Lossless Transmission Line

$$V_x = \cosh(\gamma x)V_R + Z_C \sinh(\gamma x)I_R$$

In loss less line, resistance is assumed to be zero

$$Z_C = \sqrt{\frac{R + j\omega L}{j\omega C}}$$

$$R = 0 \quad \Rightarrow \quad Z_C = \sqrt{\frac{j\omega L}{j\omega C}} = \sqrt{\frac{L}{C}}$$

$$\gamma\, x = \alpha x + j\beta x \quad \Rightarrow \quad \gamma\, x = j\beta x$$

$$\cosh(\alpha l + j\beta l) = \cosh(\alpha l)\cos(\beta l) + j\sinh(\alpha l)\sin(\beta l)$$

$$\sinh(\alpha l + j\beta l) = \sinh(\alpha l)\cos(\beta l) + j\cosh(\alpha l)\sin(\beta l)$$

$$V_x = \cos(\beta x)V_R + jZ_C \sin(\beta x)I_R$$

Surge Impedance Loading

- *Characteristic impedance* of a line is also called as *surge impedance* for the special case of loss less line.

$$Z_C = \sqrt{\frac{L}{C}} \qquad SIL = P_n = \frac{V_0^2}{Z_C}$$

- The term **surge impedance loading** or ***SIL*** is often used to indicate the nominal capacity of the line.
- The term ***SIL*** or **natural power** is a measure of power delivered by a transmission line when terminated by surge impedance.
- It is convenient to express the power transmitted in terms of per unit of SIL.

Surge Impedance Loading

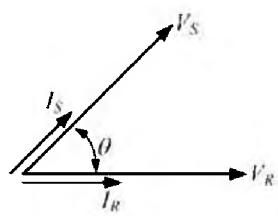
$$V_x = \cos(\beta x)V_R + jZ_C \sin(\beta x)I_R$$
$$I_x = j(1/Z_C)\sin(\beta x)V_R + \cos(\beta x)I_R$$

➢ If the line is terminated with surge impedance Z_c :

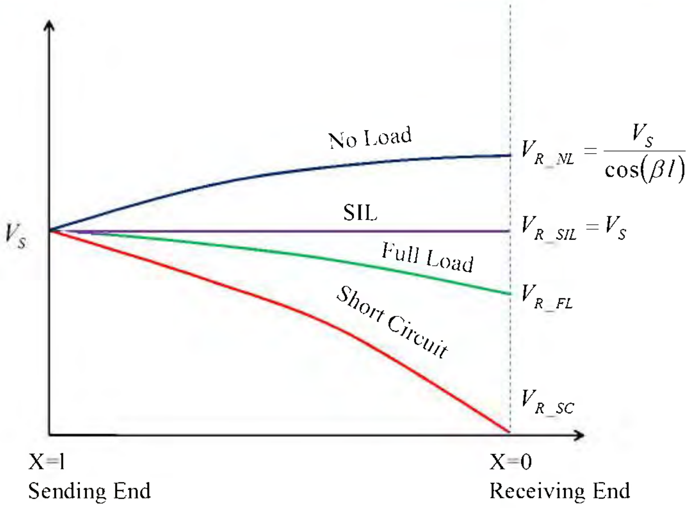
$$V_R = Z_C I_R \quad \Rightarrow \quad Z_C = \frac{V_R}{I_R}$$

$$V_x = V_R(\cos(\beta x) + j\sin(\beta x)) = V_R e^{-j\beta x}$$
$$I_x = I_R(\cos(\beta x) + j\sin(\beta x)) = I_R e^{-j\beta x}$$

$$V_S = V_R e^{-j\beta l}$$
$$I_S = I_R e^{-j\beta l}$$



Comparison of Different Loading

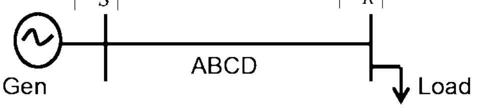


Surge Impedance Loading

Voltage Level (kV)	SIL (MW)	Thermal Limit (MVA)
132	50	94
220	132	237
400	515	948
765	2200	4261

Power Transfer Through Transmission Line

$|V_S|\angle\delta$ $\qquad$ $|V_R|\angle 0$



$S_S = P_S + jQ_S \qquad S_R = P_R + jQ_R$

$$V_S = AV_R + BI_R \quad \Rightarrow \quad I_R = \frac{V_S}{B} - \frac{AV_R}{B}$$

Let $A = |A|\angle\alpha$ and $B = |B|\angle\beta$

$$I_R = \frac{|V_S|}{|B|}\angle(\delta - \beta) - \frac{|A||V_R|}{|B|}\angle(\alpha - \beta)$$

Power Flow Through Transmission Line

$$I_R^* = \frac{|V_S|}{|B|}\angle(\beta-\delta) - \frac{|A||V_R|}{|B|}\angle(\beta-\alpha)$$

- Complex power $V_R I_R^*$ at receiving end:

$$V_R I_R^* = P_R + jQ_R = \frac{|V_S||V_R|}{|B|}\angle(\beta-\delta) - \frac{|A||V_R|^2}{|B|}\angle(\beta-\alpha)$$

Real Part: $$P_R = \frac{|V_S||V_R|}{|B|}\cos(\beta-\delta) - \frac{|A||V_R|^2}{|B|}\cos(\beta-\alpha)$$

Imaginary Part $$Q_R = \frac{|V_S||V_R|}{|B|}\sin(\beta-\delta) - \frac{|A||V_R|^2}{|B|}\sin(\beta-\alpha)$$

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Power Flow Through Transmission Line

Real Part: $$P_R = \frac{|V_S||V_R|}{|B|}\cos(\beta-\delta) - \frac{|A||V_R|^2}{|B|}\cos(\beta-\alpha)$$

Imaginary Part $$Q_R = \frac{|V_S||V_R|}{|B|}\sin(\beta-\delta) - \frac{|A||V_R|^2}{|B|}\sin(\beta-\alpha)$$

- Maximum power will get transferred, if $\beta=\delta$

$$P_{R\_max} = \frac{|V_S||V_R|}{|B|} - \frac{|A||V_R|^2}{|B|}\cos(\beta-\alpha)$$

$$Q_{R\_max} = -\frac{|A||V_R|^2}{|B|}\sin(\beta-\alpha)$$

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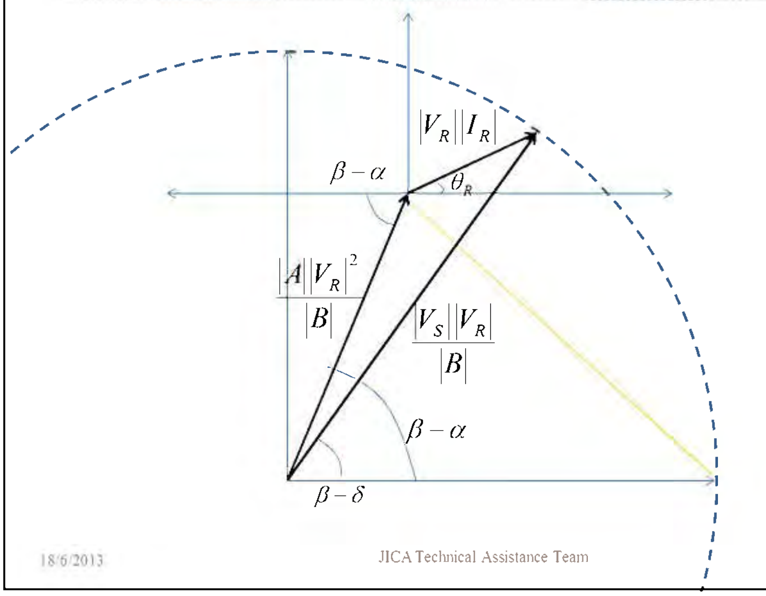
Receiving End Circle Diagram



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Maximum Power in Short Line Approximation

$$P_{R\_max} = \frac{|V_S||V_R|}{|B|} - \frac{|A||V_R|^2}{|B|}\cos(\beta - \alpha)$$

For Short line A=1, B=Z, C=0, D=1

Assuming X/R ratio is high enough to neglect resistance

$$A = D = 1\angle 0, \quad B = |Z|\angle\theta, \quad C = 0, \quad \cos\theta = R/|Z|$$

$$P_{R\_max} = \frac{|V_S||V_R|}{|Z|} - \frac{|V_R|^2}{|Z|}\cos(\theta) = \frac{|V_S||V_R|}{|Z|} - \frac{|V_R|^2}{|Z|^2}R$$

$$Q_{R\_max} = -\frac{|A||V_R|^2}{|B|}\sin(\theta)$$

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With large X/R Ratio

$$P_R = \frac{|V_S||V_R|}{|B|}\cos(\beta - \delta) - \frac{|A||V_R|^2}{|B|}\cos(\beta - \alpha)$$

$$Q_R = \frac{|V_S||V_R|}{|B|}\sin(\beta - \delta) - \frac{|A||V_R|^2}{|B|}\sin(\beta - \alpha)$$

Generally, $R << X$ then $Z = jX$

$A = D = 1\angle 0,\quad B = |X|\angle 90,\quad C = 0,$

$$P_R = \frac{|V_S||V_R|}{|X|}\sin\delta \quad \Rightarrow \quad P_{R\_max} = \frac{|V_S||V_R|}{|X|}$$

$$Q_R = \frac{|V_S||V_R|}{|X|}\cos(\delta) - \frac{|V_R|^2}{|X|} \quad \Rightarrow \quad Q_R = \frac{|V_R|}{|X|}(|V_S| - |V_R|) = \frac{|V_R|}{|X|}|\Delta V|$$

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Sending End Power

$I_S = CV_R + DI_R$ but $I_R = \dfrac{V_S}{B} - \dfrac{AV_R}{B}$

$$I_S = CV_R + \frac{D}{B}V_S - \frac{DA}{B}V_R$$

$$= \frac{D}{B}V_S - \frac{V_R(AD - BC)}{B}$$

$$I_S = \frac{DV_S}{B} - \frac{V_R}{B}$$

- Complex power $V_S I_S^*$ at receiving end:

Let $A = D = |A|\angle\alpha$ and $B = |B|\angle\beta$

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Sending End Power

$$V_S I_S^* = P_S + jQ_S = \frac{|A||V_S|^2}{|B|}\angle(\beta-\alpha) - \frac{|V_S||V_R|}{|B|}\angle(\delta+\beta)$$

Real Part:

$$P_S = \frac{|A||V_S|^2}{|B|}\cos(\beta-\alpha) - \frac{|V_S||V_R|}{|B|}\cos(\delta+\beta)$$

Imaginary Part

$$Q_S = \frac{|A||V_S|^2}{|B|}\sin(\beta-\alpha) - \frac{|V_S||V_R|}{|B|}\sin(\delta+\beta)$$

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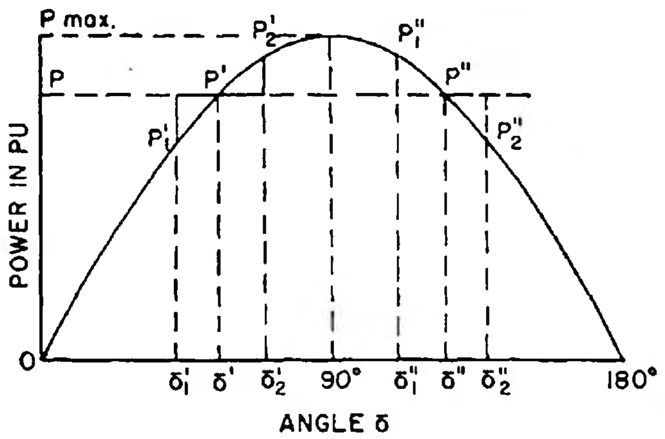
Steady State Stability Limit



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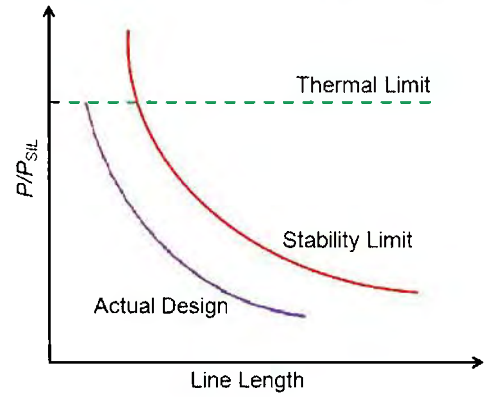
Power Transfer Capability



- Thermal Limit
- Voltage drop limit
- Stability limit

Actual Design

$$P_R = \frac{|V_S||V_R|}{|B|}\sin\delta = \frac{|V_R|^2}{|Z_c\sin(\beta l)|}\sin\delta = SIL\frac{\sin\delta}{\sin(\beta l)}$$

Main Objectives

- Choice of voltage, choice of conductor, spacing between conductors
- Calculation line constants, regulation and efficiency
- Calculation of Corona Loss
- Choosing number and type of insulators
- Choice of method of grounding
- Calculation of radio interference
- Stability considerations
- Electrostatic and electromagnetic effect
- Insulation coordination
- Protective system

Main Components of Overhead Line

- Conductors
  - Copper
  - Aluminum: ACSR, AAAR, AAC, Expanded ACSR
- Support Structure (Towers)
  - Galvanized steel (for high voltage)
  - Wood, concrete, steel (for low voltage)
- Insulators
  - Porcelain
  - Glass
  - Polymer insulation

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Mechanical Design

- Main Factors
  - Selection of line route
  - Types of tower or pole
  - Right of way
  - Ground and conductor clearance
  - Tower spacing, span length
  - Mechanical loadings
    - Weight of conductor per unit length
    - Load due to wind, ice, snow, etc.
    - Temperature
    - Conductor tension
    - Distance between the supports (Span length)

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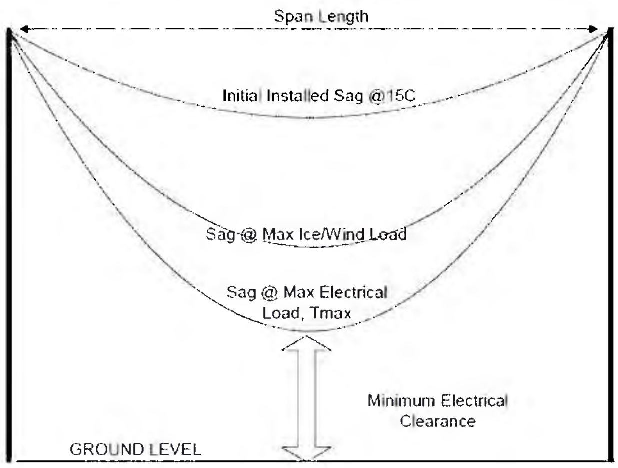
Sag and Tension:

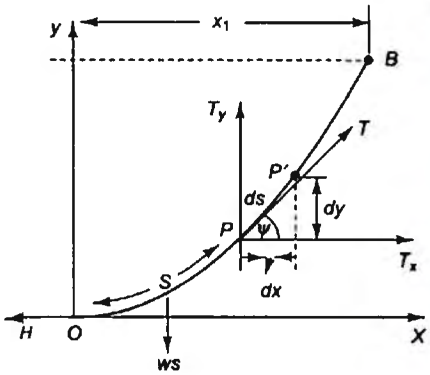


Maximum sag so that clearance to ground and other conductors can be maintained.

Maximum tension so that structures can be designed to withstand it.

Minimum sag to control structure uplift problems.

Calculation of Sag and Tension



$$H = T_x$$

$$T_y = ws$$

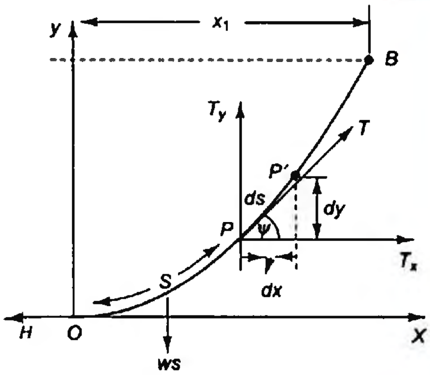
$$\tan \psi = dy/dx = T_y/T_x = ws/H$$

$$ds^2 = dx^2 + dy^2$$

$$\frac{ds^2}{dx^2} = 1 + \frac{dy^2}{dx^2}$$

$$\frac{ds}{dx} = \sqrt{1 + (dy/dx)^2} \Rightarrow \frac{ds}{dx} = \sqrt{1 + w^2 s^2 / H^2} \Rightarrow dx = \frac{ds}{\sqrt{1 + w^2 s^2 / H^2}}$$

Calculation of Sag and Tension



$$\int dx = \int \frac{ds}{\sqrt{1 + w^2 s^2 / H^2}}$$

Integrating

$$x + c_1 = \frac{H}{w} \sinh^{-1}\left(\frac{ws}{H}\right);$$

At $x=0$, $s=0$, therefore $c_1=0$

$$x = \frac{H}{w} \sinh^{-1}\left(\frac{ws}{H}\right)$$

$$s = \frac{H}{w} \sinh \frac{wx}{H}$$

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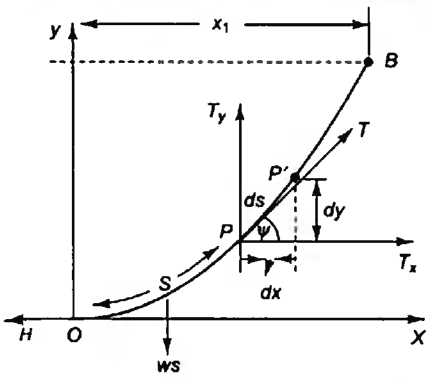
Calculation of Sag and Tension



$$s = \frac{H}{w} \sinh \frac{wx}{H}$$

$$\frac{ws}{H} = \sinh\left(\frac{wx}{H}\right)$$

Also $\frac{dy}{dx} = \frac{ws}{H}$

$$\frac{dy}{dx} = \sinh\left(\frac{wx}{H}\right)$$

$$dy = \sinh \frac{wx}{H} dx$$

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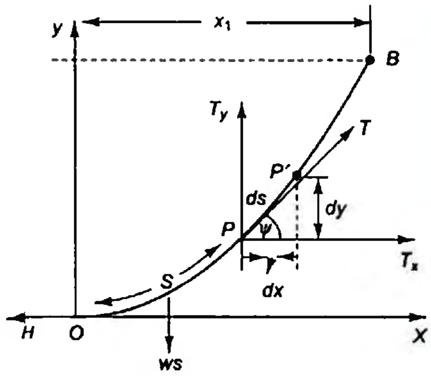
Calculation of Sag and Tension



$$\int dy = \int \sinh \frac{wx}{H}\, dx$$

Integrating

$$y = \frac{H}{w} \cosh\left(\frac{wx}{H}\right) + c_2$$

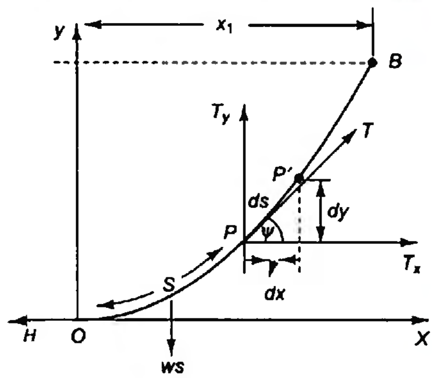
At y=0, x=0, therefore

$$c_2 = -\frac{H}{w}$$

$$y = \frac{H}{w} \cosh\left(\frac{wx}{H}\right) - \frac{H}{w}$$

$$y = \frac{H}{w}\left(\cosh \frac{wx}{H} - 1\right)$$

Calculation of Sag and Tension



For tension at point P,

$$T^2 = T_x^2 + T_y^2$$

$$= H^2 + w^2 s^2$$

We know $s = \frac{H}{w} \sinh \frac{wx}{H}$

$$T^2 = H^2 + H^2 \sinh^2\left(\frac{wx}{H}\right)$$

$$= H^2\left(1 + \sinh^2\left(\frac{wx}{H}\right)\right)$$

$$T^2 = H^2 \cosh^2\left(\frac{wx}{H}\right)$$

$$T = H \cosh \frac{wx}{H}$$

Support at Same Heights

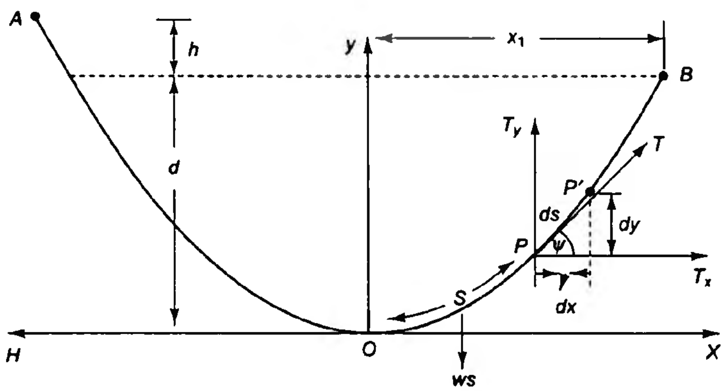
If the towers at same height and span is $2l$, i.e. half span is l

$$s = \frac{H}{w}\sinh\frac{wx}{H} \Rightarrow S = \frac{H}{w}\sinh\left(\frac{wl}{H}\right)$$

$$y = \frac{H}{w}\left(\cosh\frac{wx}{H} - 1\right) \Rightarrow d = \frac{H}{w}\left(\cosh\frac{wl}{H} - 1\right)$$

$$T = H\cosh\frac{wx}{H} \Rightarrow H\cosh\frac{wl}{H}$$

Supports at Different Heights



Supports at Different Heights

For tower B ⇒ $y_B = \frac{H}{w}\left(\cosh\frac{wx_1}{H} - 1\right)$ | $y = \frac{H}{w}\left(\cosh\frac{wx}{H} - 1\right)$

For tower A ⇒ $y_A = d + h = \frac{H}{w}\left(\cosh\frac{w(2l - x_1)}{H} - 1\right)$

Therefore, difference in tower heights

$$h = \frac{H}{w}\left(\cosh\frac{w(2l - x_1)}{H} - \cosh\frac{wx_1}{H}\right)$$

$$= \frac{2H}{w}\sinh\frac{wl}{H}\sinh\frac{w(l - x_1)}{H}$$

Approximate Formulae for Sag and Tension

$H\cosh\frac{wl}{H}$ ⇒ $T \approx H\left(1 + \frac{w^2l^2}{2H^2}\right)$ ⇒ $T \approx H$

$d = \frac{H}{w}\left(\cosh\frac{wl}{H} - 1\right)$ ⇒ $d \approx \frac{H}{w}\left(1 + \frac{w^2l^2}{2H^2} - 1\right)$ ⇒ $d \approx \frac{wl^2}{2H}$

$S = \frac{H}{w}\sinh\left(\frac{wl}{H}\right)$ ⇒ $S \approx \frac{H}{w}\left(\frac{wl}{H} + \frac{w^3l^3}{6H^3}\right)$ ⇒ $S \approx l + \frac{w^2l^3}{6H^2}$

$T \approx H$ ⇒ $d \approx \frac{wl^2}{2T}$ and $S \approx l + \frac{w^2l^3}{6T^2}$

$$\sinh x = x + \frac{x^3}{3!} + \frac{x^5}{5!} + \frac{x^7}{7!} + \cdots \quad \text{and} \quad \cosh x = 1 + \frac{x^2}{2!} + \frac{x^4}{4!} + \frac{x^6}{6!} + \cdots$$

Parabolic Approximation

- In case of short spans (distribution lines) with small sag (less than 10%), the curve can be considered as parabola.
  - Sag less than 6% could give only 0.5% error
  - Sag between 6-10 % could give only 2% error

$$y = \frac{H}{w}\left(\cosh\frac{wx}{H} - 1\right) \approx \frac{H}{w}\left(1 + \frac{w^2x^2}{2H^2} - 1\right) \Rightarrow y \approx \frac{wx^2}{2H}$$

$$y \approx \frac{wx^2}{2T} \qquad T \approx H$$

Effect of Ice Covering and Wind

- If the ice thickness is more than 0.5 cm then it is considered.
- Effect of ice covering (w_i) is to increase the weight of conductor (w_c) , and thus increases the vertical sag.
- If r is radius of conductor and t is thickness of ice layer.

$$V_i = \pi(r+t)^2 - \pi r^2$$
$$= \pi(r^2 + 2rt + t^2 - r^2)$$
$$= \pi(t^2 + 2rt) \text{ m}^3$$

If ρ is the density of ice

$$W_i = \pi\rho(t^2 + 2rt) \quad \text{kg/m}$$

Therefore, total weight (W_T)

$$W_T = W_c + W_i$$

Effect of Ice Covering and Wind

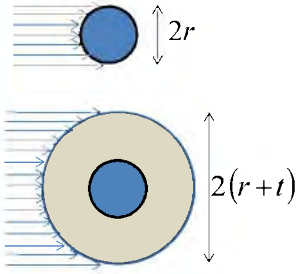
- The wind pressure acts on the conductor in horizontal direction. Assume that wind blows uniformaly.
- If p is the wind pressure, wind loading (w_w)

Conductor alone: $w_w = 2rp$ kg/m

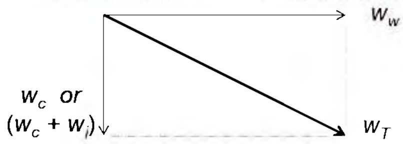
Conductor + Ice: $w_w = 2(r+t)p$ kg/m

- The wind pressure depends on the velocity of the wind.

$$p = 0.006v^2 \text{ kg/m}^2$$



Effect of Ice Covering and Wind



- The resultant weight of the conductor is:

Conductor alone: $w_T = \sqrt{w_c^2 + w_w^2}$ kg/m

Conductor + Ice: $w_T = \sqrt{(w_c + w_i)^2 + w_w^2}$ kg/m

- The angle at which loading is acting is:

Conductor alone: $\phi = \tan^{-1}(w_w / w_c)$

Conductor + Ice: $\phi = \tan^{-1}(w_w / (w_c + w_i))$

Stringing Chart

- The curves of sag and tension with temperature variation are called the *Stringing Charts*.
- Stringing chart is helpful in providing sag and tension at any temperature, if the sag and tension is know at any particular temperature.
- They are useful in erecting line conductors at specified temperature and loading conditions.
- At high temperature, sag is more and tension is less whereas at low temperature sag is less but tension is more.

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Stringing Chart

w	Load per unit length
f	Stress (tension per mm^2)
S	Conductor length (half span)
d	Sag
θ	Temperature
A	Area of cross section of conductor
α	Coefficient of linear expansion
E	Young's modulus

- Subscripts 1 and 2 denote temperatures at maximum load conditions and under stringing conditions (installation or erection of transmission line).

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Stringing Chart

- For short spans
- $d \approx \dfrac{w\,l^2}{2T}$ and $S \approx l + \dfrac{w^2\,l^3}{6\,T^2}$ $\xrightarrow{T=Af}$ $S = l + \dfrac{w^2 l^3}{6A^2 f^2}$
- At temperature θ_1

$$S_1 = l + \frac{w_1{}^2 l^3}{6A^2 f_1{}^2} \quad \text{and} \quad d_1 = \frac{w_1\, l^2}{2A\, f_1}$$

- At temperature θ_2

$$S_2 = l + \frac{w_2{}^2 l^3}{6A^2 f_2{}^2} \quad \text{and} \quad d_2 = \frac{w_2\, l^2}{2A\, f_2}$$

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Stringing Chart

- Due to increase in temperature from θ_1 to θ_2, increase in length is:

$$(\theta_2 - \theta_1)\alpha S \approx (\theta_2 - \theta_1)\alpha\, l$$

$\Delta l = l_0\, \alpha\, \Delta\theta$

- There is another effect increase in temperature from θ_1 to θ_2, decrease tension or stress from f_1 to f_2:

$$\left(\frac{f_1 - f_2}{E}\right) S \approx \left(\frac{f_1 - f_2}{E}\right) l$$

$\Delta l = \dfrac{\Delta f\, l_0}{E}$

- Therefore new length is:

$$S_2 = S_1 + (\theta_2 - \theta_1)\alpha\, l - \left(\frac{f_1 - f_2}{E}\right) l$$

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Stringing Chart

$$l + \frac{w_2^2 l^3}{6A^2 f_2^2} = l + \frac{w_1^2 l^3}{6A^2 f_1^2} + (\theta_2 - \theta_1)\alpha l - \left(\frac{f_1 - f_2}{E}\right) l$$

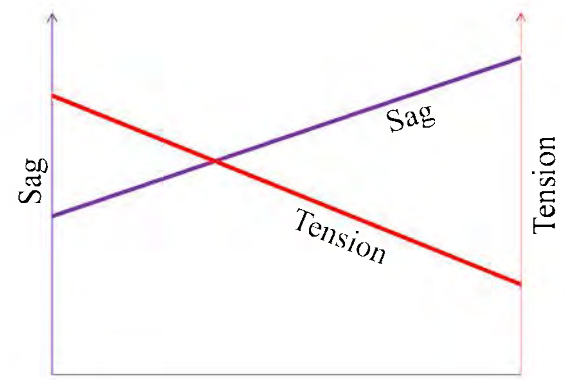
- Simplifying

$$\frac{w_2^2 l^2 E}{6A^2} = f_2^2\left(f_2 - f_1 + \frac{w_1^2 l^2 E}{6A^2 f_1^2} + (\theta_2 - \theta_1)\alpha E\right)$$

- This is cubic equation in f2 which can be solved using mathematical algorithm. Then the sag is:

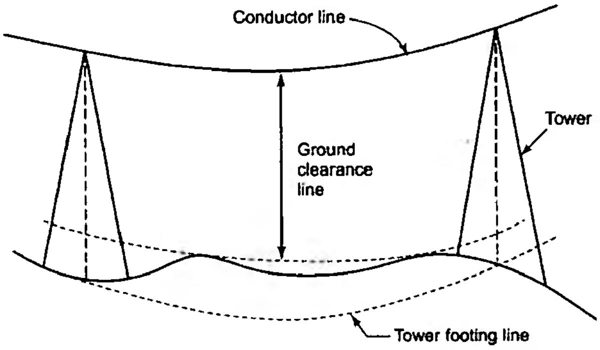
$$d_2 = \frac{w_2 l^2}{2A f_2}$$

Stringing Chart



Sag Template

- It is plot of curve used for locating the tower positions.



- Nowadays, this is done using sophisticated software programs, which take input such as cost of tower, foundation requirements, soil quality, etc.

Ruling or Equivalent Span

- There are several situations span length is not same.
- Therefore, tension in each span will be different.
- This is not possible in case of suspension type insulator, because it will swing to equalize the tension.
- Therefore, the uniform tension in each span is calculated by defining the equivalent span (or ruling span).

$$L_e = \sqrt{\frac{L_1^3 + L_2^3 + L_2^3 + \cdots + L_n^3}{L_1 + L_2 + L_3 + \cdots + L_n}}$$

- L_e is the equivalent or ruling span
- L_i is the each individual span in line

Ruling or Equivalent Span

- Also approximate ruling span is:

$$L_e = L_{avg} + \frac{2}{3}\left(L_{\max} + L_{avg}\right)$$

  - L_{avg} is the average span in line
  - L_{max} is the maximum span in line

- The *ruling span* is then used to calculate the horizontal component of tension, which is to be applied to all the spans between the anchor points. Then the sag at each span is computed using

$$d_i = \frac{w l_i^2}{2H}$$

- Span should not be more than twice the *ruling span* or less than half the *ruling span*.

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- In addition to Horizontal swing due to wind pressure, there are two types of vertical vibrations:
  - Aeolian or resonant vibrations
    - It is caused by vortex phenomena in light winds.
    - Low magnitude (up to 5 cm) and high frequency (5-40 Hz)
    - Less harmful because of small magnitude
    - These vibrations are common in conductor and more or less always present.
    - The *Armour rods* or *dampers* are used to damp these vibrations.

Armour rods

Stock-bridge dampers

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Conductor Vibrations

- Galloping (or dancing conductors)
  - Generally happened due to asymmetrical layer of ice formation.
  - When this asymmetrical ice coated conductor exposed to light winds (particularly when the slope of ground is higher).
  - High magnitude (up to 6 m) and low frequency (0.25-2 Hz).
  - These vibration may cause flashover between the conductors.
  - To avoid this flashover horizontal configuration is preferred.
  - Also if conductor is perfectly circular the effect can be minimized.
  - The stranded conductors can be wrapped up with PVC to make conductor perfectly circular.

