DI03000101: Electrical Power Transmission & Distribution

GTU Course Presentation

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Structure of the Electrical Power Grid I

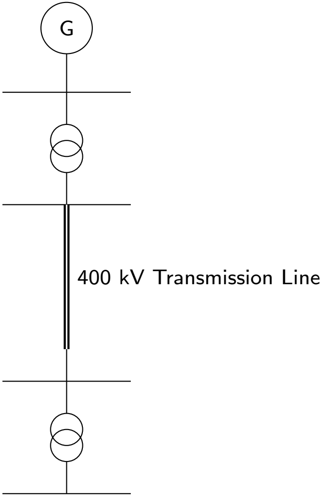
A modern electrical power system is a complex network designed to generate, transmit, and distribute electrical energy efficiently and reliably. Power is generated at lower voltages and stepped up to high voltages for long-distance transmission to minimize active power losses (I^2R).

Structure of the Electrical Power Grid II

Key Points

- Generation: Synchronous generators typically produce power at voltages ranging from 11 kV to 25 kV.
- Primary Transmission: Bulk power is transmitted over long distances at extra-high voltages (EHV) like 220 kV, 400 kV, or 765 kV.
- Secondary Transmission: Step-down transformers lower the voltage to 66 kV or 33 kV for transmission to regional receiving stations.
- Primary Distribution: Substation transformers step down the voltage to 11 kV or 6.6 kV to feed local distribution systems.
- Secondary Distribution: Distribution transformers step down the voltage to three-phase 415 V and single-phase 240 V for final consumers.

Single Line Diagram of Generation & Transmission I



Single Line Diagram of Generation & Transmission II

Key Points

- The single line diagram (SLD) simplifies the representation of a balanced three-phase system by using a single line to represent all three conductors.
- Standard IEEE/ANSI symbols are used for components: circles for generators, interlocking circles for transformers, and thick lines for buses.
- This diagram displays the flow of active and reactive power from the generating station through the step-up substation to the high-voltage transmission grid.

Key Components of Overhead Transmission Lines I

Overhead transmission lines consist of physical conductors, insulators, support structures (towers), and protection devices. Their design depends on voltage levels, environmental factors, and mechanical loads.

Key Components of Overhead Transmission Lines II

Key Points

- Conductors: Typically ACSR (Aluminum Conductor Steel Reinforced) to provide high electrical conductivity (aluminum) and high mechanical strength (steel core).
- Insulators: Prevent leakage current from conductors to ground. Usually made of porcelain, glass, or polymeric materials, and classified as suspension, tension, or pin-type.
- Supporting Structures: Steel lattice towers are used for EHV/UHV lines to maintain necessary ground clearance, while wooden, concrete, or steel poles are used for lower voltages.
- Shield (Ground) Wires: Placed at the topmost position of transmission towers to shield phase conductors from direct lightning strikes and provide a path for zero-sequence currents.

Electrical Parameters & Performance Equations I

The performance of a transmission line is characterized by its efficiency and voltage regulation. The voltage regulation is given by: $VR\% = \frac{|V_S| - |V_R|}{|V_R|} \times 100$. The active power loss in a three-phase line is given by: $P_{\text{loss}} = 3I^2R$.

Electrical Parameters & Performance Equations II

Key Points

- Resistance (R): Causes active power losses (I^2R) and voltage drop, depending on conductor temperature and skin effect.
- Inductance (L): Arises from magnetic field loops; determines the inductive reactance $X_L = 2\pi fL$, which limits power transfer capability.
- Capacitance (C): Formed between conductors and ground; leads to charging current $I_c = 2\pi fCV_R$ and shunt admittance.
- Ferranti Effect: In long, lightly loaded or unloaded transmission lines, the receiving end voltage V_R exceeds the sending end voltage V_S due to charging current ($V_R > V_S$).

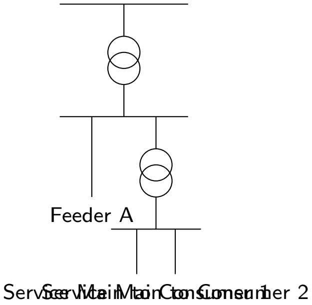
Electrical Substations & Equipment I

Substations act as physical nodes in the grid where voltage levels are changed, switching is performed, and protection is coordinated. They contain transformers, switchgear, busbars, and lightning arresters.

Key Points

- Busbars: Copper or aluminum bars that act as common electrical nodes for incoming and outgoing transmission lines.
- Circuit Breakers: Automatic switches that can break fault currents safely (using sulfur hexafluoride (SF_6), vacuum, or air as interrupting media).
- Isolators (Disconnectors): Manually or pneumatically operated switches used to isolate equipment for maintenance under no-load conditions.
- Instrument Transformers: Current Transformers (CTs) and Potential Transformers (PTs) step down currents and voltages for metering and relay protection.

Single Line Diagram of Distribution System I



Single Line Diagram of Distribution System II

Key Points

- Primary Distribution: Operates at 11 kV or 22 kV, feeding distribution transformers located near residential and industrial consumer hubs.
- Distribution Transformers: Typically delta-star (Δ-Y) step-down transformers providing a 3-phase 4-wire secondary system.
- Feeders: Direct lines connecting substations to distribution areas without intermediate taps, ensuring uniform current carrying capacity.
- Distributors & Service Mains: Distributors are tapped along their length to supply individual consumers via low-impedance service mains.

System Design Considerations and Protection I

Designing a reliable power system requires optimizing efficiency, thermal limits, voltage profiles, and protection coordination. Protection systems must isolate faults in milliseconds to prevent damage and maintain grid stability.

System Design Considerations and Protection II

Key Points

- Thermal Limits: The maximum current a conductor can carry without exceeding temperature limits that cause excessive sag or loss of tensile strength.
- Insulation Coordination: Designing insulation levels of substations and lines to withstand both operating voltages and transient overvoltages (lightning/switching surges).
- Relaying: Protective relays (overcurrent, distance, differential) continuously monitor electrical parameters and trip circuit breakers during faults.
- Neutral Grounding: System neutral points are grounded (solidly or via impedance) to stabilize voltages relative to ground and enable fault detection.

Classification of Transmission Lines I

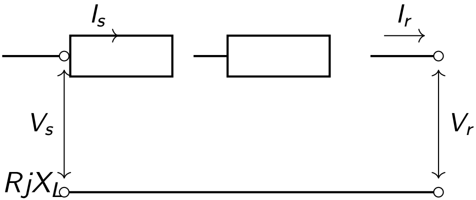
Transmission lines are classified into Short, Medium, and Long lines based on length and operating voltage. This dictates the circuit representation and mathematical analysis methods.

Classification of Transmission Lines II

Key Points

- Short lines: Length ¡ 80 km (50 miles) and operating voltage ¡ 20 kV. Shunt capacitance is neglected due to low charging current.
- Medium lines: Length 80 km to 250 km and operating voltage 20 kV to 100 kV. Shunt capacitance is lumped at one or more points (nominal-T or nominal-π).
- Long lines: Length ¿ 250 km and operating voltage ¿ 100 kV. Parameters are uniformly distributed over the entire line length.
- The classification is crucial because charging current ($I_c = \omega CV$) becomes dominant at high voltages and long distances, affecting voltage profile (Ferranti Effect).

Short Transmission Line Model I



Short Transmission Line Model II

Key Points

- Negligible capacitance simplifies the line analysis to a simple series impedance: $Z = R + jX_L$.
- Sending-end current equals receiving-end current: $I_s = I_r$.
- Sending-end voltage equation: $V_s = V_r + I_r(R + jX_L)$.
- ABCD Parameters: $A = 1$, $B = Z$, $C = 0$, $D = 1$. The network is symmetric ($A = D$) and reciprocal ($AD - BC = 1$).

Medium Transmission Line Models I

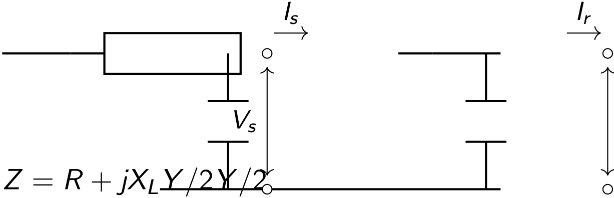
To analyze medium transmission lines, the shunt capacitance (C) is lumped at discrete points to form equivalent networks, typically the Nominal-T and Nominal-π *configurations*.

Medium Transmission Line Models II

Key Points

- Nominal-T Configuration: Half of the total series impedance ($Z/2$) is placed on each side of the lumped shunt admittance (Y).
- Nominal-T ABCD parameters: $A = D = 1 + \frac{YZ}{2}$, $B = Z(1 + \frac{YZ}{4})$, and $C = Y$.
- Nominal-$\pi Configuration:$ $Thetotalshuntadmittanceissplitequally$(Y/2)$andplacedatthesen$
- Nominal-$\pi ABCDparameters:$A = D = 1 + YZ$_{\overline{2}}$, $B = Z$, and $C = Y(1 + \frac{YZ}{4})$.
- Where $Z = R + jX_L$ is the total series impedance, and $Y = j\omega C$ is the total shunt admittance of the line.

Nominal-$\pi ModelCircuitDiagramI$



Nominal-$\pi ModelCircuitDiagramII$

Key Points

- The Nominal-$\pi modellumpshalfthetotallinecapacitance$(C/2orY/2)$atboththe$
- Sending-end voltage equation: $V_s = V_r(1 + \frac{YZ}{2}) + I_r Z$.
- Sending-end current equation: $I_s = V_r Y(1 + \frac{YZ}{4}) + I_r(1 + \frac{YZ}{2})$.
- This model is widely used in power system load flow studies to represent medium-length transmission links.

Long Transmission Lines & Distributed Parameters I

For lines exceeding 250 km, parameters are distributed uniformly. Hyperbolic functions describe the voltage and current wave propagation along the line.

Key Points

- Rigorous analytical equations:
  $V_s = V_r \cosh(\gamma l) + I_r Z_c \sinh(\gamma l)$ and
  $I_s = V_r \frac{1}{Z_c} \sinh(\gamma l) + I_r \cosh(\gamma l)$.
- Propagation constant $\gamma = \alpha + j\beta = \sqrt{zy}$, where α is the attenuation constant and β is the phase constant.
- Characteristic impedance $Z_c = \sqrt{z/y} = \sqrt{\frac{r+j\omega l}{g+j\omega c}}$. For a lossless line, it becomes Surge Impedance
  $Z_c = \sqrt{l/c} \approx 400\ \Omega$.
- Surge Impedance Loading (SIL): Power transmitted at unity power factor when the line is terminated by its surge impedance, calculated as $\text{SIL} = \frac{V_{LL}^2}{Z_c}$ MW.

Standard Voltage Levels in India I

India utilizes a mix of EHV/UHV AC and HVDC transmission systems to transmit power across its five regional grids, now unified into one national grid.

Standard Voltage Levels in India II

Key Points

- Extra High Voltage (EHV) AC levels: 220 kV and 400 kV AC. These form the primary interstate and intrastate network.
- Ultra High Voltage (UHV) AC level: 765 kV AC is currently the highest operating AC voltage in India. A 1200 kV AC test station exists at Bina, MP.
- Sub-Transmission levels: 132 kV and 66 kV AC are utilized to deliver power from grid substations to primary distribution substations.
- High Voltage Direct Current (HVDC) systems: $\pm$500 kV and $\pm$800 kV DC are used for point-to-point bulk power transmission over massive distances (e.g., Biswanath Chariali to Agra link).

Selection of Transmission Voltage I

The choice of transmission voltage is determined by economic factors, power capability limits, and technical clearances.

Selection of Transmission Voltage II

Key Points

- Still's Formula for economic line voltage: $V = 5.5\sqrt{\frac{L}{1.6} + \frac{P}{150}}$, where V is the line voltage in kV, L is line length in km, and P is power to be transmitted in kW.
- Power transfer capability is proportional to the square of voltage: $P \propto \frac{V^2}{X}$. Doubling the voltage increases power capability fourfold.
- Conductor material requirement varies inversely with the square of the voltage: $W \propto \frac{1}{V^2 \cos^2 \phi}$, reducing line losses ($I^2 R$).
- Technical limitations: Higher voltage increases the cost of transformers, switchgear, tower structures, insulation, and causes corona losses.

Overhead vs. Underground Transmission Systems I

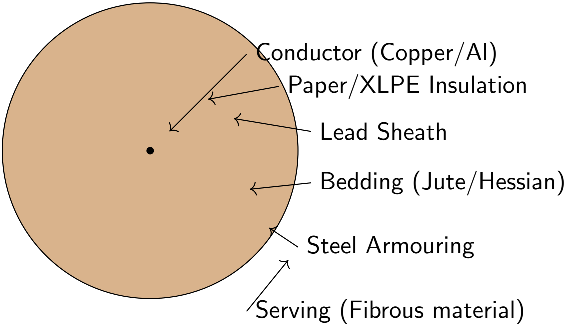
Comparative analysis of electrical, mechanical, and economic parameters governing the choice between Overhead (OH) and Underground (UG) systems.

Overhead vs. Underground Transmission Systems II

Key Points

- Public Safety & Reliability: UG systems have significantly higher safety and less exposure to atmospheric hazards (lightning, wind, storms), resulting in fewer transient faults, though permanent faults require long repair times.
- Initial Cost & Right of Way (RoW): OH systems are 10 to 15 times cheaper than UG equivalents due to insulation (dielectric cables, joints) and excavation costs. UG requires much narrower RoW but is restricted by thermal dissipation limits.
- Electrical Properties: UG cables exhibit much higher capacitance ($C = \frac{2\pi\varepsilon}{\ln(R/r)}$) and lower inductance ($L = \frac{\mu}{2\pi}\ln(D/r)$) than OH lines, leading to substantial charging current ($I_c = \omega CV$) and limiting the critical length due to reactive power generation.

Cross-Sectional Diagram of a Single-Core Underground Cable I



Cross-Sectional Diagram of a Single-Core Underground Cable II

Key Points

- Conductor Core: Typically stranded copper or aluminum, carrying the load current (I).
- Insulation: Paper impregnated with oil, or cross-linked polyethylene (XLPE) to withstand electrical stress ($E_{max} = \frac{2V}{d \ln(D/d)}$).
- Metallic Sheath: Lead or aluminum sheath to protect insulation from moisture, acids, and gases in the soil.
- Bedding, Armouring, and Serving: Bedding protects the sheath from mechanical injury due to armouring; Armouring (galvanized steel wire) provides physical protection; Serving protects armouring from atmospheric agents.

Solid and Hollow Conductor Characteristics I

Analysis of current distribution, skin effect, and corona mitigation in solid and hollow geometry.

Solid and Hollow Conductor Characteristics II

Key Points

- Solid Conductors: Simplest design but highly prone to skin effect, where current density J decays exponentially from the surface: $J(x) = J_0 e^{-x/\delta}$, where skin depth $\delta = \sqrt{\frac{\rho}{\pi f \mu}}$. This increases AC resistance ($R_{ac} > R_{dc}$).
- Skin Effect Impact: At high voltages (> 100 kV) and standard frequencies (50/60 Hz), the center of a large solid conductor carries virtually zero current, making the material usage highly inefficient.
- Hollow Conductors: By removing the inner core, weight is minimized and material is placed where current density is highest, reducing skin effect losses.
- Corona Mitigation: A hollow conductor artificially increases the outer diameter (d) without adding mass. Since the critical disruptive voltage

Stranded Conductor Technologies: AAC, AAAC, & ACSR I

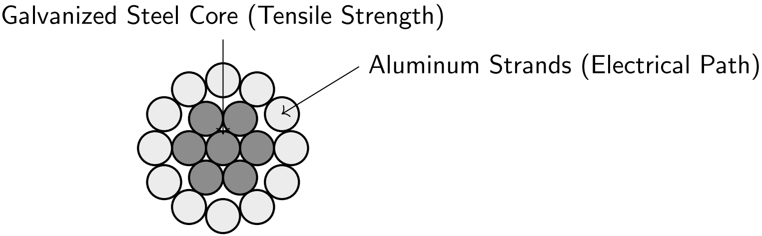
Properties and application domains of All Aluminum Conductors (AAC), All Aluminum Alloy Conductors (AAAC), and Aluminum Conductor Steel Reinforced (ACSR).

Stranded Conductor Technologies: AAC, AAAC, & ACSR II

Key Points

- AAC (All Aluminum Conductor): Manufactured from EC grade aluminum (99.5% purity). High conductivity (61% IACS) but low tensile strength (approx. 160 MPa), restricting its use to short spans in distribution networks.
- AAAC (All Aluminum Alloy Conductor): Made of Al-Mg-Si alloy (6201-T81). Offers higher tensile strength (approx. 300 MPa) and excellent corrosion resistance, making it ideal for coastal areas with moderate spans.
- ACSR (Aluminum Conductor Steel Reinforced): Features an inner core of galvanized steel strands for mechanical tensile strength, surrounded by outer layers of EC aluminum for electrical conductivity.

ACSR Conductor Cross-Sectional Geometry I



ACSR Conductor Cross-Sectional Geometry II

Key Points

- Core Strands: 7 galvanized steel wires at the center provide high mechanical support, reducing conductor sag under thermal load.
- Outer Strands: 12 high-conductivity aluminum strands wound helically in opposite directions to prevent unwinding and neutralize torsional stress.
- Stranding Advantage: Stranding increases flexibility, simplifies handling, reduces skin effect relative to a solid conductor of equivalent cross-section, and prevents fatigue failures from vibration.
- Current Distribution: Due to the high impedance of steel at 50/60 Hz, the current flows almost entirely in the outer aluminum layer, minimizing AC resistance.

Advanced conductor core materials (ACSS, ACCC) and surface engineering via passive radiative cooling.

High-Performance Conductors & Photonic Materials II

Key Points

- ACSS (Aluminum Conductor Steel Supported): Uses fully annealed aluminum (O-temper) with high thermal capacity. Can operate up to 250°C without loss of tensile strength, as the steel core supports the entire mechanical tension.
- ACCC (Aluminum Conductor Composite Core): Replaces steel with a carbon-epoxy/glass-fiber composite core. It has a thermal expansion coefficient $\alpha \approx 1.6 \times 10^{-6}/°C$ (vs. steel's 11.5×10^{-6}), virtually eliminating high-temperature sag.
- Photonic Coatings: Micro-structured or nano-porous polymer-ceramic coatings applied to the conductor surface. They maximize solar reflectance (low absorptivity $\alpha_s \leq 0.2$) and thermal emissivity (high

Covered Conductors & Dynamic Line Rating I

Safety enhancements with covered systems and optimized grid utilization through real-time thermal monitoring.

Covered Conductors & Dynamic Line Rating II

Key Points

- Covered Conductors (CC): Consists of a conductor surrounded by a non-rated insulation layer (water-tree resistant XLPE/HDPE). Prevents transient phase-to-ground or phase-to-phase short circuits caused by tree contact or wildlife.
- CC Limitation: Unlike fully insulated underground cables, covered conductors do not have metallic shields or semiconductor screens. They cannot be touched safely when energized and must be mounted on insulators.
- Dynamic Line Rating (DLR): A smart grid technology that dynamically varies line rating based on real-time environmental factors (ambient temperature, wind speed, wind direction, solar radiation) rather than static seasonal assumptions.

Physics of Skin Effect I

Skin effect refers to the phenomenon where alternating current (AC) concentrates near the outer surface (skin) of a conductor. This increases the effective resistance of the conductor compared to its DC resistance.

Physics of Skin Effect II

Key Points

- Cause: Alternating current induces changing magnetic flux, which in turn induces back-EMFs (eddy currents) in the conductor core.
- Flux linkage is maximum at the center of the conductor and decreases towards the surface.
- Higher flux linkage at the center leads to higher self-inductance and inductive reactance ($X_L = 2\pi fL$) in the core.
- Current takes the path of least impedance, crowding towards the outer surface where reactance is lowest.

Mathematical Derivation of Skin Depth I

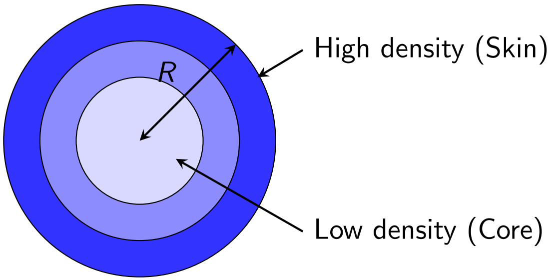
The current density J_x at depth x from the surface of a cylindrical conductor decays exponentially: $J_x = J_0 e^{-x/\delta}$, where J_0 is the surface current density and δ is the skin depth.

Mathematical Derivation of Skin Depth II

Key Points

- Skin depth δ is defined as the depth where current density drops to $1/e \approx 37\%$ of its surface value.
- Formula for skin depth: $\delta = \sqrt{\frac{\rho}{\pi f \mu}}$, where ρ is resistivity, f is frequency, and μ is magnetic permeability.
- For a copper conductor at 50 Hz, $\delta \approx 9.3$ mm; at 60 Hz, $\delta \approx 8.5$ mm.
- Effective AC resistance is expressed as: $R_{ac} = k \cdot R_{dc}$, where $k > 1$ is the skin effect factor.

Visualizing Skin Effect Current Density I



Visualizing Skin Effect Current Density II

Key Points

- Shading representation: Darker outer ring indicates higher current density, while the light center represents low current density.
- The core of the conductor is under-utilized, carrying very little current.
- For large conductor diameters (> 2 cm), the skin effect makes solid conductors highly inefficient.
- This current distribution requires alternative conductor designs like stranded or hollow conductors.

Introduction to Proximity Effect I

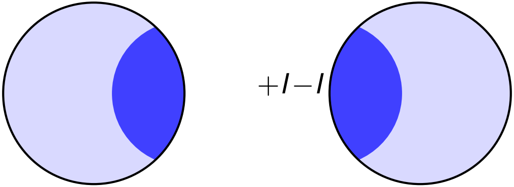
Proximity effect is the distortion of current distribution in a conductor caused by the magnetic fields generated by nearby current-carrying conductors.

Introduction to Proximity Effect II

Key Points

- When parallel conductors carry AC, their magnetic fields interact, causing non-uniform flux linkage across the cross-sections.
- Like skin effect, this non-uniform distribution increases the effective resistance and power losses of the transmission line.
- Same-direction currents: Magnetic flux lines crowd the space between them, forcing current to the outer halves (remote sides).
- Opposite-direction currents: Flux lines cancel in the space between, forcing current to the inner halves (facing sides).

Visualizing Proximity Effect (Opposite Currents) I



Visualizing Proximity Effect (Opposite Currents) II

Key Points

- The diagram displays two parallel conductors carrying currents in opposite directions ($+I$ and $-I$).
- Due to magnetic field cancellation between the conductors, the current density crowds on the adjacent (inner) faces.
- For same-direction currents, the crowding would occur on the outer (remote) faces instead.
- The magnitude of this effect is highly sensitive to the ratio of conductor diameter to conductor spacing (d/D).

Factors Influencing Skin & Proximity Effects I

Several key system and material parameters determine the severity of skin and proximity effects in overhead power lines.

Factors Influencing Skin & Proximity Effects II

Key Points

- Conductor Material Permeability: Magnetic conductors (e.g., steel) experience much stronger effects due to higher permeability (μ).
- Conductor Diameter: Larger diameters increase self-inductance variations, intensifying both skin and proximity effects.
- Operating Frequency: Both effects are proportional to $\sqrt{f}$; negligible at DC (0 Hz), minimal at 50/60 Hz for small conductors, but dominant at high frequencies.
- Conductor Spacing: Proximity effect decreases exponentially as the spacing between conductors (D) increases, becoming negligible when $D \gg 10 \times d$.

Engineering Solutions: ACSR and Stranded Conductors I

To mitigate skin and proximity effects while ensuring structural integrity and cost-efficiency, modern transmission systems utilize specialized conductor configurations.

Engineering Solutions: ACSR and Stranded Conductors II

Key Points

- Stranding: Replacing a single solid conductor with multiple smaller strands increases flexibility and slightly reduces the skin effect.
- ACSR (Aluminum Conductor Steel Reinforced): A central high-strength steel core is surrounded by outer layers of high-conductivity aluminum strands.
- Steel core provides mechanical tensile strength but carries little current due to its high reactance and the skin effect.
- Aluminum strands carry the bulk of the AC current near the skin, optimizing material usage and reducing transmission losses (I^2R).

Introduction to Bundled Conductors I

Bundled conductors consist of two or more sub-conductors per phase, spaced closely together compared to the phase-to-phase spacing.

Introduction to Bundled Conductors II

Key Points

- Used primarily in Extra High Voltage (EHV) and Ultra High Voltage (UHV) lines (typically ≥ 220 kV).
- Mitigates corona discharge by increasing the self-equivalent radius, thereby reducing the electric field intensity ($E = \frac{V}{r \ln(D/r)}$) at the conductor surface below the critical disruptive voltage threshold ($g_0 \approx 30$ kV/cm peak).
- Reduces transmission line inductance and increases line capacitance, leading to an overall reduction in characteristic surge impedance ($Z_c = \sqrt{L/C}$).
- Improves the Surge Impedance Loading ($SIL = V_L^2/Z_c$) of the transmission line, enhancing power transfer capability.

Geometric Mean Radius (GMR) Calculations I

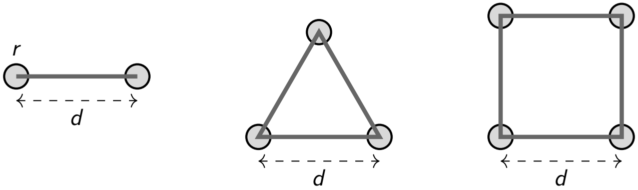
Calculating the Geometric Mean Radius (GMR) or Self-GMD (D_s^b) for different bundle configurations.

Geometric Mean Radius (GMR) Calculations II

Key Points

- For a bundle of n sub-conductors, each with self-GMR $r' = re^{-1/4} \approx 0.7788r$, the bundle GMR ($D_s^b$) is the n^2-th root of the product of all internal distances.
- For a 2-conductor bundle with spacing d: $D_s^{2b} = \sqrt{r' \cdot d}$
- For a 3-conductor bundle (equilateral triangle) with spacing d: $D_s^{3b} = \sqrt[3]{r' \cdot d^2}$
- For a 4-conductor bundle (square) with spacing d: $D_s^{4b} = \sqrt[4]{r' \cdot d^3\sqrt{2}} = 1.09 \cdot \sqrt[4]{r' \cdot d^3}$
- Increasing the bundle GMR directly reduces the per-phase inductance: $L = 2 \times 10^{-7} \ln\left(\frac{D_{eq}}{D_s^b}\right)$ H/m.

Bundle Configurations & Spacers I



Bundle Configurations & Spacers II

Key Points

- Sub-conductors are kept in their relative positions using spacers spaced at intervals of 60 to 80 meters along the span.
- Spacers must withstand mechanical stresses during short-circuit faults and prevent wind-induced sub-conductor clashing.
- Common configurations include duplex (2-bundle), triplex (3-bundle), and quad (4-bundle) systems.
- Spacing d is typically chosen in the range of 30 to 45 cm (12 to 18 inches) for optimal electrical performance.

Inductance of Bundled Lines I

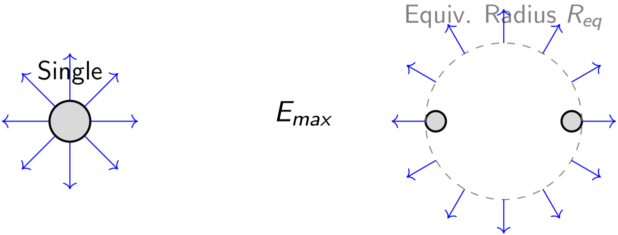
Mathematical formulation of phase inductance for bundled transmission lines.

Inductance of Bundled Lines II

Key Points

- Inductance formula: $L = 2 \times 10^{-7} \ln\left(\frac{D_{eq}}{D_s^b}\right)$ H/m/phase.
- Geometric Mean Distance (GMD) is defined as $D_{eq} = \sqrt[3]{D_{ab}D_{bc}D_{ca}}$ where D_{ij} are the inter-phase center-to-center distances.
- Because $D_s^b > r'$ (where r' is the self-GMR of a single conductor), the value of $\ln(D_{eq}/D_s^b)$ decreases, leading to lower inductive reactance $X_L = \omega L$.
- For a typical 4-conductor bundle, inductance is reduced by approximately 25% to 30% compared to a single conductor of equivalent total cross-sectional area.
- Lower inductance directly improves the transient stability limit and reactive power control of the transmission grid.

Capacitance and Electric Field Distribution I



Capacitance and Electric Field Distribution II

Key Points

- The equivalent radius R_{eq} of the bundle is much larger than the physical radius r of the individual sub-conductors.
- For a 2-bundle: $R_{eq} = \sqrt{r \cdot d}$; for a 4-bundle: $R_{eq} = 1.09\sqrt[4]{r \cdot d^3}$.
- Line capacitance to neutral increases: $C = \frac{2\pi\epsilon_0}{\ln(D_{eq}/R_{eq})}$ F/m.
- An increased capacitance combined with reduced inductance lowers the line's characteristic impedance $Z_c.
- This field redistribution mitigates radio interference (RI) and television interference (TVI) by lowering corona noise.

Technical & Economic Trade-offs I

While offering electrical benefits, bundled conductors introduce mechanical and structural challenges.

Technical & Economic Trade-offs II

Key Points

- Wind and ice loading: The larger surface area exposed to wind and ice increases the mechanical loading on towers, requiring stronger structural designs.
- Sub-conductor oscillation: Wake-induced oscillations (subspan oscillation) and Aeolian vibration can cause physical damage, requiring tuned spacers and dampers.
- Increased complexity: Higher installation costs, complex stringing procedures, and the need for specialized spacer dampers.
- Reactive power considerations: Higher capacitance leads to greater charging current ($I_c = \omega CV$), requiring shunt reactors during light-load conditions (Ferranti effect mitigation).

Summary & Industry Design Standards I

A review of industrial standards and the net impact of bundled conductors on transmission line parameters.

Summary & Industry Design Standards II

Key Points

- Main electrical advantages: Lower Corona Loss, Lower Inductance (higher stability), Higher Capacitance, and Increased Surge Impedance Loading (SIL).
- Summary Equation: $SIL = \frac{V_L^2}{\sqrt{L/C}}$. Reducing L and increasing C yields a compounding boost to the power transfer capability.
- Standard Industry practice: Duplex for 400 kV lines, Triplex/Quad for 500 kV/765 kV lines, and Hexa/Octa (6 or 8 bundles) for UHV lines ($>$ 1000 kV).
- Spacer-dampers are placed along the span to absorb energy from wind-induced oscillations and protect the conductors.

Line Supports: Desirable Properties & Steel Poles I

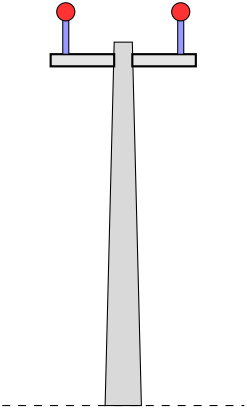
Line supports hold the conductors at a safe height above ground. Steel poles are widely used for distribution lines due to their mechanical strength, longer life, and aesthetic appeal in urban areas.

Line Supports: Desirable Properties & Steel Poles II

Key Points

- Desirable properties of line supports: High mechanical strength, light weight without loss of strength, low cost, longer lifespan, and low maintenance.
- Steel poles are classified into: Tubular poles, Rail poles (made of old railway rails), and Rolled Steel Joists (RSJ).
- Tubular poles consist of stepped sections (e.g., three sections of varying diameters welded together) to optimize material usage against bending moments.
- Safety factor for steel poles is typically 2.0 to 2.5 under maximum wind and conductor tension loads.
- Mitigation of atmospheric corrosion is achieved through hot-dip galvanizing or frequent painting, extending service life up to 40 years.

RCC Poles (Reinforced Cement Concrete) I



RCC Poles (Reinforced Cement Concrete) II

Key Points

- RCC poles have high mechanical strength, require very low maintenance, and have a long life span of over 50 years.
- They are ideal for distribution networks (voltages up to 33 kV) and are widely used in modern power grids.
- The concrete handles compressive stress, while the steel reinforcement bars handle tensile and bending stresses caused by wind and line tension.
- Pre-stressed Concrete (PSC) poles use pre-tensioned steel wires, offering higher bending strength, lighter weight, and resistance to cracking.
- A major disadvantage is their heavy weight, which increases transportation costs and requires specialized equipment for erection.

Lattice Steel Towers I

For high-voltage transmission lines (above 66 kV), lattice steel towers are employed to provide high structural reliability, handle long spans, and accommodate multiple circuits.

Lattice Steel Towers II

Key Points

- Lattice towers are built from galvanized angle sections bolted together, allowing wind to pass through, which reduces wind loading.
- Wind load calculation on conductors: $F_w = P \cdot d \cdot L \cdot C_d$, where P is wind pressure, d is projected conductor diameter, L is span length, and C_d is drag coefficient.
- Configured as Single Circuit (carrying 3 conductors) or Double Circuit (carrying 6 conductors) to maximize right-of-way (RoW) capacity.
- Designed to withstand vertical loads (conductor weight, ice loading), transverse loads (wind pressure), and longitudinal loads (broken wire tension).
- Fitted with a ground/shield wire at the peak to intercept lightning strikes, grounding them safely via tower footing resistance.

Types of Insulators and Materials I

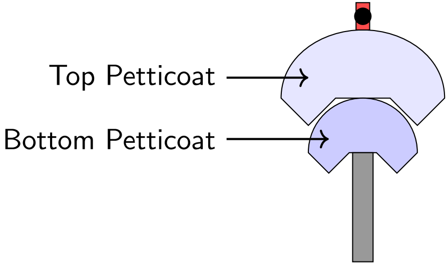
Insulators prevent leakage currents to ground and mechanically support overhead conductors. They are subjected to both high electrical stress and mechanical tension.

Types of Insulators and Materials II

Key Points

- Desirable properties: Very high electrical resistance to prevent leakage, high dielectric strength to resist breakdown, and high mechanical strength.
- Porcelain is the traditional material, produced by firing kaolin, feldspar, and quartz. It is glazed to prevent moisture accumulation.
- Toughened Glass is also used, offering higher dielectric strength, lower coefficient of thermal expansion, and easy visual inspection.
- Polymeric/Composite insulators consist of a fiberglass core rod (for mechanical strength) and silicone rubber sheds (for hydrophobicity).
- Failure modes: Flashover (arc through air along the surface) or Puncture (electrical breakdown through the material). Safety factor is defined as

Pin and Suspension Insulators I



Pin and Suspension Insulators II

Key Points

- Pin Insulators are designed for voltages up to 33 kV. They are bolted directly onto the cross-arm using a galvanized steel pin.
- Above 33 kV, pin insulators become highly uneconomical, heavy, and bulky because the puncture voltage requirements necessitate a disproportionately large size.
- Suspension Insulators are used for voltages above 33 kV. They consist of a series of porcelain discs linked together by metal fittings in a string.
- Each disc is typically designed for a dry flashover voltage corresponding to about 11 kV operating voltage.
- If a disc in a suspension string gets damaged, only that specific unit needs replacement, rather than replacing the entire insulator assembly.

Strain and Shackle Insulators I

Strain and Shackle insulators are used where the line is subjected to high mechanical tension or changes in direction.

Strain and Shackle Insulators II

Key Points

- Strain Insulators are used at dead-ends, sharp curves, and river crossings of high-voltage transmission lines (> 11 kV).
- They are placed horizontally in line with the conductor to sustain the full mechanical tension of the line span.
- For extra-high voltages (EHV), two or more suspension strings are arranged in parallel (double-strain assembly) to handle high mechanical loads.
- Shackle Insulators (also called spool insulators) are used in low-voltage distribution lines (< 11 kV).
- They are mounted on poles either vertically or horizontally using a U-clevis clamp, allowing the conductor to turn corners smoothly.

