Department of Engineering Technology

HCT-SWC

EEL 2023
Power Generation and Transmission

LO3: Basic Concepts of Electrical Power Transmission and System Stability

Course: EEL- 2023 Power Generation and Transmission
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HIGHER COLLEGES OF TECHNOLOGY

EEL 2023

Power Generation and Transmission

LO 3

Chapter 4: Basic Concepts of Electrical Power Transmission System

POWER SYSTEM PARTS

- A power system is made of the following parts:
  - Generation
  - Transmission
  - Distribution
  - Substation for voltage/current conversions
- ***Function of the Transmission system:***
  - The main function of the transmission system is to transmit bulk power to load centers and large industrial users.

TRANSMISSION LINES

- Generators and loads are connected together through **transmission lines** transporting electric power from one place to another. Transmission lines must, therefore, take power from generators, transmit it to locations where it will be used, and then distribute it to individual consumers.

- The power capability of a transmission line is ***proportional to the square of the voltage*** on the line. Therefore, very high voltage levels are used to transmit power over long distances. Once the power reaches the area where it will be used, it is stepped down to lower voltages in **distribution substation**s, and then delivered to customers through **distribution** lines.
- Power cables can be either ***Overhead Lines*** or ***Underground Lines***

TRANSMISSION LINES

- The first components that we will consider are Transmission Lines.
- We start with Characteristics of Power Lines
- Transmission lines have **resistance**, **inductance** and **capacitance**

Resistance

- The DC resistance of a conductor is given by

$$R_{DC} = \frac{\rho l}{A}$$

- Where ρ is the specific resistance (resistivity) of the material, *l* is the length, and *A* the cross-sectional area.
- Therefore, the DC resistance per meter of the conductor is

$$r_{DC} = \frac{\rho}{A}\left[\frac{\Omega}{m}\right]$$

- To keep the resistance of the lines as low as possible they should have a large diameter. Resistance reduces with the square of the radius.

Resistance

- However, resistance must be weighed against other factors, including the cost of the conductor cable itself and its weight that needs to be supported by the towers
- The resistivity of a conductor is a fundamental property of the material that the conductor is made from. It varies with both type and temperature of the material.
- The resistivity increases linearly with temperature over normal range of temperatures.

Resistance

- AC resistance of a conductor is always higher than its DC resistance due to the ***skin effect*** forcing more current flow near the outer surface of the conductor. The higher the frequency of current, the more noticeable skin effect would be.

- At frequencies of our interest (50-60 Hz), however, skin effect is not very strong.

- Wire manufacturers usually supply tables of resistance per unit length at common frequencies (50 and 60 Hz). Therefore, the resistance can be determined from such tables.

Inductance and inductive reactance

- Note that while resistance of lines is critical with regard to line losses, it is less important with regard to power flow and stability. This is because the overall impedance of a line tends to be dominated in practice by its inductive reactance, to such an extent that zero resistance is assumed.
- Recall that inductance is based on magnetic flux lines linking a loop of wire. This notion extends to a straight wire, which can be considered an ***infinitely large loop***, and the magnetic flux around the wire does link it. Since there is only a fraction of a turn in a straight line, this magnetic effect is quite weak.

Line inductance

- But inductance is cumulative on a per–unit-length basis, and with a conductor that extends over tens or hundreds of miles, it does eventually add up.
- Indeed, there are two contributions to line inductance: the ***self-inductance***, which is just a property of the individual conductor, and the ***mutual inductance***, which occurs between the conductors of the three different phases.

Inductance of a transmission line

- In most of the practical situations, the inductance of the transmission line can be found from tables supplied by line developers.
- Analysis of inductance properties shows that:
- 1. The ***greater the spacing between*** the phases of a transmission line, the ***greater the inductance*** of the line. Since the phases of a high-voltage overhead transmission line must be spaced further apart to ensure proper insulation, ***a high-voltage line*** will have a ***higher inductance*** than a ***low-voltage line.***
- Since the spacing between lines in buried cables is very small, series inductance of cables is much smaller than the inductance of overhead lines.

Inductance of a transmission line

- 2. The greater the radius of the conductors in a transmission line, the lower the inductance of the line.
- In practical transmission lines, instead of using heavy and inflexible conductors of large radii, two and more conductors are bundled together to approximate a large diameter conductor.
- The more conductors included in the bundle, the better the approximation becomes. Bundles are often used in the high-voltage transmission lines.

Capacitance and capacitive reactance

- Transmission lines have capacitance, too. It is a bit easier to see how two lines travelling next to each other would vaguely resemble opposing plates with a gap in between.
- In fact, there is also capacitance between a conductor and the ground. Because the lines are small and the gap wide, the capacitance tends to be fairly small

Capacitance of a single phase two-wire transmission line

- Analysis of capacitive properties of lines shows that:

1. The greater the spacing between the phases of a transmission line, the lower the capacitance of the line. Since the phases of a high-voltage overhead transmission line must be spaced further apart to ensure proper insulation, a high-voltage line will have a lower capacitance than a low-voltage line. Since the spacing between lines in buried cables is very small, shunt capacitance of cables is much larger than the capacitance of overhead lines. Cable lines are normally used for short transmission lines (to min capacitance) in urban areas.

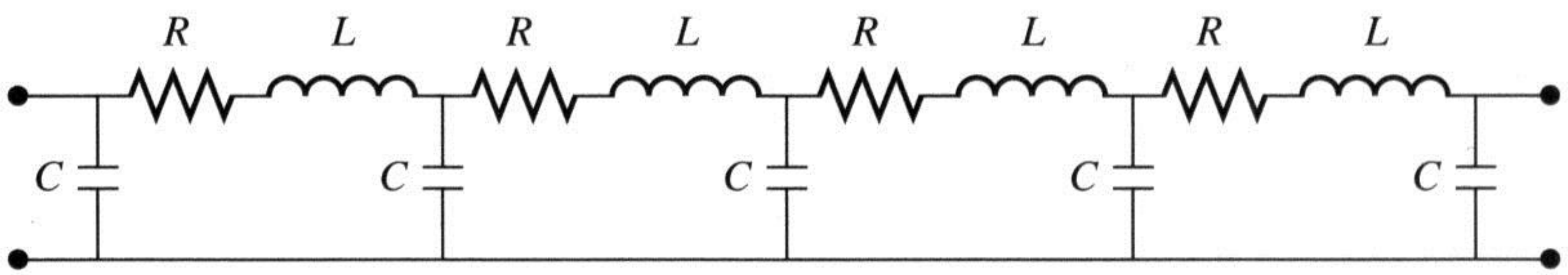
CAPACITANCE OF A SINGLE PHASE TWO-WIRE TRANSMISSION LINE

2. The greater the radius of the conductors in a transmission line, the higher the capacitance of the line.

- Good transmission line is a compromise among the requirements for low series inductance, low shunt capacitance, and a large enough separation to provide insulation between the phases.

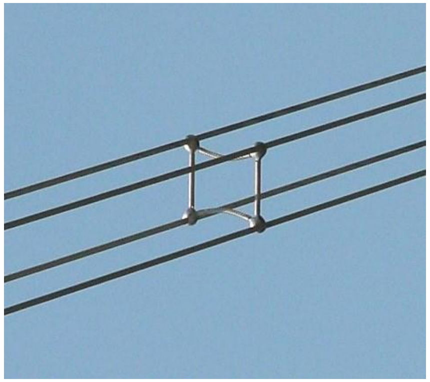
Transmission Line Model

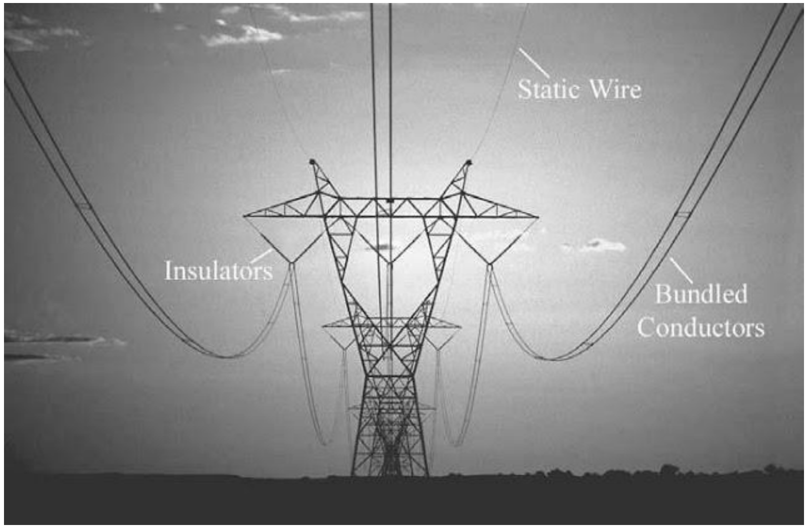
- In describing transmission-line parameters, the inductance is generally considered to be in series and the capacitance in parallel.



Single core or bundled?

- Conductors on transmission lines—especially high-voltage, high-capacity lines—are sometimes bundled, meaning that what is electrically a single conductor is actually composed of two, three, or four wires a few inches apart, held together every so often with connectors known as conducting frames.





Bundling of Conductors

There are several reasons for bundling conductors:

- Increasing heat dissipation as a result of increasing surface area,
- Reducing corona losses,
- Reducing inductance,
- Increasing the amount of current in the conductor due to reduced skin effect

BUNDLING OF CONDUCTORS

- For 220 kV lines, two-conductor bundles are usually used, for 380 kV lines usually three or even four.
- A bundle conductor results in lower reactance, compared to a single conductor.
- As a **disadvantage**, the bundle conductors have higher wind loading.

