(6 SEMESTER)

POWER SYSTEM-II (3-1-0)

MODULE-I (10 HOURS)

Lines Constants: Resistance, inductance and capacitance of single and three phase lines with symmetrical and unsymmetrical spacing transposition, charging current, skin effect and proximity effect, Performance of transmission Lines: Analysis of short, medium and long lines, equivalentcircuit, representation of the lines and calculation of transmission parameters, Power flow through transmission line, Power circle diagram, Series and shunt compensation.

MODULE-II (10 HOURS)

Corona: Power loss due to corona, practical importance of corona, use of bundled conductors in E.H.V. transmission lines and its advantages, Overhead line Insulators, voltage distribution in suspension type insulators, string efficiency, grading. Sag and stress calculation of overhead conductors, vibration dampers

Under Ground Cable: Type and construction, grading of cables, capacitance in 3 core cables and dielectric loss in cables.

MODULE-III (10 HOURS)

Definition of the load flow problem, Network model formulation, A load flow sample study,Computational aspect of the load flow problem. Gauss siedel and Newton Raphson method for power flow fast decoupled load flow, On load tap changing transformer and block regulating transformer, effects of regulating transformers.

MODULE-IV (10 HOURS)

Economic Operation of Power System: Distribution offload between units within a plant, Transmission losses as function of plant generation, Calculation of loss coefficients, Distribution of loads between plants with special reference to steam and hydel plants, Automatic load dispatching. Introduction to Flexible AC Transmission System (FACTS), SVC, TCSC, SSSC, STATCOM and UPFC

BOOKS

[1]. John J Grainger, W. D. Stevenson, “Power System Analysis”, TMH Publication
[2]. I. J. Nagrath & D. P. Kothari, “Power System Analysis”, TMH Publication

MODULE I

Transmission line

Conductors

Commonly used conductor materials:

The most commonly used conductor materials for over head lines are copper, aluminium, steel-cored aluminium, galvanised steel and cadmium copper. The choice of a particular material will depend upon the cost, the required electrical and mechanical properties and the local conditions. All conductors used for overhead lines are preferably stranded in order to increase the flexibility.In stranded conductors, there is generally one central wire and round this, successive layers of wires containing 6, 12, 18, 24 ...... wires. Thus, if there are n layers, the total number of individual wires is 3n(n + 1) + 1. In the manufacture of stranded conductors, the consecutive layers of wires are twisted or spiralled in opposite directions so that layers are bound together.

Types of Conductors

1. **Copper**. Copper is an ideal material for overhead lines owing to its high electrical conductivity and greater tensile strength. It is always used in the hard drawn form as stranded conductor. Although hard drawing decreases the electrical conductivity slightly yet it increases the tensile strength considerably.

Copper has high current density i.e., the current carrying capacity of copper per unit of X-sectional area is quite large. This leads to two advantages. Firstly, smaller X-sectional area of conductor is required and secondly, the area offered by the conductor to wind loads is reduced. Moreover, this metal is quite homogeneous, durable and has high scrap value. There is hardly any doubt that copper is an ideal material for transmission and distribution of electric power. However, due to its higher cost and non-availability, it is rarely used for these purposes. Now-a-days the trend is to use aluminium in place of copper.

2. **Aluminium**. Aluminium is cheap and light as compared to copper but it has much smaller conductivity and tensile strength. The relative comparison of the two materials is briefed below:

(i) The conductivity of aluminium is 60% that of copper. The smaller conductivity of aluminium means that for any particular transmission efficiency, the X-sectional area of conductor must be larger in aluminium than in copper. For the same resistance, the diameter of aluminium conductor is about 1·26 times the diameter of copper conductor. The increased X-section of aluminium exposes a greater surface to wind pressure and, therefore, supporting towers must be designed for greater transverse strength. This often requires the use of higher towers with consequence of greater sag.

(ii) The specific gravity of aluminium (2·71 gm/cc) is lower than that of copper (8·9 gm/cc).Therefore, an aluminium conductor has almost one-half the weight of equivalent copper conductor. For this reason, the supporting structures for aluminium need not be made so strong as that of copper conductor.

(iii) Aluminium conductor being light, is liable to greater swings and hence larger cross-arms are required.

(iv) Due to lower tensile strength and higher co-efficient of linear expansion of aluminium, the sag is greater in aluminium conductors. Considering the combined properties of cost, conductivity, tensile strength, weight etc., aluminium has an edge over copper. Therefore, it is being widely used as a conductor material. It is particularly profitable to use aluminium for heavy-current transmission where the conductor size is large and its cost forms a major proportion of the total cost of complete installation.

3. **Steel cored aluminium**. Due to low tensile strength, aluminium conductors produce greater sag. This prohibits their use for larger spans and makes them unsuitable for long distance transmission. In order to increase the tensile strength, the aluminium conductor is reinforced with a core of galvanised steel wires. The composite conductor thus obtained is known as steel cored aluminium and is abbreviated as A.C.S.R. (aluminium conductor steel reinforced).

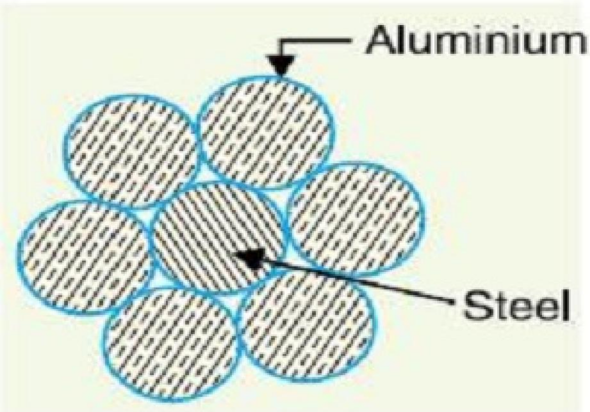


Fig 1.1:ACSR Conductor

Steel-cored aluminium conductor consists of central core of galvanized steel wires surrounded by a number of aluminium strands. Usually, diameter of both steel and aluminium wires is the same. The X-section of the two metals are generally in the ratio of 1 : 6 but can be modified to 1 : 4 in order to get more tensile strength for the conductor. Fig. shows steel cored aluminium conductor having one steel wire surrounded by six wires of aluminium. The result of this composite conductor is that steel core takes greater percentage of mechanical strength while aluminium strands carry the bulk of current. The steel cored aluminium conductors have the following advantages :

(i) The reinforcement with steel increases the tensile strength but at the same time keeps the composite conductor light. Therefore, steel cored aluminium conductors will produce smaller sag and hence longer spans can be used.

(ii) Due to smaller sag with steel cored aluminium conductors, towers of smaller heights can be used.

TRANSMISSION LINE PARAMETER

An electric transmission line has four parameters, namely resistance, inductance, capacitance and shunt conductance. These four parameters are uniformly distributed along the whole line. Each line element has its own value, and it is not possible to concentrate or lumped them at discrete points on the line. For this reason the line parameters are known as distributed parameter, but can be lumped for the purpose of analysis on approximate basis. However, the validity of assumption for the analysis on lumped basis may fail if the line is very long.

Line Inductance:

When an alternating current flows through a conductor, a changing flux is set up which links the conductor. Due to these flux linkages, the conductor possesses inductance. Mathematically, inductance is defined as the flux linkages per ampere i.e.

$$L = \frac{\psi}{I}$$

where ψ = flux linkage in weber-turns

I = current in turns

Which shows that the self inductance of an electric circuit is numerically equal to the flux linkage of the circuit per unit of current.

Flux Linkages:

As stated earlier, the inductance of a circuit is defined as the flux linkages per unit current. Therefore, in order to find the inductance of a circuit, the determination of flux linkages is of primary importance. We shall discuss two important cases of flux linkages.

1. Flux linkages due to a single current carrying conductor. Consider a long straight cylindrical conductor of radius r metres and carrying a current I amperes (rms) as shown in Fig.1.2(i). This current will set up magnetic field. The magnetic lines of force will exist inside the conductor as well as outside the conductor. Both these fluxes will contribute to the inductance of the conductor.