Stay Insulators and String Efficiency I

Stay insulators provide electrical isolation in guy wires, while string efficiency determines the voltage distribution across suspension strings.

Stay Insulators and String Efficiency II

Key Points

- Stay Insulators (or egg/guy insulators) are installed in the stay wire at least 3 meters above ground to protect people from leakage currents.
- Their design ensures that if the porcelain body breaks, the stay wire loops interlock, preventing the guy wire from falling.
- String Efficiency is defined as $\eta = \frac{V_{total}}{n \cdot V_{nearest}} \times 100\%$, where n is the number of discs and $V_{nearest}$ is the voltage across the disc closest to the conductor.
- Due to shunt capacitance (C_s) between the metal fittings and the grounded tower, the voltage distribution is non-uniform, with the bottom disc stressed the most.
- String efficiency can be improved by: (1) using longer cross-arms to reduce C_s, (2) grading the capacitance of the discs, or (3) using a corona/grading ring.

Overhead Line Insulators: Functions & Requirements I

Overhead line insulators must withstand normal operating voltage, transient overvoltages, and mechanical loads without electrical breakdown or physical failure.

Overhead Line Insulators: Functions & Requirements II

Key Points

- Primary Role: Provide electrical isolation between the energized phase conductors and the grounded tower structures.
- Mechanical Support: Support the physical weight of conductors under static loads and dynamic loads (wind, ice, and conductor vibrations).
- Operational Reliability: Must function continuously for decades under extreme environmental conditions like UV radiation, thermal cycling, and pollution.

Key Desirable Properties of Insulator Materials I

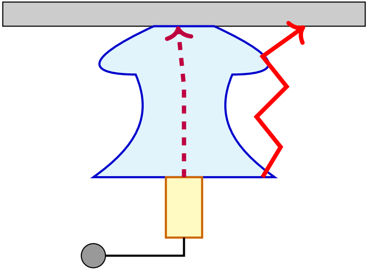
Insulator performance relies on key physical, electrical, chemical, and mechanical properties.

Key Desirable Properties of Insulator Materials II

Key Points

- High Electrical Resistivity: Prevents leakage current flowing to the ground ($R_{\text{leakage}} = \rho \frac{l}{A} \approx 10^{12}$ to 10^{15} , $\Omega \cdot \text{cm}$).
- High Dielectric Strength: Must withstand high voltage gradients without electrical breakdown (typically ≥ 140 , $\text{kV/cm} forporcelain$).
- High Mechanical Strength: High tensile and compressive strength to withstand wind loads (F_{wind}), ice loading (W_{ice}), and conductor tension (T).
- High Ratio of Flashover Voltage to Puncture Voltage: The safety factor should be high (typically > 1.0) to ensure any electrical discharge occurs through air (flashover) rather than puncturing the solid dielectric.
- Chemical Inertness: Must be non-porous and free from

Electrical Discharge: Flashover and Puncture Paths I



Electrical Discharge: Flashover and Puncture Paths II

Key Points

- Flashover: An arc discharge that occurs through the surrounding air along the outer surface of the insulator when the voltage exceeds the dry/wet flashover limit.
- Puncture: An irreversible breakdown of the dielectric material itself, creating a conductive path through the body of the insulator.
- Safety Factor: Defined as the ratio of puncture strength to flashover voltage. A high safety factor (> 2.0) ensures the insulator flashes over before it punctures, protecting the asset from permanent damage.

Causes of Insulator Failure: Mechanics & Stresses I

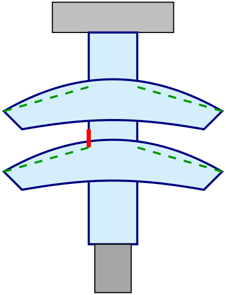
Insulator failures are caused by electrical, mechanical, environmental, and thermal stresses.

Causes of Insulator Failure: Mechanics & Stresses II

Key Points

- Electrical Puncture: Occurs if the electrical stress exceeds the dielectric strength of the material, forming a permanent conductive path inside.
- Mechanical Failure: Caused by excessive tension, bending, or compression from high winds, ice accumulation, or mechanical fatigue due to aeolian vibrations.
- Short-circuiting by Birds/Objects: External objects or wildlife bridging the air gap between the live conductor and grounded structure, initiating a flashover.
- Thermal Stress/Cracking: Unequal heating and cooling of the insulator parts (porcelain, cement, metal fittings) leads to high internal mechanical stress and micro-cracks.

Pollution-Induced Flashover Mechanism I



Pollution-Induced Flashover Mechanism II

Key Points

- Contamination: Dust, salt, or industrial emissions deposit on the insulator surface, forming a dry pollution layer.
- Moisture Ingress: Light rain, fog, or dew dissolves soluble salts in the pollution, turning it into a conductive wet film.
- Leakage Current & Dry Bands: A leakage current flows (I_{leakage}). High current density near the narrow sections causes localized heating, drying out the water and forming a high-resistance 'dry band'.
- Dry Band Arc: The entire voltage drops across the narrow dry band, causing air breakdown and localized arcing. If the arc propagates across all sheds, a full wet flashover occurs.

Specific Insulator Failures & Mitigation I

Mitigation of insulator failures requires proper design, selection of materials, and regular maintenance.

Specific Insulator Failures & Mitigation II

Key Points

- Porcelain Glaze Damage: Defective glaze exposes porous interior, allowing moisture absorption, lowering resistance, and leading to puncture.
- Cement Expansion: The thermal expansion coefficient mismatch between cement, porcelain, and metal hardware causes stress and cracking.
- Corona Discharge: High local electric field gradient ionizes air, producing ozone which degrades polymer insulators (corona cutting).
- Mitigation: Regular washing/coating (silicone grease), use of corona rings to equalize electric stress distribution, and using polymer (composite) insulators with hydrophobic properties.

Insulator Materials: Porcelain, Glass, and Composite I

Comparison of modern overhead line insulator materials.

Insulator Materials: Porcelain, Glass, and Composite II

Key Points

- Porcelain: High mechanical strength, excellent dielectric strength, long track record. Disadvantages: Heavy, prone to puncture and shattering from impact.
- Toughened Glass: High dielectric strength, transparent (easier inspection), shatters completely when damaged (easy spot-checking). Disadvantages: Prone to spontaneous breakage.
- Silicon Rubber / Composite: Light weight, excellent hydrophobicity (resists pollution wet-flashover), high tensile strength. Disadvantages: Subject to UV degradation and aging (shorter life expectancy than porcelain/glass).

Physical Basis of Non-Uniform Voltage Distribution I

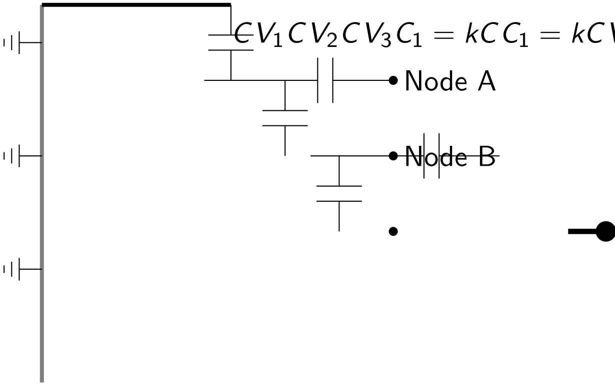
Suspension insulator strings consist of multiple porcelain discs connected in series by metal fittings. Each metal pin and cap forms a capacitor with its neighbor (Self-Capacitance, C). Additionally, a capacitor is formed between each metal fitting and the earthed tower structure/cross-arm (Shunt Capacitance, $C_1 = kC$).

Physical Basis of Non-Uniform Voltage Distribution II

Key Points

- Self-Capacitance (C): Uniformly exists across the metal links of the porcelain discs.
- Shunt Capacitance (C_1): Exists between the metal links and the earthed tower, creating leakage current paths to ground.
- Current Division: Shunt leakage currents cause the charging current through the units to decrease from the line conductor toward the cross-arm.
- Voltage Variation: Since $I_{top} < I_{middle} < I_{bottom}$, the voltage drop across the units also varies, with the lowest disc (nearest the conductor) experiencing the maximum electrical stress.

Equivalent Circuit of a 3-Unit Insulator String I



Equivalent Circuit of a 3-Unit Insulator String II

Key Points

- Representation of a standard 3-disc string: The top unit is connected to the earthed cross-arm, and the bottom unit is attached directly to the high-voltage conductor.
- Shunt capacitance ratio: The ratio of shunt capacitance to self-capacitance is defined as $k = C_1/C$. In practice, k ranges between 0.1 and 0.2.
- Nodes A and B: Show where current splits. Applying Kirchhoff's Current Law (KCL) at these nodes yields the non-uniform current profile.
- Voltage levels: $V_3 > V_2 > V_1$, demonstrating that the unit closest to the line conductor is under the highest electrical stress.

Mathematical Analysis & String Efficiency I

Derivation of voltage at each unit: Let $C_1 = kC$. Applying KCL at Node A:
$I_2 = I_1 + i_1 \implies V_2 \omega C = V_1 \omega C + V_1 \omega C_1 \implies V_2 = V_1(1+k)$.
Applying KCL at Node B:
$I_3 = I_2 + i_2 \implies V_3 \omega C = V_2 \omega C + (V_1 + V_2)\omega C_1 \implies V_3 = V_2 + k(V_1 + V_2) = V_1(1 + 3k + k^2)$. Total Voltage:
$V = V_1 + V_2 + V_3 = V_1(3 + 4k + k^2)$.

Mathematical Analysis & String Efficiency II

Key Points

- Relationship: Voltage across middle unit: $V_2 = V_1(1 + k)$. Voltage across bottom unit: $V_3 = V_1(1 + 3k + k^2)$.
- Stress concentration: Since $k > 0$, we have $V_3 > V_2 > V_1$. The unit closest to the line conductor carries the highest voltage.
- String Efficiency Definition: $\eta = \frac{\text{Voltage across the string}}{\text{Number of units} \times \text{Voltage across the unit adjacent to the line conductor}} \times 100\%$
- Mathematical formulation: $\eta = \frac{V}{n \times V_n} \times 100\%$. For a 3-unit string: $\eta = \frac{V_1+V_2+V_3}{3 \times V_3} \times 100\% = \frac{3+4k+k^2}{3(1+3k+k^2)} \times 100\%$.
- Effect of k: As $k \to 0$, $\eta \to 100\%$, which means smaller shunt capacitance leads to a more uniform voltage distribution.

Consequences of Low String Efficiency & Design Limit I

In practice, a low string efficiency means that the voltage is highly concentrated on the bottom-most disc. If the voltage across this unit exceeds its breakdown design limit (puncture or flashover voltage), the unit will fail, leading to cascade failure of the entire string.

Consequences of Low String Efficiency & Design Limit II

Key Points

- Flashover Vulnerability: The bottom unit reaches its critical flashover voltage long before the other units are fully utilized.
- Cascading Failure: Once the bottom disc punctures/flashes over, its impedance drops to zero, transferring the voltage to the remaining units, which then fail sequentially.
- Maximum Operating Limit: In an ideal scenario where string efficiency is 100%, every disc is equally stressed and the system can handle the maximum possible voltage.
- Practical Limitations: As the number of discs in the string increases, string efficiency decreases because the additional shunt capacitances draw more leakage

Methods to Improve String Efficiency: Cross-Arms & Grading I

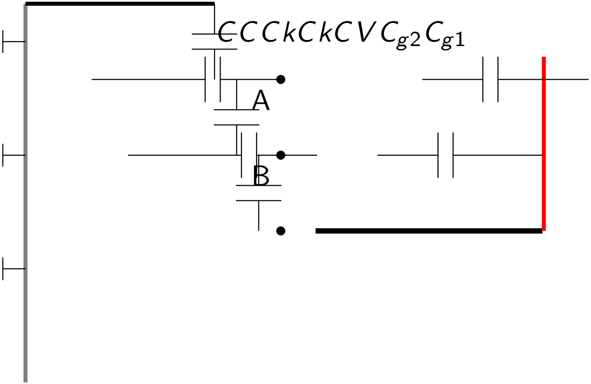
Two primary methods to reduce non-uniform voltage distribution are: (1) Increasing the ratio of self-capacitance to shunt capacitance by using longer cross-arms, and (2) Grading the self-capacitance of individual insulator discs.

Methods to Improve String Efficiency: Cross-Arms & Grading II

Key Points

- Method 1: Increasing Cross-Arm Length: Reduces the shunt capacitance (C_1) by increasing the physical distance between the insulator string and the earthed tower structure.
- Limitations of Method 1: Longer cross-arms increase mechanical stresses, tower weight, and footprint. Practically, k cannot be reduced below 0.1.
- Method 2: Capacitance Grading: Involves using discs of different sizes, with larger capacitances at the bottom (near the conductor) and smaller capacitances at the top.
- Limitations of Method 2: Discs must have different self-capacitances ($C_1 < C_2 < C_3$), which requires stocking multiple unique spare units, complicating

Method 3: Guard Ring (Grading Ring) and Equivalent Circuit I



Method 3: Guard Ring (Grading Ring) and Equivalent Circuit II

Key Points

- Guard Ring Concept: A metal ring electrically connected to the line conductor, surrounding the bottom insulator unit and extending upward.
- Guard Capacitance (C_g): Exists between the guard ring and the metal fittings (nodes A and B) of the insulator string.
- Current Cancellation: The guard capacitances inject currents into the nodes from the high-voltage conductor side, compensating for the currents leaked to the tower.
- Ideal Design Condition: By sizing the guard ring geometry such that the injected current exactly equals the shunt leakage current ($I_{gi} = I_{si}$ at each node), the string efficiency approaches 100%.

Comparison of Methods & Guard Ring Calculations I

To achieve perfect voltage distribution ($V_1 = V_2 = V_3 = V/3$), the current entering each node from the guard ring must equal the current leaving to the tower. Mathematical requirements: For Node A, $C_{g1} = \frac{kC}{2}$. For Node B, $C_{g2} = 2kC$.

Comparison of Methods & Guard Ring Calculations II

Key Points

- Mathematical matching: The guard capacitances must increase as we go down the string ($C_{g1} < C_{g2}$). This is naturally achieved because the guard ring is closer to Node B than Node A.
- Dual function of Guard Ring: In addition to improving string efficiency, the guard ring acts as a Corona Ring, distributing electric field intensity and preventing localized air ionization/corona discharge.
- Industrial Practice: Guard rings are the standard solution for EHV and UHV transmission lines due to simplicity, mechanical robustness, and lack of warehousing complexity.
- Summary Comparison: While capacitance grading is elegant, guard rings provide the most cost-effective and operationally reliable method of voltage grading in the

Physics of Insulator Strings & Mathematical Formulation I

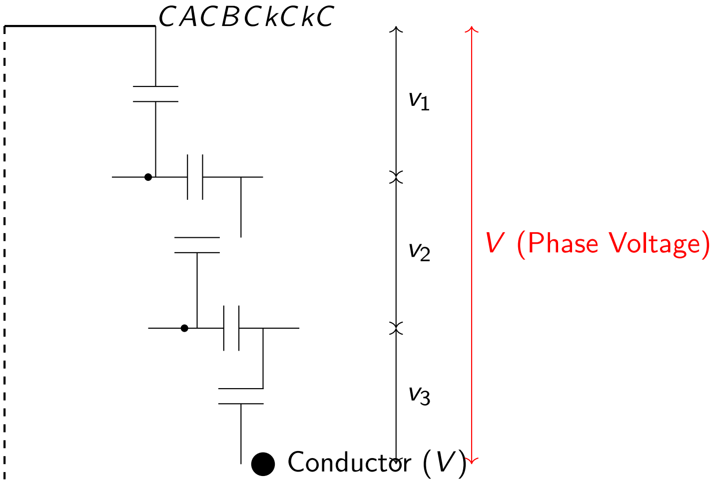
An insulator string consists of a series of suspension disc insulators connected by metal links. Due to capacitance to the grounded tower (shunt capacitance C_e), the voltage distribution along the string is non-uniform, being maximum across the disc nearest to the line conductor. Let the self-capacitance of each disc be C and the shunt capacitance of each metal joint to the tower be $C_e = kC$, where k is the shunt ratio (typically 0.1 to 0.2).

Physics of Insulator Strings & Mathematical Formulation II

Key Points

- Voltage across n-th disc from top:
  $V_n = V_{n-1} + \sum_{i=1}^{n-1} v_i \cdot k$
- For a 3-disc string: v_1 (top disc), $v_2 = v_1(1 + k)$,
  $v_3 = v_1(1 + 3k + k^2)$
- Total Voltage across the string:
  $V = v_1 + v_2 + v_3 = v_1(3 + 4k + k^2)$
- String Efficiency:
  $\eta = \frac{\text{Total Voltage } V}{n \times \text{Voltage across disc nearest to conductor } (v_n)} \times 100\%$
- Methods to improve efficiency: (1) Using longer cross-arms to reduce k, (2) Grading of insulators (varying capacitance C), (3) Using a guard/grading ring to introduce capacitance to the line conductor.

Equivalent Circuit of a 3-Disc Suspension Insulator String I



Equivalent Circuit of a 3-Disc Suspension Insulator String II

Key Points

- Equivalent network model represents self-capacitances (C) of the porcelain discs.
- Shunt capacitances ($C_e = kC$) to the steel tower body distort the voltage distribution.
- The disc nearest to the conductor (v_3 in this case) experiences the highest electrical stress.
- String efficiency degrades as the ratio $k = C_e/C$ increases.
- Reducing k (using longer cross-arms) ensures a more uniform voltage profile.

Numerical 1: Step-by-Step String Efficiency Calculation I

Problem Statement: A 3-phase overhead transmission line uses a suspension string of 3 discs. The shunt capacitance of each joint to the tower is 10% of the self-capacitance of each disc. If the line-to-line voltage is 33 kV, calculate: (i) The voltage across each disc, and (ii) The string efficiency.

Solution Strategy: 1. Identify Phase Voltage: $V = \frac{33}{\sqrt{3}} \approx 19.05$ kV. 2. Set shunt ratio $k = 0.1$. 3. Express v_2 and v_3 in terms of v_1: $v_2 = v_1(1 + k) = 1.1v_1$ $v_3 = v_1(1 + 3k + k^2) = v_1(1 + 0.3 + 0.01) = 1.31v_1$ 4. Sum of voltages: $V = v_1 + v_2 + v_3 = v_1(1 + 1.1 + 1.31) = 3.41v_1$. 5. Solve for v_1: $v_1 = \frac{19.05}{3.41} \approx 5.59$ kV. 6. Solve for v_2 and v_3: $v_2 = 1.1 \times 5.59 \approx 6.15$ kV $v_3 = 1.31 \times 5.59 \approx 7.32$ kV. 7. Calculate String Efficiency: $\eta = \frac{V}{3 \times v_3} \times 100\% = \frac{19.05}{3 \times 7.32} \times 100\% \approx 86.76\%$.

Numerical 1: Step-by-Step String Efficiency Calculation II

Key Points

- Note: Always convert line voltage to phase voltage ($V_{ph} = V_L/\sqrt{3}$) for calculations.
- The disc closest to the conductor (v_3) bears the highest electrical stress (7.32 kV vs 5.59 kV at the top).
- String efficiency of 86.76% indicates a moderately uniform distribution; reducing k would improve it.

Numerical 2: String Efficiency with Grading Ring I

Problem Statement: In a 3-disc string, the shunt ratio is $k = 0.12$. A grading ring is installed, introducing a capacitance C_{g1} between the line and the lower joint (B) equal to $0.15C$, and C_{g2} to the upper joint (A) equal to $0.05C$. Calculate the new voltage distribution and the new string efficiency for a phase voltage of 20 kV.

Solution Strategy: 1. At node A: $I_{C2} + I_{g2} = I_{C1} + I_{e1} \implies (v_2)C + (V - v_1)C_{g2} = v_1 C + v_1(kC)$ Substitute $C_{g2} = 0.05C$, $k = 0.12$: $v_2 + 0.05(V - v_1) = v_1(1.12) \implies v_2 + 0.05V = 1.17v_1$ 2. At node B: $I_{C3} + I_{g1} = I_{C2} + I_{e2} \implies (v_3)C + (V - v_1 - v_2)C_{g1} = v_2 C + (v_1 + v_2)(kC)$ Substitute $C_{g1} = 0.15C$, $k = 0.12$: $v_3 + 0.15(v_3) = v_2 + 0.12(v_1 + v_2) \implies 1.15v_3 = 0.12v_1 + 1.12v_2$ 3. Solve the system of equations with $V = 20$ kV and $v_1 + v_2 + v_3 = 20$ kV. 4. Solving yields: $v_1 \approx 6.12$ kV,

Numerical 2: String Efficiency with Grading Ring II

$v_2 \approx 6.66$ kV, $v_3 \approx 7.22$ kV. 5. New String Efficiency: $\eta = \frac{20}{3 \times 7.22} \times 100\% \approx 92.34\%$.

Key Points

- The grading ring introduces shunt capacitances from the line to the metal joints, counteracting the current diverted to the tower ground.
- This increases the voltage across the upper units (v_1, v_2) and lowers the stress on the bottom unit (v_3).
- String efficiency has increased from $\approx 85\%$ to 92.34%, illustrating the practical utility of grading rings.

Introduction to Sag and Span Mechanics I

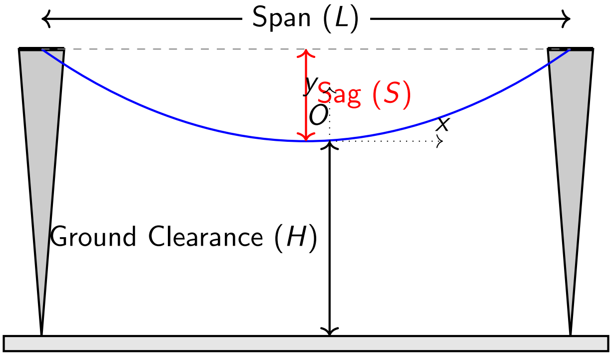
Sag is the difference in level between the points of support (towers) and the lowest point on the conductor. Adequate sag is essential in overhead line design: if the tension is too high, the conductor may break under environmental loads (wind, ice, temperature changes); if the sag is too high, the electrical clearance to the ground or crossing lines is compromised. The conductor forms a catenary curve, but for spans below 300 m, it is mathematically approximated as a parabola with highly accurate results.

Introduction to Sag and Span Mechanics II

Key Points

- Parameters: S = Sag (m), L = Span length (m), w = Weight per unit length of conductor (kg/m), T = Tension in conductor (kg).
- Governing Parabolic Equation for equal levels: $y = \frac{wx^2}{2T}$, where x is the horizontal distance from the lowest point.
- Maximum Sag (at mid-span, $x = L/2$): $S = \frac{wL^2}{8T}$
- Conductor Tension T is kept within safe limits, typically below 50% of its Ultimate Tensile Strength (UTS), by applying a Safety Factor.
- Mechanical tension is highly temperature-dependent: high temperatures increase sag and reduce tension, while low temperatures reduce sag and increase tension.

Sag Profile of Conductor with Equal Support Levels I



Sag Profile of Conductor with Equal Support Levels II

Key Points

- Supports A and B are at equal heights above the ground reference plane.
- The parabolic profile is symmetrical with the lowest point O occurring at mid-span ($x = L/2$).
- Ground clearance H must meet statutory regulatory requirements at maximum operating temperature.
- Tension T acts tangentially along the conductor curve, with minimum tension occurring at the vertex O.
- Wind load acts horizontally, and ice load acts vertically downward, modifying the effective weight w.

Sag under Environmental Loading & Numerical I

When a conductor is subjected to wind and ice loading, its weight per unit length increases, and the sag occurs in an inclined plane. **Theoretical Formulation:** - Weight of ice acting vertically downwards: $w_i = \pi \rho_{ice} t(d + t)$ where t is ice thickness and d is conductor diameter. - Wind force acting horizontally: $w_w = P \times (d + 2t)$ where P is wind pressure per unit projected area. - Total effective weight per unit length: $w_r = \sqrt{(w + w_i)^2 + w_w^2}$ - Slanted Sag: $S_{slant} = \frac{w_r L^2}{8T}$ - Vertical Sag: $S_v = S_{slant} \cos(\theta)$, where $\tan(\theta) = \frac{w_w}{w + w_i}$.
Numerical Example: A transmission conductor has a span of 150 m, wt 0.85 kg/m, and UTS of 6800 kg. The safety factor is 2. A wind pressure of 75 kg/m^2 acts on the projected area. Calculate the vertical sag. 1. Working Tension: $T = \frac{UTS}{SF} = \frac{6800}{2} = 3400$ kg. 2. Conductor Diameter: $d = 2$ cm $= 0.02$ m. 3. Wind force $w_w = P \times d = 75$ kg/m$^2 \times 0.02$ m $= 1.5$ kg/m. 4. Effective

weight: $w_r = \sqrt{w^2 + w_w^2} = \sqrt{0.85^2 + 1.5^2} \approx 1.724$ kg/m. 5. Slanted sag: $S_{slant} = \frac{1.724 \times 150^2}{8 \times 3400} \approx 1.426$ m. 6. Angle of tilt: $\cos(\theta) = \frac{w}{w_r} = \frac{0.85}{1.724} \approx 0.493$. 7. Vertical Sag: $S_v = 1.426 \times 0.493 \approx 0.703$ m.

Sag under Environmental Loading & Numerical III

Key Points

- Wind load is assumed to act horizontally, while conductor weight and ice weight act vertically downwards.
- Vertical sag is the actual vertical component of the slanted sag, determining ground clearance.
- Design safety factors (typically 2 to 3) are mandated by electricity rules to prevent mechanical failure under extreme weather conditions.

Fundamental Sag Equations and Catenary Approximation I

Under zero-wind and zero-ice conditions at a reference temperature, the conductor forms a catenary. For relatively short spans ($S < 300$ m), this is approximated as a parabola: $d = \frac{wS^2}{8T}$.

Fundamental Sag Equations and Catenary Approximation II

Key Points

- Conductor weight per unit length (w) acts vertically downwards, directly opposing the ground.
- Tension (T) is the horizontal tension at the lowest point of the conductor, assumed uniform across the span.
- The total length of the conductor in a span of length S is expressed as $L \approx S + \frac{8d^2}{3S}$.
- Overhead lines must be designed such that tension does not exceed 50% of the Ultimate Tensile Strength (UTS) under worst-case atmospheric loading.

Effect of Temperature Variation on Sag and Tension I

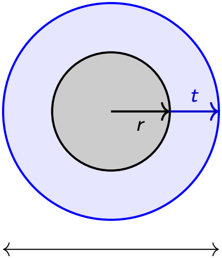
Temperature variations cause thermodynamic expansion and contraction. The change in conductor length is given by: $L_\theta = L_0(1 + \alpha\Delta\theta)$, where α is the coefficient of linear expansion.

Effect of Temperature Variation on Sag and Tension II

Key Points

- An increase in ambient temperature or high current loading (I^2R heating) causes the conductor to expand and elongate.
- Elongation increases the slack, which increases the sag (d) and reduces the conductor tension (T).
- Maximum sag typically occurs at the maximum operating temperature (often designed at 65°C or 75°C for ACSR).
- A decrease in temperature causes the conductor to contract, decreasing the sag but increasing the tension, which poses a risk of mechanical failure at support towers during extreme cold.

Effect of Ice Loading on Conductor Weight I

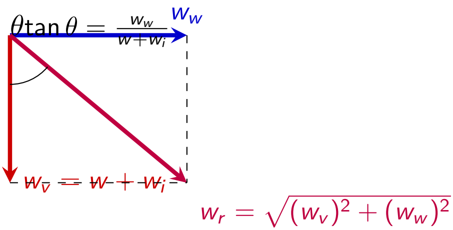


Total Diameter $D = d + 2t$

Effect of Ice Loading on Conductor Weight II

Key Points

- In cold climates, ice accumulates uniformly around the conductor, increasing its effective diameter to $D = d + 2t$.
- The weight of the ice acts vertically downwards, in the same direction as the self-weight (w) of the conductor.
- Ice volume per unit length is $V_i = \pi t(d + t)$ where t is thickness and d is conductor diameter.
- Ice weight per unit length: $w_i = \rho_i \pi t(d + t)g$, where ice density ρ_i is typically taken as 915 kg/m^3.
- Total vertical weight of the ice-loaded conductor: $w_v = w + w_i$ (N/m).


θ
$\tan\theta = \frac{w_w}{w+w_i}$
w_w
$w_v = w + w_i$
$w_r = \sqrt{(w_v)^2 + (w_w)^2}$

Effect of Wind Loading and Vector Forces II

Key Points

- Wind load acts horizontally, perpendicular to the projected area of the conductor.
- Projected area per unit length: $A_p = (d + 2t) \times 1$ for an ice-coated conductor.
- Wind load per unit length: $w_w = P \times (d + 2t)$, where P is the horizontal wind pressure (N/m^2).
- The resultant force w_r is the vector sum of horizontal and vertical loads: $w_r = \sqrt{(w + w_i)^2 + w_w^2}$.
- The conductor is deflected by an angle θ from the vertical plane: $\theta = \tan^{-1}[w_w/(w + w_i)]$.

Slanted vs. Vertical Sag Calculations I

Due to horizontal wind force, the conductor swings and the sag occurs in a slanted plane. The slanted sag is $d_s = \frac{w_r S^2}{8T}$. The vertical component of sag is $d_v = d_s \cos\theta$.

Slanted vs. Vertical Sag Calculations II

Key Points

- Slanted sag (d_s) represents the actual physical curvature and path of the conductor in its deflected plane.
- Vertical sag (d_v) is the drop of the conductor along the vertical axis, which dictates ground clearance limits.
- Using the trigonometric relation $\cos\theta = (w + w_i)/w_r$, we obtain: $d_v = \frac{(w+w_i)S^2}{8T}$.
- Wind loading increases total tension (T), reducing the actual physical sag along the line, but swings the conductor sideways, which can cause flashovers to nearby trees or tower structures.

The Conductor State Change Equation I

When environmental conditions change from State 1 (w_{r1}, t_1) to State 2 (w_{r2}, t_2), tension changes according to:

$$T_2^2 \left[T_2 - \left(T_1 - \frac{S^2 w_{r1}^2 EA}{24 T_1^2} - \alpha EA(t_2 - t_1) \right) \right] = \frac{S^2 w_{r2}^2 EA}{24}.$$

The Conductor State Change Equation II

Key Points

- This equation represents the elastic and thermal behavior of the conductor under varying atmospheric states.
- E is Young's Modulus of elasticity (N/m^2), and A is the cross-sectional area of the conductor (m^2).
- State 1 is typically chosen as the worst-case loading condition (minimum temperature, maximum wind, maximum ice) to find the maximum possible tension T_1.
- State 2 is the erection or high-temperature operating state used to determine the maximum vertical sag and verify compliance with clearance standards.

Industrial Practice: Sag-Tension Templates and Mitigation I

Power utilities employ specific software tools (like PLS-CADD) and mechanical dampers to mitigate the effects of atmospheric conditions on sag.

Industrial Practice: Sag-Tension Templates and Mitigation II

Key Points

- Sag-Tension Templates: Graphical templates representing cold-weather minimum sag, hot-weather maximum sag, and wind-swing profiles are used to position towers optimally on terrain surveys.
- Ruling Span Concept: For tension calculations over varying span lengths between tension towers, an equivalent ruling span is used: $S_R = \sqrt{\sum S_i^3 / \sum S_i}$.
- Galloping and Vibration: Wind blowing across asymmetrical ice-coated conductors causes aerodynamic instability (conductor galloping). Vibration dampers (Stockbridge type) are installed to prevent fatigue damage.
- Dynamic Line Rating (DLR): Modern smart grids

Sag with Supports at Equal Levels I

When transmission line conductors are suspended between supports at the same level, they assume a catenary shape. For short spans (up to 300 m), this curve is mathematically approximated as a parabola. The equation for maximum sag is:

$s = \frac{wl2}{8T}$

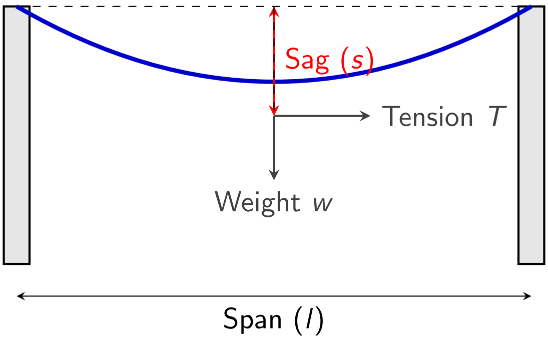
Where s is the sag (m), w is weight per unit length (N/m), l is the span length (m), and T is the horizontal tension (N).

Sag with Supports at Equal Levels II

Key Points

- The tension is assumed to be uniform and acts horizontally at the lowest point of the conductor.
- Sag is directly proportional to the weight of the conductor and the square of the span length.
- Sag is inversely proportional to the horizontal tension in the conductor.
- Conductor length can be estimated as: $L \approx l + \frac{8s^2}{3l}$

Conductor Profile (Equal Support Levels) I



Conductor Profile (Equal Support Levels) II

Key Points

- A schematic illustrating the horizontal span (l), conductor weight force (w), and the horizontal tension (T).
- The sag (s) represents the maximum vertical deflection from the horizontal line joining the supports.
- Lowest point O represents the point of maximum mechanical tension and minimum vertical clearance.

Problem Statement: An overhead line conductor has a span of 200 m between level supports. The conductor weight is 8.0 N/m, its cross-sectional area is 2.5 cm^2, and its ultimate tensile strength is 60 kN. Using a safety factor of 2.0, determine the conductor sag and the clearance height if the towers are 30 m high.

Step-by-step Solution: 1. Calculate working tension: $T = \frac{\text{Ultimate Strength}}{\text{Safety Factor}} = \frac{60000}{2} = 30000$ N. 2. Compute sag: $s = \frac{wl^2}{8T} = \frac{8.0\times200^2}{8\times30000} = \frac{320000}{240000} = 1.33$ m. 3. Calculate ground clearance: Clearance = Tower Height - s = 30 - 1.33 = 28.67 m.

Numerical Example 1: Equal Level Supports II

Key Points

- Always calculate the allowable working tension first using the specified safety factor.
- Ensure unit consistency; span in meters, weight in N/m, and tension in Newtons.
- Ground clearance is critical to prevent flashovers to ground or nearby structures.

Sag with Supports at Unequal Levels I

In hilly terrains, transmission line towers are often erected at different heights. Let the vertical difference in support levels be h and the span length be l.

If x_1 is the horizontal distance from the lower support to the lowest point O, and x_2 is the distance from the higher support to O:

$x\_1 = \frac{l}{2} - \frac{Th}{wl}$ and $x\_2 = \frac{l}{2} + \frac{Th}{wl}$

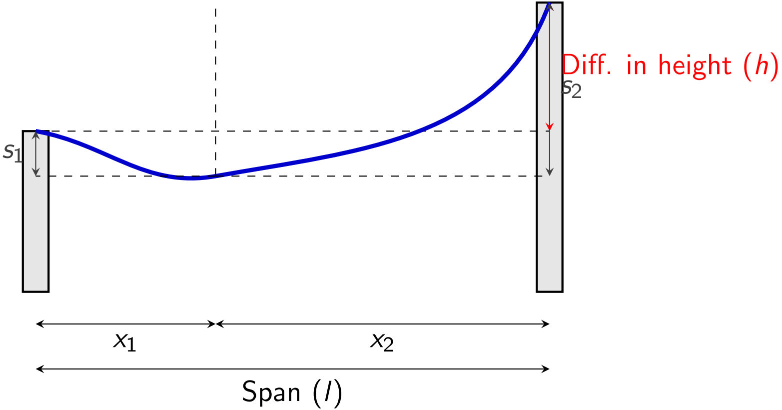
$s\_1 = \frac{wx\_1\hat{2}}{2T}$ and $s\_2 = \frac{wx\_2\hat{2}}{2T}$

Sag with Supports at Unequal Levels II

Key Points

- The horizontal distance $l = x_1 + x_2$.
- The difference between the two sags is equal to the level difference: $s_2 - s_1 = h$.
- If $x_1 < 0$, the lowest point O lies outside the span (virtual vertex), meaning the conductor rises continuously.
- Calculations assume that the tension T is approximately constant throughout the span.

