resistive component of the leakage current
- Surge Counters: Installed at the base to record the number of surge operations

Failure Modes and Pressure Relief

- Thermal Runaway: Occurs when heat generated exceeds heat dissipation capability (often due to prolonged TOV)
- Moisture Ingress: Leading cause of failure in older porcelain-housed arresters
- Pressure Relief Design: Arresters have directional pressure relief vents to prevent explosive shattering during a short circuit
- Polymer Housings: Preferred modern alternative as they tear open rather than shatter, improving safety

Summary

- MOV technology has made gapless surge arresters the industry standard
- MCOV and Ur are the most critical selection parameters
- Lead lengths must be minimized to ensure effective protection margins
- Resistive leakage current monitoring is the best indicator of arrester health
- Polymer housings provide superior safety during failure modes compared to porcelain

Key Takeaways

- The sharp knee of the ZnO V-I curve enables gapless design
- Arrester MCOV must be safely above the maximum continuous system voltage
- Third harmonic leakage current measurement is essential for predictive maintenance

Next Lecture Preview

- Topic: Insulators, Strings, Clamps, and Connectors (Part 1)
- Types of Substation Insulators
- Porcelain, Glass, and Composite Materials
- Insulator String Arrangements

Insulator, strings, Clamps and Connectors, Spacers (Part 1)

- Substation Insulators
- Materials: Porcelain, Glass, Polymer
- Configurations and String Efficiency

Agenda

- Introduction to Insulators
- Insulator Materials (Porcelain, Glass, Composite)
- Types of Substation Insulators
- Insulator String Configurations
- Voltage Distribution in Strings
- String Efficiency

Introduction to Substation Insulators

- Insulators have two primary functions: Electrical isolation and Mechanical support
- They must withstand normal operating voltages, switching surges, and lightning impulses
- Mechanically, they bear the weight of conductors, ice loads, and wind pressure
- Subjected to harsh environmental conditions: pollution, UV radiation, and temperature extremes

Key Properties of Insulating Materials

- High Dielectric Strength: To prevent electrical breakdown
- High Mechanical Strength: To support heavy loads under tension and compression
- High Insulation Resistance: To minimize leakage currents
- Non-porous Nature: To prevent moisture absorption
- Resistant to environmental degradation and tracking

Comparison of Insulator Materials

Feature	Porcelain	Toughened Glass	Composite / Polymer
Mechanical Strength	Very High (compression)	High	Very High (tension)
Weight	Heavy	Heavy	Lightweight
Pollution Performance	Moderate	Moderate	Excellent (Hydrophobic)
Vandalism Resistance	Low	Low (shatters)	High
Visual Inspection	Difficult	Easy (shatters if faulty)	Difficult

Porcelain Insulators

- The most traditional and widely used material in substations
- Made from a mixture of kaolin, feldspar, and quartz
- Glazed finish prevents moisture ingress and aids in self-cleaning during rain
- Excellent compressive strength, making them ideal for post insulators
- Prone to cracking under sudden thermal or mechanical shocks

Toughened Glass Insulators

- Made by sudden cooling of red-hot glass, putting the surface in compression
- Higher dielectric strength than porcelain
- Fail-safe visual inspection: if it fails, it completely shatters, making faulty units easy to spot from the ground
- Commonly used in suspension strings for transmission lines and substation entries

Composite (Polymer) Insulators

- Consist of a fiberglass core rod (for mechanical strength) covered by a silicone rubber housing
- Silicone housing provides weather sheds and excellent hydrophobicity
- Hydrophobicity breaks up water films into distinct droplets, preventing continuous leakage current paths
- Extremely lightweight (up to 70% lighter than porcelain)
- Superior performance in highly polluted environments (coastal or industrial areas)

Types of Substation Insulators

- Post Insulators: Used for rigid support of busbars, disconnect switches, and equipment
- Suspension Insulators: Used to hang conductors from gantry structures
- Strain / Tension Insulators: Used at dead-end structures where conductor tension must be held
- Bushing Insulators: Used to pass conductors through grounded enclosures (e.g., transformers)

Solid Core Post Insulators

Usually made of porcelain or composite materials

↓

Mounted vertically or horizontally on substation structures

↓

Designed to withstand high cantilever and torsional loads (e.g., during short circuits or switch operations)

↓

Often stacked in multiple units for higher voltage levels (e.g., 400kV)

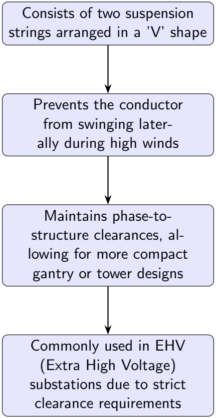
Insulator Strings: Suspension

- Formed by connecting multiple insulator discs (porcelain or glass) in series
- Number of discs depends on the system voltage
- Allows the conductor to swing freely under wind pressure
- Used at intermediate gantries inside substations or on incoming transmission lines

Insulator Strings: Tension / Strain

- Used at dead-end structures where the line terminates or changes direction significantly
- Must withstand the full longitudinal tensile stress of the conductor
- Often consists of multiple parallel strings (double, triple, or quad strings) to share heavy mechanical loads
- Mounted horizontally or at an angle

V-String Configurations



Voltage Distribution in Strings

- An insulator string is not just a set of resistors; it forms a complex capacitive network
- Mutual Capacitance (C): Capacitance between consecutive metallic pins of the discs
- Shunt / Earth Capacitance (C1): Capacitance from each pin to the grounded tower/gantry
- Due to C1, the charging current varies down the string
- Result: Voltage is NOT distributed equally across all discs

String Efficiency

- The disc nearest to the line conductor experiences the maximum voltage stress
- The disc nearest to the cross-arm (ground) experiences the minimum voltage stress
- String Efficiency = (Total Voltage across string) / (n * Voltage across disc nearest to conductor)
- Low efficiency implies unequal voltage sharing, which can lead to premature failure or flashover of the bottom disc

Methods to Improve String Efficiency

- Using longer cross-arms: Reduces the shunt capacitance to ground (C1), but increases structural cost
- Grading of Insulators: Using discs with different mutual capacitances (larger capacitance near the conductor) - impractical for mass production
- Using a Grading Ring (Guard Ring): Introduces capacitance between the line and the pins to cancel out the shunt capacitance effect
- Grading rings are the most common and practical solution in EHV systems

Summary

- Insulators provide crucial electrical isolation and mechanical support
- Composite insulators offer superior pollution performance and lower weight compared to porcelain and glass
- Insulator configurations vary based on mechanical loading (Post, Suspension, Strain)
- Voltage distribution across a string is inherently unequal due to stray ground capacitance
- String efficiency must be managed to prevent localized overstress

Next Lecture Preview

- Topic: Hardware Fittings, Clamps, and Spacers
- Grading and Corona Rings
- Substation Connectors (Bimetallic, PG)
- Bundle Conductors and Spacer Dampers

Insulator, strings, Clamps and Connectors, Spacers (Part 2)

- Substation Hardware Fittings
- Corona and Grading Rings
- Clamps, Connectors, and Spacer Dampers

Agenda

- Recap of String Efficiency
- Grading Rings vs. Corona Rings
- Substation Clamps (Suspension, Strain)
- Electrical Connectors (Bimetallic, PG)
- Bundle Conductors overview
- Spacers and Spacer Dampers
- Maintenance of Hardware Fittings

Recap: The Need for Hardware Interfacing

- Insulators alone cannot hold conductors; they require mechanical fittings
- Fittings must transfer massive physical loads safely
- Fittings must also manage electrical stress (sharp edges cause high electric fields)
- Dissimilar metals (e.g., aluminum conductors and copper terminals) require special care to prevent corrosion

Grading Rings

Purpose: To improve string efficiency in suspension and tension insulator strings

Function: They introduce a capacitance between the high-voltage line and the intermediate insulator metal pins

This counteracts the ground stray capacitance, forcing a more uniform voltage distribution

Reduces electrical stress on the bottom-most insulator disc

Corona Rings

- Purpose: To control and distribute the electric field at the ends of insulators and equipment bushings
- Sharp edges on hardware clamps cause high localized electric fields
- If the field exceeds air breakdown strength (approx 30 kV/cm), corona discharge occurs
- Corona rings are smooth, large-radius toroids that encompass the sharp hardware, smoothing out the electric field

Substation Clamps

- Hardware used to mechanically attach the conductor to the insulator string
- Must have high mechanical strength (usually made of forged steel, malleable iron, or aluminum alloy)
- Must not damage the conductor strands through excessive pinching
- Types: Suspension Clamps and Strain (Dead-end) Clamps

Suspension Clamps

- Used at intermediate support points (e.g., I-strings or V-strings)
- Conductor rests in a grooved 'boat' and is clamped down with a keeper piece and U-bolts
- Designed to allow a limited amount of conductor slippage in case of unbalanced tension (e.g., if a wire breaks in the next span)
- Reduces catastrophic cascade failures

Strain / Dead-end Clamps

- Used to terminate conductors at dead-end gantries
- Bolted Type: Relies on heavy bolting friction; easy to install but bulky
- Compression Type: A metallic sleeve is hydraulically crimped permanently onto the conductor
- Compression clamps provide the best electrical continuity and mechanical strength for EHV systems

Substation Connectors

- Unlike clamps (which carry mechanical load), connectors primarily carry electrical current
- Used for tapping off busbars, connecting to equipment terminals (transformers, breakers)
- Must provide low contact resistance to prevent overheating
- Types: T-connectors, L-connectors, straight splices, flexible expansion connectors

Bimetallic Connectors

Problem: Connecting an Aluminum conductor to a Copper equipment terminal	
Galvanic Corrosion: Moisture acts as an electrolyte; the less noble metal (Aluminum) rapidly corrodes away	
Solution: Bimetallic Connectors	
Design: Manufactured with Copper on one side and Aluminum on the other, friction-welded together in a vacuum	
Usage: Prevents direct contact between dissimilar metals on site	

PG (Parallel Groove) Clamps

- Used for non-tension electrical connections (e.g., jumper wires)
- Two parallel grooves enclose the two conductors being clamped
- Bolts apply pressure to maintain low electrical resistance
- Requires contact grease to prevent oxidation of aluminum strands before tightening

Bundle Conductors in Substations

- EHV systems (220kV and above) use multiple parallel wires (2, 4, 6, 8) per phase
- Increases the effective radius of the conductor
- Reduces electric field gradient at the surface, thereby reducing Corona loss and Radio Interference
- Increases current carrying capacity (ampacity) due to better heat dissipation

The Need for Spacers

- Bundle conductors carry current in the same direction
- This creates strong electromagnetic attractive forces (Lorentz force) pulling the sub-conductors together
- During short-circuit faults, these forces multiply, causing wires to clash violently
- Spacers hold the sub-conductors at a fixed distance to maintain the bundle geometry

Types of Spacers

- Rigid Spacers: Solid metal links. Cheap but offer no damping. Used on short jumpers.
- Flexible Spacers: Incorporate a spring or steel wire rope to absorb minor shocks.
- Spacer Dampers: The most advanced type, incorporating rubber or elastomeric hinges to absorb aeolian vibrations and wake-induced galloping.

Spacer Dampers in Detail

1. Central mass frame with articulated arms holding clamps for each sub-conductor
2. The pivot joints contain energy-absorbing elastomer elements
3. Converts mechanical vibration energy from the wind into minor heat
4. Placed at unequal intervals along a span to prevent resonant standing waves

Summary

- Rings: Grading rings improve string efficiency; Corona rings control high electric fields
- Clamps: Suspension clamps hold weight; Strain clamps hold tension
- Connectors: Must provide low-resistance electrical paths and prevent galvanic corrosion (Bimetallic)
- Spacers: Maintain bundle geometry against electromagnetic forces and dampen wind-induced vibrations

Key Takeaways

- Smooth hardware and corona rings are essential to prevent air breakdown at EHV levels
- Bimetallic interfaces are strictly required when joining aluminum and copper
- Spacer dampers serve the dual purpose of geometric separation and vibration energy absorption

Next Lecture Preview

- Topic: Power Line Carrier Communication (PLCC) - Part 1
- Substation Control and Communication
- How Power Lines are used to transmit data
- Key Components: Wave Traps, Coupling Capacitors, and LMUs

Power Line Carrier Communication (PLCC) (Part 1)

- Substation Communication Needs
- Principles of PLCC
- Line Traps, Coupling Capacitors, and Line Matching Units

Agenda

- Why do Substations need to Communicate?
- What is PLCC?
- Frequency Spectrum Used
- Block Diagram of a PLCC System
- Deep Dive: Wave Trap (Line Trap)
- Deep Dive: Coupling Capacitor (CC/CVT)
- Deep Dive: Line Matching Unit (LMU)

Substation Communication Needs

- Substations are not isolated; they form a synchronized grid
- Protection (Teleprotection): Relays must communicate instantly to isolate faults on transmission lines
- Telemetry / SCADA: Central load dispatch centers need real-time data (MW, MVAR, Volts) from every substation
- Voice Communication: Operators need reliable ways to coordinate switching operations

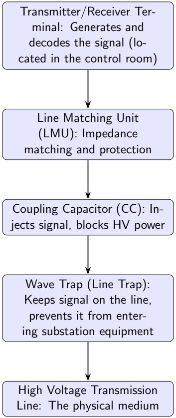
What is PLCC?

- Power Line Carrier Communication (PLCC) uses existing high-voltage transmission lines to carry communication signals
- It superimposes a high-frequency carrier signal onto the 50Hz/60Hz power frequency signal
- Cost-Effective: Eliminates the need to lay a separate, dedicated physical communication cable over vast distances
- Highly Reliable: Transmission lines are robust and rarely break compared to standard telecom cables

Frequency Range of PLCC

Parameter	Value
Power Frequency	50 Hz or 60 Hz
PLCC Carrier Frequency Range	30 kHz to 500 kHz
Bandwidth per Channel	Typically 4 kHz
Transmission Power	10W to 80W

Basic Block Diagram of PLCC



The Wave Trap (Line Trap)

- Connected in SERIES with the main transmission line at the substation entry point
- It is a parallel LC resonant circuit (Inductor and Capacitor)
- Function: Offers extremely HIGH impedance to the high-frequency PLCC signal, and negligible (LOW) impedance to the 50Hz power current
- Prevents the communication signal from 'leaking' into the substation transformers and getting grounded or attenuated

Wave Trap: Construction

- Main Coil: A heavy-duty, air-cored inductor capable of carrying the full continuous load current of the line (e.g., 2000A) and withstanding short-circuit fault currents
- Tuning Device: Capacitors and resistors that tune the trap to block specific frequency bands
- Surge Arrester: Connected in parallel across the coil to protect the tuning device from transient overvoltages (lightning)

The Coupling Capacitor (CC / CVT)

- Connected in PARALLEL between the high voltage line (after the wave trap) and the ground / LMU
- Function: Acts as a high-pass filter
- Offers HIGH impedance to 50Hz power frequency (blocking high voltage from reaching electronics)
- Offers LOW impedance to high-frequency carrier signals (allowing them to pass into the line)
- Often combined with voltage measurement as a Capacitive Voltage Transformer (CVT)

Line Matching Unit (LMU)

- Placed at the base of the Coupling Capacitor
- Impedance Matching: Matches the impedance of the coaxial cable from the control room (approx 75 ohms) to the transmission line (approx 400 ohms) to maximize power transfer
- Galvanic Isolation: Uses an isolation transformer to separate control room electronics from switchyard grounds
- Drain Coil: Drains any leaked 50Hz power currents to ground safely

Coupling Arrangements

Phase-to-Earth Coupling: Uses one phase wire and ground. Cheaper (requires only 1 Wave Trap and 1 CVT). Higher attenuation, prone to noise

↓

Phase-to-Phase Coupling: Uses two phase wires. Signal sent out on one, returns on another. Requires 2 Wave Traps and 2 CVTs. Much lower attenuation and more reliable during single-phase faults

The PLCC Terminal (Indoor)

- Located inside the air-conditioned substation control room
- Houses the Modulator, Demodulator, Amplifiers, and Filters
- Takes analog voice, digital SCADA data, and simple on/off protection commands and multiplexes them into a single carrier frequency
- Connects to the outdoor LMU via a shielded high-frequency coaxial cable

Summary of Component Roles

Component	Primary Function	Location
Wave Trap	Blocks HF signal from entering substation	Series with Line
Coupling Capacitor	Passes HF signal, Blocks HV 50Hz	Parallel to Line
LMU	Impedance matching & safety isolation	Base of CVT
Terminal	Modulation and Demodulation	Control Room

Summary

- PLCC is a cost-effective and robust method for substation-to-substation communication
- It operates by superimposing a high-frequency carrier (30-500kHz) on the 50Hz power line
- The Wave Trap forces the signal down the line rather than into the local station
- The Coupling Capacitor and LMU safely inject the signal while blocking lethal voltages

Key Takeaways

- Wave Traps are parallel LC circuits that offer high impedance to PLCC frequencies.
- Coupling Capacitors leverage the property that capacitive reactance drops as frequency increases.
- LMUs are critical for impedance matching (reducing signal reflection) and operator safety.

Next Lecture Preview

- Topic: Power Line Carrier Communication (PLCC) - Part 2
- Modulation Techniques used in PLCC
- Applications: Teleprotection, SCADA, Voice
- Limitations, Noise, and Comparison with Fiber Optics (OPGW)

Power Line Carrier Communication (PLCC) (Part 2)

- Modulation Techniques
- Substation Applications (Teleprotection)
- Limitations and the Future: OPGW

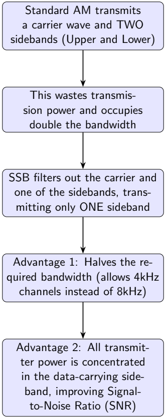
Agenda

- Recap of PLCC Hardware
- Modulation Techniques in PLCC (AM, SSB)
- Application 1: Voice Communication
- Application 2: SCADA and Telemetry
- Application 3: Teleprotection (Carrier Aided Protection)
- Limitations and Noise in Power Lines
- Comparison: PLCC vs Fiber Optics (OPGW)
- Future Trends in Substation Communication

Modulation Techniques in PLCC

- The baseband signal (voice or data) is low frequency (300Hz - 3400Hz)
- This must be modulated onto the high-frequency carrier (30kHz - 500kHz)
- Amplitude Modulation (AM) and Frequency Modulation (FM) were traditionally used
- Modern PLCC relies almost exclusively on Amplitude Modulation - Single Sideband Suppressed Carrier (AM-SSB-SC)

Why Single Sideband (SSB)?