(i) Flux linkages due to internal flux. Refer to Fig.1.2 (ii) where the X-section of the conductor is shown magnified for clarity. The magnetic field intensity at a point x metres from the centre is given by;

$$H_x = \frac{I_x}{2\pi x}$$

As $$I_x = \frac{\pi x^2}{\pi r^2} I$$

$$H_X = \frac{x}{2\pi r^2} I \quad \text{AT/m}$$

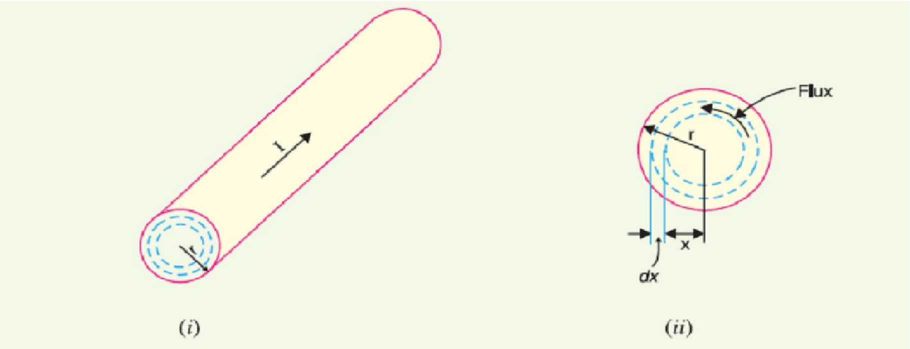


Fig 1.2: Internal flux linkage in a cylindrical conductor

If μ (=$\mu_0\mu_r$) is the permeability of the conductor, then flux density at the considered point is given by

$$B_x = \mu_0 \mu_r H_x$$

$$= \frac{\mu_0 x I}{2\pi r^2} \text{ wb/m}^2 \qquad (\mu_r = 1 \text{ for non magnetic material})$$

Now, flux $d\varphi$ through a cylindrical shell of radial thickness dx and axial length 1 m is given by

$$d\phi = B_x \times 1 \times dx = \frac{\mu_0 x I}{2\pi r^2} dx$$

This flux links with the current I_x only. Therefore the flux linkages per unit length of the conductor is

$$d\psi = \frac{\pi x^2}{\pi r^2} d\phi = \frac{\mu_0 I x^3}{2\pi r^4} dx \text{ weber-turns}$$

Total flux linkages from centre upto the conductor surface is

$$\psi_{\text{int}} = \int_0^r \frac{\mu_0 x I^3}{2\pi r^4} dx$$

$$= \frac{\mu_0 I}{8\pi} \text{ weber-turns per meter length}$$

(ii) Flux linkages due to external flux. Now let us calculate the flux linkages of the conductor due to external flux. The external flux extends from the surface of the conductor to infinity. Referring to Fig. 4.5, the field intensity at a distance x metres (from centre) outside the conductor is given by ;

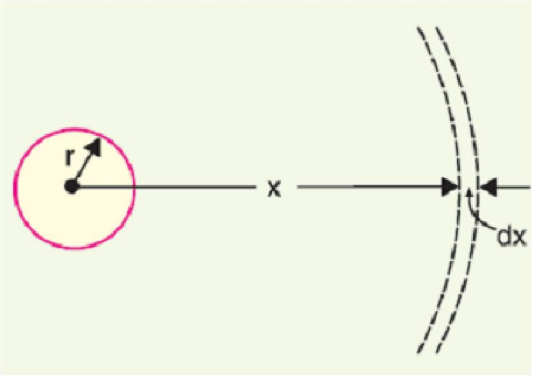


Fig 1.3: External flux linkage in a conductor

$$H_x = \frac{I}{2\pi x} \text{ AT/m}$$

$$\text{Flux density, } B_x = \mu_0 H_X = \frac{\mu_0 I}{2\pi X} \text{ wb/m}^2$$

Now, flux $d\varphi$ through a cylindrical shell of radial thickness dx and axial length 1 m is given by

$$d\phi = B_x \times 1 \times dx = \frac{\mu_0 I}{2\pi x} dx$$

The flux $d\varphi$ links all the current in the conductor once and only once.

$$d\psi = d\phi = \frac{\mu_0 I}{2\pi x} dx \quad \text{Weber-turns}$$

Total flux linkage of the conductor from surface to infinity

$$\psi_{ext} = \int_r^\infty \frac{\mu_0 I}{2\pi x} dx \quad \text{Weber-turns}$$

Over all flux linkage $\psi = \psi_{\text{int}} + \psi_{ext} = \frac{\mu_0 I}{8\pi} + \int_r^\infty \frac{\mu_0 I}{2\pi x} dx$

$$= \frac{\mu_0 I}{2\pi}\left[\frac{1}{4} + \int_r^\infty \frac{dx}{x}\right] \quad \text{weber-turns/m length}$$

Inductance of Single Phase Two Wire Line

A single phase line consists of two parallel conductors which form a rectangular loop of one turn. When an alternating current flows through such a loop, a changing magnetic flux is set up. The changing flux links the loop and hence the loop possesses inductance. It may appear that inductance of a single phase line is negligible because it consists of a loop of one turn and the flux path is through air of high reluctance. But as the X -sectional area of the loop is very large, even for a small flux density, the total flux linking the loop is quite large and hence the line has appreciable inductance.

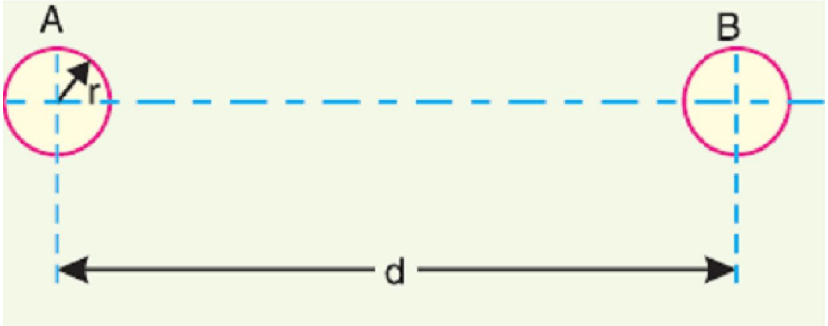


Fig 1.4: Single phase two wire transmission line

Consider a single phase overhead line consisting of two parallel conductors A and B spaced d metres apart as shown in Fig. 4.7. Conductors A and B carry the same amount of current (i.e. $I_A = I_B$), but in the opposite direction because one forms the return circuit of the other.

$$I_A + I_B = 0$$

In order to find the inductance of conductor A (or conductor B), we shall have to consider the flux linkages with it. There will be flux linkages with conductor A due to its own current I_A and also due to the mutual inductance effect of current I_B in the conductor B. Flux linkages with conductor A due to its own current

$$= \frac{\mu_0 I_A}{2\pi}\left[\frac{1}{4} + \int_r^\infty \frac{dx}{x}\right]$$

Flux linkages with conductor A due to current I_B

$$= \frac{\mu_0 I_B}{2\pi}\left[\int_d^\infty \frac{dx}{x}\right]$$

Total flux linkage with the with conductor A is

$$\psi_A = \frac{\mu_0 I_A}{2\pi}\left(\frac{1}{4} + \int_r^\infty \frac{dx}{x}\right) + \frac{\mu_0 I_B}{2\pi}\int_d^\infty \frac{dx}{x}$$

$$= \frac{\mu_0}{2\pi}\left[\left(\frac{1}{4} + \ln\infty - \ln r\right)I_A + (\ln\infty - \ln d)I_B\right]$$

$$= \frac{\mu_0}{2\pi}\left[\frac{I_A}{4} - I_A \ln r - I_B \ln d\right]$$

$$= \frac{\mu_0}{2\pi}\left[\frac{I_A}{4} + I_A \ln d - I_A \ln r\right]$$

$$= \frac{\mu_0}{2\pi}\left[\frac{I_A}{4} + I_A \ln\frac{d}{r}\right]$$

$$= \frac{\mu_0 I_A}{2\pi}\left[\frac{1}{4} + \ln\frac{d}{r}\right]$$

Inductance of conductor A, $L_A = \frac{\psi_A}{I_A}$

$$= \frac{\mu_0}{2\pi}\left[\frac{1}{4} + \ln\frac{d}{r}\right] \text{ H/m}$$

$$= 2\times10^{-7}\left[\ln e^{\frac{1}{4}} + \ln\frac{d}{r}\right]$$

$$= 2\times10^{-7}[\ln \frac{d}{re^{\frac{-1}{4}}}]$$

$$= 2\times10^{-7}\ln\frac{d}{r'}\ \text{H/m}$$

The radius r′ is that of a fictitious conductor assumed to have no internal flux but with the same inductance as the actual conductor of radius r. The quantity $e^{-1/4}$= = 0·7788 so that

$r' = r\,e^{-1/4} =$ 0·7788 r

The term r′ (= $r\,e^{-1/4}$) is called geometric mean radius (GMR) of the conductor.