Conductor Profile (Unequal Support Levels) I



Conductor Profile (Unequal Support Levels) II

Key Points

- Visualizes a parabolic conductor path between supports at different heights.
- The horizontal distance of the vertex O from each tower is dependent on level difference h.
- The tension at the supports will differ slightly due to elevation, but horizontal tension component T remains constant.
- Critical clearance checks must be performed relative to the hillside profile under the span.

Numerical Example 2: Unequal Level Supports I

Problem Statement: A transmission line is supported by two towers on a hillside with a level difference of 20 m. The span length is 250 m. The conductor weight is 6.5 N/m and working tension is 15 kN. Find the horizontal distances from the towers to the lowest point of the conductor, and calculate sags s_1 and s_2.

Step-by-step Solution: 1. Identify parameters: $l = 250$ m, $h = 20$ m, $w = 6.5$ N/m, $T = 15000$ N. 2. Compute x_1 and x_2:

$x\_1 = \frac{250}{2} - \frac{15000 \times 20}{6.5 \times 250} = 125 - 184.6 = -59.6$ m

$x\_2 = \frac{250}{2} + \frac{15000 \times 20}{6.5 \times 250} = 125 + 184.6 = 309.6$ m 3. Calculate sags:

$s\_1 = \frac{6.5 \times (-59.6)\hat{}2}{2 \times 15000} = 0.77$ m $s\_2 = \frac{6.5 \times (309.6)\hat{}2}{2 \times 15000} = 20.77$ m

Numerical Example 2: Unequal Level Supports II

Key Points

- Since x_1 is negative, the lowest point of the imaginary parabola lies outside the span to the left of Tower A.
- The conductor has a continuous upward slope from Tower A to Tower B.
- The sag difference is verified: $s_2 - s_1 = 20.77 - 0.77 = 20$ m, which matches the level difference h.

In actual field conditions, conductors are subjected to environmental forces. The design sag must incorporate wind load acting horizontally and ice load acting vertically:

$w\_r = \sqrt{(w + w\_i)\hat{}2 + w\_w\hat{}2}$

Resultant Sag $s\_r = \frac{w\_rl\hat{}2}{8T}$ and Vertical Sag $s\_v = s\_r \cos\theta$

Where $\theta =$ $\tan\hat{}-1\left(\frac{w\_w}{w+w\_i}\right) istheangleofconductordeflectionfromtheverticalplane.$

Industrial Standards: Ice and Wind Loadings II

Key Points

- Ice thickness t increases the conductor weight: $w_i = \rho_{ice} g \pi t(d + t)$ where d is conductor diameter.
- Wind load acts on the projected area: $w_w = P(d + 2t)$ where P is wind pressure.
- Vertical sag (s_v) is used to compute the physical electrical ground clearance.
- Slanted sag (s_r) is used to determine structural mechanical tension and tower spacing requirements.

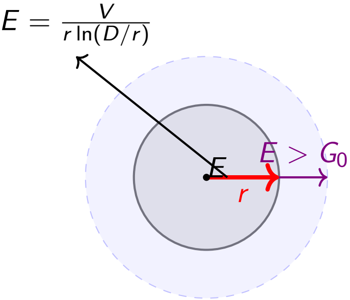
The Physics of Corona Discharge I

Corona discharge occurs when the localized electric field intensity at the conductor surface exceeds the breakdown strength of air (30 kV/cm peak or 21.2 kV/cm rms at STP), resulting in air ionization.

Key Points

- Visual appearance: Faint violet glow along the conductor length under dark conditions.
- Acoustic and chemical signs: Auditory hissing sound accompanied by the generation of ozone (O_3) gas.
- Dielectric breakdown: Air surrounding the conductor becomes ionized and starts conducting, effectively changing the surrounding dielectric behavior.

Visualizing Corona and Electric Field Gradient I



Visualizing Corona and Electric Field Gradient II

Key Points

- The region inside the dashed circle ($r < x < r_{corona}$) has an electric field E exceeding the critical disruptive gradient G_0.
- Air in this zone undergoes dielectric breakdown and becomes conducting.
- This effectively increases the virtual diameter of the conductor, reducing the field gradient at the new outer boundary.

Critical Voltages in Corona Formulation I

The onset of corona is defined by two mathematical threshold voltages: Critical Disruptive Voltage (V_d) and Visual Corona Voltage (V_v).

Critical Voltages in Corona Formulation II

Key Points

- Critical Disruptive Voltage:
  $V_d = m_0 g_0 \delta r \ln(D/r)$ kV/phase where m_0 is conductor irregularity factor (0.8 to 1.0) and g_0 is breakdown strength of air (21.2 kV/cm rms).
- Air density correction factor: $\delta = \frac{3.92b}{273+t}$, where b is barometric pressure in cm of Hg and t is temperature in $^\circ$C.
- Visual Corona Voltage:
  $V_v = m_v g_0 \delta r \left(1 + \frac{0.3}{\sqrt{\delta r}}\right) \ln(D/r)$ kV/phase,
  representing the voltage at which the visual luminous glow is first observed.

Factors Affecting Corona & Power Loss I

Corona power loss (P_c) under fair weather is calculated using Peek's Formula: $P_c = \frac{242.2}{\delta}(f + 25)\sqrt{\frac{r}{D}}(V - V_d)^2 \times 10^{-5}$ kW/km/phase.

Key Points

- System parameters: Higher frequency (f) and higher operating voltage (V) relative to V_d dramatically increase power loss.
- Conductor geometry: Larger radius (r) reduces surface electric field intensity. Greater spacing (D) increases V_d, suppressing corona.
- Surface and weather: Dirty or stranded conductors lower the irregularity factor m_0, lowering V_d. Rain and fog decrease air density factor δ, accelerating losses.

Advantages, Disadvantages & Mitigation I

Corona has detrimental operational effects but provides a transient mitigation mechanism.

Advantages, Disadvantages & Mitigation II

Key Points

- Advantages: Acts as a safety valve by dissipating high-voltage transient surges caused by lightning or switching operations.
- Disadvantages: Causes direct transmission efficiency loss, electromagnetic interference with communication lines, ozone-induced conductor corrosion, and non-sinusoidal currents.
- Mitigation via Bundling: Using bundle conductors increases the equivalent self-GMD, reducing the localized surface electric field.
- Mitigation via Geometry: Increasing conductor diameter using hollow core or steel-reinforced aluminum (ACSR) conductors.

Right of Way (ROW) in Transmission Lines I

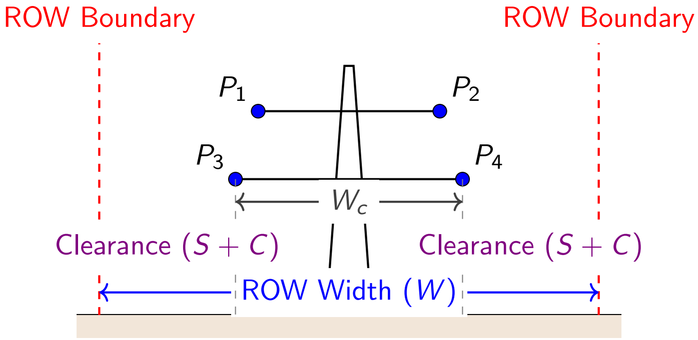
Right of Way (ROW) is the width of the protected land corridor required for safe operation, maintenance, and prevention of electrical hazards.

Right of Way (ROW) in Transmission Lines II

Key Points

- Sizing variables: Width is determined by phase spacing (W_c), maximum conductor swing due to wind (S), and safe horizontal clearance (C).
- ROW Width Formula: $W = W_c + 2(S + C)$, matching the extreme conductor displacement profiles.
- Voltage level relationships: Typical ROW is 46 m for 400 kV lines, expanding up to 64 m or 85 m for 765 kV systems.
- Statutory restrictions: Construction of buildings and growth of tall trees are strictly prohibited inside the ROW to prevent line-to-ground flashovers.

Transmission Line ROW Profile Clearance I



Transmission Line ROW Profile Clearance II

Key Points

- This profile illustrates the transverse cross-section of a double-circuit tower and its safety clearances.
- The horizontal clearance offset $(S + C)$ accounts for the conductor's maximum mechanical blowout under extreme wind loading.
- Designated ROW boundaries are established to prevent any external activities from encroaching into the high-voltage clearance zone.

Transmission Line Parameters and Classification I

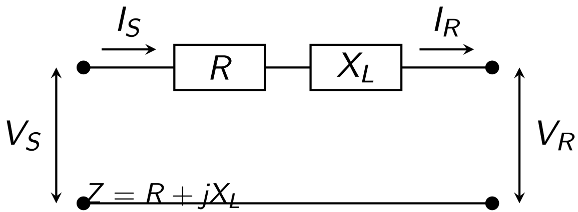
Transmission lines are characterized by four distributed parameters: series resistance R, series inductance L, shunt capacitance C, and shunt conductance G. Neglecting shunt conductance ($G \approx 0$) is standard practice for power lines.

Transmission Line Parameters and Classification II

Key Points

- Classification by length: Short lines (<80 km, voltages <20 kV), Medium lines ($80-250$ km, voltages $20-100$ kV), Long lines (>250 km, voltages >100 kV).
- For short lines, shunt capacitance is negligible, meaning only series resistance R and series inductive reactance X_L are modeled.
- For medium lines, shunt capacitance is lumped at one or more points, typically using Nominal-T or Nominal-π models.

Short Transmission Line Model I



Short Transmission Line Model II

Key Points

- The series impedance is given by $Z = R + jX_L = R + j\omega L$.
- Shunt capacitance and shunt conductance are entirely neglected due to short line length (< 80 km).
- Sending end current equals receiving end current: $I_S = I_R$.

Short Line Mathematical Analysis I

The relationship between sending-end and receiving-end parameters is represented in matrix form via ABCD parameters:

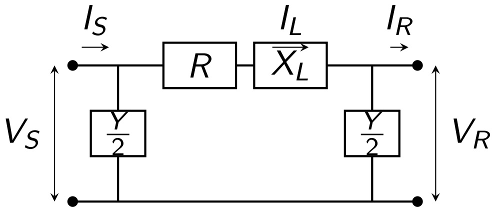
$$\begin{bmatrix} V_S \\ I_S \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_R \\ I_R \end{bmatrix}.$$

Short Line Mathematical Analysis II

Key Points

- Equations for short line: $V_S = V_R + I_R Z$ and $I_S = I_R$.
- Comparing these to the matrix definition yields the parameters: $A = 1$, $B = Z$, $C = 0$, and $D = 1$.
- Note that $AD - BC = 1 \cdot 1 - Z \cdot 0 = 1$ (network reciprocity) and $A = D$ (network symmetry).
- Voltage regulation of short line is defined as: % Regulation $= \frac{|V_S| - |V_R|}{|V_R|} \times 100\%$ when $I_R = 0$.

Medium Line: Nominal-π representation I



Medium Line: Nominal-π representation II

Key Points

- In the Nominal-π model, the total series impedance $Z = R + j\omega L$ is placed in the center branch.
- The total shunt admittance $Y = j\omega C$ is divided equally into two halves $(Y/2)$, connected at the sending and receiving ends.
- This lumped approximation provides excellent accuracy for lines between 80 km and 250 km.

Nominal-π Model: Mathematical Derivations I

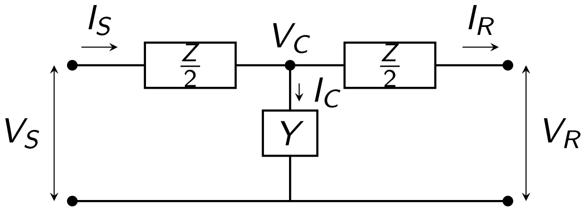
For the Nominal-π configuration, the nodal/mesh equations allow us to solve for V_S and I_S in terms of V_R and I_R. Let the current through the receiving end shunt admittance be $I_{C2} = V_R \frac{Y}{2}$. The series line current is $I_L = I_R + V_R \frac{Y}{2}$. The sending end voltage is $V_S = V_R + I_L Z = V_R + Z \left(I_R + V_R \frac{Y}{2} \right) = V_R \left(1 + \frac{YZ}{2} \right) + I_R Z$.

Nominal-π Model: Mathematical Derivations II

Key Points

- The sending end current is $I_S = I_L + I_{C1} = I_L + V_S \frac{Y}{2}$.
- Substituting V_S and I_L yields:
  $I_S = \left(I_R + V_R \frac{Y}{2}\right) + \left[V_R \left(1 + \frac{YZ}{2}\right) + I_R Z\right] \frac{Y}{2} =$
  $V_R Y \left(1 + \frac{YZ}{4}\right) + I_R \left(1 + \frac{YZ}{2}\right)$.
- The resulting ABCD parameters are: $A = D = 1 + \frac{YZ}{2}$, $B = Z$, and $C = Y \left(1 + \frac{YZ}{4}\right)$.
- We verify reciprocity:
  $AD - BC = \left(1 + \frac{YZ}{2}\right)^2 - Z \cdot Y \left(1 + \frac{YZ}{4}\right) = 1$.

Medium Line: Nominal-T Model I



Medium Line: Nominal-T Model II

Key Points

- In the Nominal-T model, the line series impedance Z is split equally $(Z/2)$ at sending and receiving sides.
- The entire shunt admittance $Y = j\omega C$ is concentrated at the center node, creating a T-shaped network.
- Node voltage V_C represents the voltage across the shunt capacitor: $V_C = V_R + I_R \frac{Z}{2}$.

Summary of ABCD Parameters & Comparison I

ABCD parameter matrices comparison: - Short Line: $A = 1$, $B = Z$, $C = 0$, $D = 1$. - Nominal-T: $A = D = 1 + \frac{YZ}{2}$, $B = Z\left(1 + \frac{YZ}{4}\right)$, $C = Y$. - Nominal-π: $A = D = 1 + \frac{YZ}{2}$, $B = Z$, $C = Y\left(1 + \frac{YZ}{4}\right)$.

Summary of ABCD Parameters & Comparison II

Key Points

- Reciprocity ($AD - BC = 1$) holds true for all three model representations.
- Symmetry ($A = D$) is satisfied by all models, signifying identical characteristics looking from either end.
- While Nominal-T and Nominal-π models differ in internal circuit topologies, their overall transmission efficiency and voltage regulation predictions are virtually identical for medium lines.

Primary Line Parameters (Constants) I

Transmission line electrical behavior is determined by four distributed parameters: Resistance (R), Inductance (L), Capacitance (C), and Conductance (G).

Primary Line Parameters (Constants) II

Key Points

- Resistance (R) causes I^2R active power loss and is temperature dependent: $R_T = R_0[1 + \alpha_0(T - T_0)]$, modified by skin effect at power frequency (50/60 Hz).
- Inductance (L) arises from internal and external magnetic flux linkages: $L = 2 \times 10^{-7} \ln(D_{eq}/D_s)$ H/m per phase, where D_{eq} is GMD and D_s is GMR.
- Capacitance (C) arises from electric field between conductors: $C = \frac{2\pi\epsilon}{\ln(D_{eq}/r)}$ F/m per phase, governing charging current $I_c = \omega CV$.
- Shunt Conductance (G) represents leakage currents over insulators and corona discharges, usually neglected ($G \approx 0$) in line performance calculations under normal operating conditions.

Classification of Transmission Lines I

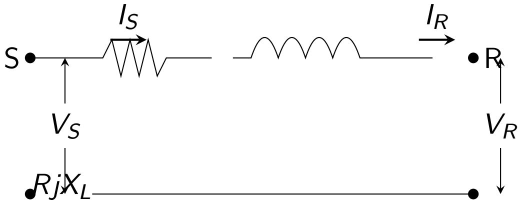
Classification dictates the simplification level in mathematical modeling based on physical length and operating frequency (typically 50/60 Hz).

Classification of Transmission Lines II

Key Points

- Short Transmission Lines: Physical length < 80 km (50 miles), line voltage < 20 kV. Shunt capacitance C is very small and completely neglected. Only series resistance R and series inductance L are considered.
- Medium Transmission Lines: Physical length 80 km to 250 km ($50 - 150$ miles), line voltage 20 kV to 100 kV. Shunt capacitance C cannot be neglected and is assumed to be lumped at one or more points.
- Long Transmission Lines: Physical length > 250 km (> 150 miles), line voltage > 100 kV. Parameters are treated as uniformly distributed along the entire length of the line.
- Product Limit: Often defined by product of frequency and length ($f \cdot l$). Short lines: $f \cdot l < 4000$ Hz$\cdot km; Mediumlines :$4000 ¡ f $\cdot l < 12000$ Hz$\cdot km$.

Short Transmission Line Model I



Short Transmission Line Model II

Key Points

- In short lines, shunt capacitance is omitted, meaning sending-end current equals receiving-end current: $I_S = I_R$.
- The total series impedance is $Z = R + jX_L = R + j\omega L$, where R and L are total line values.
- Voltage equation: $V_S = V_R + I_R Z = V_R + I_R(R + jX_L)$.
- The ABCD parameters are: $A = 1$, $B = Z$, $C = 0$, and $D = 1$.

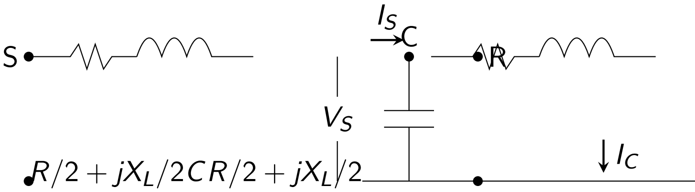
The performance is analyzed using voltage regulation and transmission efficiency under lagging, leading, or unity power factor loads.

Performance of Short Transmission Lines II

Key Points

- Voltage Regulation represents the change in receiving end voltage from no-load to full-load: $\%\text{VR} = \frac{|V_S|-|V_R|}{|V_R|} \times 100\%$.
- Approximate voltage drop: $\Delta V \approx I_R R \cos\phi_R \pm I_R X_L \sin\phi_R$, where $+$ is for lagging PF (inductive load) and $-$ is for leading PF (capacitive load).
- Condition for Zero Voltage Regulation (unity voltage ratio): occurs at leading power factor when $\tan\phi_R = -R/X_L$.
- Transmission Efficiency: $\eta = \frac{P_R}{P_S} \times 100\% = \frac{3V_R I_R \cos\phi_R}{3V_R I_R \cos\phi_R + 3I_R^2 R} \times 100\%$ (for three-phase systems).

Medium Line - Nominal T Model I



Medium Line - Nominal T Model II

Key Points

- In the Nominal T model, the total series impedance $Z = R + jX_L$ is split into two halves ($Z/2$ each), and the total shunt admittance $Y = j\omega C$ is placed at the center node.
- Current through the charging capacitance: $I_C = YV_C = Y(V_R + I_R\frac{Z}{2})$, where V_C is the center node voltage.
- Sending end current: $I_S = I_R + I_C = YV_R + (1 + \frac{YZ}{2})I_R$.
- Sending end voltage: $V_S = V_C + I_S\frac{Z}{2} = (1 + \frac{YZ}{2})V_R + Z(1 + \frac{YZ}{4})I_R$.

Medium Line - Nominal $\pi Model I$

In the Nominal π (Pi) model, the series impedance is placed in the middle, and the shunt admittance is divided equally and placed at both ends.

Medium Line - Nominal $\pi Model II$

Key Points

- The total series impedance remains $Z = R + jX_L$ in the series branch.
- The shunt admittance $Y = j\omega C$ is split into two equal halves, $Y/2$, connected at the sending and receiving ends.
- Receiving-end capacitor current: $I_{C2} = V_R \frac{Y}{2}$. The series branch current: $I_L = I_R + I_{C2} = I_R + V_R \frac{Y}{2}$.
- Sending-end voltage: $V_S = V_R + I_L Z = V_R + Z(I_R + V_R \frac{Y}{2}) = (1 + \frac{YZ}{2})V_R + ZI_R$.
- Sending-end current: $I_S = I_L + I_{C1} = I_L + V_S \frac{Y}{2} = Y(1 + \frac{YZ}{4})V_R + (1 + \frac{YZ}{2})I_R$.

Comparison of Transmission Line Models I

The ABCD parameters represent the line as a two-port network: $\begin{bmatrix} V_S \\ I_S \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_R \\ I_R \end{bmatrix}$. They must satisfy reciprocity $(AD - BC = 1)$ and symmetry $(A = D)$.

Comparison of Transmission Line Models II

Key Points

- Short Line: $A = 1$, $B = Z$, $C = 0$, $D = 1$. Symmetrical and reciprocal. Shunt effects are fully ignored.
- Nominal T Medium Line: $A = D = 1 + \frac{YZ}{2}$, $B = Z(1 + \frac{YZ}{4})$, $C = Y$. Symmetrical and reciprocal.
- Nominal π Medium Line: $A = D = 1 + \frac{YZ}{2}$, $B = Z$, $C = Y(1 + \frac{YZ}{4})$. Symmetrical and reciprocal.
- Practical Note: In planning and dispatch, medium-line modeling is vital for predicting voltage profiles, charging reactive power ($Q_c = \omega CV^2$), and tuning shunt reactors to prevent Ferranti effect.

Criteria for Classification: Length & Voltage I

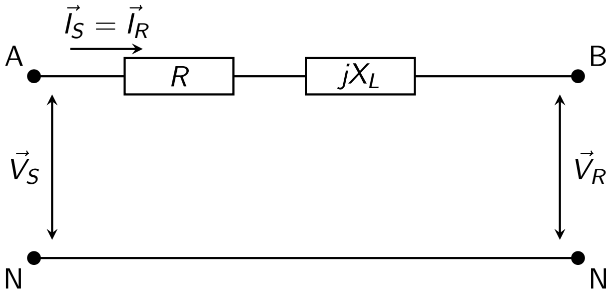
Transmission lines are classified based on physical length, nominal operating voltage, and the engineering simplification applied to their shunt capacitance.

Criteria for Classification: Length & Voltage II

Key Points

- Short Transmission Lines: Physical length ≤ 80 km (50 miles) and operating voltage < 20 kV. Shunt capacitance (C) is negligible due to small charging currents.
- Medium Transmission Lines: Physical length 80 km to 250 km (50-150 miles) and operating voltage 20 kV to 100 kV. Shunt capacitance is lumped at discrete nodes.
- Long Transmission Lines: Physical length > 250 km (150 miles) and operating voltage > 100 kV. Line constants (R, L, C, G) must be modeled as distributed parameters.
- Electromagnetic Wave Propagation Criterion: The product of frequency and length ($f \cdot l$) determines the regime. At 50 Hz: $f \cdot l < 4000$ Hz-km is short, 4000 to 12000 Hz-km is medium, and > 12000 Hz-km is long.

Short Transmission Line Model I

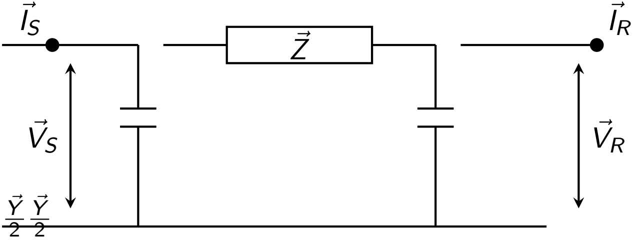


Short Transmission Line Model II

Key Points

- In short transmission lines, the shunt capacitance (C) is extremely small and can be completely neglected without sacrificing engineering accuracy.
- The line is modeled as a simple series impedance $\vec{Z} = R + jX_L$, where R is the loop resistance and X_L is the inductive reactance.
- Voltage regulation is defined as: $\%VR = \frac{|V_S| - |V_R|}{|V_R|} \times 100$ under rated receiving-end conditions.
- The ABCD parameters for a short line are: $A = 1$, $B = Z$, $C = 0$, and $D = 1$. The network is symmetric ($A = D$) and reciprocal ($AD - BC = 1$).

Medium Transmission Line: Nominal-π *ModelI*



Medium Transmission Line: Nominal-$\pi Model II$

Key Points

- The Nominal-$\pi modellumpsthetotallineshuntadmittance$(Y = j$\omega C$) into two equal halves placed at the sending and receiving ends.
- The series branch contains the total line impedance $\vec{Z} = R + jX_L$ in the middle of the network.
- Sending end current is given by: $\vec{I_S} = \vec{I_R} + \vec{V}_R \frac{\vec{Y}}{2} + \vec{V}_S \frac{\vec{Y}}{2}$, which accounts for the shunt charging currents.
- The ABCD parameters for the nominal-$\pi modelare$:A = D = 1 + ZY$_{\overline{2}}$, $B = Z$, and $C = Y\left(1 + \frac{ZY}{4}\right)$.

In the Nominal-T configuration, the total line shunt admittance is placed at the center, while the total series impedance is split equally on both sides.

Medium Transmission Line: Nominal-T Model II

Key Points

- The network is modeled with two series impedance branches of value $\vec{Z}/2$ and a central shunt admittance branch of value $\vec{Y} = j\omega C$.
- The midpoint voltage $\vec{V}_C$ is calculated as: $\vec{V}_C = \vec{V}_R + \vec{I}_R \frac{\vec{Z}}{2}$.
- The central shunt current is $\vec{I}_C = \vec{V}_C \vec{Y}$, and the sending end current is $\vec{I}_S = \vec{I}_R + \vec{I}_C$.
- The ABCD parameters for the Nominal-T model are: $A = D = 1 + \frac{ZY}{2}$, $B = Z\left(1 + \frac{ZY}{4}\right)$, and $C = Y$.
- Symmetry check: For both T and $\pi models,$AD - BC $= 1 is satisfied, indicating a reciprocal network.$

Long Transmission Line: Distributed Parameters I

For lines longer than 250 km, parameters are distributed uniformly along the line rather than lumped. This requires differential equations for voltage and current.

Long Transmission Line: Distributed Parameters II

Key Points

- Let $z = r + j\omega l$ be the series impedance per unit length, and $y = g + j\omega c$ be the shunt admittance per unit length.
- The differential equations for voltage and current along the line are: $\frac{d^2V}{dx^2} = \gamma^2 V$ and $\frac{d^2I}{dx^2} = \gamma^2 I$, where $\gamma = \sqrt{zy}$ is the propagation constant.
- The propagation constant is complex: $\gamma = \alpha + j\beta$, where α is the attenuation constant (Np/m) and β is the phase constant (rad/m).
- The characteristic impedance of the line is defined as $Z_c = \sqrt{\frac{z}{y}} = \sqrt{\frac{r+j\omega l}{g+j\omega c}}$.
- Under lossless conditions ($r = 0, g = 0$), the characteristic impedance becomes Surge Impedance $Z_c = \sqrt{L/C}$, typically $400\,\Omega$ for overhead lines.

Rigorous Mathematical Solution for Long Lines I

The solution to the wave equations yields hyperbolic functions that describe voltage and current at any point x from the receiving end.

Rigorous Mathematical Solution for Long Lines II

Key Points

- The general voltage equation at distance x from the receiving end is: $V(x) = V_R \cosh(\gamma x) + I_R Z_c \sinh(\gamma x)$.
- The general current equation at distance x from the receiving end is: $I(x) = I_R \cosh(\gamma x) + \frac{V_R}{Z_c} \sinh(\gamma x)$.
- At the sending end ($x = l$), the ABCD parameters are: $A = D = \cosh(\gamma l)$, $B = Z_c \sinh(\gamma l)$, and $C = \frac{1}{Z_c} \sinh(\gamma l)$.
- Surge Impedance Loading (SIL) represents the power transmitted when the load impedance equals the surge impedance: $SIL = \frac{V_L^2}{Z_c}$ MW, yielding a flat voltage profile.

Key Features and Differences Comparison I

A comparative summary of the parameters, modeling methods, effects, and industrial practices for the three categories of transmission lines.

Key Features and Differences Comparison II

Key Points

- Line Constants: Short (R, L lumped, C ignored); Medium (R, L lumped, C lumped at nodes); Long (R, L, C, G distributed uniformly).
- Charging Current: Negligible in short lines; significant in medium lines (must be modeled to avoid voltage errors); dominant in long lines.
- Ferranti Effect: Absent in short lines; noticeable in medium lines under no-load; highly prominent in long lines (requires shunt reactors to mitigate).
- Maximum Voltage & Power Transfer: Short ($<$ 20 kV, thermal/voltage drop limited); Medium (20-100 kV, stability/voltage drop limited); Long ($>$ 100 kV, transient stability and SIL limited).

The Root Cause: Unsymmetrical Line Spacing I

Due to structural tower configurations, phase conductors of high-voltage transmission lines are rarely arranged in an equilateral triangle. Horizontal, vertical, or flat-triangular configurations are more common.

The Root Cause: Unsymmetrical Line Spacing II

Key Points

- Unbalanced spacing ($d_{12} eq d_{23} eq d_{31}$) leads to asymmetric magnetic flux linkages for each phase.
- Even when phase currents are balanced ($I_a + I_b + I_c = 0$), the unequal distances generate unequal self and mutual inductances.
- Consequently, the inductive voltage drops ($I \cdot X_L$) across the three phases differ.
- This asymmetry propagates down the line, resulting in unbalanced terminal voltages at the receiving end.

Electromagnetic & Electrostatic Imbalance Effects I

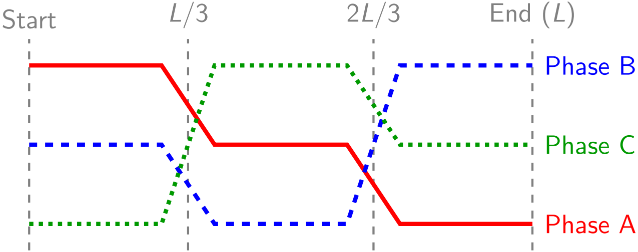
The lack of spatial symmetry yields two distinct physical imbalances: electromagnetic (inductive) and electrostatic (capacitive). Both have detrimental effects on grid operation.

Electromagnetic & Electrostatic Imbalance Effects II

Key Points

- Inductive Imbalance: Creates a net zero-sequence and negative-sequence voltage drop, degrading power quality and causing unbalanced heating in generator rotors.
- Capacitive Imbalance: The conductors' relative height to earth and mutual spacing result in unequal line-to-ground capacitances ($C_{an} eq C_{bn} eq C_{cn}$).
- Unequal capacitances draw unbalanced capacitive charging currents even under no-load conditions.
- This causes continuous neutral point displacement, creating virtual ground faults and ground-fault relay misoperations.

The Transposition Cycle and Geometry I



The Transposition Cycle and Geometry II

Key Points

- Physical positions on the tower structure are swapped periodically at equal intervals ($L/3$).
- Over the entire length (L), each phase conductor spends exactly one-third of the distance in Position 1, 2, and 3.
- As a consequence, the average inductance and capacitance of all three phases are perfectly equalized.
- This structural mitigation is executed at transposition towers designed specifically for high physical tension and clearance.

Averaging Inductance in Transposed Lines I

To calculate the balanced inductance, we compute the average flux linkages over the three transposition steps. The resulting formula relies on the geometric mean of the spaces.

Averaging Inductance in Transposed Lines II

Key Points

- The inductance per phase is:
  $L = 2 \times 10^{-7} \ln\left(\frac{D_{eq}}{D_s}\right)$ H/m
- Equivalent spacing $D_{eq} = \sqrt[3]{d_{12}d_{23}d_{31}}$ represents the mutual Geometric Mean Distance (GMD).
- Conductor self-GMD ($D_s = r' = 0.7788r$) accounts for the internal magnetic flux of a solid conductor.
- For bundled conductors, D_s is replaced by the geometric mean radius of the bundle, reducing skin and proximity effects.
- Transposition reduces the complex multi-phase unsymmetrical model to a simple symmetrical model.

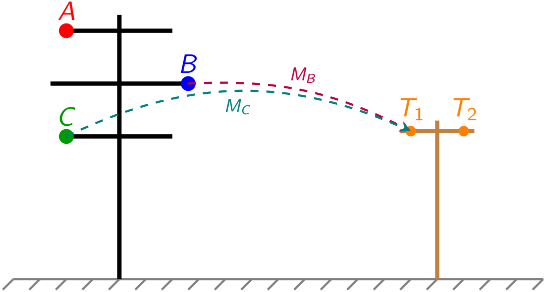
Averaging Capacitance of Transposed Lines I

The line-to-neutral capacitance calculation also assumes balanced phase charges and average conductor voltages relative to ground across the three distinct transposition sections.

Key Points

- Line-to-neutral capacitance is: $C_n = \frac{2\pi\epsilon_0}{\ln\left(\frac{D_{eq}}{r}\right)}$ F/m
- Unlike inductance, the denominator uses the actual physical radius (r) of the conductor rather than D_s.
- Permittivity of free space $\epsilon_0 \approx 8.854 \times 10^{-12}$ F/m.
- Transposition ensures that charging currents ($I_c = \omega C_n V_{ln}$) are equal in magnitude and separated by 120°, resulting in zero net neutral current.

Mitigating Electrostatic & Electromagnetic Interference I



Mitigating Electrostatic & Electromagnetic Interference II

Key Points

- Untransposed power lines running parallel to telecom lines exhibit asymmetric mutual coupling ($M_A eq M_B eq M_C$).
- This induces a longitudinal voltage in the telecommunication lines: $V_{ind} = -j\omega(M_A I_A + M_B I_B + M_C I_C) eq 0$.
- Transposition balances these mutual couplings ($M_{A,avg} = M_{B,avg} = M_{C,avg}$), resulting in a net induced voltage of zero.
- This eliminates the audible hum and potential overvoltage hazards on parallel communication circuits.

Practical Industrial Implementation & Challenges I

Although theoretically straightforward, physical transposition introduces electrical, structural, and economic challenges for high-voltage utilities.

Practical Industrial Implementation & Challenges II

Key Points

- Transposition towers are taller, heavier, and costlier due to the large clearances required for crossing conductors safely.
- Crossovers create structural weak points with higher susceptibility to wind loading and line-to-line flashovers.
- In modern systems, fiber optic communications (OPGW) make telephone interference less critical, but power system balance remains essential.
- For shorter lines (¡ 100 km), transposition is often omitted. For longer lines, it is frequently restricted to substation switchyards.

Classification of Transmission Lines I

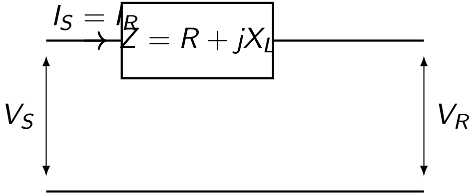
Transmission lines are classified based on physical length and operating voltage, which determines whether line capacitance can be neglected.

Classification of Transmission Lines II

Key Points

- Short Transmission Lines: Length ¡ 80 km (50 miles), voltage ¡ 20-33 kV. Capacitance is neglected due to small charging currents; represented by series resistance R and inductance L.
- Medium Transmission Lines: Length 80-250 km (50-150 miles), voltage 20-100 kV. Capacitance is significant and lumped at discrete points along the line.
- Long Transmission Lines: Length ¿ 250 km (¿150 miles), voltage ¿ 100 kV. Parameters are distributed uniformly along the entire length.
- Key performance factors: Voltage Regulation $VR = \frac{|V_{NL}| - |V_{FL}|}{|V_{FL}|} \times 100\%$ and Transmission Efficiency $\eta = \frac{P_{out}}{P_{in}} \times 100\%$.