Corona

- A corona is a process by which a current flows from an electrode with a high potential into a neutral fluid, usually air, by ionizing that fluid so as to create a region of ionized atoms around the electrode. The ions generated eventually pass charge to nearby areas of lower potential, or recombine to form neutral gas molecules.
- When the potential of the electric field is large enough at a point in the fluid, the fluid at that point ionizes and it becomes conductive. If a charged object has a sharp point, the air around that point will be at a much higher voltage gradient than elsewhere. Air near the electrode can become ionized (partially conductive), while regions more distant do not.

CORONA

- One reason for bundling conductors is to reduce corona losses. The corona results from the electric field that surrounds the conductor at high voltage.

- Microscopic arcs occur between the conductor surface at high potential and ionized air molecules in the vicinity.
- The audible crackling sound around high-voltage a.c. equipment comes from the corona of tiny arcs that discharge into the air.

Corona

- http://www.youtube.com/watch?v=rLrP9mck7eM
- http://www.youtube.com/watch?v=ehQwzTxNZ9c

Corona

- Because the arcs are so small, they are not visible even at night. Yet there is a measurable energy loss associated with what is in fact a small electric current flowing to ground through the air. The power associated with this current is the corona loss.
- When the surface area of the conductor is increased, the electric potential or surface charge density is spread out more, reducing the electric field strength. This in turn reduces the formation of arcs, and thus reduces corona losses.

Marker Balls

- http://www.youtube.com/watch?v=JAJu6nGYvh8#t=57
- http://www.youtube.com/watch?v=BQAl2r-PRpA

Planning a Transmission System

- The decision to build a transmission system results from system planning studies to determine how best to meet the system requirements. The factors that need to be considered at the planning stage are discussed in the following sections.

- ***Determination of Transmission Voltages***
- ***Deciding Between Overhead Lines and Underground Cables***

Determination of Transmission Voltages

System Voltages:

- There is no clear separation between distribution, sub-transmission, and transmission voltage levels. In some systems 69 kV may be a transmission voltage while in other systems it is classified as distribution, depending on function.

CLASSIFICATION BY OPERATING VOLTAGE

Overhead power transmission lines are classified in the electrical power industry by the range of voltages:

- **Low voltage** – less than 1000 volts, used for connection between a residential or small commercial customer and the utility.
- **Medium Voltage** (Distribution) – between 1000 volts (1 kV) and to about 33 kV, used for distribution in urban and rural areas.
- **High Voltage subtransmission** less than 100 kV; subtransmission or transmission at voltage such as 115 kV and 138 kV), used for sub-transmission and transmission of bulk quantities of electric power and connection to very large consumers.
- **Extra High Voltage (transmission)** – over 230 kV, up to about 800 kV, used for long distance, very high power transmission.
- **Ultra High Voltage** – higher than 800 kV.

Determination of Transmission System voltages

- Determining transmission voltages is a matter that requires careful study. Engineers cost out the systems employing several generally standard voltages (and standard materials and equipment). For example, the annual costs for each of the systems: 69 kV, 138 kV, and 230 kV.

- The lowest overall annual expense will generally be found to happen when the annual operating charges are approximately equal to the annual cost of the electrical losses in the system.

Determination of Transmission System voltages

- K_g : Overall cost of transmission
- K_v : The cost of losses on the transmission line
- K_a : Cost of transmission equipment
- Where,

  $K_g = K_v + K_a$

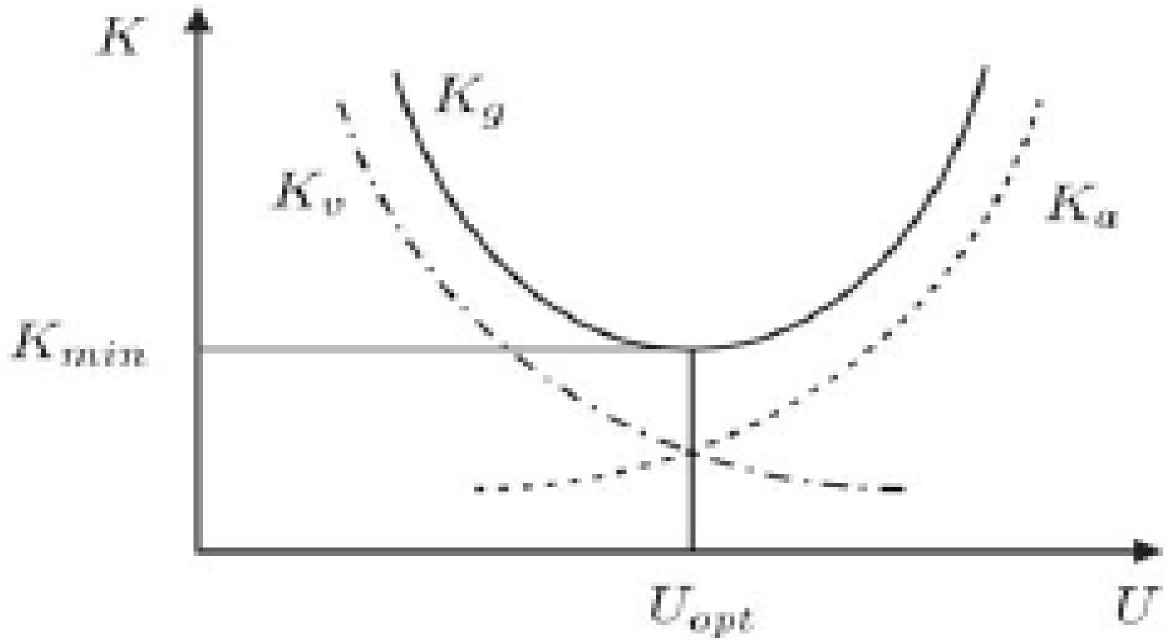


Figure 1 – Transmission System voltage versus cost of transmission

- The economic optimal transmission voltage U_{opt} results at minimal cost K_{min}.

Deciding Between Overhead Lines and Underground Cables

There are two general ways of transmitting electricity:

- Overhead and
- Underground

Comparing Overhead and Underground TLs

	Overhead Lines	*Underground Cables*
1 ***Conductors***	copper or Aluminum conductors, or Aluminum conductors steel reinforced (ACSR) are used	copper or Aluminum conductors, or Aluminum conductors steel reinforced (ACSR) are used
2 ***Insulation***	The insulation is air except at the supports (towers, poles, or other structures), where it may be porcelain, glass, or other material	The conductor is insulated with oil impregnated paper, or a special type of plastic material.
3 ***Safety***	Problems with safety as lines are exposed and prone to natural hazards like rain, wind & lightning	system is safer and less prone to natural hazards like rain, wind and lightning.
4 ***Initial cost***	Transmission systems are costly	Underground systems are much more expensive than overhead systems
5 ***Flexibility***	Overhead system is more flexible than underground system	Underground system have no flexibility
6 ***Maintenance cost***	Maintenance cost is high	Maintenance cost of underground system is very low
7 ***Frequency of failures***	Lines are prone to damage and accidents	Cables are less prone to damage and failure

Comparing Overhead and Underground TLs

8 ***Environment***	Overhead lines are not considered environmentally friendly	Underground cables are environmentally friendly
9 Fault location & repair	Faults can be located easily and the repair is easy.	if a fault occurs it is very difficult to locate that fault and its repair is difficult and expensive
10 Possible damage	Prone to damage due to thunderstorm and falling objects across the wires	Underground systems are free from interruption of service due to thunder storm lightning and objects falling across the wires.
11 charging current	Small capacitance and low charging current	On account of less spacing between the conductors cables have higher capacitance and draw higher charging current.
13 Joining	Joining is easy	Joining of underground cables is difficult so tapping for loads and service mains is not conveniently possible in underground system.
14 Surge Effects	Overhead lines are prone to severe transients because of exposure and low capacitance	*In underground system surge effect is smoothened down as surge energy is absorbed by the sheath*
15 Voltage drop	Voltage drop is high because of high inductance	Voltage drop is low because of low inductance

TRANSMISSION LINE DESIGN

- It is desirable, when transmitting large amounts of electric power, to use higher voltages, thereby employing thinner, less expensive conductors that are easier to handle. Low voltages require heavy conductors that are costly and bulky and expensive to install.
- There is a limit, however, to how high the voltage and how thin the conductors can be. In overhead construction there is the problem of supports—poles, structures, towers.
- If the conductor is made too thin, it will not be able to support itself mechanically and the cost of additional supports and insulators becomes inordinately high.