Loop inductance = 2 L_A = 2 × 2 × 10−7 log d/r′ H/m

Note that r′ = 0·7788 r is applicable to only solid round conductor.

Inductance of Three phase Overhead line:

Fig. 1.4 shows the three conductors A, B and C of a 3-phase line carrying currents I_A, I_B and I_C respectively. Let d_1, d_2 and d_3 be the spacing between the conductors as shown. Let us further assume that the loads are balanced i.e. $I_A + I_B + I_C = 0$. Consider the flux linkages with conductor A. There will be flux linkages with conductor A due to its own current and also due to the mutual inductance effects of I_B and I_C.

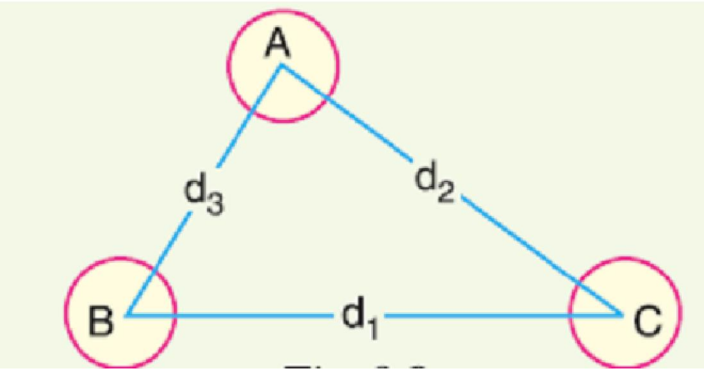


Fig 1.4 Three phase Overhead line

Flux linkages with conductor A due to its own current

$$= \frac{\mu_0 I_A}{2\pi}\left(\frac{1}{4}+\int_r^{\infty}\frac{dx}{x}\right)$$

Flux linkages with conductor A due to current I_B

$$= \frac{\mu_0 I_B}{2\pi}\left(\frac{1}{4}+\int_{d_1}^{\infty}\frac{dx}{x}\right)$$

Flux linkages with conductor A due to current I_C

$$= \frac{\mu_0 I_C}{2\pi}\left(\frac{1}{4} + \int_{d_2}^{\infty} \frac{dx}{x}\right)$$

The total flux linkage with the conductor A is

$$\psi_A = \frac{\mu_0 I_A}{2\pi}\left(\frac{1}{4} + \int_{r}^{\infty} \frac{dx}{x}\right) + \frac{\mu_0 I_B}{2\pi}\left(\frac{1}{4} + \int_{d_1}^{\infty} \frac{dx}{x}\right) + \frac{\mu_0 I_C}{2\pi}\left(\frac{1}{4} + \int_{d_2}^{\infty} \frac{dx}{x}\right)$$

As $I_A + I_B + I_C = 0$

$$\psi_A = \frac{\mu_0}{2\pi}\left[\left(\frac{1}{4} - \ln r\right) I_A + I_B \ln d3 + I_C \ln d_2\right]$$

(i) **Symmetrical Spacing:**

If the three conductors A, B and C are placed symmetrically at the corners of an equilateral triangle of side d, then, $d_1 = d_2 = d_3 = d$. Under such conditions, the flux linkages with conductor A become:

$$\psi_A = \frac{\mu_0}{2\pi}\left[\left(\frac{1}{4} - \ln r\right) I_A - (I_B + I_C)\ln d\right]$$

$$\psi_A = \frac{\mu_0}{2\pi}\left[\left(\frac{1}{4} - \ln r\right) I_A + I_A \ln d\right]$$

$$\psi_A = \frac{\mu_0 I_A}{2\pi}\left[\left(\frac{1}{4} + \ln \frac{d}{r}\right)\right]$$

Inductance of conductor A, $L_A = \frac{\psi_A}{I_A} = \frac{\mu_0}{2\pi}\left[\left(\frac{1}{4} + \ln \frac{d}{r}\right)\right]$ H/m

putting the value of $\mu_0 = 4\pi \times 10^{-7}$ in the above equation

$$L_A = 2 \times 10^{-7}\left[\left(\ln \frac{d}{r'}\right)\right] \quad \text{H/m}$$

(ii)Unsymmetrical spacing

When 3-phase line conductors are not equidistant from each other, the conductor spacing is said to be unsymmetrical. Under such conditions, the flux linkages and inductance of each phase are not the same. A different inductance in each phase results in unequal voltage drops in the three phases even if the currents in the conductors are balanced. Therefore, the voltage at the receiving end will not be the same for all phases. In order that voltage drops are equal in all conductors, we generally interchange the positions of the conductors at regular intervals along the line so that each conductor occupies the original position of every other conductor over an equal distance. Such an exchange of positions is known as transposition. Fig. 1.5 shows the transposed line. The phase conductors are designated as A, B and C and the positions occupied are numbered 1, 2 and 3. The effect of transposition is that each conductor has the same average inductance.

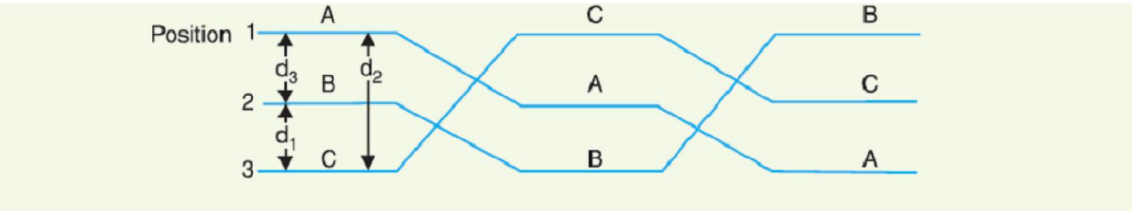


Fig 1.5: Transposition of three phase conductor

Above fig.1.5 shows a 3-phase transposed line having unsymmetrical spacing. Let us assume that each of the three sections is 1 m in length. Let us further assume balanced conditions i.e., $I_A + I_B + I_C = 0$.

The inductance per phase can be

$$L_A = 2\times 10^{-7}\left[\left(\ln \frac{\sqrt[3]{d_1 d_2 d_3}}{r'}\right)\right] \text{ H/m}$$

Electric potential

The electric potential at a point due to a charge is the work done in bringing a unit positive charge from infinity to that point. The concept of electric potential is extremely important for the determination of capacitance in a circuit since the latter is defined as the charge per unit potential. We shall now discuss in detail the electric potential due to some important conductor arrangements.