Short Transmission Line Model I

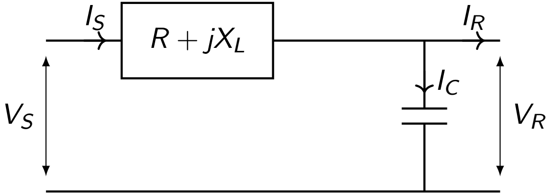


Short Transmission Line Model II

Key Points

- Equivalent circuit consists of series resistance R and series reactance X_L representing line inductance.
- Phasor relation: $\vec{V}_S = \vec{V}_R + \vec{I}\vec{Z} = \vec{V}_R + \vec{I}(R + jX_L)$.
- For lagging power factor $\cos\phi_R$, the sending end voltage magnitude is: $V_S \approx V_R + IR\cos\phi_R + IX_L\sin\phi_R$.
- Voltage regulation: $VR \approx \frac{IR\cos\phi_R + IX_L\sin\phi_R}{V_R} \times 100\%$.

Medium Lines: End Condenser Method I

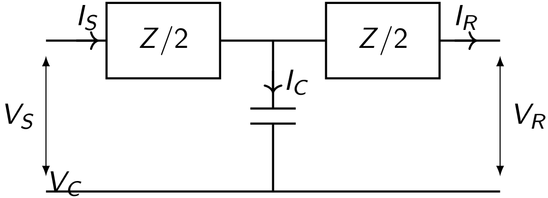


Medium Lines: End Condenser Method II

Key Points

- In this method, the entire line capacitance is assumed to be lumped or concentrated at the receiving end of the line.
- Line current is split: $\vec{I_S} = \vec{I_R} + \vec{I_C}$, where charging current $\vec{I_C} = j\omega C\vec{V_R} = \vec{Y}\vec{V_R}$.
- Sending end voltage: $\vec{V_S} = \vec{V_R} + \vec{I_S}(R + jX_L)$.
- Limitations: Over-estimates the capacitance effect, resulting in less accurate voltage regulation and efficiency predictions than Nominal T or $\pi methods$.

Medium Lines: Nominal T Method I



Medium Lines: Nominal T Method II

Key Points

- The line series impedance is divided into two equal halves $(Z/2)$, and the total shunt admittance (Y) is concentrated at the center.
- Voltage at center node: $\vec{V}_C = \vec{V}_R + \vec{I}_R \frac{\vec{Z}}{2}$.
- Shunt charging current: $\vec{I}_C = \vec{V}_C \vec{Y} = \vec{Y}\left(\vec{V}_R + \vec{I}_R \frac{\vec{Z}}{2}\right)$.
- Sending end current:
  $\vec{I}_S = \vec{I}_R + \vec{I}_C = \vec{I}_R\left(1 + \frac{\vec{Y}\vec{Z}}{2}\right) + \vec{V}_R \vec{Y}$.
- Sending end voltage:
  $\vec{V}_S = \vec{V}_C + \vec{I}_S \frac{\vec{Z}}{2} = \vec{V}_R\left(1 + \frac{\vec{Y}\vec{Z}}{2}\right) + \vec{I}_R \vec{Z}\left(1 + \frac{\vec{Y}\vec{Z}}{4}\right)$.

ABCD Parameters for Nominal T Method I

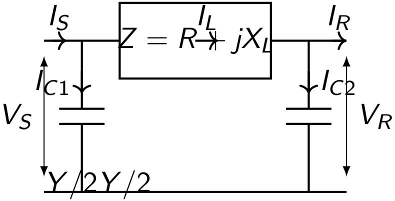
The ABCD parameters are derived from the sending end voltage and current equations: _S = A_R + B_R and _S = C_R + D_R.

ABCD Parameters for Nominal T Method II

Key Points

- $A = 1 + \frac{\vec{Y}\vec{Z}}{2}$ (Dimensionless constant representing open-circuit voltage ratio)
- $B = \vec{Z}\left(1 + \frac{\vec{Y}\vec{Z}}{4}\right)$ (Ohms, short-circuit transfer impedance)
- $C = \vec{Y}$ (Siemens, open-circuit transfer admittance)
- $D = 1 + \frac{\vec{Y}\vec{Z}}{2}$ (Dimensionless, short-circuit current ratio)
- Verification: Since $A = D$, the circuit is symmetrical. Reciprocity condition $AD - BC = 1$ is satisfied.

Medium Lines: Nominal π *MethodI*



Medium Lines: Nominal $\pi Method II$

Key Points

- The series impedance Z is kept in the center, and the total shunt admittance is divided equally $(Y/2)$ at sending and receiving ends.
- Receiving-end capacitor current: $\vec{I}_{C2} = \vec{V}_R \frac{\vec{Y}}{2}$.
- Line series current: $\vec{I}_L = \vec{I}_R + \vec{I}_{C2} = \vec{I}_R + \vec{V}_R \frac{\vec{Y}}{2}$.
- Sending end voltage: $\vec{V}_S = \vec{V}_R + \vec{I}_L \vec{Z} = \vec{V}_R \left(1 + \frac{\vec{Y}\vec{Z}}{2}\right) + \vec{I}_R \vec{Z}$.
- Sending end current: $\vec{I}_S = \vec{I}_L + \vec{V}_S \frac{\vec{Y}}{2} = \vec{V}_R \vec{Y} \left(1 + \frac{\vec{Y}\vec{Z}}{4}\right) + \vec{I}_R \left(1 + \frac{\vec{Y}\vec{Z}}{2}\right)$.

Nominal $\pi ABCD Parameters \& Comparison I$

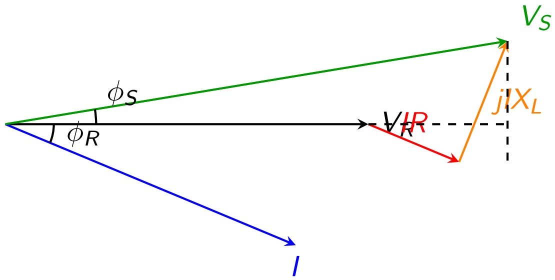
Summary of ABCD parameters for Nominal $\pi model and comparison of medium transmission line performance analysis me$

Nominal $\pi ABCDParameters\&ComparisonII$

Key Points

- Nominal π parameters: $A = D = 1 + \frac{\vec{Y}\vec{Z}}{2}$, $B = \vec{Z}$, and $C = \vec{Y}\left(1 + \frac{\vec{Y}\vec{Z}}{4}\right)$.
- Symmetry and Reciprocity: Both T and π models are symmetrical ($A = D$) and reciprocal ($AD - BC = 1$).
- Parameter Differences: For Nominal T, $B = Z(1 + YZ/4)$ and $C = Y$. For Nominal π, $B = Z$ and $C = Y(1 + YZ/4)$.
- Industrial Relevance: These models are vital for power system studies. Computer simulations use distributed parameters, but T and π models provide excellent approximations for system planning.

Mathematical Foundation of Short Transmission Lines I



Mathematical Foundation of Short Transmission Lines II

Key Points

- For a short transmission line, the sending end voltage phasor is given by: $\vec{V}_S = \vec{V}_R + \vec{I}R + j\vec{I}X_L$
- Taking receiving end voltage $\vec{V}_R = V_R\angle 0^\circ$ as reference, the lagging current is: $\vec{I} = I\cos\phi_R - jI\sin\phi_R$
- The approximate sending end voltage magnitude is: $V_S \approx V_R + IR\cos\phi_R + IX_L\sin\phi_R$
- Voltage regulation (VR) is defined as: $VR \approx \frac{I(R\cos\phi_R + X_L\sin\phi_R)}{V_R} \times 100\%$

Performance Analysis under Lagging Power Factor I

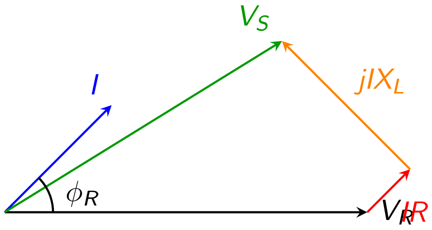
Under lagging power factor (inductive loads like induction motors and transformers), the line current lags the receiving end voltage. This represents the most common operating condition for power systems.

Performance Analysis under Lagging Power Factor II

Key Points

- Higher voltage regulation: Since both $\cos\phi_R$ and $\sin\phi_R$ are positive, V_S is significantly larger than V_R, leading to a larger voltage drop.
- Increased transmission losses: For a constant delivered active power P, a low power factor increases line current ($I = \frac{P}{\sqrt{3}V_R \cos\phi_R}$), causing I^2R losses to rise quadratically.
- Reduced efficiency: The transmission efficiency $\eta = \frac{P}{P+3I^2R} \times 100\%$ decreases due to elevated copper losses in conductors.
- Industrial impact: Utility generators must supply more reactive power ($Q = P\tan\phi_R$), loading generators and transmission lines unnecessarily.

Performance Analysis under Leading Power Factor I



Performance Analysis under Leading Power Factor II

Key Points

- Under leading power factor (capacitive loads or over-excited synchronous motors), the current leads the receiving end voltage.
- Negative voltage regulation: When $IX_L \sin\phi_R > IR\cos\phi_R$, the approximate sending end voltage formula yields $V_S < V_R$.
- Voltage rise at receiving end: The receiving end voltage is higher than the sending end voltage, which can cause dielectric stress on insulation.
- Relationship to Ferranti Effect: Charging currents in capacitive lines have a similar effect, leading to overvoltages under light or no-load conditions.

Conditions for Zero and Maximum Voltage Regulation I

Understanding extreme operating limits allows transmission engineers to design reactive power compensation systems to keep voltage profiles within standard tolerances (typically $\pm 5\%$).

Conditions for Zero and Maximum Voltage Regulation II

Key Points

- Condition for Maximum Voltage Regulation (worst drop): Occurs when $\frac{d(VR)}{d\phi_R} = 0 \implies \tan\phi_R = \frac{X_L}{R}$ lagging.
- Worst-case power factor is $\cos\phi_R = \frac{R}{\sqrt{R^2+X_L^2}} = \frac{R}{Z}$ lagging, where the phasor drop is aligned with V_R.
- Condition for Zero Voltage Regulation (perfect voltage match $V_S = V_R$): Occurs when $IR\cos\phi_R - IX_L\sin\phi_R = 0 \implies \tan\phi_R = \frac{R}{X_L}$ leading.
- Zero-regulation power factor is $\cos\phi_R = \frac{X_L}{\sqrt{R^2+X_L^2}} = \frac{X_L}{Z}$ leading.

For medium lines (80–250 km), line capacitance is significant and is modeled using Nominal-π or Nominal-T circuits, which alters the power factor performance due to line charging currents.

Medium Transmission Lines & Shunt Admittance II

Key Points

- Line charging current: The shunt admittance $\vec{Y} = j\omega C$ draws a leading current $\vec{I}_C = \vec{V}\vec{Y}$ even at no load.
- Nominal-π equation: Sending end voltage is $\vec{V}_S = \vec{V}_R(1 + \frac{\vec{Y}\vec{Z}}{2}) + \vec{I}_R\vec{Z}$, where charging current offsets lagging load current.
- Interaction with load PF: A lagging load PF is partially compensated by the line's own capacitance, resulting in slightly better regulation than a short line of same impedance.
- Leading load PF hazard: With a leading load PF, the line charging current adds constructively to the load leading current, exacerbating overvoltage risks.

Industrial Mitigation: Reactive Power Compensation I

To prevent high line losses and poor voltage regulation, power transmission utilities mandate reactive power compensation at the substation or consumer level.

Industrial Mitigation: Reactive Power Compensation II

Key Points

- Shunt Capacitor Banks: Installed at receiving-end buses to supply local leading VARs, reducing the net lagging current drawn from the transmission line.
- Required compensation calculation: $Q_C = P(\tan\phi_R - \tan\phi_{R,new})$, where $\phi_{R,new}$ is the target corrected power factor angle.
- Synchronous Condensers: Over-excited synchronous motors running at no-load act as variable capacitors, providing smooth, stepless reactive power control.
- Benefits of compensation: Lower line current, reduced active power losses (I^2R), improved voltage stability, and increased line transmission capacity.

Performance Summary & System Design Guidelines I

Transmission system design requires careful matching of conductor sizes, line length, and reactive compensation to maintain optimal power factor and system stability.

Performance Summary & System Design Guidelines II

Key Points

- Lagging Load: Low efficiency, high voltage drop (positive regulation), high conductor heating, high reactive power demand.
- Unity Load: Maximum active power transmission efficiency, small voltage drop ($VR \approx \frac{IR}{V_R}$), zero reactive power flow.
- Leading Load: Possible negative voltage regulation ($V_R > V_S$), lower current up to a point, but risks overvoltage and resonance.
- Grid Regulations: Utilities typically impose penalties on industrial customers with a power factor below 0.95 lagging, encouraging active compensation.

Introduction to Ferranti Effect I

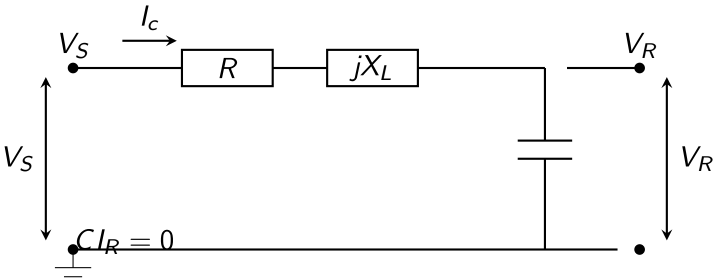
The phenomenon where the receiving-end voltage (V_R) exceeds the sending-end voltage (V_S) under no-load or light-load conditions.

Introduction to Ferranti Effect II

Key Points

- First observed by Sebastian Ziani de Ferranti in 1890 on the Deptford 10 kV cable transmission line.
- Predominantly occurs in medium and long transmission lines (typically > 80 km) and high-voltage underground cables.
- Caused by the capacitive charging current (I_c) flowing through the series line inductance (L) and resistance (R).
- The charging current acts as a leading load, causing a phase-shifted voltage drop that actually increases the voltage towards the receiving end.

Equivalent Circuit Model I

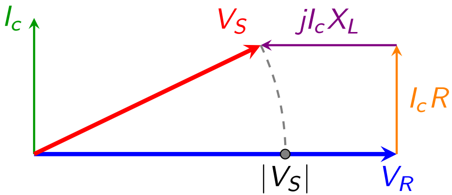


Equivalent Circuit Model II

Key Points

- Simplified lumped-parameter model of a transmission line under open-circuit (no-load) conditions.
- The charging current $I_c = j\omega C V_R$ is drawn by the line capacitance C.
- The flow of this leading current I_c through the series resistor R and inductor L results in the relation: $V_S = V_R + I_c R + jI_c X_L$.
- Neglecting line resistance, the equation simplifies to $V_S \approx V_R - \omega^2 LCV_R$, showing $V_R > V_S$.

Phasor Diagram of Ferranti Effect I



Phasor Diagram of Ferranti Effect II

Key Points

- The receiving-end voltage V_R is chosen as the reference phasor along the real axis.
- The charging current I_c leads V_R by 90°, pointing vertically upwards.
- The resistive drop $I_c R$ is in phase with I_c (pointing vertically upwards from the tip of V_R).
- The inductive drop $jI_c X_L$ leads I_c by 90° (pointing horizontally to the left from the tip of $I_c R$).
- The vector sum $V_S = V_R + I_c R + jI_c X_L$ forms a path showing that the magnitude $|V_S|$ is shorter than $|V_R|$.

Mathematical Derivation (ABCD Parameters) I

Derivation of the exact relation using transmission line theory and ABCD parameters.

Mathematical Derivation (ABCD Parameters) II

Key Points

- From transmission line equations: $V_S = AV_R + BI_R$ and $I_S = CV_R + DI_R$.
- At no load, the receiving-end current is zero ($I_R = 0$), yielding $V_S = AV_R \implies V_R = V_S/A$.
- The parameter A for a long transmission line is $A = \cosh(\gamma l) = 1 + \frac{\gamma^2 l^2}{2} + \frac{\gamma^4 l^4}{24} + \dots$, where $\gamma = \sqrt{zy}$ and l is the line length.
- Using $z = r + j\omega l$ and $y = g + j\omega c \approx j\omega c$, we find $\gamma^2 = -\omega^2 lc + j\omega rc$.
- For a lossless line ($r = 0$), $A = \cosh(j\beta l) = \cos(\beta l)$, where $\beta = \omega\sqrt{lc}$ is the phase constant.
- Thus, $V_R = \frac{V_S}{\cos(\beta l)}$. Since $\cos(\beta l) < 1$ for practical line lengths, it is mathematically proven that $V_R > V_S$.

Voltage Rise Approximation I

Approximating the percentage voltage rise to establish a direct relationship with line length.

Voltage Rise Approximation II

Key Points

- Using the Taylor series expansion for the cosine term: $\cos(\beta l) \approx 1 - \frac{\beta^2 l^2}{2}$.
- Substituting this back: $V_R \approx \frac{V_S}{1 - \frac{\beta^2 l^2}{2}}$.
- Applying the binomial approximation $(1-x)^{-1} \approx 1 + x$: $V_R \approx V_S \left(1 + \frac{\beta^2 l^2}{2}\right)$.
- The change in voltage is $\Delta V = V_R - V_S \approx V_S \frac{\beta^2 l^2}{2} = V_S \frac{\omega^2 l^2 LC}{2}$.
- Percentage voltage rise: $\frac{\Delta V}{V_S} \times 100\% \approx \frac{\omega^2 l^2 LC}{2} \times 100\%$.
- This shows that the Ferranti voltage rise is directly proportional to the square of the line length (l^2) and the square of the frequency (f^2).

Mitigation of the Ferranti Effect I

Techniques and devices used by utility engineers to counter the voltage rise.

Mitigation of the Ferranti Effect II

Key Points

- **Shunt Reactors**: Inductive reactors connected between the line and ground at receiving-end substations. They consume leading reactive power and pull the voltage down.
- **Dynamic VAr Compensators**: Utilizing FACTS devices like SVCs and STATCOMs to dynamically absorb reactive power during low-load periods.
- **Generator Under-Excitation**: Operating terminal generators in the under-excited (leading power factor) region to absorb reactive power from the grid.
- **Transformer Tap Changing**: Adjusting tap settings of line-end transformers, though limited by speed and response range.
- **Line Switching**: De-energizing parallel circuits during off-peak hours to reduce the total line

Numerical Example & Case Study I

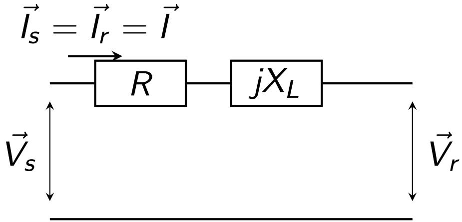
Step-by-step calculation for a 400 kV, 50 Hz, 300 km transmission line.

Numerical Example & Case Study II

Key Points

- Given parameters: $L = 1.0$ mH/km, $C = 0.012$ μF/km, and line length $l = 300$ km. Resistance is assumed negligible.
- Calculate the phase constant: $\beta = \omega\sqrt{LC} = 2\pi(50)\sqrt{1.0 \times 10^{-3} \times 0.012 \times 10^{-6}} \approx 1.088 \times 10^{-3}$ rad/km.
- Calculate electrical length: $\beta l = 1.088 \times 10^{-3} \times 300 \approx 0.3265$ rad $\approx 18.7^\circ$.
- Calculate parameter A: $A = \cos(\beta l) = \cos(0.3265 \text{ rad}) \approx 0.947$.
- Calculate receiving-end voltage: $V_R = \frac{V_S}{A} = \frac{400 \text{ kV}}{0.947} \approx 422.4$ kV.
- Result: The receiving-end voltage rises by 22.4 kV (5.6%) above the nominal sending-end voltage, which

Short Transmission Line: Mathematical Modeling I



Short Transmission Line: Mathematical Modeling II

Key Points

- Short lines are defined by length < 80 km and voltage level < 20 kV, where shunt capacitance C is negligible.
- The sending end voltage equation is: $\vec{V}_s = \vec{V}_r + \vec{I}\vec{Z} = \vec{V}_r + \vec{I}(R + jX_L)$.
- Sending end current equals receiving end current: $\vec{I}_s = \vec{I}_r = \vec{I}$.
- Voltage regulation is given by $\%VR = \frac{|V_s| - |V_r|}{|V_r|} \times 100\%$.
- Approximate formula for receiving end voltage: $V_s \approx V_r + IR\cos\phi_r \pm IX_L \sin\phi_r$ ($+$ for lagging, $-$ for leading power factor).

Numerical 1: Short Line Performance Evaluation I

A 3-phase, 50 Hz, 15 km long transmission line supplies a load of 10 MW at 11 kV, 0.8 lagging power factor. The line resistance is 0.15 Ω/km/phase and inductive reactance is 0.4 Ω/km/phase. Calculate the receiving-end line voltage, sending-end voltage, voltage regulation, and transmission efficiency.

Numerical 1: Short Line Performance Evaluation II

Key Points

- Step 1: Calculate total resistance $R = 0.15 \times 15 = 2.25\ \Omega$ and reactance $X_L = 0.4 \times 15 = 6.0\ \Omega$ per phase.
- Step 2: Receiving-end phase voltage $V_r = \frac{11000}{\sqrt{3}} = 6350.85$ V. Load current $I = \frac{P}{\sqrt{3} V_{r,\text{line}} \cos\phi_r} = \frac{10 \times 10^6}{\sqrt{3} \times 11000 \times 0.8} = 656.08$ A.
- Step 3: Determine sending-end phase voltage using vector form: $\vec{V_s} = V_r + \vec{I}(R + jX)$. With $\vec{I} = 656.08(0.8 - j0.6) = 524.86 - j393.65$ A, $\vec{V_s} = 6350.85 + (524.86 - j393.65)(2.25 + j6.0) = 9893.68 + j2263.45$ V.
- Step 4: Magnitude $|V_s| = \sqrt{9893.68^2 + 2263.45^2} = 10149.5$ V. Sending-end line voltage

Medium Lines: ABCD Parameterization I

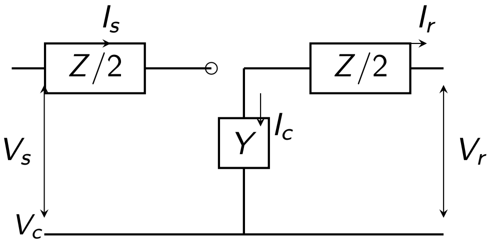
Medium transmission lines (80 km to 250 km, 20 kV to 100 kV) require representation of shunt capacitance. The general two-port network equations are: $\vec{V}\_s = A\vec{V}\_r + B\vec{I}\_r$ $\vec{I}\_s = C\vec{V}\_r + D\vec{I}\_r$ Where the parameter constraints for a symmetrical, reciprocal network are $A = D$ and $AD - BC = 1$.

Medium Lines: ABCD Parameterization II

Key Points

- Nominal-T Model: Shunt capacitance is lumped in the middle. $A = D = 1 + \frac{YZ}{2}$, $B = Z(1 + \frac{YZ}{4})$, and $C = Y$.
- Nominal-π *Model* : *Shuntcapacitanceisdividedequallyattheends*.A = D = 1 + YZ_{2}, $B = Z$, and $C = Y(1 + \frac{YZ}{4})$.
- Here, $Z = R + jX_L$ represents the total series impedance, and $Y = j\omega C$ represents the total shunt admittance of the line.
- These ABCD parameters facilitate easy computation of cascade systems and general line performance metrics.

Nominal-T Network Equivalent Circuit I



Nominal-T Network Equivalent Circuit II

Key Points

- In the Nominal-T representation, the line impedance Z is divided into two halves, each of value $Z/2$, connected at the sending and receiving ends.
- The total shunt admittance $Y = j\omega C$ is connected at the central node between the two impedance halves.
- The voltage at the central node is $V_c = V_r + I_r \frac{Z}{2}$.
- The shunt charging current is $I_c = YV_c = Y(V_r + I_r \frac{Z}{2})$.
- Sending end current $I_s = I_r + I_c = YV_r + (1 + \frac{YZ}{2})I_r$.
- Sending end voltage
  $V_s = V_c + I_s \frac{Z}{2} = (1 + \frac{YZ}{2})V_r + Z(1 + \frac{YZ}{4})I_r$.

Numerical 2: Performance using Nominal-T Model I

A 3-phase, 50 Hz, 100 km transmission line delivers 20 MW at 0.8 lagging power factor and 66 kV at the receiving end. The line parameters per phase are: resistance $R = 10\ \Omega$, reactance $X_L = 20\ \Omega$, and capacitance $C = 1.0\ \mu$F. Using Nominal-T, compute sending end voltage, current, and voltage regulation.

Numerical 2: Performance using Nominal-T Model II

Key Points

- Step 1: Compute per-phase parameters.
  $V_{r,\text{phase}} = \frac{66000}{\sqrt{3}} = 38105$ V. $I_r = \frac{20\times10^6}{\sqrt{3}\times66000\times0.8} = 218.7$ A.
- Step 2: Set receiving end voltage as reference:
  $\vec{V}_r = 38105 + j0$ V.
  $\vec{I}_r = 218.7(0.8 - j0.6) = 175.0 - j131.2$ A.
- Step 3: Define series impedance $\vec{Z}/2 = 5 + j10\ \Omega$ and shunt admittance
  $\vec{Y} = j2\pi \times 50 \times 1.0 \times 10^{-6} = j3.1416 \times 10^{-4}$ S.
- Step 4: Voltage at central node $\vec{V}_c = \vec{V}_r + \vec{I}_r(\vec{Z}/2) = 38105 + (175.0 - j131.2)(5 + j10) = 40292 + j1094$ V.
- Step 5: Shunt current $\vec{I}_c = \vec{Y}\vec{V}_c = j3.1416 \times 10^{-4}(40292 + j1094) = -0.344 + j12.66$ A.
- Step 6: Sending current $\vec{I}_s = \vec{I}_r + \vec{I}_c = 174.66 - j118.54$

Nominal-π *NetworkEquivalentCircuitI*

In the Nominal-π model, the total series impedance $Z = R + jX_L$ remains in the center branch, while the total shunt admittance is divided equally into two parts, $Y/2$, connected at the sending and receiving ends respectively. The corresponding terminal equations are: $\vec{V}\_s = \left(1 + \frac{YZ}{2}\right)\vec{V}\_r + Z\vec{I}\_r$
$\vec{I}\_s = Y\left(1 + \frac{YZ}{4}\right)\vec{V}\_r + \left(1 + \frac{YZ}{2}\right)\vec{I}\_r$

Key Points

- The current through the receiving end capacitor is $\vec{I}_{c2} = \vec{V}_r \frac{\vec{Y}}{2}$.
- The current flowing in the series impedance branch is $\vec{I}_L = \vec{I}_r + \vec{I}_{c2} = \vec{I}_r + \vec{V}_r \frac{\vec{Y}}{2}$.
- The sending end voltage is then $\vec{V}_s = \vec{V}_r + \vec{I}_L \vec{Z} = \vec{V}_r + \left(\vec{I}_r + \vec{V}_r \frac{\vec{Y}}{2}\right) \vec{Z} = \left(1 + \frac{\vec{Y}\vec{Z}}{2}\right) \vec{V}_r + \vec{Z}\vec{I}_r$.
- The current through the sending end capacitor is $\vec{I}_{c1} = \vec{V}_s \frac{\vec{Y}}{2}$.
- The total sending end current is $\vec{I}_s = \vec{I}_L + \vec{I}_{c1}$, yielding the ABCD matrix formulation.

Numerical 3: Comparison of Model Accuracy and Industry Best Practices I

Using the same transmission line parameters from Lecture 20, let's analyze the difference in voltage regulation and efficiency results across the Short-line approximation, Nominal-T, and Nominal-π models. We also outline the criteria utility engineers use to choose these models during transmission planning.

Numerical 3: Comparison of Model Accuracy and Industry Best Practices II

Key Points

- Comparison table of sending end voltages for the 100 km line: Short-line: 75.6 kV, Nominal-T: 73.49 kV, Nominal-π :$73.54 kV$.
- The short line model neglects line charging current, leading to a conservative overestimation of sending-end voltage and regulation error ($gt; 2\%$).
- Nominal-T and Nominal-π $provide comparable results (within 0.1\% difference) and are accura$
- Industrial Practice: For lines exceeding 200 km, distributed parameter modeling (Rigorous/Exact Method using hyperbolic functions) is mandatory to

Introduction & Physical Phenomenon I

The Ferranti effect is a phenomenon in high-voltage alternating-current (AC) transmission lines where the receiving-end voltage (V_R) exceeds the sending-end voltage (V_S) under no-load or lightly-loaded conditions.

Introduction & Physical Phenomenon II

Key Points

- First observed in 1890 by Sebastian Ziani de Ferranti during the installation of the 10 kV Deptford power station transmission cables.
- Caused by the interaction of the line's distributed capacitive charging current (charging reactive power or MVAR) with its series inductance.
- Particularly pronounced in long overhead transmission lines (exceeding 200 km) and high-voltage underground cables due to their significantly higher capacitance per unit length.
- Determined by the equation $V_R > V_S$ when receiving-end current $I_R \approx 0$.

Nominal Pi Model Mathematical Derivation I

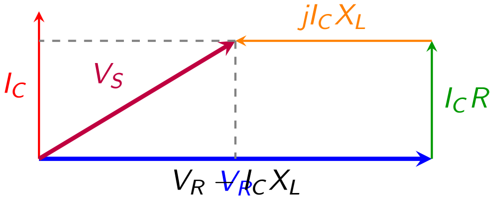
Using the nominal π model representation of a medium transmission line, we can derive the voltage rise analytically by setting the receiving end current to zero ($I_R = 0$).

Nominal Pi Model Mathematical Derivation II

Key Points

- The transmission line ABCD parameter relationship is: $V_S = AV_R + BI_R$. Under no-load, $I_R = 0$, yielding $V_S = AV_R$.
- For a nominal π model, the parameter A is defined as $A = 1 + \frac{YZ}{2}$, where Y is the total shunt admittance and Z is the series impedance.
- Neglecting line resistance ($R \approx 0$), we have $Z = j\omega L$ and $Y = j\omega C$. Thus, $YZ = (j\omega C)(j\omega L) = -\omega^2 LC$.
- Substituting YZ yields $V_S = V_R \left(1 - \frac{\omega^2 LC}{2}\right)$, leading to $V_R = \frac{V_S}{1 - \frac{\omega^2 LC}{2}}$. Since the denominator is less than 1, $V_R > V_S$.

No-Load Phasor Diagram I



No-Load Phasor Diagram II

Key Points

- The receiving-end voltage V_R is chosen as the reference phasor along the positive real axis.
- The line charging current I_C leads V_R by 90° due to the pure shunt capacitive admittance.
- The resistive drop $I_C R$ is in phase with I_C (vertical vector), and the inductive drop $jI_C X_L$ leads I_C by 90° (pointing leftwards).
- Adding these drops vectorially to V_R gives the sending-end voltage V_S, illustrating that the magnitude $|V_S| < |V_R|$.

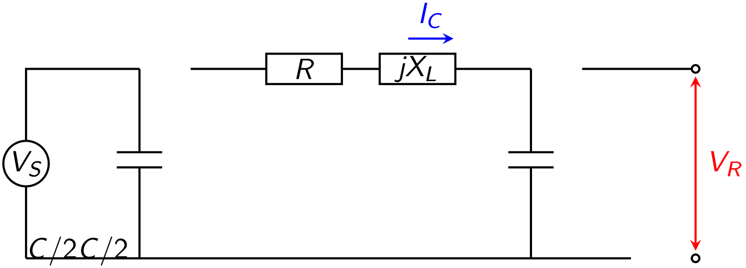
Distributed Parameter Analysis for Long Lines I

For long transmission lines, parameters are distributed. The voltage profile along a lossless transmission line of length l is modeled using hyperbolic wave equations.

Key Points

- The exact relationship under no-load is given by $V_S = V_R \cosh(\gamma l)$, where $\gamma = \alpha + j\beta$ is the propagation constant.
- For a lossless line, attenuation constant $\alpha = 0$, which gives $\gamma = j\beta$, where $\beta = \omega\sqrt{L_0 C_0}$ is the phase constant.
- Using hyperbolic identities, $\cosh(j\beta l) = \cos(\beta l)$, which simplifies the relationship to: $V_R = \frac{V_S}{\cos(\beta l)}$.
- Approximating with a Taylor series expansion: $V_R \approx \frac{V_S}{1 - \frac{(\beta l)^2}{2}} \approx V_S \left(1 + \frac{\beta^2 l^2}{2}\right) = V_S \left(1 + \frac{\omega^2 L_0 C_0 l^2}{2}\right)$.

Nominal Pi Circuit Schematic Under No-Load I



Nominal Pi Circuit Schematic Under No-Load II

Key Points

- Circuit diagram modeling the line using a lumped parameter nominal π configuration under no-load condition ($I_R = 0$).
- The sending-end voltage V_S supplies the charging currents of the two shunt capacitors ($C/2$ at each end).
- The charging current flowing through the series inductance (jX_L) causes a voltage rise across the line.
- As the receiving-end terminal is open-circuited, no real load current opposes the capacitive charging effect.

Industrial Implications & Overvoltage Risks I

The voltage rise from the Ferranti effect presents significant risks to grid infrastructure, equipment insulation, and operational stability.

Industrial Implications & Overvoltage Risks II

Key Points

- Causes severe temporary overvoltages (TOV), which can exceed the maximum continuous operating voltage (MCOV) of surge arresters and insulation systems.
- Accelerates the degradation of transformer winding insulation and cable dielectrics due to sustained electrical and thermal stress.
- Increases the risk of magnetic core saturation in receiving-end transformers, leading to high harmonic generation and overheating.
- Promotes corona discharge activity along the conductors, leading to increased active power losses, radio interference (RI), and audible noise.

Mitigation Strategies: Shunt Reactors & Control I

Power utilities employ several active and passive methods to mitigate the Ferranti effect, primarily by neutralizing the line's capacitive VARs.

Mitigation Strategies: Shunt Reactors & Control II

Key Points

- Installation of Shunt Reactors (inductive reactors) at the receiving end and intermediate switching stations to consume excess capacitive charging MVARs.
- Use of Static VAR Compensators (SVCs) and STATCOMs to provide fast, dynamic, and continuously variable reactive power support during load rejection events.
- Temporary operation at reduced sending-end voltage or adjustment of transformer load tap changers (LTC) during light load periods.
- Utilization of flexible AC transmission systems (FACTS) and scheduling line energization procedures under controlled voltage profiles.