Insulators for Overhead Line

- *Insulators* are used to insulate towers from the live conductors
- The insulators are attached to the tower and support the line conductors.
- Important characteristics:
  - It should be completely homogeneous materials without voids and impurities.
  - Leakage current through it should be minimum.
  - Breakdown strength of the material should be high and it should withstand over-voltages and normal working voltages.
  - It should be mechanically strong to bear the conductor load and should have longer life.

Insulator Ratings

- Three voltages ratings
  - Working voltage
  - Puncture voltage
  - Flashover voltage

- Flashover voltage is less than puncture.

$$\text{Safety Factor} = \frac{\text{Flashover Voltage}}{\text{Working Voltage}}$$

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Insulators for Overhead Line

- Porcelain:
  - Porcelain is widely used as it is cheap.
  - It is thoroughly vitrified to remove voids and glazed before use to keep surface free of dust and moisture.
  - Breakdown strength is around 6-12 kV/mm

- Glass:
  - Toughened glass is another choice having higher dielectric strength (120 kV/mm), mechanical strength and life.
  - Flaws can be detected easily by visual inspection.
  - Main disadvantage is moisture rapidly condenses on the surface giving high surface leakage current.

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Insulators for Overhead Line

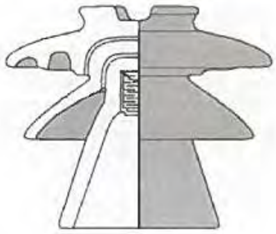
- Polymeric Insulation:
  - Silicone rubber and EPDM (Ethylene propylene diene monomer) are used for insulation purpose.
  - Low cost, light weight, higher life, improved dielectric performance under contamination or pollution.
  - They are used in combination with fiber glass rod.
  - These are under field trials and may take time to be used extensively.
  - Tracking and erosion of the shed material, which led to pollution and caused flashover.
  - Chalking and crazing of the insulator's surface, which resulted in increased contaminant collection, arcing, and flashover.

Types of Insulators

- Pin type insulators
- Suspension type insulators
- Strain type insulators

- Shackle insulator
- Post type insulators
- Composite polymeric insulators

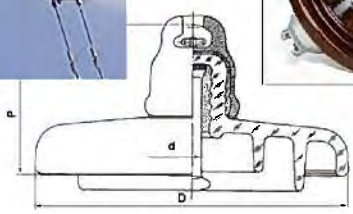
Pin Type Insulator



- Supported on steel bolt or pin which is firmly supported on cross-arm.
- Conductor is tied to insulator on groove by annealed binding wire.
- Generally used for 11 kV and 33 kV lines.
- They can be made in one piece up to 33 kV and two pieces for higher voltages.
- Pin type insulators are uneconomical for higher voltages.
- The leakage or creep age distance is from line to pin radially along the surface.

Suspension Type Insulators

- Consists of one or more insulating units hung from cross arm and conductor is connected at lowest unit.
- String is free to swing (lower mechanical stresses); thus long cross arms are required.
- Economical voltages above 33 kV. Each typical unit is designed for 11 kV.



- Failed unit can be changed without changing whole string.
- V shaped insulator strings can also be used to avoid the swings.
- 400 -> 19 units -> 3.84 m

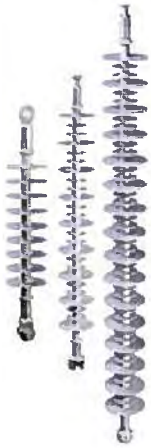
Strain Type Insulator

- The insulators are similar to suspension type insulator but used in horizontal position.
- Generally used at the towers with dead end, angle towers, and road and river crossings.
- They can take tension off the conductors. When tension is very high two or more are used in parallel.

Shackle, Post and Polymeric insulators

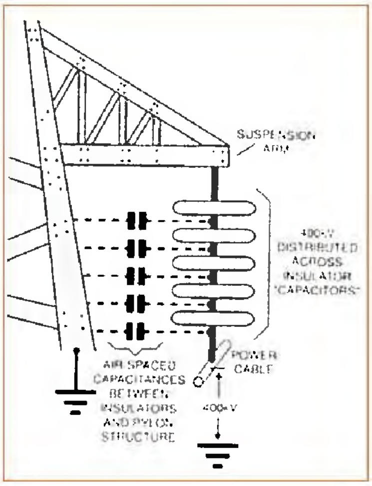
Shackle insulators or spool insulators

Post type insulators



Polymeric insulators

Potential Distribution over String



- Capacitance of disc: Capacitance between metal work of the insulator units; some times called as mutual capacitance.
- Capacitance to ground: capacitance between metal work of insulator to tower.

$$m = \frac{\text{Capacitance per insulator}}{\text{Capacitance to ground}} = \frac{mC}{C}$$

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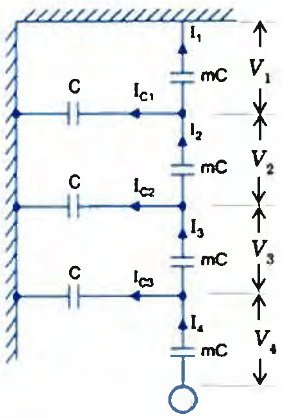
Potential Distribution over the String



$$m = \frac{\text{Capacitance per insulator}}{\text{Capacitance to ground}} = \frac{mC}{C}$$

- If V is voltage across the conductor and ground. We have:

$$V = V_1 + V_2 + V_3 + V_4$$

Also $\quad I_2 = I_1 + I_{C_1}$

$$V_2 m\omega C = V_1 m\omega C + V_1\omega C$$

$$V_2 = \frac{V_1}{m}(m+1) = \frac{m+1}{m}V_1$$

$$V_2 = V_1\left[1 + \frac{1}{m}\right]$$

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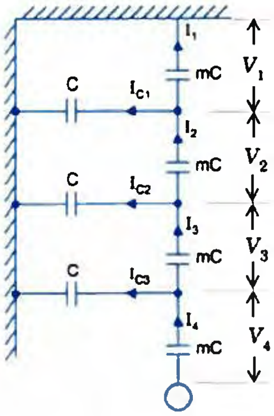
Potential Distribution over the String



- Similarly, $I_3 = I_2 + I_{c_2}$

$$V_3 m\omega C = V_2 m\omega C + (V_1 + V_2)\omega C$$

$$V_3 m\omega C = V_2 \omega C(m + 1) + V_1 \omega C$$

Substituting $V_2 = \frac{m+1}{m} V_1$

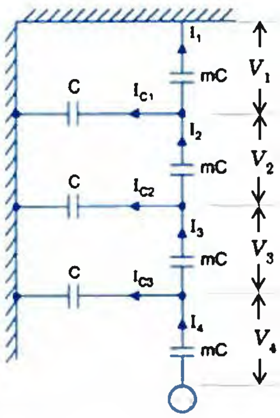
$$V_3 m\omega C = \frac{m+1}{m} V_1 \omega C(m + 1) + V_1 \omega C$$

$$= V_1 \omega C \left[\frac{(m+1)^2}{m} + 1\right]$$

$$V_3 = V_1 \left[\frac{m^2 + 3m + 1}{m^2}\right]$$

$$V_3 = V_1 \left[1 + \frac{3}{m} + \frac{1}{m^2}\right]$$

Potential Distribution over the String



- Similarly, $I_4 = I_3 + I_{c_3}$

$$V_4 m\omega C = V_1 \omega C \left[\frac{m^2 + 3m + 1}{m}\right] + \omega C \, [V_1 + V_2 + V_3]$$

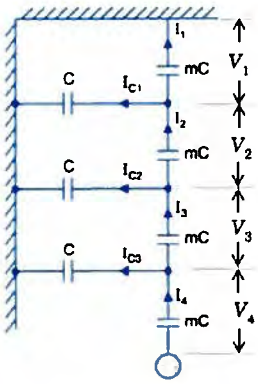
$$= V_1 \omega C \left[\frac{m^2 + 3m + 1}{m}\right]$$

$$+ \omega C \left[V_1 + \frac{m+1}{m} V_1 + \frac{m^2 + 3m + 1}{m^2} V_1\right]$$

$$V_4 = V_1 \cdot \left[\frac{m^2 + 3m + 1}{m^2} + \frac{3m^2 + 4m + 1}{m^3}\right]$$

$$V_4 = V_1 \left[1 + \frac{6}{m} + \frac{5}{m^2} + \frac{1}{m^3}\right]$$

String Efficiency



- Let m = 5

$$V_2 = V_1\left[1 + \frac{1}{m}\right] \Rightarrow V_2 = 1.2V_1$$

$$V_3 = V_1\left[1 + \frac{3}{m} + \frac{1}{m^2}\right] \Rightarrow V_2 = 1.64V_1$$

$$V_4 = V_1\left[1 + \frac{6}{m} + \frac{5}{m^2} + \frac{1}{m^3}\right] \Rightarrow V_2 = 2.41V_1$$

$$String\ Effciency = \frac{Voltage\ Across\ String}{n \times Voltage\ across\ unit\ adjacent\ to\ line} \times 100$$

$$= \frac{(1 + 1.2 + 1.64 + 2.41)V_1}{4 \times 2.41V_1} \times 100 = 63.8\%$$

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Methods of Equalizing the Potential

- Methods to improve string efficiency
  - Selection of *m*
  - Grading of units
  - Static shielding or guard rings

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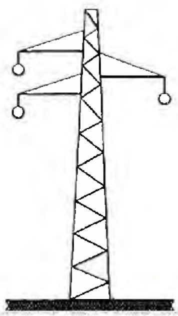
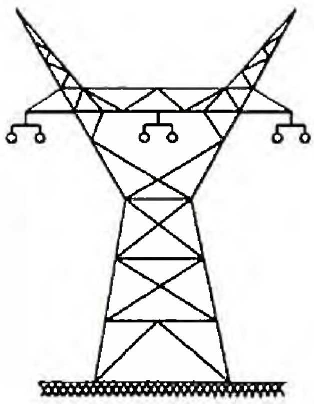
Line Support

- **Wooden Poles**
  - Cheapest, used for small spans (30-40m)
  - Tendency to rot at ground and life can not be predicted.
- **Reinforced concrete poles**
  - Long life and low maintenance
  - High cost of transport because of weight
- **Tubular steel poles**
  - Longer spans than wooden, longer life, light weight, high strength
  - Need galvanization
- **Lattice steel towers**
  - Economical for long spans, tall supports and HV transmission
  - Galvanized and painted

Typical Towers





- Main stem
- Cross arms
- Insulator
- Guy wire (Optional)

Type of Towers

- Type A tower (Tangent tower with suspension string)
  - Used on straight runs and up to 2^0 line diversions
- Type B tower (small angle tower with tension string)
  - Used for line diversions from 2^0 to 15^0
- Type C tower (Medium angle tower with tension string)
  - Used for line diversions from 15^0 to 30^0
- Type D tower (Large angle tower with tension string)
  - Used for line diversions from 30^0 to 60^0
- Type E tower (Dead End tower with tension string)
  - Used for line termination and starting
- Special tower
  - Suspension tower: (Span about 1000m) for river or mountain crossing
  - Transposition tower: Transposition of line

Innovative Designs




VI. TRANSMISSION AND DISTRIBUTION SYSTEM

OVERHEAD TRANSMISSION LINES ELECTRICAL DESIGN

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Methods of Equalizing the Potential

- Methods to improve string efficiency
  - Selection of *m*
  - Grading of units
  - Static shielding or guard rings

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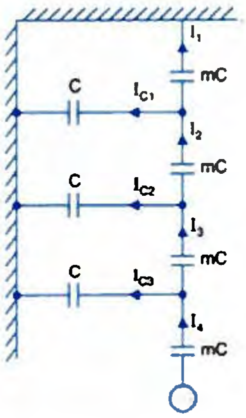
Selection of m



- If the value of *m* is increased, which can be achieved by increasing the cross-arm length.
- Increased cross-arm length decreases the capacitance between earth and metallic connections.
- However increasing cross-arm length is not economical after certain distance.
- Theoretically, one can achieve equal voltage distribution when *m* is infinity.
- It is found that value of *m* greater than 10 is not economical.

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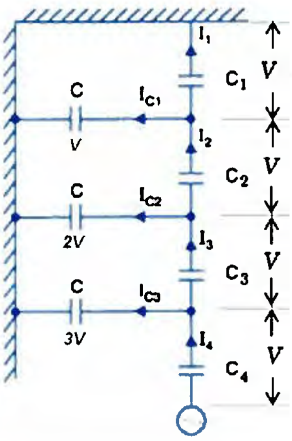
Grading of Units



- Voltage across capacitor is inversely proportional to the capacitance for given current.
- By correct grading of capacitances complete equality voltage can be achieved.
- We have,

$$I_2 = I_{C1} + I_1$$
$$\omega C_2 V = \omega C V + \omega C_1 V$$
$$C_2 = (C + C_1)$$

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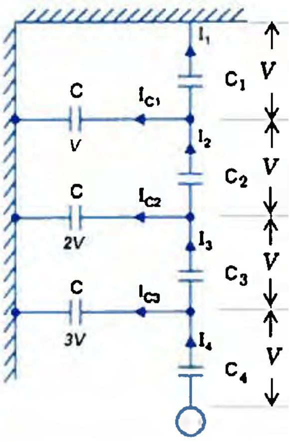
Grading of Units



$$I_3 = I_{C2} + I_2$$

$$\omega C_3 V = 2\omega CV + \omega C_2 V$$

$$But \;\; C_2 = (C + C_1)$$

$$\omega C_3 V = 2\omega CV + \omega (C + C_1)V$$

$$C_3 = 3C + C_1$$

$$C_3 = C_1 + (1+2)C$$

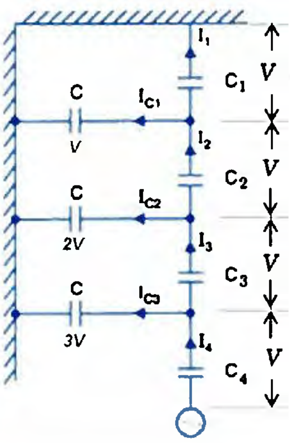
Generalized case:

$$C_n = C_1 + (1 + 2 + 3 + \cdots + (n-1))C$$

Therefore, if C_1=5C, then

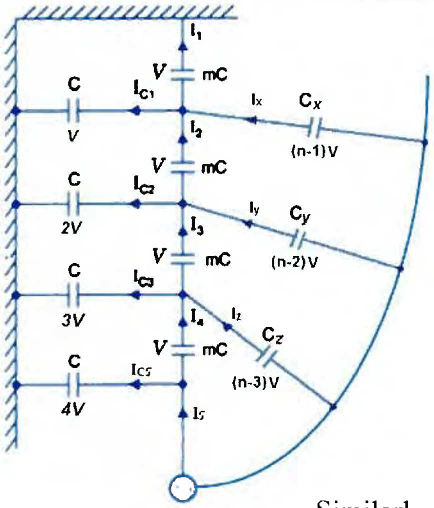
$C_2 = 6C$, $C_3 = 8C$, $C_4 = 11C$, and so on

Grading of Units



- Thus if capacitance of one unit is fixed other capacitances can be easily determined.
- This requires units of different capacities, which is uneconomical and impractical.
- Therefore this method is usually not employed except for very high voltage lines.
- In that case, string is graded in groups, ma be two/three.

Static Shielding



$$I_2 + I_x = I_1 + I_{C1}$$
$$I_3 + I_y = I_2 + I_{C2}$$
$$I_4 + I_z = I_3 + I_{C3}$$

Voltages can be equal if

$$I_x = I_{C1}$$
$$\omega Cx(n-1)V = \omega CV$$
$$C_x = \frac{C}{(n-1)}$$

Also, $I_y = I_{C2}$

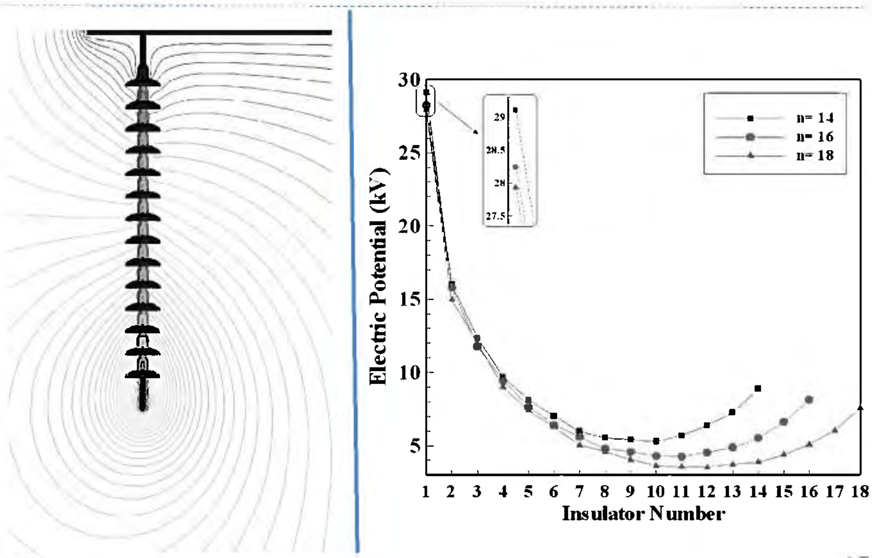
$$\omega Cy(n-2)V = 2\omega CV$$
$$C_y = \frac{2C}{(n-2)}$$

Similarly, $C_Z = \dfrac{3C}{(n-3)}$ and $C_p = \dfrac{pC}{(n-p)}$

Static Shielding

- In practice, it is very difficult to achieve the condition of equal voltages.
- However the partial advantage can be gained by this method (*guard ring*) and used normally.
- Further, when the horn gap is also used, it also protect the insulator from the flashover.

Numerical Method (FEM, BEM, FDM, etc.)



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VI. TRANSMISSION AND DISTRIBUTION SYSTEM

OVERHEAD TRANSMISSION LINES

CORONA

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What is Corona?

- " Corona is a luminous discharge due to ionization of the air surrounding an electrode, caused by a voltage gradient exceeding a certain critical value."

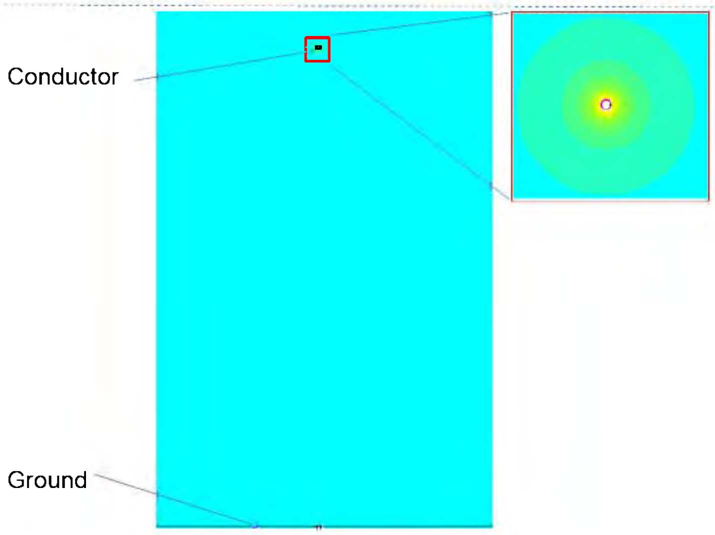
Why Corona is Important?

- Corona from conductors may cause audible noise and radio noise.
- Audible noise from conductors may violate noise standards.
- Radio noise from conductors may interfere with communications systems.
- Corona loss may be significant when compared with resistive loss of conductors.
- Corona can cause possible damage to polymeric insulators.
- Therefore, corona free lines needs to be designed which requires an understanding of factors that affect corona

Partial Discharge

- The breakdown of a gas takes place when a self sustained discharge or ionization process is set in.
- This takes place when the electric field stress exceeds a certain critical value.
- In the case of uniform field this condition is satisfied at all the points and there will be complete breakdown by forming an arc between the electrodes.
- For air breakdown strength (at 25^0C and 760 mm Hg) is 30 kV/cm for DC and 30 kV/cm (peak) for AC.
- However, if the electric field is highly non-uniform the breakdown condition may not be all over the gap.

Non-Uniform Field

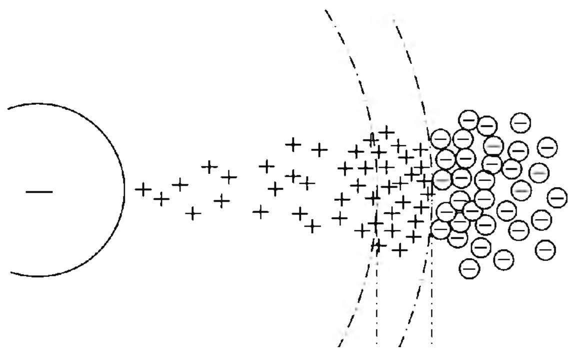


Corona

- Therefore in non-uniform field, some region of dielectric experiences higher field strength than the critical value, while other region field stress is well below critical value.
- Thus, self sustained discharge condition will be valid only in the strong field region giving rise to partial discharge called corona.
- This associated with a glow (bluish or violet tuffs, streamers, and/or glow) and a hissing sound and when it takes place in air ozone, oxides of nitrogen and nitric acid (in the presence of moisture) are formed.
- Light is produced by recombination of nitrogen atom with free electrons.

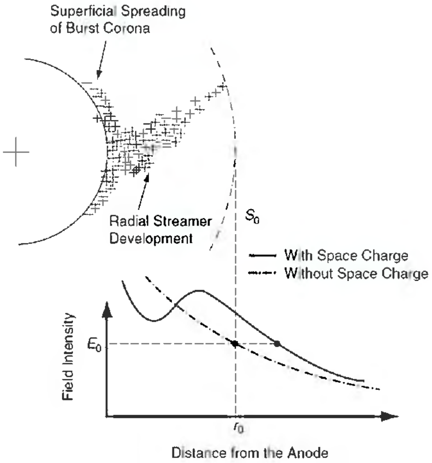
Mechanism of Corona Formation

- Conductors at Negative DC voltage



Mechanism of Corona Formation

- Conductors at Positive DC voltage



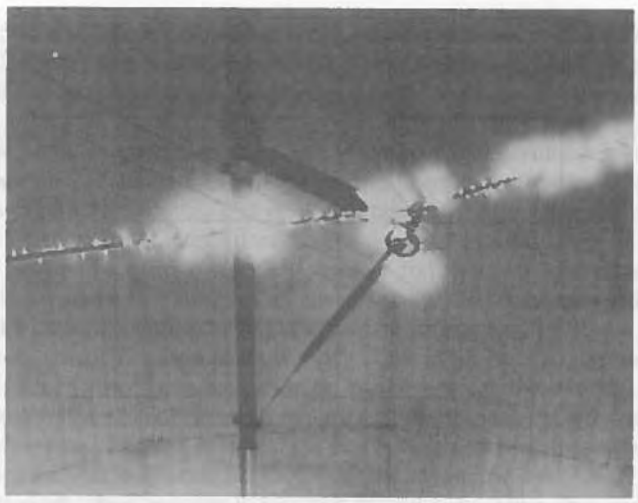
Mechanism of Corona Formation

- Conductors at AC voltage:
  - In positive half cycle:
    - when voltage exceeds corona inception value, ionization starts and intensity progressively increases till peak.
    - Electrons quickly reach conductor but before positive ions reach other electrode polarity changes.
    - Some positive ions remain virtually cutoff from both electrodes.
  - In negative half cycle:
    - In negative half cycle corona again starts when voltage exceeds corona inception value.
    - Electrons spreads out from the conductor and neutralize the stranded ions.

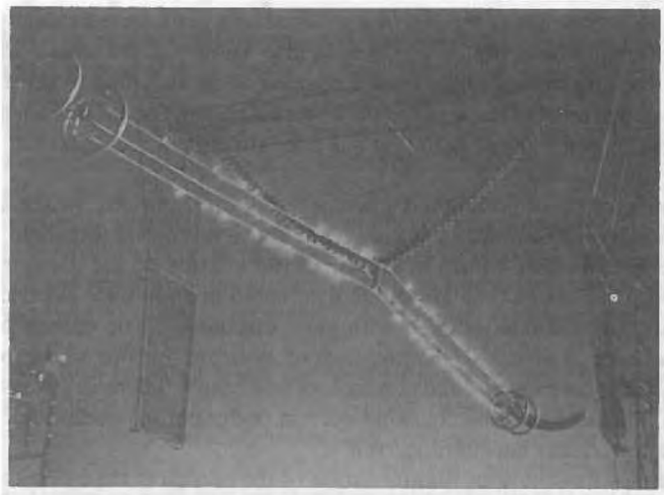
Mechanism of Corona Formation

- Conductors at AC voltage:
  - In this way, in every cycle some space charge need to be neutralized and result will be loss in charges from the source.
  - The energy continuously lost in the corona space.
  - Recombination of opposite charges will release energy in the surrounding air, which is heated up.

Corona (Laboratory Testing)



Corona (Laboratory Testing)



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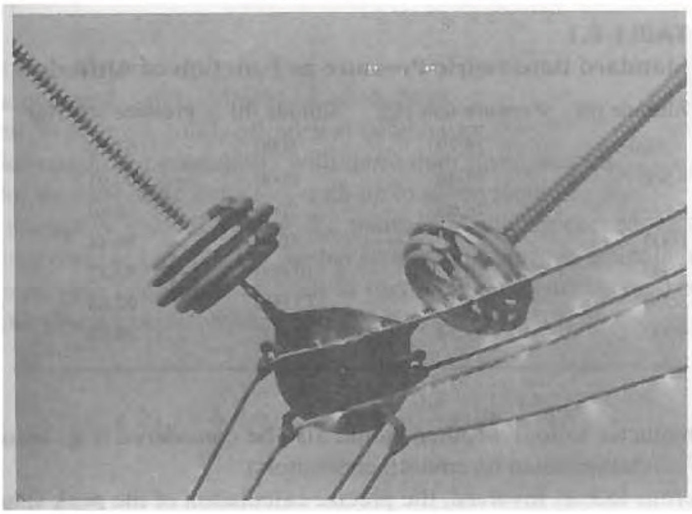
Corona (Testing)



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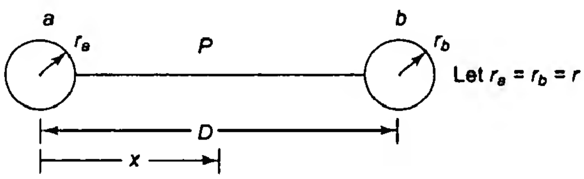
Corona

Critical Disruptive Voltage

- The minimum potential difference required between the conductor to start ionization is called *critical disruptive voltage* or *corona inception voltage*



$$E_x = \frac{q}{2\pi \epsilon_0 x} + \frac{q}{2\pi \epsilon_0 (D-x)} = \frac{q}{2\pi \epsilon_0}\left[\frac{1}{x} + \frac{1}{D-x}\right]$$

$$= \frac{q}{2\pi \epsilon_0} \frac{D}{x(D-x)}$$

Critical Disruptive Voltage

Potential Difference between the conductor

$$V = -\int_{D-r}^{r} E_x \, dx = \int_{r}^{D-r} \frac{q}{2\pi \epsilon_0}\left[\frac{1}{x} + \frac{1}{D-x}\right] dx$$

$$= \frac{q}{\pi \epsilon_0} \ln D/r \quad \Rightarrow \quad q = \frac{\pi \epsilon_0 V}{\ln D/r}$$

Therefore,

$$E_x = \frac{q}{2\pi \epsilon_0} \frac{D}{x(D-x)} \quad \Rightarrow \quad E_x = \frac{\pi \epsilon_0 V}{\ln D/r} \frac{1}{2\pi \epsilon_0} \frac{D}{x(D-x)}$$

$$= \frac{V}{2 \ln D/r} \frac{D}{x(D-x)}$$

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Critical Disruptive Voltage

$$E_x = \frac{V}{2 \ln D/r} \frac{D}{x(D-x)}$$

- Above expression is for single phase line and $V' = V/2$

$$E_x = \frac{V' D}{x(D-x) \ln D/r}$$

- Now this can be used to single phase with $V' = V/2$ or for three phase line $V' = V/\sqrt{3}$

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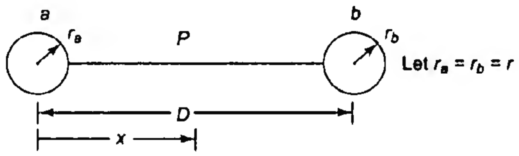
Critical Disruptive Voltage



$$E_x = \frac{V'D}{x(D-x)\ln D/r}$$

- Gradient increase a x decreases and will be maximum at conductor surface i.e. $x=r$

$$g_{max} = E_r = E_{max} = \frac{V'D}{r(D-r)\ln D/r} \cong \frac{V'}{r \ln D/r}$$

- Therefore, $$V' = r g_{max} \ln D/r$$

Critical Disruptive Voltage

$$V' = r g_{max} \ln D/r$$

- When g_{max} reaches g_0 (breakdown strength of air) air breaks down.

g_0 = 30 kV/cm. For AC voltages $g_0 = \frac{30}{\sqrt{2}}$ = 21.2 kV (rms)/cm

Above g_0 is for fair (standard) whether conditions, at any other condition

$$g_0' = g_0 \delta$$

where $\delta = \frac{p}{273+t} \cdot \frac{273+25}{760} = 0.392 \frac{p}{273+t}$

δ is the relative air density or air density correction factor

Critical Disruptive Voltage

- The *critical disruptive voltage* or *corona inception voltage* is then given by

$$V_d = r\, g_0\, \delta \ln \frac{D}{r} \text{ kV}$$

- Here, the assumption is conductor is solid having smooth surface, however in practical cases (like ACSR), conductor will not be having smooth surface. To account for surface irregularities a factor m_0 is used. Thus,

$$V_d = r\, g_0\, \delta\, m_0 \ln D/r \text{ kV}$$

m_0 = surface irregularity factor or stranding factor

Critical Disruptive Voltage

- Surface irregularity factor depends on state of cross section of conductor and state of its surface.
- It also considers dust and dirt on the conductor surface.
- The value of m_0 lies between 0.8 to 1.
  - m_0 = 1 for smooth, polished, and round conductors
  - m_0 = 0.92 – 0.98 for rough surfaced conductors
  - m_0 = 0.8 – 0.88 for stranded conductors
- Now when *d* and *r* expressed in cm.

$$V_d = (30\ \delta\, m_0)\ [r \ln(D/r)] \quad \text{kV (Peak)}$$
$$V_d = (21.1\ \delta\, m_0)\ [r \ln(D/r)] \quad \text{kV (rms)}$$

Critical Disruptive Voltage

$$V_c = g_{max}\left(r \ln \frac{D}{r}\right)$$

Fair (or standard) whether conditions and solid conductor with smooth surface → $g_{max} = g_0$; $g_0 = 30$ kV/Cm (Peak); $g_0 = 21.1$ kV/Cm (rms) → $V_c = g_0\left(r \ln \frac{D}{r}\right)$

Other (or foul) whether conditions than standard and solid conductor with smooth surface → $g_{max} = \delta\, g_0$; $\delta = 0.392 \frac{p}{273+t}$ → $V_c = g_0\, \delta \left(r \ln \frac{D}{r}\right)$

Other whether conditions than standard and conductor with irregular surface (ACSR) → $g_{max} = m_0\, \delta\, g_0$; The value m_0 is 0.8 to 1 → $V_c = m_0 g_0\, \delta \left(r \ln \frac{D}{r}\right)$

Visual Critical Disruptive Voltage

- At the critical disruptive voltage corona starts, but it will not be visible. It requires further ionization by collision.
- If the voltage is further increased at some point corona becomes visible. This voltage is called as *visual critical disruptive voltage* or *visual corona inception voltage.*
- The voltage gradient (g_v) for visual corona is given by [*Peek*]:

$$g_v = g_0\, \delta \left(1 + \frac{0.301}{\sqrt{r\,\delta}}\right) \text{ kV/cm}$$

- Therefore, $V_d = g_v\, m_v\, r \ln(D/r)$ kV

$$V_d = g_0\, \delta \left(1 + \frac{0.301}{\sqrt{r\,\delta}}\right) m_v \left[r \ln(D/r)\right] \text{ kV}$$

Visual Critical Disruptive Voltage

- Surface irregularity factor (m_v) is different from m_0.
- Local corona: For conductor with irregular surface, visual corona occurs at different point than whole surface called as *local corona.*
  - m_v = 0.72 for local visual corona on stranded conductor
  - m_v = 0.82 for general (or decided) corona on stranded conductor
  - m_v = 1 for smooth and polished conductor
- Now when *d* and *r* expressed in cm.

$$V_d = 30\,\delta\left(1+\frac{0.301}{\sqrt{r\,\delta}}\right) m_v\,\left[r\ln(D/r)\right] \quad \text{kV (Peak)}$$

$$V_d = 21.1\,\delta\left(1+\frac{0.301}{\sqrt{r\,\delta}}\right) m_v\,\left[r\ln(D/r)\right] \quad \text{kV (rms)}$$

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Visual Critical Disruptive Voltage

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Critical Disruptive Voltage

$$V_c = g_{max}\left(r \ln \frac{D}{r}\right)$$

Critical Disruptive Voltage or corona inception voltage	$g_{max} = m_0\, \delta\, g_0$ The value m_0 is 0.8 to 1	$V_c = m_0 g_0\, \delta \left(r \ln \frac{D}{r}\right)$
Visual critical disruptive voltage or visual corona inception voltage	$g_v = g_0\, \delta \left(1 + \frac{0.301}{\sqrt{r\,\delta}}\right)$ in kV/cm	$V_d = m_v\, g_v \left[r \ln\left(\frac{D}{r}\right)\right]$

Corona Loss

- The ionized charges near the conductor surface take energy from the supply system and thus there is loss of some energy due to corona.
- Peek's Empirical relation for corona in fair whether condition

$$P_c = 241 \times 10^{-5} \times \frac{f+25}{\delta} \sqrt{\frac{r}{d}} (V_p - V_c)^2 \quad \text{kW/phase/km}$$

Where V_P phase to neutral operating voltage in kV and f is frequency.