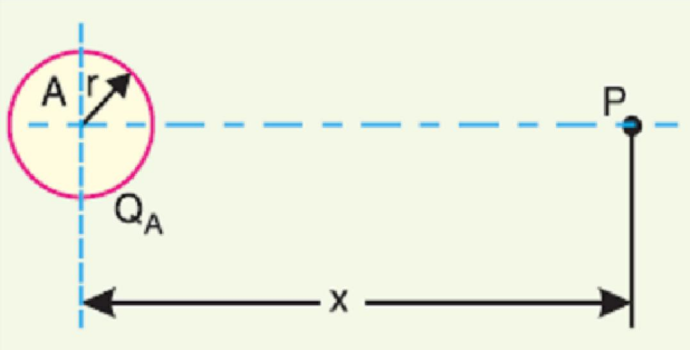


Fig 1.6 Potential of single conductor

(i) Potential at a charged single conductor. Consider a long straight cylindrical conductor A of radius r metres. Let the conductor operate at such a potential (VA) that charge Q_A coulombs per metre exists on the conductor. It is desired to find the expression for VA. The electric intensity E at a distance x from the centre of the conductor in air is given by

$$E = \frac{Q_A}{2\pi\varepsilon_0 x} \text{ volts/m}$$

As x approaches infinity, the value of E approaches zero. Therefore, the potential difference between conductor A and infinity distant neutral plane is given by:

$$V_A = \frac{Q_A}{2\pi\varepsilon_0}\int_r^\infty \frac{dx}{x}$$

Capacitance of Single Phase Two Wire Line

Consider a single phase overhead transmission line consisting of two parallel conductors A and B spaced d metres apart in air. Suppose that radius of each conductor is r metres. Let their respective charge be + Q and − Q coulombs per metre length.

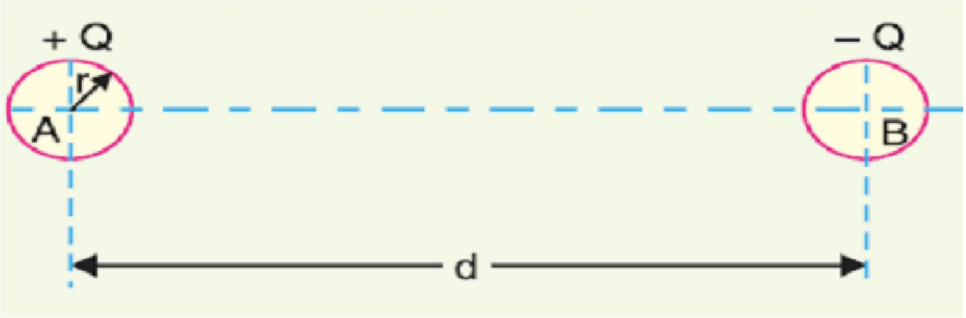


Fig 1.7: Single phase two wire transmission line

The total p.d. between conductor A and neutral "infinite" plane is

$$V_A = \frac{Q}{2\pi\varepsilon_0}\int_r^\infty \frac{dx}{x} - \frac{Q}{2\pi\varepsilon_0}\int_d^\infty \frac{dx}{x}$$

$$= \frac{Q}{2\pi\varepsilon_0}\ln\frac{d}{r} \text{ Volts}$$

Similarly, p.d. between conductor B and neutral "infinite" plane is

$$V_B = \frac{-Q}{2\pi\varepsilon_0}\int_r^\infty \frac{dx}{x} + \frac{Q}{2\pi\varepsilon_0}\int_d^\infty \frac{dx}{x}$$

$$= \frac{-Q}{2\pi\varepsilon_0} \ln\frac{d}{r} \text{ Volts}$$

Both these potentials are w.r.t. the same neutral plane. Since the unlike charges attract each other, the potential difference between the conductors is

$$V_{AB} = 2V_A = \frac{2Q}{2\pi\varepsilon_0} \ln\frac{d}{r}$$

$$C_{AB} = \frac{Q}{V_{AB}} = \frac{\pi\varepsilon_0}{\ln\frac{d}{r}} \text{ F/m}$$

Capacitance to neutral: Above equation gives the capacitance between the conductors of a two wire line. Often it is desired to know the capacitance between one of the conductors and a neutral point between them. Since potential of the mid-point between the conductors is zero, the potential difference between each conductor and the ground or neutral is half the potential difference between the conductors. Thus the capacitance to ground or capacitance to neutral for the two wire line is twice the line-to-line capacitance.

$$C_N = C_{AN} = C_{BN} = 2C_{AB} = \frac{2\pi\varepsilon_0}{\ln\frac{d}{r}}$$

Capacitance of a 3-Phase Overhead Line

In a 3-phase transmission line, the capacitance of each conductor is considered instead of capacitance from conductor to conductor. Here, again two cases arise viz., symmetrical spacing and unsymmetrical spacing.

(i) **Symmetrical Spacing.** Fig. 1.8 shows the three conductors A, B and C of the 3-phase overhead transmission line having charges Q_A, Q_B and Q_C per metre length respectively. Let the Conductors be equidistant (d metres) from each other. We shall find the capacitance from line conductor to neutral in this symmetrically spaced line. Referring to Fig.1.8 overall potential difference between conductor A and infinite neutral plane is given by

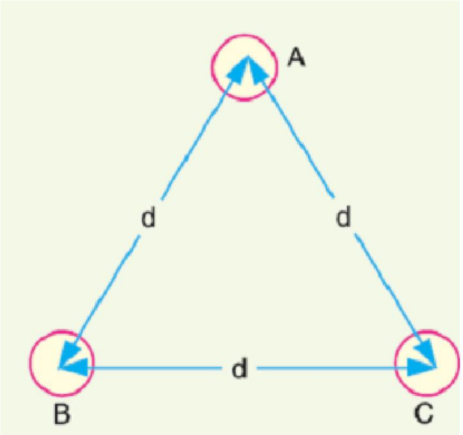


Fig 1.8 Three phase symmetrically spaced transmission line

$$V_A = \int_r^\infty \frac{Q_A}{2\pi\varepsilon_0 x}dx + \int_d^\infty \frac{Q_B}{2\pi\varepsilon_0 x}dx + \int_d^\infty \frac{Q_c}{2\pi\varepsilon_0 x}dx$$

Assuming $Q_A+Q_B+Q_C=0$

$$V_A = \frac{Q_A}{2\pi\varepsilon_0}\ln\frac{d}{r}$$

Capacitance of conductor A with respect to neutral

$$C_A = \frac{Q_A}{V_A} = \frac{2\pi\varepsilon_0}{\ln\frac{d}{r}} \quad \text{F/m}$$

Note that this equation is identical to capacitance to neutral for two-wire line. Derived in a similar manner, the expressions for capacitance are the same for conductors B and C.

(ii) Unsymmetrical spacing. Fig.1.9 shows a 3-phase transposed line having unsymmetrical spacing. Let us assume balanced conditions i.e. $Q_A + Q_B + Q_C = 0$.

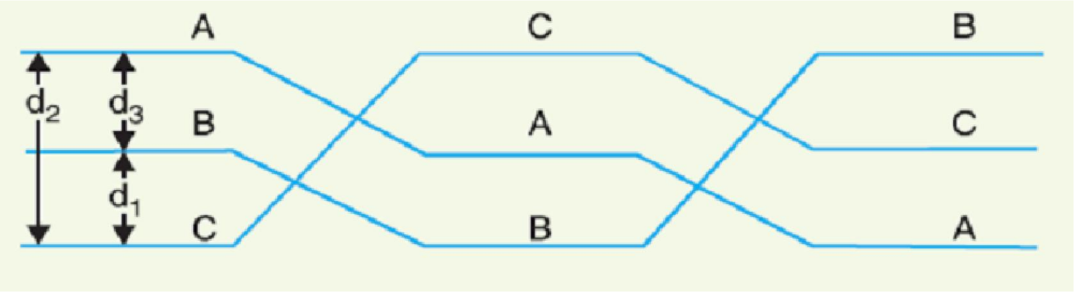


Fig 1.9: Unsymmetrically spaced transposed three phase line

$$V_A = \frac{Q_A}{2\pi\varepsilon}\ln\frac{\sqrt[3]{d_1 d_2 d_3}}{r}$$

Capacitance from conductor to neutral is

$$C_A = \frac{Q_A}{V_A} = \frac{2\pi\varepsilon_0}{\ln\frac{\sqrt[3]{d_1 d_2 d_3}}{r}}$$

Performance of Transmission Line

The transmission lines are categorized as three types-

1) Short transmission line– the line length is up to 80 km and the operating voltage is < 20 kV.