TRANSMISSION LINE DESIGN

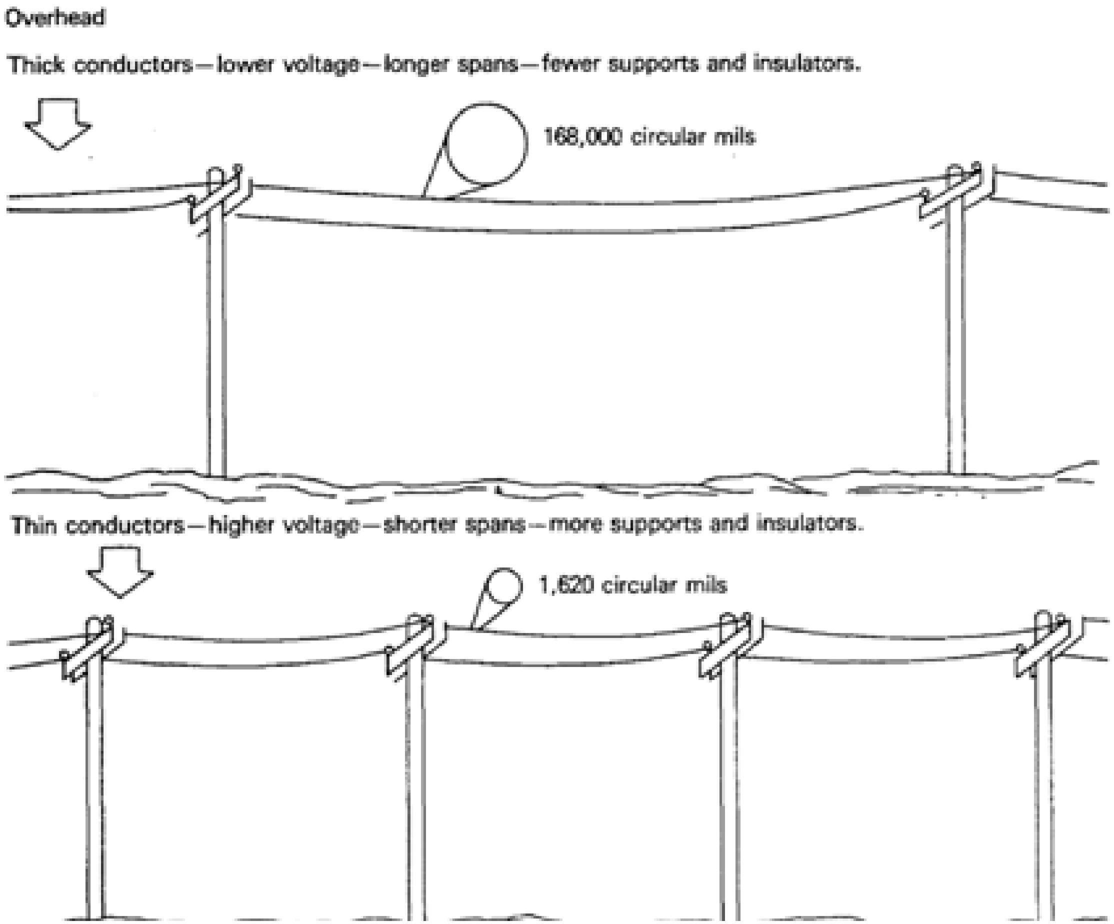


Figure 1.2 Practical economics affect the size of a transmission line.

UNDERGROUND CABLES

- Underground construction faces the same economic limitations, and in this case, the expense of insulation.
- A cable must be thoroughly insulated and sheathed from corrosion. The greater the overall size of the cable, the more sheathing becomes necessary and more difficulty experienced in its handling.

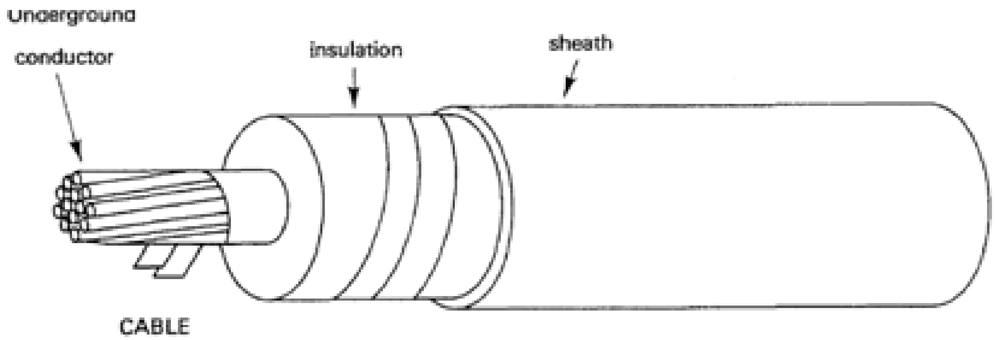
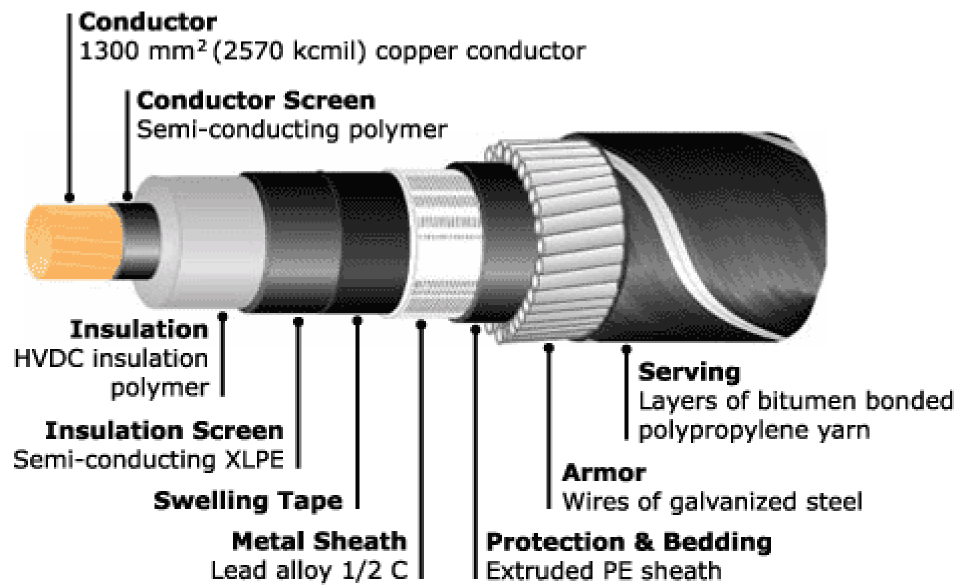


Figure 2 – Design considerations of transmission systems

Underground Cables



COST COMPARISON BETWEEN OVERHEAD LINES AND UNDERGROUND CABLES

- The initial cost of underground system is much more expensive than overhead lines.
- For a particular amount of power to be transmitted at a given voltage the underground system costs more than overhead system.
- The approximate cost ratios are as foloows:

System voltage, KV	0.4	11	33	66	132	220	400
Cost ratio cable/overhead line	2	3	5	7	9	13	24

Overhead Transmission Lines types and Designs Considerations

- Transmission system design involves the selection of the necessary lines and equipment which will deliver the required power and quality of service for the lowest overall average cost over the service life.
- The system must also be capable of expansion with minimum changes to existing facilities.

Conductor Selection Considerations

i- General Properties of Transmission Conductors:

Line conductors are one of the main parts of overhead lines. The important characteristics, which the line conductors must have are:

1. High tensile strength:

The material for the conductor of an overhead line should have a high tensile strength (high breaking load) so that the spans between transmission line towers can be as long as possible and the sag as small as possible thus reducing the number and height of towers, and number of insulators.

Conductor Selection Considerations

2. Low resistivity:

The conductor should have low resistivity to reduce the power losses and voltage drop.

3. Low cost:

The cost of its installation and maintenance should be low and it should have a long life.

4. Low Corrosion:

Conductors must be stable against corrosion.

5. Low Skin Effect and Corona Losses:

The structure of the conductor should be such that to minimize the additional losses due to skin effect or corona effect in case of high and extra high voltages.

Conductor Materials

- *The final choice of material is often a compromise.*
- Copper, aluminum, steel and steel-cored aluminum conductors are generally employed in an overhead lines to transmit electrical energy.
- The following is a list of properties of each of these materials.

Conductor Materials

a) Copper.

The most common conductor material used for transmission is hard drawn copper, because it is twice as strong as soft drawn copper. The merits of this metal as a line conductor are:

1. It has a best conductivity in comparison to other metals.

2. It has higher current density, so for the given current density (rating), less cross sectional area of conductor is required and hence it provides lesser cross sectional area to wind loads.

3. The metal is quite homogenous.

4. It has low specific resistance.

5. It is durable and has a higher scrap value.

Conductor Materials

b) Aluminum:

Next to copper, aluminum is the conductor used in order of preference as far as the conductivity is concerned. Its merits and demerits are:

1. It is cheaper than copper.
2. It is lighter in weight.
3. It is second in conductivity among the metals used for transmission.
4. For same Ohmic resistance, its diameter is about 1.27 times that of copper.

Aluminium

5. Since the diameter of the conductor is more, so it is subjected to greater wind pressure due to which greater is the swing of the conductor and greater is the sag.

6. Since the conductors are liable to swing, so it requires larger cross arms.

7. As the melting point of the conductor is low, so the short circuits and similar effects will damage it.

8. Joining of aluminum is much more difficult than that of any other material.

Conductor Materials

c) Steel:

No doubt it has got the greater tensile strength, but it is least used for transmission of electrical energy as it has got high resistance. Bare steel conductors are not used since they deteriorate rapidly owing to rusting. Generally galvanized steel wires are used where high strength is desired. It has the following properties:

1. It has high internal reactance.
2. It is lowest in conductivity,
3. It is much subjected to eddy current and hysteresis losses.
4. In a damp atmosphere it rusts quickly.

Hence its use is limited and the main application is for ground wires.

Conductor Materials

d) Aluminum conductor with steel reinforced (ACSR).

An aluminum conductor having a central core of galvanized steel wires is used in stranded conductors for high voltage transmission purposes. This is done to increase the tensile strength of aluminum conductors. The galvanized steel core is covered by one or more strands of aluminum wires. The steel conductors used are galvanized in order to prevent rusting and electrolytic corrosion.

Examples of such conductors are shown in Figure 3.

ACSR LINES

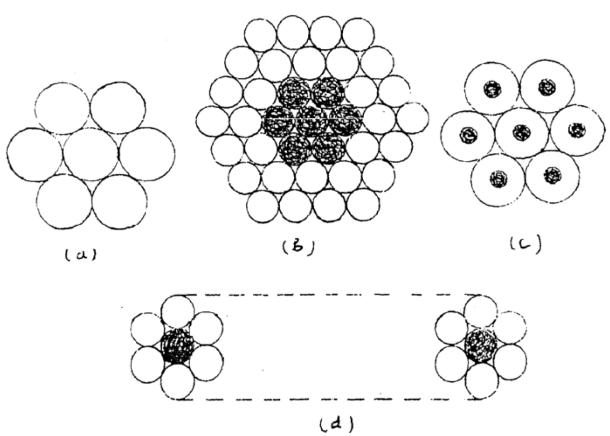


Figure 3: Stranded conductors

(a)Multi-core homogeneous conductor

(b)Multi-core non-homogeneous conductor

(c)Multi-core bimetallic conductor

(d) Multi-core bundled conductor

INSULATORS

- **Insulators** must support the conductors and withstand both the normal operating voltage and surges due to switching and lightning. Insulators are broadly classified as either
- **pin-type**, which support the conductor above the structure, or
- **suspension type**, where the conductor hangs below the structure. The invention of the **strain-insulator** was a critical factor in allowing higher voltages to be used.