- For storm or foul whether condition voltage is 0.8 V_c

$$P_c = 241 \times 10^{-5} \times \frac{f+25}{\delta} \sqrt{\frac{r}{d}} (V_p - 0.8V_c)^2 \quad \text{kW/phase/km}$$

This relation is correct results when 1) Corona loss is predominant 2) Frequency lies between 25 and 125 Hz 3)Ration of $V_p/V_c > 1.8$ 4) radius of conductor is greater than 0.25 cm.

Corona Loss

- When the ratio $V_p/V_c < 1.8$ Peterson's formula gives good results

$$P_c = \frac{1.11066 \times 10^{-4} f V^2}{(\ln(d/r))^2} F \quad \text{kW/Phase/km}$$

- Here F is corona factor determined by test depends on V_p/V_c.

V_p/V_c	1	1.4	1.6
F	0.05	0.3	1

Factors Affecting Corona

- Atmospheric factors
  - Temperature
  - Pressure
  - Dust and dirt
  - Rain, snow, fog
- Electrical factor
  - Frequency
  - Supply voltage
- Line configuration
  - Conductor configuration
  - Profile of conductor
  - Diameter of conductor
  - Surface condition
  - Number of conductor per phase
  - Heating of conductor by load current
  - Conductor spacing

Factors Affecting Corona

- Atmospheric Factors

$$\delta = \frac{p}{273+t} \cdot \frac{273+25}{760} = 0.392 \frac{p}{273+t}$$

$$V_c = m_0 g_0 \delta \left(r \ln \frac{D}{r} \right)$$

$$P_c = 241 \times 10^{-5} \times \frac{f+25}{\delta} \sqrt{\frac{r}{d}} (V_p - V_c)^2 \quad \text{kW/phase/km}$$

  - Temperature:
  - Pressure:
  - Dust, dirt:
  - Rain, snow, fog:

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Factors Affecting Corona

- Electrical Factor

$$\delta = \frac{p}{273+t} \cdot \frac{273+25}{760} = 0.392 \frac{p}{273+t}$$

$$V_c = m_0 g_0 \delta \left(r \ln \frac{D}{r} \right)$$

$$P_c = 241 \times 10^{-5} \times \frac{f+25}{\delta} \sqrt{\frac{r}{d}} (V_p - V_c)^2 \quad \text{kW/phase/km}$$

  - Frequency
  - Voltage

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Factors Affecting Corona

- Line configuration

$$V_c = m_0 g_0 \delta \left(r \ln \frac{D}{r} \right)$$

$$P_c = 241 \times 10^{-5} \times \frac{f + 25}{\delta} \sqrt{\frac{r}{d}} (V_p - V_c)^2 \quad \text{kW/phase/km}$$

- Conductor configuration
- Diameter of conductor
- Number of conductor per phase
- Conductor spacing
- Profile of conductor
- Surface condition
- Heating of conductor by load current

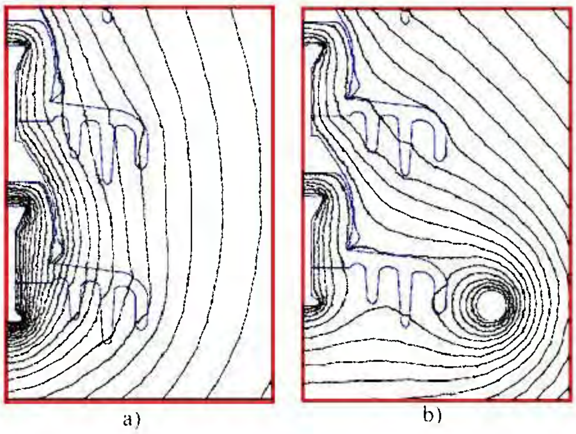
Merits and Demerits of Corona

- Merits
  - Act as safety valve during lightning and switching surges.
  - The waves gets dissipated as corona loss.
  - Other applications:
    - Van de Graaff generator, Electrostatic precipitator, Electro printing, Ionization counting, Electrostatic deposition
- Demerits
  - Corona loss reduces efficiency.
  - Ionized air around the conductor works as conducting medium increases effective diameter of conductor.
  - This increases capacitance and decrease surge impedance loading.
  - Interference with communication lines.

Prevention of Corona

- Economic consideration, it is advisable to build the line corona free for all the whether. Modern practice is to build corona free line in fair whether condition.
- To prevent corona loss, critical disruptive voltage higher the phase voltage.
  - Increasing conductor spacing
  - Increasing radius of conductor (Expanded ACSR)
  - Use of bundled conductors
  - Spacing between bundled conductor
  - Homogenous Insulators:
  - Elimination of sharp points:
  - Using Corona rings:
  - Surface Treatments:

Corona Ring



a) contour plots without corona ring
b) contour plots with corona ring

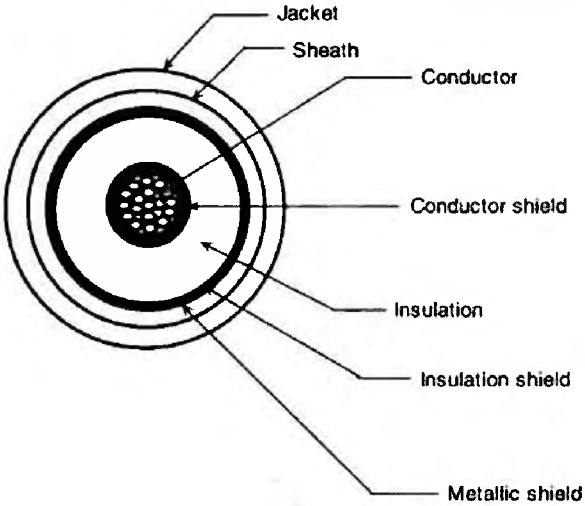
... POWER SYSTEM ENGINEERING

UNDERGROUND CABLES

Advantage of Underground Cables

- Underground cables are technically advantages than the overhead lines
  - Not exposed to environmental conditions
  - Inductance is lower in cable so voltage drop is less
- However, high erection cost, low heat dissipation and high charging current makes it uneconomical for long distance transmission
- Cables are preferred in following conditions:
  - Public safety involved and low interference is required
  - Large populated cities
  - Scenic beauty of city is important
  - Submarine crossing, and substation and transformer connections

Components of Power Cable



Components of Power Cable

- *Conductor* for carrying current
- *Conductor shield* to provide smooth radial electric field
- *Insulation* to insulate high voltage conductor
- *Insulation shield (optional)* to provide smooth radial electric field. Also act as hermitic seal of cable.
- *Metallic sheath and/or plastic jacket* for mechanical protection. Metal sheath protect cable from water ingress.
- *Metal wire armoring (optional)* for mechanical protection

Materials Used in Cables

- Conductors
  - Copper or aluminum
  - Stranded for flexibility
  - Size is decided by required ampacity
  - Temperature rise should be in limit to avoid degradation of the insulation
- Insulation Material
  - Paper (impregnated)
  - PVC (polyvinyl cloride)
  - Thermoset materials (XLPE, TR-XLPE, EPR)
  - Liquid and gaseous insulation

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Insulation: Paper

- Dry paper is excellent insulator but losses the property quickly if it becomes wet.
- Dry paper is hygroscopic, so it must be sealed from air contact.
- Thus, it is sheathed with water resistant materials.
- Performance is improved by impregnating with mineral oil.
- It has relative permittivity of 3.6 and can withstand 20kV/mm.
- Ratings: 80^0C continuous loading, 130^0C short time overload and 200^0C for short circuit.
- Requires special jointing mechanism to ensure the appropriate sealing.
- Weight of cable is also higher as compared to PVC and XLPE

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Insulation: Thermoset Materials

- These are also synthetic materials which do not soften, flow or get distorted when subjected to heat and pressure.
- XLPE (Cross linked polyethylene)
  - Long chains of polyethylene molecules are linked by carbon atoms.
  - Better electrical properties than PVC.
  - Extensively used for medium and high voltage cables (up to 500 kV).
  - Can be used up to 90^0C conductor temperature and worked upto -40^0C.
  - It has relative permittivity of 2.5 and can withstand 18 kV/mm.
  - Good mechanical strength and lighter in weight
- TR-XLPE (tree retardant XLPE): It contains special additive which resists tree formation.
- EPR (Ethylene propylene rubber): Higher thermal rating, thus higher ampacity. Dielectric properties are lesser than XLPE

Insulation: Liquid and Gaseous Insulation

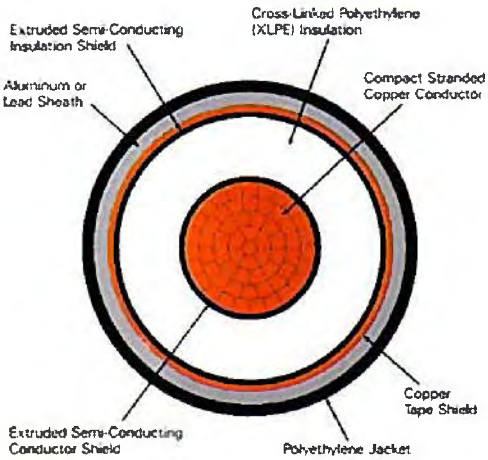
- In solid insulation voids are main problem which starts the partial discharge and may lead to breakdown.
- Void formation can be prevented by
  - Filling the cable with an insulating gas (N or SF6) at high pressure.
  - Use of low viscosity oil under (mineral oil) pressure.
- This results in much higher safe electric stresses and also high permissible operating temperature.

- temp

Different types of cable

- Belted
- Screened
- Pressure cables

Cable Structure



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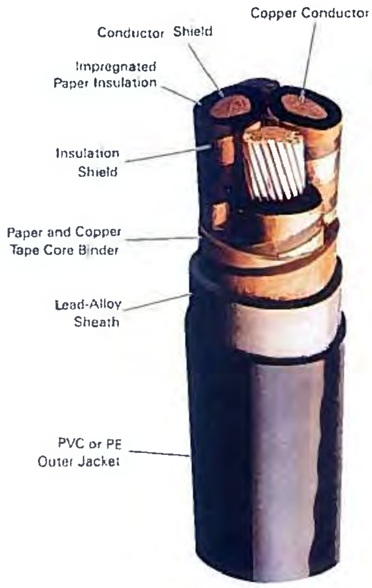
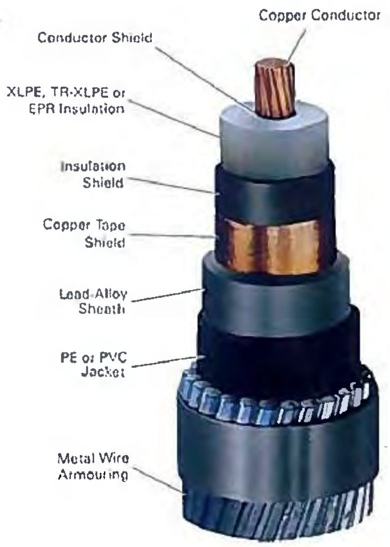


Paper-Insulated Lead-Covered Cables (PILC)



Sub- Marine Cable

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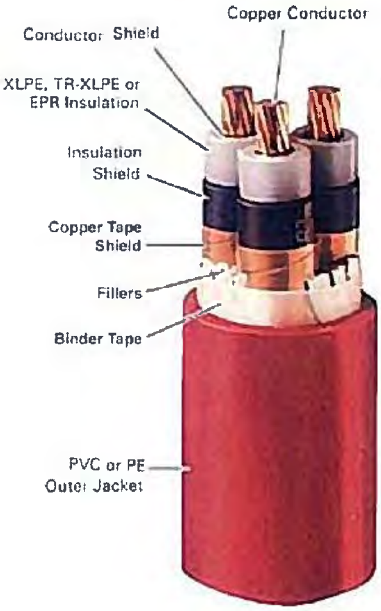
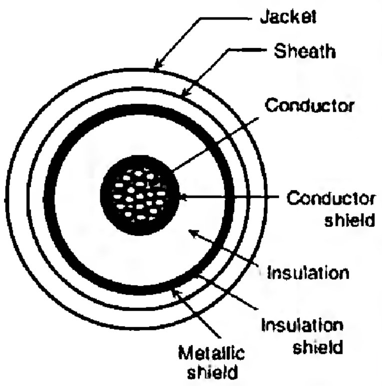


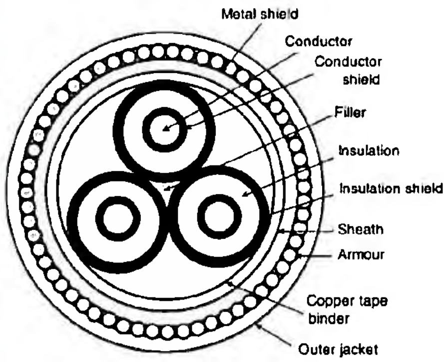
Materials of Cable Component

Conductor	Insulation	Shield	Sheath	Jacket	Armor
•Copper or •Aluminum (Stranded)	•Paper •PVC •XLPE •TR-XLPE •EPR •Vulcanized rubber •Polythene	•Semicondu-cting (Insulation with carbon impregnati-on) •Aluminum Copper (tape)	•Lead •Aluminum	•PVC •Polythene •Nylon •Neoprene	•Galvanized steel

Single Core and Three Core Cables

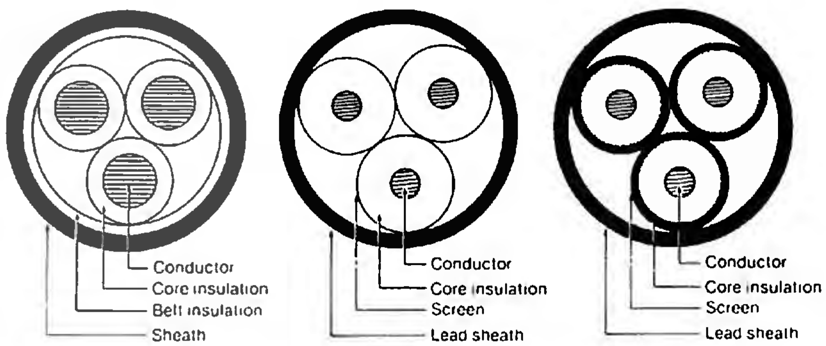


Single Core Cable



Three Core Cable
(Below 66 kV)

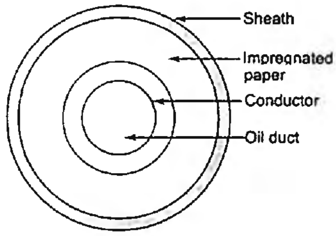
Belted and Screened or shielded Cable

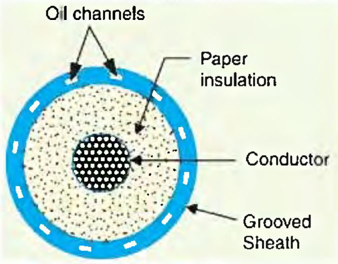


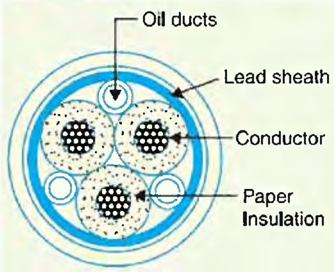
Belted **H-Type Screened** **S.L. Type Screened**

- Belted cables are used up to 11 kV.
- There are two types of screened cables H-Type (Hochstadter) and S.L. type (Separate lead). Used up to 33 kV

Pressurized Cable (Oil filled & oil pressure)







- Above 220 kV, It is necessary to avoid void formation.
- Voids are generally formed by cyclic heating and cooling and can be prevented by use of oil under pressure.
- Oil channel is made by spiral steel tape.

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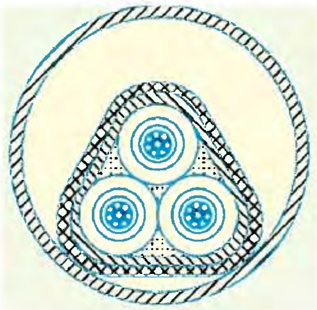
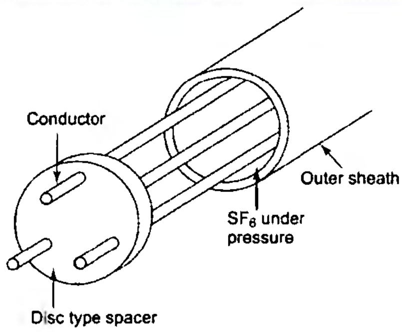
Gas Pressurized and Gas Filled Cables





- Mainly two types: 1. impregnated gas pressure cable 2. gas filled cables.
- More revolutionary are the cables incorporating cryogenic cooler.
- Used up to 132 kV to 500 kV

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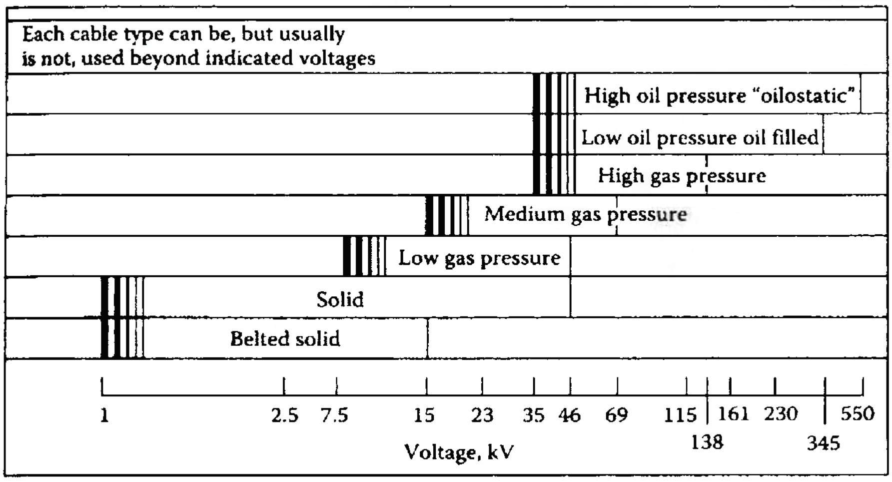
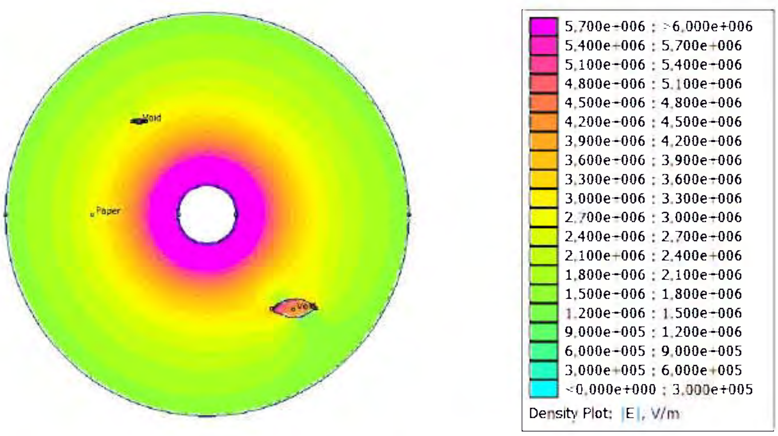
Operating Range of the Cables

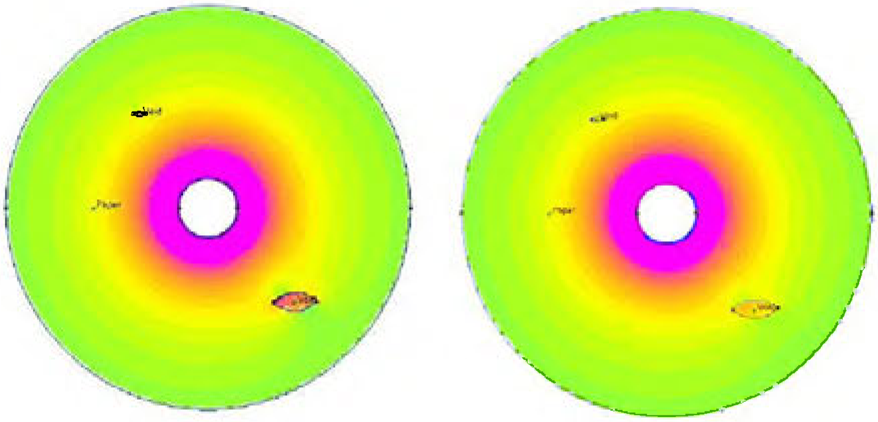


Recommended voltage ranges for various of paper-insulated paper cables.

Electric Field Intensity with Voids



Effect of Void Permittivity



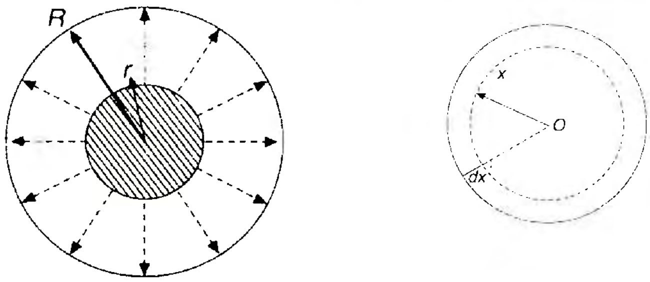
Air Voids

Voids filled with oil

Electrical Characteristics of Cables

- Insulation resistance
- Conductor inductance
- Cable capacitance
- Electrical stress inside insulation
  - Grading of cable
    - Capacitance grading
    - Inter-sheath grading
- Dielectric losses and tan delta (loss tangent)
- Sheath and armor losses

Insulation Resistance



- Resistance of small section *dx* is: $dR_x = \frac{\rho dx}{2\pi x l}$
- Therefore insulation resistance is $R_i = \frac{\rho}{2\pi l}\int_r^R \frac{dx}{x} = \frac{\rho}{2\pi l} \ln \frac{R}{r}$ ohm
- Insulation per unit length $R_i = \frac{\rho}{2\pi} \ln \frac{R}{r}$ ohm/m

Conductor Inductance

- For single core cable:

$$L = 2 \times 10^{-7} \ln \left(\frac{D}{r'}\right) \text{ H/metre}$$

D = separation distance between phase conductors
r' = 0.7788r
r = radius of the conductor

- For three core cable:

$$L = 2 \times 10^{-7} \ln \left(\frac{D}{r'}\right) \text{ H/metre}$$

D = separation distance between cores
r' = 0.7788r

Inductance of Cable

Formula for inductance

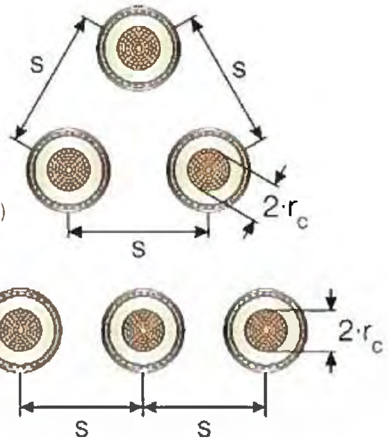
$$L = 0.05 + 0.2 \cdot \ln\left(\frac{K \cdot s}{r_c}\right) \ [mH/km]$$

Where trefoil formation: K = 1
flat formation: K = 1.26
s = distance between conductor axes (mm)
r_C = conductor radius (mm)

Formula for inductive reactance

$$X = 2\pi f \cdot \frac{L}{1000} \ [\Omega/km]$$

Where f = frequency (Hz)
L = inductance (mH/km)



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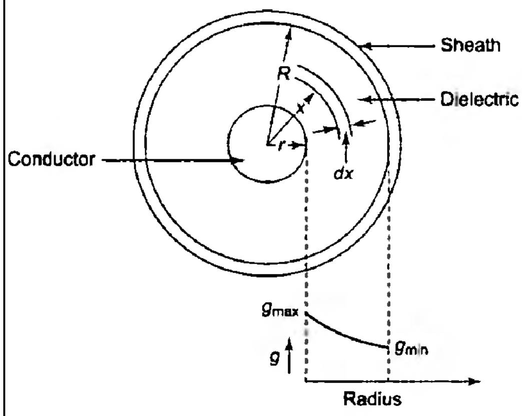
Capacitance of Cable



$$g = \frac{q}{2\pi kx} \ \text{V/m}$$

Therefore, voltage is

$$V = \int_r^R g \cdot dx = \int_r^R \frac{q}{2\pi kx} dx$$

$$V = \frac{q}{2\pi k} \ln \frac{R}{r}$$

Therefore, capacitance between core to sheath

$$c = \frac{2\pi k_0 k_r}{\ln R/r} \ \text{F/m}$$

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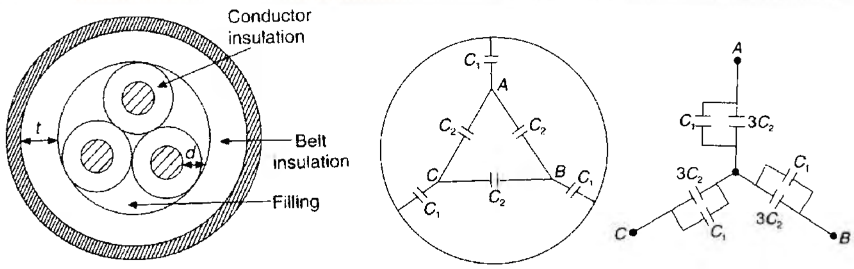
Capacitance of Three Core Belted Cable

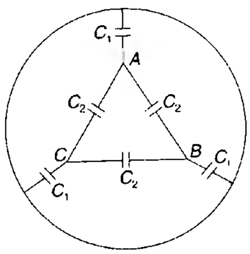


C_0 $(=C_1 + 3C_2)$

$$C_0 = \frac{0.0298\varepsilon_r}{\log_{10}\left(1+\frac{T+t}{d}\left(3.84-1.70\frac{t}{T}+0.52\frac{t^2}{T^2}\right)\right)} \quad \mu\text{F/km}$$

where ε_r is the relative permittivity of the insulation, t the thickness of belt insulation, d the diameter of the conductor and T the conductor insulation thickness.

How to find C1 and C2



Take following measurements:

1. All the three conductors joined together and measure the capacitance between sheath and conductors.

   $C_x = 3C_1$ ⇨ $C_1 = C_x/3$

1. Connect two conductors and sheath together and measure the capacitance between sheath and remaining conductors

   $C_y = 2C_2 + C_1$

   ⇨ $C_2 = \frac{C_y}{2} - \frac{C_1}{2} = \frac{C_y}{2} - \frac{C_x}{6}$

Therefore $C_0 = C_1 + 3C_2 = \frac{C_x}{3} + 3\left(\frac{C_y}{2} - \frac{C_x}{6}\right) = \frac{3C_y}{2} - \frac{C_x}{6}$

Electric Stress in The Cable

$$V = \frac{q}{2\pi\varepsilon}\ln\frac{R}{r} \quad \Rightarrow \quad \frac{q}{2\pi\varepsilon} = \frac{V}{\ln(R/r)}$$

$$E_x = \frac{q}{2\pi\varepsilon x} \quad \Rightarrow \quad E_x = \frac{V}{x\ln(R/r)}$$

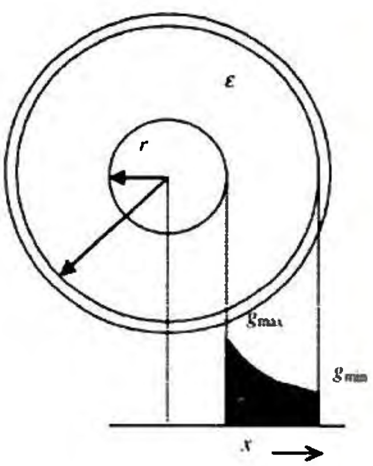
- Maximum stress occurs at the surface of conductor

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

- Minimum stress occurs at the sheath surface

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

Electric Stress in The Cable



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

- Optimal radius minimum stress

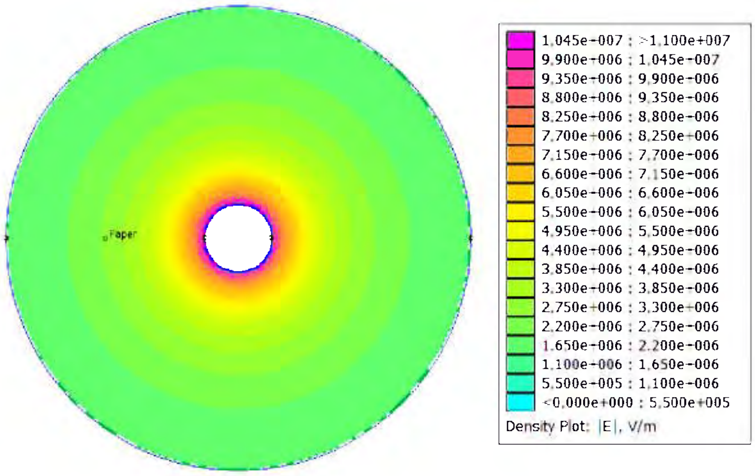
$$\frac{dE_{max}}{dr} = 0$$

$$r \times \frac{r}{R} \times \left(-\frac{R}{r^2}\right) + \ln\frac{R}{r} = 0$$

$$\ln\frac{R}{r} = 1 \quad \text{or} \quad \frac{R}{r} = e$$

$$E_{max} = \frac{V}{r} = \frac{Ve}{R} \qquad R = 2.718r$$

Electric Stress in The Cable



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Grading of Cables

- Electric field inside the cable is not uniform, maximum at conductor surface and minimum at the sheath.
- Thus insulation material is not properly utilized.
- The insulation near conductor surface is stressed more while there is very less stress at the outer diameter of cable.
- Grading is used to decrease difference between E_{max} and E_{min}.
- Grading can be broadly classified into two categories.
  - Capacitance Grading
  - Intersheath Grading

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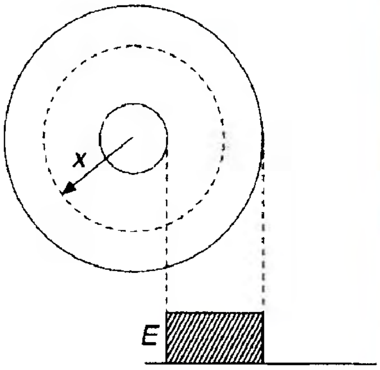
Capacitance Grading



Ideal condition for stress in cable

$$E_x = \frac{q}{2\pi\varepsilon x} = k$$

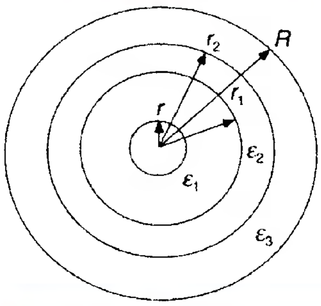
There fore the permittivity is

$$\varepsilon = \frac{k_1}{x}$$

This can not be realized in practice since it requires infinite number of dielectric materials with varying permittivity

In practice, this can be realized by two or three layers of the dielectric materials.