2) Medium transmission line– the line length is between 80 km to 160 km and the operating voltage is > 20 kV and < 100kV

3) Long transmission line – the line length is more than 160 km and the operating voltage is > 100 kV

Whatever may be the category of transmission line, the main aim is to transmit power from one end to another. Like other electrical system, the transmission network also will have some power loss and voltage drop during transmitting power from sending end to receiving end. Hence, performance of transmission line can be determined by its efficiency and voltage regulation.

$$\text{Efficiency of transmission line}=\frac{\text{Power delivered at receiving end}}{\text{Power sent from sending end}}\times 100\%$$

Power sent from sending end – line losses = Power delivered at receiving end.

Voltage regulation of transmission line is measure of change of receiving end voltage from no-load to full load condition.

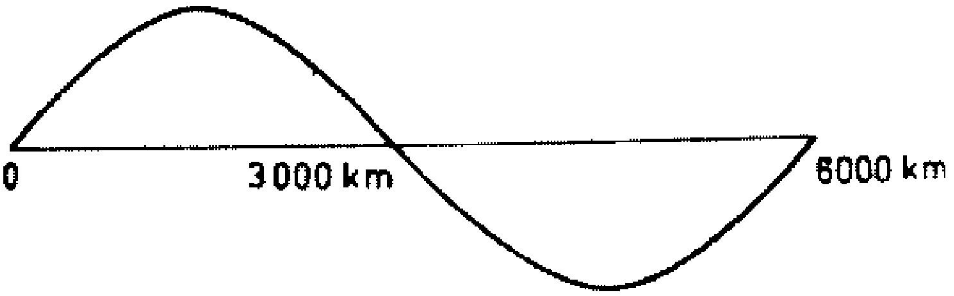
$$\%\ \text{regulation}=\frac{\text{no load receiving end voltage-full load receiving end voltage}}{\text{full load voltage}}\times 100\%$$

Every transmission line will have three basic electrical parameters. The conductors of the line will have electrical resistance, inductance, and capacitance. As the transmission line is a set of conductors being run from one place to another supported by transmission towers, the parameters are distributed uniformly along the line.

The electrical power is transmitted over a transmission line with a speed of light that is $3X10^8$ m/ sec. Frequency of the power is 50 Hz. The wave length of the voltage and current of the power can be determined by the equation given below, f.λ = v where f is power frequency, & λ is wave length and v is the speed of light.

Therefore $\lambda = \frac{v}{f} = \frac{3\times10^{8}}{50} = 6 \times 10^{6}$ meter $= 6000$ km

Hence the wave length of the transmitting power is quite long compared to the generally used line length of transmission line.



Voltage distribution of 50 Hz supply

For this reason, the transmission line, with length less than 160 km, the parameters are assumed to be lumped and not distributed. Such lines are known as electrically short transmission line. This electrically short transmission lines are again categorized as short transmission line (length up to 80 km) and medium transmission line(length between 80 and 160 km). The capacitive parameter of short transmission line is ignored whereas in case of medium length line the , capacitance is assumed to be lumped at the middle of the line or half of the capacitance may be considered to be lumped at each ends of the transmission line. Lines with length more than 160 km, the parameters are considered to be distributed over the line. This is called long transmission line.

TWO PORT NETWORK

A major section of power system engineering deals in the transmission of electrical power from one particular place (e.g. generating station) to another like substations or distribution units with maximum efficiency. So it is of substantial importance for power system engineers to be thorough with its mathematical modeling. Thus the entire transmission system can be simplified to a **two port network** for the sake of easier calculations.

The circuit of a 2 port network is shown in the diagram below. As the name suggests, a 2 port network consists of an input port PQ and an output port RS. Each port has 2 terminals to connect itself to the external circuit. Thus it is essentially a 2 port or a 4 terminal circuit, having

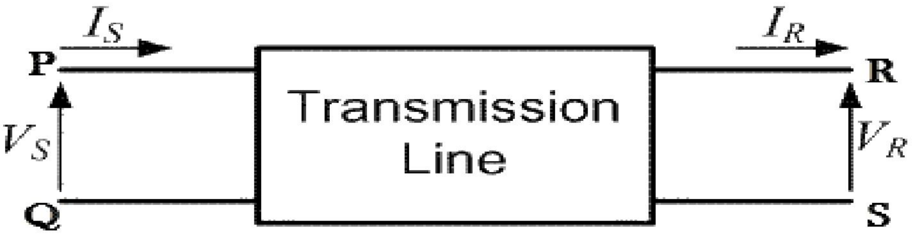


Fig 1.10: Representation of Two port network

Supply end voltage=V_s
Supply end current=I_s
Given to the input port P Q.
Receiving end voltage=V_R
Receiving end current=I_R
Given to the output port R S.

Now the **ABCD parameters** or the transmission line parameters provide the link between the supply and receiving end voltages and currents, considering the circuit elements to be linear in nature.

Thus the relation between the sending and receiving end specifications are given using **ABCD parameters** by the equations below.

$$V_s = AV_R + BI_R \qquad (1)$$

$$I_S = CV_R + DI_R \qquad (2)$$

Now in order to determine the ABCD parameters of transmission line let us impose the required circuit conditions in different cases.

ABCD Parameters (When Receiving End is Open Circuited)

The receiving end is open circuited meaning receiving end current $I_R = 0$.

Applying this condition to equation (1) we get,

$$V_S = AV_R + B0$$

$$V_S = AV_R + 0$$

$$A = \frac{V_S}{V_R}(I_R = 0)$$

Thus it implies that on applying open circuit condition to ABCD parameters, we get parameter A as the ratio of sending end voltage to the open circuit receiving end voltage. Since dimension wise A is a ratio of voltage to voltage, A is a dimension less parameter.

Applying the same open circuit condition i.e. $I_R = 0$ to equation (2)

$$Is = CV_R + D0$$

$$I_s = CV_R + 0$$

$$C = \frac{I_S}{V_R}(I_R = 0)$$

Thus its implies that on applying open circuit condition to ABCD parameters of transmission line, we get parameter C as the ratio of sending end current to the open circuit receiving end voltage. Since dimension wise C is a ratio of current to voltage, its unit is mho.

Thus C is the open circuit conductance and is given by $C = I_S/V_R$ mho.

ABCD Parameters (When Receiving End is Short Circuited)

Receiving end is short circuited meaning receiving end voltage $V_R = 0$

Applying this condition to equation (1) we get,

$$V_S = A0 + BI_R$$

$$V_S = 0 + BI_R$$

$$B = \frac{V_S}{I_R}(V_R = 0)$$

Thus its implies that on applying short circuit condition to ABCD parameters, we get parameter B as the ratio of sending end voltage to the short circuit receiving end current. Since dimension wise B is a ratio of voltage to current, its unit is Ω. Thus B is the short circuit resistance and is given by

$$B = V_S/I_R\ \Omega.$$

Applying the same short circuit condition i.e. $V_R = 0$ to equation (2) we get

$$I_s = C0 + DI_R$$

$$I_s = 0 + DI_R$$

$$D = \frac{I_s}{I_R}(V_R = 0)$$

Thus its implies that on applying short circuit condition to ABCD parameters, we get parameter D as the ratio of sending end current to the short circuit receiving end current. Since dimension wise D is a ratio of current to current, it's a dimension less parameter.

Short Transmission Line

The transmission lines which have length less than 80 km are generally referred as **short transmission lines**.

For short length, the shunt capacitance of this type of line is neglected and other parameters like electrical resistance and inductor of these short lines are lumped, hence the equivalent circuit is represented as given below, Let's draw the vector diagram for this equivalent circuit, taking receiving end current I_r as reference. The sending end and receiving end voltages make angle with that reference receiving end current, of φ_s and φ_r, respectively.