Insulators

- Insulators are usually made of wet-process ***porcelain*** or **toughened glass** , with increasing use of glass-reinforced polymer insulators.
- Suspension insulators are made of multiple units, with the number of unit insulator disks increasing at higher voltages. The number of disks is chosen based on line voltage, lightning withstand requirement, altitude, and environmental factors such as fog, pollution, or salt spray.

Line Supports

Line supports can be made up of poles or towers and has to perform the following functions:

a- Keep appropriate spacing between the conductors.

b- Maintain the specified ground clearance.

Line Supports

Poles:

Poles are usually used for short spans in low voltage lines. Various types of poles are used, such as: Wooden poles, concrete poles and steel poles.

Towers:

High voltage lines require large air and ground clearances. Steel towers were developed for such lines where very long spans are essential. They are classified as:

a) Self - supporting towers.

b) Guyed towers.

Self-Supporting Towers

These can be:

- **Wide-base**: In wide base towers, ***lattice*** type construction with bolted connection is adopted. Each leg has a separate foundation.
- **Narrow-base** towers. These use latticed construction of angle, channel or tubular steel sections with bolted or welded connections. They use less steel in comparison with wide-base towers, but use more costly foundation.

Self-Supporting Towers

- A narrow-base tower requires lesser steel in comparison with a wide-base tower, but its cost of foundation is more. The selection between the two has to be made on the basis of comparison between the cost of material and foundation.
- Figure 4 shows various types of steel towers.

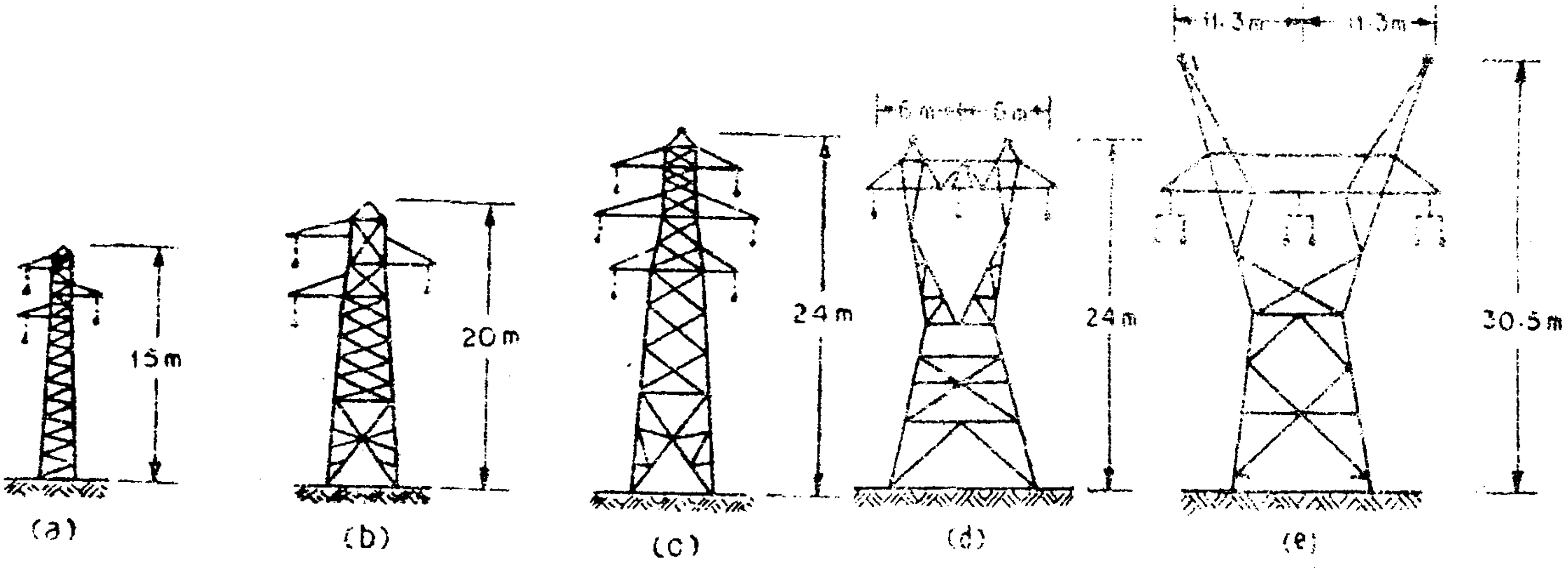


Figure 4 - Steel Towers:

(a) 33 kV, narrow base Single circuit

(b) 66 kV, broad base, single circuit

(c) 132 kV, double circuit, broad base

(d) 220 kV Cat’s head, single circuit

(e) 400 kV, single circuit with two sub-conductors per phase

Wide-Base Towers

- Wide-Base towers are classified into:
- ***Suspension towers:*** Suspension towers are used in the straight sections of a line. They are designed mainly to withstand stresses in a transverse direction resulting from wind pressure on ice-covered conductors. In a longitudinal direction they are designed to carry a certain amount of unbalanced stresses due to broken conductors and wind loading. Certain torsion stresses due to unequal conductor loading must also be taken into account.
- ***Angle towers:*** Angle towers are designed to withstand both the balanced stresses due to the angle in the line and any unbalanced stresses due to wind pressure and unequal conductor loading as well as possible broken conductors.

WIDE-BASE TOWERS

- ***Strain or dead-end towers:*** Strain towers are used at dead-end points in the line and must be designed for full lateral stresses the same as suspension towers, also for the lull longitudinal stresses of all the loaded conductors and for torsion stresses due to broken conductors.

- ***Semi strain towers:*** Semi strain towers are sometimes used for situations where the longitudinal stresses are intermediate between those of suspension and strain towers.

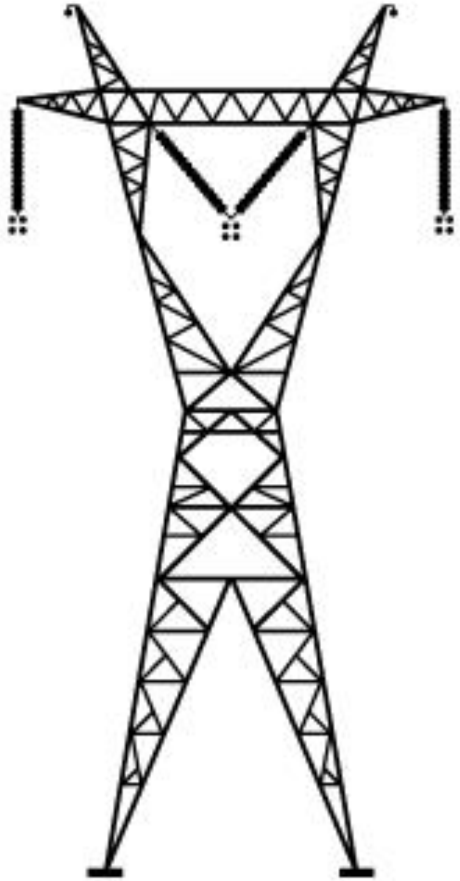
GUYED TOWERS

- Guyed towers are used to reduce weight and cost of towers, as well as in certain terrain applications. Guyed towers are either portal type or V-type. Both of them have two masts connected at the top by a cross arm and provided with four guys. In case of portal type of structure, each mast rests on its own foundation. The four guys are anchored to two double-acting guy anchors. A V-tower has two masts resting at an angle to one another on one thrust footing only which is of heavier type. Separate anchorages are provided for each of the four guys. The purpose of the guy anchorages is to meet varying soil conditions and to take large uplift forces.

Waist-Type Tower

Waist-type tower

This is the most common type of transmission tower. It's used for voltages ranging from 110 to 735 kV. Because they're easily assembled, these towers are suitable for power lines that cross very uneven terrain.