Application 1: Voice Communication

- Provides dedicated telephone links between substation control rooms, load dispatch centers, and maintenance crews
- Independent of public telecom networks (vital during blackouts or natural disasters)
- Typically occupies the lower portion of the 4kHz channel band (e.g., 300Hz to 2000Hz)
- Operation is similar to an intercom system using Priority Calling

Application 2: SCADA and Telemetry

- Supervisory Control and Data Acquisition (SCADA)
- Transmits real-time grid data: Voltage, Current, Active Power (MW), Reactive Power (MVAR), and Breaker Status
- Allows remote control (e.g., dispatch center opening a breaker 200km away)
- Data is usually sent via Audio Frequency Shift Keying (AFSK) in the upper part of the 4kHz band (e.g., 2000Hz - 3400Hz)

Application 3: Teleprotection

- The most critical and time-sensitive application of PLCC
- Used for Carrier-Aided Distance Protection schemes
- If a fault occurs on a transmission line, relays at BOTH ends must open their breakers simultaneously
- The local relay detects the fault and sends a high-speed 'trip' or 'block' command via PLCC to the remote end relay

Teleprotection Signaling

- Because it is so critical, Teleprotection often gets its own dedicated, unshared PLCC channel
- Commands are simple: usually just a shift in frequency (FSK) to indicate 'Trip' or 'Block'
- Requires extremely high reliability and low latency (under 15-20 milliseconds)
- Must function perfectly even when the power line itself is short-circuited (which heavily attenuates the signal)

Limitations and Disadvantages of PLCC

- Limited Bandwidth: Max capability is usually a few kilobits per second (kbps). Insufficient for modern digital needs (video, heavy data, IEC 61850)
- High Noise Environment: Corona discharge, switching transients, and lightning create massive electrical noise on the line
- Attenuation: Signal strength drops significantly over long distances, requiring expensive repeater stations for very long lines
- Weather Dependent: Rain, ice, and fog increase corona noise and signal attenuation

The Alternative: Optical Ground Wire (OPGW)

- The modern replacement for PLCC in EHV networks
- Replaces the traditional steel earth wire (shield wire) at the very top of the transmission tower with a wire that contains optical fibers in its core
- Dual Purpose: Acts as a lightning shield for the power lines AND provides massive communication bandwidth
- Completely immune to electrical noise, magnetic fields, and corona discharge

Comparison: PLCC vs Fiber Optics (OPGW)

Feature	PLCC	OPGW (Fiber Optics)
Bandwidth / Speed	Low (kbps)	Extremely High (Gbps/Tbps)
Immunity to EMI	Low (prone to noise)	Total Immunity
Cost of Installation	Low (uses existing line)	High (requires new cable stringing)
Suitability for Digital Substations	Poor	Excellent (IEC 61850 standard)
Signal Attenuation	High	Very Low

Future Trends: Migration Strategies

- New EHV lines (220kV, 400kV, 765kV) are almost exclusively built with OPGW from day one
- Older lines are retrofitted with OPGW during maintenance cycles
- PLCC is rarely used for primary data in modern substations anymore, but remains highly relevant as a Backup Protection channel
- Redundancy: Utilities often use OPGW as Main-1 communication and PLCC as Main-2 for teleprotection

Summary

- PLCC utilizes SSB modulation to conserve bandwidth and maximize signal power
- Primary applications are Voice, SCADA Telemetry, and high-speed Teleprotection
- PLCC suffers from severe bandwidth limitations and susceptibility to electrical noise
- OPGW provides massive bandwidth and total EMI immunity, becoming the modern standard
- PLCC still serves a vital role as a redundant backup communication path in EHV networks

Key Takeaways

- Single Sideband (SSB) is crucial for maximizing the limited frequency spectrum of power lines.
- Teleprotection requires ultra-low latency signaling to trip breakers simultaneously across long distances.
- OPGW is replacing PLCC for data, but PLCC remains a highly cost-effective and reliable backup.

Next Lecture Preview

- Topic: Introduction to Unit 5 - Earthing and Grounding
- Importance of Substation Earthing
- Step Voltage and Touch Voltage
- Design of the Substation Earth Mat

Batteries and DC Systems (Part 1 of 2)

- Substation Engineering (DI04009011)
- Unit 5: Auxiliary Systems and Routine Operations
- Lecture 21: Batteries and DC Systems

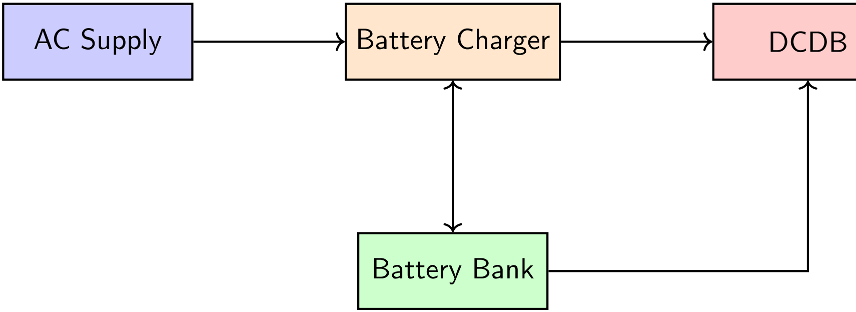
Agenda

- Importance of DC Systems in Substations
- Components of a Substation DC System
- Types of Batteries (Lead-Acid vs. Ni-Cd)
- Battery Terminology and Ratings
- Substation DC Load Profiles
- Basics of Battery Sizing

Importance of DC Systems in Substations

- Provides independent, reliable power for critical substation equipment
- Operates protective relays, control circuits, and automation systems
- Powers the trip and close coils of high-voltage circuit breakers
- Maintains operation during complete AC station power failure (blackout)
- Emergency lighting and communication systems rely on the DC bank

Components of a Substation DC System



- AC Auxiliary Supply (input from Station Service Transformer)
- Battery Charger (Rectifier): Converts AC to DC
- Battery Bank: Stores DC energy
- DC Distribution Board (DCDB): Distributes DC power to various loads
- Protection Devices: Fuses and DC Miniature Circuit Breakers (MCBs)

Types of Batteries Used in Substations

Feature	Vented Lead-Acid (VLA)	Valve Regulated Lead-Acid (VRLA)	Nickel-Cadmium (Ni-Cd)
Electrolyte	Liquid Sulfuric Acid	Gelled/Absorbed Acid	Potassium Hydroxide (Alkaline)
Maintenance	High (add water)	Low	Moderate
Life Expectancy	15-20 years	5-10 years	20+ years
Cost	Moderate	Low	High

Vented Lead-Acid (VLA) Batteries

- Composed of lead dioxide (positive) and sponge lead (negative) plates
- Submerged in an electrolyte of dilute sulfuric acid
- Nominal voltage per cell is 2.0V
- Transparent cases allow visual inspection of plates and electrolyte levels
- Requires periodic topping up with distilled water due to outgassing

Nickel-Cadmium (Ni-Cd) Batteries

- Uses nickel oxide hydroxide (positive) and metallic cadmium (negative)
- Alkaline electrolyte (Potassium Hydroxide) does not participate directly in the chemical reaction
- Nominal voltage per cell is 1.2V
- Highly resistant to temperature extremes and deep discharging
- Does not suffer from sudden death syndrome like some lead-acid types

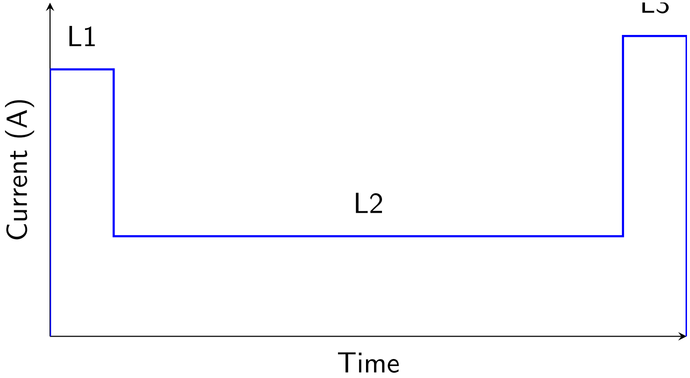
Battery Terminology: Ampere-Hour (Ah) Capacity

- Capacity is measured in Ampere-Hours (Ah) at a specific discharge rate
- Standard rating for substation batteries is usually the 8-hour rate (C8)
- Example: A 400 Ah battery can supply 50 Amps for 8 hours (50A x 8h = 400Ah)
- Capacity varies with discharge time; higher discharge currents yield lower effective capacity
- Temperature affects capacity: rated at 25 degrees Celsius (77 degrees Fahrenheit)

Battery Terminology: C-Rate and Depth of Discharge

- C-Rate: A measure of the rate at which a battery is discharged relative to its maximum capacity
- 1C rate means discharge in 1 hour; 0.1C rate means discharge in 10 hours
- Depth of Discharge (DoD): The percentage of battery capacity that has been discharged
- Example: Discharging 100 Ah from a 400 Ah battery equals 25% DoD
- End of Discharge Voltage (EODV): Minimum allowable voltage before permanent damage occurs (typically 1.75V for Lead-Acid)

Substation DC Load Profile



Classification of DC Loads

Load Type	Description	Duration	Example
Continuous	Always energized	Entire duty cycle	Relays, SCADA RTU, indicators
Non-Continuous	Energized for a specific time	Minutes to hours	Emergency lighting, lube pumps
Momentary	Instantaneous high current	Fraction of a second	Breaker trip/close coils, motor charging springs

Battery Sizing Considerations (IEEE 485)

- Determine the duty cycle based on utility standards (e.g., 4 or 8 hours of backup)
- Calculate continuous, non-continuous, and momentary loads
- Apply Design Margin (typically 10-15%) for future growth
- Apply Aging Factor (typically 25% extra capacity so it meets load at end of life)
- Apply Temperature Correction Factor for lowest expected ambient temperature

The Battery Charger

- Usually a solid-state thyristor (SCR) based rectifier
- Sized to carry the continuous DC load PLUS recharge a fully depleted battery within a specified time (e.g., 12 hours)
- Features two primary modes: Float Charge and Boost (Equalize) Charge
- Equipped with alarms for AC fail, DC under/over voltage, and charger failure
- Dual charger schemes (redundant) are used in critical EHV substations

Summary

- DC systems provide uninterrupted power to critical protection and control equipment
- The system consists of the AC source, charger, battery bank, and DCDB
- Vented Lead-Acid and Ni-Cd are the primary battery chemistries used
- Battery sizing requires understanding continuous, non-continuous, and momentary loads
- IEEE 485 standard dictates applying margins for aging, temperature, and future design

Preview of Next Lecture

- Float vs. Boost Charging operations in detail
- Battery maintenance, inspection, and testing procedures
- Measuring specific gravity and using a hydrometer
- DC system ground faults and detection methods
- Safety precautions in the battery room

Batteries and DC Systems (Part 2 of 2)

- Course: Substation Engineering (DI04009011)
- Unit 5: Auxiliary Systems and Routine Operations
- Lecture 22: Batteries and DC Systems (Part 2 of 2)

Agenda

- Battery Charging Modes: Float vs. Boost
- Routine Battery Maintenance and Inspection
- Specific Gravity and Voltage Measurements
- Battery Capacity and Discharge Testing
- Safety Precautions and Ventilation
- DC System Ground Faults and Detection

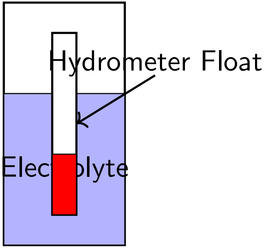
Battery Charging Modes

Parameter	Float Charge (Trickle)	Boost Charge (Equalize)
Purpose	Maintain full charge, supply continuous load	Recharge depleted battery, balance cell voltages
Voltage Level	Nominal (e.g., 2.15V - 2.25V per cell)	Elevated (e.g., 2.33V - 2.40V per cell)
Duration	Continuous	Temporary (8-24 hours)
Gassing	Minimal	Significant (requires ventilation)

Routine Battery Maintenance and Inspection

- Visual inspection for cracks, leaks, and corrosion on terminals
- Checking electrolyte levels (must be between min and max marks)
- Cleaning battery terminals and applying anti-corrosion petroleum jelly
- Verifying torque on inter-cell connections to prevent high resistance
- Ensuring the battery room environment is clean and climate-controlled

Measuring Specific Gravity



- Specific gravity (SG) indicates the state of charge in Lead-Acid cells
- Measured using a hydrometer or digital density meter
- Fully charged cell: SG typically 1.210 to 1.250 at 25°C
- Discharged cell: SG drops as sulfuric acid turns into water and lead sulfate
- Temperature correction must be applied to SG readings

Cell Voltage Measurements

- Individual cell voltages must be measured and recorded monthly
- Pilot cells: Selected cells monitored continuously for a representative snapshot
- Uneven cell voltages indicate the need for an equalize (boost) charge
- Internal resistance measurements (using specialized meters) help identify degraded cells
- A sudden drop in internal resistance or voltage indicates a failing cell

Capacity and Discharge Testing

- The ultimate test of a battery's health is a load test (capacity test)
- Performed using a dummy load bank to discharge the battery at a constant current
- Voltage is monitored until it reaches the End of Discharge Voltage (EODV)
- IEEE standards recommend a capacity test upon installation, then every 5 years
- If capacity drops below 80% of rated value, the battery must be replaced

Safety Precautions in Battery Rooms

- Acid Spills: Neutralize with baking soda (sodium bicarbonate) and wash with water
- PPE Required: Acid-resistant apron, face shield, rubber gloves
- Insulated tools must be used to prevent accidental short circuits
- Eye wash stations must be installed within or immediately adjacent to the room
- No smoking or open flames allowed due to explosive gas risks

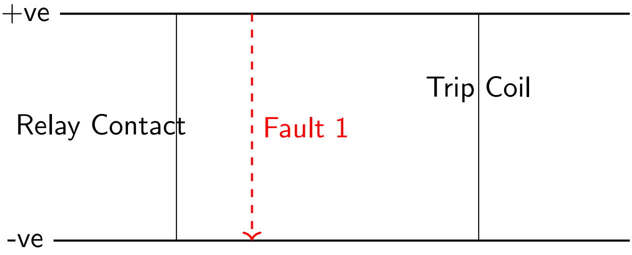
Hydrogen Gas Evolution and Ventilation

- During boost charging, lead-acid batteries undergo electrolysis, releasing Hydrogen gas
- Hydrogen is explosive at concentrations between 4% and 75% in air
- Battery rooms require forced ventilation (exhaust fans) to keep H2 levels below 1%
- Explosion-proof light fittings and switches are recommended
- Hydrogen detectors provide alarms to SCADA if ventilation fails

DC System Ground Faults

- Substation DC systems are typically ungrounded (floating)
- A single ground fault (e.g., positive to ground) does not cause a short circuit or blow a fuse
- However, a second ground fault on the opposite pole will cause a short circuit
- Can lead to blown fuses, loss of DC power, or false tripping of circuit breakers
- Immediate location and repair of the first ground fault is critical

Impacts of DC Ground Faults on Relays



Ground Fault Detection Methods

- Simple Method: Two series lamps connected across the DC bus, with the center point grounded. A fault dims one lamp and brightens the other
- Modern Relays: Injection of a low-frequency AC signal to measure insulation resistance to ground
- Portable Fault Locators: Inject a traced signal and use a clamp-on ammeter to trace the fault down to the specific circuit
- Sequential Isolation: Turning off DC MCBs one by one until the ground alarm clears (highly disruptive)

Redundancy in DC Systems

- Extra High Voltage (EHV) substations employ dual redundant DC systems (DC System 1 and DC System 2)
- Physically separated battery rooms and duplicated chargers
- Main 1 and Main 2 protection relays are fed from independent DC systems
- Circuit breakers are equipped with dual trip coils (TC1 and TC2)
- Ensures that a complete failure of one DC system does not leave the substation unprotected

Summary

- Float charging maintains the battery, while boost charging restores it
- Maintenance involves checking specific gravity, voltages, and terminal tightness
- Hydrogen outgassing requires strict ventilation and safety protocols
- DC systems are ungrounded; a single ground fault must be addressed immediately to prevent false tripping
- Redundant DC systems provide maximum reliability for EHV substations

Preview of Next Lecture

- Introduction to Routine Substation Operations
- Safe Switching Principles
- Operation of Isolators vs. Circuit Breakers
- Isolation and Tagging (LOTO) Procedures
- Substation Interlocking Schemes

Routine Substation Operations (Part 1 of 3)

- Course: Substation Engineering (DI04009011)
- Unit 5: Auxiliary Systems and Routine Operations
- Lecture 23: Switching Principles and Isolation

Agenda

- Introduction to Substation Operations
- Circuit Breakers vs. Isolators
- General Rules for Safe Switching Sequences
- Interlocking Schemes (Electrical and Mechanical)
- Line Energization and De-energization Procedures
- Isolation and Tagging (Lockout/Tagout)

Introduction to Routine Operations

- Substation operations involve changing the topology of the electrical network
- Purpose: Taking equipment out for maintenance, transferring loads, or isolating faults
- Performed locally via control panels or remotely via SCADA
- Requires strict adherence to authorized switching programs
- Safety of personnel and equipment is the highest priority

Circuit Breakers vs. Isolators (Disconnect Switches)

Feature	Circuit Breaker (CB)	Isolator (Disconnect Switch)
Load Current Breaking	Yes, designed to interrupt full load	No, cannot break load current
Fault Current Breaking	Yes, interrupts short circuits	No, will cause massive arc if opened under fault
Arc Quenching Medium	SF6, Vacuum, Oil	Air (no dedicated quenching chamber)
Visual Isolation	Enclosed contacts (cannot see)	Visible break in the air
Operation Speed	Very fast (cycles)	Slow (motorized or manual)

Safe Switching Principles

- Always use the Circuit Breaker to interrupt or initiate current flow
- Isolators are operated only when the associated Circuit Breaker is OPEN
- Earth switches are closed only after the equipment is fully isolated and verified dead
- Verify the open/close status of devices visually and via panel indicators
- Never bypass safety interlocks without explicit high-level authorization

Line De-energization Procedure

- Step 1: Open the Line Circuit Breaker (interrupts load current)
- Step 2: Verify zero current and breaker open status
- Step 3: Open the Line Isolator (creates a visible gap to the line)
- Step 4: Open the Bus Isolator (creates a visible gap to the busbar)
- Step 5: Lock and tag isolators in the open position

Line Energization Procedure

- Energization is the exact reverse of de-energization
- Step 1: Verify all Earth Switches are OPEN and clearances are canceled
- Step 2: Close the Bus Isolator
- Step 3: Close the Line Isolator
- Step 4: Close the Circuit Breaker (initiates current flow)
- Step 5: Verify voltage and current on panel meters

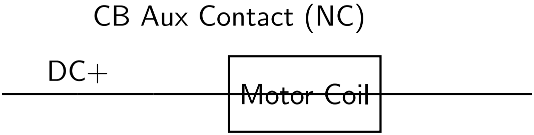
Substation Interlocking Schemes

- Interlocks prevent incorrect sequence of operations
- They enforce the rule: Isolator cannot move unless the Breaker is OPEN
- Earth switch cannot close unless the Isolator is OPEN
- Protects against human error, stress, and miscommunication
- Two main types: Mechanical and Electrical Interlocks

Electrical vs. Mechanical Interlocks

Feature	Electrical Interlocking	Mechanical / Key Interlocking (Castell Keys)
Mechanism	Auxiliary contacts in control circuits	Physical keys trapped in locks
Application	Motor-operated isolators, complex bus schemes	Manual isolators, earth switches, simple bays
Flexibility	High, easily integrated into SCADA	Low, physically rigid
Reliability	Dependent on DC control voltage	Highly reliable, failsafe, requires no power

Electrical Interlocking Scheme (Example)



- Control circuit for the Motor Operated Isolator (MOI)
- A Normally Closed (NC) auxiliary contact of the Circuit Breaker is wired in series with the Isolator's motor contactor
- If the CB is closed, the NC contact opens, breaking the circuit to the Isolator motor
- Result: Pressing the 'Open' or 'Close' button on the Isolator has no effect

Visual Verification of Contacts

- Never trust panel indicator lights alone (lamps can fail or stick)
- Operators must physically walk to the switchyard and visually confirm all 3 phases of an isolator are fully open
- Look for proper alignment of the male and female contacts when closed
- Binoculars are often used to inspect elevated isolators
- Confirming the physical 'air gap' is mandatory before issuing work permits

Isolation and Tagging (LOTO)

- Lockout / Tagout (LOTO) secures equipment for maintenance
- Lockout: Applying physical padlocks to isolator operating handles or control switches
- Tagout: Attaching prominent 'DO NOT OPERATE' warning tags with the operator's details
- Control circuit fuses are also pulled to prevent remote SCADA operation
- Ensures no one can accidentally re-energize the circuit while workers are present

Communication Protocols During Switching

- Use of three-way communication to prevent misunderstandings
- 1. Dispatcher gives command (e.g., 'Open Breaker 52-1')
- 2. Operator repeats command back ('Repeat: Open Breaker 52-1')
- 3. Dispatcher confirms ('That is correct, execute')
- Standardized nomenclature must be used (no slang or abbreviations)
- All commands are recorded in voice logs and written switching programs

Summary

- Breakers break load current; Isolators provide visual isolation and cannot break load
- Always operate Isolators under no-load conditions (Breaker open)
- Interlocks (electrical and mechanical) enforce proper switching sequences
- Visual verification of physical switchyard contacts is mandatory
- LOTO and strict communication protocols protect personnel during maintenance