Evolution of the Indian Grid & Integration I

Transition to a Unified National Grid (One Nation, One Grid, One Frequency)

Evolution of the Indian Grid & Integration II

Key Points

- Development of the Indian power sector began with isolated state networks, which were grouped into five regional grids (Northern, Western, Southern, Eastern, North-Eastern) in the 1960s.
- Synchronous integration began with the Eastern and North-Eastern grids in October 1991.
- The Western, Eastern, and North-Eastern grids were interconnected synchronously in August 2006, and the Northern Grid was added in August 2007, creating the synchronously operating NEW grid.
- Integration was finalized on December 31, 2013, with the commissioning of the 765 kV Raichur-Solapur line connecting the Southern Grid synchronously.
- The unified National Grid operates at a single nominal frequency of 50 Hz across the entire country, enabling

Hierarchical Load Despatch Control Structure I

5 Regions (NRLDC, WRLDC, SRLDC, ERLDC, NERLDC); ode[fill=yellow!20, minimum width=6.5cm, minimum height=0.8cm] (SLDC) at (0,0) **State Load Despatch Centres (SLDCs)**-time monitoring and intra-state dispatch control; ode[fill=green!20, minimum width=6.5cm, minimum height=0.8cm] (ALDC) at (0,-2) **Area Load Despatch Centres (ALDCs)**-transmission level monitoring and coordination; ode[fill=blue!20, minimum width=6.5cm, minimum height=0.8cm] (GEN) at (0,-4) **Generating Stations and Substation Terminals**asset control and local execution; [-¿, ultra thick, ¿=stealth] (NLDC) – (RLDC); [-¿, ultra thick, ¿=stealth] (RLDC) – (SLDC); [-¿, ultra thick, ¿=stealth] (SLDC) – (ALDC); [-¿, ultra thick, ¿=stealth] (ALDC) – (GEN);

Key Points

- Hierarchical coordination ensures decentralized operational authority coupled with central supervision for system security.
- National Load Despatch Centre (NLDC) in New Delhi monitors and schedules inter-regional power flow and coordinates with Regional Load Despatch Centres (RLDCs).
- RLDCs execute real-time grid operation, schedule power, and monitor transmission constraints in their respective regions.
- State Load Despatch Centres (SLDCs) manage intra-state power generation scheduling and coordination with local Area Load Despatch Centres (ALDCs).

Legal Foundations: Electricity Act, 2003 & IEGC

Legislative & Regulatory Framework II

Key Points

- Section 26 of the Electricity Act, 2003 mandates the establishment of the National Load Despatch Centre.
- Section 28 and Section 32 outline the roles, responsibilities, and functions of RLDCs and SLDCs respectively.
- The Indian Electricity Grid Code (IEGC) provides the regulatory framework, setting rules for grid discipline, operation standards, and scheduling protocols.
- Deviation Settlement Mechanism (DSM) is implemented to commercially penalize utilities drawing or injecting power off-schedule, regulating grid frequency.
- CERC (Central Electricity Regulatory Commission) is the nodal regulatory body defining the operating bands and transmission tariffs.

Grid Transmission Voltage Hierarchy I

765 kV, 400 kV, 220 kV AC and $\pm 800 kV / \pm 500 kV HVDC$;
ode[fill=yellow!20, minimum width=6.5cm] (S) at (0,0)
Sub-Transmission Level
132 kV, 66 kV, 33 kV AC;
ode[fill=green!20, minimum width=6.5cm] (D) at (0,-1.5) **Primary Distribution**
11 kV AC;
ode[fill=blue!20, minimum width=6.5cm] (C) at (0,-3) **Secondary Distribution (Consumers)**
415 V (3-phase) / 230 V (1-phase) AC; [-¿, ultra thick, ¿=stealth] (G) – (P) node[midway, right, font=] Step-up Transformers; [-¿, ultra thick, ¿=stealth] (P) – (S) node[midway, right, font=] Grid Substations; [-¿, ultra thick, ¿=stealth] (S) – (D) node[midway, right, font=] Distribution Substations; [-¿, ultra thick, ¿=stealth] (D) – (C) node[midway, right, font=] Distribution Transformers (DTs);

Key Points

- Grid hierarchy is structured to minimize transmission losses ($P_{loss} = I^2 R$) by using extra-high and ultra-high voltage levels for long-distance bulk power transfer.
- UHV/EHV AC transmission lines are complemented by high-capacity High-Voltage Direct Current (HVDC) corridors for point-to-point transmission.
- Sub-transmission and distribution networks handle local delivery and are step-down systems managed by state-owned and private Discoms.

Bulk Power Transmission over Long-Distance Corridors

Inter-Regional Corridors & HVDC Infrastructure II

Key Points

- Asymmetric generation resource allocation (coal in East/Central, hydro in North, solar/wind in West/South) necessitates long-distance transmission corridors.
- The grid employs high-capacity ±800 kV HVDC bipole transmission links including Raigarh-Pugalur (6000 MW, 1765 km) and Champa-Kurukshetra (6000 MW).
- HVDC Back-to-Back stations (e.g. at Vindhyachal, Gazuwaka, and Chandrapur) connect asynchronous regions or enable controlled power transfer without fault propagation.
- Inter-regional transmission capacity of the Indian National Grid exceeds $112,000$ MW, enhancing system reliability and establishing a competitive electricity

Frequency Regulation Framework under IEGC

Key Points

- The operational frequency of the National Grid is tightly controlled within the IEGC-mandated narrow band of 49.90 Hz $\leq f \leq$ 50.05 Hz.
- Primary control is achieved through local turbine speed governors on generating units responding with a droop characteristic of $3\% - 6\%$ within seconds.
- Secondary frequency control uses Automatic Generation Control (AGC) central loops calculated at the NLDC level to distribute power demands every 4 seconds.
- AGC is driven by the Area Control Error formula: $ACE = (I_a - I_s) - 10B(f_a - f_s)$, where I represents tie-line interchange, f represents frequency, and B is the frequency bias coefficient.
- Wide Area Measurement Systems (WAMS) utilize Phasor Measurement Units (PMUs) to capture

Defense Mechanisms against Cascading Failures

Grid Security, Protection & Islanding Schemes II

Key Points

- System Protection Schemes (SPS) are programmed automatic response systems that execute generator tripping, load shedding, or HVDC power modulation during contingencies.
- Under-Frequency Relays (UFR) and Rate of Change of Frequency (df/dt) relays automatically trip predefined load blocks if the grid frequency drops rapidly below critical levels (e.g. 49.2 Hz).
- Islanding schemes are implemented for major cities (e.g., Mumbai, Delhi) to isolate local generation and load from the main grid during disturbances, ensuring localized survival.
- Black Start procedures specify steps for restoring grid sections using self-starting generators (hydro, gas turbines) to charge EHV transmission paths sequentially.

Solar Irradiance and the Diurnal Cycle I

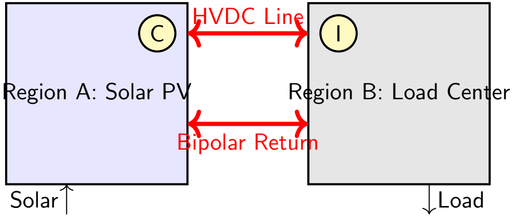
Understanding the solar resource: The Solar Constant $G_{sc} = 1.361$ kW/m^2. Due to Earth's rotation, solar power is locally diurnal. Transnational grids leverage longitude differences to transform local intermittent solar power into global continuous base-load power.

Solar Irradiance and the Diurnal Cycle II

Key Points

- The Earth rotates at 15° per hour, creating continuous sunset and sunrise transitions across time zones.
- Global solar potential is governed by $P_{\text{solar}} = A \cdot \eta \cdot G_{sc} \cos(\theta)$, where θ is the solar zenith angle, rendering local production highly variable.
- By interconnecting regions spanning 360° longitude, the net solar power injection remains relatively constant: $P_{\text{net}}(t) = \sum_i P_i(t) \approx \text{constant}$.
- Mitigates the need for massive utility-scale battery energy storage systems (BESS) by using the grid itself as a virtual balancer.

HVDC Supergrid Conceptual Topology I



HVDC Supergrid Conceptual Topology II

Key Points

- Schematic of a transnational HVDC link transferring solar power from a sunlit Region A to a peak-demand/dark Region B.
- Utilizes Voltage Source Converters (VSC) at both ends to control active and reactive power independently (P-Q control).
- HVDC is preferred over HVAC for long distances due to the absence of capacitive charging current: $I_c = 2\pi fCV = 0$ in DC.
- Bipolar configuration ensures redundancy: if one pole fails, the system can operate at 50% capacity using ground/metallic return.

High-Voltage Direct Current (HVDC) Transmission Physics I

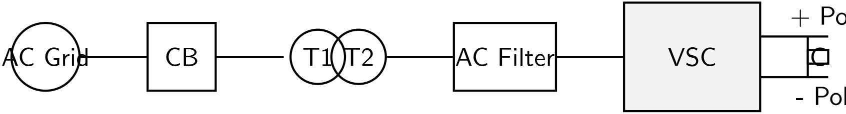
For long-distance transmission ($L > L_{\text{breakeven}} \approx 600 - 800$ km overhead, 50 km submarine), HVDC is technically and economically superior. Losses are dominated by conductor resistance: $P_{\text{loss}} = I^2 R = \left(\frac{P}{V}\right)^2 R$.

High-Voltage Direct Current (HVDC) Transmission Physics II

Key Points

- Increasing transmission voltage (e.g., to ± 800 kV or ± 1100 kV UHVDC) minimizes currents and reduces losses exponentially.
- Skin effect is absent in DC ($f = 0$), meaning the entire cross-sectional area of the conductor is utilized, reducing effective resistance \$R $= \rho \frac{l}{A}$.
- No reactive power transmission or reactive line drop: $Q = 0$, eliminating stability issues associated with phase angle limits (steady-state stability limit: $P = \frac{V_1 V_2}{X} \sin \delta$).
- VSC-HVDC enables black-start capability and dynamic voltage support for weak grids at the receiving end.

VSC-HVDC Converter Station Single-Line Diagram I



VSC-HVDC Converter Station Single-Line Diagram II

Key Points

- Single-line schematic of a Voltage Source Converter (VSC) station acting as an interface between local AC grids and the HVDC backbone.
- AC Grid connects via Circuit Breaker (CB) and Interface Transformer (T1/T2) matching converter voltage levels.
- AC Harmonic Filters suppress high-frequency switching harmonics generated by high-frequency Pulse Width Modulation (PWM) of IGBTs.
- DC capacitor (C) acts as a voltage source, smoothing voltage ripples and providing energy storage for transient power variations.

As synchronous machines are replaced by inverter-based resources (IBRs) like solar PV and HVDC links, grid inertia (H) drops: $H_{\text{sys}} = \frac{\sum S_i H_i}{\sum S_i}$. This increases the Rate of Change of Frequency (RoCoF) following contingencies.

[allowframebreaks]OSOWOG Phase-wise Global Roadmap The deployment of One Sun, One World, One Grid is divided into three distinct operational phases spanning local, regional, and global interconnections.

Key Points

- Phase 1: Middle East-South Asia-Southeast Asia (MESASEA) interconnection. Interconnecting Indian grid with Middle East (via undersea cables in the Arabian Sea) and Southeast Asia.
- Phase 2: Integration of African power pools. Linking solar-rich North African regions (e.g., Sahara Solar projects) with Southern Europe and sub-Saharan Africa.
- Phase 3: Final Global Interconnection. Connecting pan-Eurasian, African, and American grids to complete the continuous global green energy loop.
- Key projects include the India-UAE link, EuroAsia Interconnector (Greece-Cyprus-Israel), and Xlinks Morocco-UK Power Project (3,800 km HVDC submarine cable).

Economic Load Dispatch & Optimization I

LDCs optimize generation scheduling to meet demand at minimum cost while ensuring system security.

Economic Load Dispatch & Optimization II

Key Points

- Economic Load Dispatch (ELD) minimizes the total fuel cost: $C_{total} = \sum_{i=1}^{N} C_i(P_i)$.
- Incremental Cost criterion (without losses): $\frac{dC_i}{dP_i} = \lambda$ for all active generators.
- Transmission Loss inclusion: $L_i \frac{dC_i}{dP_i} = \lambda$, where $L_i = \frac{1}{1 - \frac{\partial P_L}{\partial P_i}}$ is the penalty factor.
- Unit Commitment: Solves a mixed-integer non-linear optimization problem to schedule generator ON/OFF states over 24 hours.

Grid Discipline & Commercial Regulations I

Commercial mechanisms enforce grid discipline to prevent frequency instability and line overloading.

Grid Discipline & Commercial Regulations II

Key Points

- Availability Based Tariff (ABT): Implements a capacity charge, energy charge, and frequency-linked deviation charge.
- Deviation Settlement Mechanism (DSM): Charges or rewards utilities based on scheduled vs. actual generation/drawl.
- Grid Code Compliance: Mandates that all grid users (generators, transmission licensees, and distribution licensees) follow LDC orders.
- Restoration Coordination: Coordinates black-start units (e.g., hydro stations) to energize transmission paths after grid collapses.

The Trade-off in Transmission Voltage I

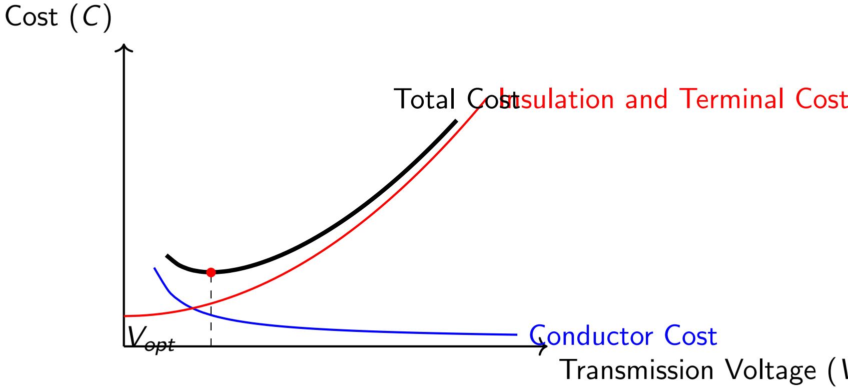
Selecting the optimal transmission voltage is a balance between conductor cost, insulation cost, and power loss. As voltage increases, current decreases for the same power transfer, reducing conductor cross-section and losses, but insulation, tower, and terminal equipment costs increase.

The Trade-off in Transmission Voltage II

Key Points

- Line Losses: For a active power P at power factor $\cos\phi$, line current is $I = \frac{P}{\sqrt{3}V\cos\phi}$. Power loss $P_{\text{loss}} = 3I^2R \propto \frac{1}{V^2}$.
- Conductor Cost: Since $P_{\text{loss}} \propto \frac{1}{V^2}$, required conductor cross-sectional area A decreases for a fixed loss, reducing volume and weight of copper/aluminum.
- Equipment Cost: Switchgear, transformers, lightning arrestors, and tower dimensions/insulation string lengths scale nonlinearly with system voltage V.

Cost Curves and the Economic Voltage I



Cost Curves and the Economic Voltage II

Key Points

- Optimal Voltage (V_{opt}): The voltage at which the sum of the capital costs of conductors, support towers, insulators, and terminal equipment is minimized.
- Hyperbolic Curve: Conductor cost decreases hyperbolically with voltage due to lower current carrying requirements.
- Parabolic/Exponential Curve: Insulator and terminal equipment costs increase sharply with voltage, especially above 220 kV.

In practice, initial estimates for the transmission line voltage are calculated using standard empirical formulas that factor in both line length and power to be transmitted.

Empirical Formulations for Economical Voltage II

Key Points

- Alfred Still's Formula (Three-phase system): $V = 5.5\sqrt{\frac{d}{1.6} + \frac{P}{150}}$ where V is line voltage in kV, d is distance in km, and P is maximum power per phase in kW.
- Modern IEEE/EPRI Standard Empirical Equation: $V = 5.5\sqrt{\frac{L}{1.61} + \frac{P_{total}}{100}}$ where L is line length in km and P_{total} is total three-phase power in kW.
- Limitations: Empirical formulas serve as a starting point. Detailed project designs require load flow studies, stability analyses, and local grid code compliance checks.

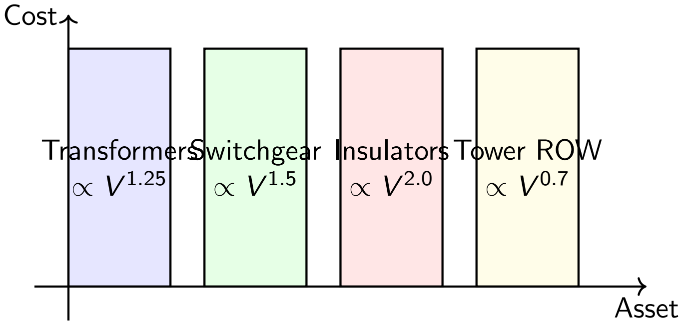
While economic analysis yields a theoretical optimum, physical limitations and operating security play a critical role in selecting the final system voltage.

Technical Constraints Beyond Economy II

Key Points

- Corona Loss: At high voltages (typically > 220 kV), the electric field intensity exceeds the dielectric strength of air, causing corona discharge: $P_c \propto (V - V_d)^2$. This necessitates bundled conductors.
- Voltage Regulation: Line impedance causes voltage drop: $\Delta V \approx I(R\cos\phi + X\sin\phi)$. Higher voltage reduces current I and minimizes percent voltage drop over long distances.
- System Stability: Steady-state power limit is $P_{max} = \frac{V_S V_R}{X}$. Higher voltage reduces system reactance X (relatively) or allows larger power transfers without losing synchronism.

Cost Breakdown of Substation Equipment I



Cost Breakdown of Substation Equipment II

Key Points

- Substation Transformers: Cost escalates with BIL (Basic Impulse Insulation Level) which is directly proportional to voltage.
- Circuit Breakers and Switchgear: Interruption rating and clearances dictate physical size and gas volume, driving up costs.
- Right-of-Way (ROW): Higher voltage requires wider clearances and taller towers to prevent ground flashovers, increasing land acquisition costs.

Kelvin's Law states that the most economical area of conductor is that for which the annual interest and depreciation on the conductor equal the annual cost of energy wasted as I^2R loss.

Kelvin's Law and Its Limitations II

Key Points

- Annual Capital Cost: $C_1 = a + bA$, where a is constant (installation, structures) and b is proportional to conductor cross-sectional area A.
- Annual Wasted Energy Cost: $C_2 = \frac{c}{A}$, where c depends on resistivity, load current, load factor, and unit cost of energy.
- Mathematical Optimum: $bA = \frac{c}{A} \implies A = \sqrt{\frac{c}{b}}$.
- Limitations in Practice: Kelvin's Law does not account for corona loss, mechanical strength, safe current density, voltage drop constraints, and interest rate fluctuations.

Summary of Decision Framework I

The selection of transmission voltage follows an iterative process coordinating grid expansion plans, financial models, and system stability.

Summary of Decision Framework II

Key Points

- Step 1: Estimate power requirement (P) and transmission distance (d).
- Step 2: Apply empirical formulas (Still, IEEE) to find initial trial voltages.
- Step 3: Conduct load flow analysis to evaluate losses and voltage profile.
- Step 4: Execute economic life-cycle cost analysis comparing capital expenditure (CAPEX) and operational expenditure (OPEX) over 30-40 years.

The Trade-offs in Conductor Sizing I

Determining the optimal conductor size is a critical engineering task that balances initial capital expenditure against long-term operational losses.

The Trade-offs in Conductor Sizing II

Key Points

- Small conductor size reduces initial capital cost of copper/aluminum and line support structures.
- However, a small conductor has high resistance ($R = \rho L/a$), leading to high I^2R losses and large voltage drops.
- Large conductor size reduces line losses and improves voltage regulation but increases initial capital expenditure significantly.
- Thus, an economic compromise is needed to find the optimum conductor cross-sectional area that minimizes total annual cost.

Annual Cost Components of a Transmission Line I

The total annual cost of a transmission line can be split into two main parts: annual capital charges and the annual cost of energy wasted.

Annual Cost Components of a Transmission Line II

Key Points

- 1. Annual Capital Charges (C_1): Interest, depreciation, maintenance of conductors, supports, and installation. Expressed as $C_1 = P_1 + P_2 \cdot a$.
- P_1 is the constant part independent of conductor size (e.g., cost of structures, right of way, basic erection).
- $P_2 \cdot a$ is the variable part proportional to the conductor cross-sectional area a.
- 2. Annual Cost of Wasted Energy (C_2): Cost of energy lost as heat (I^2R) over the year. Expressed as $C_2 = P_3/a$, where P_3 is a constant proportional to resistivity, load factor, and energy rate.

Derivation of Kelvin's Law I

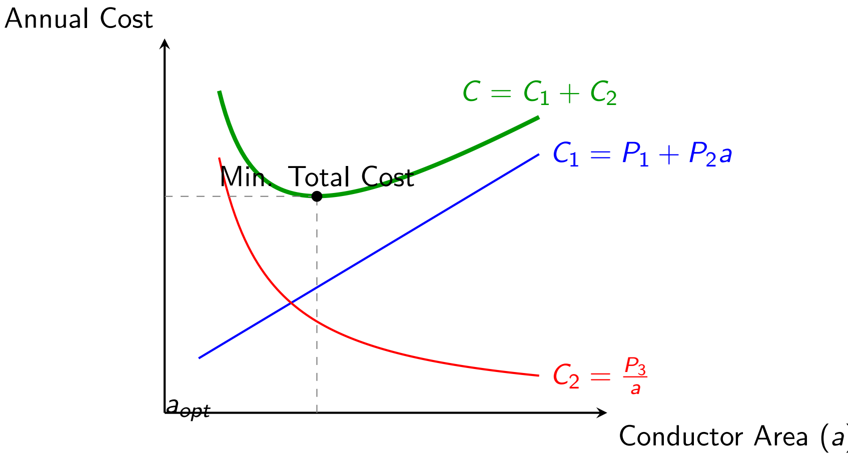
Kelvin's Law states that the most economical area of conductor is that for which the annual cost of interest and depreciation on the variable capital cost of the conductor is equal to the annual cost of energy lost.

Derivation of Kelvin's Law II

Key Points

- Total Annual Cost: $C = C_1 + C_2 = (P_1 + P_2 \cdot a) + \frac{P_3}{a}$
- To find the minimum total cost, differentiate C with respect to area a and set to zero: $\frac{dC}{da} = 0$.
- $\frac{dC}{da} = P_2 - \frac{P_3}{a^2} = 0 \implies P_2 = \frac{P_3}{a^2} \implies P_2 \cdot a = \frac{P_3}{a}$.
- This yields the optimal cross-sectional area: $a_{opt} = \sqrt{\frac{P_3}{P_2}}$.
- Conclusion: Variable portion of annual capital cost $(P_2 \cdot a)$ = Annual cost of energy wasted (P_3/a).

Graphical Representation of Kelvin's Law I



Graphical Representation of Kelvin's Law II

Key Points

- The straight line represents the capital cost $C_1 = P_1 + P_2 a$ showing a linear relationship with area.
- The hyperbolic curve represents the annual energy loss cost $C_2 = P_3/a$ showing a decreasing trend as area increases.
- The total cost curve C has a minimum point directly above the intersection of the variable capital cost line and the loss cost curve.
- The optimum conductor area a_{opt} corresponds to this minimum total cost point.

Practical Limitations of Kelvin's Law I

Although mathematically elegant, Kelvin's law is difficult to apply directly in practice due to several physical and economic uncertainties.

Practical Limitations of Kelvin's Law II

Key Points

- Difficulty in estimating load factor and load curve shape over the 20-30 year lifespan of the transmission line.
- Fluctuations in interest rates, depreciation rates, and the cost of generating/purchasing energy over time.
- The assumption that capital cost is strictly linear with conductor area a is often an oversimplification for complex cable/tower systems.
- Physical constraints like current carrying capacity (thermal limit), voltage drop, and corona loss often dictate a larger size than a_{opt}.

Technical Design Constraints I

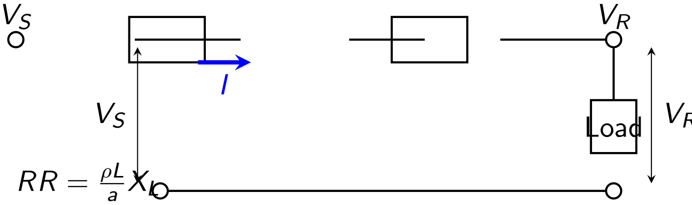
Economic optimization must be subordinate to technical safety and operational guidelines of modern grids.

Technical Design Constraints II

Key Points

- Safe Current Carrying Capacity: Conductor temperature must not exceed limits (typically 75°C to 90°C for ACSR) to prevent excessive sag.
- Voltage Drop Limits: The line regulation must remain within permissible limits (typically ±5% to ±10% of nominal voltage).
- Corona Loss and Interference: At extra high voltages (EHV), corona discharge dictates minimum conductor diameter, regardless of Kelvin's law.
- Mechanical Strength: Conductor must withstand wind, ice loading, and tensile stress under worst-case weather conditions.

Transmission Line Loss Representation I



Transmission Line Loss Representation II

Key Points

- Electrical model of a short transmission line feeder showing series impedance parameters.
- Line resistance $R = \rho L/a$ is inversely proportional to conductor area a, representing the physical source of I^2R loss.
- For three-phase systems, total active power loss is $P_{loss} = 3I^2R = 3I^2\left(\frac{\rho L}{a}\right)$.
- This basic loss mechanism forms the operational cost foundation for Kelvin's Law analysis.

Technical Motivation: EHV Power Transfer Physics I

Power transmission capability increases quadratically with voltage: $P = \frac{V_S V_R}{X} \sin \delta$.

Technical Motivation: EHV Power Transfer Physics II

Key Points

- Reducing Line Current: For a given power level P, current $I = \frac{P}{\sqrt{3}V\cos\phi}$ is inversely proportional to transmission voltage V.
- Loss Reduction: Line losses are proportional to $I^2R = \left(\frac{P}{\sqrt{3}V\cos\phi}\right)^2 R$. Thus, increasing voltage from 220 kV to 400 kV reduces losses by over 70%.
- Voltage Regulation: Percent voltage drop is given by $\frac{I(R\cos\phi + X\sin\phi)}{V} \times 100\%$. Higher voltages reduce current and improve voltage profiles.

Diagram: Power-Angle Relationship in EHV Transmission I

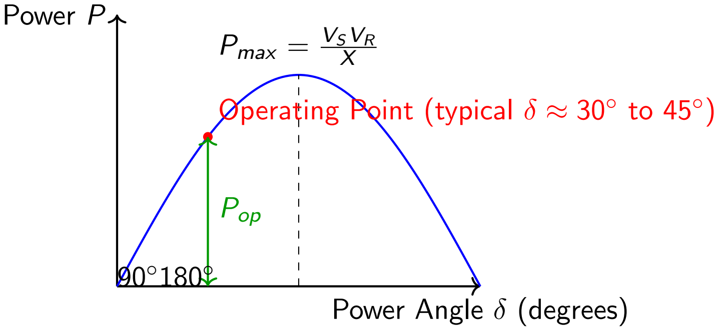


Diagram: Power-Angle Relationship in EHV Transmission II

Key Points

- The power angle δ is the phase difference between sending-end (V_S) and receiving-end (V_R) voltages.
- To maintain transient stability during network faults, EHV lines are designed to operate well below the limit $\delta = 90^\circ$.
- Increasing transmission voltage directly scales up the stability limit peak, allowing higher loadability.

Key Technical and Economic Advantages I

EHV AC transmission systems provide substantial savings in materials, infrastructure, and right-of-way footprint.

Key Technical and Economic Advantages II

Key Points

- Reduction in Conductor Size: Due to decreased line current, the copper/aluminum weight required per unit of power decreases.
- Increased Transmission Capacity: Transmission capacity increases roughly as the square of the voltage ($P \propto V^2$).
- Reduction in Line Losses: Line losses drop as $\frac{1}{V^2}$, raising transmission efficiency up to 96% to 98%.
- Optimized Land Use: A single 765 kV circuit replaces multiple lower-voltage circuits, reducing total Right-of-Way (ROW) width.

Technical Limitations: Corona Loss and Interference I

The high surface electric field gradient on EHV conductors initiates Corona, causing power loss and environmental issues.

Technical Limitations: Corona Loss and Interference II

Key Points

- Visual & Audible Phenomena: Corona discharge occurs when the local electric field gradient exceeds the breakdown strength of air (30 kV/cm peak under dry conditions).
- Power Loss Formula: Peek's formula shows Corona loss is proportional to $(f + 25)(V - V_d)^2\sqrt{\frac{r}{D}}$, where V_d is the disruptive critical voltage.
- Electromagnetic Interference: Corona causes Radio Interference (RI), TV Interference (TVI), and high-frequency audible noise (hissing/crackling).
- Mitigation: Bundled conductors are mandatory to increase the effective radius, lowering the surface field gradient below the corona threshold.

Diagram: Bundle Conductor Electrostatic Fields I

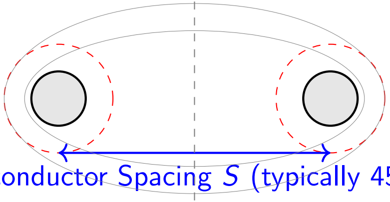


Diagram: Bundle Conductor Electrostatic Fields II

Key Points

- Bundling configuration (e.g. duplex, triplex, quad) increases the self Geometric Mean Radius (GMR).
- This configuration splits the total line current among sub-conductors, significantly reducing peak surface voltage gradients.
- Bundling also lowers line inductance and increases line charging capacitance, improving overall line impedance characteristics.

System Limitations: Ferranti Effect and Charging Current I

EHV AC lines exhibit high capacitive charging current ($I_c = \omega CV$), which leads to severe voltage control issues.

System Limitations: Ferranti Effect and Charging Current II

Key Points

- Ferranti Effect: On long, lightly loaded or open-circuited lines, charging current flowing through the series inductance causes the receiving-end voltage V_R to exceed sending-end voltage V_S.
- Reactive Power Excess: Charging MVAR generated by the line capacitance ($Q_C = 3\omega CV^2$) must be absorbed to prevent overvoltages.
- Compensation Solution: Shunt reactors must be installed at terminals and intermediate substations to offset the capacitive MVAR.
- Switching Surges: Switching operations at EHV trigger transient overvoltages (2.0 to 2.5 p.u.) that dictate insulator string length and clearances.

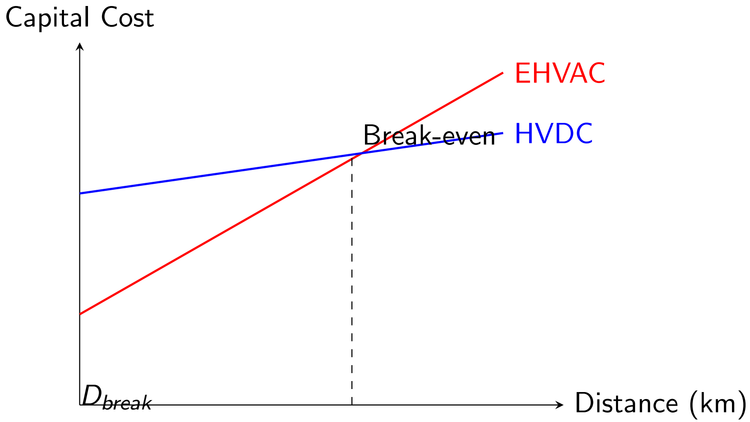
The mechanical, structural, and capital equipment requirements for EHV AC grids present significant hurdles.

Economic and Operational Limitations of EHV AC II

Key Points

- Substation Equipment Costs: EHV switchgear, SF6 gas-insulated circuit breakers, instrument transformers, and surge arresters are highly complex and expensive.
- Structural Support Requirements: Tower heights and structural strengths must be massive to maintain safe ground clearances and support heavy bundle conductors.
- Right-of-Way (ROW) Constraints: EHV corridors demand wide zones of land, e.g., 35-40m for 400 kV and 70-85m for 765 kV, leading to severe land acquisition and environmental issues.
- Grid Stability Limits: Thermal limits are rarely reached; instead, steady-state, transient, and voltage stability limits constrain maximum operating power.

Economic Factors & Break-Even Distance I



Economic Factors & Break-Even Distance II

Key Points

- Capital cost of EHVAC lines increases linearly with length at a steeper rate than HVDC due to three-phase configuration and reactive compensation costs.
- HVDC terminal converter stations represent a massive initial capital expenditure, making HVDC costlier than EHVAC for short distances.
- The break-even distance is the crossover point where the accumulated line savings of HVDC equal the higher terminal station costs.
- For typical overhead transmission lines, this break-even distance ranges between 600 km and 800 km.

Stability & Power Transfer Capacity Limits I

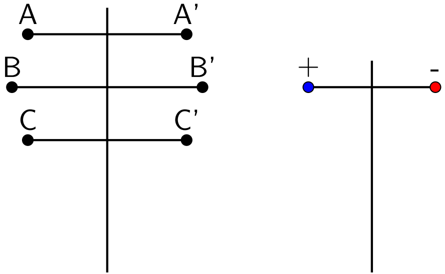
EHVAC Power Transfer Limit: $P = \frac{V_s V_r}{X} \sin \delta$

Stability & Power Transfer Capacity Limits II

Key Points

- EHVAC line reactance X increases with distance, reducing the maximum power transfer and threatening rotor angle stability.
- To maintain transient stability during network faults, the operational load angle δ must be restricted, limiting the line loadability.
- HVDC power flow is fully controlled by converters: $P = \frac{V_{d1} - V_{d2}}{R_d}$, rendering it independent of transmission distance stability.
- Long EHVAC lines require series capacitors to reduce virtual line impedance, introducing concerns like sub-synchronous resonance (SSR).

Right-of-Way & Tower Footprint Comparison I



Right-of-Way & Tower Footprint Comparison II

Key Points

- A double-circuit EHVAC line requires six conductor bundles and two shield wires, necessitating wide cross-arms and massive towers.
- A Bipolar HVDC system requires only two conductor bundles (positive and negative poles), significantly reducing tower width and weight.
- The Right-of-Way (ROW) required for HVDC is much narrower than EHVAC for equivalent power ratings, reducing land acquisition costs.
- Environmental impacts, visual profile, corona losses, and electromagnetic field effects are substantially lower in Bipolar HVDC designs.

EHVAC Continuous Charging Current: $I_c = \omega CV$

Transmission Losses & Charging Current Constraints II

Key Points

- EHVAC lines continuously draw charging current due to high line-to-earth capacitance, increasing ohmic losses (I^2R) and voltage rise at no-load.
- Underground and submarine AC cables have high capacitance; their charging current consumes the entire current rating within 40–80 km.
- HVDC lines carry direct current under steady state, resulting in zero capacitive charging current ($I_c = 0$), removing length limits for cables.
- HVDC lacks skin effect, leading to lower conductor resistance ($R_{dc} < R_{ac}$) and reduced transmission losses compared to EHVAC lines.

Grid Interconnection: Synchronous vs. Asynchronous I

HVDC Asynchronous Power Flow: $P = \frac{V_{d1}\cos\alpha - V_{d2}\cos\gamma}{R_d}$

Grid Interconnection: Synchronous vs. Asynchronous II

Key Points

- EHVAC interconnections require synchronous operation; frequency deviations or major faults in one grid immediately impact the other.
- HVDC provides asynchronous interconnection, serving as a buffer that prevents cascading outages and stabilizes grid frequency.
- HVDC can interconnect systems operating at different nominal frequencies (e.g., 50 Hz to 60 Hz) or with arbitrary phase-angle differences.
- Rapid control response of HVDC converter valves allows active damping of power swings and dynamic frequency control during contingencies.

Short-Circuit Levels & Reactive Power Demands I

LCC Static Reactive Power Requirement: $Q_{req} \approx 0.5P_{dc}$ to $0.6P_{dc}$

Short-Circuit Levels & Reactive Power Demands II

Key Points

- EHVAC transmission increases fault currents (short-circuit MVA) at terminal buses, potentially requiring upgrading of circuit breakers.
- HVDC links do not increase the short-circuit level of the connected AC systems as converter controls limit fault currents.
- Line-Commutated Converter (LCC) stations consume substantial reactive power, necessitating massive capacitor banks and AC filters.
- Voltage Source Converter (VSC) HVDC systems control active and reactive power independently, providing voltage support to weak grids.