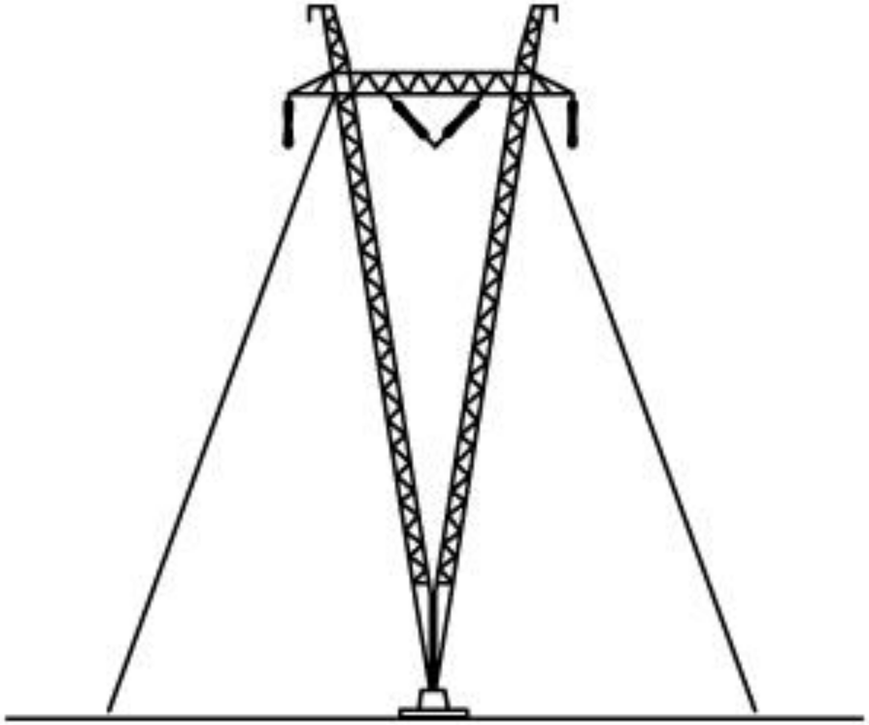


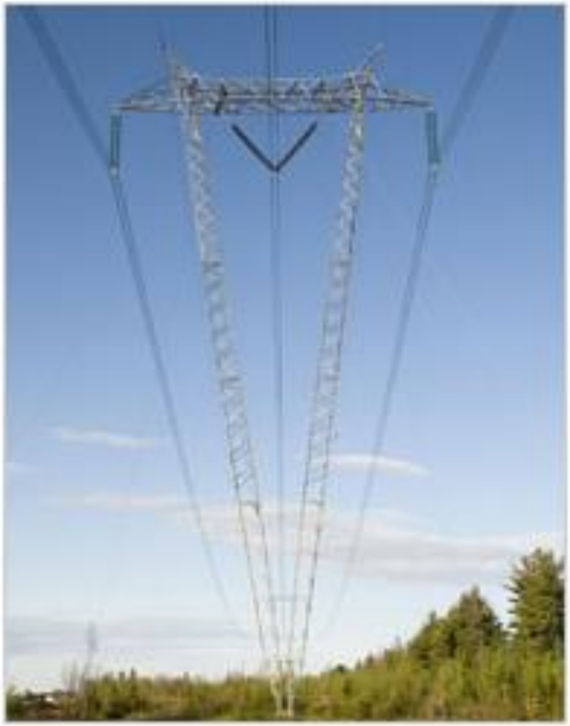
Double-circuit tower

This small-footprint tower is used for voltages ranging from 110 to 315 kV. Its height ranges from 25 to 60 metres.

Guyed-V tower

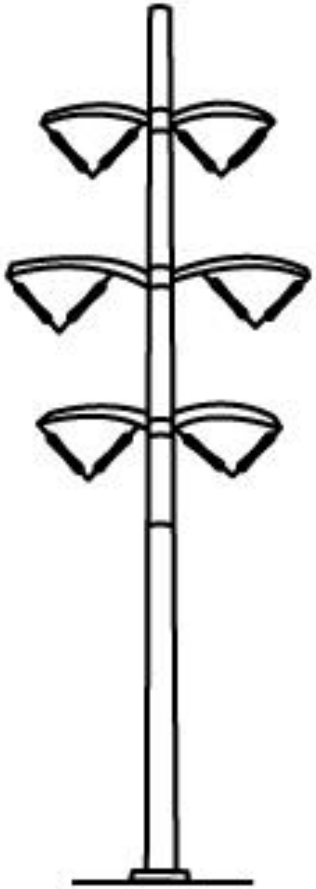
This tower is designed for voltages ranging from 230 to 735 kV. It's used mainly for power lines leaving the La Grande and Manic-Outardes hydroelectric complexes. The guyed-V tower is more economical than the double-circuit and waist-type towers.





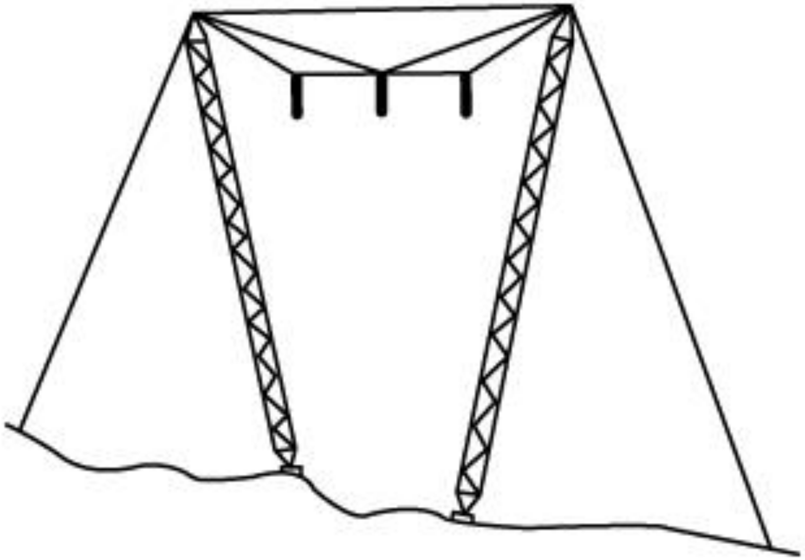
Tublar steel pole

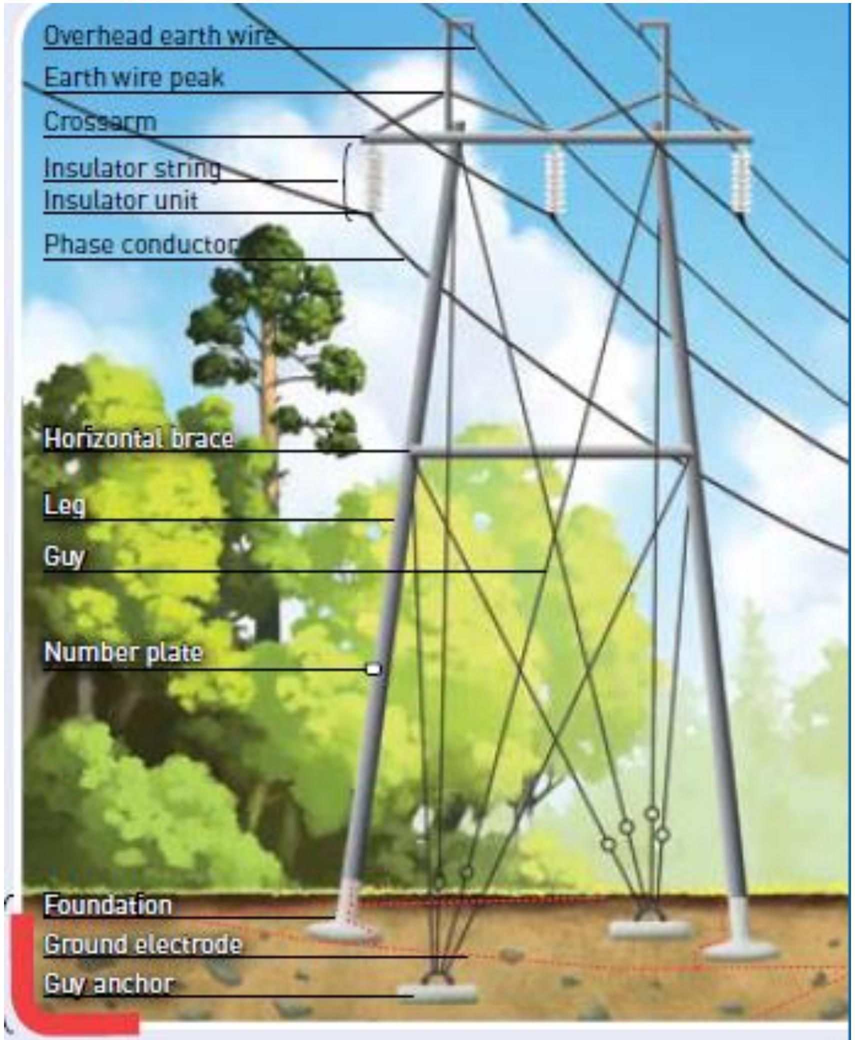
Featuring a streamlined, aesthetic shape, this structure is less massive than other towers, allowing it to blend easily into the environment. For this reason, it's being used more and more in urban centres. Measuring between 27 and 45 metres in height, it's suitable for voltages ranging from 110 to 315 kV.



Guyed cross-rope suspension tower

With its simple design, this tower is easy to assemble. It's used on some sections of power lines leaving the La Grande complex and supports 735-kV conductors. This type of structure requires less galvanized steel than the guyed-V tower, making it lighter and less costly.





The tower type shown in the picture is the most commonly used guyed portal tower, but so-called self-supporting steel towers without guys are also used.

Wind-Induced Motion of Overhead Conductors

- In addition to ordinary "blowout" of overhead conductors (i.e., the swinging motion of the conductor due to the normal component of wind), there are three types of cyclic wind-induced motion that can be a source of damage to structures or conductors or that can result in sufficient reduction in electrical clearance to cause flashover. The categories of wind-induced cyclic motion are ***Aeolian vibration***, ***galloping***, and ***wake-induced oscillation***.

AEOLIAN VIBRATION

- ***Aeolian vibration*** can occur when conductors are exposed to a steady low-velocity wind. If the amplitude of such vibration is sufficient, it can result in strand fatigue and/or fatigue of conductor accessories.
- The amplitude of vibration can be reduced by reducing the conductor tension, adding damping by using dampers (or clamps with damping characteristics), or by the use of special conductors which either provide more damping than standard conductors or are shaped so as to prevent resonance between the tensioned conductor span and the wind-induced vibration force.

Galloping Lines

- ***Galloping*** is normally confined to conductors with a coating of glaze ice over at least part of their circumference and thus is not a problem in those areas where ice storms do not occur. Such ice formation leads to self-excited vibrations produced on line conductor by aerodynamic forces acting on the resulting non-circular cross section of the conductor.
- Galloping may be controlled by the use of various accessories attached to the conductor in the span to change mechanical and/or damping characteristics.
- The amplitude of galloping motions can be reduced by the use of higher conductor tensions and evidence suggests higher tensions can also reduce the possibility of occurrence.
- Galloping and Aeolian vibration occur in both single and bundled conductors.