Preview of Next Lecture

- Bus Transfer Operations
- Switching in Main and Transfer Bus schemes
- Double Bus Double Breaker operations
- Breaker-and-a-Half scheme switching complexities
- Transformer and Capacitor Bank switching

Routine Substation Operations (Part 2 of 3)

- Course: Substation Engineering (DI04009011)
- Unit 5: Auxiliary Systems and Routine Operations
- Lecture 24: Bus Transfer and Complex Switching

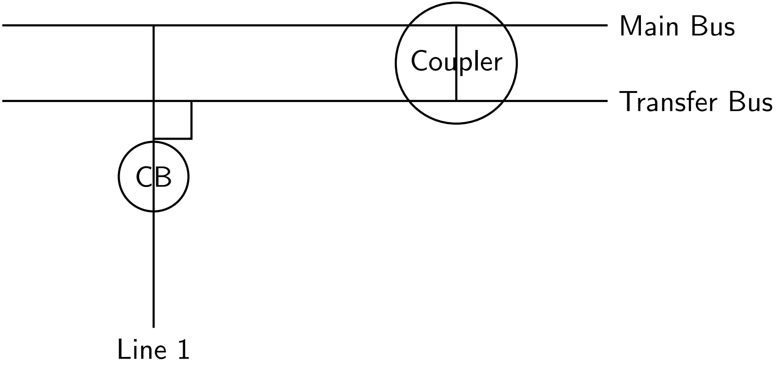
Agenda

- The Concept of Bus Transfer
- Main and Transfer Bus Switching Sequence
- Double Bus Single Breaker Transfer
- Breaker-and-a-Half Scheme Operations
- Transformer Energization (Inrush Current)
- Capacitor Bank and Reactor Switching

The Concept of Bus Transfer

- Objective: To take a busbar or a circuit breaker out for maintenance without interrupting power to the connected lines
- Requires 'paralleling' the two buses temporarily before opening the old path
- Make-before-break operation: The new path is closed before the old path is opened
- Requires careful synchronization and checking that phase angles are identical
- Protection relay settings often need to be modified or transferred during the process

Main and Transfer Bus Scheme (Review)



- Normal Operation: Line connects to Main Bus via its dedicated Line Breaker
- Transfer Bus is normally de-energized
- Bus Coupler Breaker (Transfer Breaker) is open
- Goal: Take the Line Breaker out for maintenance while keeping the line energized via the Transfer Bus

Switching Sequence: Main to Transfer Bus

- Step 1: Close Bus Coupler Isolators (Main and Transfer side)
- Step 2: Close Bus Coupler Breaker (energizes the Transfer Bus)
- Step 3: Verify Transfer Bus voltage is healthy
- Step 4: Close the Transfer Isolator for the specific line (parallels the breakers)
- Step 5: Open the Line's dedicated Circuit Breaker
- Step 6: Open the Line's Main Bus Isolator (isolates the breaker)

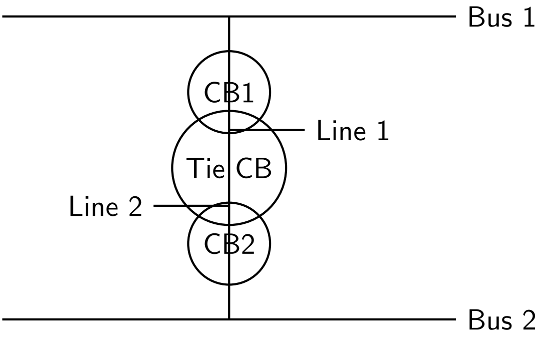
Protection Transfer During Bus Transfer

- When transferring a line to the Bus Coupler, the Line Breaker's protection relays must be switched over
- The Bus Coupler must now trip if a fault occurs on the line
- Trip circuits are physically switched using a 'Transfer Switch' on the control panel
- Current Transformer (CT) secondary circuits may also be switched to the Bus Coupler relays
- Failure to transfer protection leaves the line unprotected or causes bus bar trips

Double Bus Single Breaker Transfer

- Objective: Move a line from Bus 1 to Bus 2 without interruption
- Step 1: Close Bus Coupler Isolators and Breaker (parallels Bus 1 and Bus 2)
- Step 2: Close the Bus 2 Isolator for the target line (Make)
- Step 3: Open the Bus 1 Isolator for the target line (Break)
- Step 4: Open Bus Coupler Breaker (if required to split buses again)

Breaker-and-a-Half Scheme Operations



- Three breakers in series between two main buses, serving two circuits
- Normal operation: All three breakers are CLOSED. Both buses energized
- Taking a bus out: Simply open all breakers adjacent to that bus. No load is lost
- Taking a breaker out: Open the specific breaker and its

Switching Complexities Comparison

Bus Scheme	Operational Flexibility	Switching Complexity	Maintenance Outage Impact
Single Bus	Low	Simple	High (drops load)
Main & Transfer	Moderate	High (complex sequences)	Low (transfer via coupler)
Double Bus	High	High (bus paralleling)	Low
Breaker-and-a-Half	Very High	Low (just open breaker)	None (redundant paths)

Transformer Energization: Inrush Currents

- Energizing a power transformer draws a massive transient 'magnetizing inrush current'
- Can be up to 10-15 times the full load current, lasting several cycles
- Caused by the core magnetic flux saturating depending on the point-on-wave of closing
- Operations impact: Inrush can cause voltage dips on the busbar
- Differential relays must be configured with harmonic restraint to avoid false tripping during energization

Transformer Switching Sequences

- Always energize from the High Voltage (HV) side if possible (lower inrush current due to higher impedance)
- Energizing: Close HV breaker -¿ Wait for inrush to subside -¿ Close LV breaker to connect load
- De-energizing: Open LV breaker (drop load) -¿ Open HV breaker (drop magnetizing current)
- Tap changers (OLTC) should be set to proper tap before paralleling transformers
- Cooling fans/pumps must be confirmed operational

Capacitor Bank Switching

- Used for voltage support and power factor correction
- Switching capacitors causes severe high-frequency voltage and current transients
- Energizing creates high inrush currents; de-energizing risks restrikes in the breaker
- Point-on-Wave (Synchronous) Switching relays are often used to close contacts exactly at voltage zero
- Operators must wait for internal discharge resistors to drain voltage before re-closing (typically 5 minutes)

Reactor Switching Operations

- Shunt reactors absorb reactive power to lower voltage on long transmission lines
- Switching highly inductive loads is difficult for circuit breakers (current chopping)
- Current chopping forces current to zero prematurely, causing massive overvoltage spikes (L*di/dt)
- Breakers for reactors are often fitted with surge arresters or specialized contacts
- Synchronous switching is also used here (opening at current zero)

Summary

- Bus transfers require paralleling buses to allow make-before-break switching
- Protection schemes must be transferred along with the primary current paths
- Breaker-and-a-half schemes simplify switching by eliminating bus transfer sequences
- Transformer energization requires managing massive magnetizing inrush currents
- Switching reactive equipment (caps and reactors) creates severe electrical transients

Preview of Next Lecture

- Substation Grounding Procedures
- Temporary Protective Grounds
- Permit to Work (PTW) Systems
- Step and Touch Potential Risks during operations
- Logbooks, Shift Handovers, and Record Keeping

Routine Substation Operations (Part 3 of 3)

- Course: Substation Engineering (DI04009011)
- Unit 5: Auxiliary Systems and Routine Operations
- Lecture 25: Grounding, PTW, and Administration

Agenda

- Substation Grounding Procedures
- Earth Switches vs. Temporary Protective Grounds
- Applying and Removing Portable Grounds
- Step and Touch Potential Risks
- Permit to Work (PTW) System
- Logbooks and Shift Handovers

Substation Grounding (Earthing) Procedures

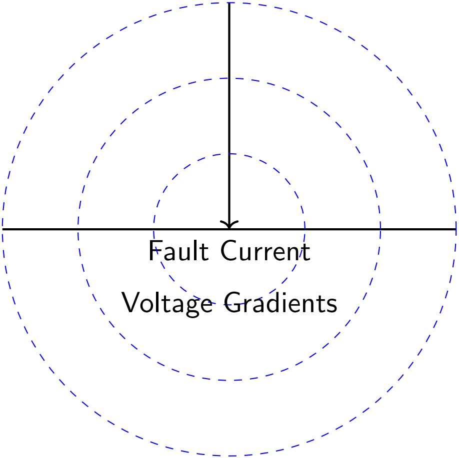
- De-energizing and isolating equipment is NOT enough to make it safe to touch
- Adjacent energized lines induce dangerous voltages (capacitive and inductive coupling) on isolated equipment
- Lightning strikes or accidental re-energization can occur
- All isolated equipment must be solidly grounded (earthed) before work begins
- Grounding creates an equipotential zone, keeping the worker at the same potential as the equipment

Earth Switches vs. Temporary Protective Grounds

Feature	Fixed Earth Switches	Temporary Protective Grounds (Portable)
Location	Permanently installed on isolators	Portable, carried by maintenance crews
Operation	Motorized or manual crank	Applied manually with hot sticks
Fault Rating	Rated for full system short circuit current	Rated based on cable size, subject to mechanical forces
Primary Use	Primary grounding of lines/buses	Working grounds applied directly at the work location

Applying Temporary Protective Grounds

- Rule 1: Always test for absence of voltage using a verified voltage detector before applying grounds
- Rule 2: ALWAYS connect the ground-end (earth grid) clamp FIRST
- Rule 3: Connect the phase-end (conductor) clamp LAST using an insulated hot stick
- Removal is the exact reverse: Remove phase-end first, ground-end last
- This ensures the operator is never in the path to ground if the line is accidentally live



- During a fault, massive current flows into the substation earth grid
- This raises the ground potential locally (Ground Potential Rise - GPR)

Permit To Work (PTW) System

Role	Responsibilities
Control Center (Dispatcher)	Authorizes the outage, oversees the grid
Authorized Person (Issuer)	Substation operator who executes switching, applies LOTO and fixed grounds, issues the PTW
Competent Person (Executor)	Maintenance supervisor who receives the PTW, applies portable grounds, and oversees the work party
Work Party	Technicians working under the Executor's supervision

Permit To Work Lifecycle

- 1. Request and Approval (days/weeks in advance)
- 2. Isolation and Earthing (performed by Operator)
- 3. Issue of Permit (Issuer explains hazards to Executor, both sign)
- 4. Execution of Work (Executor controls the work zone)
- 5. Clearance and Cancellation (Tools removed, personnel clear, Executor signs off)
- 6. Restoration (Operator removes LOTO and re-energizes)

Sanction for Test (SFT)

- A special type of permit used for testing equipment (e.g., relays, breaker timing, high voltage testing)
- Unlike a standard PTW, an SFT allows the temporary removal of grounds for testing purposes
- Requires stricter supervision because the equipment may become temporarily energized (e.g., via test sets)
- Work party must step out of the hazard zone during test injections
- Once testing is complete, grounds are reapplied or the equipment is returned to service

Substation Logbooks

- The official, legal record of all events in the substation
- Must record: Switching operations, alarms received, visitors entering/exiting, PTWs issued
- Written in indelible ink; mistakes are struck through with a single line and initialed (no white-out)
- Chronological order with exact time stamps
- Crucial for incident investigations and audits

Shift Handover Procedures

- The most critical time for operational errors is during shift changes
- Outgoing operator must brief the incoming operator on:
- 1. Current system configuration (abnormal alignments)
- 2. Active Permits to Work and grounded equipment
- 3. Active alarms or equipment defects
- Both operators must sign the logbook to formalize the transfer of responsibility

Emergency Operating Procedures

- In the event of a fire, explosion, or severe safety threat, operators have the authority to act without waiting for dispatcher orders
- Emergency trips can be initiated to de-energize the entire station
- Clearance distances must be maintained even during rescues
- Post-emergency: Secure the site, treat injured personnel, and preserve evidence
- Detailed incident reports follow immediately

Use of Personal Protective Equipment (PPE)

- Standard PPE: Hard hat, safety glasses, steel-toed boots, high-visibility clothing
- Arc Flash PPE: Flame-resistant (FR) clothing rated for the specific calorie/cm^2 exposure level
- Electrical PPE: Insulated rubber gloves with leather protectors (tested daily)
- PPE is the last line of defense in the safety hierarchy (after elimination and engineering controls)

Review of Routine Substation Operations

- Always prioritize safety: use breakers for load, isolators for isolation
- Respect interlocks and verify switchyard contacts visually
- Grounding (Earthing) is non-negotiable for working on isolated equipment
- The PTW system rigidly controls the transfer of equipment from operations to maintenance
- Accurate logbooks and shift handovers are essential for operational continuity

Course Wrap-up

- End of Module 5: Auxiliary Systems and Routine Operations
- Review all material for the final examination
- Focus on: Single Line Diagrams, Protection Schemes, Battery Sizing, and Switching Procedures
- Practical lab sessions will cover physical LOTO and Relay testing

Earthing Systems (IS 3043) (Part 1)

- Substation Earthing System
- Introduction to Earthing
- Guidelines as per IS 3043 Code of Practice

Lecture Agenda

- What is Earthing?
- Purpose and Need for Earthing
- Introduction to IS 3043 Standard
- System Earthing vs Equipment Earthing
- Types of Earth Electrodes
- Pipe Earthing Specifications
- Plate Earthing Specifications

Introduction to Earthing

- Earthing (Grounding) is the connection of the non-current carrying parts of electrical equipment or the neutral point of a supply system to the general mass of earth.
- It provides an intentional, low-impedance path for fault currents to flow into the earth.
- Earth acts as a massive sink with zero potential, ensuring equipment frames stay at zero volts.
- The connection is made via an 'Earth Electrode' buried in the ground.

Purpose and Need for Earthing

- Human Safety: Protects operating personnel from fatal electric shock in case of insulation failure.
- Equipment Protection: Provides a return path for fault currents, allowing protective relays to operate and isolate the faulty section.
- Voltage Stabilization: Maintains the voltage of healthy phases at a stable level during single line-to-ground faults.
- Lightning Protection: Discharges lightning surges and overvoltages safely to the ground.

Introduction to IS 3043

- IS 3043 is the Indian Standard Code of Practice for Earthing.
- Provides guidelines on design, installation, and maintenance of earthing systems.
- Covers definitions, soil resistivity measurement, calculation of earth fault currents, and selection of earthing conductors.
- Specifies the dimensions and materials for earth electrodes (pipe, plate, strip).
- Harmonizes with international standards while addressing specific Indian soil and environmental conditions.

Key Terminology in Earthing

- Earth Electrode: A metal plate, pipe, or rod driven into the ground to make electrical contact with the earth.
- Earth Continuity Conductor (ECC): The wire that connects equipment enclosures to the main earthing terminal.
- Earthing Lead: The conductor connecting the main earthing terminal to the earth electrode.
- Earth Resistance: The total resistance offered by the earth electrode and the surrounding soil to the flow of fault current.

Categories of Earthing

- Earthing systems in substations are broadly classified into two categories:
- 1. System Earthing (or Neutral Earthing)
- 2. Equipment Earthing (or Safety Earthing)
- Both are physically interconnected in a substation via the earth grid, but they serve different distinct purposes.

System Earthing (Neutral Earthing)

- Connecting the neutral point of a star-connected transformer or generator to earth.
- Purpose: Protects the system against arcing grounds and high overvoltages.
- Ensures relay operation by providing a closed loop for zero-sequence fault currents.
- Types: Solid earthing, Resistance earthing, Reactance earthing, Peterson coil earthing.
- Vital for stabilizing phase voltages during asymmetric faults.

Equipment Earthing (Safety Earthing)

- Connecting non-current carrying metallic parts (frames, enclosures, structures) to earth.
- Purpose: Ensures these parts remain at or near zero potential even if live parts accidentally touch them.
- Prevents electrocution of personnel.
- Requires very low resistance so fault current prefers the earth path over a human body.
- In substations, all transformer tanks, breaker bodies, isolator bases, and fences must be grounded.

Types of Earth Electrodes

- IS 3043 specifies several types of electrodes depending on soil conditions and fault current magnitude:
- 1. Pipe Electrode
- 2. Plate Electrode
- 3. Strip or Conductor Electrode
- 4. Rod Electrode
- For bulk installations like substations, Pipe and Plate earthing are historically common, while modern substations rely heavily on a buried grid (mesh) of strips.

Pipe Earthing Configuration

- A galvanized iron (GI) pipe is buried vertically in the earth.
- Surrounded by alternating layers of charcoal and salt to retain moisture and improve conductivity.
- A funnel is provided at the top for pouring water to maintain soil dampness.
- The earthing lead is bolted to the top of the pipe.

Diagram/Visual: Detailed cross-sectional diagram of pipe earthing showing GI pipe, perforations, charcoal/salt layers, and funnel assembly.

Pipe Earthing: IS 3043 Specifications

- Pipe Material: Galvanized Iron (GI) or Cast Iron.
- Pipe Internal Diameter: Minimum 38 mm for GI, 100 mm for Cast Iron.
- Pipe Length: Minimum 2.5 meters (for normal soil), up to 2.75m for dry soil.
- Depth of burial: The top of the pipe should not be less than 1.25 meters below ground level.
- Perforations: 12 mm diameter holes drilled at intervals for moisture diffusion.

Plate Earthing Configuration

- A copper or GI plate is buried vertically in a deep pit.
- Like pipe earthing, the plate is surrounded by 15 cm thick layers of charcoal and salt.
- Earthing lead is securely bolted to the plate using a GI or copper pipe.
- Offers a larger surface area in contact with the soil compared to a pipe.

Diagram/Visual: Cross-sectional diagram of plate earthing showing the vertical plate, bolted connection, and charcoal/salt fill.

Plate Earthing: IS 3043 Specifications

- Plate Dimensions: Minimum 60 cm x 60 cm (0.6m x 0.6m).
- Thickness: Minimum 3.15 mm for Copper, 6.3 mm for Galvanized Iron (GI).
- Depth of burial: Minimum 3.0 meters below ground level.
- Orientation: The plate must be placed vertically in the earth pit.
- Watering arrangement: A 19 mm dia pipe is provided to pour water and keep the pit moist.

Comparison: Pipe vs Plate Earthing

Feature	Pipe Earthing	Plate Earthing
Electrode	GI Pipe	Copper or GI Plate
Surface Area	Less	More (for a given depth)
Fault Current Capacity	Moderate	High
Cost	More Economical	Higher Cost (especially Copper)
Application	General purpose, domestic, small sub-stations	Heavy duty, power stations, large substations

Factors Influencing Earth Resistance

- Condition of the soil (moisture content).
- Temperature of the soil.
- Depth of the electrode.
- Spacing between multiple electrodes.
- Material and dimensions of the electrode.
- Presence of salts and chemical composition of the earth.

Summary of Lecture 26

- Earthing connects equipment to the general mass of earth for safety and protection.
- System earthing handles neutral points; Equipment earthing handles metallic enclosures.
- IS 3043 is the guiding Indian standard for earthing practices.
- Pipe and Plate earthing are two traditional methods, each with specific dimensional requirements.
- Charcoal and salt are used to artificially lower soil resistivity around the electrode.

Next Lecture Preview

- In the next lecture, we will discuss:
- Soil Resistivity and its measurement.
- Factors affecting Soil Resistivity.
- Measurement of Earth Resistance using the Fall of Potential method.
- Wenner 4-pin method for soil resistivity testing.

- Substation Earthing System
- Soil Resistivity & Earth Resistance Measurement

Lecture Agenda

- Concept of Soil Resistivity (ρ)
- Factors Affecting Soil Resistivity
- Wenner 4-Pin Method for Soil Resistivity
- Earth Resistance vs Soil Resistivity
- Acceptable Limits of Earth Resistance
- Measurement of Earth Resistance
- Fall of Potential Method and the 61.8% Rule

What is Soil Resistivity?