Feasibility & Selection Matrix I

Choice Criteria: $L > L_{break-even} \implies$ HVDC

Feasibility & Selection Matrix II

Key Points

- Use HVDC for long-distance bulk power transmission (overhead lines > 600–800 km) and subsea cables (> 50 km).
- Select HVDC when connecting asynchronous networks, limiting fault currents, or requiring highly controllable power paths.
- Choose EHVAC for shorter distances where intermediate tapping is needed, leveraging lower substation costs and simpler protection schemes.
- Hybrid networks utilize EHVAC for local distribution/regional transmission and HVDC as overlay corridors for bulk power transfer.

Introduction to the HVDC Single Line Diagram (SLD) I

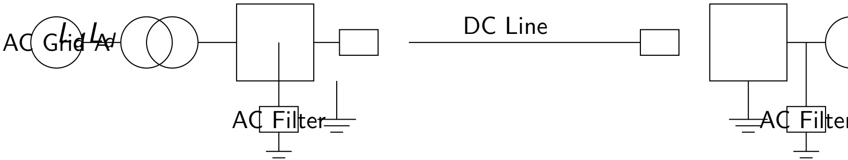
The Single Line Diagram (SLD) of an HVDC transmission system outlines the path of electrical energy from the sending-end AC grid, through transformation, conversion, transmission, inversion, and final insertion back into the receiving-end AC grid.

Introduction to the HVDC Single Line Diagram (SLD) II

Key Points

- Illustrates the electrical boundary interfaces between the AC switchyard, converter station, and DC transmission link.
- Crucial for analyzing power flow control, reactive power demands, harmonic performance, and protection zones.
- Standard topologies represented include monopolar, bipolar, and back-to-back configurations.
- Key functional blocks must manage high-power rectification ($AC \rightarrow DC$) and inversion ($DC \rightarrow AC$) using power electronics.

Monopolar HVDC Link Schematic I



Monopolar HVDC Link Schematic II

Key Points

- Monopolar HVDC single line diagram configuration with Earth/Sea return path.
- AC Filters located on converter AC buses to block harmonic flow into Grid A and Grid B.
- Smoothing reactors (L_d) installed at each terminal in series with the high voltage pole.
- Converter transformers isolate the AC grids from the DC offset voltage stress.

Converter Transformers in HVDC Systems I

Converter transformers interface the standard AC grid with the thyristor or VSC valve halls. They must operate under unique electrical conditions, handling both AC sinusoidal voltages and high DC bias offset potentials.

Converter Transformers in HVDC Systems II

Key Points

- Provides the necessary galvanic isolation between the AC system and the DC converter valve bridges.
- Standard configurations utilize one Star-Star ($Y - Y$) and one Star-Delta ($Y - \Delta$) transformer to produce a 30° phase shift.
- The 30° phase shift eliminates the 5th and 7th characteristic harmonics on the AC side and 6th harmonic on the DC side.
- Winding insulation must withstand combined AC voltage stresses and high DC bias voltages (V_{dc} stresses).
- Equipped with On-Load Tap Changers (OLTC) with wide tap ranges to regulate voltage variations and control firing angle range.

Converter Bridges: 6-Pulse and 12-Pulse Topologies I

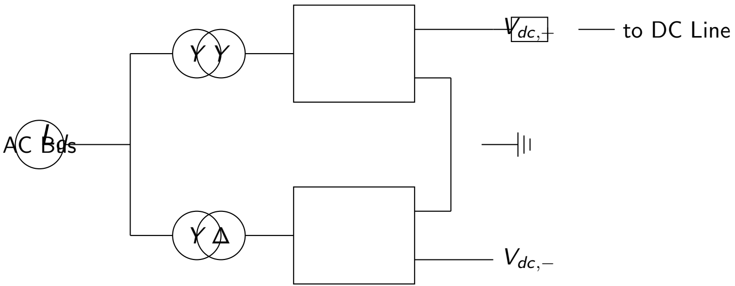
The converter bridge is the active block that regulates the power conversion. Modern systems favor 12-pulse configurations to reduce harmonic filtering requirements, while using Line Commutated Converters (LCC) or Voltage Source Converters (VSC).

Converter Bridges: 6-Pulse and 12-Pulse Topologies II

Key Points

- The basic unit is the Graetz bridge (6-pulse converter) consisting of six thyristor or IGBT valve units.
- A 6-pulse converter generates characteristic AC harmonics of order $h = 6k \pm 1$ (5^{th}, 7^{th}, 11^{th}, 13^{th}, etc.).
- Two 6-pulse bridges connected in series, fed by $Y - Y$ and $Y - \Delta$ transformers respectively, form the 12-pulse converter.
- The 12-pulse converter cancels out harmonics of order $h = 6(2n + 1) \pm 1$ (5^{th}, 7^{th}, 17^{th}, 19^{th}), drastically reducing filter footprint.
- DC voltage equation of a 12-pulse converter: $V_d = 2 \times V_{d0} \cos\alpha - \frac{6}{\pi} X_c I_d$, where $V_{d0} = \frac{3\sqrt{2}}{\pi} V_{LL}$.

12-Pulse Converter Configuration Diagram I



12-Pulse Converter Configuration Diagram II

Key Points

- 12-pulse converter configuration combining Star-Star and Star-Delta transformer secondary windings.
- Bridges connected in series on the DC output side to double the DC voltage level ($V_{dc,+} - V_{dc,-}$).
- Neutral point grounded to stabilize voltages and define the reference potential.
- Smoothing reactor (L_d) placed at the high-voltage outlet to suppress ripple before the line interface.

AC/DC Filters and Reactive Power Compensation I

HVDC converter stations consume significant reactive power and inject harmonics back into both AC and DC networks. High-performance filtering networks are vital to meet grid compliance codes.

AC/DC Filters and Reactive Power Compensation II

Key Points

- AC Filters: Eliminate characteristic AC harmonics (11^{th}, 13^{th}, 23^{rd}, 25^{th} in 12-pulse) and act as shunt capacitors at fundamental frequency.
- Reactive Power consumption of LCC converters is around $50 - 60\%$ of the transmitted active power P.
- The reactive power balance equation is given by $Q = P \tan \phi$, where the displacement power factor angle ϕ is regulated by the firing angle α.
- DC Filters: Connected across the DC pole and earth to bypass high-frequency harmonics, avoiding interference with parallel telecommunication lines.
- Smoothing Reactors (L_d): Limit transient fault currents (dI/dt), prevent continuous conduction mode breakdown, and reduce DC current ripple.

Transmission Modes, Grounding, and Electrode Lines I

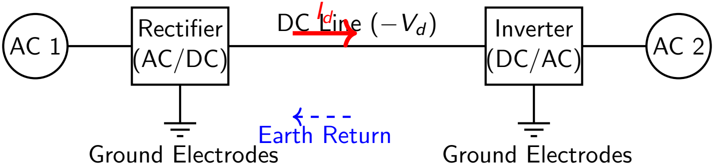
The choice of the DC transmission line topology (monopolar, bipolar, or homopolar) defines the terminal grounding requirements, redundancy levels, and overall system reliability.

Transmission Modes, Grounding, and Electrode Lines II

Key Points

- Monopolar Link: Single conductor (typically negative polarity) with ground or metallic return. Cost-effective but causes soil/sea electrolysis and corrosion.
- Bipolar Link: Two conductors of opposite polarity ($+$ and $-$). Under balanced conditions, current in the neutral/ground path is zero, eliminating corrosion concerns.
- Bipolar Redundancy: If one pole fails, the system can temporarily operate as a monopolar system using the ground return at 50% rated power.
- Homopolar Link: Two or more conductors of the same polarity (typically negative) with ground return; rarely used due to continuous return currents.

Monopolar HVDC Link Configuration I

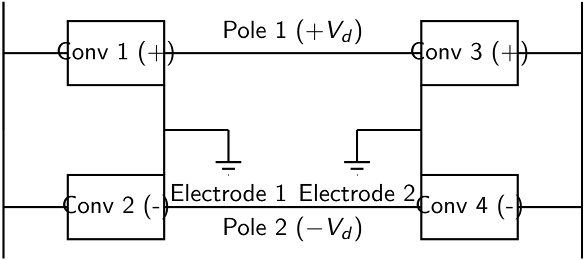


Monopolar HVDC Link Configuration II

Key Points

- Uses a single conductor, typically operated at negative polarity ($-V_d$) relative to the ground to exploit lower corona discharge losses.
- Employs ground or sea electrodes to provide the continuous return path for the direct current flow.
- In environmentally sensitive regions where ground return current is prohibited due to electrochemical corrosion of pipes, a metallic return conductor is installed.
- Typically selected for low-power submarine cable installations or as the first operational stage of a long-term bipolar project.

Bipolar HVDC Link Configuration I



Bipolar HVDC Link Configuration II

Key Points

- Consists of two independent conductors: one positive pole ($+V_d$) and one negative pole ($-V_d$) with respect to ground.
- Under balanced conditions, the currents in the two poles are equal ($I_+ = I_-$), resulting in zero net ground return current.
- Provides high system reliability: if a fault occurs on one pole, the system automatically transitions to monopolar mode using ground return, maintaining 50% to 80% transmission capability.
- The standard configuration for bulk power, long-distance overhead HVDC transmission lines globally.

A configuration characterized by two or more conductors of the same polarity (typically negative) operating with a common ground return path.

Homopolar HVDC Link II

Key Points

- All line conductors are operated with negative polarity relative to ground, reducing overall corona loss and radio frequency interference.
- Requires a continuous ground return path designed to carry the sum of all conductor currents ($I_g = N \times I_d$, where N is the number of conductors).
- If a fault occurs on one conductor, the remaining healthy conductors can continue to operate and carry the power load.
- Due to severe issues with ground current electrochemistry, metallic corrosion, and magnetic interference, it is rarely deployed in modern installations.

Back-to-Back (B2B) HVDC Systems I

An HVDC system where both converter stations (rectifier and inverter) are situated in the exact same substation facility, with no transmission line.

Back-to-Back (B2B) HVDC Systems II

Key Points

- The DC link is represented solely by a short, high-current DC busbar connecting the converter valves within the same building.
- Primarily used to interconnect two adjacent, asynchronous AC networks operating at different frequencies (e.g., 50 Hz to 60 Hz) or phase angles.
- Enables precise active power flow control ($P = V_d I_d$) between grids while blocking the propagation of transient AC faults and short-circuit currents.
- Ideal for stabilizing weak grid interconnections without requiring synchronous coupling.

Multi-terminal HVDC (MTDC) Networks I

Advanced HVDC configurations consisting of three or more converter stations connected to a unified DC transmission network.

Multi-terminal HVDC (MTDC) Networks II

Key Points

- Classified into Parallel MTDC (constant DC voltage, variable current) and Series MTDC (constant current, variable converter voltages). Parallel is preferred.
- Allows flexible bilateral or multilateral power exchange among multiple geographical areas and independent AC power grids.
- Requires coordinated active power sharing using DC voltage droop control: $I_j = K_j(V_{dc} - V_{dc,ref})$ to distribute load changes without high-speed communications.
- Key technology for integrating large-scale offshore wind hubs (e.g., North Sea Grid) directly to onshore transmission systems.

Comparative Analysis of HVDC Link Topologies I

Selection criteria based on technical, economic, and environmental performance indices.

Comparative Analysis of HVDC Link Topologies II

Key Points

- **Reliability**: Bipolar is superior due to independent dual-pole redundancy. Monopolar has no redundancy unless configured with a metallic return conductor.
- **Environmental Footprint**: Bipolar is highly preferred because it eliminates the physical and chemical impacts of continuous earth current return.
- **Capital Expenditure (CAPEX)**: Back-to-Back is the most cost-effective for asynchronous boundary coupling as it avoids high line development costs.
- **Corona Effects**: Homopolar systems experience lower corona losses compared to equivalent bipolar configurations due to negative pole operation.

Steady-State Converter and Link Equations I

Mathematical formulations governing the power transfer and voltage characteristics of HVDC links.

Steady-State Converter and Link Equations II

Key Points

- Rectifier average DC output voltage: $V_{dr} = \frac{3\sqrt{2}}{\pi} V_{LLr} \cos\alpha - \frac{3}{\pi} X_{cr} I_d$, where α is the firing delay angle and X_{cr} is the commutation reactance.
- Inverter average DC voltage: $V_{di} = \frac{3\sqrt{2}}{\pi} V_{LLi} \cos\gamma + \frac{3}{\pi} X_{ci} I_d$, where γ is the extinction angle.
- DC line current flow: $I_d = \frac{V_{dr} - V_{di}}{R_d}$, where R_d is the total resistance of the DC link conductors.
- Active power delivered to the receiving terminal: $P_{dc} = V_{di} I_d$, showing that direct current operation eliminates reactive line losses ($Q_{line} = 0$).

Introduction to HVDC Transmission I

High Voltage Direct Current (HVDC) transmission is a proven technology used for transmitting bulk electricity over long distances or interconnecting asynchronous power grids. Unlike standard HVAC systems where voltage and current alternate sinusodially, i.e., $V(t) = V_m \sin(\omega t + \phi)$, HVDC operates at a constant voltage V_d and current I_d, which eliminates reactive power losses and line-charging constraints.

Introduction to HVDC Transmission II

Key Points

- AC power is generated, stepped up, and converted to DC at a rectifier station for transmission.
- At the receiving end, an inverter station converts the DC back to AC to feed the local AC grid.
- Underground and submarine AC cables are severely limited by continuous capacitive charging current $I_c = \omega CV$; HVDC cables suffer no such physical limits.
- HVDC offers asynchronous link capabilities, allowing the interconnection of grids with different nominal frequencies (50 Hz and 60 Hz).

Economic Merits of HVDC Transmission I

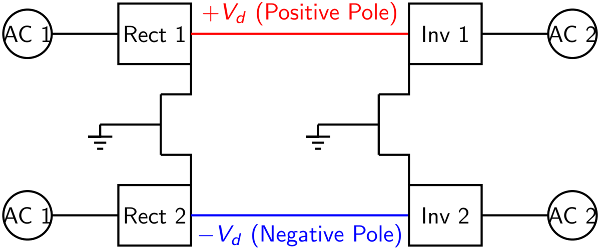
The choice between HVAC and HVDC involves balancing the high capital cost of converter stations against the lower cost of DC transmission lines. Over short distances, HVAC is cheaper, but beyond a critical break-even distance, HVDC becomes more economical. The break-even distance typically lies between 600-800 km for overhead lines and 50-80 km for submarine/underground cables.

Economic Merits of HVDC Transmission II

Key Points

- Fewer conductors required: HVDC needs only two conductors for a bipolar system or one for a monopolar system, compared to three conductors for three-phase HVAC.
- Reduced Right-of-Way (RoW): Narrower transmission corridors are needed due to fewer conductors, simplifying land acquisition and reducing environmental footprint.
- Lower line losses: Skin effect is absent, ensuring uniform current density. Additionally, there are no reactive power losses, keeping the line losses limited to $P_{loss} = 2I_d^2 R_{dc}$.
- Economic Break-Even Formula: The distance D at which the total cost of HVAC equals HVDC: $C_{station\,AC} + C_{line\,AC} \cdot D = C_{station\,DC} + C_{line\,DC} \cdot D$.

Bipolar HVDC Link Configuration I



Bipolar HVDC Link Configuration II

Key Points

- A bipolar link features two poles operating at equal but opposite voltages relative to ground ($+V_d$ and $-V_d$).
- Under normal balanced operation, the currents in both poles are equal, resulting in zero net current through the ground path.
- In the event of a line or converter fault on one pole, the remaining pole can continue operating using ground return, maintaining 50% power delivery.
- Bipolar configurations provide high system reliability, flexible power routing, and are the standard choice for bulk power long-distance overhead lines.

Technical Merits of HVDC Transmission I

HVDC transmission solves critical stability, synchronization, and control problems associated with HVAC systems. It provides fast control of active power flow, does not contribute to system short-circuit currents at the receiving end, and eliminates stability limits related to phase angle difference ($P = \frac{V_1 V_2}{X} \sin \delta$).

Technical Merits of HVDC Transmission II

Key Points

- No stability limit: The power transfer capability is determined solely by the thermal limit of conductors, as there is no system phase angle stability restriction.
- Asynchronous interconnections: Enables power transfer between systems with different frequency control philosophies, avoiding propagation of grid instabilities.
- Fast power modulation: Thyristor firing angles can be adjusted within milliseconds to dynamically modulate power ($P_d = V_d I_d$) and damp power oscillations in the AC grid.
- No skin effect: Current density is uniform across the conductor, allowing more efficient use of cross-sectional area compared to AC lines.

HVDC Converter Station Components I

(Valves);
ode[draw, rectangle, right of=conv, node distance=2.5cm, minimum width=1.2cm, minimum height=0.8cm, align=center] (reactor) Smoothing
Reactor;
ode[right of=reactor, node distance=2.2cm] (dc) DC Line;
[-¿] (ac) – (filter); [-¿] (filter) – (trans); [-¿] (trans) – (conv); [-¿] (conv) – (reactor); [-¿] (reactor) – (dc);

Key Points

- AC Filters: Filter harmonic currents $n = 6k \pm 1$ or $n = 12k \pm 1$ generated by the conversion process and supply reactive power support.
- Converter Transformer: Adjusts AC voltage levels and provides a phase shift (e.g., 30° star-delta) to eliminate lower-order harmonics.
- Converter (Valves): Performs conversion using line-commutated thyristor bridges or self-commutated IGBT valves.
- Smoothing Reactor: Reduces ripple in direct current, prevents current interruption, and limits rate of rise of fault currents.

Demerits and Technical Challenges of HVDC I

Despite its advantages, HVDC systems are not universally adopted due to high terminal costs, complexity, harmonic generation, and reactive power demands of Line Commutated Converters (LCCs). Tapping power from intermediate locations is also highly complex compared to simple AC transformers.

Demerits and Technical Challenges of HVDC II

Key Points

- High converter station costs: High cost of power electronic valves, control mechanisms, cooling systems, and specialized transformers.
- Harmonics and filter design: Converters behave as harmonic sources, requiring massive filtering arrays on both AC and DC sides to prevent interference.
- Reactive power demand: LCCs require reactive power equal to 50-60% of the active power transmitted, demanding shunt capacitors or static var compensators.
- DC circuit breaking: The lack of a natural current zero-crossing in DC makes extinguishing electric arcs in circuit breakers highly difficult, limiting multi-terminal DC development.

Industrial Applications of HVDC Systems I

HVDC transmission is applied selectively where HVAC is physically or economically impractical. Key industrial applications include long-distance bulk power transmission, submarine cable links, asynchronous grid interconnections, and stabilizing weak AC transmission networks.

Industrial Applications of HVDC Systems II

Key Points

- Long-distance bulk power transmission: Transmitting thousands of megawatts over distances ¿1000 km (e.g., Xiangjiaba-Shanghai UHVDC, 800 kV, 2071 km).
- Submarine cable links: Connecting grids separated by sea barriers, where cables exceed the critical length for AC (e.g., Baltic Cable, 250 km).
- Asynchronous interconnections: Coupling systems running at different frequencies or with independent dispatch systems (e.g., US Eastern-Western interconnections).
- Offshore wind integration: Transmitting bulk wind power from offshore platforms to mainland grids using Voltage Source Converter (VSC) technology.

Economic Comparison: Capital Costs vs. Distance I

Transmission cost comparison is dominated by initial terminal costs versus line costs per kilometer. The total cost is represented as:
$C_{total} = C_{terminal} + C_{line} \cdot d$

Economic Comparison: Capital Costs vs. Distance II

Key Points

- HVDC terminal stations (converters, filters, transformers) have significantly higher initial capital costs ($C_{terminal,DC} \gg C_{terminal,AC}$).
- HVDC transmission lines have lower cost per unit distance ($C_{line,DC} < C_{line,AC}$) due to two conductors instead of three, smaller towers, and reduced right-of-way (RoW).
- The break-even distance d_{break} is where $C_{total,AC} = C_{total,DC}$, typically ranging from 600 to 800 km for overhead lines, and 50 to 80 km for submarine/underground cables.
- For distances exceeding d_{break}, the savings in line costs and losses outweigh the high cost of HVDC terminal stations.

Right-of-Way (RoW) Comparison: HVDC vs. HVAC Towers I

$$W_{DC} < W_{AC}$$

$P_{DC} \approx P_{AC}$;

Key Points

- HVDC lines require a narrower Right-of-Way (RoW) compared to HVAC lines of the same power rating because they only require two poles (positive and negative) instead of three phases.
- Bipolar HVDC configuration has smaller tower structures and lesser visual impact, making environmental approvals easier.
- Right-of-way width savings can range from 30% to 50%, significantly lowering land acquisition costs in densely populated areas.

Technical Comparison: Power Flow and Stability I

HVDC power flow is fully controllable and independent of the phase angle difference between sending and receiving systems. Power flow is governed by: $P = \frac{V_d(V_{d1} - V_{d2})}{R_d}$

Technical Comparison: Power Flow and Stability II

Key Points

- HVAC transmission capacity is limited by transient stability and thermal limits, often governed by the power-angle relationship: $P = \frac{V_s V_r}{X} \sin \delta$.
- HVDC transmission does not have stability limits related to transmission distance, allowing lines to be operated up to their thermal limits.
- Asynchronous interconnection: HVDC can connect networks operating at different frequencies (e.g., 50 Hz and 60 Hz) or with different phase angles, preventing cascade failures.
- Fast modulation of DC power can damp power oscillations in the surrounding AC networks, improving overall transient stability.

Line Losses and Cable Limits I

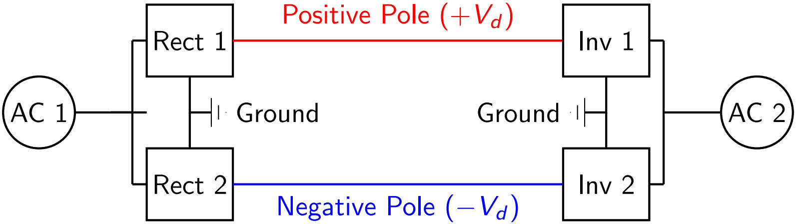
AC cable transmission is severely restricted by continuous charging current due to high shunt capacitance: $I_c = \omega CV$. DC cables do not suffer from continuous capacitive charging currents.

Line Losses and Cable Limits II

Key Points

- For HVAC underground or submarine cables, capacitive charging current I_c increases linearly with distance. Beyond the critical length (typically 40-80 km), the cable's current-carrying capacity is entirely consumed by charging current.
- HVDC cables have no continuous reactive charging current (only during energization/transients), making long-distance undersea power transmission technically feasible.
- Skin effect is absent in DC lines ($f = 0$ Hz), leading to uniform current distribution and lower conductor resistance compared to AC lines of the same cross-section.
- HVDC overhead lines have lower corona losses and radio interference under wet conditions than equivalent

Bipolar HVDC System Schematic I



Bipolar HVDC System Schematic II

Key Points

- A bipolar HVDC system features two independent poles of opposite polarity (+ and -) and a neutral return path.
- Under normal balanced operation, current flows through the positive pole and returns via the negative pole, yielding zero ground return current.
- During a fault on one pole, the system can operate in monopolar mode with ground return or metallic return, transmitting up to 50% of the total rated power.
- This configuration provides higher reliability and operational flexibility compared to standard HVAC circuits.

Environmental Impacts and Operational Stability I

Comparative environmental footprint and operational behaviors under abnormal grid conditions.

Environmental Impacts and Operational Stability II

Key Points

- Corona loss is lower in HVDC compared to HVAC: $P_{corona} \propto (f + 25)$, meaning at 0 Hz DC has substantially lower corona loss and acoustic noise.
- Reactive power compensation: HVAC lines require shunt reactors (for charging current limit) and series capacitors (for stability limit). HVDC lines require no reactive power support along the route.
- Short-circuit contribution: HVDC converters do not increase the short-circuit level of the connected AC systems, limiting the need to upgrade existing circuit breakers.
- DC ground return operation: In monopolar or unbalanced bipolar configurations, the earth can be used as a return conductor, which reduces losses but requires careful mitigation of galvanic corrosion on

Comparative Matrix: Summary of HVDC vs. HVAC I

A summary of key performance indicators for high voltage transmission systems.

Comparative Matrix: Summary of HVDC vs. HVAC II

Key Points

- Economic: HVDC is preferred for long distances ($>$ 800 km overhead, $>$ 50 km subsea/underground) due to lower line costs outweighing converter station costs.
- Control: HVDC provides rapid, bidirectional power flow control and asynchronous decoupling; HVAC power flow is dictated by grid impedance and phase angles.
- Charging Currents: HVAC is distance-limited in cables due to $I_c = \omega CV$; HVDC has no distance limit from charging currents.
- Grid Faults: HVDC acts as a firewall preventing fault propagation; HVAC propagates faults immediately across connected AC grids.

Evolution of HVDC Transmission in India I

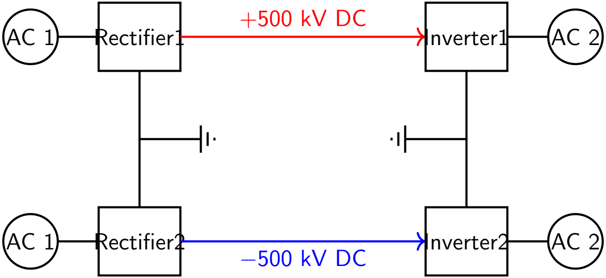
India's power grid utilizes HVDC technology for bulk power transfer over long distances and asynchronous interconnection of regional grids. The unique geographical distribution of generation resources (coal in the east/central, hydro in the north/northeast) and load centers (west/south/north) necessitates high-capacity transmission corridors.

Evolution of HVDC Transmission in India II

Key Points

- First commercial HVDC project: Vindhyachal 500 MW back-to-back station (1989), connecting Northern and Western regional grids asynchronously.
- Major long-distance bi-pole links: Rihand-Delhi (1500 MW, ±500*kV*, 814*km*)*andTalcher* − *Kolar*(2500*MW*, ±500*kV*, 1450*km*)*designedforbulkhydro*/*ther*
- Ultra-High Voltage DC (UHVDC) systems: North East-Agra (6000 MW, ±800*kV*, *multi* − *terminal*, 1728*km*)*andChampa* − *Kurukshetra*(6000*MW*, ±800*kV*, *usingdedicatedmetallicreturn*
- Recent advancement: Raigarh-Pugalur ±800*kV*, 6000*MWUHVDClink*, *incorporatingVoltageSourceCo* *Trichursectionforimprovedgridstability*.

Bipolar HVDC System Configuration I



Bipolar HVDC System Configuration II

Key Points

- In a bipolar system, two independent poles operate at equal and opposite DC voltages (e.g., $\pm 500 kV$), *doublingpowercapability*.
- Under normal operations, currents in both poles are balanced, and ground return current is negligible ($I_{ground} \approx 0$).
- If a fault occurs on one pole (e.g., pole-to-ground fault), the healthy pole continues to operate using the ground/metallic return, carrying up to 50% of the rated capacity.
- Ground electrodes are placed 10 to 50 km away from converter stations to avoid corrosion of station grounding grids and piping systems.

Need of Flexible AC Transmission Systems (FACTS) I

Conventional AC transmission networks rely on mechanical switches (circuit breakers, tap changers) which are slow and subject to high wear. FACTS technology introduces high-speed power electronic controllers to regulate the power flow and enhance stability dynamically.

Need of Flexible AC Transmission Systems (FACTS) II

Key Points

- Dynamic Power Flow Control: Prevents loop flows and parallel path congestion by forcing power to flow along contractually agreed transmission corridors.
- Enhancing Stability Limits: Transient stability, voltage stability, and angular stability limits are raised, allowing lines to load safely up to their thermal limits.
- Mitigation of Sub-Synchronous Resonance (SSR): Active control schemes suppress hazardous interactions between generator shaft torsional modes and series-compensated line capacitance.
- Fast Reactive Power Compensation: Provides rapid, continuous reactive power injection/absorption to damp power system oscillations and prevent cascading voltage collapse.

Classification and Types of FACTS Devices I

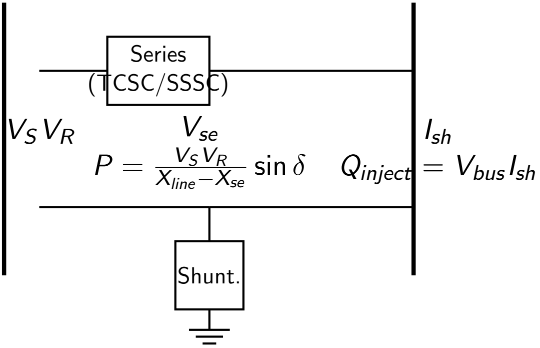
FACTS controllers are classified by their connection topology and the power electronic valves they employ. They are divided into four main categories: Series, Shunt, Combined Series-Series, and Combined Series-Shunt.

Classification and Types of FACTS Devices II

Key Points

- Shunt Controllers: Inject current in shunt with the bus. Examples: Static Var Compensator (SVC - thyristor controlled) and Static Synchronous Compensator (STATCOM - VSC based).
- Series Controllers: Inject voltage in series with the line. Examples: Thyristor Controlled Series Capacitor (TCSC) and Static Synchronous Series Compensator (SSSC).
- Combined Controllers: Unified Power Flow Controller (UPFC) is a combined series-shunt device that can independently control line active power, reactive power, and bus voltage.
- Device Evolution: First-generation devices (SVC, TCSC) use thyristor switches. Second-generation devices (STATCOM, SSSC, UPFC) employ

Shunt and Series FACTS Schemes I



Shunt and Series FACTS Schemes II

Key Points

- Series compensation dynamically alters line reactance X, allowing direct control of active power transmission capacity.
- Shunt compensation injects controllable reactive current to regulate local bus voltage and improve power transfer margins.
- By combining both shunt and series, a Unified Power Flow Controller (UPFC) enables full control over voltage, impedance, and phase angle.
- These devices use high-power thyristor/IGBT switches to respond to system load transitions or fault contingencies within 10-20 ms.

The fundamental active power flow equation over a lossless transmission line is given by: $P = \frac{V_s V_r}{X_{line}} \sin \delta$. FACTS devices manipulate one or more of these three parameters (V, X, δ) to optimize power transmission.

Mathematical Modeling & Power Flow Control II

Key Points

- Reactance Control (Series Compensation): With a Series Capacitor, $X_{eff} = X_{line} - X_C$. The power transferred is: $P = \frac{V_s V_r}{X_{line} - X_C} \sin\delta$. TCSC varies X_C dynamically.
- Voltage Support (Shunt Compensation): STATCOM regulates the midpoint voltage V_m to 1.0 p.u. The power transmission doubles to: $P = \frac{2V^2}{X_{line}} \sin(\frac{\delta}{2})$ at $\delta = 90^\circ$.
- Phase Angle Control (Phase Shifter / UPFC): Injects a series voltage vector with a perpendicular component to shift the voltage phase angle by θ, changing power to: $P = \frac{V_s V_r}{X_{line}} \sin(\delta \pm \theta)$.
- Dynamic Stability: Transient stability margins are improved as FACTS devices quickly increase power transfer capability during deceleration phases of

Advantages and Practical Applications of FACTS I

Deploying Flexible AC Transmission Systems (FACTS) provides significant operational, technical, and financial benefits to high-voltage transmission networks.

Advantages and Practical Applications of FACTS II

Key Points

- Asset Optimization: Increases thermal utilization of existing transmission lines, avoiding or delaying the massive capital expenditure of constructing new rights-of-way.
- Damping Oscillations: Actively dampens power system oscillations (inter-area and local modes) using auxiliary damping control inputs (POD controllers).
- Renewable Integration: Mitigates voltage fluctuations, flickers, and transient stability issues associated with large-scale wind and solar farm interconnections.
- Grid Resilience: Minimizes loop flows, reduces system losses, improves voltage profile, and prevents cascading blackouts by providing fast reactive power reserve.

Requirement 1: Voltage Regulation I

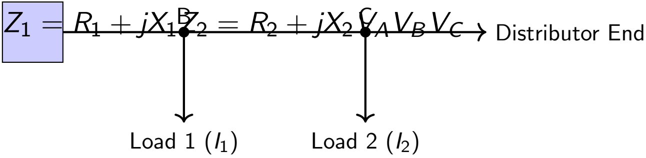
Maintaining terminal voltage within statutory limits is critical. Voltage variation at consumer terminals must not exceed $\pm 6\%$ of nominal voltage to ensure proper performance of electrical equipment.

Requirement 1: Voltage Regulation II

Key Points

- Low voltage drops in feeders and distributors prevent damage and erratic behavior of appliances.
- Terminal voltage: $V_t = V_s - \Delta V$, where V_s is sending end voltage and ΔV is loop impedance drop.
- Voltage drop approximation: $\Delta V \approx I(R\cos\phi + X\sin\phi)$, showing a dependency on load power factor.
- Fluctuations are managed using automatic tap-changing transformers and induction regulators at substations.

Voltage Drop Along a Radial AC Distributor I



Voltage Drop Along a Radial AC Distributor II

Key Points

- Representation of a radial AC distributor feeding multiple concentrated loads at different power factors.
- The feeding point 'A' maintains nominal voltage, while subsequent taps experience cumulative impedance drops.
- Impedances Z_1 and Z_2 represent loop impedances (both go and return conductors in single-phase systems).
- Vectorial calculation of voltage drop is required: $\bar{V}_B = \bar{V}_A - \bar{I}_1 \bar{Z}_1$.

Requirement 2: Supply Reliability I

Continuous supply of power is a prime necessity. Outages cause economic losses and compromise public safety.

Requirement 2: Supply Reliability II

Key Points

- System reliability is tracked via indices like SAIFI (System Average Interruption Frequency Index) and SAIDI.
- Transitioning from radial to ring main or interconnected layouts drastically reduces interruption frequency.
- Utilizing automatic sectionalizers, auto-reclosers, and Ring Main Units (RMUs) helps isolate faults swiftly.
- Auxiliary feeders are routed to critical loads (e.g., hospitals, factories) for automatic switchover capability.

Requirement 3: Efficiency & Loss Minimization I

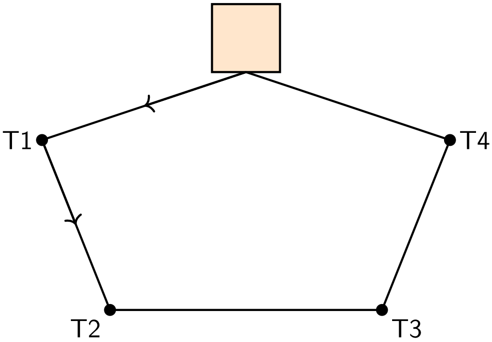
Power distribution networks account for the highest proportion of technical losses in a power system. Designing for efficiency is key.

Requirement 3: Efficiency & Loss Minimization II

Key Points

- Copper losses (I^2R) are minimized by optimization of conductor cross-sectional areas.
- Active power loss in a 3-phase line: $P_{loss} = 3I^2R = \frac{P^2R}{V^2\cos^2\phi}$, making loss inversely proportional to power factor squared.
- Improving load power factor using shunt capacitor banks decreases line currents and reduces thermal losses.
- Increasing distribution voltage (e.g., primary distribution at 11 kV instead of 415 V) yields exponential loss reductions.

Ring Main Distribution System Design I



Ring Main Distribution System Design II

Key Points

- A Ring Main System starts and terminates at the same substation busbar, forming a closed loop.
- If any section of the distributor fails or undergoes maintenance, power can be fed from the alternative path.
- This configuration ensures continuous supply to all distributors even under single-fault conditions (N-1 contingency).
- Voltage drop at load terminals is significantly lower compared to an equivalent radial system of the same length.

An ideal distribution network should maintain balanced phase currents and ensure complete safety under fault conditions.

Requirement 4 & 5: Balanced Loading & Safety II

Key Points

- Unequal connection of single-phase loads on a three-phase, 4-wire $(3\phi, 4W)$ system leads to neutral shift.
- Neutral current $I_N = I_A + I_B + I_C$ should be close to zero to minimize neutral-to-ground voltage rise.
- System must have sufficient overload capacity to handle transient motor starting currents and load cycles.
- Adequate protection schemes, including molded case circuit breakers (MCCBs) and earth leakage protection (ELCBs/RCCBs), are vital.