Capacitance Grading (With Same Safety Factor)



- While designing cable $E_{max} = \frac{G}{F}$
- Let dielectric strengths of material is G1 G2 and G3 corresponding to ε1, ε2, and ε3 and F is safety factor same for all materials.

Layer 1 (ε_1)	Layer 1 (ε_2)	Layer 1 (ε_3)
$\frac{q}{2\pi\varepsilon_1 r} = \frac{G_1}{F}$	$\frac{q}{2\pi\varepsilon_2 r_1} = \frac{G_2}{F}$	$\frac{q}{2\pi\varepsilon_3 r_2} = \frac{G_3}{F}$

Capacitance Grading (With Same Safety Factor)

$$q = 2\pi\varepsilon_1 r\frac{G_1}{F} = 2\pi\varepsilon_2 r_1\frac{G_2}{F} = 2\pi\varepsilon_3 r_2\frac{G_3}{F}$$

$$\varepsilon_1 r G_1 = \varepsilon_2 r_1 G_2 = \varepsilon_3 r_2 G_3$$

- Since $r < r_1 < r_2$ ⇒ $\varepsilon_1 G_1 > \varepsilon_2 G_2 > \varepsilon_3 G_3$
- Therefore material having highest product of permittivity and dielectric strength should be kept near to the conductor. The operating voltage of Cable is given by

$$V = \int_r^{r_1} E_1\,dx + \int_{r_1}^{r_2} E_2\,dx + \int_{r_2}^{R} E_3\,dx$$

$$= \frac{q}{2\pi}\left(\frac{1}{\varepsilon_1}\ln\frac{r_1}{r} + \frac{1}{\varepsilon_2}\ln\frac{r_2}{r_1} + \frac{1}{\varepsilon_3}\ln\frac{R}{r_2}\right)$$

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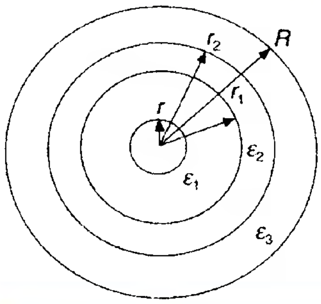
Capacitance Grading (With Same Maximum Stress)



- If the materials are subjected to same maximum stress at the r , r_1, *and* r_2

Layer 1 (ε_1)	Layer 1 (ε_2)	Layer 1 (ε_3)
$E_{max} = \frac{q}{2\pi\varepsilon_1 r}$	$E_{max} = \frac{q}{2\pi\varepsilon_2 r_1}$	$E_{max} = \frac{q}{2\pi\varepsilon_3 r_2}$

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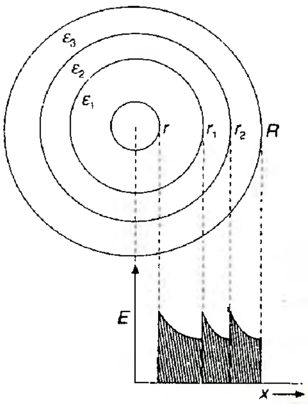


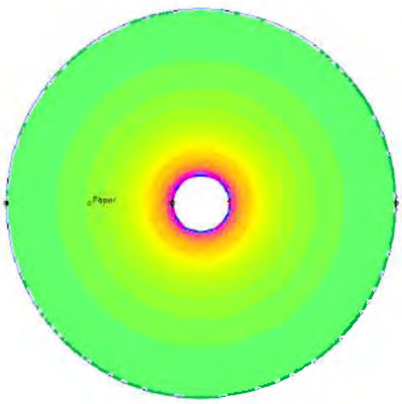
$$E_{max} = \frac{q}{2\pi\varepsilon_1 r} = \frac{q}{2\pi\varepsilon_2 r_1} = \frac{q}{2\pi\varepsilon_3 r_2}$$

$$\varepsilon_1 r = \varepsilon_2 r_1 = \varepsilon_3 r_2$$

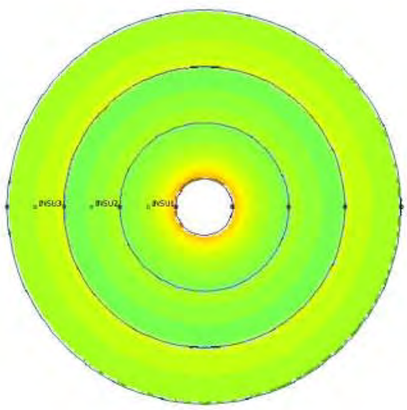
- Since $r < r_1 < r_2$ ⇒ $\varepsilon_1 > \varepsilon_2 > \varepsilon_3$
- Therefore same maximum stress material having highest permittivity needs to be kept at surface of conductor.

$$V = E_{max}\left(r \ln\frac{r_1}{r} + r_1 \ln\frac{r_2}{r_1} + r_2 \ln\frac{R}{r_2}\right) \text{volt}$$

Capacitance Grading

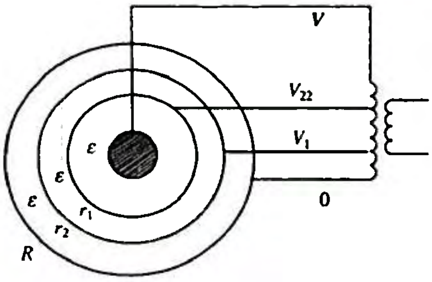


Without grading



With capacitance grading

Intersheath Grading



➢ Metal Sheaths having radii r_1 and r_2 are kept at potential V_1 and V_2. using auxiliary transformer .

Layer 1 (V)	Layer 1 (V_1)	Layer 1 (V_2)
$E_{max} = \dfrac{V - V_2}{r \ln (r_1/r)}$	$E_{max} = \dfrac{V_2 - V_1}{r_1 \ln (r_2/r_1)}$	$E_{max} = \dfrac{V_1}{r_2 \ln (R/r_2)}$

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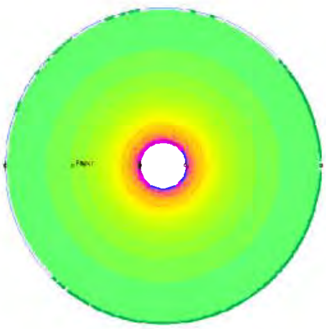
Intersheath Grading

➢ Since the material is same, the maximum stress is also same:

$$\frac{V - V_2}{r \ln (r_1/r)} = \frac{V_2 - V_1}{r_1 \ln (r_2/r_1)} = \frac{V_1}{r_2 \ln (R/r_2)}$$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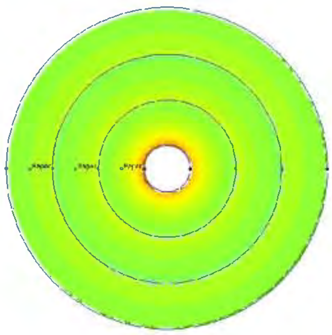
Intersheath grading

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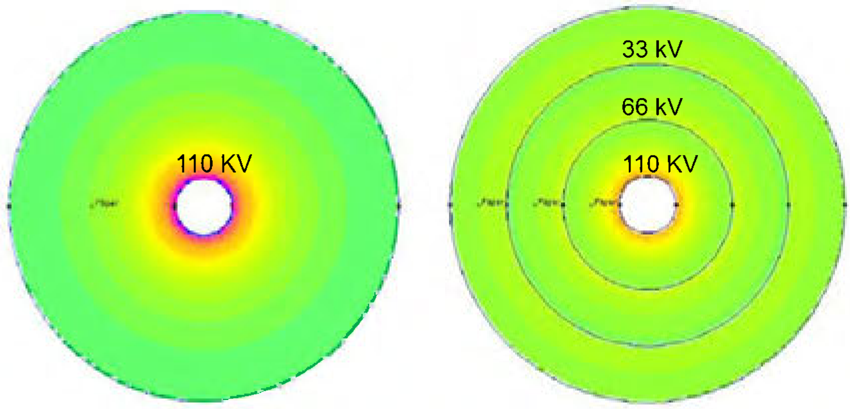
Intersheath Grading



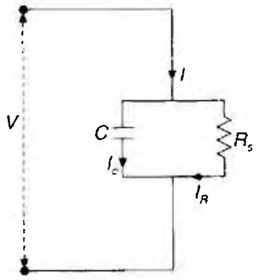
Without grading

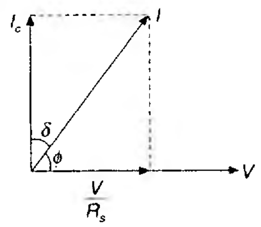
Intersheath grading

Grading of Cable

- Generally not used for following reasons:
  - Non-availability of material with varying permittivity materials
  - Change in permittivity with time
  - Damage of intersheath during cable laying
  - Charging current through the intersheath can damage the cable due to overheating
  - Resonance due to cable capacitance and transformers inductance

Dielectric Losses or Loss Tangent





Power loss in leakage resistance

$$P_l = \frac{V^2}{R_s}$$

For small angle δ

$$\delta \approx \tan\delta \approx \sin\delta \approx \sin(90 - \phi) = \cos\phi$$

From phasor diagram

$$\frac{V/R_s}{V\omega C} = \tan\delta \Rightarrow \frac{V}{R_s} = V\omega C \tan\delta$$

Therefore, dielectric power loss:

$$P_l = V^2\omega C \tan\delta = V^2\omega C\delta \text{ watt}$$

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Loss Tangent of Different Materials

Material	Tan δ
Impregnated Paper	0.01
Oil filled paper insulation	0.004
PVC	0.1
XLPE	0.0004

- The loss angle depends on the temperature.
- Roughly it follows 'V' curve, i.e. Loss angle will be minimum at certain temperature.

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Other Topics

- Breakdowns in Cable Insulation
  - Intrinsic Breakdown or puncture:
  - Thermal Breakdown:
  - Tracking:
- Sheath and armour losses

Underground Cable System

Japanese Technical Assistance
on Strengthening Institutional Capacity
of National Development Agency (ADN)
in Democratic of Timor-Leste

-- POWER --

Syllabus

No.	Contents
1	Introduction
2	Power Station (Diesel)
3	Substation
4	Transmission and Distribution System
5	Power System Study
6	Power Flow Analysis
7	Renewable Energy (Photovoltaic Power)
8	Protecting System
9	Power System Operation and Control
10	Others

The contents may be changed depending on conditions.
I would like to discuss about the contents with Mr. Miguel and YOU.

VII. POWER SYSTEM STUDY

VII. POWER SYSTEM STUDY

INTRODUCTION

Introduction

- Power System consists of three major divisions viz. Generation, Transmission and Distribution. Transmission Systems are the links between generating stations and the Distribution systems. Distribution system connects all the loads to transmission lines at substations.
- AC Electrical system was developed in 1885 in US. Until 1917 these systems were usually operated as individual units. With the increase of load and increase in the demand for reliability, interconnection between neighboring systems started growing.
- Interconnections are advantageous economically because fewer machines are required as reserve (reserve capacity) for operation at peak loads and fewer machines running without load (spinning reserve) are required to take care of sudden unexpected increase in load.

Introduction

- But inter connections brought many new problems. It increases the amount of current which flows when a short circuit occurs on a system, which requires installation of breakers of higher breaking capacity. The disturbance caused by short circuit on one system may spread to other interconnected system unless proper protection systems are provided at the point of inter connection. Moreover, the synchronous machines of one system must remain in step with the synchronous machines of the other interconnected systems.
- It is thus obvious that for reliable operation of power system all the above are known and addressed. This knowledge is obtained through Power System studies, the parts of which are –

  1) Fault Study
  2) Load Flow Study and
  3) Stability Study

VII. POWER SYSTEM STUDY

FAULT STUDY

Fault Study

- When a fault occurs, the immediate current flows (Sub-Transient current) through different element of Power System differs from that flowing a few cycle later (Transient Current) when the circuit breakers are called upon to open and both these currents differ widely from the current under normal operating condition (Steady State Current). Selection of circuit breaker at any particular position depends, apart from nominal steady state current capability, upon –

  1) Sub-Transient Current, which the breaker must withstand

  2) Transient Current which the breaker must interrupt

- Fault studies determine these currents for various types of faults at various locations of the system. The data obtained from fault calculation is also utilized to determine the settings of the relays.

VII. POWER SYSTEM STUDY

LOAD FLOW STUDY

Load Flow Study

- In an electrical network, the power flow through any element depends upon the difference in magnitude and phase angle of voltage across the element. Thus a change in load or change in voltage owing to alteration in network leads to change in power flow through the element.
- Through this study, voltage, current, active power, reactive power and power factor at various point in the network are determined under various modes of power system operation. Load flow studies are also essential in planning the future development / alteration of the power system.

VII. POWER SYSTEM STUDY

STABILITY STUDY

Stability Study

- When a synchronous generator runs in parallel with other generator/s, the power output depends on –
  - i) Magnitude of its generated internal voltage
  - ii) Phase angle of this voltage w.r.t. the generated voltage of the other generator/s
  - iii) Characteristics of the network
- When a change in load occurs, all the generators connected to the system will respond to the change by adjusting the magnitude and or phase angle of the generated voltages. *Voltage stability* is the ability of a power system to maintain steady acceptable voltage magnitude at all buses in the system under normal operating condition and after being subjected to a disturbance.
- The phase angles of the generated voltages depend upon the relative positions of the rotors of the machines. If the phase angle of these generated voltages change constantly and progressively with respect to each other, satisfactory operation would be impossible. Rotor *Angle Stability* is the ability of interconnected synchronous machines to remain in synchronism.

VII. POWER SYSTEM STUDY

SYMMETRICAL THREE PHASE FAULT AT GENERATOR TERMINAL

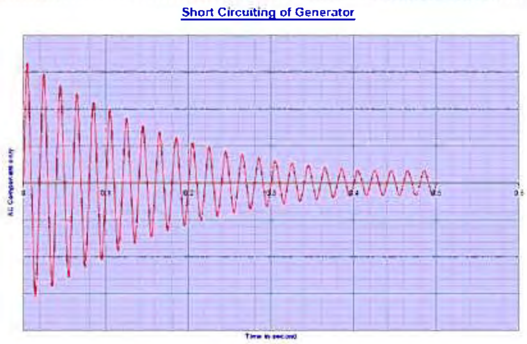
Symmetrical Three Phase Fault at Generator Terminal

- When a short circuit is applied to the terminals of a synchronous generator, the initial resistance to the fault current is offered by the sub-transient reactance (X_d") of the machine. With passage of time (a few cycles), armature reaction comes into play and a new higher resistance is offered by the transient reactance (X_d') of the machine. If the condition is allowed to persist for some more time (a few more cycles), the resistance to the fault current further increases and is offered by synchronous reactance (X_d) of the machine.
- From the knowledge of sudden energizing of series RL circuit we know that depending upon the instant of switching, a unidirectional DC component of current is introduced and the total current is the AC component superimposed on the DC component.

$$i= \{V_{max} / |Z|\} \{\sin(wt+\alpha - \theta) - e^{-Rt/L} \sin(\alpha- \theta)\}$$

- Since the voltages of the phases of the three phase machine are displaced by 120^0 from each other, the short circuit occurs at different points on the voltage wave of each phase. For this reason, the DC component of current is different in each phase. If the DC component of current is removed from each phase, the resulting wave for each phase is as shown below;

Symmetrical Three Phase Fault at Generator Terminal



- From the above it is clear that, short circuiting at generator terminal leads to fault current which diminishes with time. For the first few cycles, the fault current is of maximum value and is called as sub-transient fault current followed by the transient fault current. The fault current continuously diminishes till a stable fault current called as steady state fault current is reached. On the basis of the study objective, relevant reactances and hence relevant fault currents are considered.

VII. POWER SYSTEM STUDY

PER-UNIT SYSTEM

Introduction

- In power systems there are so many different elements such as Motors, Generators and Transformers with very different sizes and nominal values.
- To be able to compare the performances of a big and a small element, per unit system is used.

Power System Representation

- Physical Components in the system are represented by a mathematical model.
- Mathematical models of components are connected in exactly the same way as the physical components to obtain the system representation.
- Various physical components have different ratings or basis.
- It is convenient to obtain the representation with respect to a common basis.

Per Unit And Percent Representation

- The numerical ***per unit*** value of any quantity is its ratio to the chosen base quantity of the same dimensions.
- Thus a per unit quantity is a normalized quantity with respect to a chosen base value.
- Percent is the per unit quantity multiplied by a 100.

Advantages

- In the per-unit system of representation, device parameters tend to fall in a relatively fixed range, making erroneous values prominent.
- Ideal transformers are eliminated as circuit elements. This results in a large saving in component representation and reduces computational burden.
- The voltage magnitude throughout a given power system is relatively close to unity in the per-unit system for a power system operating normally. This characteristic provides a useful check on the calculations.

Base Quantities(1)

- In power system calculations the nominal voltage of lines and equipment is almost always known, so the voltage is a convenient base value to choose.
- The apparent power (volt-ampere) is usually chosen as a second base. In equipment this quantity is usually known and makes a convenient base.

Base Quantities(2)

- The choice of these two base quantities will automatically fix the base of current, impedance, and admittance.
- In a system study, the volt-ampere base can be selected to be any convenient value such as 100 MVA, 200 MVA, etc.

Base Quantities(3)

- The same volt-ampere base is used in all parts of the system. One base voltage in a certain part of the system is selected arbitrarily. All other base voltages must be related to the arbitrarily selected one by the turns ratio of the connecting transformers.

Per Unit System(1)

- Power system quantities such as voltage, current and impedance are often expressed in per unit or percent of specified values.
- Per unit quantities are calculated as:

$$\text{Per Unit Value} = \frac{\text{Actual Value}}{\text{Base Value}}$$

Per Unit System(2)

- Per Unit Values

$$S_{pu} = \frac{|S|}{S_{base}} \quad I_{pu} = \frac{|I|}{I_{base}} \quad V_{pu} = \frac{|V|}{V_{base}} \quad Z_{pu} = \frac{|Z|}{Z_{base}}$$

- Conversion of Per Unit Values

$$Z_{pu} = \frac{|Z|}{Z_{base}} = \frac{S_{base}}{V^2_{base}} |Z|$$

$$|Z| = Z_{base} Z_{pu} = \frac{V^2_{base}}{S_{base}} Z_{pu}$$

Per Unit System(3)

- Usually, the nominal apparent power (S) and nominal voltage (V) are taken as the base values for power (S_{base}) and voltage (V_{base}).

- The base values for the current (I_{base}) and impedance (Z_{base}) can be calculated based on the first two base values.

Per Unit System(4)

$$Z_{\%} = \frac{Z_{actual}}{Z_{base}} \times 100\%$$

- The percent impedance
- e.g. in a synchronous generator with 13.8 kV as its nominal voltage, instead of saying the voltage is 12.42 kV, we say the voltage is 0.9 p.u.

Per Unit in 3phase Circuit(1)

- Simplified:
  - Concerns about using phase or line voltages are removed in the per-unit system
  - Actual values of R, X_C and X_L for lines, cables, and other electrical equipment typically phase values.
  - It is convenient to work in terms of base VA (base volt-amperes)

Per Unit in 3phase Circuit(2)

- Usually, the 3-phase S_B or MVA_B and line-to-line V_B or kV_B are selected
- I_B and Z_B dependent on S_B and V_B

$$S_B = \sqrt{3} V_B I_B \qquad V_B = \sqrt{3} I_B Z_B$$

$$I_B = \frac{S_B}{\sqrt{3} V_B}, \qquad Z_B = \frac{V_B / \sqrt{3}}{I_B} = \frac{(V_B)^2}{S_B}$$

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Change of Base(1)

- The impedance of individual generators & transformer, are generally in terms of percent/per unit based on their own ratings.
- Impedance of transmission line in ohmic value
- When pieces of equipment with various different ratings are connected to a system, it is necessary to convert their impedances to a per unit value expressed on the same base.

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Change of Base(2)

Z_{pu}^{old} be the per unit impedance on the power base S_B^{old} & voltage base V_B^{old}

$$Z_{pu}^{old} = \frac{Z_{\Omega}}{Z_B^{old}} = \left(\frac{S_B^{old}}{\left(V_B^{old}\right)^2}\right) \bullet Z_{\Omega} \qquad (1)$$

Z_{pu}^{new} be the new per unit impedance on the new power base S_B^{new} & new voltage base V_B^{new}

$$Z_{pu}^{new} = \frac{Z_{\Omega}}{Z_B^{new}} = \left(\frac{S_B^{new}}{\left(V_B^{new}\right)^2}\right) \bullet Z_{\Omega} \qquad (2)$$

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Change of Base(3)

- From (1) and (2), the relationship between the old and the new per unit value

$$Z_{pu}^{new} = Z_{pu}^{old}\left(\frac{S_B^{new}}{S_B^{old}}\right)\left(\frac{V_B^{old}}{V_B^{new}}\right)^2$$

- If the voltage base are the same,

$$Z_{pu}^{new} = Z_{pu}^{old}\left(\frac{S_B^{new}}{S_B^{old}}\right)$$

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General Relations Between Circuit Quantities

$Y-Connection$

$$Z_Y = \frac{V_{LN}}{I_L} = \frac{V_{LL}\angle -30^o}{\sqrt{3}} * \frac{\sqrt{3}V_{LL}}{S_{3\phi}} = \frac{V_{LL}^2\angle -30^o}{S_{3\phi}}$$

$\Delta-Connection$

$$I_D = \frac{I_L\angle 30^o}{\sqrt{3}} = \frac{V_{LL}}{Z_D} = \frac{S_{3\phi}\angle 30^o}{3V_{LL}}$$

$$Z_D = \frac{V_{LL}}{I_D} = \frac{\sqrt{3}V_{LL}\angle -30^o}{I_L} = \sqrt{3}V_{LL}\angle -30^o * \frac{\sqrt{3}V_{LL}}{S_{3\phi}} = \frac{3V_{LL}^2\angle -30^o}{S_{3\phi}}$$

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Base Conversion

$$Z_{pu(new)} = Z_{pu(old)} * \frac{MVA_{base(new)}}{MVA_{base(old)}} * \frac{KV_{base(old)}^2}{KV_{base(new)}^2}$$

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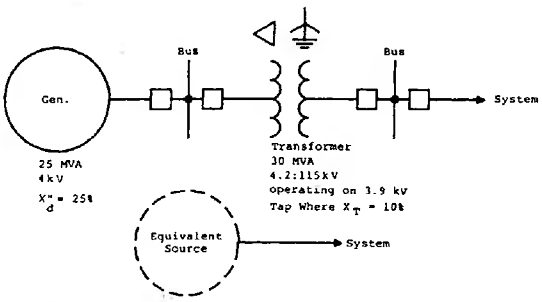
Example One: Base Conversion

- A 50-MVA, 34.5:161 kV transformer with 10% reactance is connected to a power system where all the other impedance values are on a 100 MVA, 34.5 or 161 kV base. The reactance of the transformer under new base is:

$$Z_{pu(new)} = 0.1 * \frac{100}{50} * \frac{KV^2_{base(old)}}{KV^2_{base(new)}} = 0.2$$

Example Two: Base Conversion

- A generator and transformer, as shown below, are to be combined into a single equivalent reactance on a 100 MVA, 110 kV (high voltage side) base.



Xeg = 151.43% = 1.154 pu on 100 MVA, 110kV Base

Advantages(1)

- More meaningful when comparing different voltage levels
- The per unit equivalent impedance of the transformer remains the same when referred to either the primary or the secondary side
- The per unit impedance of a transformer in a three-phase system is the same, regardless the winding connection

Advantages(2)

- Manufacturers usually specify the impedance of the equipment in per unit or percent on the base of its nameplate ratings
- The per unit impedance values of various ratings of equipment lie in a narrow range

Advantages(3)

- Transformer equivalent circuit can be simplified by properly specifying base quantities.
  - Give a clear idea of relative magnitudes of various quantities such as voltage, current, power and impedance.
  - Avoid possibility of making serious calculation error when referring quantities from one side of transformer to the other.

Advantages(4)

- Per-unit impedances of electrical equipment of similar type usually lie within a narrow numerical range when the equipment ratings are used as base values.
  - Manufacturers usually specify the impedances of machines and transformers in per-unit or percent in nameplate rating.

Advantages(5)

- The circuit laws are valid in per unit systems, and the power and voltage equation are simplified since the factor √3 and 3 are eliminated in the per-unit systems.
- Ideal for the computerized analysis and simulation of complex power system problems.

VII. POWER SYSTEM STUDY

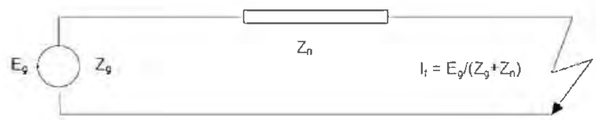
CALCULATION OF FAULT CURRENT IN A NETWORK

- When a fault occurs in a network, the fault current is determined by

    i) the internal emfs of the machines in the system,

    ii) their impedances and

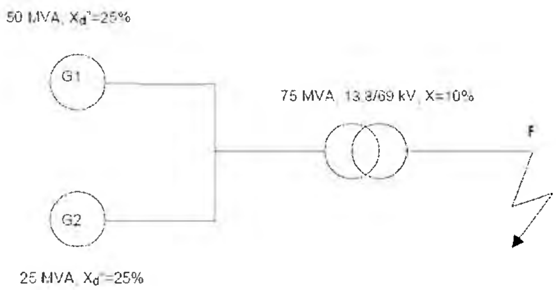
    iii) the impedances in the network between the fault and machines.



- Alternatively Fault MVA = Base MVA / PU Impedance.

Example

For a network shown below, find the fault current, voltages at primary terminal of the transformer and generator terminals for a three phase symmetrical fault at point F. Also find the contribution of fault current by the generators. Ignore the impedances of the lines.



Solution

Let us choose Base MVA = 75

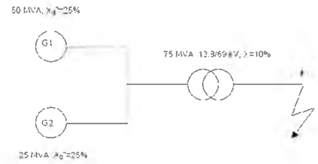
The new Per-Unit impedances of the elements on new Base of 75 MVA are as under:

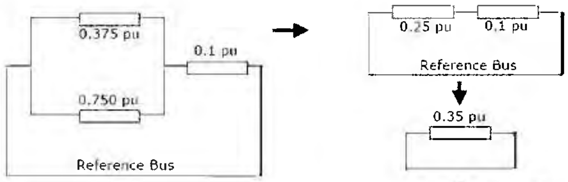
X_d" of G1 = 0.25 * 75/50 = 0.375 pu

X_d" of G2 = 0.25 * 75/25 = 0.750 pu

X of transformer = 0.1 pu

Reactance diagram of the system is as under





Fault MVA = 75 / 0.35 = 214 MVA

Fault Current = 214 * 1000/(√3*69)= 1.79kA

Fault Current = Ea / PU Z = 1 / 0.35 PU

Fault Current = 2.857 PU

= 2.875*√3*75*1000/69

= 1.79 kA

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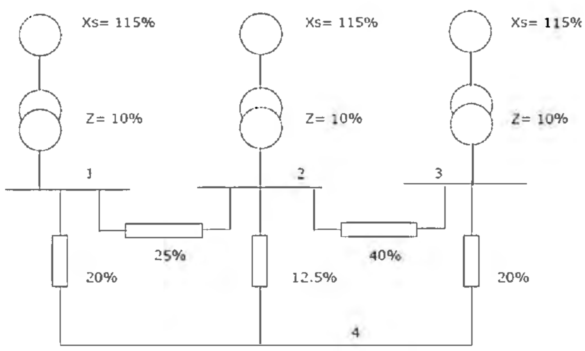
Fault calculation by the method described so far becomes laborious & time consuming for actual networks which are big & complicated in nature.

Here we will develop methods for formation of network equations.

Let us consider the following network (Impedances on same base)



(Single line diagram)

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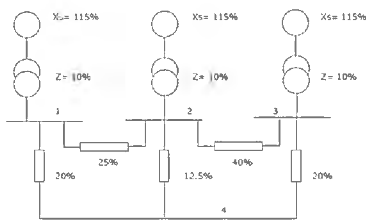
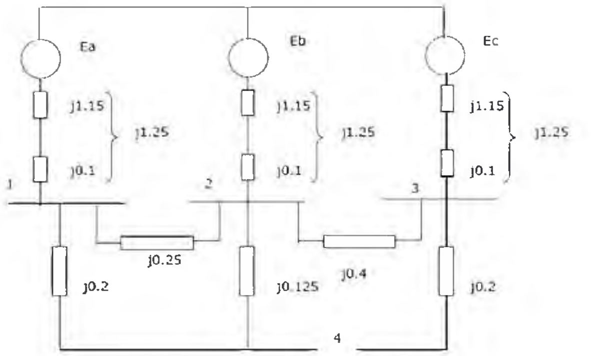
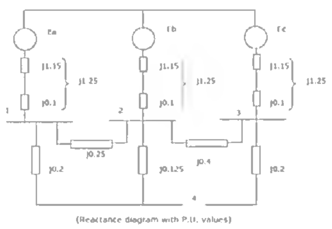


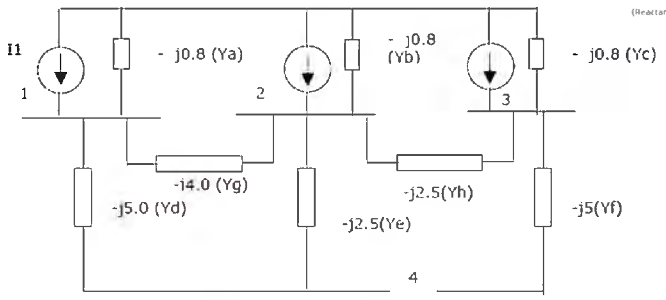
(Single line diagram)



(Reactance diagram with P.U. values)

Replacing the voltage sources and series impedances by equivalent current sources and shunt admittances (shunt admittance = 1/ series impedance)





(Admittance Diagram with P.U. values)

Applying Kirchoff's current law at Bus 1

$I_1 = V_1Y_a + (V_1\text{-}V_2)Y_g + (V_1\text{-}V_4)Y_d$

$= V_1(Y_a+Y_g+Y_d) - V_2Y_g - V_4Y_d$

$Y_a+Y_g+Y_d$=Self admittance of Bus 1=Sum of all admittances connected to Bus=Y_{11}

$-Y_g$ = Mutual admittance between Bus 1 & 2 = Y_{12}

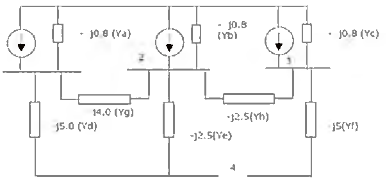
$-Y_d$ = Mutual admittance between Bus 1 & 4 = Y_{14}

0 = Mutual admittance between Bus 1 & 3 = Y_{13}

Hence $I_1 = Y_{11}V_1 + Y_{12}V_2 + Y_{13}V3 + Y14V4$

The general equation in Matrix form is

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix} = \underbrace{\begin{bmatrix} Y_{11} & Y_{12} & Y_{13} & Y_{14} \\ Y_{21} & Y_{22} & Y_{23} & Y_{24} \\ Y_{31} & Y_{32} & Y_{33} & Y_{34} \\ Y_{41} & Y_{42} & Y_{43} & Y_{44} \end{bmatrix}}_{\text{Y Bus}} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{bmatrix}$$



(Admittance Diagram with P.U. values)

$I = Y_{bus} V$

Premultiplying both sides by Y_{bus}-1

$V = Y_{bus}^{-1} I = Z_{bus} I$ (as $Y_{bus}^{-1} = Z_{bus}$)

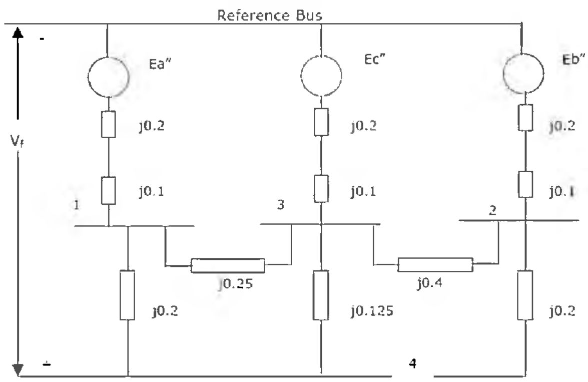
In Matrix form.