- Soil Resistivity (ρ) is a measure of how much the soil resists the flow of electricity.
- It is the resistance of a cube of soil of unit dimensions (1 meter x 1 meter x 1 meter).
- Unit: Ohm-meters (Ω·m).
- It is a key variable in designing any substation earthing grid; you cannot design an earth grid without knowing this value.

Importance in Earthing Design

- Determines the size, spacing, and burial depth of the earth grid conductors.
- Affects the Step and Touch potentials (which we cover in Part 3).
- High soil resistivity requires more extensive and expensive earthing networks (more electrodes, longer trenches).
- Soil resistivity varies wildly from place to place and even at different depths in the same location.

Factors Affecting Soil Resistivity: Moisture & Temp

- Moisture Content: Dry soil has high resistivity. Adding moisture drastically lowers resistivity up to about 20% moisture content.
- Temperature: Resistivity increases as temperature drops. If soil freezes (drops below 0°C), resistivity spikes dramatically.
- This is why earth electrodes must be buried deep enough to be below the frost line and reach permanent moisture.

Factors Affecting Soil Resistivity: Soil Type & Salts

- Type of Soil: Loam, clay, and marshy soils have low resistivity (10-50 Ω·m). Sandy and rocky soils have high resistivity (1000+ Ω·m).
- Chemical Composition (Salts): Pure water is a poor conductor. The presence of dissolved salts provides ions for current flow.
- Artificial Treatment: IS 3043 recommends treating soil with salt (NaCl), magnesium sulfate, or copper sulfate if natural resistivity is too high.

Measuring Soil Resistivity

- To design an earthing system, the designer needs a soil resistivity profile of the site.
- Measurements must be taken at multiple locations across the substation site.
- Measurements should reflect conditions at different depths.
- The standard method endorsed by IEEE 80 and IS 3043 is the Wenner 4-Pin Method.

Wenner 4-Pin Method

- Four test spikes (electrodes) are driven into the ground in a straight line at equal spacing 'a'.
- An earth tester injects a known current (I) between the two outer current spikes (C1, C2).
- The voltage drop (V) is measured between the two inner potential spikes (P1, P2).
- The tester calculates the resistance $R = V/I$.

Diagram/Visual: Diagram of four pins labeled C1, P1, P2, C2 with spacing 'a'. Current loops going deep into the earth.

Wenner Method Formula

- The apparent soil resistivity (ρ) is calculated as:
- $\rho = 2 * \pi * a * R$
- Where:
- $\rho =$ Apparent soil resistivity in Ohm-meters
- a = Distance between adjacent spikes in meters
- R = Resistance value read from the earth tester in Ohms
- Note: The depth of the spikes (b) should be small compared to 'a' (usually b ¡ a/20) so it can be ignored.

Earth Resistance vs Soil Resistivity

- Soil Resistivity (ρ): A property of the earth itself. Measured before the substation is built. Used to design the grid.
- Earth Resistance (R): The resistance of the installed electrode/grid to the earth. Measured after installation to verify the design.
- Objective: Design an electrode system in soil of resistivity ρ such that the final Earth Resistance R meets the required safety limits.

Acceptable Limits of Earth Resistance

Installation Type	Maximum Acceptable Resistance
Large Power Stations	0.5 Ohms
Major Substations (Grid)	1.0 Ohms
Small Substations	2.0 Ohms
Industrial Plant	1.0 Ohms
Domestic Installation	5.0 - 8.0 Ohms

Measurement of Earth Resistance

- Once an electrode (or grid) is installed, its resistance to the general mass of earth must be tested.
- Requires measuring the voltage drop and current flow through the electrode.
- The standard method used is the Fall of Potential Method (also known as the 3-terminal method).
- Uses an Earth Megger (Earth Tester).

Fall of Potential Method

- The electrode under test is terminal 'E'.
- A current spike 'C' is driven far away from 'E'. Current I is passed between E and C.
- A potential spike 'P' is driven between E and C. Voltage V is measured between E and P.
- Resistance R = V / I.
- The potential spike 'P' is moved to different positions to find the true resistance.

Diagram/Visual: Diagram showing the Earth electrode E, Potential probe P, and Current probe C. E, P, and C are in a straight line.

Fall of Potential: Procedure and Curve

- Plot resistance values on the Y-axis and distance of probe 'P' on the X-axis.
- Near 'E', the resistance rises steeply (influence zone of electrode E).
- Near 'C', the resistance rises steeply again (influence zone of spike C).
- In the middle, there should be a flat section (the 'plateau').
- The true earth resistance is the value at this flat plateau.

The 61.8% Rule

- Finding the plateau can be tedious.
- Mathematical analysis shows that for a hemispherical electrode, the true resistance occurs when the potential probe 'P' is placed at exactly 61.8% of the distance to the current probe 'C'.
- If distance to C is D, place P at 0.618 * D.
- This is widely used in field testing to get a quick and accurate reading.

Practical Challenges in Measurement

- Stray Currents: Underground pipes, railway tracks, and existing grid currents can interfere with the earth tester readings.
- Large Grid Sizes: For a large substation, the current probe 'C' must be placed very far away (up to 5-10 times the diagonal of the grid) to get a true plateau. Finding space for this is hard.
- Test Frequency: Testers use AC (e.g., 128 Hz) rather than 50 Hz to avoid interference from the power system frequency.

Summary of Lecture 27

- Soil resistivity is critical for design and depends heavily on moisture, temp, and soil type.
- Wenner 4-pin method is standard for measuring soil resistivity ($\rho = 2\pi$aR).
- Earth resistance must be ¡ 1 Ohm for major substations.
- Fall of Potential method (3-pin) is used to measure installed earth resistance.
- The 61.8% rule simplifies finding the true resistance on the Fall of Potential curve.

Next Lecture Preview

- In Part 3, we will cover:
- Substation Earth Grid (Mat) design.
- Tolerable limits of body current.
- Understanding Step Potential and Touch Potential.
- Design considerations based on IEEE 80 / IS 3043.

Earthing Systems (IS 3043) (Part 3)

- Substation Earthing System
- Earth Grid Design, Step & Touch Potentials

Lecture Agenda

- The Substation Earth Grid (Earth Mat)
- Ground Potential Rise (GPR)
- Human Body Limits to Electric Current
- Understanding Step Potential
- Understanding Touch Potential
- Mesh and Transferred Potentials
- Earth Grid Design Steps (IEEE 80 / IS 3043)
- Safety Enhancements (Crushed Rock, Rods)

The Substation Earth Grid (Earth Mat)

- In large substations, isolated earth pits (pipes/plates) cannot handle massive fault currents (e.g., 40 kA to 60 kA).
- Instead, a network of bare conductors is buried in a crisscross pattern over the entire substation area.
- This is called an Earth Grid or Earth Mat.
- Equipment is connected to this mat via multiple risers.
- Buried typically at 0.5m to 1.0m depth.

Ground Potential Rise (GPR)

- During a severe earth fault, thousands of amperes flow into the earth mat.
- Ohm's Law applies: $V = I * R$.
- GPR = (Maximum Grid Current) * (Grid Resistance).
- If grid current = 10,000 A and Grid Resistance = 0.5 Ohms, the voltage of the grid (and everything connected to it) rises to 5,000 Volts above remote earth.
- This voltage rise creates life-threatening gradients on the surface.

Human Body Resistance & Limits

- For earthing calculations, the human body resistance is standardized at 1000 Ohms.
- Currents above 50-100 mA can cause ventricular fibrillation (fatal disruption of heart rhythm).
- Tolerable body current depends on fault duration (clearing time).
- Faster relay operation means higher tolerable current limits.
- Formula (50kg body): $I\_B = 0.116 / sqrt(t)$, where t is fault clearing time in seconds.

Step Potential

- Definition: The voltage difference between a person's two feet while standing 1 meter apart on the ground during a fault.
- As current flows through the earth, voltage drops occur across the soil.
- If a person steps across this voltage gradient, a current path forms up one leg and down the other.
- Current bypasses the vital organs, but can cause violent muscle contraction.

Diagram/Visual: Diagram of a person walking near a fault. Equipotential lines on the ground show different voltages under each foot. Current loops up one leg and down the other.

Touch Potential

- Definition: The voltage difference between the ground where a person is standing and the grounded metallic structure they are touching.
- Current path: Enters via the hand, flows through the heart region, and exits via the feet.
- Highly dangerous and often fatal if limits are exceeded.
- Grid must be designed so Actual Touch Potential ¡ Tolerable Touch Potential.

Diagram/Visual: Diagram of a person touching a transformer tank. Current flows from the tank, through the hand, heart, out the feet into the ground.

Mesh and Transferred Potentials

- Mesh Potential: The maximum touch voltage within a mesh of the grid. Occurs at the center of the grid square, furthest from any buried conductor.
- Transferred Potential: A special case of touch potential where a voltage is transferred into or out of the substation by an external conductor (e.g., a railway track, communication cable, or neutral wire).
- Transferred potentials can subject distant personnel to the full Ground Potential Rise of the substation.

Designing the Earth Grid: IEEE 80 / IS 3043

- The standard for earth grid design globally is IEEE 80. IS 3043 incorporates these principles.
- Goal 1: Ensure Grid Resistance is low enough.
- Goal 2: Ensure Step and Touch potentials are within safe limits.
- Design is an iterative process: guess a layout, calculate potentials, check if safe. If not, add more conductors.

Earth Mat Design Steps

- 1. Collect Field Data: Soil resistivity (ρ), Fault current (If), Fault duration (tc).
- 2. Calculate Conductor Size: Based on thermal limits to withstand short circuit current.
- 3. Calculate Tolerable Limits: E_step and E_touch for 50kg/70kg body.
- 4. Initial Design: Lay out a grid with spacing D, depth h, total length L.
- 5. Calculate Grid Resistance (R).
- 6. Calculate Actual Mesh and Step Potentials.
- 7. Verify: Actual ¡ Tolerable. If so, design is safe.

Conductor Sizing

- The grid conductor (usually Mild Steel or Copper) must not melt during the fault.
- Size depends on:
- - Maximum RMS fault current.
- - Fault clearing time.
- - Maximum allowable temperature (e.g., 500°C for welded joints).
- Formula relies on the specific heat and thermal conductivity of the material.

Improving Safety: Crushed Rock Layer

- Substation yards are covered with a 10-15 cm layer of crushed rock (gravel).
- Why?
- High Surface Resistivity: Dry rock has a resistivity of ˜3000 Ω·m.
- It acts as a high-resistance layer under the feet of personnel.
- This drastically increases the contact resistance of the feet, thereby increasing the Tolerable Step and Touch potential limits.

Use of Earth Rods in Grid Design

- A purely horizontal grid might not reach deep, low-resistivity soil layers.
- Vertical earth rods (pipes/rods) are welded to the grid at the perimeter and key interior points.
- Benefits:
- - Lowers overall grid resistance (reaches moisture).
- - Prevents surface freezing from ruining grid performance.
- - Discharges lightning and steep-front surges effectively.

Grid Spacing Optimization

- Mesh spacing is not always uniform.
- Voltage gradients are steepest at the edges and corners of the grid.
- To economize on copper/steel, engineers use unequally spaced grids.
- Meshes are closely spaced at the perimeter (e.g., 1m x 1m) and widely spaced in the center (e.g., 5m x 5m).

Comparison of Mitigation Methods

Problem	Mitigation Technique	Effect
High Grid Resistance	Add vertical rods / treat soil	Lowers R, lowers GPR
High Step Potential	Decrease mesh spacing / add gravel	Smooths gradient, increases foot resistance
High Touch Potential	Tighter mesh near equipment	Reduces voltage diff between mat and soil
Transferred Potential	Isolate fences / use fiber optics	Prevents voltage export

Summary of Substation Earthing

- Earthing grids distribute high fault currents over a large area.
- Ground Potential Rise (GPR) creates dangerous surface voltage gradients.
- Step and Touch potentials dictate human survival during faults.
- IEEE 80 / IS 3043 provide the iterative steps for safe mat design.
- Gravel surfacing is a critical safety component in substations.

Next Unit Preview: Compensation Equipment

- Next, we begin Unit 6: Reactive Power Compensation.
- Why do we need compensation in power systems?
- Shunt Capacitors for power factor improvement.
- Series Capacitors for line reactance compensation.

Compensation Equipment (Part 1)

- Reactive Power Compensation
- Shunt and Series Capacitors

Lecture Agenda

- What is Reactive Power?
- The Need for Compensation
- Types of Compensation (Series vs Shunt)
- Shunt Capacitors: Operation and Benefits
- Location of Shunt Capacitors
- Series Capacitors: Operation and Benefits
- Increasing Power Transfer Capability
- Challenges with Series Capacitors (SSR)

Understanding Reactive Power (Q)

- In AC systems, power has two components: Active (P, in MW) and Reactive (Q, in MVAR).
- Active power does real work (spins motors, lights lamps).
- Reactive power sustains the electromagnetic fields of inductive equipment (transformers, induction motors).
- Q continuously oscillates between the source and the load.
- It does no useful work but occupies capacity in the transmission lines.

Why is Reactive Power Problematic?

- 1. Increased Line Losses: Flow of Q increases the total current (I). Since losses are I^2R, more Q means higher thermal losses.
- 2. Voltage Drop: Reactive current flowing through the line reactance (X) causes a significant voltage drop ($\Delta V \approx Q*X/V$).
- 3. Reduced Capacity: The apparent power limit (MVA) of transformers and lines gets filled up by Q, leaving less room for real power (P).
- 4. Poor Power Factor: Requires generators to operate at lower power factors.

The Need for Compensation

- Instead of transmitting Q from the generator, we 'compensate' or generate it locally near the load.
- Objectives of Compensation:
- - Improve voltage profile across the network.
- - Improve Power Factor (PF).
- - Reduce I^2R losses in transmission lines.
- - Increase the active power transfer capability of existing lines.

Types of Compensation Methods

- Compensation equipment is classified by how it is connected to the network:
- 1. Shunt Compensation: Connected in parallel with the load/line.
- - E.g., Shunt Capacitors, Shunt Reactors.
- 2. Series Compensation: Connected in series with the transmission line.
- - E.g., Series Capacitors.
- We can also classify them as Passive (fixed/switched capacitors) or Active/Dynamic (SVC, STATCOM).

Shunt Capacitors: Function

- Most industrial loads (motors) are highly inductive (lagging PF).
- Shunt capacitors draw leading reactive current.
- This leading current locally cancels out the lagging reactive current demanded by the load.
- Result: The generator only needs to supply active power (P), and power factor near the source becomes close to unity.

Diagram/Visual: Phasor diagram showing inductive load current (lagging) and capacitor current (leading) summing to a smaller total current.

Advantages of Shunt Capacitors

- Cost-effective and simple to install.
- Improves voltage at the load bus (boosts sagging voltages).
- Reduces kVA demand on the supplying transformers.
- They can be switched in and out in steps (using circuit breakers) depending on the load demand.
- Zero active power consumption (ideally).

Location of Shunt Capacitors

- The closer the capacitor is to the inductive load, the better.
- 1. Load Level: Directly at the motor terminals (best, but expensive).
- 2. Plant Level: At the main LV busbar of an industry (common).
- 3. Substation Level: Large capacitor banks connected to the MV/HV busbars of a distribution substation.
- Substation banks correct the PF of an entire feeder.

Series Compensation Overview

- Used on very long Extra High Voltage (EHV) transmission lines.
- Long lines have high inductive reactance (X_L), which restricts power flow.
- A capacitor is connected in series with the line phase conductor.
- The capacitive reactance (X_C) cancels out a portion of the line's inductive reactance (X_L).
- Net line reactance becomes: $X_{net} = X_L - X_C$.

Power Transfer Capability

- Power flow equation: P = (Vs * Vr * sin(δ)) / X_net
- By reducing X_net using series capacitors, the maximum power P_max increases significantly.
- Degree of Compensation (k) = X_C / X_L.
- Usually, k is kept between 20% to 70%.
- Allows utilities to push more megawatts through existing right-of-ways without building new towers.

Voltage Stability with Series Capacitors

- Unlike shunt capacitors which provide a fixed voltage boost regardless of load, series capacitors are self-regulating.
- Voltage boost = I * X_C.
- When load current (I) increases, the voltage boost automatically increases.
- Excellent for improving voltage stability on long lines subjected to rapid load changes.

Challenges with Series Capacitors: SSR

- Sub-Synchronous Resonance (SSR).
- The series capacitor forms an LC resonant circuit with the line inductance.
- This electrical resonance can interact with the mechanical torsional frequencies of nearby turbine-generator shafts.
- If resonance occurs, it can physically snap the generator shaft.
- Requires complex damping and bypass schemes (e.g., spark gaps, MOVs) to protect the equipment during faults.

Comparison: Shunt vs Series Capacitors

Feature	Shunt Capacitor	Series Capacitor
Connection	Parallel to load/bus	Series with line
Primary Purpose	Power Factor correction	Increase power transfer limit
Voltage Boost	Fixed (if unswitched)	Proportional to load current
Application	Distribution & Transmission	Long EHV Transmission lines
Fault Current Effect	Little effect	Increases short-circuit levels

Equipment layout of Series Capacitors

- Because it is in series with the line, the entire capacitor bank sits at line voltage (e.g., 400kV).
- The banks are mounted on fully insulated platforms.
- Requires an intricate bypass circuit (Bypass breaker, Metal Oxide Varistor) to protect the capacitor from blowing up during a line fault.

Diagram/Visual: Diagram showing the main capacitor in parallel with an MOV, a spark gap, and a bypass breaker.

Summary of Lecture 29

- Reactive power increases losses and causes voltage drops.
- Compensation generates reactive power locally.
- Shunt capacitors improve power factor and support voltage.
- Series capacitors reduce line reactance, boosting power transfer limits.
- SSR is a major mechanical risk associated with series compensation.

Next Lecture Preview

- In Part 2, we will explore:
- Shunt Reactors (to prevent overvoltage).
- Synchronous Condensers (rotating compensation).
- Static Var Compensators (SVC).
- STATCOM (Advanced dynamic compensation).

Compensation Equipment (Part 2)

- Reactive Power Compensation
- Reactors, Synchronous Condensers & FACTS

Lecture Agenda

- The Ferranti Effect on lightly loaded lines
- Shunt Reactors: Function and Construction
- The need for Dynamic Compensation
- Synchronous Condensers
- Introduction to FACTS technology
- Static Var Compensator (SVC)
- Static Synchronous Compensator (STATCOM)
- Comparison of SVC and STATCOM

The Ferranti Effect

- Occurs on long, lightly loaded or open-circuited EHV transmission lines.
- The line capacitance generates huge amounts of reactive power (charging current).
- This capacitive current flows through the line inductance, causing a voltage rise.
- Result: The receiving end voltage (Vr) becomes significantly higher than the sending end voltage (Vs).
- Can lead to insulation failure of substation equipment.

Diagram/Visual: Phasor diagram showing the capacitive charging current leading the voltage, resulting in Vr ¿ Vs.

Shunt Reactors: Function

- To counter the Ferranti effect, we use Shunt Reactors.
- A reactor is essentially a giant inductor connected in parallel (shunt) with the line.
- It absorbs the excess capacitive reactive power generated by the long line.
- Keeps the receiving end voltage within safe operational limits during light load conditions.

Shunt Reactors: Construction

- They look very similar to power transformers (oil-filled, radiators, bushings).
- However, they only have one winding per phase.
- The magnetic core is heavily gapped (air gaps) to prevent magnetic saturation from the continuous high reactive current.
- Can be connected directly to the EHV line or to the tertiary winding of a transformer.

The Need for Dynamic Compensation

- Fixed capacitors and reactors are 'passive'. They are either ON or OFF.
- Mechanical switching via circuit breakers is slow and causes voltage transients.
- Modern grids with renewable energy and fluctuating industrial loads (like arc furnaces) require instantaneous, continuous, step-less reactive power control.
- Solution: Dynamic Compensation devices.

Synchronous Condensers

- A synchronous motor running without a mechanical load.
- By varying the DC excitation field, it can either generate or absorb reactive power smoothly.
- Over-excited: Acts like a capacitor (supplies Q, boosts voltage).
- Under-excited: Acts like a reactor (absorbs Q, lowers voltage).
- Provides crucial mechanical inertia to the grid.