Wake-induced Oscillation

- ***Wake-induced oscillation*** is limited to lines having bundled conductors and results from aerodynamic forces on the downstream conductor of the bundle as it moves in and out of the wake of the upstream conductor.
- Wake-induced oscillation is controlled by maintaining sufficiently large conductor spacing in the bundle, unequal sub-span lengths, and tilting the bundles.

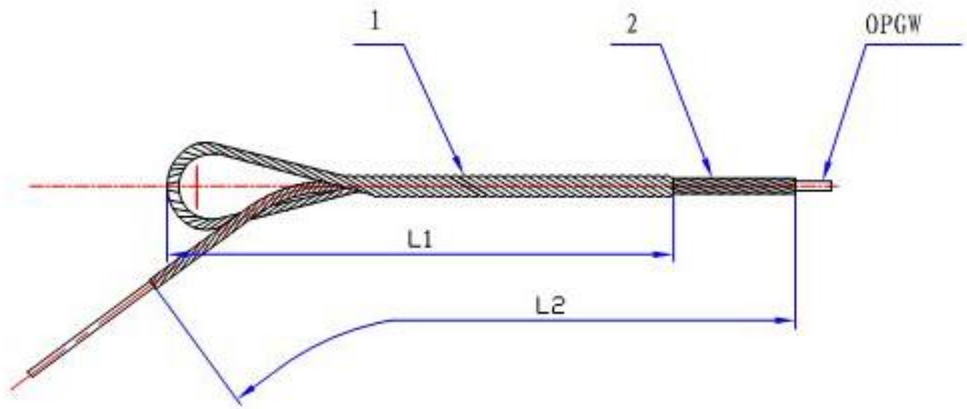
Prevention of Vibration

Vibration of transmission line conductors can effectively be minimized or dominated by using the following:

1- Armor Rods:

- These consist of layers of wires twisted spirally around the conductor for a short distance on either side of the point of support. They provide reinforcement of the conductor at tension points and reduce the amplitude of vibration. They relieve and distribute the stresses at the support point. They also serve as protection against flashover burns of conductors.

Armor Rods



2- Stockbridge Dampers

- The Stockbridge damper consists of two weights joined together by a flexible steel wire. It is provided with a clamp at its middle point to attach it to the conductor. Usually one damper is attached at each end of the span, for spans up to 300m long.

EEL 2023

Power Generation and Transmission

Chapter 5

Transmission System Stability

Power System Stability

- Power system stability is directly related to synchronous generator stability.
- A synchronous machine is said to be stable if, under steady state conditions, it is operating in equilibrium.
- Equilibrium denotes perfect power balance between input and output powers.

Power System Stability

- A synchronous machine connected to an infinite bus is said to be working in a stable condition, if it is in *synchronism*, or in step, with the bus. Unstable operation denotes loss of synchronism or falling out of step.
- *Synchronism* - The tendency of a power system to develop forces to maintain equilibrium (i.e. to stay synchronized).

Stability Definition

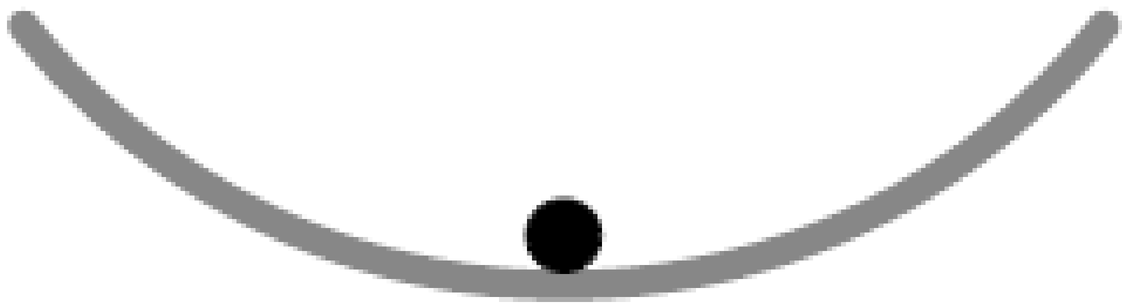
- Stability is a condition of equilibrium between opposing forces
- Instability results when a disturbance causes imbalance between the opposing forces.

Power System Stability

- A Power system is stable when it can regain a state of operating equilibrium after being subjected to a physical disturbance.

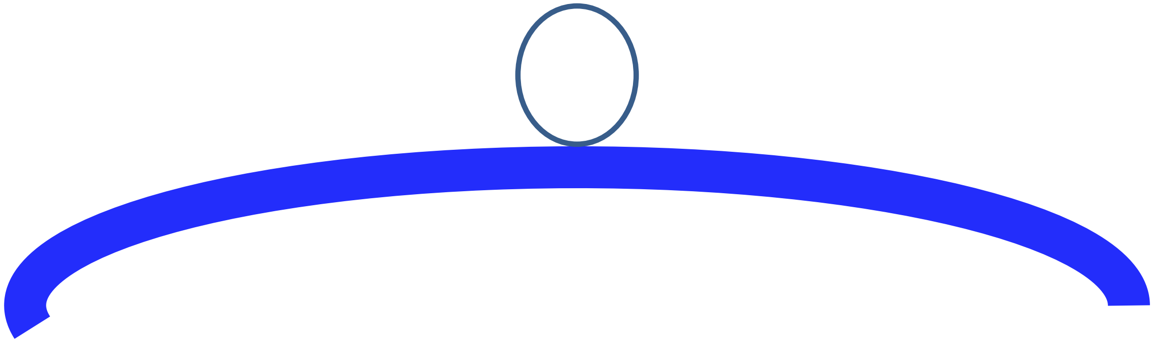
A Simple Mechanical Analogy of Stability:

- ***Stable Equilibrium:***
- A marble rests at the bottom of the bowl. Displace the marble from this resting position, it it will move up and down and settles again at the bottom.
- This is a stable equilibrium.
- Gravity is the restoring force in this case.



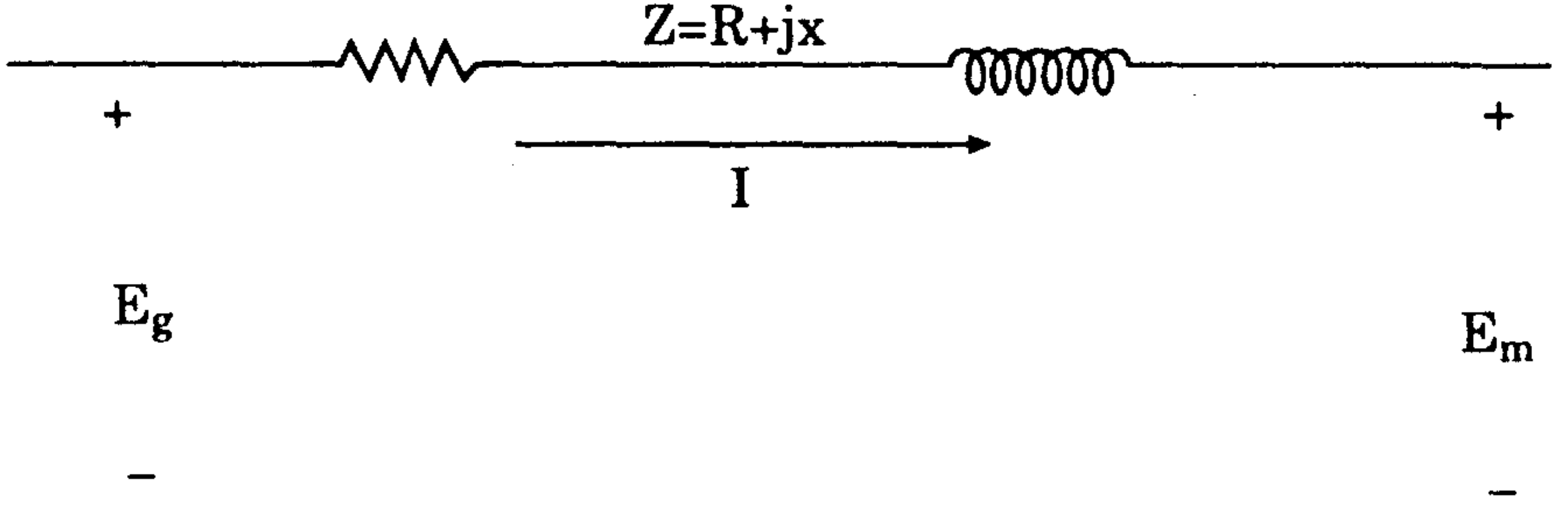
A Simple Mechanical Analogy of Stability:

- ***Unstable Equilibrium:***
- In this case, the marble is balanced at the top of the bow. Any movement will cause loss of equilibrium.
- This type of equilibrium is unstable.