Summary of Ideal AC Distribution Design I

A high-performance AC distribution system balances capital cost, efficiency, and operational safety.

Summary of Ideal AC Distribution Design II

Key Points

- Strict adherence to statutory limits (e.g., $\pm 6\%$) for voltage variation is mandatory.
- Conductors must be sized based on continuous current rating (thermal limit) and maximum allowable voltage drop.
- Topology selection (radial, ring, or interconnected) depends on the reliability criteria of the load center.
- Distributed reactive power control using capacitor banks is essential to mitigate losses and boost terminal voltage.

Power distribution forms the final stage of the grid, stepping down high voltage to utilization levels. This structure consists of three distinct electrical components serving specific roles.

Structure of a Distribution System II

Key Points

- Primary distribution systems operate at 11 kV, 6.6 kV, or 3.3 kV using 3-phase, 3-wire systems to feed distribution substations.
- Secondary distribution systems deliver power directly to consumer loads at 415 V (3-phase) and 230 V (single-phase) using a 3-phase, 4-wire configuration.
- The network's primary topological elements are the feeder, the distributor, and the service mains, which have unique electrical design requirements.

Feeders: Definition and Design Principles I

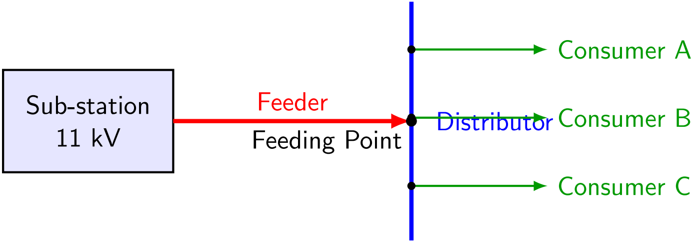
A feeder is a radial or loop conductor connecting the primary substation to the distribution area (distributor feeding points) without any intermediate consumer tapping.

Feeders: Definition and Design Principles II

Key Points

- Constant Current: Since no tapping is allowed along the length, the current carrying capacity remains uniform throughout the feeder ($I_{in} = I_{out}$).
- Design Criterion: Feeders are designed primarily based on current-carrying capacity (thermal limits) to prevent degradation of insulation and mechanical strength.
- Economic Sizing: Kelvin's Law is applied to find the optimal conductor area by balancing the annual interest on capital cost against the cost of annual I^2R losses.

Schematic of a Radial Distribution System I



Schematic of a Radial Distribution System II

Key Points

- Substation: Feeds electrical power to the system at primary voltage (e.g., 11 kV).
- Feeder (Red): Transmits bulk power with no intermediate connections, feeding the distributor directly at a single point.
- Distributor (Blue) & Service Mains (Green): The distributor has multiple tappings, which connect to individual consumers via service mains.

Distributors: Principles and Loading Configurations I

A distributor is a conductor designed to deliver electrical energy directly to consumers, characterized by multiple tapping points along its length.

Distributors: Principles and Loading Configurations II

Key Points

- Varying Current: The current magnitude drops at every tapping point, meaning the line current is not constant along the distributor.
- Design Criterion: Designed primarily based on permissible voltage drop. The maximum voltage variation at any consumer terminal must not exceed statutory limits (e.g., $\pm 6\%$ of the nominal voltage).
- Loading Topologies: Distributors are classified based on feed points: fed at one end, fed at both ends (equal/unequal voltages), or fed at the center.

Service Mains: The Consumer Connection I

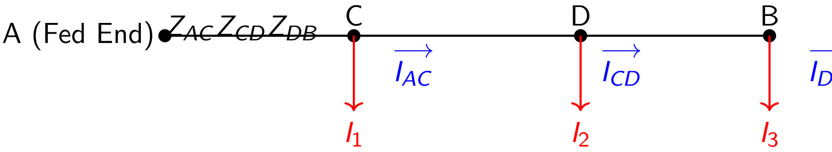
Service mains are small cable lines connecting the local distributor's tapping point to the consumer's premises or energy meter.

Service Mains: The Consumer Connection II

Key Points

- Dedicated Power Delivery: Service mains handle the specific consumer's load and carry a current proportional to the consumer's demand.
- Design Criteria: Sized primarily based on mechanical strength, insulation level, and localized voltage drop (which must be negligible, e.g., $< 1\%$).
- Single-Phase vs. Three-Phase: Domestic consumers are supplied via a single-phase 230 V system, while industrial and large commercial consumers use a three-phase 415 V system.

Distributor Fed at One End with Concentrated Loads I



Distributor Fed at One End with Concentrated Loads II

Key Points

- In a distributor fed at one end, the current in any section is the sum of all subsequent load currents: $I_{DB} = I_3$, $I_{CD} = I_2 + I_3$, $I_{AC} = I_1 + I_2 + I_3$.
- Total voltage drop to the far end B is the sum of section voltage drops: $V_{\text{drop}} = I_{AC}Z_{AC} + I_{CD}Z_{CD} + I_{DB}Z_{DB}$.
- The minimum voltage always occurs at the point furthest from the feeding source (Point B for a radial distributor).

Key Differences and Engineering Summary I

Understanding the core operating principles of feeders, distributors, and service mains is crucial for efficient grid design, reliability, and regulatory compliance.

Key Differences and Engineering Summary II

Key Points

- Feeders carry high, constant current directly from substation to feeding points; design constraint is purely thermal (current density).
- Distributors have multiple intermediate taps for consumers; design constraint is voltage regulation (maximum allowable voltage drop).
- Service mains connect the distributor directly to the meter; design constraint is mechanical robustness and safety of the final connection.
- System configuration (Radial, Ring Main, Interconnected) determines the loading profile and backup availability of these components.

Classification by Character of Service & Voltage I

Distribution systems are categorized based on the nature of current (A.C. vs. D.C.) and their relative operational voltage level (Primary vs. Secondary).

Classification by Character of Service & Voltage II

Key Points

- A.C. Distribution System: Universally adopted due to voltage transformation flexibility. Operates as 3-phase, 3-wire for primary or 3-phase, 4-wire for secondary levels.
- D.C. Distribution System: Limited to specialized applications such as electric traction systems, high-density urban microgrids, and electric vehicle charging infrastructure.
- Primary Distribution: Operates at voltages between 3.3 kV and 33 kV. Feeds large industrial consumers directly and feeds distribution substations.
- Secondary Distribution: Directly feeds residential/commercial loads at standard utilization voltages (415 V line-to-line, 230 V line-to-neutral under IEC standards).

Classification by Type of Construction I

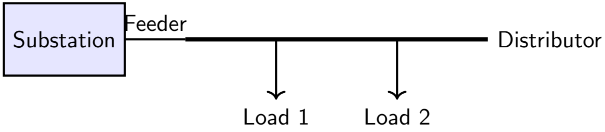
Physical topology dictates reliability, safety, environmental vulnerability, and overall capital (CAPEX) and operating (OPEX) costs.

Classification by Type of Construction II

Key Points

- Overhead System: Utilizes bare conductors supported on poles/structures. Capital cost is 5 to 10 times lower than underground systems.
- Overhead Disadvantages: High exposure to weather hazards (lightning, wind, ice), public safety concerns, and aesthetic clutter.
- Underground System: Employs insulated cables laid in trenches or conduits. Provides high reliability, aesthetic integration, and lower voltage drops.
- Underground Disadvantages: Extremely high initial cost, challenging fault location, and charging current constraints due to high cable capacitance: $I_c = \omega CV$.

Connection Scheme: Radial Distribution System I

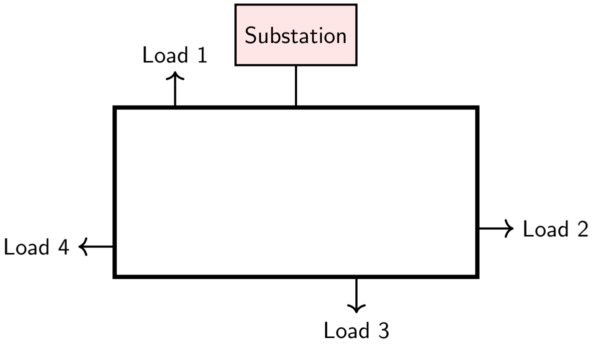


Connection Scheme: Radial Distribution System II

Key Points

- Topology: Separate feeder lines radiate from a single substation. Each distributor is energized from one end only.
- Vulnerability: A single fault on the feeder or distributor causes complete outage to all downstream consumers ($N - 0$ reliability).
- Voltage Profile: Consumers at the far end experience significant voltage drop during peak hours: $V(x) = V_S - \int_0^x I(z)Z(z)dz$.
- Application: Commonly applied in rural areas where load density is low and low cost is prioritized over continuous reliability.

Connection Scheme: Ring Main Distribution System I



Connection Scheme: Ring Main Distribution System II

Key Points

- Topology: The distributor pathway forms a closed loop, beginning and ending at the substation busbars.
- Redundancy: Every distributor tap points can be supplied from two directions, achieving $N - 1$ reliability in the loop.
- Voltage Quality: The loop configuration lowers equivalent impedance, yielding a flatter voltage profile and smaller terminal fluctuations.
- Operational Flexibility: Sections can be isolated via sectionalizing switches for maintenance without disrupting service to other loads.

Connection Scheme: Interconnected System I

An interconnected system is formed when a closed-loop distributor grid is energized by two or more independent substations.

Connection Scheme: Interconnected System II

Key Points

- High Reliability: If one substation fails, feed is maintained continuously by active substations, preventing localized load shedding.
- Peak Load Sharing: Reduces total reserve capacity requirements; excess capacity from one sub can support adjacent loaded areas.
- System Stability: Enhances transient stability and fault-withstand capabilities due to parallel sources of generation/transmission.
- Mathematical Model: Net complex power injection at node i is defined by: $S_i = V_i \sum_{j=1}^{n} Y_{ij}^* V_j^*$ where Y_{ij} is the bus admittance matrix.

Distribution wiring configurations depend on the balancing requirements and load characteristics of the consumers.

Classification by Number of Wires & Configuration II

Key Points

- Two-Wire D.C. System: Uses one positive and one negative conductor. Simple, but offers no neutral path or dual voltage capabilities.
- Three-Wire D.C. System: Consists of positive, negative, and middle neutral lines, providing both V and $2V$ voltage options.
- Three-Phase, Three-Wire A.C. System: Feeds balanced three-phase loads (e.g., primary motors). Savings in conductor material relative to 4-wire systems.
- Three-Phase, Four-Wire A.C. System: Standard secondary configuration. Accommodates unbalanced loads, neutral current given by: $I_N = I_A + I_B e^{-j120^\circ} + I_C e^{j120^\circ}$.

Technical Design Criteria & Choice of System I

Engineers must evaluate voltage regulation, thermal constraints, loss performance, safety standards, and life-cycle economics.

Technical Design Criteria & Choice of System II

Key Points

- Voltage Regulation Limits: Standard limits mandate consumer voltage stay within $\pm 6\%$ of nominal levels (ANSI C84.1 / EN 50160).
- Ampacity Constraints: Overhead conductors and underground cables must not exceed safety limits to avoid phase annealing or insulation breakdown.
- Loss Mitigation: Distributor copper loss $P_{\text{loss}} = 3I^2R$ is controlled by power factor correction capacitors and higher primary feed voltage.
- Application Strategy: High-density business centers require interconnected underground grids, while radial overhead remains standard for rural regions.

33kV/11kV; [thick, -¿] (2,0.75) – (5,0.75) node[midway, above] Feeder (11kV); [thick] (5.4,0.75) circle [radius=0.4]; [thick] (6.0,0.75) circle [radius=0.4];
ode at (5.7,-0.25) [align=center] XFMR
11kV/415V; [thick, -¿] (6.4,0.75) – (10,0.75) node[midway, above] Distributor (415V); [thick, -¿] (7.5,0.75) – (7.5,-0.7) node[below] Service Mains;
ode at (7.5,-1.2) Consumer A; [thick, -¿] (9.0,0.75) – (9.0,-0.7) node[below] Service Mains;

ode at (9.0,-1.2) Consumer B;

Key Points

- Feeders: Bulk power lines connecting substation to distribution areas. Sized based on thermal/current carrying capacity.
- Distributors: Tapped lines supplying individual consumers. Sized primarily based on voltage drop constraints.
- Service Mains: Small cable connections linking the distributor to consumer terminals.

Primary AC Distribution System I

Primary distribution forms the backbone of municipal electrical grids. It operates at medium-high voltages, typically 11 kV, 6.6 kV, or 3.3 kV (standard in IEC regions) or 13.8 kV (standard in ANSI regions) to minimize line current and I^2R losses over distances of 2 to 15 km.

Primary AC Distribution System II

Key Points

- Three-Phase, Three-Wire System: Since the load on primary distribution (step-down transformers and bulk consumers) is balanced, a neutral conductor is omitted to save copper/aluminum cost.
- Industrial Consumers: Large factories often receive power directly at 11 kV or 33 kV and maintain their own step-down substations.
- Feeder Layouts: Feeders can be arranged in radial, ring main, or interconnected topologies depending on reliability requirements.
- Current Capacity Constrained: Feeder conductors are sized based on maximum continuous current rating to prevent overheating and sag.

Ring Main Primary System I

(11 kV Loop);

Key Points

- Closed Loop Topology: The feeder starts from the substation bus, forms a closed loop passing through load centers, and returns to the substation.
- Redundancy & Reliability: Any single feeder fault can be isolated using circuit breakers on both sides without interrupting service to other nodes.
- Improved Voltage Regulation: Since load points are fed from two parallel directions, the effective line impedance is halved, minimizing voltage drops.
- Isolation & Maintenance: Sections of the ring can be de-energized for maintenance while maintaining supply to all substations.

Voltage Drop in AC Distributors I

AC voltage drops depend on both line impedance $\vec{Z} = R + jX$ and the load power factor angle ϕ. The vector formula for the sending-end voltage $\vec{V}_S$ relative to the receiving-end voltage $\vec{V}_R$ is: $\vec{V}\_S = \vec{V}\_R + \vec{I}\vec{Z}$ Assuming the current $\vec{I} = I(\cos\phi - j\sin\phi)$ lags $\vec{V}_R$:

$$\Delta$$

V $\approx I(R\cos\phi + X\sin\phi)$

Voltage Drop in AC Distributors II

Key Points

- Active & Reactive Component: $R \cos \phi$ represents resistive drop in-phase with the load current; $X \sin \phi$ represents reactive drop.
- Lagging vs Leading PF: If the load is capacitive (leading PF), the sign of the reactive drop changes: $\Delta V \approx I(R \cos \phi - X \sin \phi)$. This can lead to a voltage rise.
- Three-Phase Systems: For a balanced 3-phase distributor, the line-to-line voltage drop is $\sqrt{3} \cdot I(R \cos \phi + X \sin \phi)$, where I is the line current and R, X are per-phase line constants.
- Voltage Drop Limits: Statutory requirements generally mandate that the voltage at any consumer terminal must not vary by more than $\pm 6\%$ of the declared nominal voltage.

Secondary AC Distribution System I

Secondary distribution carries power from the step-down distribution transformer (11 kV/415 V or 11 kV/230 V) to the consumer's premises. It is the final link in the power delivery chain, operating at utilization voltage levels.

Secondary AC Distribution System II

Key Points

- Three-Phase, Four-Wire System: Employs a star-connected secondary transformer providing three line phases (Red, Yellow, Blue) and a common Neutral wire ($RYBN$).
- Voltage Levels: Line-to-line voltage is 415 V (used for 3-phase motors, small commercial/industrial loads) and line-to-neutral voltage is 230 V (used for domestic lighting, heating, appliances).
- Distributor Sizing: Secondary distributors are designed strictly on the basis of voltage drop constraints, as consumers are sensitive to low voltage.
- Grounding: The neutral point is solidly grounded at the substation to clamp neutral potential to zero and ensure earth fault currents trigger protective breakers.

Operating a modern secondary distribution grid requires active mitigation of load imbalance, phase current variations, and harmonic distortions introduced by consumer appliances.

Practical Industrial Challenges II

Key Points

- Phase Unbalance: Unbalanced loading across the three phases shifts the neutral point, leading to over-voltages on lightly loaded phases and under-voltages on heavily loaded ones.
- Neutral Current: In an unbalanced 3-phase system, current flows in the neutral conductor ($I_N = I_R + I_Y + I_B$), which increases overall line losses and heats the neutral wire.
- Triplen Harmonics: Non-linear electronic loads (computers, LED drivers) inject $3rd, 9th, 15th$ harmonics. These do not cancel out in the neutral; they sum up constructively, necessitating double-sized neutral wires in commercial zones.
- Protection Coordination: Leverages fuses, MCBs (Miniature Circuit Breakers), and MCCBs (Molded Case

Primary vs. Secondary Distribution I

The transition from primary to secondary distribution marks the shift from high-voltage bulk transit to low-voltage localized delivery.

Primary vs. Secondary Distribution II

Key Points

- Voltage Level: Primary runs at 11 kV – 33 kV (medium voltage), whereas Secondary operates at 415 V/230 V (low voltage).
- Conductor Phase Wires: Primary uses a 3-phase, 3-wire system; Secondary utilizes a 3-phase, 4-wire system to accommodate single-phase loads.
- Conductor Dimensioning: Primary feeder size is dictated by continuous thermal current capacity. Secondary distributor size is dictated by the permissible voltage drop limit ($\pm 6\%$) under peak load conditions.
- System Reliability: Primary systems often employ ring or interconnected configurations; secondary systems are predominantly radial due to cost and localized nature.

Overview of Distribution Connection Schemes I

Electrical distribution networks link transmission substations to consumers. Design selection is guided by reliability requirements, voltage stability, and cost constraints.

Overview of Distribution Connection Schemes II

Key Points

- Primary objective: Maintain consumer terminal voltage within standard regulatory limits (e.g., ±6% of nominal).
- Key reliability metrics tracked by utilities: SAIDI (System Average Interruption Duration Index) and SAIFI (System Average Interruption Frequency Index).
- Feeder sizing is constrained by thermal limits (current capacity), while length is constrained by maximum permissible voltage drop.
- The three primary layout configurations utilized in utility networks are Radial, Ring Main, and Interconnected systems.

Radial Distribution System I

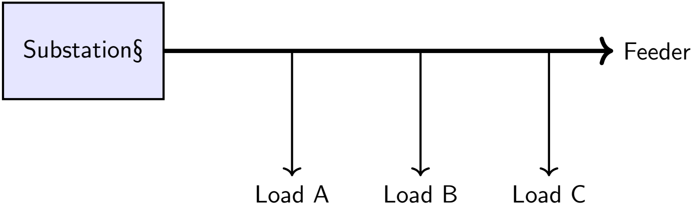
A radial system features feeders radiating from a single substation, feeding distributors with power flowing in only one path.

Radial Distribution System II

Key Points

- Characterized by the lowest initial capital cost due to minimal requirement for switchgear, isolators, and feeders.
- Major drawback: A fault at any point along the feeder shuts down power to all downstream consumers (no redundancy).
- Voltage regulation is poor at the far end of the feeder, where the cumulative voltage drop is at its maximum: $\Delta V = I(R\cos\phi + X\sin\phi)$.
- Distributors are fed at only one end, meaning the current load tap-offs lead to a non-uniform voltage profile along the line.

Radial System Schematic Diagram I



Key Points

- Unidirectional power flow ensures that the feeder current decreases at each consecutive distributor tap-off.
- A fault between Substation S and Distributor A trips the main circuit breaker, interrupting supply to all three loads.
- Voltage at Load C is highly sensitive to load changes at A and B due to shared feeder impedance.

Ring Main (Loop) Distribution System I

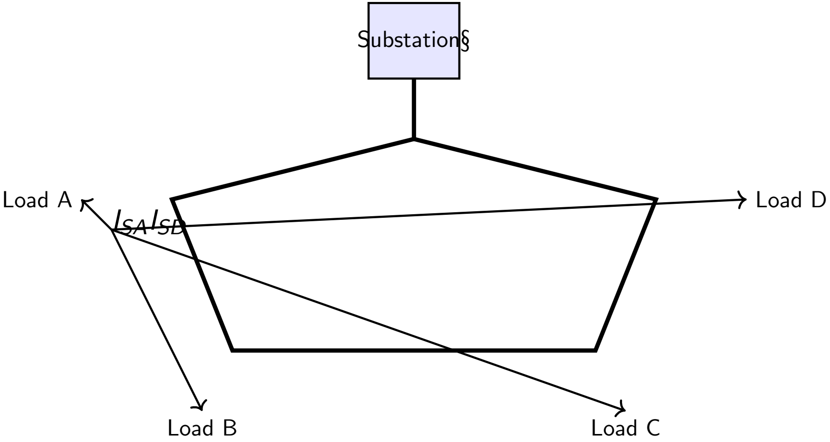
A ring main system forms a closed loop starting and terminating at the same substation, providing two parallel paths of supply to each distributor.

Ring Main (Loop) Distribution System II

Key Points

- High reliability: If a fault occurs on any section, that section can be isolated via breakers while maintaining power flow from the alternate path.
- Improved voltage regulation: Loop topology reduces equivalent impedance, minimizing overall voltage drop at consumer terminals.
- Ease of maintenance: Sectionalizing isolators allow scheduled maintenance on lines without causing service interruptions.
- Calculated as a closed loop network; node currents are resolved using Kirchhoff's Voltage Law (KVL) around the loop.

Ring Main System Schematic Diagram I



Ring Main System Schematic Diagram II

Key Points

- Distributors A, B, C, and D are connected in a loop. Substation S feeds into the loop node.
- If feeder segment A-B is isolated due to a fault, Load A is fed via S-A, and Load B is fed via S-D-C-B.
- Mathematical analysis: The loop current must satisfy $\sum I\_kZ\_k = 0, whereZ\_krepresentssectionimpedance.$

An interconnected system consists of a closed-loop distributor network fed by two or more independent substations or generating sources.

Interconnected Distribution System II

Key Points

- Highest reliability: If any substation suffers an outage, the load is automatically shared and carried by the remaining active substations.
- Active power flow control and reactive power dispatch can be optimized to minimize transmission losses: $P_{loss} = 3 \sum I_i^2 R_i$.
- Stiff voltage profile: Multiple source feeds reduce voltage fluctuations during peak demand periods or high motor-starting transient currents.
- Disadvantage: High system complexity requiring synchronized sources, differential relays, and high-capacity switchgear.

Comparative Engineering Analysis I

The selection of distribution schemes represents a classic trade-off between capital expenditure (CAPEX) and system reliability.

Comparative Engineering Analysis II

Key Points

- Radial configuration is suited for low-density rural zones where lower cost outweighs occasional supply interruptions.
- Ring main is standard for urban residential and light commercial zones to minimize downtime during localized maintenance.
- Interconnected scheme is essential for heavy industrial facilities, critical infrastructure, and dense high-rise urban cores.
- Comparative voltage drop: Max drop in a radial feeder of length L is $\propto L$, whereas for a ring main it is generally $\propto L/4$ under uniform loading.

Feeders vs. Distributors: Core Differences I

Feeders and distributors are the two primary components of an electrical distribution system. While feeders connect the substation to the distributor area without any intermediate tapping, distributors have multiple tappings for consumer connections. This fundamental difference dictates their design criteria.

Feeders vs. Distributors: Core Differences II

Key Points

- Feeders carry bulk power from substations to distributing nodes with no intermediate tappings; hence, current remains constant throughout the length.
- Distributors are tapped at various intervals to supply power directly to individual consumers; hence, current varies along the length.
- Service mains connect the distributor to the consumer's energy meter.
- Design of feeders is primarily governed by current carrying capacity (thermal limits) and economic conductor size (Kelvin's Law).
- Design of distributors is primarily governed by the permissible voltage drop (statutory limits) to ensure power quality.

Technical & Economic Design of Feeders I

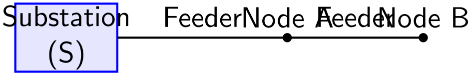
The design of feeders must satisfy safety (thermal limits), economic viability, and reliability. Conductor sizing is determined by thermal capabilities and Kelvin's Law.

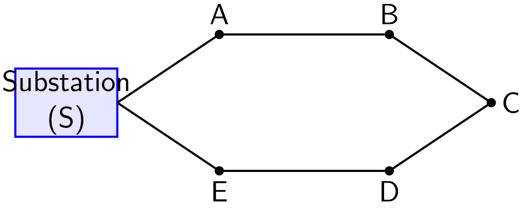
Technical & Economic Design of Feeders II

Key Points

- Current Carrying Capacity: The feeder must carry the maximum load current without overheating the insulation. Thermal limits depend on conductor material, cross-sectional area, lay (overhead/underground), and ambient conditions.
- Kelvin's Law for Economical Conductor Size: States that the most economical area of conductor is that for which the annual interest and depreciation on the capital cost of the conductor equals the annual cost of energy wasted (I^2R losses).
- Mathematical Formulation: Let annual interest and depreciation be $C_1 = P_1 + P_2 a$ and annual cost of energy loss be $C_2 = P_3/a$. Total cost $C = C_1 + C_2$. Minimizing C with respect to cross-sectional area a gives $P_2 = P_3/a^2$, or $P_2 a = P_3/a$, meaning annual

Radial vs. Ring Main Feeder Layouts I





Radial vs. Ring Main Feeder Layouts II

Key Points

- Radial Feeders: Simple and low capital cost, but have poor reliability. A fault on the feeder results in complete power interruption to all downstream nodes.
- Ring Main Feeders: The feeder loop starts and terminates at the substation. Provides redundant paths, ensuring supply continuity even if a section of the feeder is isolated for maintenance or due to a fault.
- Interconnected Feeders: Multiple feeders fed from different substations, offering the highest level of reliability and flexibility under peak load conditions.
- Design Choice: Industrial and urban areas use ring main or interconnected systems, whereas rural areas might rely on radial feeders for simplicity.

Technical Design of Distributors I

The primary criterion for distributor design is the limit on voltage variations at the consumer terminals. Standard codes dictate strict tolerances to protect consumer appliances and ensure standard utility operation.

Technical Design of Distributors II

Key Points

- Statutory Voltage Limits: In typical networks, voltage variations at the consumer's terminal must be within $\pm 6\%$ (or $\pm 5\%$ in some standards) of the declared nominal voltage.
- Components of Voltage Drop: In A.C. distributors, voltage drop depends on resistance (R), reactance (X), and load power factor ($\cos\phi$). The drop is approximately $I(R\cos\phi \pm X\sin\phi)$.
- Conductor Sizing: Unlike feeders, distributors are sized to limit cumulative voltage drop from the feeding point to the farthest consumer node.
- Loading Patterns: Distributors can be fed at one end, fed at both ends, or fed at the center. Loads can be concentrated at specific points or uniformly distributed.
- Current Density: Current density varies along the

Radial Distributor with Concentrated Loads I

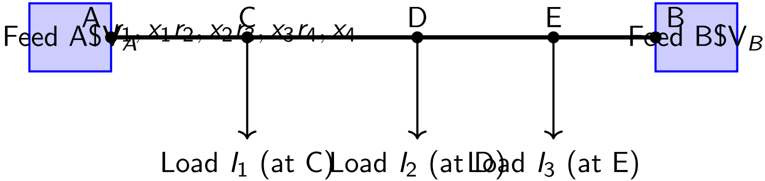
Consider a distributor AB fed at end A with concentrated loads $I_1, I_2, \ldots, I_n$ tapped at distances $x_1, x_2, \ldots, x_n$ from A. The impedance of sections is $Z_1, Z_2, \ldots, Z_n$.

Radial Distributor with Concentrated Loads II

Key Points

- Current in Sections: The current in any section is the sum of currents tapped downstream. Section nearest to the feeding point carries the total current.
- Voltage Drop Equation: The total voltage drop to any node is the sum of voltage drops in individual sections. For node k: $V_{drop} = \sum_{j=1}^{k} I_{section,j} \cdot Z_{section,j}$.
- Uniformly Distributed Load: If the distributor has a load of i amperes per meter run, the total current entering is $I = iL$. The current at distance x from the feeding point is $i(L - x)$.
- Total Voltage Drop for Uniform Load: $V_{drop} = \int_0^L i(L - x)r\,dx = \frac{1}{2}irL^2 = \frac{1}{2}IR$, where $R = rL$ is the total resistance. Thus, the total voltage drop is equal to that of the total load concentrated at the midpoint of the distributor.

Distributor Fed at Both Ends I



Distributor Fed at Both Ends II

Key Points

- Double-Ended Feeding: If a distributor is fed at both ends, the voltage drop is significantly reduced compared to single-ended feeding, allowing smaller conductor cross-sections.
- Minimum Voltage Point: There is always a node where the current enters from both directions. This point has the minimum potential in the distributor.
- Calculations: By applying Kirchhoff's laws, the currents supplied by feeds A and B can be calculated. If $V_A = V_B$, the point of minimum potential is typically close to the center.
- Operational Advantages: In case of a fault in any section, the distributor can be isolated, and both parts can still receive power from their respective ends, improving reliability.

Summary of key differences in design factors, along with standard values used in industrial A.C. distribution.

Design Comparison & Practical Summary II

Key Points

- Primary Variable: Feeder conductor area is chosen based on economic current density ($A = I_{max}/J_{eco}$). Distributor conductor area is chosen based on maximum allowable voltage drop (ΔV_{max}).
- Kelvin's Law Application: Usually applied to transmission lines and feeders where tappings are absent, making current constant.
- Power Factor Influence: In A.C. distribution, low power factor increases current for the same active power, escalating both voltage drop and thermal losses. Shunt capacitors are often installed along distributors to maintain power factor near unity.
- Statutory Standard: Under normal operating conditions, IEC 60038 recommends a voltage tolerance of $\pm 10\%$, but national standards (like ANSI C84.1 or Indian

Classification of Loads on Distributors I

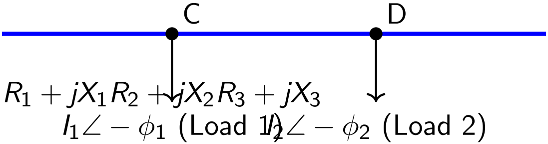
Distribution networks are analyzed by classifying loads as concentrated or distributed.

Classification of Loads on Distributors II

Key Points

- Concentrated Loads: Power is tapped off at discrete points along the distributor. Examples include industrial customers, sub-distribution panels, or transformers.
- Distributed Loads: Power is tapped off continuously along the distributor line. A common example is residential service connections along a street.
- Mathematical Representation: Distributed loads are represented as a load density (i amperes per unit length), whereas concentrated loads are discrete phasors ($I_k \angle - \phi_k$).
- Line Impedance: A.C. distributors have series impedance per unit length $z = r + jx$ (composed of resistance r and inductive reactance x).

Concentrated Loading Schematic I



Concentrated Loading Schematic II

Key Points

- Schematic of a distributor fed from one end (A) with concentrated loads at points C and D.
- The current in section AC is the vector sum of all downstream loads: $I_{AC} = I_1\angle-\phi_1 + I_2\angle-\phi_2$.
- The current in section CD is $I_{CD} = I_2\angle-\phi_2$, and the current in section DB is zero.
- Voltage drops in each section are calculated as the product of the section current and section impedance.

Voltage Drop Formulation for Concentrated Loads I

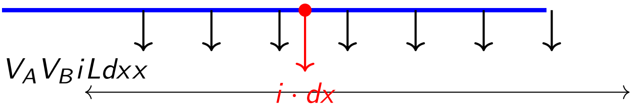
For concentrated loads, voltage drop calculations must account for the vector nature of currents and impedances.

Voltage Drop Formulation for Concentrated Loads II

Key Points

- Vector Voltage Drop: The total voltage drop is $V_{drop} = \vec{V}_A - \vec{V}_B = \sum \vec{I}_k \vec{Z}_k$.
- Using receiving-end voltage V_B as the reference phasor ($V_B = V_B \angle 0^\circ$): the currents are written as $I_k(\cos\phi_k - j\sin\phi_k)$.
- Approximate Drop Formula: For any section, the active voltage drop is approximately $I(R\cos\phi + X\sin\phi)$, which is the projection along the reference voltage.
- Phase Angle Difference: The reactive drop is $I(X\cos\phi - R\sin\phi)$. Total voltage magnitude drop is $V_{drop} \approx R_t I_a + X_t I_r$ where I_a and I_r are active and reactive currents.

Distributed Loading Schematic I



Distributed Loading Schematic II

Key Points

- Schematic of a distributor fed from one end with a uniformly distributed load of i amperes per unit length.
- The current at a distance x from the feeding end A is $I_x = i(L - x)$, since it supplies only the remaining length $(L - x)$.
- We analyze the differential voltage drop across a small element dx at distance x.
- The series impedance of the differential element is $dZ = z \cdot dx = (r + jx)dx$.

Derivation of Voltage Drop for Distributed Loads I

By integrating the differential voltage drops along the length of the distributor, we obtain the total voltage drop.

Key Points

- Differential Drop: $dV = I_x \cdot dZ = i(L - x) \cdot (r + jx)dx$.
- Total Integration:
  $V_{drop} = \int_0^L i(r + jx)(L - x)dx = i(r + jx)\left[Lx - \frac{x^2}{2}\right]_0^L$.
- Simplified Expression:
  $V_{drop} = \frac{1}{2}i(r + jx)L^2 = \frac{1}{2}(iL)((r + jx)L) = \frac{1}{2}IZ$.
- Physical Significance: The total voltage drop is equivalent to the entire load $I = iL$ concentrated at the midpoint of the distributor (impedance $Z/2$).

Uniform distributed load analysis reveals important relationships for power loss and alternative feeding strategies.

Power Loss and Feeding Configuration Performance II

Key Points

- Power Loss Calculation:
  $P_{loss} = \int_0^L I_x^2 r dx = \int_0^L [i(L-x)]^2 r dx = \frac{1}{3} i^2 r L^3 = \frac{1}{3} I^2 R$.
- Double-Ended Feeding (Equal Voltages): Feeding the distributor from both ends ($V_A = V_B$) yields a minimum voltage point at the center $x = L/2$.
- Double-Ended Maximum Voltage Drop:
  $V_{max} = \frac{1}{8} izL^2 = \frac{1}{8} IZ$. This is 25% of the single-ended drop.
- Double-Ended Power Loss: The power loss becomes $P_{loss} = \frac{1}{12} I^2 R$, which is a 75% reduction compared to single-ended feeding.

Distribution engineers must comply with regulations on voltage limits, thermal capability, and power quality.

Industrial Design Considerations & Standards II

Key Points

- Voltage Regulation Limits: Statutory limits (e.g., ANSI C84.1 or regional grid codes) require maintaining supply voltage within $\pm 5\%$ to $\pm 6\%$ of nominal value.
- Voltage Drop Mitigation: If limits are exceeded, solutions include conductor size upgrading, adding shunt capacitors, or employing tap-changing transformers.
- Power Factor Variation: In real A.C. networks, tap-off points have varying power factors, requiring vector integration of active and reactive currents.
- Thermal vs. Voltage Constraint: Short distribution lines are typically thermal-rating limited, whereas long lines are almost always voltage-drop limited.

Vector Representation and Impedance Calculations I

In AC distribution, vector algebra must be employed because currents and voltages are phasor quantities with phase angles. The impedance of any section is represented as $Z = R + jX$ and current as $I = I\cos\phi - jI\sin\phi$ (for lagging power factor).