Pros and Cons of Synchronous Condensers

Advantages	Disadvantages
Provides smooth, stepless Q control	High maintenance (rotating parts)
Adds short-circuit strength to the grid	Slower response than static devices
Provides physical inertia for frequency stability	Significant active power losses to keep spinning
Can survive severe voltage dips without tripping	Very expensive foundation and installation

Introduction to FACTS

- FACTS: Flexible AC Transmission Systems.
- Uses high-power electronics (Thyristors, IGBTs) to control power flow and improve stability.
- Offers millisecond response times.
- Two main shunt FACTS devices for reactive compensation:
- 1. SVC (Static Var Compensator)
- 2. STATCOM (Static Synchronous Compensator)

Static Var Compensator (SVC)

- An SVC uses Thyristors to rapidly switch capacitors or control reactors.
- Components:
- - TCR: Thyristor Controlled Reactor (allows continuous absorption of Q).
- - TSC: Thyristor Switched Capacitor (steps of Q generation).
- - Harmonic Filters.
- The control system adjusts the thyristor firing angles to maintain exact bus voltage.

Diagram/Visual: Schematic of an SVC showing a TCR (inductor with anti-parallel thyristors) and TSC (capacitor with thyristors) connected to a bus via a step-down transformer.

SVC Operation Characteristics

- Provides smooth control from lagging (inductive) to leading (capacitive).
- Disadvantage: The reactive power generated by a capacitor is proportional to the square of the voltage ($Q = V^2/Xc$).
- If grid voltage drops severely (e.g., during a fault), the SVC's ability to inject Q drops drastically exactly when it is needed most.
- Creates harmonic distortion (due to TCR switching), requiring bulky filter banks.

STATCOM (Static Synchronous Compensator)

- The most advanced shunt compensator.
- Uses a Voltage Source Converter (VSC) with IGBTs and a DC capacitor.
- It electronically synthesizes a 3-phase AC voltage waveform.
- If synthesized voltage ¿ Grid voltage: Injects Q (Acts capacitive).
- If synthesized voltage ¡ Grid voltage: Absorbs Q (Acts inductive).

Diagram/Visual: Block diagram of a STATCOM: DC Capacitor -¿ VSC (IG-BTs) -¿ Coupling Transformer -¿ Grid.

Advantages of STATCOM over SVC

- Constant Current Capability: STATCOM can provide full rated capacitive current even if the grid voltage drops to near zero.
- Faster Response: Uses IGBTs which switch at high frequencies, offering sub-cycle response times.
- Smaller Footprint: Does not require bulky passive reactors and large capacitor banks. Takes up much less land in the substation.
- Less Harmonic Filtration needed.

Comparison: SVC vs STATCOM

Feature	SVC	STATCOM
Technology	Thyristors (LCC)	IGBTs (VSC)
Space Required	Large (Capacitor/Filter yards)	Small (Compact indoor valves)
Low Voltage Performance	Poor (Q drops with V^2)	Excellent (Constant current)
Response Time	Fast (1-2 cycles)	Very Fast (¡1 cycle)
Cost	Lower	Higher

Summary of Compensation Equipment

- Shunt Reactors control the Ferranti effect by absorbing Q.
- Synchronous Condensers offer dynamic Q and mechanical inertia.
- FACTS devices (SVC/STATCOM) provide sub-second electronic voltage control.
- SVC uses switched passive components.
- STATCOM synthesizes waveforms electronically for superior low-voltage performance.

End of Unit 6 / Preview

- This concludes Unit 6 on Reactive Power Compensation.
- In the next series of lectures, we will move to Unit 7:
- Substation Automation and SCADA Systems.
- Introduction to IEC 61850.

Safety Standards and Regulations (Part 1 of 2)

- Substation Engineering
- Lecture 31
- Unit 5: Substation Safety and Regulations

Agenda

- Introduction to Substation Safety
- Primary Safety Hazards
- Regulatory Bodies and Standards Overview
- National Electrical Safety Code (NESC)
- IEEE Std 80: Safety in AC Substation Grounding
- Step and Touch Potentials
- Human Body Resistance Model

Introduction to Substation Safety

- Substations are inherently dangerous environments due to high voltage equipment
- Safety must be integrated into the design phase, not just operation
- Primary goal: Protect personnel (utility workers) and the public
- Secondary goal: Protect equipment from damage during faults
- Compliance with safety standards is mandatory and legally enforced

Primary Safety Hazards in Substations

- Electric Shock: Contact with energized parts or unacceptable ground potentials
- Arc Flash: Explosive release of energy due to an electrical arcing fault
- Magnetic and Electric Fields (EMF): Exposure limits for personnel
- Fire and Explosions: From oil-filled equipment like transformers
- Trips and Falls: Uneven terrain, trenches, and elevated work

Regulatory Bodies and Standards Overview

- Safety is governed by a combination of national codes and industry standards
- Codes provide the 'what' (legal minimum requirements)
- Standards provide the 'how' (engineering practices to meet the codes)
- Major organizations: IEEE, ANSI, NEMA, OSHA, NFPA
- Local jurisdictions may have additional specific requirements

Key Substation Safety Standards

IEEE 80	Guide for Safety in AC Substation Grounding
NESC (IEEE C2)	National Electrical Safety Code
NFPA 70E	Standard for Electrical Safety in the Workplace
IEEE 979	Guide for Substation Fire Protection
OSHA 1910.269	Electric Power Generation, Transmission, and Distribution

National Electrical Safety Code (NESC)

- Published by IEEE, updated every 5 years
- Sets ground rules for practical safeguarding of persons during installation, operation, and maintenance
- Covers supply and communication lines, and associated equipment
- Adopted as law by most US states and Public Utility Commissions
- Part 1 specifically covers Rules for the Installation and Maintenance of Electric Supply Stations

NESC Rules for Substations (Part 1)

- Rule 110: General Requirements (Enclosure of equipment, rooms, and spaces)
- Rule 111: Illumination requirements under normal and emergency conditions
- Rule 112: Floor, floor openings, passageways, and stairs
- Rule 124: Guarding live parts (clearance from live parts)
- Fences must be minimum 7 feet high (often 6 ft fabric + 1 ft barbed wire)

IEEE 80: Guide for Substation Grounding

- Primary standard for designing safe grounding systems in AC substations
- Objective 1: Provide means to carry electric currents into the earth under normal and fault conditions
- Objective 2: Assure that a person in the vicinity is not exposed to danger of critical electric shock
- Establishes safe limits for potential differences during a fault
- Provides mathematical models for calculating grounding grid resistance

Step and Touch Potential Concept

Fault current flows into the ground grid, causing a Ground Potential Rise (GPR)
Step Potential: Voltage difference between a person's two feet (1 meter apart)
Touch Potential: Voltage difference between a person's hand touching a grounded structure and their feet
Mesh Potential: Maximum touch voltage within a mesh of a ground grid
Current through the heart is the fatal mechanism (fibrillation)

Touch Voltage Limits

- Most critical safety criteria in substation design
- Assumes a person is standing on the ground and touching a grounded structure
- Current path is from hand to both feet
- Calculated touch voltage must be less than the 'Tolerable Touch Voltage'
- Addition of crushed rock on the surface increases contact resistance to shoes

Step Voltage Limits

- Voltage between two points on the earth surface 1 meter apart
- Current path is from one foot, through the legs, to the other foot
- Does not usually pass directly through the heart, making it slightly less lethal
- Tolerable step voltage is much higher than tolerable touch voltage
- Calculated step voltage must be less than 'Tolerable Step Voltage'

Human Body Resistance Model

- IEEE 80 models the human body resistance (Rb) as 1000 Ohms
- This value represents hand-to-feet or foot-to-foot resistance
- Skin resistance is ignored because high voltage breaks it down instantly
- Fibrillation current thresholds are based on body weight (50 kg and 70 kg models)
- Formula for permissible body current: Ib = k / sqrt(ts)

Tolerable Body Current (IEEE 80)

Body Weight	Formula for Fibrillation Limit
50 kg person	Ib = 0.116 / sqrt(ts)
70 kg person	Ib = 0.157 / sqrt(ts)
ts (Fault Time)	Typically 0.5 seconds for backup clearing
Note: 70 kg allows slightly higher current	

Fault Current and Clearing Time

- The safety limits are heavily dependent on time (ts)
- Faster relay operation and circuit breaker clearing = higher tolerable voltages
- Typical fault durations used for safety calculation: 0.25 to 0.5 seconds
- Backup clearing time must be considered in case primary protection fails
- Ground grid must be designed for the maximum expected future fault current

Safe Grounding Grid Requirements

- If Actual Mesh Voltage ¡ Tolerable Touch Voltage, design is safe
- If Actual Step Voltage ¡ Tolerable Step Voltage, design is safe
- If criteria are not met: add more conductors, use ground rods, or increase surface rock layer
- Software tools like CDEGS or ETAP are used for complex 3D grid modeling
- Final design must be validated by field testing after construction

Summary

- Substation safety is governed by strict codes (NESC) and standards (IEEE 80)
- NESC dictates physical requirements like fences and guarding
- IEEE 80 provides the engineering foundation for safe ground grids
- Step and Touch potentials are the primary metrics for shock hazard
- Tolerable limits depend on human body weight and fault clearing time

Next Lecture Preview

- Safety Standards and Regulations (Part 2 of 2)
- Electrical clearance distances in detail
- Fire protection and oil containment
- Personal Protective Equipment (PPE) for arc flash
- Lockout/Tagout (LOTO) procedures

Safety Standards and Regulations (Part 2 of 2)

- Substation Engineering
- Lecture 32
- Unit 5: Substation Safety and Regulations

Agenda

- Electrical Safety Clearances
- NESC Clearance Requirements
- Substation Fire Protection
- Oil Containment and Environmental Regulations
- Arc Flash Hazards
- Personal Protective Equipment (PPE)
- Lockout/Tagout (LOTO) Procedures

Electrical Safety Clearances

- Clearances are the minimum required air distances between objects
- Phase-to-Phase (P-P): Distance between energized conductors
- Phase-to-Ground (P-G): Distance between energized part and grounded structure
- Safety Clearances: Distance between energized parts and areas accessible to personnel
- Air is the primary insulating medium in Air Insulated Substations (AIS)

NESC Clearance to Live Parts

- NESC Rule 124 mandates guarding of live parts
- Live parts must be placed at a vertical and horizontal distance out of reach
- Vertical Clearance: Distance from the ground up to the lowest live part
- Horizontal Clearance: Distance from a walkway to a live part
- Distances scale exponentially with system voltage and Basic Insulation Level (BIL)

Minimum Clearance Distances (NESC)

Nominal Voltage (kV)	Vertical Clearance	Horizontal Clearance
15 kV	9 ft 0 in	3 ft 4 in
34.5 kV	9 ft 3 in	3 ft 7 in
115 kV	11 ft 2 in	5 ft 5 in
230 kV	15 ft 3 in	9 ft 7 in
345 kV	18 ft 5 in	12 ft 9 in

Working Clearances and Maintenance

- Clearances must allow for safe maintenance of de-energized equipment while adjacent bays are energized
- Minimum Approach Distance (MAD): Safest distance a qualified worker can approach an energized object
- Vehicle Clearance: Access roads must allow bucket trucks to pass under live buses
- Fences must be placed far enough from live parts to prevent accidental contact from outside

Fire Protection in Substations

- Guided by IEEE 979 and NFPA standards
- Primary fire risk: Mineral oil in large power transformers
- A transformer failure can result in an explosion and oil pool fire
- Risk mitigation: Physical separation between transformers
- Fire Walls (Blast Walls): Used when adequate physical separation is not possible

Fire Suppression Systems

- Active systems designed to extinguish or control fires
- Water Deluge Systems: Spray rings around the transformer
- Foam Systems: Suppress oil fires rapidly
- Nitrogen Injection: Depressurizes the transformer tank and injects inert gas to prevent explosion
- Control house fire alarms and clean agent suppression (FM-200 / Novec 1230)

Oil Containment and SPCC Plans

- Environmental regulation: Spill Prevention, Control, and Countermeasure (SPCC)
- Mandated by the EPA to prevent oil discharge into navigable waters
- Substations with ¿1320 gallons of oil require an SPCC plan
- Secondary Containment: Moats, pits, or berms around transformers
- Containment must hold 100% of the oil of the largest piece of equipment + rainwater

Arc Flash Hazards

- An arc flash is a rapid release of energy due to an arcing fault
- Generates extreme heat (up to 35,000°F), blinding light, and acoustic blast
- Most common during switching operations or racking circuit breakers
- NFPA 70E provides guidelines for arc flash risk assessment
- Arc flash boundaries must be calculated and labeled on equipment

Personal Protective Equipment (PPE)

- Last line of defense against electrical hazards
- Standard PPE: Hard hat, safety glasses, steel-toe EH rated boots
- Arc-Rated (AR) Clothing: Flame resistant daily wear (Category 2)
- Arc Flash Suits: Full 'bomb suit' for high energy tasks (Category 4)
- Voltage-rated rubber gloves with leather protectors for live work

Lockout/Tagout (LOTO) Procedures

- OSHA mandated procedure to ensure equipment is completely de-energized
- 1. Identify and shut down the equipment
- 2. Isolate from all energy sources (open disconnects)
- 3. Apply locks and tags to the isolation devices
- 4. Verify absence of voltage (Test Before Touch)
- 5. Apply personal grounds

Test Before Touch & Personal Grounds

- Never assume a circuit is dead based on a breaker position
- Use rated voltage detectors (hot sticks) to verify zero energy
- Induced voltages can still be lethal in de-energized lines
- Personal Protective Grounding (PPG) cables must be applied after testing
- Creates a short circuit to ground to trip breakers if accidentally energized

Substation Security

- Physical security is critical to prevent vandalism, theft (copper), and sabotage
- NERC CIP (Critical Infrastructure Protection) mandates security for critical bulk power assets
- Measures include access control, perimeter fencing, surveillance cameras
- Ballistic walls may be used for critical transformers to prevent sniper attacks
- Cybersecurity of control systems (SCADA) is increasingly critical

Summary

- Electrical clearances (vertical and horizontal) ensure safe spaces for personnel
- Fire protection and oil containment protect adjacent equipment and the environment
- Arc flash hazards require strict adherence to PPE standards (NFPA 70E)
- LOTO and grounding procedures are non-negotiable for safe maintenance
- Physical and cyber security are critical aspects of modern substation design

Next Lecture Preview

- Gas Insulated Substations (GIS) - Part 1
- Introduction to GIS technology
- Advantages of GIS over conventional AIS
- Properties of SF6 (Sulfur Hexafluoride) gas
- Dielectric characteristics and environmental concerns

Gas Insulated Substations (GIS) & Hybrid GIS Substations (Part 1 of 4)

- Substation Engineering
- Lecture 33
- Unit 6: Gas Insulated and Hybrid Substations

Agenda

- Introduction to Gas Insulated Substations
- Evolution and History of GIS
- Comparison: AIS vs. GIS
- Why Choose GIS? (Advantages & Disadvantages)
- Introduction to SF6 Gas
- Physical, Chemical, and Dielectric Properties of SF6
- Environmental Impact and Alternatives

What is a Gas Insulated Substation (GIS)?

- A compact, metal-enclosed switchgear consisting of high-voltage components
- Uses compressed gas (typically SF_6) as the primary insulating medium
- Phase conductors are enclosed in grounded metallic pipes
- Replaces the large air clearances required in conventional AIS
- Can be installed indoors or outdoors, even in dense urban areas

Evolution and History of GIS

- First developed in the 1960s to solve space constraints in cities
- Initially operated at lower transmission voltages (110kV)
- Technology rapidly scaled to 400kV, 500kV, and eventually 800kV+
- Modern GIS designs are highly modular and compact
- Ongoing evolution focuses on reducing SF_6 usage due to environmental concerns

AIS vs. GIS: Space Requirements

Air Insulated Substation
(AIS) requires large land area
GIS requires 10% to 25% of
the space of a comparable AIS
Volume reduction is up to 90%
Allows installation in basements,
high-rises, or offshore platforms

Comparison: AIS vs GIS

Feature	Air Insulated (AIS)	Gas Insulated (GIS)
Insulating Medium	Air at atmospheric pressure	SF6 gas at 3-6 bar
Space Requirement	Large (100%)	Very Small (10-25%)
Maintenance	High (exposed to weather)	Low (sealed system)
Initial Cost	Lower	Higher
Reliability	Moderate	Very High
Erection Time	Longer	Shorter (factory assembled modules)

Why Choose GIS?

- High land costs or unavailable land (urban areas, mountainous terrain)
- Severe environmental conditions (heavy pollution, salt spray, sandstorms)
- High reliability requirements (completely immune to external faults like lightning strikes or animal contact)
- Visual aesthetics and noise reduction (can be hidden inside a standard building)
- Offshore wind farms where platform space is extremely expensive

Introduction to SF6 Gas

- Sulfur Hexafluoride (SF6) is a synthetic, fluorinated compound
- It is the lifeblood of modern GIS technology
- Chemically stable and inert under normal conditions
- Non-toxic, non-flammable, and colorless
- Has extraordinary electrical insulating and arc-quenching properties

Physical and Chemical Properties of SF_6

- High density: About 5 times heavier than air
- Liquefaction point: Must be monitored to ensure it remains a gas at high pressures and low temperatures
- Highly electronegative: Readily captures free electrons
- Recombines quickly after an arc is extinguished (self-healing)
- Does not degrade insulation materials like solid cast resin

Dielectric Strength of SF6

- At atmospheric pressure, SF6 has 2.5 to 3 times the dielectric strength of air
- At 3 to 5 bar pressure (typical GIS), strength increases significantly
- Allows for very small clearance distances between the live conductor and grounded enclosure
- Follows Paschen's Law: Breakdown voltage is a function of pressure and gap distance
- Highly sensitive to local electric field enhancements (e.g., sharp edges or metallic particles)

Arc-Quenching Capabilities

- Used not just for insulation, but for breaking current in Circuit Breakers
- SF_6 cools the arc 100 times faster than air
- During an arc, SF_6 dissociates into lower-order fluorides (SF_4, SF_2)
- After current zero, these compounds quickly recombine back into SF_6
- Maintains dielectric strength immediately after current interruption

Byproducts of Arcing in SF_6

- While SF_6 is non-toxic, arc byproducts are highly toxic and corrosive
- Includes compounds like SOF_2, SO_2F_2, and HF (Hydrofluoric acid)
- Moisture in the gas exacerbates the creation of corrosive byproducts
- GIS compartments contain desiccants (absorbers) to trap moisture and byproducts
- Maintenance personnel require special PPE when opening arced compartments

Environmental Impact of SF6

- SF6 is the most potent greenhouse gas known to science
- Global Warming Potential (GWP): 23,500 times that of CO2
- Atmospheric lifetime: 3,200 years
- Strict regulations mandate gas accounting, leak detection, and recovery
- Venting SF6 into the atmosphere is strictly prohibited globally

The Push for SF6 Alternatives

Gas Mix	GWP	Characteristics
Pure SF6	23,500	Industry standard, excellent performance
g3 (Green Gas)	¡ 400	Fluoronitrile mixture, 98% less environmental impact
AirPlus	¡ 10	Fluoroketone mixture, used up to 145kV
Clean Air / N2	0	Requires larger dimensions, used for lower voltages

Summary

- GIS reduces substation footprint by up to 90% and offers high reliability
- SF6 is an electronegative gas with incredible dielectric and thermal properties
- By pressurizing SF6, clearance distances are massively reduced
- Arcing creates toxic byproducts that must be managed
- Due to its massive Global Warming Potential, the industry is shifting to eco-friendly gas alternatives

Next Lecture Preview

- GIS and Hybrid GIS (Part 2 of 4)
- Internal architecture of a GIS module
- Detailed look at GIS Components:
- Busbars and Insulators
- Circuit Breakers and Disconnectors
- Fast Acting Earthing Switches (FAES)