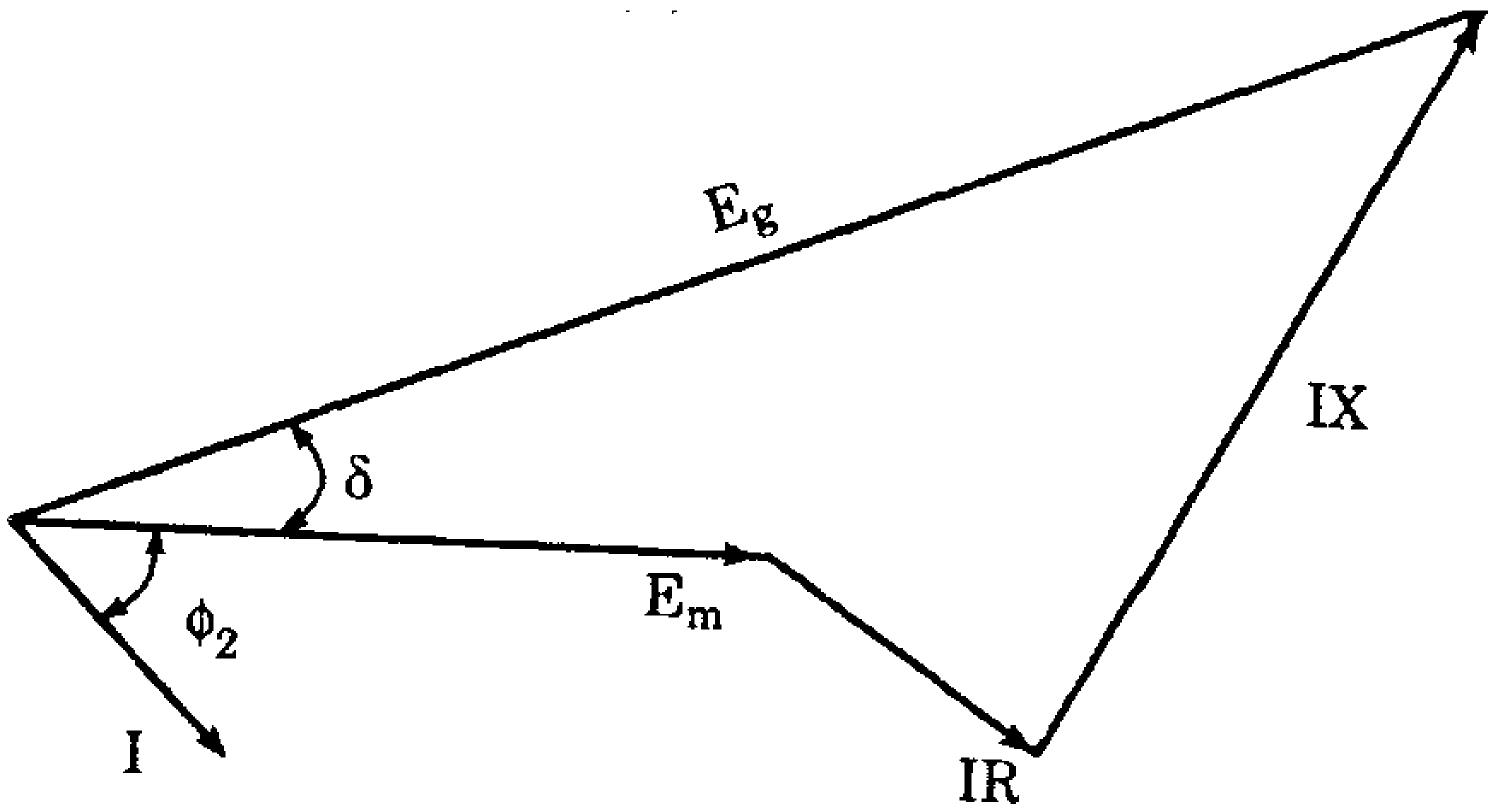


Steady-State Stability:

- To study the steady-state stability, consider the two-machine system represented by the simple two-terminal circuit shown in the following figure.



- The phasor diagram of the circuit is shown in the following figure:



The power delivered to the load, P_m, is:

$$P_m = E_m\, I \cos\Phi_2 \qquad (1)$$

where Φ_2 is the phase angle between E_m and I.

The current I is given by:

$$I = \frac{E_g - E_m}{Z} \qquad (2)$$

The current, *I*, can also be written as:

$$I = \frac{E_g \angle \delta - E_m \angle 0°}{|Z| \angle \phi_z} = \frac{E_g}{|Z|} \angle \delta - \phi_z - \frac{E_m}{|Z|} \angle -\phi_z \qquad (3)$$

where

E_g = sending end voltage
E_m = receiving end voltage
δ = phase angle between E_g and E_m
Φ_2 is the phase angle between E_m and I

$I\ Cos\Phi_2$ can be written as:

$$I \cos \phi_2 = \frac{E_g}{|Z|} \cos(\delta - \phi_z) - \frac{E_m}{|Z|} \cos(-\phi_z) \qquad (4)$$

Substitute equation (4) into equation (1) we get:

$$P_m = \frac{E_g E_m}{|Z|} \cos(\delta - \phi_z) - \frac{E_m^2 R}{|Z|^2} \qquad (5)$$

Power Angle

- If the line resistance R is negligible, it can be shown that P can be written as:

$$P_g = P_m = \frac{E_g E_m}{X} \sin \delta \qquad (6)$$

This is the *power angle equation* of the system.

where

E_g = sending end voltage

E_m = receiving end voltage

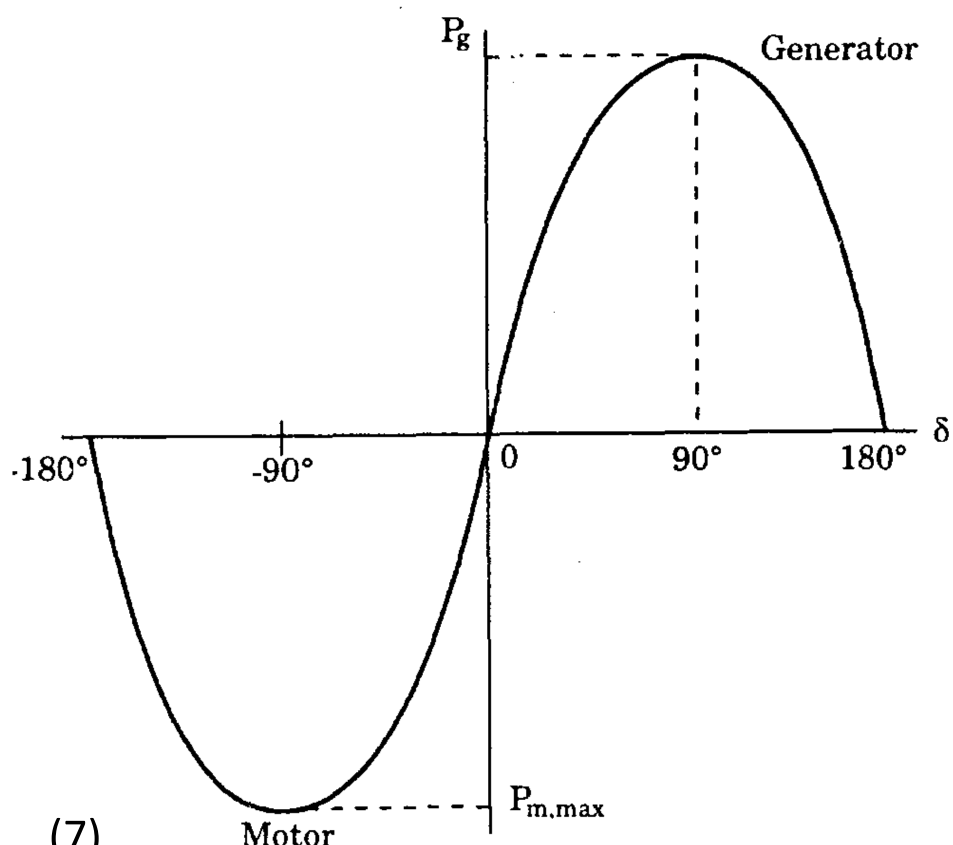
δ = phase angle between E_g and E_m

P_g is the power produced by the generator

P_m is the power delivered to the load.

Power Angle curve

The real power variation with power angle for both generator and motor action for constant values of Eg, Em and X are shown below. This curve is known as *power angle curve*.



If R = 0, the maximum power is given by:

$$P_{g,\max} = P_{m,\max} = \frac{E_g E_m}{X} \quad (7)$$

This maximum power occurs at 90°.

Power Angle (δ)

- In a power system, the parameter that determines the stability of the system is the power angle (δ) between generators or systems.

Power System Disturbances

- ***<u>Small disturbances:</u>***
- These can be due to load changes that occur continually. The system adjusts to such changing conditions without loss of stability.
- ***<u>Large Disturbances:</u>***
- Large disturbances, such as a short-circuit on a transmission line or loss of a large generator can occur. A stable system should survive such disturbances.

Rotor Angle Stability

- *Rotor angle stability* *means that* interconnected synchronous machines should remain in synchronism under normal and abnormal operating conditions.
- *Instability* occurs when the power angle of some generators increases leading to their loss of synchronism.

Maintaining Stability

- Q. ***How do interconnected system maintain stability ?***
- When synchronous machines in a power system start to accelerate or decelerate, due to disturbances, restoring forces are developed which will act so as to keep the speed constant.

Stability And Instability

- *Example of Stability & Instability Conditions:*
- In a system of two generators, if one generator runs faster, its load angle will advance.
- This angular difference transfers part of the load from the slow machine to the fast machine.
- This will reduce the speed difference and hence the angular separation which restores stability.

Methods for increasing stability limits

- An increase in generator excitation increases the maximum power that can be transferred between the machines, and stability.
- If the internal voltages of generators are increased without an increase in the power transferred, the torque angle decreases.
- Any reduction in the reactance of the network increases the stability limit.