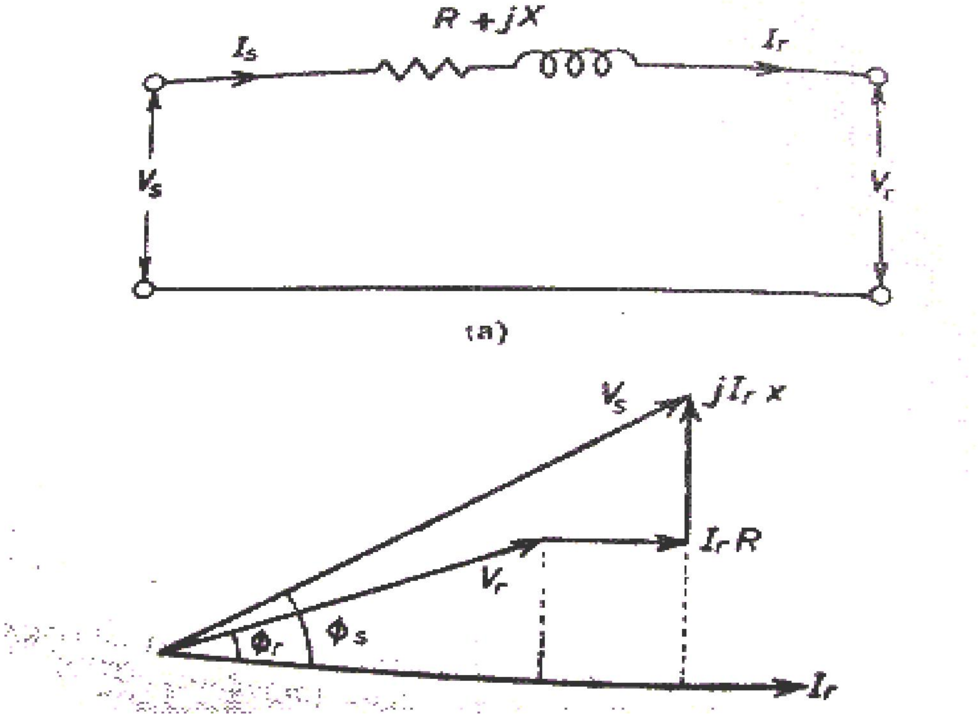


Fig.1.11 Representation of a short transmission line

As the shunt capacitance of the line is neglected, hence sending end current and receiving end current is same, i.e.

$I_s = I_R$.

Now if we observe the vector diagram carefully, we will get,

V_s is approximately equal to

$V_R + I_R.R.\cos\varphi_R + I_R.X.\sin\varphi_R$

That means,

$V_s \cong V_R + I_R.R.\cos\varphi_R + I_R.X.\sin\varphi_R$ as it is assumed that $\varphi_s \cong \varphi_R$

As there is no capacitance, during no load condition the current through the line is considered as zero, hence at no load condition, receiving end voltage is the same as sending end voltage.

As per definition of voltage regulation of power transmission line,

$$\%regulation = \frac{V_s - V_R}{V_R} \text{X}100\%$$

$$= \frac{I_R R \cos\Phi_R + I_R X \sin\Phi_R}{V_R} X100\%$$

Any electrical network generally has two input terminals and two output terminals. If we consider any complex electrical network in a black box, it will have two input terminals and output terminals. This network is called two – port network. Two port model of a network simplifies the network solving technique. Mathematically a two port network can be solved by 2 by 2 matrix.

A transmission as it is also an electrical network; line can be represented as two port network.

Hence two port network of transmission line can be represented as 2 by 2 matrixes. Here the concept of ABCD parameters comes. Voltage and currents of the network can represented as,

$$V_s = AV_R + BI_R$$
$$I_S = CV_R + DI_R$$

Where A, B, C and D are different constant of the network.

If we put $I_R = 0$ at equation (1), we get,

$$A = \left(\frac{V_S}{V_R}\right)_{I_R=0}$$

Hence, A is the voltage impressed at the sending end per volt at the receiving end when receiving end is open. It is dimension less.

If we put $V_R = 0$ at equation (1), we get

$$B = \left(\frac{V_S}{I_R}\right)_{V_R=0}$$

That indicates it is impedance of the transmission line when the receiving terminals are short circuited. This parameter is referred as transfer impedance.

$$C = \left(\frac{I_S}{V_R}\right)_{I_R=0}$$

C is the current in amperes into the sending end per volt on open circuited receiving end. It has the dimension of admittance.

$$D = \left(\frac{I_S}{I_R}\right)_{V_R=0}$$

D is the current in amperes into the sending end per amp on short circuited receiving end. It is dimensionless.

Now from equivalent circuit, it is found that,

$$V_s = V_R + I_R Z \text{ and } I_s = I_R$$

Comparing these equations with equation (1) and (2) we get, A = 1, B = Z, C = 0 and D = 1. As we know that the constant A, B, C and D are related for passive network as,

$$AD - BC = 1.$$

Here, A = 1, B = Z, C = 0 and D = 1

$$\Rightarrow 1.1 - Z.0 = 1$$

So the values calculated are correct for short transmission line

From above equation (1),

$$V_s = AV_R + BI_R$$

When $I_R = 0$ that means receiving end terminals is open circuited and then from the equation (1), we get receiving end voltage at no load.

$$V_R^{'} = \frac{V_S}{A}$$

and as per definition of voltage regulation of power transmission line,

$$\text{\% voltage regulation} = \frac{V_s / A - V_r}{V_r} X100\ \%$$

Efficiency of Short Transmission Line

The efficiency of short line as simple as efficiency equation of any other electrical equipment, that means

$$\%\text{efficienc y} = \frac{\text{Power received at receiving end}}{\text{Power received at receiving end} + 3I_R^2 R} X100$$

R is per phase electrical resistance of the transmission line.

Medium Transmission Line

The transmission line having its effective length more than 80 km but less than 250 km, is generally referred to as a **medium transmission line**. Due to the line length being considerably high, admittance Y of the network does play a role in calculating the effective circuit parameters, unlike in the case of short transmission lines. For this reason the modeling of a **medium length transmission line** is done using lumped shunt admittance along with the lumped impedance in series to the circuit.

These lumped parameters of a medium length transmission line can be represented using two different models, namely-

1) Nominal **Π** representation.
2) Nominal **T** representation.

Let's now go into the detailed discussion of these above mentioned models.

Nominal Π Representation of a Medium Transmission Line

In case of a nominal **Π** representation, the lumped series impedance is placed at the middle of the circuit where as the shunt admittances are at the ends. As we can see from the diagram of the Π network below, the total lumped shunt admittance is divided into 2 equal halves, and each half with value Y / 2 is placed at both the sending and the receiving end while the entire circuit impedance is between the two. The shape of the circuit so formed resembles that of a symbol **Π**, and for this reason it is known as the nominal Π representation of a medium transmission line. It is mainly used for determining the general circuit parameters and performing load flow analysis.

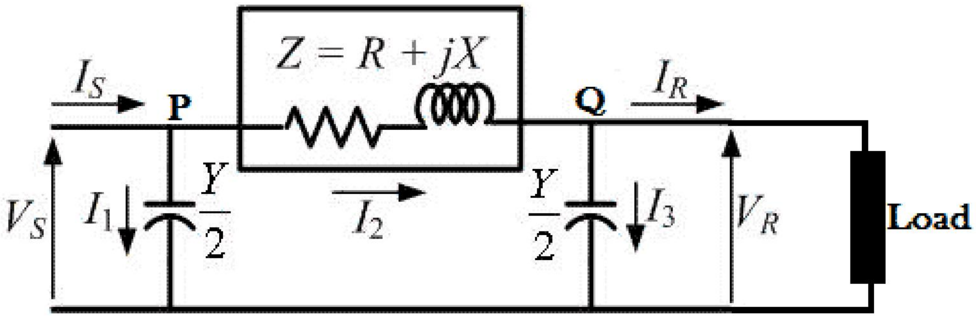


Fig.1.12: Nominal Π Representation of a Medium Transmission Line

As we can see here, V_S and V_R is the supply and receiving end voltages respectively, and I_s is the current flowing through the supply end.

I_R is the current flowing through the receiving end of the circuit.

I_1 and I_3 are the values of currents flowing through the admittances. And

I_2 is the current through the impedance Z.