Gas Insulated Substations (GIS) & Hybrid GIS Substations (Part 2 of 4)

- Substation Engineering
- Lecture 34
- Unit 6: Gas Insulated and Hybrid Substations

Agenda

- GIS Architecture and Modular Design
- Conductors and Enclosures
- Cast Resin Spacers (Cone Insulators)
- Gas Compartmentalization Strategy
- GIS Circuit Breakers
- Disconnectors (Isolators)
- Earthing Switches (Standard and Fast-Acting)
- Instrument Transformers in GIS

GIS Architecture and Modular Design

- GIS is designed as a series of interconnected, standardized modules
- Modules are flanged and bolted together with O-ring seals
- Allows for flexible layouts (linear, stacked, double bus, etc.)
- Factory assembled and tested, reducing on-site erection time
- Enclosures are typically made of cast aluminum alloy

Conductors and Enclosures

- Inner Conductor: Made of high-conductivity aluminum or copper tubing
- Outer Enclosure: Grounded aluminum pipe that contains the SF_6 gas
- Aluminum is preferred for enclosures to prevent magnetic heating (eddy currents)
- Enclosure acts as a continuous shield, confining electric fields entirely inside
- GIS surface is safe to touch while energized (zero electric field outside)

Cast Resin Spacers (Cone Insulators)

- Solid insulators that support the inner conductor within the enclosure
- Made of epoxy resin cast with alumina or silica fillers
- Typically shaped like cones or discs to manage electric field stress
- Must withstand extreme mechanical forces during short circuits
- Also serve as gas-tight barriers between different compartments

Gas Compartmentalization Strategy

A GIS is not one giant continuous gas volume
Divided into isolated gas zones
using barrier cone insulators
Reasons for compartmentalization:
1. Limit the loss of SF6 if a leak occurs
2. Allow maintenance on one component without depressurizing the whole substation
3. Prevent arc byproducts from contaminating adjacent healthy sections

Gas Monitoring Systems

- Each compartment has its own gas density monitor
- Density is monitored, not just pressure, to account for temperature fluctuations
- Two-stage alarm system:
- Stage 1 Alarm: Low density (requires gas top-up)
- Stage 2 Trip: Critical density (lockout or trip to prevent catastrophic dielectric failure)
- Modern systems use continuous online digital monitoring

GIS Circuit Breakers

- The most critical and complex module in the GIS
- Almost exclusively use SF6 puffer or self-blast technology
- Typically mounted horizontally or vertically depending on space
- Requires the largest gas volume and highest operating pressure
- Fitted with powerful spring, hydraulic, or motor drives

GIS Disconnectors (Isolators)

- Used for visible isolation of circuits for maintenance
- Operate off-load (cannot break fault current)
- Driven by motor mechanisms externally mounted on the enclosure
- Must be able to break small capacitive currents (bus charging currents)
- Provide a guaranteed dielectric gap larger than the rest of the system

Maintenance Earthing Switches

- Used to ground de-energized parts for personnel safety
- Interlocked with disconnectors to prevent closing onto a live circuit
- Slow operating mechanism (motor or manual)
- Ensures no induced voltages harm maintenance workers
- Often combined with disconnectors into a 3-position switch (Closed, Open, Earthed)

Fast Acting Earthing Switches (FAES)

- Specialized grounding switches with a high-speed spring mechanism
- Located at the incoming/outgoing line terminals of the GIS
- Designed with 'making capacity'—can safely close onto an energized line!
- Used to discharge trapped charges or in case a line is accidentally energized
- Protects the GIS from damage if the switch is operated in error

Ratings of GIS Components

Component	Function	Fault Making Capacity	Fault Breaking Capacity
Circuit Breaker	Clear faults	Yes	Yes
Disconnector	Isolate circuits	No	No (Bus charging only)
Maintenance Earth	Safety grounding	No	No
Fast Earth Switch	Line grounding	Yes	No

Instrument Transformers in GIS

- Current Transformers (CT): Often ring-type, mounted over the GIS enclosure (outside the gas) or integrated inside
- Voltage Transformers (VT): Inductive types are enclosed in their own gas compartment
- VTs use SF6 as insulation instead of oil, eliminating fire risk
- Non-conventional instrument transformers (Rogowski coils, optical sensors) are becoming popular in digital GIS

Interfaces: Cable and Overhead Line Terminations

- GIS must eventually connect to the rest of the grid
- SF6-to-Air Bushings: Used to connect GIS directly to overhead transmission lines
- SF6-to-Cable Terminations: Used to connect GIS directly to underground XLPE cables
- SF6-to-Oil Bushings: Used for direct connection to power transformers without exposed air connections

Summary

- GIS is built from modular enclosures that contain SF_6 gas and high-voltage conductors
- Epoxy spacers support the conductors and divide the system into gas zones
- Compartmentalization ensures reliability and maintainability
- Switching components (CBs, Disconnectors, Earth Switches) are specialized for enclosed operation
- FAES provides critical safety at line terminals by closing onto active faults

Next Lecture Preview

- GIS and Hybrid GIS (Part 3 of 4)
- GIS layout configurations (Single Bus, Double Bus)
- Space optimization and building design
- Introduction to Mixed Technology Switchgear (Hybrid GIS)
- Bridging the gap between AIS and GIS

Gas Insulated Substations (GIS) & Hybrid GIS Substations (Part 3 of 4)

- Substation Engineering
- Lecture 35
- Unit 6: Gas Insulated and Hybrid Substations

Agenda

- GIS Layout Configurations
- Single Bus vs. Double Bus GIS
- Indoor vs. Outdoor GIS Installations
- Civil and Foundation Requirements
- Introduction to Mixed Technology Switchgear (MTS / Hybrid GIS)
- Components of a Hybrid GIS
- Advantages and Applications of Hybrid GIS

GIS Layout Configurations

- Just like AIS, GIS can be configured in any standard bus scheme
- Common schemes: Single Bus, Double Bus, Double Breaker, 1.5 Breaker
- The modular nature of GIS allows 3D stacking of phases to save space
- Phase arrangement can be single-phase enclosed (UHV) or three-phase enclosed (up to 170kV)
- Routing of control cables and gas piping must be integrated into the layout

Single Bus vs. Double Bus GIS Layout

Single Bus GIS:
- Extremely compact and simple
- Lower cost, but requires shutdown of the bay for busbar maintenance

Double Bus GIS:
- Features two parallel gas-insulated busbars running horizontally
- Disconnectors connect the bay to either Bus 1 or Bus 2
- Allows maintenance flexibility without dropping load

Space Optimization Techniques

- GIS allows for creative spatial arrangements
- Underground Substations: Entire substations built below city parks or commercial buildings
- Multi-story Substations: Cable terminations in the basement, GIS on the ground floor, transformers outside
- Vertical Stacking: Busbars can be stacked vertically to reduce building footprint
- Integrated control cabinets directly on the GIS modules

Indoor vs. Outdoor GIS Installations

Characteristic	Indoor GIS	Outdoor GIS
Weather Protection	Excellent	Exposed to sun, rain, snow
Building Cost	High (Requires civil structure)	Low (Only foundations)
Maintenance	Easy (climate controlled)	Harder (dependent on weather)
Visual Impact	Low (looks like a building)	Moderate (industrial look)
Corrosion Risk	Minimal	Higher (requires special coatings)

Civil and Foundation Requirements

- GIS imposes highly concentrated loads on floors
- Floor tolerances must be exceptionally flat (typically +/- 2mm per meter)
- Modules must align perfectly to prevent stress on cast resin spacers
- Embedment plates are poured into the concrete floor to weld or bolt GIS frames
- Overhead cranes are mandatory in GIS buildings for installation and maintenance

Introduction to Hybrid GIS

- Also known as Mixed Technology Switchgear (MTS)
- Combines the compactness of GIS with the simplicity of Air Insulated Substations (AIS)
- Circuit breakers, disconnectors, and CTs are gas-insulated
- Busbars and connections between bays remain air-insulated
- Provides a 'best of both worlds' solution

Features of Mixed Technology Switchgear (MTS)

- Highly integrated modules (Breaker, CT, VT, Isolators in one tank)
- Bushings protrude from the tank to connect to overhead air-insulated buses
- Completely factory assembled and transported as a single unit
- Plug-and-play installation minimizes on-site work
- Common market products: PASS (ABB/Hitachi), HIS (Siemens)

Hybrid GIS Substation Layout

Unlike full GIS, Hybrid GIS requires standard air clearances between bays
However, the bay depth is drastically reduced
Replaces 4 or 5 separate AIS components with 1 MTS module
Reduces bay footprint by approximately 50-70% compared to full AIS
Ideal for replacing aging AIS bays within the same property boundary

Advantages of Hybrid GIS

- Space Savings: 60% reduction over AIS
- Cost Effective: Cheaper than full GIS, no building required
- Reliability: The most critical component (breaker) is protected in SF6
- Fast Installation: Pre-assembled and tested
- Clear demarcation of isolation: Air-insulated disconnects provide visible open points

Comparison: AIS vs GIS vs Hybrid GIS

Metric	AIS	Hybrid GIS (MTS)	Full GIS
Space Required	100%	40-50%	10-25%
Capital Cost	Low	Medium	High
Installation Time	Weeks	Days	Weeks (plus building)
Environmental Vulnerability	High	Low	Zero
Gas Inventory (SF6)	None/Low	Moderate	High

Typical Applications for Hybrid GIS

- Brownfield Expansions: Adding new bays to a constrained existing AIS yard
- Rapid Substation Deployment: Emergency replacements or fast-track industrial projects
- Seismic Zones: Lower center of gravity than AIS components
- Mobile Substations: Mounted on trailers for temporary power restoration

Summary

- GIS layout design leverages 3D stacking to fit massive power capacity into small buildings
- Civil requirements for GIS are extremely tight to ensure mechanical integrity
- Hybrid GIS (MTS) combines SF6-insulated components with air-insulated busbars
- Hybrid GIS cuts footprint by 50% while avoiding the high costs of full GIS
- MTS is ideal for upgrading existing substations and fast-track deployments

Next Lecture Preview

- GIS and Hybrid GIS (Part 4 of 4)
- Testing and Commissioning of GIS
- High-voltage dielectric testing on site
- Partial Discharge (PD) measurement techniques (UHF and Acoustic)
- Lifecycle maintenance and SF6 gas handling procedures

Gas Insulated Substations (GIS) & Hybrid GIS Substations (Part 4)

- Gas Insulated Substations (GIS) & Hybrid GIS Substations
- Part 4 of 4: Hybrid GIS Configurations
- Course: Substation Engineering (DI04009011)

Agenda

- Introduction to Hybrid GIS (HGIS)
- Components of HGIS
- Comparison: AIS, GIS, and HGIS
- Space Optimization with HGIS
- HGIS Configurations (PASS and MTS)
- Reliability and Maintenance
- Case Studies and Applications
- Summary and Q&A

What is Hybrid GIS (HGIS)?

- A hybrid approach combining Air Insulated Substation (AIS) and Gas Insulated Substation (GIS) technologies.
- Utilizes SF6 or alternative gas-insulated switchgear for a compact footprint.
- Busbars are often air-insulated, while circuit breakers, disconnectors, and earth switches are gas-insulated.
- Provides a balance between the high cost of full GIS and the large footprint of full AIS.

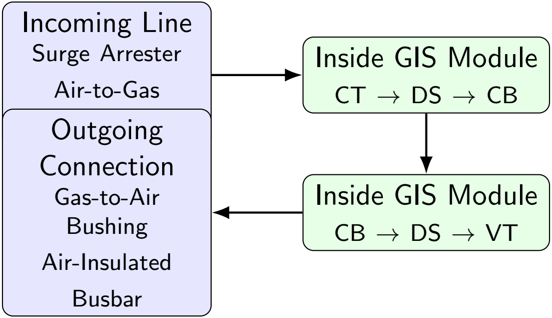
Why Choose Hybrid GIS?

- Cost-effective alternative to full GIS for substation upgrades.
- Reduces space requirements by up to 50% compared to conventional AIS.
- Higher reliability and lower maintenance than standard AIS.
- Faster installation and commissioning due to modular design.
- Suitable for heavily polluted or seismically active areas.

Key Components of HGIS

- Gas-Insulated Switchgear Module: Houses the circuit breaker, disconnector, and earthing switch.
- Air-Insulated Busbars: Connect the GIS modules to the rest of the network.
- Outdoor Bushings: Interface between the gas-insulated components and the air-insulated busbars.
- Current and Voltage Transformers: Often integrated into the gas-insulated module to save space.
- Local Control Cabinet (LCC): Provides control, monitoring, and interlocking functions.

HGIS Module Architecture



Comparison: AIS vs GIS vs HGIS

Feature	**AIS**	**HGIS**	**GIS**
Footprint	Large (100%)	Medium (50%)	Small (10-20%)
Capital Cost	Low	Medium	High
Maintenance	High	Low	Very Low
Environmental Vulnerability	High	Medium	Low
Installation Time	Long	Medium	Short

Space Optimization Strategies

- Brownfield Extensions: Adding bays to an existing AIS without acquiring new land.
- Urban Substations: Fitting higher capacity into limited city plots.
- Integration of multiple functions (CB, DS, ES, CT) into a single compact module.
- Flexible busbar routing to avoid existing obstacles in upgraded substations.

HGIS Configurations: PASS

- PASS (Plug and Switch System) is a popular HGIS configuration.
- Pre-assembled and pre-tested at the factory.
- Reduces on-site installation time from weeks to days.
- Features a rotating bushing design for flexible connection to different busbar layouts.
- Available in various voltage levels up to 420 kV.

HGIS Configurations: MTS

- MTS (Mixed Technology Switchgear) is another common term for HGIS.
- Highly customizable based on the specific substation layout.
- Can be configured as a single busbar, double busbar, or breaker-and-a-half arrangement.
- Often utilizes standard GIS components for the enclosed sections to ensure reliability and spare parts availability.

Reliability and Maintenance of HGIS

- Reduced Maintenance: Critical moving parts are protected in SF6 gas, minimizing wear and corrosion.
- Extended Lifespan: Lower exposure to environmental factors extends the life of the switchgear.
- Condition Monitoring: HGIS modules are often equipped with sensors for SF6 density, partial discharge, and circuit breaker wear.
- Visual Inspection: Unlike full GIS, the air-insulated busbars allow for easy visual inspection of connections.

Environmental Considerations

- SF6 Usage: HGIS uses significantly less SF6 gas than full GIS.
- Leakage Rates: Modern HGIS modules have extremely low guaranteed leakage rates (under 0.1% per year).
- Visual Impact: Lower profile than AIS, making it easier to integrate into sensitive landscapes.
- Noise Reduction: Enclosed circuit breakers produce less noise during operation than open-air AIS breakers.

Case Study: Urban Substation Upgrade

- Scenario: 132 kV AIS substation in a growing city needed expansion from 4 to 6 bays.
- Challenge: No adjacent land available for expansion; high pollution levels.
- Solution: Replaced two existing AIS bays with HGIS modules, freeing up space for two additional bays.
- Result: 50% capacity increase achieved within the existing fence line; improved reliability against pollution.

Summary of Gas Insulated Technologies

- GIS provides ultimate compactness and reliability for severe space or environmental constraints.
- HGIS offers a balanced approach, ideal for brownfield expansions and cost-sensitive projects.
- Both technologies rely on the superior insulating properties of SF6 (or modern alternatives).
- Proper gas handling and condition monitoring are critical for the lifecycle of both GIS and HGIS.

Next Lecture Preview

- Introduction to High Voltage Direct Current (HVDC) Substations.
- Why HVDC? Advantages over HVAC for long-distance transmission.
- Basic components of an HVDC converter station.
- Types of HVDC links (monopolar, bipolar, back-to-back).

HVDC Substations (Part 1)

- High Voltage Direct Current (HVDC) Substations
- Part 1 of 3: Introduction and Fundamentals
- Course: Substation Engineering (DI04009011)

Agenda

- Historical Background of DC Transmission
- HVAC vs. HVDC Transmission
- Advantages of HVDC
- Basic HVDC System Configuration
- What is an HVDC Converter Station?
- Main Components of an HVDC Substation
- Applications of HVDC
- Summary and Q&A

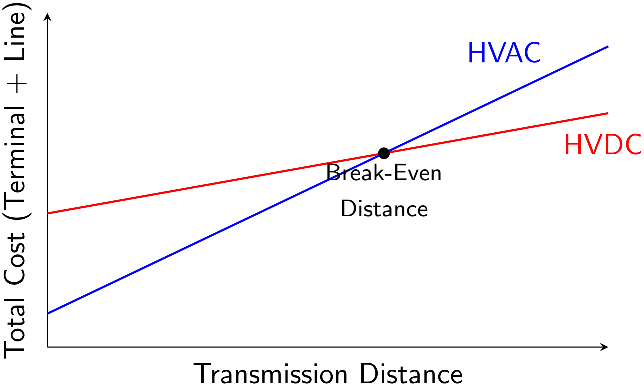
The War of the Currents

- Late 19th Century: Edison championed DC, while Tesla/Westinghouse championed AC.
- AC won for general transmission due to the invention of the transformer (easy voltage stepping).
- DC transmission was limited by the inability to efficiently step up/step down voltages.
- 1950s: Development of high-voltage mercury-arc valves made HVDC viable.
- Modern Era: Thyristors and IGBTs revolutionized HVDC transmission.

HVAC vs. HVDC Transmission

Parameter	HVAC	HVDC
Number of Conductors	3 (3-phase)	2 (Bipolar) or 1 (Monopolar)
Skin Effect	Present	Absent (full cross-section utilized)
Reactive Power	Requires compensation	None (no charging current)
Right of Way (RoW)	Wider	Narrower
Terminal Station Cost	Lower	Significantly Higher

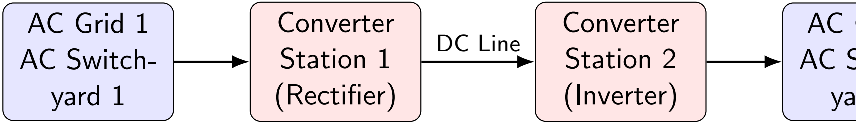
Break-Even Distance



Technical Advantages of HVDC

- No asynchronous issues: Can connect two AC grids operating at different frequencies (e.g., 50Hz and 60Hz).
- Power flow control: Precise and rapid control of active power flow.
- No stability limits: Distance is not limited by stability considerations.
- Lower line losses: No reactive power flow means lower I^2R losses.
- Less corona loss and radio interference compared to HVAC.

Basic HVDC System Architecture



What is an HVDC Converter Station?

- A specialized substation that converts alternating current (AC) to direct current (DC) or vice versa.
- Acts as the interface between the AC grid and the DC transmission line.
- Can operate in either rectifier mode (AC to DC) or inverter mode (DC to AC).
- Contains massive power electronic valves, transformers, and filters.

Main Components of an HVDC Substation

- AC Switchyard: Connects to the AC network.
- Converter Transformers: Step voltage and provide galvanic isolation.
- Valve Hall: Houses the thyristor or IGBT valves for conversion.
- AC Filters: Filter out harmonics generated by the conversion process.
- DC Filters: Smooth the DC voltage output.
- Smoothing Reactor: Reduces ripple in the DC current.

The Valve Hall

- The most critical and sensitive area of the HVDC substation.
- A large, electromagnetically shielded building.
- Contains the thyristor or IGBT valve structures.
- Requires strict climate control and air purification to prevent flashovers.
- Cooling systems (usually deionized water) remove heat generated by the valves.

HVDC Applications: Long Distance Bulk Power

- Transmitting massive amounts of power from remote generation to load centers.
- Example: Hydropower from remote mountains to distant cities.
- Lower transmission losses and narrower right-of-way make it ideal.
- Ultra-High Voltage DC (UHVDC) links operate at 800 kV or even 1100 kV.

HVDC Applications: Submarine Cables

- AC cables have high capacitance, leading to large charging currents.
- Beyond roughly 50-80 km, an AC submarine cable would carry mostly charging current, leaving no capacity for active power.
- DC cables have no continuous charging current.
- Used for offshore wind farm connections and interconnecting countries across bodies of water.