Methods for increasing stability limits

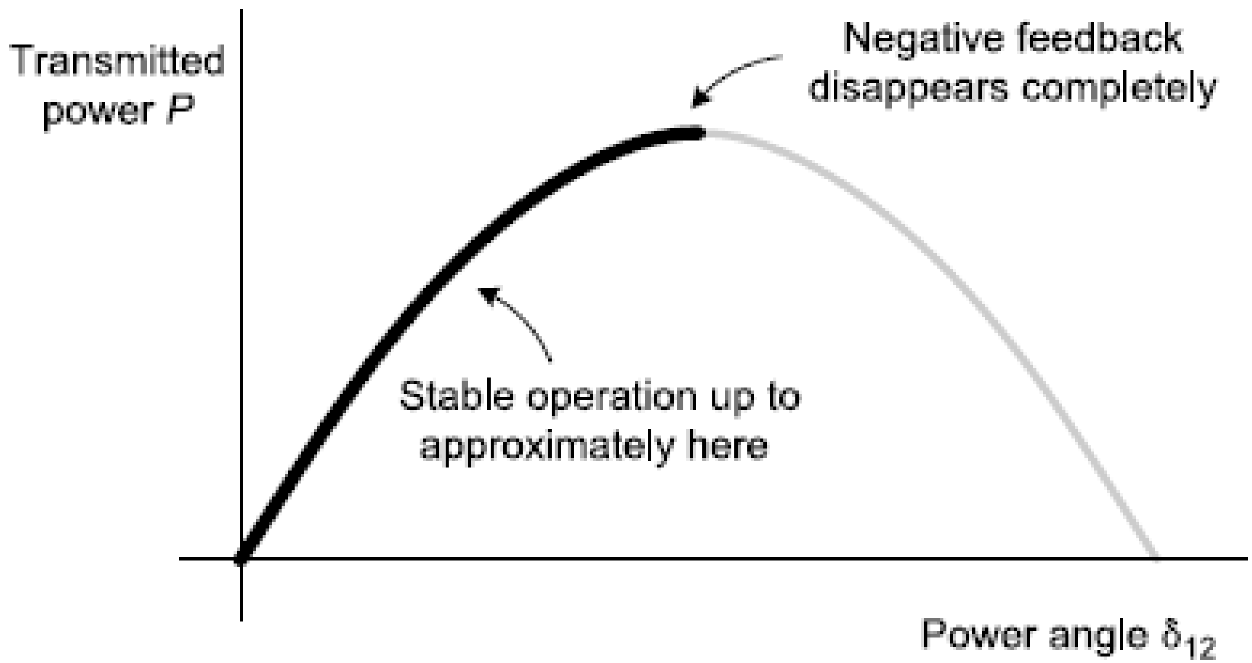
- Stability of a power system can be increased by using two parallel transmission lines instead of one.
- Series capacitors can be used on transmission lines to decrease the line reactance and raise the system stability limit.

Maintaining stability limits

- If the system is disturbed, one of two things can happen:
- **If the system is stable**, it will reach a new equilibrium state (new power angle) with practically the entire system intact
- **If the system is unstable**, it will result in a progressive increase in the load angle of generators, or a progressive decrease in bus voltages. An unstable system condition could lead to a shut-down of a major portion of the power system.

- Generators in synchronism develop restoring forces that slow down a generator that has sped up and to speed up a generator that has slowed down.
- Such restoring forces exist. The force results from the fact that a generator whose power angle is ahead of others must supply additional power (thus tending to restrain the turbine more), whereas the generator whose power angle is behind supplies less power (thus relieving the restraint on the turbine).

- This figure shows the limits of steady-state stability. The slope of the Sine curve is steep for small δ_{12} and gets flatter as δ_{12} increases. A flatter slope means that, for a given increment in δ_{12}, there is only a small increment in P.

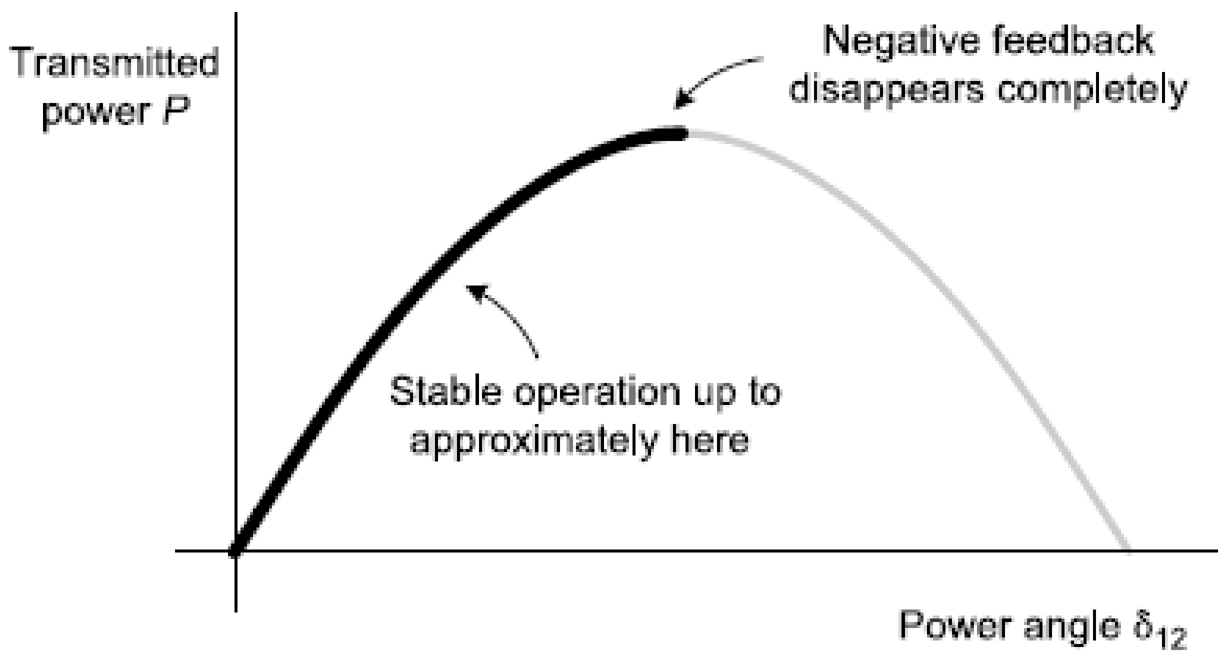


- For a stable generator, increment in P needs to be large. This is analogous to the slope of the sides of the bowl with the marble:
- A deep bowl (a) means strong restoring forces – stability assured.

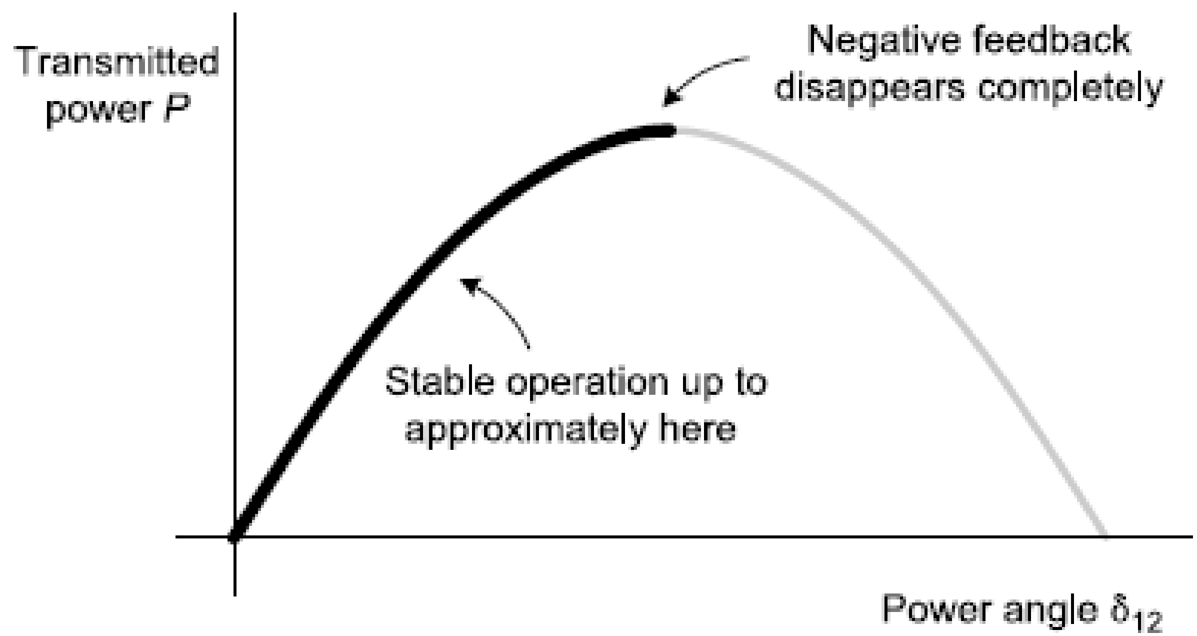
❖ A shallow bowl (b) means weak restoring force - stability not assured.

(a) (b)

- Therefore, it is preferable to operate with a small δ_{12} where the slope of Sin δ_{12} ,and the incremental change in P, is large.



- Stability limit is when the slope of Sin δ_{12} is just steep enough. Based on experience, power engineers generally consider 40° to 50° a reasonable limit on δ_{12}



Steady-State Stability of Interconnected Systems:

- Steady-state stability is not only related to interconnected synchronous generators but also to power systems interconnected by transmission lines.

$$P = \frac{V_1 V_2}{X} \sin \delta_{12}$$

Where:

- δ_{12} is the difference in power angles between the sending and receiving end of the line
- V_1 and V_2 are the voltage magnitudes at either end of the line,
- X is the reactance of the line in between.

- For short lines, the reactance X is small, so that a small δ_{12} still results in a large amount of power transmitted.
- Consequently, if δ_{12} is allowed to take it’s maximum value in such a line, the power transmitted could easily exceed the line’s thermal capacity.
- For long lines the reactance becomes more significant and a high δ_{12} may well be reached before the thermal limit of the line.

This figure shows the stability limits and thermal limits of transmission lines as a function of line length.

The label P_{12}/P_{SIL} is the real power transmitted between the two ends of the line, expressed as a ratio of the actual power in watts and the surge impedance loading, which is a characteristic of a given line