$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{bmatrix} = \underbrace{\begin{bmatrix} Z_{11} & Z_{12} & Z_{13} & Z_{14} \\ Z_{21} & Z_{22} & Z_{23} & Z_{24} \\ Z_{31} & Z_{32} & Z_{33} & Z_{34} \\ Z_{41} & Z_{42} & Z_{43} & Z_{44} \end{bmatrix}}_{\text{Z Bus}} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix}$$

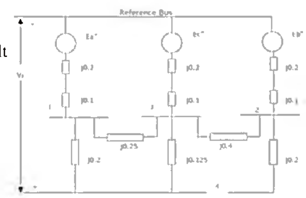
VII. POWER SYSTEM STUDY

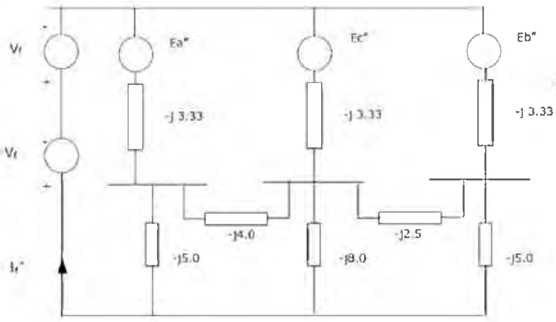
USE OF BUS IMPEDANCE MATRIX IN FAULT CALCULATION

We would now simulate a three phase symmetrical fault at Bus 4 of our network. As our objective is to find out subtransient fault current, we would replace the synchronous reactances of the generator by subtransient reactances and no load generated voltage by sub transient internal voltages of the machines as under. Let the voltage of Bus 4 be V_f



We would now replace the reactances by admittances as below and simulate short circuit by connecting - V_f in series with V_f. Let the fault current be I_f"





If E_a", E_b", E_c" and V_f are short circuited, the voltages and currents are due to $-V_f$ only. The only current entering at Bus 4 is $-I_f$"

Hence our Matrix equation reduces to

$$\begin{bmatrix} 0 \\ 0 \\ 0 \\ I_f'' \end{bmatrix} = \begin{bmatrix} -12.33 & 0 & 4.0 & 5.0 \\ 0 & -10.83 & 2.5 & 5.0 \\ 4.0 & 2.5 & -17.83 & 8.0 \\ 5.0 & 5.0 & 8.0 & -18.0 \end{bmatrix} \begin{bmatrix} V_1' \\ V_2' \\ V_3' \\ -V_f \end{bmatrix}$$

$(I = Y_{bus} V)$

Where V1', V2' and V3' are the change in voltages due to fault.

Premultiply both sides by $Ybus^{-1}$,

$$\begin{bmatrix} V_1' \\ V_2' \\ V_3' \\ -Vf \end{bmatrix} = \begin{bmatrix} & & Z_{bus} & & \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 0 \\ -I_f'' \end{bmatrix}$$

Where

$$Z_{bus} = \begin{bmatrix} 0.1488 & 0.0651 & 0.0864 & 0.0978 \\ 0.0651 & 0.1554 & 0.0799 & 0.0967 \\ 0.0864 & 0.0798 & 0.1341 & 0.1058 \\ 0.0978 & 0.0967 & 0.1058 & 0.1566 \end{bmatrix}$$

$$\begin{bmatrix} V_1' \\ V_2' \\ V_3' \\ -V_f \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} & Z_{13} & Z_{14} \\ Z_{21} & Z_{22} & Z_{23} & Z_{24} \\ Z_{31} & Z_{32} & Z_{33} & Z_{34} \\ Z_{41} & Z_{42} & Z_{43} & Z_{44} \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 0 \\ -I_f'' \end{bmatrix}$$

Therefore $- V_f = Z_{44} X (-I_f'')$

Therefore $I_f'' = V_f / Z_{44}$, for our system $I_f'' = 1/0.1566 = 6.38$ PU

Similarly

$V_1' = -I_f'' X Z_{14}$, $V_2' = -I_f'' X Z_{24}$, $V_3' = -I_f'' X Z_{34}$

Normally, while studying fault, the network is considered offloaded and the prefault voltage of all buses including faulted bus is considered 1 PU

Hence post fault voltage of buses are

$V_1 = V_f + V_1' = 1 - I_f'' Z_{14} = (1 - 6.38*0.0978)PU = 0.376$ PU

$V_2 = V_f + V_2' = 1 - I_f'' Z_{24} = (1 - 6.38*0.0967)PU = 0.383$ PU

$V_3 = V_f + V_3' = 1 - I_f'' Z_{34} = (1 - 6.38*0.1058)PU = 0.324$ PU

$V_4 = V_f - V_f = 0$

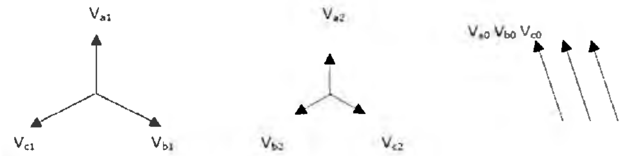
Current in any part of the network can be found out from the post fault voltages of the buses and relevant element of Y_{bus}.

Hence the current between Bus 1 & Bus 3 during a fault at Bus 4 = $(V_1 - V_3)$ X Y_{13}

VII. POWER SYSTEM STUDY

SYMMETRICAL COMPONENTS

Theorem : Any set of n unbalanced vectors can be resolved to n sets of balanced vectors.



$V_a = V_{a1} + V_{a2} + V_{a0}$

$V_b = V_{b1} + V_{b2} + V_{b0} = a^2V_{a1} + aV_{a2} + V_{a0}$

$V_c = V_{c1} + V_{c2} + V_{c0} = aV_{a1} + a^2V_{a2} + V_{a0}$

Therefore in Matrix form

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{bmatrix}$$

$$\begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{bmatrix} = \frac{1}{3} \underbrace{\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}}_{A^{-1}} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

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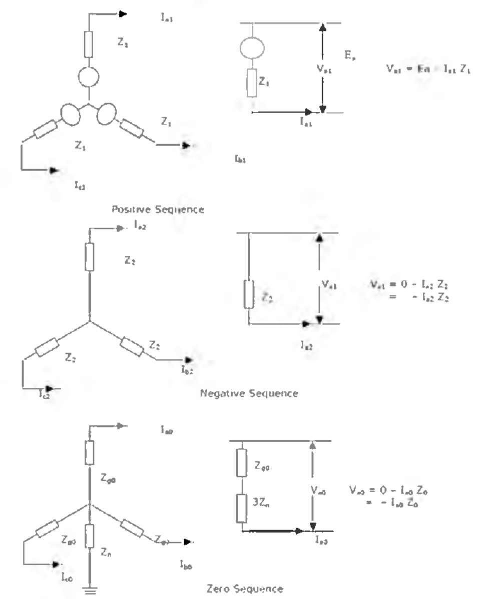
Sequence network of unloaded generator



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Unsymmetrical faults

Regardless of type of faults on unloaded generator

$$\begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{bmatrix} = \begin{bmatrix} 0 \\ E_a \\ 0 \end{bmatrix} - \begin{bmatrix} Z_0 & 0 & 0 \\ 0 & Z_1 & 0 \\ 0 & 0 & Z_2 \end{bmatrix} \begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{bmatrix}$$

Single line to ground fault on unloaded generator

$$\begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

Let us consider that there is a single line to ground fault in phase "a"

Therefore $V_a = 0, I_b = 0, I_c = 0$

Hence

$$\begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} I_a \\ 0 \\ 0 \end{bmatrix}$$

Therefore $I_{a0} = 1/3\, I_a$, $I_{a1} = 1/3\, I_a$, $I_{a2} = 1/3\, I_a$

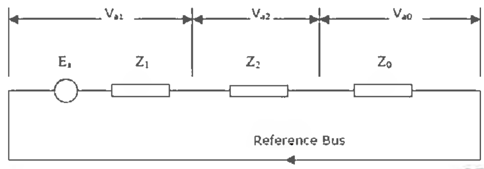
$$\begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{bmatrix} = \begin{bmatrix} 0 \\ E_a \\ 0 \end{bmatrix} - \begin{bmatrix} Z_0 & 0 & 0 \\ 0 & Z_1 & 0 \\ 0 & 0 & Z_2 \end{bmatrix} \begin{bmatrix} I_{a1} \\ I_{a1} \\ I_{a1} \end{bmatrix}$$

$V_{a0} = -I_{a1} Z_0$, $V_{a1} = E_a - I_{a1} Z_1$, $V_{a2} = -I_{a2} Z_2$

$V_{a0} + V_{a1} + V_{a2} = E_a - I_{a1}(Z_0 + Z_1 + Z_2) = V = 0$

Hence $I_{a1} = E_a / (Z_0 + Z_1 + Z_2)$, $I_a = 3 I_{a1}$

Hence all the sequence networks are in series for a single line to ground fault.



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Japanese Technical Assistance
on Strengthening Institutional Capacity
of National Development Agency (ADN)
in Democratic of Timor-Leste

-- POWER --

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Syllabus

No.	Contents
1	Introduction
2	Power Station (Diesel)
3	Substation
4	Transmission and Distribution System
5	Power System Study
6	Power Flow Analysis
7	Renewable Energy (Photovoltaic Power)
8	Protecting System
9	Power System Operation and Control
10	Others

The contents may be changed depending on conditions.
I would like to discuss about the contents with Mr. Miguel and YOU.

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VIII. POWER FLOW ANALYSIS

VIII. POWER FLOW ANALYSIS

INTRODUCTION

Introduction

Power systems typically operate under slowly changing conditions which can be analyzed using steady state analysis. Further, transmission systems operate under balanced or near balanced conditions allowing per-phase analysis to be used with a high degree of confidence in the solution. Power flow analysis computationally models these conditions and provides the starting point for most other analyses. For example, the small signal and transient stability effects of a given disturbance are dramatically affected by the "pre-disturbance" operating conditions of the power system. (A disturbance resulting in instability under heavily loaded system conditions may not have any adverse effects under lightly loaded conditions.) Additionally, fault analysis and transient analysis can also be impacted by the "pre-disturbance" operating point of a power system (although, they are usually affected much less than transient stability and small signal stability analysis).

The Power Flow Problem

- Power flow analysis is fundamental to the study of power systems forming the basis for other anlayses. Power flow analyses play a key role in the planning of additions or expansions to transmission and generation facilities as well as establishing the starting point for many other types of power system analyses. In addition, power flow analysis and many of its extensions are an essential ingredient of the studies performed in power system operations. In this latter case, it is at the heart of contingency analysis and the implementation of real-time monitoring systems.
- The power flow problem (also known as the load flow problem) can be stated as follows:

  For a given power network, with known complex power loads and some set of specifications or restrictions on power generations and voltages, solve for any unknown bus voltages and unspecified generation and finally for the complex power flow in the network components.

- Additionally, the losses in individual components and the total network as a whole are usually calculated. Furthermore, the system is often checked for component overloads and voltages outside allowable tolerances.

Power flow equations

Power flow equations represent the fundamental balancing of power as it flows from the generators to the loads through the transmission network. Both real and reactive power flows play equally important roles in determining the power flow properties of the system. Power flow studies are among the most significant computational studies carried out in power system planning and operations in the industry. Power flow equations allow the computation of the bus voltage magnitudes and their phase angles as well as the transmission line current magnitudes. In actual system operation, both the voltage and current magnitudes need to be maintained within strict tolerances for meeting consumer power quality requirements and for preventing overheating of the transmission lines, respectively.

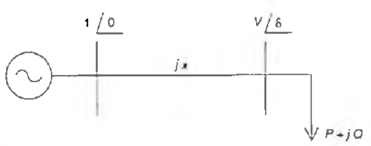
Nonlinear nature

- The difficulty in computing the power flow solutions arises from the fact that the equations are inherently nonlinear because of the balancing of power quantities. Moreover, the large size of the power network implies that power flow studies involve solving a very large number of simultaneous nonlinear equations. Fortunately, the sparse interconnected nature of the power network reflects itself in the computational process, facilitating the computational algorithms.
- Here, we first study a simple power flow problem to gain insight into the nonlinear nature of the power flow equations. We then formulate the power flow problem for the large power system.
- Next, usually like in school, a classical power flow solution method based on the Gauss-Seidel algorithm will be studied. The popular Newton-Raphson algorithm, which is the most commonly used power flow method in the industry today, will be introduced.
- But I will not introduce the algorithm here. I will leave copies of some textbooks, then try to read.

VIII. POWER FLOW ANALYSIS

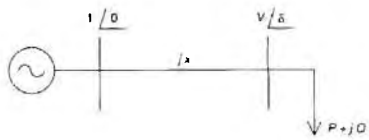
SIMPLE EXAMPLE OF A POWER FLOW PROBLEM

Let us consider a single generator delivering the load P + jQ through the transmission line with the reactance x. The generator bus voltage is assumed to be at the rated voltage, and it is at 1 per unit (pu). The generator bus angle is defined as the phasor reference, and hence, the generator bus voltage phase angle is set to be zero. The load bus voltage has magnitude V and phase angle δ. Because the line has been assumed to be lossless, note that the generator real power output must be equal to the real power load P. However, the reactive power output of the generator will be the sum of the reactive load Q and the reactive power "consumed" by the transmission line reactance x.



Let us write down the power flow equations for this problem. Given a loading condition P + jQ, we want to solve for the unknown variables, namely, the bus voltage magnitude V and the phase angle δ. For simplicity, we will assume that the load is at unity power factor of Q = 0. The line current phasor I from the generator bus to the load bus is easily calculated as:

$$I = \frac{1\angle 0 - V\angle\delta}{jx}. \quad (1)$$



Next, the complex power S delivered to the load bus can be calculated as:

$$S = VI^* = \frac{V\angle(\delta + \pi/2)}{x} - \frac{V^2\angle(\pi/2)}{x}. \quad (2)$$

Therefore, we get the real and reactive power balance equations:

$$P = \frac{-V\sin\delta}{x} \text{ and } Q = \frac{-V^2 + V\cos\delta}{x}. \quad (3)$$

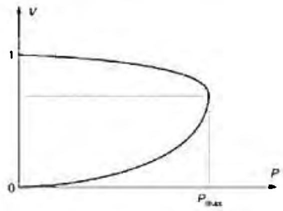
After setting Q = 0 in equation (3), we can simplify equation (3) into a quadratic equation in V^2 as follows:

$$V^4 - V^2 + x^2P^2 = 0. \quad (4)$$

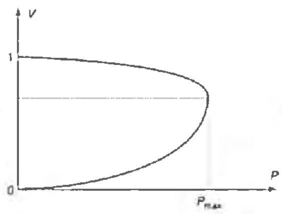
Therefore, given any real power load P, the corresponding power flow solution for the bus voltage V can be solved from equation (4). We note that for nominal load values, there are two solutions for the bus voltage V, and they are the positive roots of V^2 in the next equation:

$$V^2 = \frac{1 \pm \sqrt{1 - 4x^2P^2}}{2}. \qquad (5)$$

Equation (5) implies that there exist two power flow solutions for load values $P < P_{max}$ where $P_{max} = 1/(2x)$, and there exist no power-flow solutions for $P > P_{max}$. A qualitative plot of the power flow solutions for the bus voltage V in terms of different real power loads P is shown in Figure.



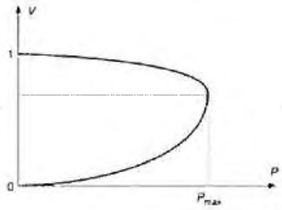
Qualitative Plot of the Power-Flow Solutions



Qualitative Plot of the Power-Flow Solutions

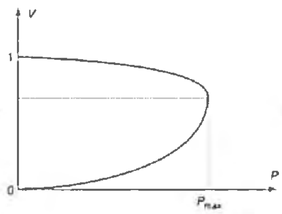
From the plot and from the analysis thus far, we can make the following observations:

1. The dependence of the bus voltage V on the load P is very much nonlinear. It has been possible for us to compute the power flow solutions analytically for this simple system. In the large power system with hundreds of generators delivering power to thousands of loads, we have to solve for thousands of bus voltages and their phase angles from large coupled sets of non-linear power flow equations, and the computation is a nontrivial task.



Qualitative Plot of the Power-Flow Solutions

2. Multiple power flow solutions can exist for a specified loading condition. In Figure, there exist two solutions for any load $P < P_{max}$. Among the two solutions, the solution on the upper locus with voltage V near 1 pu is considered the nominal solution. For the solutions on the lower locus, the bus voltage V may be unacceptably low for normal operation. The lower voltage solution also requires higher line current to deliver the specified load P, and the line current values can become unacceptably high. In general, for any specified loading condition, we would like to locate the power flow solution that has the most acceptable values of voltages and currents among the multiple power flow solutions. In this example of a single generator delivering power to a single load, there exist two power flow solutions. In a large power system, there may exist a very large number of possible power flow solutions.



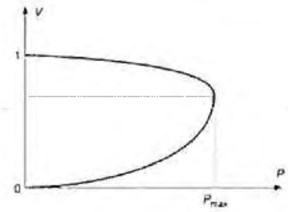
Qualitative Plot of the Power-Flow Solutions

3. Once the bus voltage V has been computed from equation (5), the bus voltage phase angle δ can be computed from equation (3). Then, the line current phasor I can be solved from equation (1). Specifically, we would like to ensure that the magnitude of the line current I stays below the thermal limit of the transmission line for preventing potential damage to the expensive transmission line.

(5) $$V^2 = \frac{1 \pm \sqrt{1 - 4x^2P^2}}{2}.$$

(3) $$P = \frac{-V\sin\delta}{x} \text{ and } Q = \frac{-V^2 + V\cos\delta}{x}.$$

(1) $$I = \frac{1\angle 0 - V\angle\delta}{jx}.$$

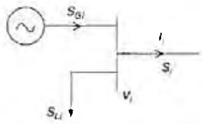


Qualitative Plot of the Power-Flow Solutions

4. Power flow solutions may fail to exist at high loading conditions, such as when $P > P_{max}$ in Figure. The loading value P_{max} beyond which power flow solutions do not exist is called the static limit in the power literature. Because power flow solutions denote the steady-state operating conditions in our formulation, lack of power flow solutions implies that it is not possible to transfer power from the generator to the load in a steady-state fashion, and the dynamic interactions of the generators and the loads become significant. Operating the power system at loading conditions beyond the static limit may lead to catastrophic failure of the system.

VIII. POWER FLOW ANALYSIS

POWER FLOW PROBLEM FORMULATION



Complex Power Balance at Bus i

Here, we will construct the power flow equations in a structured manner using the admittance matrix Y_{bus} representation of the transmission network. The admittance matrix Y_{bus} is assumed to be known for the system under consideration. Let us first look at the complex power balance at any bus, say bus i, in the network.

The power balance equation is given by:

$$S_i = V_i I_i^* = S_{G_i} - S_{L_i}. \quad (6)$$

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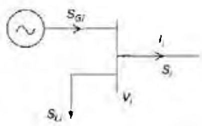

Complex Power Balance at Bus i

$$S_i = V_i I_i^* = S_{G_i} - S_{L_i}. \quad (6)$$

Let us denote the vector of bus voltages as $\underline{V}_{bus}$ and the vector of bus injection currents as $\underline{I}_{bus}$. By definition, the admittance matrix $\underline{Y}_{bus}$ provides the relationship $\underline{I}_{bus} = \underline{Y}_{bus} \underline{V}_{bus}$. Suppose the ith or jth entry Y_{ij} of the Ybus matrix has the magnitude Yij and the phase "Yij. Then, we can simplify the current injection I_i as:

$$I_i = \sum_j Y_{ij} V_j = \sum_j Y_{ij} V_j \angle(\delta_j + \gamma_{ij}). \quad (7)$$

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Then, combining equations (6) and (7), we get the complex power balance equations for the network as:

$$\mathbf{S}_i = \mathbf{S}_{G_i} - \mathbf{S}_{L_i} = \sum_j Y_{ij} V_i V_j \angle(\delta_i - \delta_j - \gamma_{ij}). \quad (8)$$

Taking the real and imaginary parts of the complex equation (8) gives us the real and reactive power flow equations for the network:

$$P_i = P_{G_i} - P_{L_i} = \sum_j Y_{ij} V_i V_j \cos(\delta_i - \delta_j - \gamma_{ij}). \quad (9)$$

$$Q_i = Q_{G_i} - Q_{L_i} = \sum_j Y_{ij} V_i V_j \sin(\delta_i - \delta_j - \gamma_{ij}). \quad (10)$$

Generally speaking, our objective in this section is to solve for the bus voltage magnitudes V_i and the phase angles δ_i when the power generations and loads are specified. For a power system with N buses, there are 2N number of power flow equations. At each bus, there are six variables: P_{Gi}, Q_{Gi}, P_{Li}, Q_{Li}, V_i, and δ_i. Depending on the nature of the bus, four of these variables will be specified at each bus, leaving two unknown variables at each bus. We will end up with 2N unknown variables related by 2N equations (9) and (10), and our aim in the rest of this section is to develop algorithms for solving this problem.

Let us consider a purely load bus first, that is, with $P_{Gi} = Q_{Gi} = 0$. In this case, the loads P_{Li} and Q_{Li} are assumed to be known either from measurements or from load estimates, and the bus voltage variables V_i and δ_i are the unknown variables. Purely load busses with no generation support are called **PQ busses** in power flow studies because both real power injection P_i and reactive power Q_i have been specified at these busses.

Typically, every generator in the system consists of two types of internal controls, one for maintaining the real power output of the generator and the other for regulating the bus voltage magnitude. In power flow studies, we usually assume that both these control mechanisms are operating perfectly and so the real power output P_{Gi} and V_i are maintained at their specified values. Again, the load variables P_{Li} and Q_{Li} are also assumed to be known. This leaves the generator reactive output Q_{Gi} and the voltage phase angle δ_i as the two unknown variables for the bus. In terms of injections, the real power injection P_i and the bus voltage V_i are then the specified variables; thus, the generator busses are normally denoted **PV busses** in power flow studies.

In reality, the generator voltage control for keeping the bus voltage magnitude at a specified value becomes inactive when the control is pushed to the extremes, such as when the reactive output of the generator becomes either too high or too low. This voltage control limitation of the generator can be represented in power flow studies by keeping track of the reactive output Q_{Gi}. When the reactive generation Q_{Gi} becomes larger than a prespecified maximum value of $Q_{Gi,max}$ or goes lower than a prespecified minimum value $Q_{Gi,min}$, the reactive output is assumed to be fixed at the limiting value $Q_{Gi,max}$ or $Q_{Gi,min}$, respectively, and the voltage control is disabled in the formulation; that is, the reactive power Q_{Gi} becomes a known variable, either at $Q_{Gi,max}$ or $Q_{Gi,min}$, and the voltage V_i then becomes the unknown variable for bus i. In power flow terminology, we say that the generator at bus i has "reached its reactive limits" and, hence, bus i has changed from a PV bus to a PQ bus. Owing to space limitations, we will not discuss generator reactive limits in any more detail here.

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In addition to PQ busses and PV busses, we also need to introduce the notion of a **slack bus** in the power flow formulation. Note that power conservation demands that the real power generated from all the generators in the network must equal the sum of the total real power loads and the line losses on the transmission network:

$$\sum_i P_{G_i} = \sum_i P_{L_i} + \sum_i \sum_j P_{losses_{ij}}. \qquad (11)$$

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The line losses associated with any transmission line in turn depend on the line resistance and the line current magnitude. As stated earlier, one of the main objectives of power flow studies is to compute the line currents, and as such, the line current values are not known at the beginning of a power flow computation. Therefore, we do not know the actual values for the line losses in the transmission network. Looking at equation (11), we need to assume that at least of one of the variables P_{Gi} or P_{Li} should be a free variable for satisfying the real power conservation. Traditionally, we assume that one of the generations is a "slack" variable, and such a generator bus is denoted the slack bus. At the slack bus, we specify both the voltage V_i and the angle δ_i. The power injections P_i and Q_i are the unknown variables. Again, by tradition, we set the voltage at slack bus to be the rated voltage or at 1 pu and the phase angle to be at zero.

VIII. POWER FLOW ANALYSIS

ANOTHER APPROACH FOR UNDERSTANDING

A two-bus example, shown in Fig. 1, is used to simplify the development of the power-flow equations. The system consists of two busses connected by a transmission line. One can observe that there are six electrical quantities associated with each bus: P_D, P_G, Q_D, Q_G, $|V|$, and δ. This is the most general case, in which each bus is shown to have both generation and demand. In reality, not all busses will have power generation. The impedance diagram of the two-bus system is shown in Fig. 2. The transmission line is represented by a π-model and the synchronous generator is represented by a source behind a synchronous reactance. The loads are assumed to be constant impedance for the sake of representing them on the impedance diagram. Typically, the load is represented by a constant power device, as shown in subsequent figures.

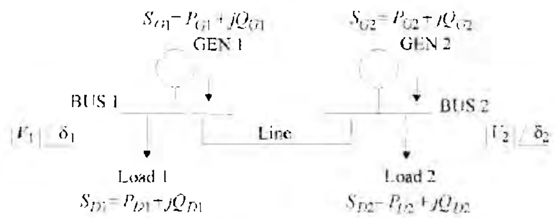

FIG.1 A two-bus power system.

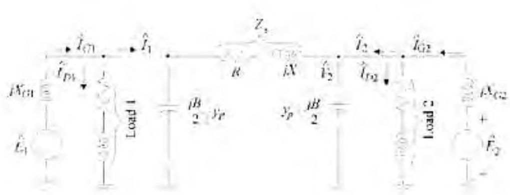

FIG.2 Impedance diagram for the two-bus power system.

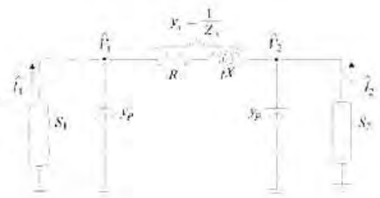

FIG.3 Bus powers with transmission line π-model for the two-bus system.

Fig. 3 is the same as Fig. 2 but with the generation and demand bundled together to represent "bus power," which represents bus power injections. Bus power is defined as

$$S_1 = S_{G1} - S_{D1} = (P_{G1} - P_{D1}) + j(Q_{G1} - Q_{D1}) \quad (1)$$

and

$$S_2 = S_{G2} - S_{D2} = (P_{G2} - P_{D2}) + j(Q_{G2} - Q_{D2}) \quad (2)$$

Also, injected current at bus 1 is

$$\hat{I}_1 = \hat{I}_{G1} - \hat{I}_{D1} \quad (3)$$

and injected current at bus 2 is

$$\hat{I}_2 = \hat{I}_{G2} - \hat{I}_{D2} \quad (4)$$

All quantities are assumed to be per unit. Then, since

$$S_1 = \hat{V}_1\hat{I}_1^* \Rightarrow P_1 + jQ_1 = \hat{V}_1\hat{I}_1^* \Rightarrow (P_1 - jQ_1) = \hat{V}_1^*\hat{I}_1 \quad (5)$$

and

$$S_2 = \hat{V}_2\hat{I}_2^* \Rightarrow P_2 + jQ_2 = \hat{V}_2\hat{I}_2^* \Rightarrow (P_2 - jQ_2) = \hat{V}_2^*\hat{I}_2 \quad (6)$$

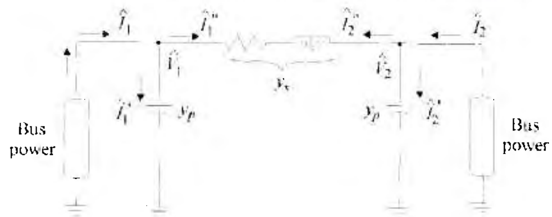

FIG.4 Current flows in the network model.

Let us define current flows in the circuit as shown in Fig. 4. Therefore, at bus 1

$$\hat{I}_1 = \hat{I}_1' + \hat{I}_1''$$

$$= \hat{V}_1 y_p + (\hat{V}_1 - \hat{V}_2)y_s$$

$$\hat{I}_1 = (y_p + y_s)\hat{V}_1 + (-y_s)\hat{V}_2 \quad (7)$$

$$\therefore \hat{I}_1 = Y_{11}\hat{V}_1 + Y_{12}\hat{V}_2 \quad (8)$$

where $Y_{11} \triangleq$ sum of admittances connected at bus $1 = y_p + y_s$ (9)

$Y_{12} \triangleq$ negative of the admittance between busses 1 and 2 $= -y_s$ (10)

Similarly, at bus 2

$$\hat{I}_2 = \hat{I}_2' + \hat{I}_2''$$

$$= \hat{V}_2 y_p + (\hat{V}_2 - \hat{V}_1) y_s$$

$$\hat{I}_2 = (-y_s)\hat{V}_1 + (y_p + y_s)\hat{V}_2 \qquad (11)$$

$$\hat{I}_2 = Y_{21}\hat{V}_1 + Y_{22}\hat{V}_2 \qquad (12)$$

$Y_{22} \triangleq$ sum of admittances connected at bus $2 = y_p + y_s$ (13)

$Y_{21} \triangleq$ negative of the admittance between busses 2 and 1 $= -y_s = Y_{12}$ (14)

Hence, for the two-bus power system, the current injections are

$$\begin{bmatrix} \hat{I}_1 \\ \hat{I}_2 \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix} \begin{bmatrix} \hat{V}_1 \\ \hat{V}_2 \end{bmatrix} \qquad (15)$$

In matrix notation,

$$I_{bus} = Y_{bus} V_{bus} \qquad (16)$$

The two-bus system can easily be extended to a larger system. Consider an n-bus system. Fig. 5a shows the connections from bus 1 of this system to all the other busses. Fig. 5b shows the transmission line models. Equations (5) through (16) that were derived for the two-bus system can now be extended to represent the n-bus system. This is shown next.

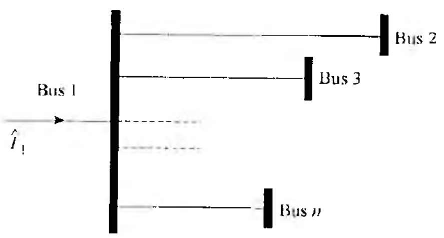

FIG. 5a Extending the analysis to an n-bus system.

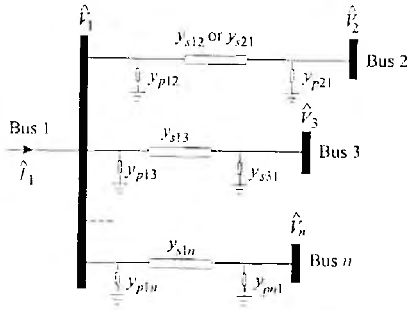

FIG. 5b The π-model for the n-bus system.

$$\hat{I} = \hat{V}_1 y_{p12} + \hat{V}_1 y_{p13} + \cdots + \hat{V}_1 y_{p1n} + (\hat{V}_1 - \hat{V}_2) y_{s12} + (\hat{V}_1 - \hat{V}_3) y_{s13} + \cdots + (\hat{V}_1 - \hat{V}_2) y_{s1n}$$

$$= (y_{p12} + y_{p13} + \cdots + y_{p1n} + y_{s12} + y_{s13} + \cdots + y_{s1n})\hat{V}_n - y_{s12}\hat{V}_2 - y_{s13}\hat{V}_3 + \cdots - y_{s1n}\hat{V}_n \quad (17)$$

$$\hat{I}_1 = Y_{11}\hat{V}_1 + Y_{12}\hat{V}_2 + Y_{13}\hat{V}_3 + \cdots + Y_{1n}\hat{V}_n \quad (18)$$

where $Y_{11} = (y_{p12} + y_{p13} + \cdots + y_{p1n} + y_{s12} + y_{s13} + \cdots + y_{s1n})$ (19)

= sum of all admittances connected to bus 1

$$Y_{12} = -y_{S12};\ Y_{13} = -y_{S13};\ Y_{1n} = -y_{s1n} \quad (20)$$

$$\therefore \hat{I}_1 = \sum_{j=1}^{n} Y_{1j}\hat{V}_j \quad (21)$$

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Also, extending the power Eq. (5) to an n-bus system,

$$P_1 - jQ_1 = \hat{V}_1^* I_1 = \hat{V}_1^* \sum_{j=1}^{n} Y_{1j}\hat{V}_j \quad (22)$$

Equation (22) can be written for any generic bus i:

$$P_i - jQ_i = \hat{V}_i^* \sum_{j=1}^{n} Y_{ij}\hat{V}_j \qquad i = 1, 2, \ldots, n \quad (23)$$

Equation (23) represents the nonlinear power-flow equations. Equation (15) can also be rewritten for an n-bus system:

$$\begin{bmatrix} \hat{I}_1 \\ \hat{I}_2 \\ \vdots \\ \hat{I}_n \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} & \cdots & Y_{1n} \\ Y_{21} & Y_{22} & \cdots & Y_{2n} \\ \vdots & \vdots & & \vdots \\ Y_{n1} & Y_{n2} & \cdots & Y_{nn} \end{bmatrix} \begin{bmatrix} \hat{V}_1 \\ \hat{V}_2 \\ \vdots \\ \hat{V}_n \end{bmatrix} \cdots \quad (24)$$

or

$$I_{bus} = Y_{bus} V_{bus} \quad (25)$$

where

$$Y_{bus} = \begin{bmatrix} Y_{11} & Y_{12} & \cdots & Y_{1n} \\ Y_{21} & Y_{22} & \cdots & Y_{2n} \\ \vdots & \vdots & & \vdots \\ Y_{n1} & Y_{n2} & \cdots & Y_{nn} \end{bmatrix} = \text{bus admittance matrix} \quad (26)$$

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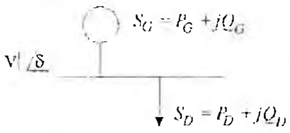

FIG. 6 A generic bus.