HVDC Applications: Asynchronous Interconnections

- Connecting two grids that operate at different frequencies (e.g., 50 Hz and 60 Hz in Japan).
- Connecting two grids at the same frequency but not synchronized.
- Back-to-Back HVDC Stations: Rectifier and Inverter are in the same building.
- Prevents cascading failures from spreading between grids.

Summary

- HVDC is economically viable for long-distance overhead lines and long submarine cables.
- HVDC provides superior control over active power flow and connects asynchronous grids.
- An HVDC converter station is the interface, converting AC to DC or DC to AC.
- Key components include the valve hall, converter transformers, and filters.

Next Lecture Preview

- Deep dive into HVDC Converter Station Equipment.
- Thyristor Valves vs VSC (Voltage Source Converters).
- Converter Transformers: How they differ from standard power transformers.
- Harmonic filtering and Reactive Power compensation.

HVDC Substations (Part 2)

- High Voltage Direct Current (HVDC) Substations
- Part 2 of 3: Equipment and Converter Technologies
- Course: Substation Engineering (DI04009011)

Agenda

- Converter Technologies: LCC vs VSC
- Line Commutated Converters (LCC / Classic HVDC)
- Voltage Source Converters (VSC / Modern HVDC)
- Converter Transformers
- Thyristor Valves and Valve Halls
- Harmonic Generation and Filters (AC & DC)
- Smoothing Reactors
- Summary and Q&A

Two Generations of HVDC Technology

- LCC (Line Commutated Converter): Also known as Classic HVDC. Uses Thyristors.
- VSC (Voltage Source Converter): Also known as VSC-HVDC or Light HVDC. Uses IGBTs (Insulated Gate Bipolar Transistors).
- LCC relies on the AC grid voltage for commutation (turning off the valves).
- VSC has self-commutating capability; it can create its own AC voltage waveform.

Line Commutated Converters (LCC)

- Mature technology, capable of the highest power and voltage ratings (up to 1100 kV, 12000 MW).
- Valves can only be turned on by a gate signal; they turn off naturally when current crosses zero (requires a strong AC grid).
- Consumes significant reactive power (approx. 50% of active power transmitted).
- Requires large AC filter banks and capacitor banks for reactive compensation.

Voltage Source Converters (VSC)

- Modern technology, power ratings up to around 3000 MW.
- IGBTs can be turned on AND off via gate signals (self-commutating).
- Can operate with weak AC grids or even dead networks (black start capability).
- Independent control of active and reactive power.
- Generates fewer harmonics, requiring significantly smaller filters.

Comparison: LCC vs VSC

Feature	LCC (Thyristor)	VSC (IGBT)
Max Power Capability	Very High (>10 GW)	High (∼3 GW)
Reactive Power	Consumes ∼50%	Can generate/consume
Minimum AC Grid Strength	Strong grid required	Can operate on weak/dead grids
Footprint	Very Large (huge filters)	Compact (small filters)
Black Start Capability	No	Yes

Converter Transformers

- Act as the galvanic interface between the AC grid and the DC valves.
- Provide the necessary ungrounded AC voltage to the converter bridges.
- Typically arranged to provide a 30-degree phase shift between bridges to create a 12-pulse system.
- Subjected to severe electrical stress: combined AC and DC voltages.

Design Challenges of Converter Transformers

- DC Insulation Stress: Insulation must handle DC voltage, which distributes based on resistivity (temperature dependent), not capacitance.
- Harmonics: High harmonic currents flow through the windings, causing extra heating and requiring robust cooling.
- DC Magnetization: Even slight DC currents can saturate the transformer core, causing noise and overheating.
- Often built as single-phase units due to massive size and transport limitations.

Thyristor Valves and Assembly

- A single thyristor can only block a few kilovolts.
- Hundreds of thyristors are connected in series to withstand hundreds of kilovolts.
- Arranged in modular 'valve structures' suspended from the ceiling in the valve hall (especially for high seismic zones).
- Fired simultaneously using light pulses via fiber optics (Light Triggered Thyristors).

Harmonics in HVDC Systems

- The switching process of converters inherently generates harmonic currents and voltages.
- A standard 12-pulse LCC generates characteristic AC harmonics of order $12n \pm 1$ (11th, 13th, 23rd, 25th...).
- Generates characteristic DC harmonics of order $12n$ (12th, 24th...).
- These harmonics can cause overheating in equipment, telecom interference, and grid resonance.

AC and DC Filters

- AC Filters: Large banks of capacitors, inductors, and resistors tuned to absorb specific harmonic frequencies (e.g., 11th and 13th).
- In LCC systems, AC filters also provide the large amount of reactive power required by the converter.
- DC Filters: Located on the DC side to prevent harmonic currents from flowing down the DC line, which acts like a giant broadcasting antenna.
- VSC systems use much smaller filters due to high-frequency Pulse Width Modulation (PWM).

Smoothing Reactors

- Massive inductors placed in series with the DC line.
- Functions:
- 1. Smooth the ripple in the direct current.
- 2. Limit fault currents on the DC line.
- 3. Prevent commutation failures in the inverter.
- Typically air-core, dry-type reactors to avoid core saturation issues.

Control Systems (Brief Overview)

- HVDC control systems act in milliseconds.
- Rectifier normally controls the DC Current.
- Inverter normally controls the DC Voltage.
- Protection systems must quickly detect DC line faults and block the valves to prevent equipment damage.

Summary of Converter Equipment

- LCC uses thyristors (high power, strong grid) while VSC uses IGBTs (flexible, weak grid).
- Converter transformers face unique AC and DC stresses simultaneously.
- Valves consist of hundreds of series-connected semiconductors.
- Filters and smoothing reactors are essential to manage harmonics and maintain stable DC flow.

Next Lecture Preview

- HVDC Transmission Link Configurations.
- Monopolar Links (Ground return vs Metallic return).
- Bipolar Links and their redundancy advantages.
- Multi-terminal HVDC systems.
- Back-to-Back configurations.

HVDC Substations (Part 3)

- High Voltage Direct Current (HVDC) Substations
- Part 3 of 3: System Configurations and Topologies
- Course: Substation Engineering (DI04009011)

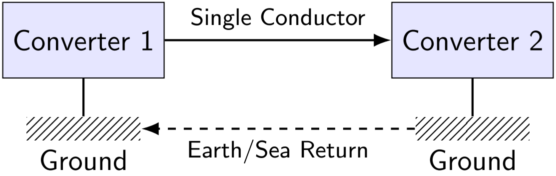
Agenda

- Introduction to HVDC Link Topologies
- Monopolar Links (Ground and Metallic Return)
- Bipolar Links and Redundancy
- Homopolar Links (Brief Overview)
- Back-to-Back HVDC Systems
- Multi-Terminal HVDC (MTDC) Networks
- HVDC Grids of the Future
- Summary and Q&A

Why Different Configurations?

- Cost considerations: Number of conductors drastically affects line cost.
- Reliability requirements: Ability to transmit partial power if one line or converter fails.
- Environmental limits: Restrictions on ground currents in certain areas.
- Application type: Submarine cable vs. overhead line vs. asynchronous connection.

Monopolar Link: Ground Return

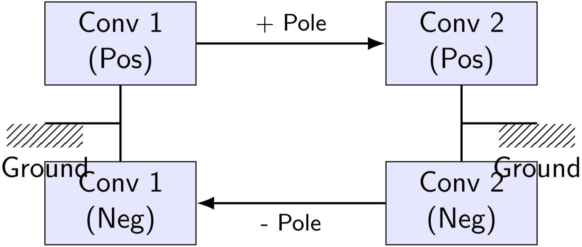


- Single high-voltage conductor (typically negative polarity to reduce corona).
- Return path is through the Earth or sea.
- Requires large ground electrodes at both converter stations.

Monopolar Link: Metallic Return

- Single high-voltage conductor for the forward path.
- A low-voltage metallic conductor is used for the return path.
- No current flows through the earth.
- Advantage: Solves environmental and corrosion issues of ground return.
- Disadvantage: Increased cost due to the second conductor, higher losses.

Bipolar Link



- Most common configuration for overhead HVDC transmission.
- Two high-voltage conductors: One positive pole, one negative pole.
- The midpoint of the converters at both ends is grounded.

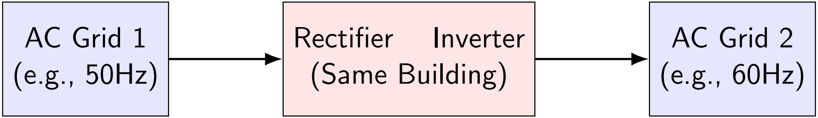
Advantages of a Bipolar Link

- High Reliability: If one pole (conductor or converter) fails, the other can continue operating.
- In case of a pole failure, the system temporarily operates as a monopolar link with ground return (if permitted).
- Provides double the power capacity of a monopolar link.
- Zero continuous ground current during normal, balanced operation.

Homopolar Link

- Rarely used in modern applications.
- Two or more conductors having the same polarity (usually negative to minimize corona).
- Return path is always through the ground or a metallic return.
- If one conductor faults, the converter equipment can be switched to the healthy conductor.

Back-to-Back HVDC System



- Rectifier and Inverter are located in the same substation.
- No DC transmission line is used.
- Connects two asynchronous AC grids or grids at different frequencies.
- Allows precise control of power flow between regions without synchronization issues.

Comparison of Topologies

Topology	Cost	Reliability	Ground Current	Main Application
Monopolar (Ground)	Lowest	Low	Continuous	Early subsea cables
Monopolar (Metallic)	Medium	Low	Zero	Environmentally sensitive subsea
Bipolar	High	High	Zero (Normal)	Long distance overhead
Back-to-Back	N/A	High	Zero	Asynchronous grid ties

Multi-Terminal HVDC (MTDC)

- More than two converter stations connected to the same DC network.
- Can be Series connected or Parallel connected (Parallel is more common).
- Highly complex control systems required to coordinate power flow between multiple terminals.
- VSC technology makes MTDC much more feasible than classic LCC.

Challenges of MTDC and DC Grids

- DC Circuit Breakers: Interrupting DC current is extremely difficult because there is no natural 'zero crossing' like in AC.
- Protection Coordination: Faults on a DC grid propagate very rapidly; isolation must occur in milliseconds.
- Standardization: Currently, different manufacturers' HVDC equipment does not easily interface on the DC side.

Future Trend: The Supergrid

- Concept of a wide-area DC grid overlaying the existing AC network.
- Facilitates massive integration of renewable energy (e.g., offshore wind in the North Sea to load centers inland).
- Relies entirely on advanced VSC technology and fast DC breakers.
- Increases overall continental grid stability and resilience.

Summary of HVDC Module

- HVDC is critical for long-distance, bulk power, and subsea transmission.
- LCC provides brute power; VSC provides flexibility and control.
- Bipolar configurations offer the best mix of reliability and power capacity for overhead lines.
- Multi-terminal DC grids represent the future of renewable energy integration.

Next Lecture Preview

- Introduction to Substation Automation Basics.
- Evolution of control systems in substations.
- Introduction to SCADA (Supervisory Control and Data Acquisition).
- The shift from hardwired relay logic to microprocessor-based IEDs.

Substation Automation Basics (Part 1)

- Substation Automation Basics
- Part 1 of 3: Evolution, SAS Functions, and SCADA
- Course: Substation Engineering (DI04009011)

Agenda

- The Evolution of Substation Control
- What is a Substation Automation System (SAS)?
- Key Benefits of SAS
- Core Functions of SAS (Control, Monitor, Protect)
- Introduction to SCADA
- Intelligent Electronic Devices (IEDs)
- Basic Architecture of an Automated Substation
- Summary and Q&A

Evolution of Substation Control: The Past

- Conventional Substations: Relied heavily on human operators.
- Control: Huge panels with manual pushbuttons and semaphore indicators.
- Protection: Electromechanical relays (moving parts, springs, magnets).
- Monitoring: Analog dials and chart recorders.
- Wiring: Massive amounts of copper wire connecting every single device point-to-point to the control room.

Evolution of Substation Control: The Present

- Modern Substations: Fully digitized and networked.
- Control: Human-Machine Interfaces (HMIs) and remote control centers.
- Protection: Microprocessor-based digital relays.
- Monitoring: Digital logging, alarm management, and real-time data trending.
- Wiring: Copper replaced largely by fiber optic cables and Ethernet networks.

What is a Substation Automation System (SAS)?

- A collection of hardware and software components used to monitor, control, and protect a substation.
- It integrates various Intelligent Electronic Devices (IEDs) via a communication network.
- Eliminates the need for constant on-site personnel.
- Provides real-time data to grid operators (load dispatch centers).

Key Benefits of Substation Automation

- Enhanced Reliability: Faster fault detection and clearing.
- Reduced Operational Costs: Unmanned operation and remote troubleshooting.
- Improved Safety: Operators control equipment remotely rather than standing near high voltage.
- Better Asset Management: Condition monitoring of transformers and breakers extends lifespan.
- Smaller Control Rooms: Reduced footprint due to digital integration.

Core Functions of SAS

Function Category	**Description**	**Examples**
Control	Operating switchgear	Opening a CB, changing transformer tap
Monitoring	Measuring parameters	Voltage, Current, SF6 gas pressure
Protection	Isolating faults	Overcurrent trip, distance protection
Logging/Alarms	Recording events	Sequence of Events (SOE) recording

Intelligent Electronic Devices (IEDs)

- The building blocks of SAS.
- Microprocessor-based controllers associated with power system equipment.
- Examples: Digital Protective Relays, Bay Controllers, Smart Meters, Digital Fault Recorders.
- An IED receives data from sensors (CTs/PTs), processes it, issues commands (trip/close), and communicates with the network.

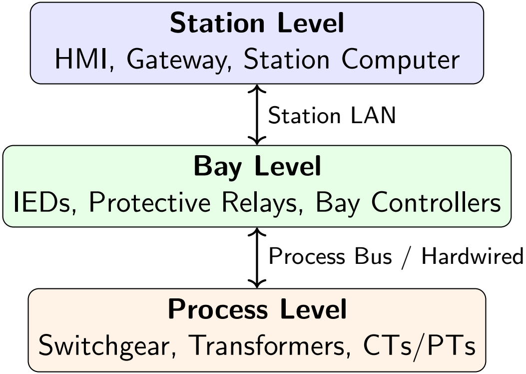
Introduction to SCADA

- SCADA: Supervisory Control and Data Acquisition.
- Supervisory Control: Sending commands to remote equipment (e.g., 'Open Breaker 1').
- Data Acquisition: Gathering status and measurements from remote equipment.
- SCADA is the overarching software platform that interfaces the human operator with the SAS.

SCADA Components in a Substation

- RTU (Remote Terminal Unit): The traditional device used to interface physical wiring to the SCADA network. (Being replaced by IEDs).
- Data Concentrator / Gateway: Collects data from all IEDs and sends it to the central control center.
- HMI (Human-Machine Interface): The local computer screen where operators can view the single line diagram and control the substation.

Basic SAS Architecture (The 3 Levels)



The Shift: Hardwiring vs. Networking

- Old Method: Every status contact and control coil required a dedicated copper wire running to the control room.
- New Method: Equipment is wired locally to an IED at the Bay Level. The IED digitizes the info.
- Data travels over an Ethernet network (often fiber optic) to the Station Level.
- Result: Massive reduction in copper cabling, reduced fire risk, and easier expansion.

Reliability and Redundancy in SAS

- If the network fails, does the substation blow up?
- No. Protection IEDs operate autonomously. They do not rely on the network or SCADA to trip a breaker during a fault.
- SAS networks are designed with high redundancy (e.g., ring topologies) so a single cable break doesn't cause loss of visibility.
- Station batteries (DC system) ensure the SAS runs even during a total AC blackout.

Summary

- Substation control has evolved from analog, hardwired panels to digital, networked IEDs.
- SAS provides control, monitoring, and protection, improving reliability and safety.
- SCADA systems gather data from IEDs/RTUs and present it to operators via HMIs.
- Modern SAS architecture is divided into Process, Bay, and Station levels.

Next Lecture Preview

- Deep dive into SAS Architecture and Protocols.
- Detailed look at the Station, Bay, and Process levels.
- Introduction to communication protocols (Modbus, DNP3, IEC 61850).
- Why IEC 61850 is the global standard for modern substations.

Substation Automation Basics (Part 2 of 3)

- Course: Substation Engineering (DI04009011)
- Unit 5: Substation Automation System (SAS)
- Focus: SAS Architecture & IEDs

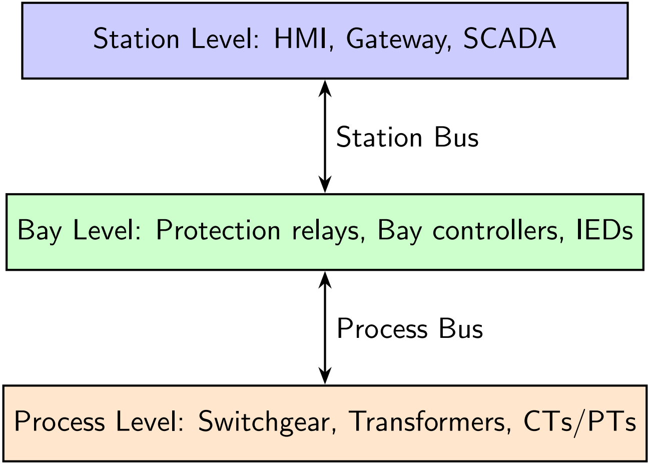
Agenda

- Review of SAS Concepts
- The Three-Level Architecture of SAS
- Station Level Functions
- Bay Level Functions
- Process Level Functions
- Introduction to Intelligent Electronic Devices (IEDs)
- Key Functions of IEDs
- Integration of IEDs in the Substation

Recap: What is a Substation Automation System?

- Integration of protection, control, and monitoring functions.
- Replaces traditional hardwired control panels with digital networks.
- Enhances reliability, reduces outage times, and enables remote management.

Hierarchical Architecture of SAS



The Station Level

- Highest level within the substation.
- Houses the Substation HMI (Human Machine Interface).
- Contains engineering and maintenance workstations.
- Acts as a gateway for communication with remote control centers (SCADA).

Station Level: Key Components

Component	Primary Function	Location
HMI Server	Data visualization and local control	Station Control Room
Gateway	Protocol conversion to communicate with NCC	Station Control Room
Time Server (GPS)	Precise time synchronization for all devices	Station Control Room

The Bay Level

- Intermediate level directly controlling individual substation bays (e.g., line bay, transformer bay).
- Operates independently of the Station Level (distributed intelligence).
- Consists primarily of Intelligent Electronic Devices (IEDs) acting as bay controllers and protection relays.
- Ensures bay-level interlocking.

The Process Level

- The physical primary equipment in the switchyard.
- Includes Circuit Breakers, Disconnectors, Transformers.
- Includes primary sensors like Current Transformers (CTs) and Potential Transformers (PTs).
- In modern SAS, it includes Merging Units (MUs) that digitize analog signals.

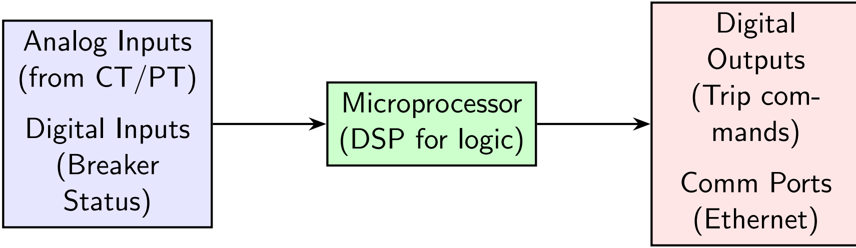
Intelligent Electronic Devices (IEDs)

- Microprocessor-based controllers of power system equipment.
- Receive data from sensors and power equipment.
- Issue control commands (e.g., trip circuit breakers) based on programmed logic.
- Replace discrete protection relays, meters, and controllers.