Key Points

- Load power factors can be referenced either to the sending-end voltage (V_S) or to the respective local node voltages (V_A, V_B, etc.). Referencing to receiving-end voltage simplifies calculation as it acts as the reference phasor ($V_R = V_R\angle 0^\circ$).
- Voltage drop in a section k is given by the complex equation: $\vec{V}_{drop} = \vec{I}_k \cdot \vec{Z}_k$, which resolves to: $V_{drop} \approx I_k(R_k \cos\phi_k + X_k \sin\phi_k)$ for the in-phase component, and $I_k(X_k \cos\phi_k - R_k \sin\phi_k)$ for the quadrature component.
- For short lines or distributors, the quadrature component of the voltage drop is often neglected, but for precise numerical computations, the complete complex expression must be evaluated: $V_{sending} = \sqrt{(V_{receiving} + V_{drop,active})^2 + (V_{drop,reactive})^2}$.

Diagram: Single-Phase AC Distributor with Concentrated Loads I

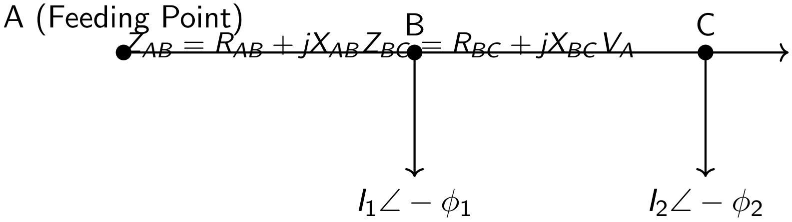


Diagram: Single-Phase AC Distributor with Concentrated Loads II

Key Points

- Schematic representation of a single-phase radial AC distributor fed at feeding point A with two concentrated loads at nodes B and C.
- Load currents I_1 and I_2 have lagging power factors $\cos\phi_1$ and $\cos\phi_2$ respectively, referenced to the receiving-end voltage V_C or local node voltages V_B, V_C.
- The current in section BC is $\vec{I}_{BC} = \vec{I}_2$, while the current in section AB is the phasor sum of the load currents: $\vec{I}_{AB} = \vec{I}_1 + \vec{I}_2$.

Numerical 1: Single-Phase Radial Distributor I

Problem statement: A single-phase distributor 200 m long is fed at point A at 230 V. It has two loads of 50 A at 0.8 p.f. lagging and 100 A at 0.6 p.f. lagging, at distances of 100 m (point B) and 200 m (point C) respectively from the feeding end. The total resistance and reactance of the distributor are 0.2 Ω and 0.1 Ω per kilometer (go and return).

Numerical 1: Single-Phase Radial Distributor II

Key Points

- Step 1: Calculate the resistance and reactance of the sections. Section AB (length 0.1 km): $R_{AB} = 0.2 \times 0.1 = 0.02\ \Omega$, $X_{AB} = 0.1 \times 0.1 = 0.01\ \Omega$. Section BC (length 0.1 km): $R_{BC} = 0.02\ \Omega$, $X_{BC} = 0.01\ \Omega$.
- Step 2: Define reference voltage. Let the receiving-end voltage V_C be the reference phasor: $V_C = V_C\angle 0^\circ$ V. Note: If the power factors are referenced to the respective receiving end voltage, we refer load currents to V_C.
- For this numerical, assume the power factors of the loads are referred to the voltage at the feeding end V_A, or alternatively, referred to the local voltages at B and C. We will solve using the common industrial assumption that power factors are referred to the

Let $V_C = V_C\angle 0^\circ$ be the reference voltage. The load currents are:
$\vec{I_C} = 100(0.6 - j0.8) = 60 - j80$ A and
$\vec{I_B} = 50(0.8 - j0.6) = 40 - j30$ A. Section currents are:
$\vec{I}_{BC} = \vec{I_C} = 60 - j80$ A
$\vec{I}_{AB} = \vec{I_B} + \vec{I_C} = (40 + 60) - j(30 + 80) = 100 - j110$ A.

Step-by-Step Mathematical Solution for Numerical 1 II

Key Points

- Calculate voltage drop in section BC: $\vec{V}_{drop,BC} = \vec{I}_{BC} \cdot \vec{Z}_{BC} = (60 - j80)(0.02 + j0.01) = (1.2 + 0.8) + j(0.6 - 1.6) = 2.0 - j1.0$ V.
- Calculate voltage drop in section AB: $\vec{V}_{drop,AB} = \vec{I}_{AB} \cdot \vec{Z}_{AB} = (100 - j110)(0.02 + j0.01) = (2.0 + 1.1) + j(1.0 - 2.2) = 3.1 - j1.2$ V.
- Total voltage drop $\vec{V}_{drop} = \vec{V}_{drop,AB} + \vec{V}_{drop,BC} = (3.1 + 2.0) - j(1.2 + 1.0) = 5.1 - j2.2$ V. Now, feeding point voltage is $\vec{V}_A = \vec{V}_C + \vec{V}_{drop}$. Therefore, $230\angle\theta = V_C + 5.1 - j2.2$. Solving for magnitude: $(V_C + 5.1)^2 + (-2.2)^2 = 230^2$. This yields $V_C \approx 224.89$ V.

Diagram: AC Distributor Fed at Both Ends (Different Voltages) I

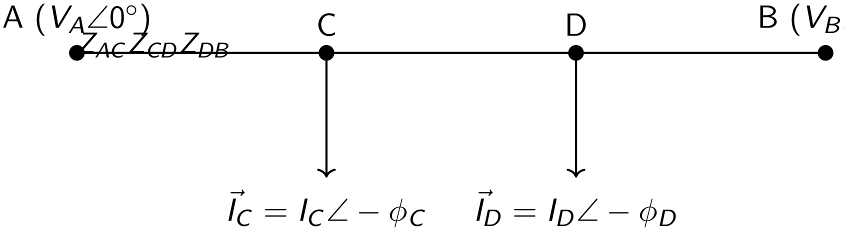


Diagram: AC Distributor Fed at Both Ends (Different Voltages) II

Key Points

- Distributor fed at both ends is more reliable, reduces overall voltage drop, and increases power supply continuity.
- If feeding voltages V_A and V_B are unequal and have a phase difference δ, there will be a continuous circulating current even under no-load conditions.
- Mathematical relation for solving: $\vec{V}_A - \vec{V}_B = \vec{I}_{AC}\vec{Z}_{AC} + \vec{I}_{CD}\vec{Z}_{CD} + \vec{I}_{DB}\vec{Z}_{DB}$. Using this, the point of minimum potential is identified where current changes direction.

Numerical 2: AC Distributor Fed at Both Ends I

Problem statement: A 3-phase, 400 V distributor is fed at both ends, A and B, at equal voltages ($V_A = V_B = 400$ V). The loads at C and D are 100 A at 0.8 p.f. lagging and 150 A at 0.6 p.f. lagging respectively. Impedances of the sections are:
$\vec{Z}_{AC} = (0.04 + j0.03)\ \Omega$, $\vec{Z}_{CD} = (0.02 + j0.015)\ \Omega$,
$\vec{Z}_{DB} = (0.03 + j0.0225)\ \Omega$. Power factors are referenced to feeding point voltage V_A.

Numerical 2: AC Distributor Fed at Both Ends II

Key Points

- Step 1: Set V_A as the reference phasor: $\vec{V}_A = 400/\sqrt{3}\angle 0^\circ \approx 231\angle 0^\circ$ V (per phase calculation). All currents must be referenced to $\vec{V}_A$.
- Step 2: Express load currents as phasors: $\vec{I}_C = 100(0.8 - j0.6) = 80 - j60$ A, $\vec{I}_D = 150(0.6 - j0.8) = 90 - j120$ A.
- Step 3: Let current in section AC be $\vec{I}_{AC} = I_x + jI_y$. Express other section currents: $\vec{I}_{CD} = \vec{I}_{AC} - \vec{I}_C = (I_x - 80) + j(I_y + 60)$, and $\vec{I}_{DB} = \vec{I}_{CD} - \vec{I}_D = (I_x - 170) + j(I_y + 180)$. Solve using $\vec{V}_A - \vec{V}_B = \vec{I}_{AC}\vec{Z}_{AC} + \vec{I}_{CD}\vec{Z}_{CD} + \vec{I}_{DB}\vec{Z}_{DB} = 0$, giving $\vec{I}_{AC} \approx 111.54 - j103.85$ A.

Industrial Analysis & Voltage Regulation in AC Systems I

In real-world power distribution utilities (such as IEEE standards or municipal utilities), voltage regulation at the consumer end must be maintained within strictly regulated limits (typically $\pm 6\%$ or $\pm 10\%$ of nominal voltage).

Industrial Analysis & Voltage Regulation in AC Systems II

Key Points

- Power factor correction using shunt capacitor banks is strategically placed at the distribution nodes to reduce reactive current component ($I \sin \phi$), thereby decreasing both active/reactive line losses and node voltage drops.
- Loop distributors are analytically treated as distributors fed at both ends with equal voltages ($V_A = V_B$), which drastically minimizes calculations but requires careful modeling of mutual inductances in three-phase systems.
- Modern distribution management systems (DMS) continuously solve these AC load flow equations in real-time using Newton-Raphson or backward-forward sweep algorithms to dynamic control tap-changing transformers (OLTC).

Overhead vs. Underground Transmission I

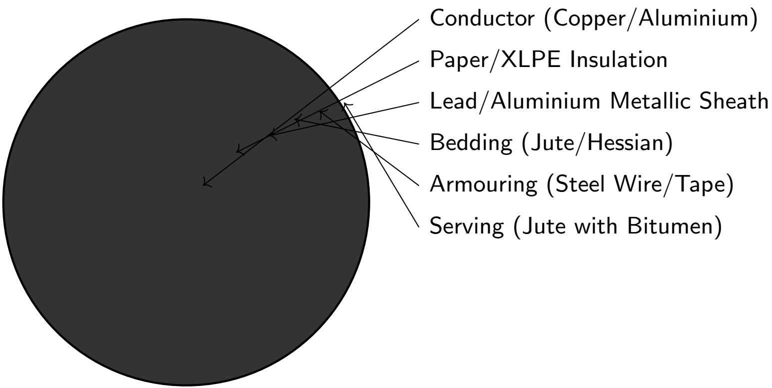
Comparative analysis of transmission systems and the necessity of underground cables.

Overhead vs. Underground Transmission II

Key Points

- Underground cables are necessary in densely populated urban areas, near airports, and in congested metropolitan districts where overhead lines pose safety hazards and aesthetic issues.
- They offer high safety and low vulnerability to environmental factors such as wind storms, lightning, and traffic accidents.
- However, they require significantly higher initial capital cost (approx. 10 to 15 times that of overhead lines) and have complex fault localization.
- System charging current is higher due to larger capacitance $C = \frac{2\pi\varepsilon_0\varepsilon_r}{\ln(D/d)}$ compared to overhead systems.

General Construction of a Single-Core Cable I



General Construction of a Single-Core Cable II

Key Points

- The core/conductor transmits the electrical power and is made of stranded copper or aluminium.
- Insulation (impregnated paper, varnished cambric, or XLPE) prevents leakage currents between conductor and sheath.
- Metallic sheath protects the cable from moisture, acids, or alkalies in the soil.
- Bedding protects the metallic sheath from corrosion and mechanical injury from the armouring.
- Armouring consists of galvanized steel wire or tape to protect the cable from mechanical damage during laying.
- Serving is a layer of fibrous material (like jute) to protect the armouring from atmospheric conditions.

Conductor & Insulation Specifications I

Engineering details on core conductor materials and dielectric properties.

Conductor & Insulation Specifications II

Key Points

- Conductors: Standard conductor materials are stranded Copper (Cu) or Aluminium (Al) to provide flexibility. Electrical conductivity of Cu is higher, meaning smaller diameter cables can be used compared to Al for the same current rating.
- Operating temperature limit: Paper insulation (approx. 65°C to 80°C), XLPE (Cross-linked Polyethylene) up to 90°C under normal load, and 250°C under short-circuit conditions.
- Dielectric Strength: Impregnated paper has a breakdown strength of 20 to 30 kV/mm, whereas XLPE is typically 20 to 40 kV/mm.
- Insulation Thickness (t) calculation: Determined by the maximum electric stress (g_{max}) at the conductor surface, given by: $g_{max} = \frac{2V}{d \ln(D/d)}$ where V is

Protective Layers: Sheath, Bedding, Armour & Serving I

The physical barriers ensuring cable longevity under harsh subterranean conditions.

Protective Layers: Sheath, Bedding, Armour & Serving II

Key Points

- Metallic Sheath: Extruded Lead (Pb), Lead alloy, or Aluminium (Al) is used to create a completely moisture-proof barrier. Since lead is soft and heavy, Aluminium sheaths are sometimes preferred for lighter weight and higher mechanical strength, though they are more prone to corrosion.
- Bedding: Consists of a fibrous material like jute or hessian tape treated with a preservative compound (bitumen). Thickness is typically around 1.5 mm to 2 mm. It prevents galvanic action between the steel armouring and lead sheath.
- Armouring: Steel wire armour (SWA) or double steel tape armour (DSTA) provides high tensile strength to withstand tension during installation and protect

$$g_{max} = \frac{V}{r \ln(R/r)}$$

$$g_{min} = \frac{V}{R \ln(R/r)} \; ;$$

Key Points

- The potential gradient or electric stress (g_x) at any point x in the dielectric is inversely proportional to the distance from the center.
- Stress is maximum (g_{max}) at the conductor surface ($x = r$) and minimum (g_{min}) at the inner sheath surface ($x = R$).
- Ratio of stresses: $\frac{g_{max}}{g_{min}} = \frac{R}{r} = \frac{D}{d}$. A low ratio ensures uniform stress distribution.
- To design a cable with minimum size for a given voltage V and maximum stress g_{max}, the optimum ratio is $R/r = e \approx 2.718$.

Requirements of Insulating Materials I

Key physical and electrical properties required for underground cable insulation.

Requirements of Insulating Materials II

Key Points

- High Insulation Resistance: To avoid leakage currents, resistivity (ρ) must be extremely high (10^{12} to 10^{16} Ω·cm at operating temperature).
- High Dielectric Strength: Must withstand high electric stress without breakdown. Typically needs to be > 20 kV/mm.
- Low Dielectric Loss: Power loss in the insulation ($P_{loss} = \omega C V^2 \tan\delta$) must be minimized to avoid thermal runaway.
- Mechanical Properties: Must be flexible and possess high mechanical strength to withstand bending during transport and installation.
- Chemical Inertness: Non-hygroscopic (does not absorb moisture from soil/air) and non-inflammable, resistant to soil acids and alkalis.

Industrial Applications & Design Limits I

Summary of underground cable applications, advantages, disadvantages, and future trends.

Industrial Applications & Design Limits II

Key Points

- Applications: Crucial for distribution in crowded city streets, railway networks, substation exits, submarine crossings, and offshore wind connections.
- Advantages: Low maintenance cost, neat appearance, less chance of faults from weather, zero risk of direct contact shock.
- Disadvantages: High charging currents due to high capacitance, difficulty in finding and repairing faults, strict limits on operating voltage due to heat dissipation issues.
- Future Trends: Transitioning from traditional oil-filled cables to XLPE (Cross-linked Polyethylene) and superconducting cables for high power density transmission.

Classification by Voltage Rating I

Underground cables are classified into five major classes according to their operating voltage levels.

Classification by Voltage Rating II

Key Points

- Low Tension (L.T.) Cables: Operating voltage up to 1 kV. Used mostly for low-voltage distribution networks.
- High Tension (H.T.) Cables: Operating voltage up to 11 kV. Suitable for primary distribution systems.
- Super Tension (S.T.) Cables: Operating voltage from 22 kV to 33 kV.
- Extra High Tension (E.H.T.) Cables: Operating voltage from 33 kV to 66 kV.
- Extra Super Voltage Cables: Operating voltage beyond 132 kV, typically requiring specialized oil-filled or gas-filled technologies.

Classification by Core Configuration I

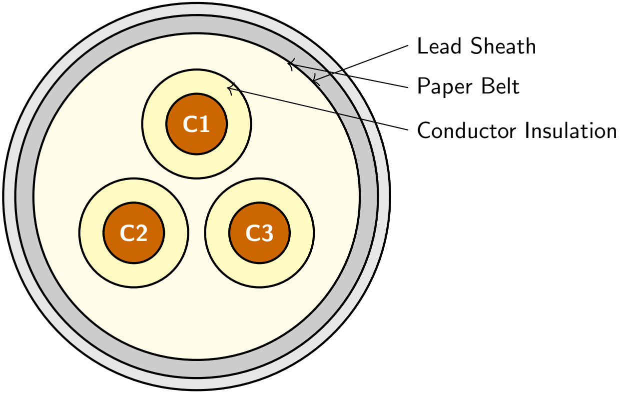
Cables are classified based on the number of conducting cores, dictated by the electrical system configuration (single-phase, three-phase, or three-phase with neutral).

Classification by Core Configuration II

Key Points

- Single-Core Cables: Used for high voltage applications where space is not a constraint and sheath currents can be managed.
- Three-Core Cables: Standard configuration for three-phase balanced or unbalanced three-wire systems.
- Three-and-a-Half Core Cables: Contains three main cores of equal cross-section for phases and one neutral core of half the cross-section ($A_{neutral} = 0.5 \times A_{phase}$) for unbalanced current return in 3-phase, 4-wire systems.
- Four-Core Cables: Used in low-voltage distribution where neutral current is expected to be significant, meaning all four cores have equal cross-sectional areas.

Construction of a Three-Core Belted Cable I



Construction of a Three-Core Belted Cable II

Key Points

- Belted cables are used for voltages up to 22 kV due to high tangential electrostatic stress at higher voltages.
- The spaces between cores are filled with fibrous jute material to provide a circular shape and mechanical stability.
- The paper belt binds the three insulated cores together, providing additional inter-phase and phase-to-earth insulation.
- For voltages > 22 kV, tangential stress (E_{tan}) causes dielectric breakdown along paper laminations, necessitating screened or pressure cables.

Classification by Dielectric Medium I

The selection of insulation dictates the thermal limits, current rating, and maximum voltage class of the transmission cable.

Classification by Dielectric Medium II

Key Points

- Paper Insulation: High dielectric strength, low dielectric loss, but highly hygroscopic. Requires a moisture-proof lead or aluminum sheath (PILC cables). Maximum continuous conductor temperature is around 70°C to 80°C.
- Polyvinyl Chloride (PVC) Insulation: Widely used for low-voltage (L.T.) distribution. Excellent chemical resistance and flame retardant properties, but has high dielectric constant and losses, limiting it to under 11 kV.
- Cross-linked Polyethylene (XLPE) Insulation: The modern standard for high-voltage and extra-high-voltage systems. Thermosetting polymer with a high continuous operating temperature limit of 90°C (and 250°C under short-circuit conditions).
- Ethylene Propylene Rubber (EPR): Highly flexible.

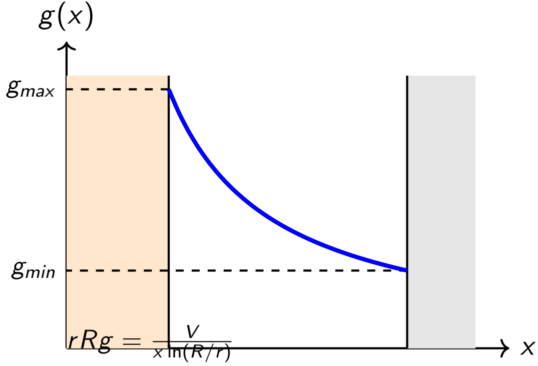
In a single-core cable, the electrostatic stress (electric field intensity g) at a distance x from the center of the conductor of radius r is given by the relation: $g = \frac{V}{x \ln(R/r)}$

Electrostatic Stress & Grading of Cables II

Key Points

- Max Stress (g_{max}): Occurs at the conductor surface where $x = r$, yielding $g_{max} = \frac{V}{r \ln(R/r)}$.
- Min Stress (g_{min}): Occurs at the inner surface of the sheath where $x = R$, yielding $g_{min} = \frac{V}{R \ln(R/r)}$.
- Stress Ratio: $\frac{g_{max}}{g_{min}} = \frac{R}{r}$. A high ratio signifies highly non-uniform stress distribution.
- For a given operating voltage V and sheath radius R, the conductor radius r is optimized when $\ln(R/r) = 1$, which implies $R/r = e \approx 2.718$. This minimizes the maximum stress at the conductor surface.

Radial Electrostatic Stress Distribution I



Radial Electrostatic Stress Distribution II

Key Points

- The electrostatic stress distribution is highly non-uniform, peaking at the conductor boundary ($x = r$) and decaying hyperbolically towards the sheath boundary ($x = R$).
- Grading of cables is the process of achieving uniform electrostatic stress distribution in the cable dielectric.
- Capacitance Grading: Employs multiple layers of different dielectrics with varying permittivity (ε), satisfying $\varepsilon_1 > \varepsilon_2 > \varepsilon_3$ such that $\varepsilon_1 r = \varepsilon_2 r_1 = \varepsilon_3 r_2$.
- Intersheath Grading: Uses a homogeneous dielectric material separated by metallic intersheaths held at intermediate electrical potentials via external tapping or capacitive division.

Screened and Pressure Cable Types I

For voltages exceeding 22 kV, specialized constructions are utilized to eliminate void formation, control radial stress, and manage high thermal dissipation.

Screened and Pressure Cable Types II

Key Points

- H-Type Cables (Hochstadter): Consist of perforated metallic foils surrounding each core's paper insulation. The foils are connected together and grounded to the lead sheath, eliminating tangential electric stresses and converting them to purely radial stresses.
- S.L. Type Cables (Separate Lead): Each core has its own individual thin lead sheath. Offers better heat dissipation, allows greater bending flexibility, and reduces mechanical damage during installation.
- Oil-Filled Cables: Contain channels through which low-viscosity oil flows under pressure (typically 1 to 4 bar). Voids are immediately filled with oil, raising dielectric strength and allowing ratings up to 400 kV.
- Gas-Filled Cables: Utilize dry nitrogen gas under high pressure (12 to 15 bar) within the sheath. The gas

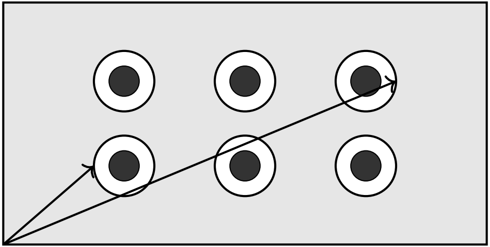
The direct laying method involves digging a trench in the ground and laying the cable directly on a protective bed of sand, covered with bricks or concrete slabs for mechanical protection.

Direct Laying (Trenching) Method II

Key Points

- Trench depth: Typically 0.9 m to 1.2 m for high-voltage cables (> 11 kV) to avoid damage from heavy surface traffic and farming.
- A 10 cm bed of fine sand is laid at the bottom of the trench to act as a cushion, preventing sharp stones from damaging the outer sheath.
- Protective coverings: Concrete slabs, tiles, or bricks are placed over the sand layer above the cable to provide warning and mechanical protection against subsequent excavations.
- Advantages: Simple, cheapest method, facilitates rapid heat dissipation due to direct contact with surrounding soil (lower soil thermal resistance θ_g).
- Disadvantages: Localization and repair of faults is expensive, requires reopening the trench, and is not

The Draw-in System of Cable Laying I



The Draw-in System of Cable Laying II

Key Points

- Used primarily in congested urban areas where frequent excavation is impossible or highly disruptive.
- Cables are pulled through conduits/pipes (made of glazed stoneware, cement concrete, or PVC) laid in concrete blocks.
- Manholes are provided at regular intervals (typically 50 m to 100 m) along the route to facilitate pulling, splicing, and inspection.
- High safety and lower cost of future cable replacements, as no excavation is needed; old cables can be pulled out and new ones drawn in.
- Thermal limitation: Poor heat dissipation due to air gap inside the duct, reducing the current carrying capacity compared to direct laying ($I \propto 1/\sqrt{R_{th}}$).

The Solid System of Cable Laying I

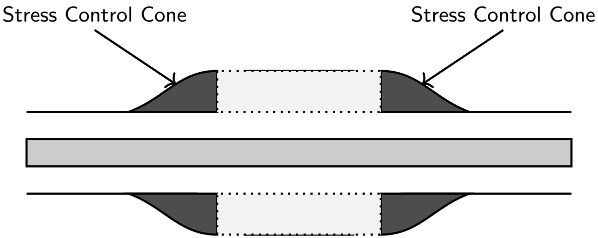
In the solid system, the cable is laid in open troughs made of cast iron, stoneware, or treated wood. Once the cable is positioned, the trough is completely filled with a bituminous or asphaltic compound.

The Solid System of Cable Laying II

Key Points

- The bituminous compound acts as an additional impervious barrier, protecting the cable sheath against chemical attack, moisture ingress, and soil corrosion.
- Provides excellent mechanical protection, making it highly reliable in areas with acidic soil or chemical contamination.
- Requires highly skilled labor to melt and pour the compound uniformly without creating voids or air pockets.
- Very high initial cost and difficult repair procedures, since the solid compound must be broken or melted away to access a faulted section.
- Heat dissipation is poor because the bituminous compound acts as an additional thermal insulator, lowering the continuous current rating of the cable.

Electrical Stress Control in HV Joints I



Electrical Stress Control in HV Joints II

Key Points

- When a cable is cut for jointing, the electrostatic shield is terminated, creating high electric field concentration at the shield cutback.
- The maximum electric field E_{max} occurs at the conductor surface and is given by: $E_{max} = \frac{V}{r \ln(R/r)}$, where V is applied voltage, r is conductor radius, and R is inner sheath radius.
- Stress control cones or high-permittivity materials (refractive stress control) are utilized to redistribute the equipotential lines and prevent electrical breakdown.
- The stress cone increases the effective radius of the shield terminal, thereby reducing the longitudinal electrical stress along the insulation interface.
- Improper stress control installation leads to partial discharges (PD), treeing, and ultimate dielectric

Types of Cable Joints and Splices I

Cable joints are classified based on function, mechanical design, and application. The choice of joint depends on operating voltage, cable type (paper insulated PILC, polymer XLPE/EPR), and environmental exposure.

Types of Cable Joints and Splices II

Key Points

- Straight-through joints: Used to connect two lengths of similar cables to form a continuous run, ensuring mechanical and electrical continuity of conductor, screen, and sheath.
- Tee (Branch) joints: Utilized in distribution systems to branch off a main cable feeder to supply a customer or substation without cutting the main line.
- Potheads / Terminations: Specialized joints that transition an underground cable to an overhead line or connect it to substation switchgear/transformers.
- Cold-shrink vs. Heat-shrink joints: Heat-shrink uses thermoplastic tubes shrunk using a propane torch; cold-shrink uses pre-stretched elastomeric sleeves on a removable plastic core.
- Transition joints: Designed to connect different cable

Requirements of a Reliable Cable Joint I

A cable joint is historically the weakest link in an underground network. A reliable joint must maintain the same electrical, thermal, and mechanical integrity as the parent cable.

Requirements of a Reliable Cable Joint II

Key Points

- Low Electrical Resistance: The contact resistance $R_{contact}$ of the jointed conductor must be less than or equal to an equivalent length of continuous conductor to prevent local hot spots.
- High Dielectric Strength: The joint insulation must withstand operating AC voltage, impulse voltages, and transient overvoltages without dielectric breakdown.
- Mechanical Strength: The mechanical tensile strength of the joint must be at least 70% of the parent cable to withstand ground settlement or thermal expansion forces.
- Hermetic Sealing: Moisture ingress is the primary cause of insulation failure (especially in paper/XLPE). Joints must be completely sealed using mastic sealants or resin casts.

Practical Jointing & Laying Precautions I

Adherence to precise installation protocols is essential to prevent premature cable failures. Testing and inspection must be carried out pre- and post-installation.

Practical Jointing & Laying Precautions II

Key Points

- Bending Radius: Never bend a cable below its minimum bending radius ($R_{min} \approx 12$ to $20 \times D$, where D is overall cable diameter) to avoid damage to insulation/sheath.
- Pulling Tension: Max pulling tension T_{max} must not exceed the limit of the conductor material: $T_{max} = \sigma \times A$, where $\sigma \approx 50$ N/mm^2 for copper and A is cross-sectional area.
- Moisture Protection: Jointing should never be performed in rainy or humid conditions without a shelter, as moisture film on insulation surfaces causes electrical tracking.
- Cleanliness: Absolute cleanliness of tools, hands, and cable insulation surfaces is mandatory; even microscopic conductive/dust particles act as stress concentrators.
- Post Installation Testing: Insulation resistance (Megger)

Composition of Power Cables & The Need for Recycling I

High-voltage and medium-voltage power cables contain valuable metals and complex polymeric insulation that cannot simply be landfilled due to environmental hazards and economic loss.

Composition of Power Cables & The Need for Recycling II

Key Points

- Conductive Core: Typically contains high-purity copper (99.9%) or electrical-grade aluminum (99.5%), which have high scrap value.
- Insulation Layers: Formulated using Cross-linked Polyethylene (XLPE), Polyvinyl Chloride (PVC), Paper Insulated Lead Covered (PILC), or Ethylene Propylene Rubber (EPR).
- Shielding and Armoring: Consists of lead sheaths, steel tape/wire armoring, and copper wire screens for mechanical and electromagnetic protection.
- Sustainability Imperative: Prevents heavy metal pollution (e.g., lead from PILC cables) and significantly reduces greenhouse gas emissions compared to primary smelting (≈ 85% savings for Cu).

Mechanical Shredding & Separation Flowsheet I

(Shearing to 50-100 mm);
ode (gran) at (0, -3.0) Secondary Granulation
(Reduction to ¡5 mm);
ode (dens) at (0, -4.5) Density Separation
(Air/Water Tables);
ode (metal) at (3.5, -4.5) [fill=yellow!15] Heavy Fraction
(Copper/Aluminum);
ode (plastic) at (-3.5, -4.5) [fill=red!10] Light Fraction
(PVC/XLPE Fines); [-¿, ¿=stealth, thick] (in) – (shred); [-¿, ¿=stealth, thick] (shred) – (gran); [-¿, ¿=stealth, thick] (gran) – (dens); [-¿, ¿=stealth, thick] (dens) – (metal); [-¿, ¿=stealth, thick] (dens) – (plastic);

Key Points

- Step 1 (Pre-shredding): Rotary cutters shear heavy armored cables into manageable segments.
- Step 2 (Granulation): High-speed granulators reduce materials to fine particle sizes to liberate metals from insulation.
- Step 3 (Air Classification): Gravity separators use fluidizing air and vibration to separate dense metals from lighter plastics.
- Recovery Efficiency: Mechanical processing yields up to $98 - 99\%$ metal purity if the feedstock is properly classified.

Pyrolysis is a thermochemical process that decomposes the organic polymer matrix of cable insulation under an inert atmosphere (absence of oxygen) to recover metals without oxidation.

Pyrolysis & Thermal Degradation of Insulation II

Key Points

- Reaction Atmosphere: Conducted in nitrogen or vacuum at temperatures ranging from 400°C to 700°C.
- Chemical Equation: Polymer (XLPE/PVC) $\xrightarrow{\Delta,\ \text{No } O_2}$ Pyrolytic Gas + Pyrolytic Oil + Char + Metals.
- Metal Quality Preservation: Unlike open burning, pyrolysis prevents the oxidation of copper to CuO or Cu_2O, preserving its high conductivity and market value.
- Byproduct Utilization: The volatile organic gases produced can be condensed into pyrolytic oil or combusted to supply the process heat, enhancing thermal efficiency.

(Liquid Nitrogen Bath at -196°C);
ode (shat) at (0, -3.0) Hammer Mill / Shatter Mill (High-velocity impact);
ode (sep) at (0, -4.5) Vibrating Screen &Separator;
ode (cu) at (3.5, -4.5) [fill=yellow!15] Clean Copper/Aluminum (High Purity);
ode (pl) at (-3.5, -4.5) [fill=red!10] Polymer Powder (Clean XLPE/PVC); [-¿, ¿=stealth, thick] (in) – (cryo); [-¿, ¿=stealth, thick] (cryo) – (shat); [-¿, ¿=stealth, thick] (shat) – (sep); [-¿, ¿=stealth, thick] (sep) – (cu); [-¿, ¿=stealth, thick] (sep) – (pl);

Key Points

- Glass Transition Principle: Polymer insulation is cooled below its glass transition temperature ($T_g \approx -40^{\circ}$C to -110°C), rendering it extremely brittle.
- Ductility Retention: Metals (Copper and Aluminum) remain ductile at these low temperatures, preventing metal dusting or loss.
- Delamination: Upon impact in the hammer mill, the frozen, brittle polymer shell shatters instantly and cleanly detaches from the metallic core.
- Purity: Produces extremely clean copper fractions ($> 99.9\%$) with zero thermal degradation or gas emissions.

Recycling of Lead-Sheathed & Paper-Insulated Cables I

Paper-Insulated Lead-Covered (PILC) cables were widely used in old distribution networks. Recycling them requires specialized containment and processing to handle hazardous lead and oil-impregnated paper.

Recycling of Lead-Sheathed & Paper-Insulated Cables II

Key Points

- Lead Sheath Recovery: Lead ($T_m \approx 327.5^\circ$C) is stripped mechanically or melted at low temperatures, ensuring zero lead volatilization (which occurs at $> 600^\circ$C).
- Oil-Impregnated Paper: The paper insulation contains hydrocarbon-based insulating oils, requiring solvent extraction or controlled thermal treatment to prevent soil/water contamination.
- Hydrometallurgical Refining: Recovered lead undergoes electrorefining or pyrometallurgical refining to remove copper and antimony impurities, restoring it to battery-grade purity ($> 99.97\%$, ASTM B29).
- Environmental Protection: Strict ventilation and

Environmental Regulations & Halogenated Plastics I

Recycling plastic cable insulation, especially Polyvinyl Chloride (PVC), presents significant environmental challenges due to the release of toxic halogens and plasticizers during thermal treatment.

Environmental Regulations & Halogenated Plastics II

Key Points

- Dehydrochlorination of PVC: When PVC is heated above 250°C, it undergoes thermal degradation releasing corrosive hydrochloric acid gas: $\text{-(CH}_2\text{-CHCl)-}_n \xrightarrow{\Delta} \text{-(CH=CH)-}_n + n\text{HCl}$.
- Dioxin and Furan Formation: Incomplete combustion of chlorinated polymers leads to the emission of highly carcinogenic polychlorinated dibenzo-p-dioxins (PCDD) and dibenzofurans (PCDF).
- Acid Gas Scrubbing: Wet scrubbers using alkaline solutions (e.g., sodium hydroxide NaOH or calcium hydroxide $Ca(OH)_2$) are required to neutralize acid gases: $HCl + NaOH \rightarrow NaCl + H_2O$.
- XLPE Recycling Bottlenecks: Cross-linked Polyethylene (XLPE) cannot be remelted like thermoplastic PE because of its 3D thermoset network, requiring

Circular Economy & Economic Feasibility I

The economics of cable recycling are driven by the high commodity prices of copper and aluminum, balanced against the operational costs of sorting, shredding, and environmental compliance.

Circular Economy & Economic Feasibility II

Key Points

- Resource Efficiency Index: Recycling copper consumes only about 15% of the energy required for primary copper mining and refining ($E_{\text{primary}} \approx 30 - 85$ MJ/kg vs. $E_{\text{recycling}} \approx 10$ MJ/kg).
- Cost-Benefit Analysis: ROI is heavily dependent on throughput volume and the purity of recovered metals. High-purity scrap copper commands up to 95% of the London Metal Exchange (LME) spot price.
- Design for Recycling (DfR): Modern cable manufacturing trends focus on using halogen-free flame-retardant (HFFR) compounds and thermoplastic elastomers (TPE) that are easier to recycle than XLPE and PVC.
- Extended Producer Responsibility (EPR): Regulatory frameworks enforce that utilities and manufacturers