Now applying KCL, at node P, we get

$$I_S = I_1 + I_2 \tag{1}$$

Similarly applying KCL, to node Q.

$$I_2 = I_3 + I_R \tag{2}$$

Now substituting equation (2) to equation (1)

$$\begin{aligned} I_S &= I_1 + I_3 + I_R \\ &= \frac{Y}{2}V_S + \frac{Y}{2}V_R + I_R \end{aligned} \tag{3}$$

Now by applying KVL to the circuit,

$$\begin{aligned} V_S &= V_R + ZI_2 \\ &= V_R + Z(V_R\frac{Y}{2} + I_R) \\ &= (Z\frac{Y}{2} + 1)V_R + ZI_R \end{aligned} \tag{4}$$

Now substituting equation (4) to equation (3), we get

$$\begin{aligned} I_s &= \frac{Y}{2}[(\frac{Y}{2}Z + 1)V_R + ZI_R] + \frac{Y}{2}V_R + I_R \\ &= Y(\frac{Y}{4}Z + 1)V_R + (\frac{Y}{2}Z + 1)I_R \end{aligned} \tag{5}$$

Comparing equation (4) and (5) with the standard ABCD parameter equations we derive the parameters of a medium transmission line as:

$$A = \left(\frac{Y}{2} Z + 1 \right)$$

$$B = Z$$

$$C = Y\left(\frac{Y}{4} Z + 1\right)$$

$$D = \left(\frac{Y}{2} Z + 1\right)$$

Nominal T Representation of a Medium Transmission Line

In the **nominal T** model of a medium transmission line the lumped shunt admittance is placed in the middle, while the net series impedance is divided into two equal halves and placed on either side of the shunt admittance. The circuit so formed resembles the symbol of a capital **T**, and hence is known as the nominal T network of a medium length transmission line and is shown in the diagram below.

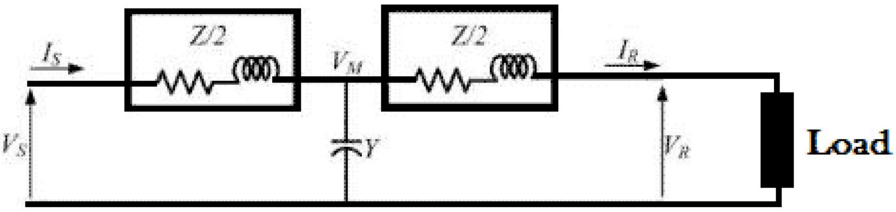


Fig.1.13: Nominal T representation of medium transmission line

Here also V_s and V_R is the supply and receiving end voltages respectively, and

I_s is the current flowing through the supply end.

I_R is the current flowing through the receiving end of the circuit.

Let M be a node at the midpoint of the circuit, and the drop at M, be given by V_M.

Applying KVL to the above network we get,

$$\frac{V_S - V_M}{Z/2} = YV_M + \frac{V_M - V_R}{Z/2}$$
$$V_M = \frac{2(V_S + V_R)}{YZ + 4} \qquad (6)$$

And the receiving end current

$$I_R = \frac{2(V_M - V_R)}{Z/2} \tag{7}$$

Now substituting V_M from equation (6) to (7) we get

$$V_S = \left(\frac{Y}{2}Z + 1\right)V_R + Z(\frac{Y}{4}Z + 1)I_R \tag{8}$$

Now the sending end current is,

$$I_S = YV_M + I_R \tag{9}$$

Substituting the value of V_M to equation (9) we get,

$$I_S = YV_R + (\frac{Y}{2}Z + 1)I_R \tag{10}$$

Again comparing equation (8) and (10) with the standard ABCD parameter equations, the parameters of the **T** network of a medium transmission line are

$$A = (\frac{Y}{2}Z + 1)$$

$$B = Z(\frac{Y}{4}Z + 1)$$

$$C = Y$$

$$D = (\frac{Y}{2}Z + 1)$$

Long Transmission Line

A power transmission line with its effective length of around 250 ms or above is referred to as a **long transmission line**. Calculations related to circuit parameters (ABCD parameters) of such a power transmission is not that simple, as was the case for a short transmission line or medium transmission line. The reason being that, the effective circuit length in this case is much higher than what it was for the former models (long and medium line) and, thus ruling out the approximations considered there like.

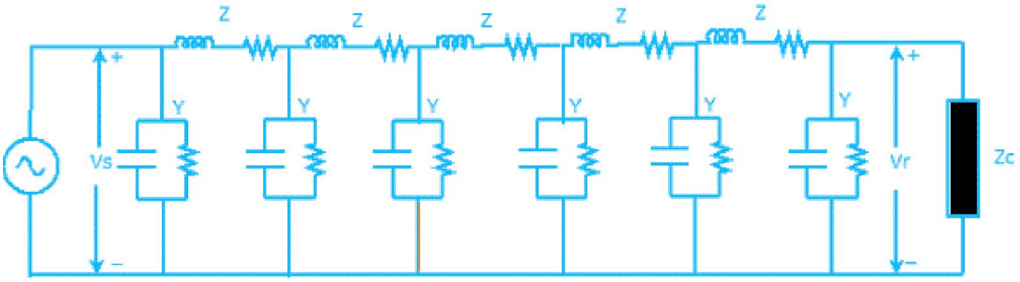


Fig.1.14: Long line model

a) Ignoring the shunt admittance of the network, like in a small transmission line model.

b) Considering the circuit impedance and admittance to be lumped and concentrated at a point as was the case for the medium line model.

Rather, for all practical reasons we should consider the circuit impedance and admittance to be distributed over the entire circuit length as shown in the figure below.

The calculations of circuit parameters for this reason are going to be slightly more rigorous as we will see here. For accurate modeling to determine circuit parameters let us consider the circuit of the **long transmission line** as shown in the diagram below.

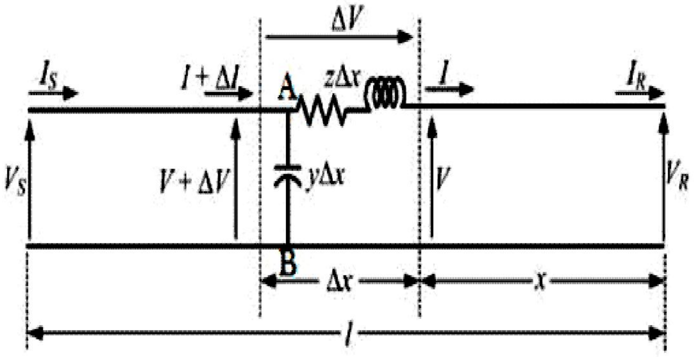


Fig.1.15: Modeling of long transmission line

Here a line of length l > 250km is supplied with a sending end voltage and current of V_S and I_S respectively, where as the V_R and I_R are the values of voltage and current obtained from the receiving end. Lets us now consider an element of infinitely small length Δx at a distance x from the receiving end as shown in the figure 1.15 where.

V = value of voltage just before entering the element Δx.

I = value of current just before entering the element Δx.

$V+\Delta V$ = voltage leaving the element Δx.

$I+\Delta I$ = current leaving the element Δx.

ΔV = voltage drop across element Δx.

$z\Delta x$ = series impedence of element Δx

$y\Delta x$ = shunt admittance of element Δx

Where $Z = z\,l$ and $Y = y\,l$ are the values of total impedance and admittance of the long transmission line.

Therefore, the voltage drop across the infinitely small element Δx is given by

$\Delta V = Iz\Delta x$

Now to determine the current ΔI, we apply KCL to node A.

$\Delta I = (V+\Delta V)y\Delta x = V\,y\Delta x + \Delta V\,y\Delta x$ (1)

Since the term $\Delta V\,y\Delta x$ is the product of 2 infinitely small values, we can ignore it for the sake of easier calculation.

Therefore, we can write $dI/dx = V\,y$ (2)

Now derivating both sides of eqn (1) with respect to x,

$d^2 V/d\,x^2 = z\,dI/dx$

Now substituting $dI/dx = V\,y$ from equation (2)

$d^2 V/d\,x^2 = zyV$

or $d^2 V/d\,x^2 - zyV = 0$ (3)

The solution of the above second order differential equation is given by.

$V = A_1\,e^{x\sqrt{yz}} + A_2\,e^{-x\sqrt{yz}}$ (4)

Derivating equation (4) w.r.to x.