TABLE 1 Bus Classifications

Bus classification	Prespecified variables	Unknown variables
Slack or swing	$\|V\|, \delta, P_D, Q_D$	P_G, Q_G
Voltage-controlled	$\|V\|, P_G, P_D, Q_D$	δ, Q_G
Load	P_G, Q_D, P_D, Q_D	$\|V\|, \delta$

Let us take a generic bus as shown in Fig. 6. As mentioned earlier, each bus has six quantities or variables associated with it. They are $|V|$, δ, P_G, Q_G, P_D, and Q_D. Assuming that there are n busses in the system, there would be a total of 6n variables.

The power-flow Eq. (23) can be resolved into the real and reactive parts as follows:

$$\therefore P_i = \text{Real}\left[\dot{V}_i^* \sum_{j=1}^{n} Y_{ij}\dot{V}_j\right] \qquad i = 1, 2, \ldots, n \qquad (27)$$

$$Q_i = -\text{Imag}\left[\dot{V}_i^* \sum_{j=1}^{n} Y_{ij}\dot{V}_j\right] \qquad i = 1, 2, \ldots, n \qquad (28)$$

Thus, there are 2n equations and 6n variables for the n-bus system. Since there cannot be a solution in such case, 4n variables have to be prespecified. Based on parameter specifications, we can now classify the busses as shown in Table 1.

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Japanese Technical Assistance
on Strengthening Institutional Capacity
of National Development Agency (ADN)
in Democratic of Timor-Leste

-- POWER --

Syllabus

No.	Contents
1	Introduction
2	Power Station (Diesel)
3	Substation
4	Transmission and Distribution System
5	Power System Study
6	Power Flow Analysis
7	Power System Stability
8	Renewable Energy (Photovoltaic Power)
9	Protecting System
10	Power System Operation and Control
11	Others

The contents may be changed depending on conditions.
I would like to discuss about the contents with Mr. Miguel and YOU.

IX. POWER SYSTEM STABILITY

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IX. POWER SYSTEM STABILITY

DEFINITION & CLASSIFICATION OF POWER SYSTEM STABILITY

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Overview

- Power system is defined as a network of one or more generating units, loads and power transmission lines including the associated equipments connected to it.
- The stability of a power system is its ability to develop restoring forces equal to or greater than the disturbing forces to maintain the state of equilibrium.
- Power system stability problem gets more pronounced in case of interconnection of large power networks.

Definition

Power system stability is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact.

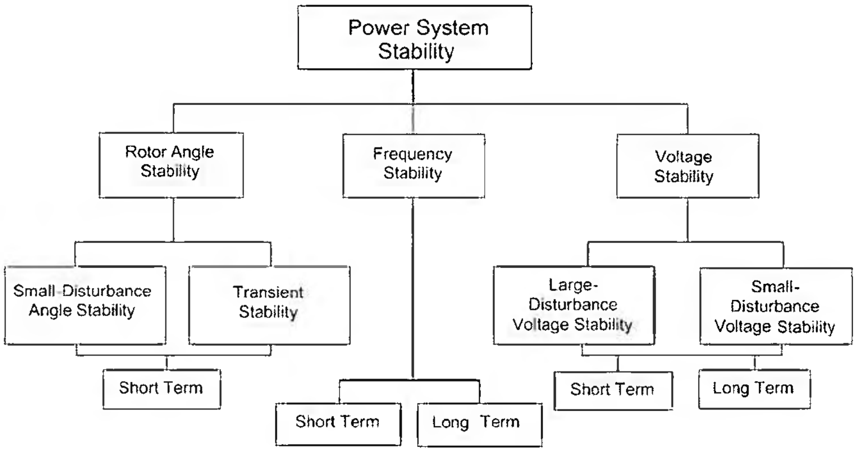
Need of Stability Classification

- Stability analysis is easier. Also it leads to proper and effective understanding of different power system instabilities.
- Key factors that leads to instability can be easily identified.
- Methods can be devised for improving power system stability.

Power System Stability Classification

- Rotor angle stability.
  - Small disturbance angle stability.
  - Transient stability.
- Voltage stability.
  - Small disturbance voltage stability.
  - Large disturbance voltage stability.
- Frequency stability.
  - Short term frequency stability.
  - Long term frequency stability.

Stability Classification at a Glance



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Rotor Angle Stability

- Rotor angle stability refers to the ability of synchronous machines of an interconnected power system to remain in synchronism after being subjected to a disturbance.
- Rotor angle instability occurs due to angular swings of some generators leading to their loss of synchronism with other generators.

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Rotor Angle Stability(2)

- Depends on the ability to maintain/restore equilibrium between electromagnetic torque and mechanical torque of each synchronous machine.
- At equilibrium, Input mechanical torque equals output electromagnetic torque of each generator. In case of any disturbance the above equality doesn't hold leading to acceleration/ deceleration of rotors of machines.

Rotor Angle Stability Classification

- Small Disturbance Rotor Angle Stability:
  - It is the ability of the power system to maintain synchronism under **small disturbances**.
  - Disturbances are considered to be sufficiently small such that the linearization of system equations is permissible for purposes of analysis.
  - The time frame of interest in small-disturbance stability studies is of the order of 10 to 20 seconds following a disturbance.

Rotor Angle Stability Classification(2)

- Large Disturbance Rotor Angle Stability:
  - It is the ability of the power system to maintain synchronism under a **severe disturbance**, such as a short circuit on a transmission line.
  - Disturbances are large so that the linearization of system equations is **not permissible** for purposes of analysis.
  - The time frame of interest in small-disturbance stability studies is of the order of 3 to 5 seconds following a disturbance.

Voltage Stability

- Voltage stability refers to the ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating condition.
- A system is voltage instable if for at least one bus in the system, the voltage magnitude decreases as reactive power injection is increased.
- Voltage instability results in progressive fall or rise of voltages of some buses.

Voltage Stability(2)

- Large scale effect of voltage instability leads to **Voltage collapse.** It is a process by which the sequence of events accompanying voltage instability leads to a blackout or abnormally low voltages in a significant part of the power system.
- The driving force for voltage instability is usually the loads.
- Voltage stability problems is also experienced at terminals of HVDC links connected to weak ac systems.

Voltage Stability Classification

- Small Disturbance Voltage Stability:
  - Small-disturbance voltage stability refers to the system's ability to maintain steady voltages when subjected to small disturbances such as incremental changes in system load.
  - A combination of both linear and non-linear techniques are used for analysis.

Voltage Stability Classification(2)

- Large Disturbance Voltage Stability:
  - Large-disturbance voltage stability refers to the system's ability to maintain steady voltages following large disturbances such as system faults, loss of generation, or circuit contingencies.
  - The study period of interest may extend from a few seconds to tens of minutes.

Frequency Stability

- Frequency stability refers to the ability of a power system to maintain steady frequency following a severe system upset resulting in a significant imbalance between generation and load.
- Frequency instability leads to tripping of generating units and/or loads.
- Frequency stability may be a short-term phenomenon or a long-term phenomenon.

Rotor Angle Stability vs. Voltage Stability

- Rotor angle stability is basically a generator stability while voltage stability means load stability.
- Rotor angle stability is mainly interlinked to real power transfer whereas voltage stability is mainly related to reactive power transfer.

IX. POWER SYSTEM STABILITY

REACTIVE POWER MANAGEMENT, VOLTAGE STABILITY AND FACTS APPLICATIONS

==

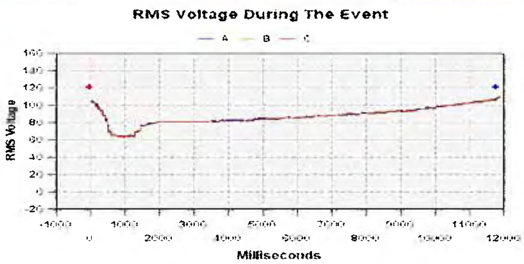
The contents here are general theories.

In general, reactive power is lacking in power system.

However, in the case of the power system of Timor-Leste, here is excess reactive power.

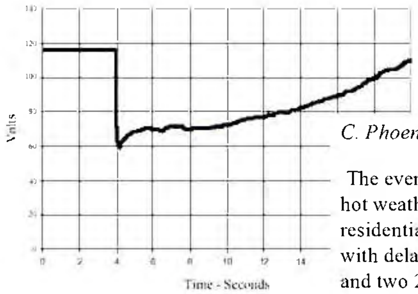
==

Voltage Profile during Aug 14th Blackout (2003 in the U.S and Canada)



- Voltages decay to almost 60% of normal voltage. This is probably the point that load started dropping off.
- However, the recovery is too slow and generators are not able to maintain frequency during this condition.
- Many generators trip, load shedding goes into effect, and then things just shut down due to a lack of generation.

A "Near" Fast Voltage Collapse in Phoenix in 1995



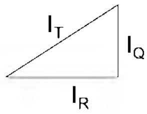
C. Phoenix Area, July 28, 1995 [3]

The event occurred on a Saturday afternoon during very hot weather (44⁰C, 112⁰F). Much of the load was residential air conditioning. A 230-kV capacitor bank fault with delayed clearing resulted in loss of five 230-kV lines and two 230/69-kV transformers. About 2100 MW of load was lost. Voltage recovery took up to 20 seconds (Figure 1). Presumably, many residential air conditioners stalled, and then tripped off after some seconds to allow eventual recovery of the remaining power system. Recordings show high reactive power output of area generators during the recovery period. High reactive power output from generators at the nearby Palo Verde nuclear plant was essential for the recovery.

North American Electric Reliability Council, System Disturbances, Review of Selected 1995 Electric System Disturbances in North America, March 1996.

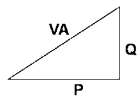
Laws of Reactive Physics

- System load is comprised of resistive current (such as lights, space heaters) and reactive current (induction motor reactance, etc.).
- Total current I_T has two components.
  - I_R resistive current
  - I_Q reactive current
  - I_T is the vector sum of I_R & I_Q
  - $I_T = I_R + jI_Q$



Laws of Reactive Physics

- Complex Power called Volt Amperes ("VA") is comprised of resistive current I_R and reactive current I_Q times the voltage.
  - "VA" = VI_T^* = $V(I_R - jI_Q)$ = $P + jQ$

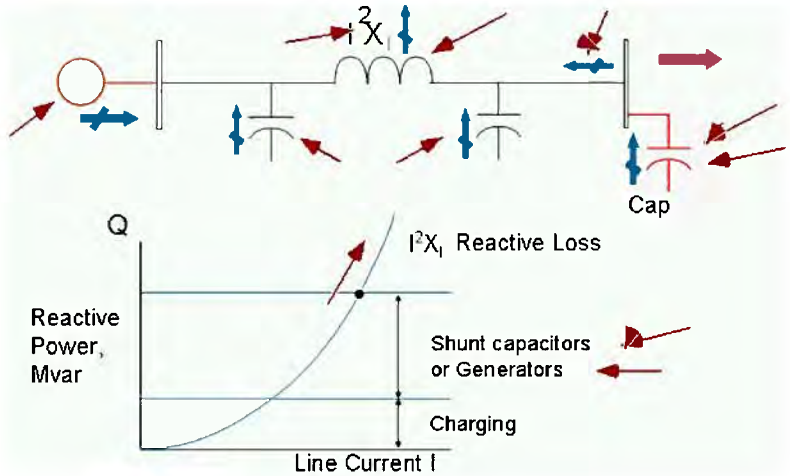


- Power Factor ("PF") = Cosine of angle between P and "VA"
  - P = "VA" times "PF"
- System Losses
  - $P_{loss} = I_T^2 R$ (Watts)
  - $Q_{loss} = I_T^2 X$ (VARs)

Reactive Physics – VAR loss

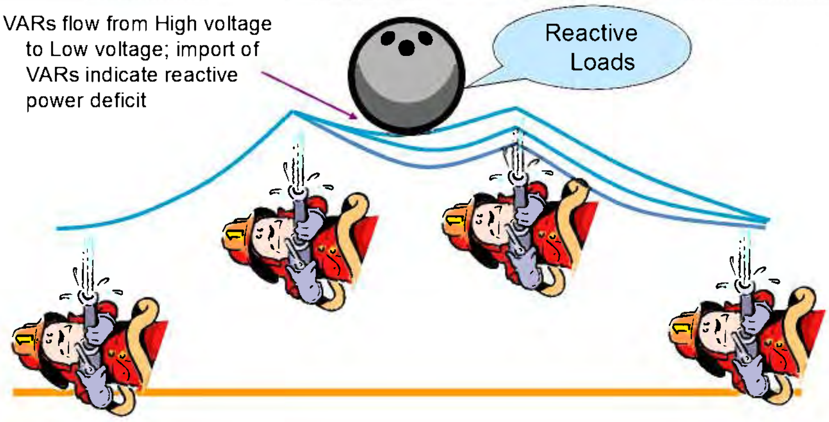
- Every component with reactance, X: VAR loss = $I_T^2 X$
- Z is comprised of resistance R and reactance X
  - On 138kV lines, X = 2 to 5 times larger than R.
  - One 230kV lines, X = 5 to 10 times larger than R.
  - On 500kV lines, X = 25 times larger than R.
  - R decreases when conductor diameter increases. X increases as the required geometry of phase to phase spacing increases.
- VAR loss
  - Increases in proportion to the square of the total current.
  - Is approximately 2 to 25 times larger than Watt loss.

Line Charging versus Reactive Demand



Reactive Power for Voltage Support

VARs flow from High voltage to Low voltage; import of VARs indicate reactive power deficit



Reactive Power Management/Compensation

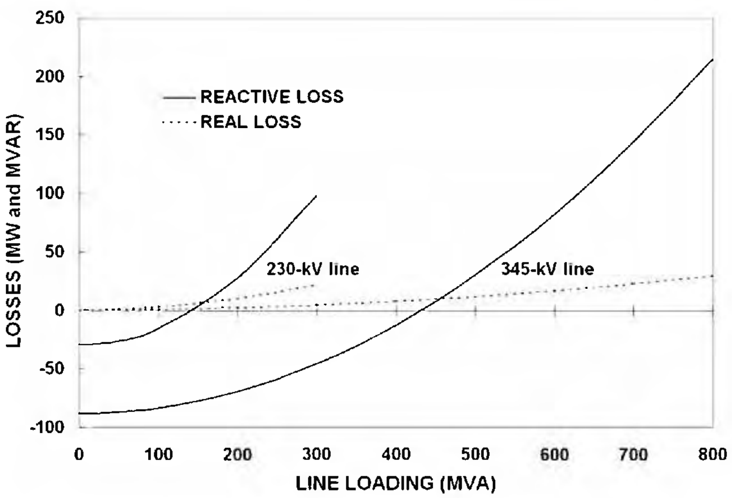
What is Reactive Power Compensation?

- Effectively balancing of capacitive and inductive components of a power system to provide sufficient voltage support.
  - Static and dynamic reactive power
- Essential for reliable operation of power system
  - prevention of voltage collapse/blackout

Benefits of Reactive Power Compensation:

- Improves efficiency of power delivery/reduction of losses.
- Improves utilization of transmission assets/transmission capacity.
- Reduces congestion and increases power transfer capability.
- Enhances grid reliability/security.

Transmission Line Real and Reactive Power Losses vs. Line Loading



Static and Dynamic VAR Support

- Static Reactive Power Devices
  - Cannot quickly change the reactive power level as long as the voltage level remains constant.
  - Reactive power production level drops when the voltage level drops.
  - Examples include capacitors and inductors.
- Dynamic Reactive Power Devices
  - Can quickly change the MVAR level independent of the voltage level.
  - Reactive power production level increases when the voltage level drops.
  - Examples include static VAR compensators (SVC), synchronous condensers, and generators.

IX. POWER SYSTEM STABILITY

VOLTAGE STABILITY

Common Definitions

- **Voltage stability** - ability of a power system to maintain steady voltages at all the buses in the system after disturbance.
- **Voltage collapse** - A condition of a blackout or abnormally low voltages in significant part of the power system.
- **Short term voltage stability** - involves the dynamics of fast acting load components such as induction motors, electronically controlled loads, and HVDC converters.
- **Long term voltage stability** - involves slower acting equipments such as tap-changing transformer, thermostatically controlled loads, and generator limiters.

What is Voltage Instability/Collapse?

- A power system undergoes voltage collapse if post-disturbance voltages are below "**acceptable limits**"
  - voltage collapse may be due to voltage or angular instability
- Main factor causing voltage instability is the inability of the power systems to "**maintain a proper balance of reactive power and voltage control**"

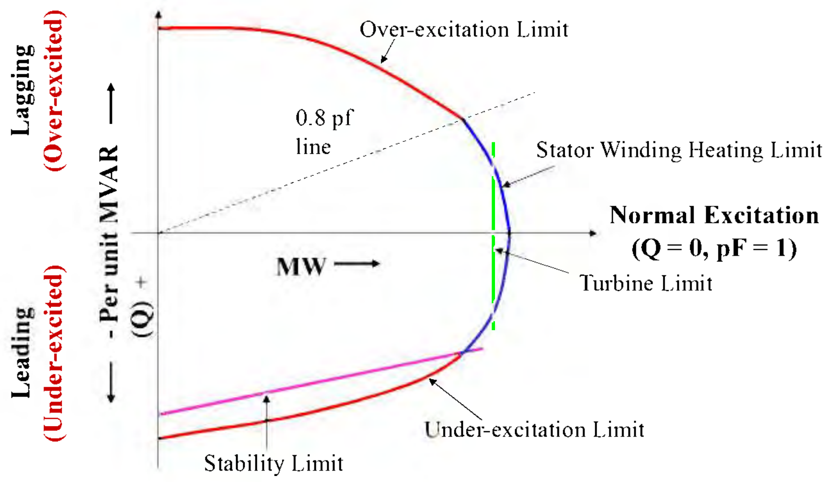
Voltage Instability/Collapse

- The driving force for voltage instability is usually the load
- The possible outcome of voltage instability:
  - loss of loads
  - loss of integrity of the power system
- Voltage stability timeframe:
  - transient voltage instability: 0 to 10 secs
  - long-term voltage stability: 1 – 10 mins

Voltage stability causes and analysis

- Causes of voltage instability
  - Generators, synchronous condensers, or SVCs reaching reactive power limits
  - Tap-changing transformer action
  - Load recovery dynamics
  - Increase in loading
  - Tripping of heavily loaded lines, generators
- Methods of voltage stability analysis
  - Static analysis methods
    - Algebraic equations, bulk system studies, power flow or continuation power flow methods
  - Dynamic analysis methods
    - Differential as well as algebraic equations, dynamic modeling of power system components required

Generator Capability Curve



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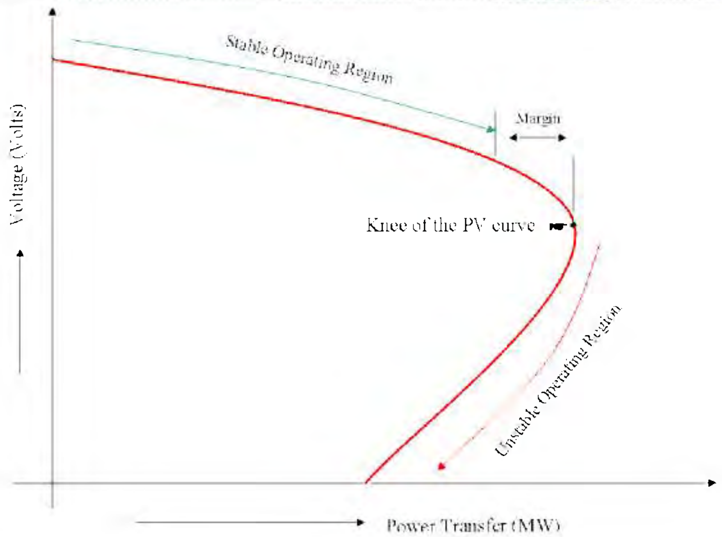
P-V Curve



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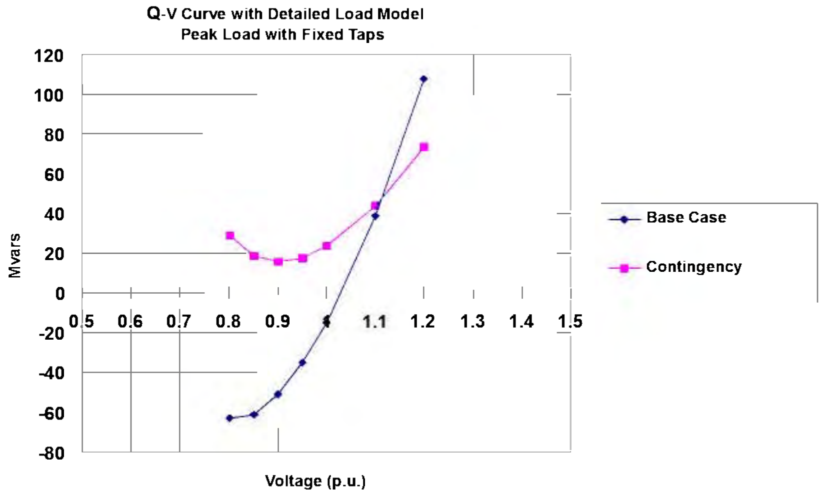
Q-V Curve



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Possible Solutions for Voltage Instability

- Install/Operate Shunt Capacitor Banks
- Add dynamic Shunt Compensation in the form of SVC/STATCOM to mitigate transient voltage dips
- Add Series Compensation on transmission lines in the problem area
- Implement UVLS Scheme
- Construct transmission facilities

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IX. POWER SYSTEM STABILITY

FACTS

What is FACTS?

- Alternating Current Transmission Systems Incorporating Power Electronic Based and Other Static Controllers to Enhance Controllability and Increase Power Transfer Capability.

- power semi-conductor based inverters
- information and control technologies

Major FACTS Controllers

- Static VAR Compensator (SVC)
- Static Reactive Compensator (STATCOM)
- Static Series Synchr. Compensator (SSSC)
- Unified Power Flow Controller (UPFC)
- Back-To-Back DC Link (BTB)

Static VAr compensator (SVC)

- Variable reactive power source
- Can generate as well as absorb reactive power
- Maximum and minimum limits on reactive power output depend on limiting values of capacitive and inductive susceptances.

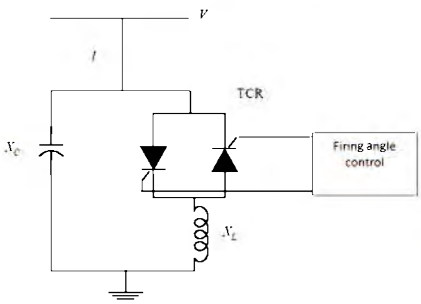

Fig. Schematic diagram of an SVC

- Droop characteristic

Static compensator (STATCOM)

- Voltage source converter device
- Alternating voltage source behind a coupling reactance
- Can be operated at its full output current even at very low voltages
- Depending upon manufacturer's design, STATCOMs may have increased transient rating both in inductive as well as capacitive mode of operation

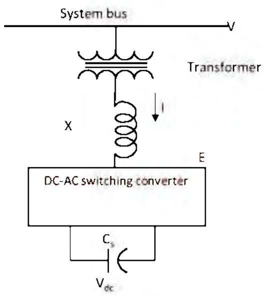

Fig. Schematic diagram of STATCOM

Summary

- The increasing need to operate the transmission system at its maximum safe transfer limit has become a primary concern at most utilities
- Reactive power supply or VAR management is an important ingredient in maintaining healthy power system voltages and facilitating power transfers
- Inadequate reactive power supply was a major factor in most of the recent blackouts

IX. POWER SYSTEM STABILITY

ANGLE STABILITY

Introduction

Power systems are generally made up of a large interconnection of synchronous machines. In normal operation these machines remain in synchronism with each other, maintaining steady synchronising frequency and constant machine power angle differences between each other. Following a disturbance in a system the frequencies of synchronous machines undergo transient deviations from the synchronous frequency of 50Hz and the machine power angles undergo transient change.

- The category of angle stability can be considered in terms of two main subcategories:
- 1. **Steady-State/Dynamic**: This form of instability results from the inability to maintain synchronism and/or dampen out system transients and oscillations caused by small system changes, such as continual changes in load and/or generation.
- 2. **Transient**: This form of instability results from the inability to maintain synchronism after large disturbances such as system faults and/or equipment outages.
- These notes will focus in particular on the transient stability subcategory and on the techniques that can be used to analyse the transient stability of a system following a disturbance.
- The aim of transient stability studies being to determine if the machines in a system will return to a steady synchronised state following a disturbance.

The Swing Equation

Consider a generating unit consisting of a three-phase synchronous generator and prime mover, as shown in Figure 1.

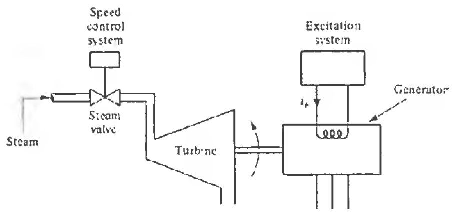

Figure 1 Generating Unit

The motion of the synchronous generator's rotor is determined by newtons second law, which is given as:

$$J\alpha_m(t) = T_m(t) - T_e(t) = T_a(t) \quad (1)$$

Where

J = Total moment of inertia of the rotating masses (prime mover and generator) (kgm²)

α_m = Rotor angular acceleration (rad/s²)

T_m = Mechanical torque supplied by the prime mover minus the retarding torque due to mechanical losses (eg. Friction) (Nm)

T_e = Electrical torque, accounting for the total three-phase power output and losses (Nm)

T_a = Net accelerating torque (Nm)

The machine and electrical torques, T_m and T_e, are positive for generator operation.

The rotor angular acceleration is given by

$$\alpha_m(t) = \frac{d\omega_m(t)}{dt} = \frac{d^2\theta_m(t)}{dt^2} \quad (2)$$

$$\omega_m(t) = \frac{d\theta_m(t)}{dt} \quad (3)$$

Where

ω_m = Rotor angular velocity (rad/s)

θ_m = Rotor angular position with respect to a stationary axis (rad)

- In steady state conditions the mechanical torque equals the electrical torque and the accelerating torque is zero. There is no acceleration and the rotor speed is constant at the synchronous velocity.
- When the mechanical torque is more than the electrical torque then the acceleration torque is positive and the speed of the rotor increases.
- When the mechanical torque is less than the electrical torque then the acceleration torque is negative and the speed of the rotor decreases.
- Since we are interested in the rotor speed relative to the synchronous speed it is convenient to measure the rotor angular position with respect to a synchronously rotating axis instead of a stationary one.

We therefore define

$$\theta_m(t) = \omega_{msyn} t + \delta_m(t) \qquad (4)$$

Where

ω_{msyn} = Synchronous angular velocity of the rotor, rad/s

δ_m = Rotor angular position with respect to a synchronously rotating reference

To understand the concept of the synchronously rotating reference axis consider the diagram in Figure 2. In this example the rotor is rotating at half the synchronous speed, $\omega_{msyn}/2$, such that in the time it takes for the reference axis to rotate 45° the rotor only rotates 22.5° and the rotor angular position with reference to the rotating axis changes from -45° to -67.5° .

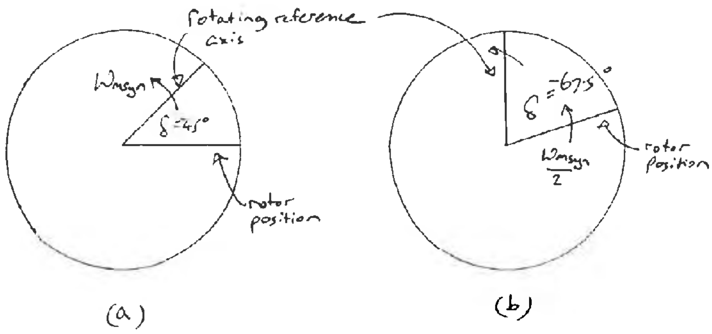

Figure 2 Synchronously rotating reference axis

From (2) and (4), we see that equation (1) can be written as

$$J\alpha_m(t) = J\frac{d^2\theta_m(t)}{dt^2} = J\frac{d^2\delta_m(t)}{dt^2} = T_m(t) - T_e(t) = T_a(t) \qquad (5)$$

Being that we are analysing a power system we are interested in values of power more than we are in values of torque. It is therefore more convenient to work with expressions of power. Furthermore it is convenient to consider this power in per unit rather than actual units.

Power is equal to the angular velocity times the torque and per unit power can be obtained by dividing by , so that:

$$\frac{J\omega_m(t)}{S_{rated}}\frac{d^2\delta_m(t)}{dt^2} = \frac{\omega_m(t)T_m(t) - \omega_m(t)T_e(t)}{S_{rated}} = \frac{p_m(t) - p_e(t)}{S_{rated}} = p_{mpu}(t) - p_{epu}(t) \qquad (6)$$

P_{mpu} = Mechanical power supplied by the prime mover minus mechanical losses (per unit)

P_{epu} = Electrical power output of generator plus electrical losses (per unit)

We define a constant value known as the normalised inertia constant, or "H" constant.

$$H = \frac{\text{stored kinetic energy at synchronous speed}}{\text{generator voltampere rating}}$$

$$= \frac{\frac{1}{2}J\omega_{msyn}^2}{S_{rated}} \quad (joules/VA \quad or \quad per\ unit-seconds) \qquad (7)$$

Equation (6) becomes

$$2H\frac{\omega_m(t)}{\omega_{msyn}^2}\frac{d^2\delta_m(t)}{dt^2} = p_{mpu}(t) - p_{epu}(t) = p_{apu}(t) \qquad (8)$$

Where P_{apu} = Accelerating power

We define per-unit rotor angular velocity as:

$$\omega_{pu}(t) = \frac{\omega_m(t)}{\omega_{msyn}} \qquad (9)$$

Equation (8) becomes

$$\frac{2H}{\omega_{msyn}}\omega_{pu}(t)\frac{d^2\delta_m(t)}{dt^2} = p_{mpu}(t) - p_{epu}(t) = p_{apu}(t) \qquad (10)$$

When a synchronous generator has P poles, the synchronous electrical angular velocity, ω_{syn}, known more correctly as the synchronous electrical radian frequency, can be related to the synchronous mechanical angular velocity by the following relationship.

$$\omega_{syn} = \frac{P}{2}\omega_{msyn} \quad (11)$$

To understand how this relationship arises, consider that the number of mechanical radians in one full revolution of the rotor is 2π. If, for instance, a generator has 4 poles (2 pairs), and there are 2π electrical radians between poles in a pair then the electrical waveform will go through $2*2\pi=4\pi$ electrical radians within the same revolution of the rotor.

In general the number of electrical radians in one revolution is the number of mechanical radians times the number of pole pairs (the number of poles divided by two).