Core Functions of an IED

Function	Description
Protection	Detects faults and isolates them instantly.
Control	Opens/closes breakers and switches locally or remotely.
Monitoring	Measures voltage, current, power, and equipment health.
Communication	Transmits data to the Station Level and other IEDs.

IED Architecture



Benefits of IED Integration

- Reduced Wiring: Fiber optic cables replace hundreds of copper wires.
- Self-Monitoring: IEDs can detect their own internal failures.
- Event Analysis: High-resolution oscillography helps diagnose fault causes.
- Flexibility: Logic can be updated via software rather than rewiring panels.

Interlocking Logic in IEDs

- Prevents unsafe operations (e.g., opening a disconnector under load).
- Traditional: Hardwired through auxiliary contacts.
- Modern SAS: Implemented via software logic inside the Bay Control Unit (IED).
- Allows complex, fail-safe interlocking schemes.

Summary

- SAS architecture is divided into Station, Bay, and Process levels.
- Station level handles global control and external communication.
- Bay level operates specific equipment via IEDs.
- Process level includes the primary high-voltage equipment.
- IEDs consolidate protection, control, and monitoring into smart digital units.

Next Lecture Preview

- How do these IEDs talk to each other?
- Introduction to Communication Protocols.
- The IEC 61850 Standard.
- SCADA integration in substations.

Substation Automation Basics (Part 3 of 3)

- Course: Substation Engineering (DI04009011)
- Unit 5: Substation Automation System (SAS)
- Focus: Communication Protocols (IEC 61850) & SCADA

Agenda

- The Need for Communication Protocols
- Legacy Protocols vs. Modern Standards
- Introduction to IEC 61850
- Key Concepts: GOOSE and MMS
- Network Topology in Substations
- What is SCADA?
- SCADA Integration in SAS
- Course Wrap-up for Unit 5

Why Standard Protocols?

- In the past, each manufacturer (Siemens, ABB, GE) had proprietary protocols.
- Proprietary protocols made it difficult to mix devices from different vendors.
- Utilities needed Interoperability to avoid vendor lock-in.
- Standards ensure long-term stability and easier system integration.

Legacy Protocols in Substations

- Modbus: Simple, widely used, but slow and lacks standardized data models.
- DNP3 (Distributed Network Protocol): Very common in North America, robust, but not optimized for high-speed local bay communication.
- IEC 60870-5-103/104: European standards, reliable but increasingly replaced by newer standards.

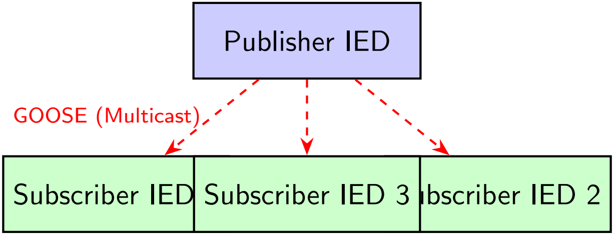
Introduction to IEC 61850

- The global standard for communication networks and systems in substations.
- Standardizes not just the protocol, but the data models and engineering process.
- Uses Ethernet as the underlying physical network.
- Achieves true interoperability between different vendors' IEDs.

Key Features of IEC 61850

Feature	**Description**
Data Modeling	Standardized names for data (e.g., XCBR for Circuit Breaker).
SCL Language	Substation Configuration Language (XML-based) for system design.
Ethernet Based	High speed, scalable, using standard IT network hardware.
Future-Proof	Separates data models from the specific communication technology.

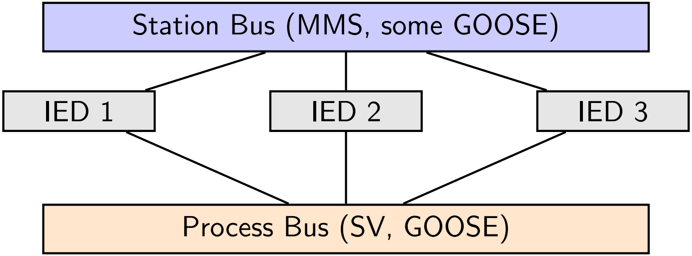
GOOSE Messaging



MMS and Sampled Values (SV)

- MMS (Manufacturing Message Specification): Used for reporting data, monitoring, and control commands from Station HMI to IEDs. Slower than GOOSE.
- Sampled Values (SV): Digitized instantaneous values of voltage and current from CTs/PTs.
- SV allows the complete digitization of the Process Level.

Substation Network Topology



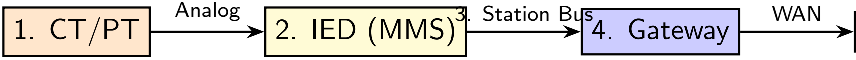
What is SCADA?

- Supervisory Control and Data Acquisition.
- A system operating at the utility's National or Regional Control Center.
- Provides operators a wide-area view of the entire power grid, not just one substation.
- Collects data from substations and allows remote control of breakers.

SAS Integration with SCADA

- The Substation Gateway acts as the bridge between SAS and SCADA.
- Gateway translates IEC 61850 data from IEDs into protocols understood by SCADA (like DNP3 or IEC 104).
- Transmits alarms, measurements, and status updates.
- Receives remote switching commands from SCADA operators.

Data Acquisition Flow



Benefits of SCADA Integration

- Faster fault location and isolation across the grid.
- Reduced need for personnel to travel to remote substations.
- Better load management and prevention of cascading blackouts.
- Historical data archiving for post-fault analysis.

Summary

- Standard protocols like IEC 61850 ensure vendor interoperability.
- GOOSE messaging allows high-speed communication for protective tripping over Ethernet.
- SCADA systems provide wide-area monitoring and control.
- Substation Gateways link the local SAS to the remote SCADA control centers.

Next Lecture Preview

- Future Trends in Substation Engineering.
- What is a fully Digital Substation?
- The impact of the Process Bus.
- Moving beyond traditional switchyards.

Future of Substations (Part 1 of 3)

- Course: Substation Engineering (DI04009011)
- Unit 6: Future Trends in Substation Engineering
- Focus: Digital Substations & Process Bus

Agenda

- What is a Digital Substation?
- Evolution from Conventional to Digital
- Non-Conventional Instrument Transformers (NCITs)
- Optical CTs and PTs
- The Merging Unit (MU)
- Station Bus vs. Process Bus
- Benefits of the Process Bus
- Summary

What is a Digital Substation?

- A substation where all data—from primary equipment to protection relays—is digitized.
- Replaces traditional copper signaling cables with fiber optic networks.
- Relies heavily on the IEC 61850 standard.
- Integrates primary process level equipment directly into the digital communication network.

Evolution of Substation Technology

Generation	Protection Type	Communication	Wiring
1st Gen	Electromechanical	Hardwired	Heavy Copper, 100% Analog
2nd Gen	Static/Numerical IEDs	Serial/Modbus	Copper from yard to control room
3rd Gen (SAS)	IEC 61850 IEDs	Ethernet (Station Bus)	Copper from yard, Fiber between relays
4th Gen (Digital)	Fully Digital	Ethernet (Process Bus)	100% Fiber Optic

Limitations of Conventional Transformers

- Traditional CTs and PTs use heavy iron cores and copper windings.
- Prone to magnetic saturation during high fault currents.
- Require thick copper cables to carry analog signals to the control room.
- Open-circuiting a conventional CT secondary is extremely dangerous (high voltage).

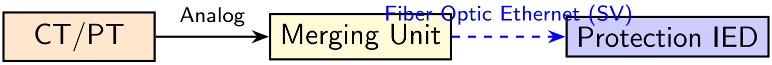
Non-Conventional Instrument Transformers (NCITs)

- Also known as Optical or Electronic Instrument Transformers.
- Use optical sensors instead of magnetic cores.
- Current measurement based on the Faraday Effect (rotation of polarized light).
- Voltage measurement based on the Pockels Effect.

Benefits of NCITs

- No Saturation: Highly accurate for both metering and protection.
- Safety: Output is an optical signal; no high voltage hazards from open secondaries.
- Lightweight: Dramatically smaller footprint and weight compared to oil-filled CTs.
- Eco-Friendly: No insulating oil required (reduces fire and leak risks).

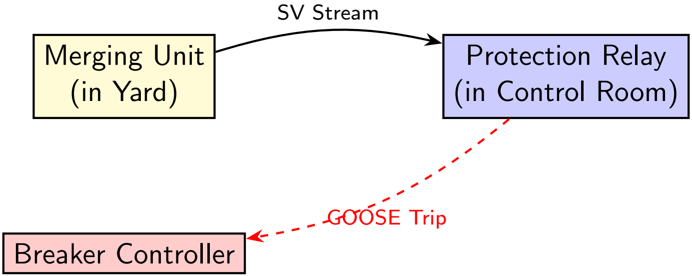
The Merging Unit (MU)



Station Bus vs. Process Bus

Feature	Station Bus (IEC 61850-8-1)	Process Bus (IEC 61850-9-2)
Location	Control Room	Switchyard to Control Room
Data Types	MMS (Reporting), GOOSE (Tripping)	Sampled Values (SV), GOOSE
Purpose	IED to IED, IED to HMI/SCADA	Primary Equipment to IEDs
Wiring Replaced	Inter-panel wiring	Long yard-to-panel wiring

Process Bus Architecture



Sampled Values (IEC 61850-9-2 LE)

- Continuous stream of digital data representing the AC waveform.
- 'LE' stands for Light Edition (an early implementation guideline).
- Sampling Rate: Typically 80 samples per cycle for protection, 256 for power quality.
- Requires highly precise time synchronization (PTP - Precision Time Protocol).

Advantages of the Process Bus

- Dramatic Copper Reduction: Up to 80% reduction in cabling costs.
- Increased Safety: Complete galvanic isolation; no electrical connection between yard and control room.
- Late Binding: Physical wiring doesn't dictate function. IEDs can subscribe to any MU on the network.
- Easier Expansion: Adding a new bay simply requires plugging an MU into the network switch.

Challenges of Digital Substations

- Network Reliability: The Ethernet network is now mission-critical. Switch failure means lost protection.
- Cybersecurity: Expanding the network into the yard increases attack surfaces.
- Skill Gap: Requires engineers skilled in IT networking, not just power systems.
- Time Synchronization: Loss of GPS/PTP can disrupt Sampled Values processing.

Summary

- Digital substations replace copper wiring with fiber optics and Ethernet networks.
- NCITs use optical properties to measure current and voltage safely and accurately.
- Merging Units digitize analog signals into IEC 61850 Sampled Values.
- Process Bus networks transmit these Sampled Values from the yard to control room IEDs.

Next Lecture Preview

- How do renewable energy sources affect substations?
- Integrating Solar and Wind farms.
- The rise of Microgrids.
- Energy Storage Systems (BESS) at the substation level.

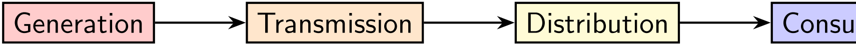
Future of Substations (Part 2 of 3)

- Course: Substation Engineering (DI04009011)
- Unit 6: Future Trends in Substation Engineering
- Focus: Renewable Integration & Microgrids

Agenda

- The Traditional Power Grid Model
- The Shift to Distributed Generation (DG)
- Challenges of Renewable Integration
- Bi-directional Power Flow & Protection Issues
- Inverter-Based Resources (IBR)
- Introduction to Microgrids
- Battery Energy Storage Systems (BESS)
- Substations as Energy Hubs

The Traditional Grid Model



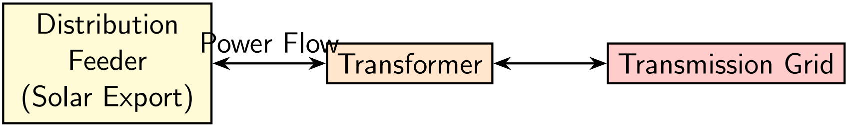
The Shift to Distributed Generation (DG)

- Power generation is moving closer to the load.
- Rooftop solar, local wind farms, biomass.
- Consumers become 'Prosumers' (producing and consuming power).
- Results in a highly decentralized and complex power network.

Challenges of Renewable Integration

- Intermittency: Solar and wind output fluctuates rapidly with weather.
- Voltage Regulation: Rapid power fluctuations cause voltage sags and swells.
- Reduced Inertia: Solar panels don't have heavy spinning rotors; the grid loses its natural kinetic stability.
- Fault Current Issues: Inverters cannot supply the massive fault currents that traditional generators can.

Bi-directional Power Flow



Impact on Protection Schemes

- Loss of Sensitivity: High fault contribution from DG can 'blind' relays at the main substation.
- Sympathetic Tripping: A fault on one feeder causes DG on a healthy feeder to contribute to the fault, tripping the healthy feeder.
- Requirement: Modern substations require adaptive protection relays (IEDs) that can change settings based on grid conditions.

Inverter-Based Resources (IBR)

Characteristic	Synchronous Generator	Inverter (Solar/Wind)
Inertia	High (Kinetic energy)	Zero (Electronic)
Fault Current	5x to 10x rated current	Limited to $\sim$1.2x rated current
Control Speed	Slow (Mechanical governors)	Extremely Fast (Power electronics)

What is a Microgrid?

- A localized group of electricity sources and loads.
- Normally operates connected to the traditional wide-area synchronous grid.
- Can disconnect to 'island mode' and function autonomously.
- Used for critical facilities (hospitals, military) or remote communities.

Substations in Microgrids

- The Point of Common Coupling (PCC) is usually a substation.
- The substation must manage the transition between grid-connected and islanded modes.
- Requires advanced synchrophasor measurements (PMUs) to ensure safe reconnection to the main grid.
- Must balance local generation and load precisely.

Battery Energy Storage Systems (BESS)

- Large-scale batteries installed directly at substations.
- Mitigates the intermittency of renewables (store solar during day, use at night).
- Provides 'synthetic inertia' by injecting power instantly to stabilize grid frequency.
- Enables Peak Shaving: Discharging during high demand to avoid overloading transformers.

BESS Applications in Substations

Application	Description	Benefit
Frequency Regulation	Absorbs/injects active power rapidly.	Maintains grid frequency at 50Hz/60Hz.
Voltage Support	Injects/absorbs reactive power via smart inverters.	Maintains stable local voltage.
Black Start	Provides initial power to restart the grid after a total blackout.	Faster system recovery.

Substations as Energy Hubs

- Future substations will not just be passive switching nodes.
- They become active Energy Hubs.
- Managing local generation, massive EV charging stations, and grid-scale storage.
- Rely heavily on AI and advanced SAS to optimize power flows in real-time.

Summary

- Distributed generation causes bi-directional power flow and alters fault currents.
- Traditional protection schemes must be upgraded to adaptive, intelligent relays.
- Microgrids provide local resilience and require precise synchronization at the substation PCC.
- BESS mitigates renewable intermittency and provides critical grid stability services.

Next Lecture Preview

- The digital era brings new threats: Cybersecurity in Substations.
- Understanding vulnerabilities in IEC 61850 networks.
- AI and Machine Learning for Predictive Maintenance.
- Concluding thoughts on the future of the power grid.

Future of Substations (Part 3 of 3)

- Course: Substation Engineering (DI04009011)
- Unit 6: Future Trends in Substation Engineering
- Focus: Cybersecurity & Artificial Intelligence

Agenda

- The Cybersecurity Threat Landscape
- Why Digital Substations are Vulnerable
- IT vs. OT (Operational Technology)
- Securing Substation Automation Systems
- Introduction to Condition Monitoring
- From Preventive to Predictive Maintenance
- AI and Machine Learning Applications
- Course Wrap-Up and Final Thoughts

The Threat Landscape

- Power grids are Critical Infrastructure.
- Cyber attacks can cause massive blackouts, equipment damage, and economic disruption.
- Real-world Example: 2015 Ukraine power grid cyberattack (attackers remotely opened substation breakers).
- Threat Actors: Nation-states, hacktivists, ransomware syndicates.

Why Digital Substations are Vulnerable

- Traditional substations were 'air-gapped' (no connection to the internet).
- Modern SAS relies on Ethernet, standard IP networks, and SCADA gateways.
- Increased connectivity vastly expands the 'Attack Surface'.
- Legacy protocols (Modbus, DNP3) were designed for reliability, not security (no encryption, no authentication).

IT vs. OT Security Priorities

Priority	IT (Information Technology)	OT (Substations/Power Grid)
Primary Goal	Confidentiality (Protect data)	Availability (Keep power flowing)
Patching	Frequent, often automated	Rare, requires scheduled outages
Network Speed	Milliseconds/Seconds	Microseconds (for GOOSE tripping)
Lifecycle	3-5 Years	15-30 Years

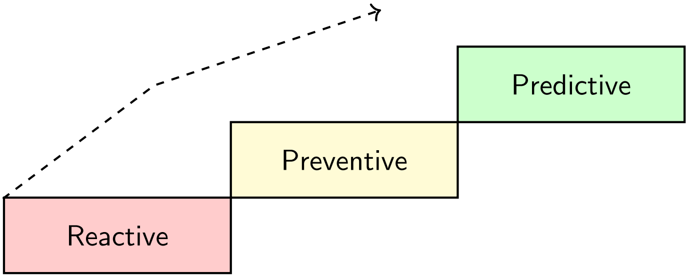
Securing Substation Automation Systems

- Defense-in-Depth Strategy: Multiple layers of security.
- Perimeter Firewalls: Strict control between SAS and the external utility WAN.
- Network Segmentation: Isolating Process Bus, Station Bus, and corporate networks.
- Role-Based Access Control (RBAC): Strict authentication for operators and engineers.

Condition Monitoring

- Continuous monitoring of physical parameters of substation equipment.
- Transformers: Dissolved Gas Analysis (DGA), oil temperature, moisture.
- Circuit Breakers: Gas pressure (SF_6), contact wear, operating mechanism timing.
- Sensors provide massive amounts of data directly to the Station Level.

Evolution of Maintenance Strategies



AI & Machine Learning in Substations

- Substations generate Terabytes of data (Sampled Values, DGA results, thermal images).
- Humans cannot analyze this volume of data effectively.
- Machine Learning algorithms are trained on historical data of normal and faulty equipment.
- AI can spot subtle anomalies and trends weeks before a human would notice.

Applications of AI for Predictive Maintenance

Equipment	AI Application	Benefit
Power Transformer	Analyzing DGA trends and acoustic emissions.	Prevents catastrophic internal faults and fires.
Circuit Breaker	Analyzing trip coil current profiles and timing.	Detects mechanical wear and lubrication issues.
Switchyard	Computer vision/Drones analyzing thermal imagery.	Spots 'hot spots' on joints before they melt.

Digital Twins

- A virtual, real-time digital replica of the physical substation.
- Powered by continuous data streams from physical sensors.
- Used for simulation, testing 'what-if' scenarios, and predicting future behavior.
- Allows engineers to test new protection settings virtually before deploying them.

Challenges of Implementing AI

- Data Quality: 'Garbage in, garbage out.' Algorithms require clean, accurate sensor data.
- Integration: Getting old legacy equipment to communicate with modern cloud AI platforms.
- Cybersecurity: Sending sensitive grid data to cloud environments requires strict security.
- Trust: Operators must learn to trust AI recommendations over traditional intuition.

The Future Engineer

- Substation engineering is no longer just about concrete, copper, and high voltage.
- Future engineers must be multidisciplinary.
- Core Skills Needed: Power Systems + IT Networking + Cybersecurity + Data Analytics.
- The grid of the future relies on smart software as much as heavy iron.

Summary

- Digital connectivity exposes substations to serious cyber threats, requiring Defense-in-Depth.
- OT security prioritizes availability above all else.
- Condition monitoring provides the data needed for predictive maintenance.
- AI and Machine Learning analyze vast datasets to predict failures, extending equipment life and reliability.

Course Conclusion

- We've covered: Substation Types, Equipment, Busbar Schemes, Grounding, SAS, and Future Trends.
- Thank you for your participation and hard work.
- Good luck on your final exams and your future careers in power engineering!