The relationship shown in (11) also holds for the electrical angular acceleration t$\alpha(t)$, the electrical radian frequency $\omega(t)$, and the electrical power angle δ values.

$$\alpha(t) = \frac{P}{2}\alpha_m(t)$$
$$\omega(t) = \frac{P}{2}\omega_m(t) \quad (12)$$
$$\delta(t) = \frac{P}{2}\delta_m(t)$$

From (9) we see that

$$\omega_{pu}(t) = \frac{\omega_m(t)}{\omega_{msyn}} = \frac{\frac{2}{P}\omega(t)}{\frac{2}{P}\omega_{syn}} = \frac{\omega(t)}{\omega_{syn}} \quad (13)$$

Therefore equation (10) can be written in electrical terms rather than mechanical:

$$\frac{2H}{\omega_{syn}}\omega_{pu}(t)\frac{d^2\delta(t)}{dt^2} = p_{mpu}(t) - p_{epu}(t) = p_{apu}(t) \quad (14)$$

This equation is known as the "***SWING-EQUATION***" and is the fundamental equation in determining rotor dynamics in transient stability studies.

The swing equation is non-linear because $p_{mpu}(t)$ is a non-linear function of δ and because of the $\omega_{pu}(t)$ term. The rotor speed, however, does not vary a great deal from the synchronous speed during transients and a value of $\omega_{pu}(t) \approx 1.0$ is often used in hand calculations.

Electric power equation

In the swing equation the mechanical power from the prime mover, P_{mpu}, is considered to be constant. This is a reasonable assumption as the conditions in the electrical network can be expected to change before the slower acting control governor can cause the turbine to react.

The electrical power, P_{epu}, will therefore determine wether the rotor accelerates, decelerates or remains at a constant synchronous speed. Electrical network disturbances resulting from extreme changes in system loading, network faults and circuit breaker operation will cause the generator output to change rapidly and transients will exist.

The synchronous machine is represented in transient stability studies by a transient internal voltage E' in series with its transient reactance X'_d as shown in Figure 3.

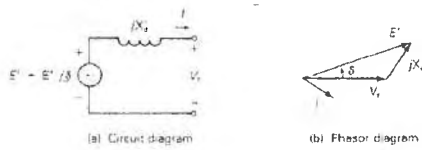

Figure 3 Simplified synchronous machine model for transient stability studies

Generators are normally connected to systems composed of transmission lines, transformers and other machines. When systems are large enough, as they most often are, an "infinite bus" behind a system reactance can represent them. An infinite bus is an ideal voltage source that maintains constant voltage magnitude, phase and frequency. Figure 4 illustrates the connection arrangement of the synchronous generator to the equivalent system.

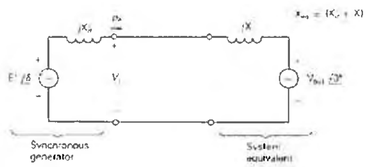

Figure 4 Synchronous generator connected to a system equivalent

The real power delivered from the generator to the infinite bus (and therefore the system) is therefore:

$$p_e = \frac{|E||V_{bus}|}{X_{eq}} \sin\delta = p_{max} \sin\delta \qquad (15)$$

Where $X_{eq} = X'_d + X$

The equal area criterion

A method known as the equal area criterion can be used for a quick prediction of stability. This method determines if a machine maintains its stability after a disturbance by graphical interpretation of the energy stored in the rotating mass. It is, however, restricted to either one machine systems connected to an infinite bus or to two machine systems. More complex and accurate numerical solution of the non-linear swing equation can be performed by computer and is especially applicable to the analysis of multi-machine systems. In these notes we will not focus on this numerical solution method, preferring to look at the simpler equal area method.

Figure 5 shows plots of electrical power P_e and mechanical power P_m versus the power angle δ. The generating unit illustrated in Figure 5 is initially operating in a steady state and $Pe = P_m = P_{m0}$ and $\delta = \delta_0$.

If a step change in the mechanical power occurs so that it increases to $P_m = P_{m1}$ at time equals zero. The rotor has inertia and as such the rotor position cannot change instantaneously, $\delta_m(0-) = \delta_m(0+)$. As the electrical power angle is related to the rotor position and electrical power is related to the electrical power angle then the electrical power does not change instantaneously, $\delta\,(0-) = \delta\,(0+) = \delta_0$ and $Pe\,(0-) = Pe\,(0+)$.

The mechanical and electrical powers will be unbalanced and the accelerating power will act to increase the rotor speed and δ will increase. When the angle δ reaches the desired value of δ_1 then the acceleration, $d^2\delta/dt^2$, will be zero but as the velocity is above synchronous the angle δ will continue to increase and overshoot the target. Once past δ_1 the electrical power becomes greater than the mechanical power and the rotor decelerates. After reaching a maximum value it begins to swing back towards δ_1. If there were no damping present then the angle δ would continue to oscillate about the δ_1 point. Damping, however is present due to mechanical and electrical losses, and δ eventually settles down to its final steady state value δ_1.

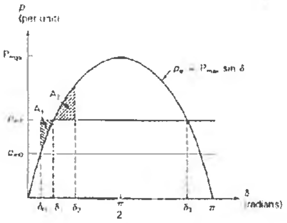

Figure 5 Electrical and Mechanical power versus δ

If we consider now the swing equation and assume that $\omega_{pu}(t) \approx 0.1$ then:

$$\frac{2H}{\omega_{syn}}\frac{d^2\delta}{dt^2} = p_{mpu} - p_{epu} \qquad (16)$$

If we multiply both sides by $d\delta/dt$ and use the identity

$$\frac{d}{dt}\left[\frac{d\delta}{dt}\right]^2 = 2\left(\frac{d\delta}{dt}\right)\left(\frac{d^2\delta}{dt^2}\right)$$

Equation (16) becomes

$$\frac{2H}{\omega_{syn}}\left(\frac{d^2\delta}{dt^2}\right)\left(\frac{d\delta}{dt}\right) = \frac{H}{\omega_{syn}}\frac{d}{dt}\left(\frac{d\delta}{dt}\right)^2 = (p_{mpu} - p_{epu})\left(\frac{d\delta}{dt}\right) \qquad (17)$$

Multiplying equation (17) by dt and integrate from δ_0 to δ we obtain the following expression:

$$\frac{H}{\omega_{syn}}\int_{\delta_0}^{\delta} d\left(\frac{d\delta}{dt}\right)^2 = \int_{\delta_0}^{\delta}(p_{mpu} - p_{epu})d\delta \qquad (18)$$

Or

$$\frac{H}{\omega_{syn}}\left(\frac{d\delta}{dt}\right)^2\Bigg|_{\delta_0}^{\delta} = \int_{\delta_0}^{\delta}(p_{mpu} - p_{epu})d\delta \qquad (19)$$

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Note that the above integration begins at δ_0 and ends at some arbitrary angle δ. The value of $d\delta / dt$ is zero at δ_0 as the machine is in steady state. The value of $d\delta / dt$ is also zero at δ equal to δ_2, as the rotor changes direction back towards δ_1. The left hand side of (19) equals zero for $\delta = \delta_2$ and therefore:

$$\int_{\delta_0}^{\delta}(p_{mpu} - p_{epu})d\delta = 0 \qquad (20)$$

If we separate (20) into accelerating and decelerating areas we obtain the following equation:

$$\underbrace{\int_{\delta_0}^{\delta_1}(p_{mpu} - p_{epu})d\delta}_{areaA1} + \underbrace{\int_{\delta_1}^{\delta_2}(p_{mpu} - p_{epu})d\delta}_{areaA2} = 0 \qquad (21)$$

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Note how the two elements of (21) equate to the areas A1 and A2 shown in Figure 5 and in order for the two equations to be satisfied the two areas must be equal. This is why we call this the "***equal area***" criterion.

In practice, sudden changes in mechanical power do not occur as the time constants associated with the prime mover dynamics are in the order of seconds. However, stability phenomena similar to that described above can also occur from sudden changes in electrical power due to system changes such as system faults.

Design methods for improving transient stability

There are a number of design measures that can be implemented to improve the transient stability of a power system:

1. Improve the maximum power transfer capability

Improving the maximum power transfer capability of a system means that power can be transferred through alternative un-faulted portions of the network when a fault occurs. The effect of a fault on the system will not be as extreme. The maximum transfer capability of a system can be improved by the following methods:

a. Implement and use higher system voltage levels (system losses will decrease as current flows will be lower, especially important in cases where line distances are large)
b. Install additional transmission lines.
c. Install lines and transformers with smaller reactance values
d. Install series capacitive transmission line compensation to reduce the overall reactance of lines
e. Install static VAR compensators and flexible AC transmission systems (FACTS)

2. Implement high speed fault clearing

It is vital to clear faults before the critical clearing time is reached so the quicker a fault is cleared the better.

3. Implement high speed re-closure of circuit breakers

As the majority of transmission line short circuits are temporary, re-closure post fault can be beneficial in providing better power transfer capability. Care must be taken in this case to ensure that the re-closing on a permanent fault and any subsequent re-opening will not adversely affect the stability of the system.

4. Implement single pole switching

The majority of short circuits are single line to ground and the independent switch out of only the faulted phase means that some power flow can continue across the faulted line. Studies have shown that single line to ground faults are self-clearing even when only the faulted phase is de-energised.

5. Use generators with larger machine inertia and with lower transient reactance

A larger synchronous machine inertia constant (H) results in a reduction in angular acceleration and therefore a slowing down of angular swings. The critical clearing time is increased.

Reducing the machine transient reactance increases the power transfer capability during faults and in the periods post fault.

6. Use fast responding, high gain exciters

Modern excitation systems can be designed to act quickly and with high gain in the event of sensing a low terminal voltage during faults. The effect is to increase the generator output during the fault and post fault periods. Critical clearing times are increased.

7. Implement fast valving

Some steam turbines are equipped with fast valving to divert steam flows and rapidly decrease the mechanical output. When a fault occurs near to the generator the electrical power output is reduced and the fast valving acts to balance the mechanical and electrical powers. This provides reduced acceleration and longer critical clearing times.

8. Breaking Resistors

In power systems, areas of generation can be temporarily separated from the load areas. When the separation occurs the breaking resister can be inserted into the generation area for a second or two in order to slow the acceleration.

Japanese Technical Assistance
on Strengthening Institutional Capacity
of National Development Agency (ADN)
in Democratic of Timor-Leste

-- POWER --

Syllabus

No.	Contents
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2	Power Station (Diesel)
3	Substation
4	Transmission and Distribution System
5	Power System Study
6	Power Flow Analysis
7	Power System Stability
8	An Example of Power System Analysis (Using PSS/E)
9	Renewable Energy (Photovoltaic Power)
10	Protecting System
11	Power System Operation and Control
12	Others

The contents may be changed depending on conditions.
I would like to discuss about the contents with Mr. Miguel and YOU.

X. AN EXAMPLE OF POWER SYSTEM ANALYSIS (USING PSS/E)

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X. AN EXAMPLE OF POWER SYSTEM ANALYSIS (USING PSS/E)

INTRODUCTION TO PSS/E

Sorry for the following 6pages looking like advertisements.

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Overview

- PSS®E is the premier software tool used by electrical transmission participants world-wide. The probabilistic analyses and advanced dynamics modeling capabilities included in PSS®E provide transmission planning and operations engineers a broad range of methodologies for use in the design and operation of reliable networks. PSS®E is the standard Siemens offering for electrical transmission analysis that continues to be the technology of choice in an ever-growing market that exceeds 115 countries.
- Since its introduction in 1976, the **P**ower **S**ystem **S**imulator for **E**ngineering tool has become the most comprehensive, technically advanced, and widely used commercial program of its type. It is widely recognized as the most fully featured, time-tested and best performing commercial program available.

analytical capabilities

- PSS®E is an integrated, interactive program for simulating, analyzing, and optimizing power system performance. It provides the user with the most advanced and proven methods in many technical areas:
  - PSS®E analytical capabilities include:
    - Power flow
    - Contingency analysis
    - Probabilistic contingency
    - Dynamic simulation (including
    - extended term)
    - Short circuit (including IEC 60909).
  - Optional modules provide:
    - Optimal power flow (OPF)
    - Small signal stability analysis (NEVA)
    - Graphical model builder (GMB).

PSS®E Version 33 released May 2011.

Power flow

- Fast powerful, and real-world tested system models up to 150,000 buses
- Graphical user interface (GUI)
- User-defined subsystems — subsystems based on areas, owners, zones, bus kV or combinations
- Over 30 years of commercial use and user-suggested enhancements have made

Contingency analysis

When performing a contingency analysis in PSS®E, contingencies can be specified either automatically (e.g., all N-1 contingencies) or by a user-defined list. The result is a comprehensive list of contingencies tested and those that identify violations. The PSS®E Corrective Action feature can then be applied to automatically mitigate contingency violations that then provides a refined list of the most serious violations to be resolved.

Probabilistic contingency

Siemens PTI brings you comprehensive transmission probabilistic contingency analysis by enhancing the core state-of-the-art analytical formulations from our PSS®TPLAN software and integrating them into PSS®E. The probabilistic contingency capabilities feature easy configuration, detailed modeling of remedial action schemes, effective identification of voltage collapse conditions, and automatic handling of generation dispatch and load shedding requirements. These combined features provide program users with an all-inclusive tool to evaluate transmission reliability performance in large or small power systems on a deterministic and probabilistic basis.

Dynamic simulation

- The dynamic simulation module of PSS®E is a versatile tool to investigate system response to disturbances that cause large and sudden changes in the power system. The dynamic simulation module not only offers a vast library of built-in tested models for modeling different types of equipment, it also offers the capability to create user-defined models of any complexity.
- User models can be developed using Fortran code, or the Graphical Model Builder (GMB) can be used to graphically build and test control block diagrams for use in PSS®E and other PSS® products. An integrated plotting package allows the user to specify comprehensive and customizable plots with the ability to export to several popular graphic formats.

X. AN EXAMPLE OF POWER SYSTEM ANALYSIS (USING PSS/E)

POWER FLOW ANALYSIS USING PSS/E

BUSES

- Bus Number: Displays the number assigned to a specific bus (1 through 999997).
- Bus Name: Alphanumeric identifier assigned to bus "#". The name may be up to twelve characters. The bus name may contain any combination of blanks, uppercase letters, numbers and special characters. The bus name is twelve blanks by default.
- Base kV: Bus base voltage; entered in kV.
- Code: Bus type code:

  1 - Load bus (no generator boundary condition)
  2 - Generator or plant bus (either voltage regulating or fixed Mvar)
  3 - Swing bus
  4 - Disconnected (isolated) bus
  5 – Same as type 1, but located on the boundary of an area in which an equivalent is to be constructed
  Code = 1 by default.
- Voltage (PU): Bus voltage magnitude; entered in per unit, V = 1.0 by default.

Bus Number	Bus Name	Base kV	CODE	Voltage	Angle
1010	Dili	150	1		
1020	Hera	150	1		
1030	Manatuto	150	1		
1040	Baucau	150	1		
1050	Lospalos	150	1		
1060	Viqueque	150	1		
1070	Same	150	1		
1080	Cassa	150	1		
1090	Suai	150	1		
1100	Maliana	150	1		
1110	Liquica	150	1		
110	Dili	20	1		
120	Hera	15	3	1.00	0.00
130	Manatuto	20	1		
140	Baucau	20	1		
150	Lospalos	20	1		
160	Viqueque	20	1		
170	Same	20	1		
175	Betano	15	2		
180	Cassa	20	1		
190	Suai	20	1		
200	Maliana	20	1		
210	Liquica	20	1		

Branches

- From Bus: Branch "from bus" number outside brackets with bus name and bus kV enclosed in brackets.
- To Bus: Branch "to bus" number outside brackets with bus name and bus kV enclosed in brackets.
- Line R (PU): Branch resistance; entered in per unit. A value of R must be entered for each branch.
- Line X (PU): Branch reactance; entered in per unit. A nonzero value of X must be entered for each branch.
- Charging (PU) Total branch charging susceptance (imaginary part of admittance); entered in per unit. B = 0.0 by default.
- Rate A (MVA): First power rating; entered in MVA. Rate A = 0.0 (bypass check for this branch) by default.
- Rate B (MVA): Second power rating; entered in MVA. Rate B = 0.0 by default.
- Rate C (MVA): Third power rating; entered in MVA. Rate C = 0.0 by default.
- Length: Line length; entered in user-selected units.

- Here, line constants were assumed from the standard data of the Kansai Electric Power of Japan.
- R=0.669, X=2.1, Y=0.0078 [%/km/cct,154kV, 1,000MVA base], ACSR,200mm^2

➔R=0.669*154^2/150^2 /100=0.00705pu/km/cct
X=2.1*154^2/150^2*(50/60)/100=0.018pu/km/cct
Y=0.0078*150^2/154^2*(50/60)/100=0.000062pu/km/cct

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From I	From Bus Name	To E	To Bus Name	Id	Line R (pu)	Line X (pu)	Charging (pu)	Length[km]
	Dili		Hera	1	0.06922395	0.176742	0.000608778	9.819
	Dili		Hera	2	0.06922395	0.176742	0.000608778	9.819
	Hera		Manatuto	1	0.2883591	0.736236	0.002535924	40.902
	Hera		Manatuto	2	0.2883591	0.736236	0.002535924	40.902
	Manatuto		Baucau		0.36891945	0.941922	0.003244398	52.329
	Baucau		Laspalos		0.44766795	1.142982	0.003936938	63.499
	Baucau		Viqueque		0.30403125	0.77625	0.00267375	43.125
	Loasplos		Viqueque		0.72924495	1.861902	0.006413218	103.439
	Viqueque		Same		0.59554875	1.52055	0.00523745	84.475
	Same		Casa		0.1791264	0.457344	0.001575296	25.408
	Casa		Suai		0.27181275	0.69399	0.00239041	38.555
	Suai		Maliana		0.41019015	1.047294	0.003607346	58.183
	Maliana		Liquica		0.31669305	0.808578	0.002785102	44.921
	Liquica		Dili		0.2736669	0.698724	0.002406716	38.818
					0.00705	0.018	0.000062	1.0

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Loads

- Bus Number/Name: the bus name
- Id: This is a one, or two, character uppercase, nonblank, alphanumeric load identifier. It is used to distinguish among multiple loads at the same "Bus Number/Name". At buses in which there is a single load present, the ID = 1.
- In-Service: A check mark indicates that a certain load at a "Bus Number/Name" is fully operational. If for any reason a certain load at a "Bus Number/Name" needs to be taken out of service, simply un-check that particular one and click the line above or below to make your changes final.
- Pload (MW): Active power component of constant MVA load; entered in MW.
- Qload (MW): Reactive power component of constant MVA load; entered in MVAR.

Assumptions for Load Condition

- The sum of active power load of all Timor Leste is the output value of Hera power plant around 15:00 on June 18, 2013.➔35.4MW
- The value of load above is allocated by the capacity ratio of the distribution substation.
- Power factor of each load is 90 %.

Bus Number	Bus Name	Id	In Service	Pload (MW)	Qload (Mvar)	Capacity (MVA)	
110	Dili		1	10.91	5.28	63	
130	Manatuto		1	1.73	0.84	10	
140	Baucau		1	5.45	2.64	31.5	
150	Lospalos		1	3.46	1.68	20	
160	Viqueque		1	1.73	0.84	10	
170	Same		1	1.73	0.84	10	(Assumption)
180	Cassa		1	1.73	0.84	10	
190	Suai		1	3.46	1.68	20	
200	Maliana		1	3.46	1.68	20	
210	Liquica		1	1.73	0.84	10	

SUM	35.40	17.15	204.5

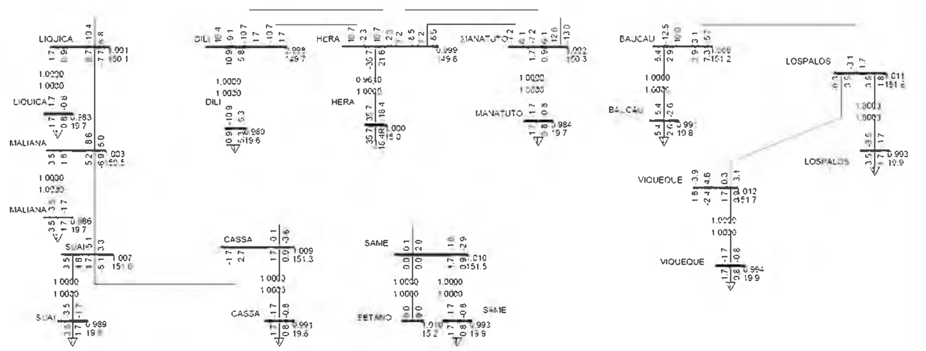
Pall	35.40
PF	0.90

Machines

- Bus Number/Name: This displays the Bus Number (where the machine is located) outside of the brackets and displays the bus name as well as the bus voltage in kV inside the brackets.
- Id: This is a one, or two, character uppercase, nonblank, alphanumeric machine identifier. It is used to distinguish among multiple machines at a plant (i.e., at a generator bus). At buses in which there is a single machine present, ID = 1.
- In-Service: A check mark indicates that a certain machine at a "Bus Number/Name" is fully operational. If for any reason a certain machine at a "Bus Number/Name" needs to be taken out of service, simply un-check that particular one and click the line above or below to make your changes final.
- Pgen: This is the active power that the generator is putting out; entered in MW.
- Pmin: This is the minimum active power that the generator can output; entered in MW.
- Pmax: This is the maximum active power that the generator can output; entered in MW.
- Qgen: This is the reactive power that the generator is putting out; entered in MVAR.
- Qmin: This is the minimum reactive power that the generator can output; entered in MVAR.
- Qmax: This is the maximum reactive power that the generator can output; entered in MVAR.

Bus Number	Bus Name	Id	In Service	Pgen (MW)
120	Hera		1	36.0

The value has no meaning because Hera is slack.



What we can know from the result

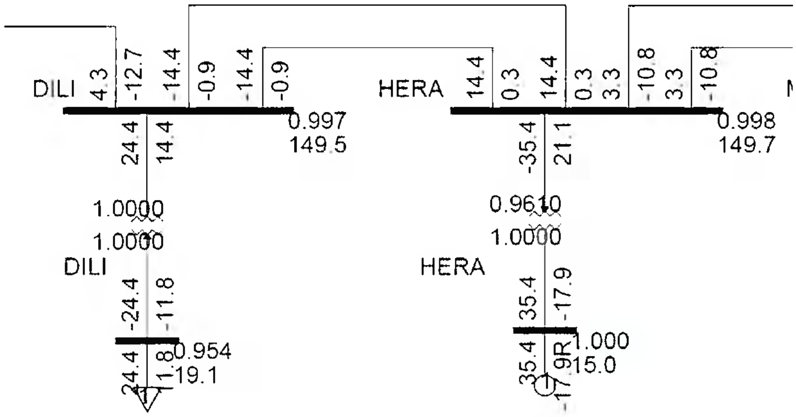
- Loss of active power in the all system 0.3 MW.
- Load of Dili should be larger. It may be 10 MW (30.2-21.4=8.8) larger.

Bus Number	Bus Name	Id	In Service	Pload (MW)	Qload (Mvar)	Capacity (MVA)
110	Dili		1	24.43	11.83	63
130	Manatuto		1	0.75	0.37	10
140	Baucau		1	2.38	1.15	31.5
150	Lospalos		1	1.51	0.73	20
160	Viqueque		1	0.75	0.37	10
170	Same		1	0.75	0.37	10
180	Cassa		1	0.75	0.37	10
190	Suai		1	1.51	0.73	20
200	Maliana		1	1.51	0.73	20
210	Liquica		1	0.75	0.37	10
			SUM	35.10	17.00	141.5

+8.8

Pall	35.10	10.67
PF	0.90	

Pall−load of Dili



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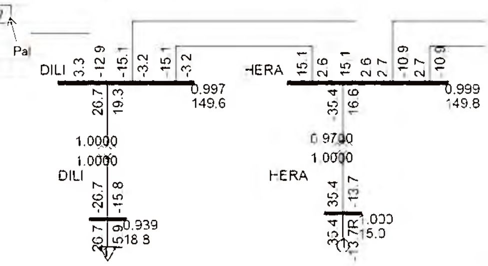
Ajustment

Bus Number	Bus Name	Id	In Service	Pload (MW	Qload (Mvar)	Capacity (MVA)
110	Dili		1	26.73	15.86	63
130	Manatuto		1	0.59	0.35	10
140	Baucau		1	1.86	1.11	31.5
150	Lospalos		1	1.18	0.70	20
160	Viqueque		1	0.59	0.35	10
170	Same		1	0.59	0.35	10
180	Cassa		1	0.59	0.35	10
190	Suai		1	1.18	0.70	20
200	Maliana		1	1.18	0.70	20
210	Liquica		1	0.59	0.35	10
			SUM	35.10	20.83	141.5
	+8.8+1.4+0.6+0.3					
			Pall	35.10	8.37	
			PF	0.86		



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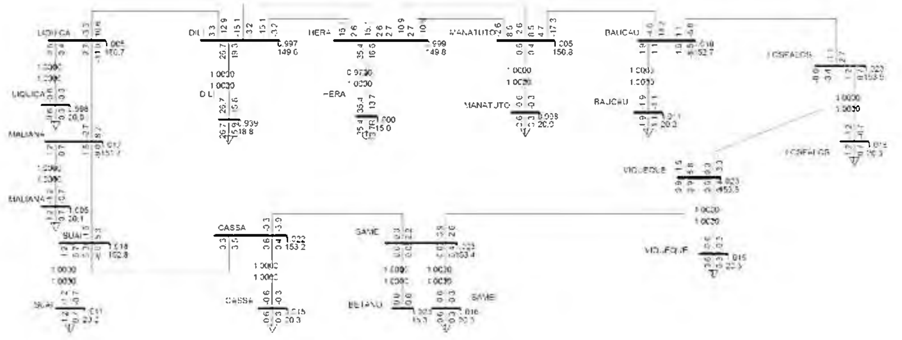
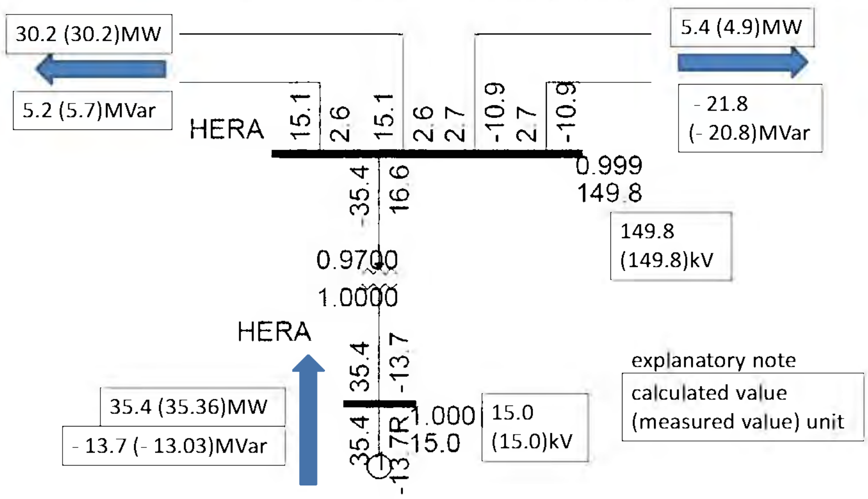
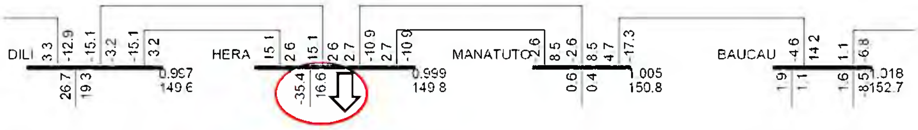
The Result



Comparing with measured values

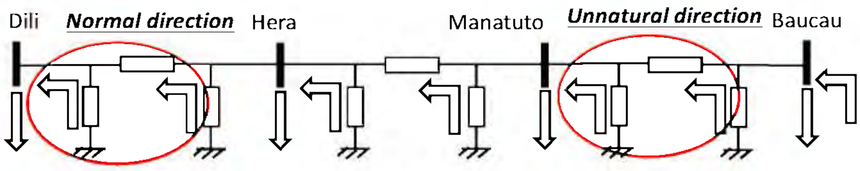


The reason of Leading Power Factor Operation

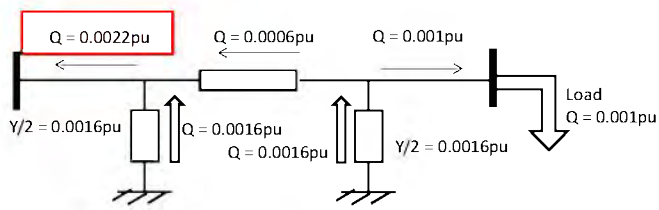


- The very low consumption of power
- Long distance of the lines

The Reactive Power Flow

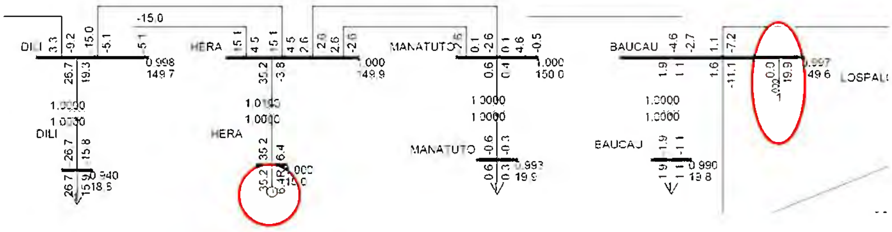


- Charging of the line (Y) between Manatuto and Baucau (52km) is 0.0032pu (150kV, 1,000MVAbase).
- Y/2 = 0.0016
- If bus voltage is 1.0 pu, reactive power, Q=0.0016pu is generated.
- On the other hand, for example, the reactive power load of Baucau is 1.0Mvar (0.001pu).
- Therefore, 0.0016+0.0006 = 0.0022pu = 2.2MVar is not consumed and flow to generators. The loss of transmission line is ignored.



Countermeasure

- One of countermeasures is installing of a shunt reactor in the north-east area.



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Japanese Technical Assistance
on Strengthening Institutional Capacity
of National Development Agency (ADN)
in Democratic of Timor-Leste

-- POWER --

Syllabus

No.	Contents
1	Introduction
2	Power Station (Diesel)
3	Substation
4	Transmission and Distribution System
5	Power System Study
6	Power Flow Analysis
7	Power System Stability
8	An Example of Power System Analysis (Using PSS/E)
9	How to Use the Result of Power System Analysis
10	Renewable Energy (Photovoltaic Power)
11	Protecting System
12	Power System Operation and Control
13	Others

The contents may be changed depending on conditions.
I would like to discuss about the contents with Mr. Miguel and YOU.

XI. HOW TO USE THE RESULT OF POWER SYSTEM ANALYSIS

Overview

- This materials explains how the results of power system analysis (Transmission System Studies) are used in actuality by introducing the material, ‘An Overview of Transmission System Studies’ (REA BULLETIN 1724E-202) published by UNITED STATES DEPARTMENT OF AGRICULTURE

1. INTRODUCTION:

- Recent trends in power system complexity, energy conservation and economic performance of REA-financed projects reinforce the need for careful system planning for transmission facilities. Planning studies generally involve the modeling of these facilities in order that system performance can be conveniently observed and evaluated.

2. PURPOSE:

- The purpose of this bulletin is to outline the system studies that should be considered to support design criteria for REA-financed transmission facilities from 34.5 through 765 kilovolts (kV).
- Presented in Section 3 is a list of transmission system studies for various facility applications that should be considered. Section 4 contains the input data required to perform each study. A flow chart is presented in Section 5 that relates the interdependency of each study to the overall system planning concept. Section 6 contains a detailed explanation of each study.

3. SYSTEM STUDY APPLICABILITY:

- Table 1 represents a list of the type transmission system studies and requirements to support REA related financing arrangements for projects from 34.5 kV through 765 kV. These system studies should be considered in conjunction with the long range system and financial planning requirements. This list of studies is not necessarily complete nor is it listed in any order of priority. Each study should be completed or considered as required in Table 1 for the specific facility in question in order that system performance can be evaluated. (Refer to Sections 5 and 6 of this bulletin for a detailed description of each study.)

- The column numbers in the table refer to the following studies:

  1) Facility Feasibility
  2) Load Flow
  3) Reactive Compensation
  4) Stability
  5) Subsynchronous Resonance
  6) Statistical Line Design
  7) Short Circuit
  8) Insulation Coordination
  9) Corona and Radio Interference
  10) Electrostatic and Electromagnetic
  11) Transmission Facility Economics

- Symbols used in Table 1 are defined as follows:
  - An "X" indicates study should be performed and submitted to REA in conjunction with a request for REA action on financing arrangements.
  - A "Y" indicates study should be performed and submitted to REA with the project design information.
  - A "Z" indicates study should be performed but not submitted for review unless requested by REA.
  - An "O" indicates it may be advisable to have study performed depending on system complexity. REA should be informed whether or not study will be completed at which time the borrower will be informed if REA desires to review results.
  - No mark indicates the study is not generally applicable.

4. INPUT DATA REQUIREMENTS:

- Prior to developing system models for each planning study, data must be developed:

  (1) to permit mathematical simulation of the real system,

  (2) to aid in the analysis of system performance related to equipment performance, and

  (3) to provide constraints so that system improvements can be made.
- A brief description of such input data will now be presented for generators, transformers, lines and loads.

4.1 Generators:

- For steady-state analysis, generators are represented in terms of the real and reactive power to the system. Conversely, for transient performance, system studies may require full representation of the electrical and mechanical characteristics of each generator.

4.2 Transformers:

- Most system studies require information about core and winding loss resistances, leakage reactances, turns ratios at available taps, and automatic tap-changing limits.

analytical capabilities

- PSS®E is an integrated, interactive program for simulating, analyzing, and optimizing power system performance. It provides the user with the most advanced and proven methods in many technical areas:
  - PSS®E analytical capabilities include:
    - Power flow
    - Contingency analysis
    - Probabilistic contingency
    - Dynamic simulation (including
    - extended term)
    - Short circuit (including IEC 60909).
  - Optional modules provide:
    - Optimal power flow (OPF)
    - Small signal stability analysis (NEVA)
    - Graphical model builder (GMB).

PSS®E Version 33 released May 2011.

4.3 Transmission Lines:

- Transmission lines are generally represented by single phase models with equivalent series impedances (resistance-inductance combinations) between line terminals and equivalent shunt admittances at each terminal. For a balanced three-phase transmission system the manner in which a single phase is represented should depend on the line length and accuracy required. In selecting a model, it is usual to classify transmission lines as short, medium, or long. There is no definite length that can be stipulated to divide short and long line analysis. For the majority of the cases, a sufficient degree of accuracy may be obtained by the short line model on lines up to 50 miles (80 kilometers). The degree of accuracy varies with line length and configuration and also with conductor diameter and spacing.

4.4 Loads:

- In load flow studies, loads are usually represented by constant real and reactive power flow requirements. For stability studies, large motor loads are characterized by induction motor equivalent electrical circuits.

4.5 Miscellaneous:

- Input data are also developed in order to determine relay settings in terms of loading limits. Transient and dynamic stability studies require knowledge of relay and breaker times and operating sequences. Outage rates and durations for all major equipment are also necessary for developing reliability data.

5. SYSTEM STUDY FLOW CHART:

- The following is a list of system studies that should be considered to support the design criteria along with a system study flow chart that relates each study to the overall planning concept. These studies are listed in Section 3 and are repeated below for convenience:

1) Facility Feasibility
2) Load Flow
3) Reactive Compensation
4) Stability
5) Subsynchronous Resonance (SSR)
6) Statistical Line Design
7) Short Circuit
8) Insulation Coordination
9) Corona and Radio Interference
10) Electrostatic and Electromagnetic
11) Transmission Facility Economics

- SSR, item 5, primarily may occur when series compensation is employed. Statistical Line Design Parameters, item 6, are presented in the 1993 edition of the National Electrical Safety Code (NESC) for EHV transmission lines.

- A system study flow chart is shown in Figure 1. The facility feasibility study yields information pertaining to voltage level, system capacity, conductor type, and the approximate location of transmission circuits. Once a basic plan is established, a more complete transmission system study is used in order to perform detailed load flow and stability studies. The results of load flow studies help determine the adequacy of the design with regard to acceptable voltage, phase angle, impedance, and power flow variations. Reactive compensation studies utilize information from load flow studies to establish optimum types of reactive (var) sources. Similarly, results from stability studies may show several alternatives to achieve stability before equipment characteristics are specified. After the load flow and stability studies, then possible switching over-voltage problems are investigated via a statistical line design study since these voltages influence line and apparatus insulation levels.

- Other statistical line design investigations include lightning, contamination, and flashover strength studies to yield an optimum insulation system for the transmission facility. Short circuit studies are then performed to assure proper selection of protective relays and circuit breaker interrupting characteristics. Similarly, insulation coordination studies are necessary to assure proper protection of facilities against system over-voltage (internal-switching surges and external-lightning strokes).

- Extra-high-voltage (EHV) investigations that concern environmental and safety factors are corona, radio interference, electrostatic (E/S) and electromagnetic (E/M) studies. Finally, transmission facility economic studies should be considered that include tower, conductor, hardware, equipment, and right-of-way trade-off cost analyses.

6. DISCUSSION OF INDIVIDUAL SYSTEM STUDIES:

- This section gives additional details about each type of study.

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6.1 Facility Feasibility:

- Facility feasibility studies include load and rating requirements, system voltage, surge impedance loading and system capacity.

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6.1.1 Load Requirements :

- The foundation of any system planning study is a determination of the load to be served which should be compatible with an approved Power Requirements Study (7 CFR 1710, Subpart E). This load is viewed in terms of magnitude; daily and seasonal variation; area distribution; behavior characteristics with voltage and frequency variations; and reliability requirements. In addition to requiring full knowledge of the existing load and its characteristics, the planning process calls for the careful projection of load growth. In general, loads are projected for the entire system as well as for each region and each major existing and future substation.

6.1.2 Rating Requirements :

- Besides their use in operating the system under abnormal conditions, this type of study is essential to the system planning function.
- Each type of electrical equipment has a thermal rating which varies as a function of load cycle, ambient, loss of life, sun exposure, etc. Most utilities develop ratings similar to the following:

  1) Normal (continuous)
  2) Emergency - 4 hours, 8 hours, 24 hours
  3) Emergency - 1 month, 6 months

- These ratings are used for both planning continuous loads and contingency loads. They also assist in planning for the different equipment loading characteristics in summer and winter.

6.1.3 System Voltage :

- Transmission system voltages below the extra-high-voltage (EHV) level are between 34.5 and 230 kilovolts (kV). The nominal EHV levels in the United States are 345, 500 and 765 kV.
- If a transmission facility is to be developed economically, voltage steps should be neither too large nor too small. In general, a 230 kV transmission system will find it is most economical to stay at 230 kV until load growth requirements dictate 500 kV as a economical level. Similarly, 345 kV systems will probably bypass 500 kV in favor of 765 kV when load growth requirements dictate a higher voltage level.

6.1.4 Surge Impedance Loading :

- Surge impedance loading (SIL) is a convenient indicator of comparing the approximate load-carrying capability of transmission lines of different voltages. SIL is the load that the line will carry when each phase is terminated in an impedance of:

$$Z_o = \frac{Z_L}{Y_C}$$ Eq. 1

(formula is squared)

where:

Z_o = surge impedance, in ohms

Z_L = series line impedance, in ohms per unit length

Y_C = shunt line admittance, in ohms per unit length

- The SIL, in megawatts (MW), is a function of the magnitude of Z_o (or ° Zo°) and the square of the voltage as shown in the following equation:

SIL = V¨ / ° Zo° Eq. 2

where:

V = root mean squared (RMS) line-to-line voltage, in kilovolts (kV).

- While SIL gives a general idea of the relative loading capability of a line, it is usual to load lines less than 300 miles (480 kilometers) above the SIL. Conversely, because of stability limitations, it is usual to load lines greater than 300 miles (480 kilometers) below the SIL unless capacitor compensation is employed. Computer-generated SIL tables of REA transmission structures and lines are presented in REA Bulletin 1724E-201, "Electrical Characteristics of REA AC Transmission Line Designs."

6.1.5 Transmission Line Capacity :

- The capacity of a transmission line is dependent on the operating voltage, heating limit, economic limit, and stability limit.

6.1.5.1 Heating Limit

- Because of power losses, the current flowing in any conductor results in a temperature rise, and if permitted to reach the annealing point, the conductor may be damaged. However, before the annealing point is reached, vertical clearance requirements may be the limiting factor. The load required to create this condition, normally called the heating limit, will vary considerably, depending on the ambient temperature, wind velocity, conductor type and surface condition. (As the heating limit is approached, vertical clearances are generally reduced due to additional sag.) A newly installed aluminum conductor steel reinforced (ACSR) or all aluminum conductor (AAC) has a lower heating limit than a conductor which is weathered and turned dark. The heating limit is not normally a determining factor on long transmission lines unless the conductor is small and loaded beyond the economic limit; on short lines the heating limit is normally reached before the stability limit.

6.1.5.2 Economic Limit

- The determination of the most economical conductor size is complex because of the many variables involved. These variables include: (1) rate of load growth, (2) change in geographical distribution and kinds of loads, (3) cost of right-of-way, (4) location of new power supply points, (5) load factor, (6) emergency service, and (7) continuity of service. For system voltages well below the EHV range, conductor sizes can generally be chosen satisfactorily by the application of Kelvin's Law; i.e., the most economical size of conductor is that for which the investment charges are equal to the cost of energy losses.

- However, the application of this law to EHV transmission lines will not generally result in the selection of the optimum conductor size. This is because Kelvin's Law does not reflect the change in supporting structures with changes in conductor size, and also does not include the transformer capacity. A complete cost analysis should account for all effects that result from changes in conductor size and circuit loading. These include: (1) total annual fixed cost of the complete transmission line as a function of conductor size, (2) annual cost of power losses, (3) annual cost of reactive (var) supply needed to support the receiving-end voltage, and (4) an annual cost of terminals and transformer capacity required at the sending and receiving ends.

6.1.5.3 Stability Limit

- Another factor which may influence line capacity is the stability or power limit. Stability is that attribute of the system which enables it to develop restoring forces equal to or greater than disturbing forces. Steady-state stability is a condition which exists in a power system when there are no sudden disturbances on the system. Transient stability is a condition which exists if, after a sudden disturbance has taken place, the system regains equilibrium. The transient limit is usually lower and of greater importance than the steady-state limit. For relatively long lines, series capacitors or autotransformers may be used to decrease the effective line reactance and therefore increase the stability limit (Section 6.3.1.).

- A good "rule of thumb" relationship for obtaining the approximate steady-state capability of a transmission circuit between two terminals is as follows:

$$P_{max} = 0.75\ V^{\cdot\cdot} / M \qquad \text{Eq. 3}$$

where:

P_{max} = Maximum transferred power, in megawatts (MW)
V = RMS line-to-line voltage, in kilovolts (kV)
M = Distance between terminals, in miles.

6.2 Load Flow:

- Once facility feasibility studies are performed, a thorough check of the transmission system plan is made with load flow study programs. System planners confirm the adequacy of the proposed transmission network, considering line loadings, bus voltages and reactive (var) supplies. Cases are run as specified by the system planner under normal and outage contingency conditions along with the reliability criteria for each load region. A base case study provides a reference to determine the emergency and future loadings of facilities.
- The base case utilizes information corresponding to normal operating conditions. Such a case serves as a comparison to other system conditions that need to be studied. A first contingency case is also recommended since as a general minimum contingency situation, the system should perform with a single facility out of service.

- Once a base case is established, one or more changes can be introduced to determine variations in system performance. These changes may include any combination of the following:

a) Take any line or bus out of service;
b) Add loads to any or all buses and lines;
c) Change regulated bus voltages and phase angles;
d) Add or delete new interconnecting lines;
e) Add new generation to any bus;
f) Change transformer taps;
g) Increase conductor size of any line;
h) Control reactive (var) power flow;
i) Increase or decrease transformer capacity;
j) Take any bulk substation transformer out of service.

- The performance of the system as indicated by several load flow cases is properly reproduced only within the limits established by the system planner. Each case represents power flows and voltages which would exist on the system if all input data such as loads and generation were precisely reproduced. Although the load flow study results might never duplicate actual system conditions, they are meaningful primarily because the mathematical model can be tested beyond the acceptable performance range of the real system, thus better identifying limiting conditions. An example of a typical digital load flow study is shown in Appendix A.

- Load flow programs presently used automatically take into account the voltage regulating capability of synchronous condensers and transformers, while maintaining designated generation schedules as well as net interchange among interconnected systems. Specified changes in system facilities and methods of operation are automatically calculated for a number of cases in sequence.
- The required input data for load flow programs generally include: (1) bus designations, (2) line and transformer impedances, (3) real and reactive (var) power flows for each load, (4) generator power output, (5) voltage schedules and reactive (var) power flow limits of generators, synchronous condensers and switched capacitors, (6) tie-line designations, and (7) system interchange information.

- Printed output includes the (1) calculated voltage magnitude and phase angle at each bus, (2) transformer, capacitor and reactor data, (3) real and reactive (var) power flows for each line and transformer, (4) net system interchange and tie-line power flows and (5) a record of system changes. Special output features are available or can be developed to aid the planner in the analysis of the system. Examples include lists of facilities loaded beyond preestablished limits, and lists of buses where the voltage is below desirable levels.

6.3 Reactive Compensation:

- Reactive (var) compensation studies utilize information from load flow studies to establish optimum types and sizes of reactive (var) sources. There are two basic types of system compensation: (1) series compensation, in terms of impedance, is used to reduce a transmission line's effective reactance, and (2) shunt compensation, in terms of reactive power, is used to reduce the magnitude of reactive (var) power that flows in the network.

6.3.1 Series Reactive Compensation :

- Inductive reactance of transmission lines is one of the most important parameters limiting power flow capability. The insertion of capacitive reactance in series with the line's inductive reactance decreases the line impedance. This helps to increase the transmission system capability requirements. Series compensation effectively increases the transmission line capacity. This reduces the need for higher transmission voltages or greater number of circuits. (When series compensation is used, a subsynchronous resonance (SSR) study should be performed.) When applying series capacitors on EHV systems (345-765 kV), it is important that they do not introduce undue limitations on the flexibility of future system development. The location of series capacitors along the line has a significant effect on the voltage profile, and power losses. For compensation less than 50 percent, it is usually advantageous to locate the capacitors at the midpoint of the line to improve the voltage profile. Unfortunately, this may not be economically practical unless a substation exists near the midpoint of the line.

6.3.2 Shunt Reactive Compensation:

- As transmission voltages and line lengths increase, the capacitive charging currents from EHV lines also increase. These currents can cause undesirable overvoltages on generators and transformers, as well as increase power losses. In order to reduce the capacitive charging currents, shunt reactors are utilized to minimize the overvoltages during lightly loaded, switching or transient conditions. Shunt reactors may be either switched or directly connected at the transmission line terminals or to the tertiary windings of autotransformers. Tertiary shunt reactors can be switched as system reactive power requirements and voltages vary whereas permanently connected line shunt reactors cannot be separated from the line during switching operations.

6.4 Stability:

- The starting point of stability studies is the steady-state conditions (determined by the load flow study) immediately before the system disturbance under investigation occurs. Information which can be derived from a steady-state stability study includes the rotor or stability phase angle, real and reactive (var) power flow, bus voltage and system frequency. Transient (first swing) and dynamic (multiple swing) studies are generally performed either on analog devices or a digital computer.

6.4.1 Transient Stability :

- Generally, a transient stability program utilizes initial voltages and power flows obtained from the load flow program and converts the system to that required for the analysis of transient phenomena. For specified fault conditions and switching operations, the program calculates synchronous and induction machine electrical and mechanical torques, speeds, rotor torque angles, currents, and system voltages. In addition, some programs calculate currents and impedances of selected lines and simulate the automatic operation of impedance-type relays during severe systems oscillations. Switching operations and fault conditions are automatically simulated in sequence to represent the occurrence and clearing of faults.

- Input data required depend upon the complexity of the machine representation desired. For the simplest representation, the data required for a synchronous machine is the real and reactive (var) power, stator resistance, transient reactance, and inertia constant. A more detailed representation requires the characteristics of the turbine governor system and generator excitation system, and the detailed reactance, time constants, and magnetic saturation parameters associated with the machine. For most modern studies, the more detailed machine representation is utilized to provide a better understanding of system performance. For an induction machine, the real power, rotor, stator and magnetizing impedances, and the load speed-torque relationships are usually required.

6.4.2 Dynamic Stability :

- Transient stability studies are generally limited to the analysis of performance within one or two seconds after the fault. It is also important in many cases to simulate subsequent redistribution of power flows according to system inertias and governor characteristics. These dynamic stability conditions generally are important after the sudden loss of large units or generating plants, or a large concentration of load. A number of computer programs for dynamic simulation are available that take into account large system models and accurately represent the dynamic response of loads such as induction motors.

6.4.3 Results From Studies :

- Transient studies can help determine: (1) need for faster protective relay system, (2) system operating and design weaknesses, (3) desirability of fast valving, and (4) initial heavy loading of key transmission facilities. Dynamic studies generally simulate system performance during the period following sudden loss of generation or load. These studies can aid in system design by determining: (1) high speed excitation performance, (2) effect of load shedding, and (3) potential system cascading effects.

6.4.4 Methods to Improve Stability :

- Presented below are several methods which may be employed to improve system stability.

Conventional Remedies

- The most common remedy for improving power-system stability is to speed up the protective system and to increase the amount of transmission capacity. At this point in time, improving relay and breaker clearing times is difficult due to technological and economic considerations (state-of-the-art circuit breakers generally interrupt currents when the ac wave passes through current zero). The time interval between adjacent current zeros on an ac power system is determined by the power-system frequency and generally cannot be changed by the circuit breaker designer. Also, most present day protective relay methods depend on the determination of direction, distance, or impedance parameters that inherently require a certain minimum amount of measurement time for accurate results.

Fast Valving

- A source of power system instability is the excess energy supplied by the prime mover during the disturbance. If this energy is reduced or made equal to the energy needed by the generator during the disturbance, the generator acceleration problem is also reduced. Valves on modern large generating stations are usually very heavy and if the fast valving process is to be effective, the valve must be operated in a very short time. In several cases, whether the generator will remain stable is determined in less than a second. Thus, the energy input from the turbine must be changed very rapidly.

Breaker Selection and Relay Protection

- A stuck breaker on a close in three-phase fault may cause loss of synchronism resulting in instability problems. The use of power circuit breakers (PCB), whose poles can be operated individually, is an approach to prevent this condition. If each of the poles can trip independently, there is less probability that more than one of the poles will be stuck. Thus, a three-phase fault can be converted to a single-phase fault in normal relaying time. If the PCB fails to trip because it did not receive the trip signal from protective relays, the preceding method is invalid. For this situation, the installation of the PCB with individual poles will not provide any benefits. The most common method is the use of "stuck breaker" schemes employing overcurrent relays and high speed timers. In this situation the stuck breaker scheme is timed to clear the adjacent breakers within the maximum clearing time. The primary relay scheme must be sped up accordingly.

System Damping

- System damping is a method of providing restoring forces in order to decrease undesired oscillations or large system swings. Generally, it is difficult to apply fast valving and braking resistors in such a way that there will be negligible system swings after the fault is cleared. In the more usual case where such controls are not used, the swings may be sufficient to cause loss of synchronism after the fault is cleared. Swings that cause loss of synchronism, loss of load, or large voltage excursions, should be controlled to reduce them to acceptable proportions. Damping restores equilibrium between the generator input and output so that minimum power is available for acceleration or deceleration. Two forms of system damping are insertion of a dc tie between two ac lines and load shedding.

- A dc tie between two ac lines provides a solution to the stability problem since no phase synchronization exists between the ac lines. The dc tie has characteristics that are suited for the damping function. HVDC controls can be arranged so that the power flow over the dc lines is independent of the conditions existing on the ac lines. Thus, it becomes possible to have the dc tie surge power in accordance with the operating needs of the interconnecting ac systems. Besides high costs, difficulties may be experienced in the practical design of control circuits that develop the intelligence necessary to control the dc line.

- Load shedding is another form of system damping. Generally, load shedding relays are installed to disconnect load when there is insufficient generation to maintain normal system frequency. This is a related system problem that is brought about because generator synchronism is lost for other reasons. Voltage reduction is another form of load shedding. This method is complicated by the necessity for extremely high speed underfrequency relays. Because of their sensitivity they often false-trip and cause start-up problems.

6.5 Subsynchronous Resonance:

- Subsynchronous resonance (SSR) occurs when the natural frequencies associated with the mechanical torques of synchronous machines are close to those imposed by the connecting networks. Steady-state SSR involves spontaneous oscillations that are either sustained or slowly increased in magnitude with time. Transient SSR generally refers to transient torques on the generator shaft resulting from oscillating currents in the electrical network caused by faults or switching operations. The study of SSR requires two phases: (1) stability analysis to insure that oscillations cannot build up during normal operation, and (2) the simulation of switching operations and faults to insure that associated torques do not exceed shaft stress limits. Results from SSR investigations yield the probability of occurrence of SSR in the system. Corrective measures required to reduce SSR are the use of filters to block currents at SSR frequencies and the use of other design techniques besides series compensation to meet system stability requirements.

- Transmission systems containing series compensation may exhibit subsynchronous resonance at frequencies below 60 Hz. Thus, currents at subsynchronous frequencies may be amplified by synchronous machines causing undesirable oscillations and potential stability problems. The buildup or decay of these currents is dependent on the series resistance and loading levels of the transmission system.

6.6 Statistical Line Design:

- The main objectives of overvoltage, short circuit, and insulation coordination investigations are to (1) set criteria for transmission line electrical design, (2) establish ratings of surge arresters and other protective devices, and (3) specify equipment insulation levels. These three investigations will now be discussed.
- Line design studies include switching surge evaluations, lightning performance, and contamination and flashover performance. All these factors influence transmission line and apparatus insulation levels. For transmission voltages between 34.5 and 230 kV, line insulation studies may not be necessary if insulation requirements are specified as in REA Bulletin 1724E-200.

6.6.1 Switching Surge Evaluation :

- One severe overvoltage which the transmission facility must withstand is the switching surge. Switching surges are produced by switching of apparatus such as circuit breakers and disconnecting switches. These overvoltages appear across the line and station insulation, both phase-to-ground and phase-to-phase. Together with lightning and contaminated considerations they determine the required line insulation levels. Switching surge requirements are also used in insulation coordination studies for substation equipment (Section 6.8).

- Insulation strength characteristics (which vary with such statistical data as wind, precipitation, and air density) are utilized in the switching surge evaluation. Other factors which affect the insulation system are breaker insertion resistors, line length, configuration, and loading. These parameters determine the waveshape and magnitude of switching surge which, in turn, influence the insulation flashover strength characteristic. Studies on the transient network analyzer (TNA) are an excellent starting point for determination of system insulation based on switching surge performance. These TNA studies may include the following statistical parameter evaluations:

a. Probability of proper circuit breaker operation
b. Probability that an insulator string will swing to a certain position.
c. Probability that weather factors will reduce flashover voltage performance across insulators and gaps.
d. Probability that a voltage surge will exceed the critical flashover voltage rating of an insulator string.

- As noted above, switching surge performance is determined primarily by the line insulation. The number of insulators is selected so that the probability of flashover from switching surges does not exceed design specifications. In general, for transmission voltages below EHV (34.5-230 kV), switching surges do not limit the tower insulation design since the insulation strength increases in proportion to the phase-to-structure clearance. At EHV levels (345-765 kV) the air gap begins to saturate and switching surge line performance may become the limiting factor in the choice of tower dimensions and clearances.

6.6.2 Lightning Performance :

- Besides switching surge studies, a second major consideration in designing transmission lines is lightning performance. Analytically, the lightning problem is extremely complicated being a function of many lightning statistics such as stroke current amplitude, rise times, hit probabilities and frequency of occurrence. (Thunderstorm-day activity is shown on the Isokeraunic map. From the map data, a relative comparison is made of thunderstorm activity in each area.)

- Lightning evaluation of transmission facilities includes consideration of storm incidence in the area, tower height and configuration, and insulator string length. Overhead ground wires (OHGW) are usually used to shield phase conductors from direct strokes. The number and location of OHGWs are major factors in estimating the number of shielding failures. In addition to OHGWs, a combination of line insulation and tower footing resistance parameters are used to minimize lightning flashovers across a transmission line.

- To obtain an accurate estimate of lightning performance of a proposed line design, transient network analyzers (TNA), digital computers and system modeling methods are employed to determine such parameters as the trip-out rate. Surge arrester ratings for transmission system applications are normally based on data from TNA studies. The resultant transient overvoltages from these studies are statistical in nature and are combined with insulation strength probability studies to estimate lightning flashover performance.

6.6.3 Contamination Performance :

- The third major line design study is contamination performance of transmission line insulation. Unlike switching surge and lightning studies, which estimate transient performance, contamination studies relate to the 60 Hz or fundamental frequency performance.
- Results from contamination studies yield flashover insulation levels of (1) air gaps at extreme swing angles and (2) contaminated insulator strings. Both of these levels are based on statistical parameter such as geographical location and transmission system configuration (such as tower size and geometry).

6.7 Short Circuit:

- The principal purposes of short circuit studies are listed below:

a. Provide information for proper selection of protective relays to establish system performance requirements and settings.

b. Provide information for proper selection of circuit breaker interrupting requirements.

c. Evaluate voltages during faulted conditions which would affect insulation coordination and the application of surge arresters.

d. Design the type and capability of grounding systems.

e. Establish the electromechanical forces to be withstood by system facilities.

f. Provide data for a variety of network calculations during the process of planning and designing the system.

- A variety of computer programs have been developed for performing short circuit studies. Some are designed specifically to facilitate relay studies, while others provide information primarily used in planning. All represent the system by symmetrical component equivalent reactances of various facilities. The programs generally calculate for each bus of a specified system the total three-phase and line-to-ground bus faults, including effects of zero-sequence mutual impedances. Also specified are the three-phase and line-to-ground fault contributions for each line or transformer connected to the faulted bus.

- Input data required include bus identification, positive and zero-sequence impedances of lines and transformers, and transient and subtransient reactances of synchronous machines.
- The printed output includes all bus faults and line contributions for three-phase and line-to-ground faults for both normal and switched conditions. This allows quick identification of the breaker duties under the worst conditions, and provides data in a form usable for evaluation purposes. In addition, a variety of printouts of currents and voltages can be specified in any combination for every faulted bus.

6.8 Insulation Coordination:

- Insulation coordination is defined as the protection of electrical systems and apparatus from harmful overvoltages by the correlation of characteristics of protective devices and the equipment being protected.
- To coordinate insulation and protective devices, impulse voltage levels are defined in terms of both BIL (basic impulse insulation level) and BSL (basic switching surge level).

- Insulation coordination is defined as the protection of electrical systems and apparatus from harmful overvoltages by the correlation of characteristics of protective devices and the equipment being protected. To coordinate insulation and protective devices, impulse voltage levels are defined in terms of both BIL (basic impulse insulation level) and BSL (basic switching surge level).

- Similarly, the BSL describes the equipment's ability to withstand switching surges. The standard BSL waveform is 250/2500 which is a wave that has a front time of 250 microseconds and reaches half magnitude at 2500 microseconds.
- Results from insulation coordination studies yield the expected stress requirements on the system equipment. Other outputs include BIL and BSL performance, arrester selection, and system operating constraints for a given or assumed overvoltage, lightning, waveshape and insulation strength characteristics.

6.9 Corona and Radio Interference :

- Radio and television noise or electromagnetic interference (EMI), and audible interference are rapidly becoming controlling factors in the design and planning of transmission systems, especially at EHV and UHV. Two of the most reported environmental effects caused by transmission facilities operating at EHV and UHV (345 kV and above) are corona noise interference and voltage induction. (See Section 6.10)

- Electrical discharges due to either corona or gap sparkover are the basic sources of radio and audible noise (AN) interference. The pulses caused by these discharges are injected into the transmission line phase conductors or other conducting components which may act as a radiating antenna or transmission media.
- Thus, EMI from the transmission lines is caused either by complete electrical discharges across small gaps or by partial electrical discharges such as corona.

- Gap-type noise sources can occur in the following transmission line components:
  a. Insulators that are dirty, cracked or loose,
  b. Splices,
  c. Tie wires,
  d. Between hardware parts (clamps, brackets, insulator pins, crossarm braces, and guy wires),
  e. At small gaps between ground wires and hardware parts,
  f. With electrical apparatus that is either defective, damaged, improperly designed, or improperly installed (such as corroded or loose fuse elements, transformer insulation failure, noisy contacts in relays, meters and regulators).
- These gap-type noise sources can be located by equipment that traces EMI such as broadcast radio sets and battery operated portable television receivers. Noise sources can be electrically short circuited or minimized by improving the bonding between adjacent conducting parts or by tightening loose connections.

- At EHV and UHV corona (an electrical discharge through ionized air) is generally the main source of noise interference. Corona is formed when voltage gradients are above the critical gradient. For a specified operating voltage, conductor contamination is the main cause of corona. However, conductor surface burrs and scratches, and weather (rain, snow, and humidity) cause an increase in corona effects. Other corona byproducts are power loss in conductors and ozone production (a chemical reaction of the corona discharge). Thus, transmission line corona is a source of radio interference (RI) and audible noise (AN) at EHV and UHV. The measure of corona depends on existing ambient conditions prior to line construction and also on the level of noise from the energized line. For RI, the ambient conditions consist of the received signal strength and background noise level. The quality of reception during ambient conditions depends on the ratio of these two components and is called the ambient signal-to-noise ratio (ASNR). RI, resulting from transmission line corona, depends on the ratio of the received signal strength and the noise level produced by the line. This is referred to as the interference signal-to-noise ratio (SNR). The comparison of ASNR and SNR is a measure of the corona produced by a line at any one location. If both the ASNR and SNR levels are high, reception quality will also be high.

6.10 Electrostatic and Electromagnetic :

- At EHV and UHV the medical and biological concerns due to electric field gradients and the electrostatic (E/S) and electromagnetic (E/M) coupling between overhead transmission lines and conductive objects should be considered.

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6.10.1 Medical and Biological :

- Medical and biological studies deal with the direct physiological effects on humans, animals, and plants subjected to strong electric field. The mag nitude of
- electric field strength (or voltage gradient) at ground level is
- usually used in medical studies to determine permissible field
- strength limits for people and animals near energized
- transmission lines.

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6.10.2 Induced Voltage :

- Electrostatically induced voltages are possible when a conductive object insulated from ground is in the vicinity of alternating current overhead lines. Similarly, electromagnetic induction effects are possible when transmission line phase conductors carrying fault currents cause induced voltages at the open ends of an insufficiently grounded r the E/S case, a steady-state shock current magnitude of five milliamperes is considered as the "let-go" level in the 1993 edition of the National Electrical Safety Code (NESC). Other practical considerations may dictate that the shock current magnitude be kept below the one milliampere "threshold of perception" level. For the E/M case, object grounding intervals are based on transient current levels through a person or animal.
- Results from E/S and E/M studies help determine the grounding requirements for stationary metallic objects (fences and buildings) and insulated conductive vehicles.

6.11 Transmission Facility Economics :

- The last system study discussed is that of transmission facility economics. Several of the factors that should be considered in an economic study include tower, conductor, accessory, and right-of-way costs. While all these factors enter into a study of transmission costs, two basic elements that are of significant importance are (1) the load-carrying capability of lines in terms of voltage and distance, and (2) the associated equipment, particularly transformers and switchgear. Related to both transmission capability and cost is a third element; an evaluation of the economics of intermediate switching stations. Some of the questions that should be answered in a transmission facility economic study are the following:

a. What diameter of conductor is necessary to reduce radio interference and corona loss to acceptable levels?

b. What line insulation is necessary?

c. What should the BIL of the station equipment be?

d. How much load can be safely associated with a transmission circuit?

e. What is the economic comparison with lower voltage transmission or even high voltage direct current (HVDC) transmission for some installations?

f. What should the electrostatic and electromagnetic requirements be to minimize the effects of voltage induction and field gradients on humans, animals, and plants near overhead lines?

7. CONCLUSIONS:

- In conclusion, an overview of eleven system studies is presented to support REA-financed transmission facilities from 34.5 to 765 kV. These studies are not necessarily complete nor are they listed in any order of priority. Each study should be considered for the specific facility in question in order that system performance can be observed and evaluated.