$dV/dx = \sqrt{(yz)}\,A_1\,e^{x\sqrt{yz}} - \sqrt{(yz)}A_2e^{-x\sqrt{yz}}$ (5)

Now comparing equation (1) with equation (5)

$$I = \frac{dV}{dX} = \sqrt{\frac{y}{z}}A_1e^{-X\sqrt{YZ}} \qquad (6)$$

Now to go further let us define the characteristic impedance Z_c and propagation constant δ of a long transmission line as

$Z_c = \sqrt{(z/y)}\ \Omega$
$\delta = \sqrt{(yz)}$

Then the voltage and current equation can be expressed in terms of characteristic impedance and propagation constant as

$V = A_1\, e^{\delta x} + A_2\, e^{-\delta x}$ (7)

$I = A_1/ Z_c\, e^{\delta x} + A_2 / Z_c\, e^{-\delta x}$ (8)

Now at x=0, V= V_R and I= I_R. Substituting these conditions to equation (7) and (8) respectively.

$V_R = A_1 + A_2$ (9)

$I_R = A_1/ Z_c + A_2 / Z_c$ (10)

Solving equation (9) and (10),

We get values of A_1 and A_2 as,

$A_1 = (V_R + Z_C I_R)/2$

And $A_1 = (V_R - Z_C I_R)/2$

Now applying another extreme condition at x=l, we have $V = V_S$ and $I = I_S$.

Now to determine V_S and I_S we substitute x by l and put the values of A_1 and A_2 in equation (7) and (8) we get

$V_S = (V_R + Z_C\, I_R)e^{\delta l}/2 + (V_R - Z_C\, I_R)e^{-\delta l}/2$ (11)

$I_S = (V_R/Z_C + I_R)e^{\delta l}/2 - (V_R / Z_C - I_R)e^{-\delta l}/2$ (12)

By trigonometric and exponential operators we know

$\sinh \delta l = (e^{\delta l} - e^{-\delta l})/2$

And $\cosh \delta l = (e^{\delta l} + e^{-\delta l})/2$

Therefore, equation(11) and (12) can be re-written as

$V_S = V_R \cosh \delta l + Z_C\, I_R \sinh \delta l$

$I_S = (V_R \sinh \delta l)/Z_C + I_R \cosh \delta l$

Thus comparing with the general circuit parameters equation, we get the ABCD parameters of a long transmission line as,

$A = \cosh \delta l$

$B = Z_C \sinh \delta l$

$$C = \sinh \delta l / Z_C$$

$$D = \cosh \delta l$$

Skin Effect

The phenomena arising due to unequal distribution of current over the entire cross section of the conductor being used for long distance power transmission is referred as the skin effect in transmission lines. Such a phenomena does not have much role to play in case of a very short line, but with increase in the effective length of the conductors, skin effect increases considerably. So the modifications in line calculation needs to be done accordingly. The distribution of current over the entire cross section of the conductor is quite uniform in case of a DC system. But what we are using in the present era of power system engineering is predominantly an alternating current system, where the current tends to flow with higher density through the surface of the conductors (i.e. skin of the conductor), leaving the core deprived of necessary number of electrons. In fact there even arises a condition when absolutely no current flows through the core, and concentrating the entire amount on the surface region, thus resulting in an increase in the effective electrical resistance of the conductor. This particular trend of an AC transmission system to take the surface path for the flow of current depriving the core is referred to as the skin effect in transmission lines.

Why Skin Effect Occurs in Transmission Lines?

Having understood the phenomena of **skin effect** let us now see why this arises in case of an AC system. To have a clear understanding of that look into the cross sectional view of the conductor during the flow of alternating current given in the diagram below.

Let us initially consider the solid conductor to be split up into a number of annular filaments spaced infinitely small distance apart, such that each filament carries an infinitely small fraction of the total current.

Like if the total current = I

Let us consider the conductor to be split up into n filament carrying current '*i*' such that I = n*i* .

Now during the flow of an alternating current, the current carrying filaments lying on the core has a flux linkage with the entire conductor cross section including the filaments of the surface as well as those in the core. Whereas the flux set up by the outer filaments is restricted only to the surface itself and is unable to link with the inner filaments. Thus the flux linkage of the conductor increases as we move closer towards the core and at the same rate increases the inductor as it has a direct proportionality relationship with flux linkage. This results in a larger inductive reactance being induced into the core as compared to the outer sections of the conductor. The high value of reactance in the inner section results in the current being distributed in an un-uniform manner and forcing the bulk of the current to flow through the outer surface or skin giving rise to the phenomena called **skin effect in transmission lines**.

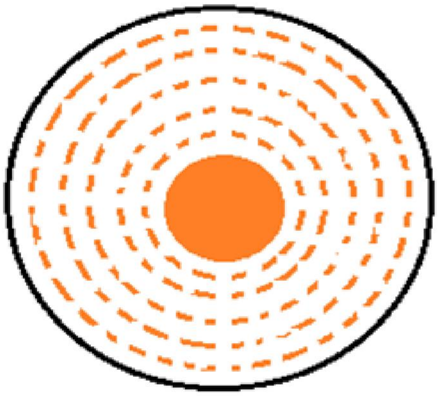


Fig.1.16: Current distribution in a conductor

Factors Affecting Skin Effect in Transmission Lines

The skin effect in an ac system depends on a number of factors like:-

1) Shape of conductor.
2) Type of material.
3) Diameter of the conductors.
4) Operational frequency.

Proximity Effect:

Proximity means nearness in space or time, so as the name suggests, proximity effect in transmission lines indicates the effect in one conductor for other neighbouring conductors. When the alternating current is flowing through a conductor, alternating magnetic flux is generated surrounding the conductor. This magnetic flux associates with the neighbouring wires and generates a circulating current (it can be termed as 'eddy current' also). This circulating current increases the resistance of the conductor and push away the flowing current through the conductor, which causes the crowding effect.

When the gaps between two wires are greater the proximity effect is less and it rises when the gap reduces. The flux due to central conductor links with right side conductor. In a two wire system more lines of flux link elements farther apart than the elements nearest to each other as shown above. Therefore, the inductance of the elements farther apart is more as compared to the elements near to each other and hence the current density is less in the elements farther apart than the current density in the element near to each other. As a result the effective resistance of the conductor is increased due to non uniform distribution of current. This phenomenon is actually referred as proximity effect. This effect is pronounced in the case of cables where the distance between the conductor is small whereas proximity effect in transmission lines in the case of overhead system, with usual spacing is negligibly small.

Series and shunt compensation:

The demand of active power is expressing Kilo watt (kw) or mega watt (mw). This power should be supplied from electrical generating station. All the arrangements in electrical pomes system are done to meet up this basic requirement. Although in alternating power system, reactive power always comes in to picture. This reactive power is expressed in Kilo VAR or Mega VAR. The demand of this reactive power is mainly originated from inductive load connected to the system. These inductive loads are generally electromagnetic circuit of electric motors, electrical transformers, inductance of transmission and distribution networks, induction furnaces, fluorescent lightings etc. This reactive power should be properly compensated otherwise, the ratio of actual power consumed by the load, to the total power i.e. vector sum of active and reactive power, of the system becomes quite less. This ratio is alternatively known as electrical power factor, and fewer ratios indicates poor power factor of the system. If the power factor of the system is poor, the ampere burden of the transmission, distribution network, transformers, alternators and other equipments connected to the system, becomes high for required active power. And hence reactive power compensation becomes so important. This is commonly done by capacitor bank.

Let's explain in details,
we know that active power is expressed =VIcosθ
where,cosθ is the power factor of the system. Hence, if this power factor has got less valve, the corresponding current (I) increases for same active power P.

As the current of the system increases, the ohmic loss of the system increases. Ohmic loss means, generated electrical power is lost as unwanted heat originated in the system. The cross-section of the conducting parts of the system may also have to be increased for carrying extra ampere burden, which is also not economical in the commercial point of view. Another major disadvantage, is poor voltage regulation of the system, which mainly caused due to poor power factor.

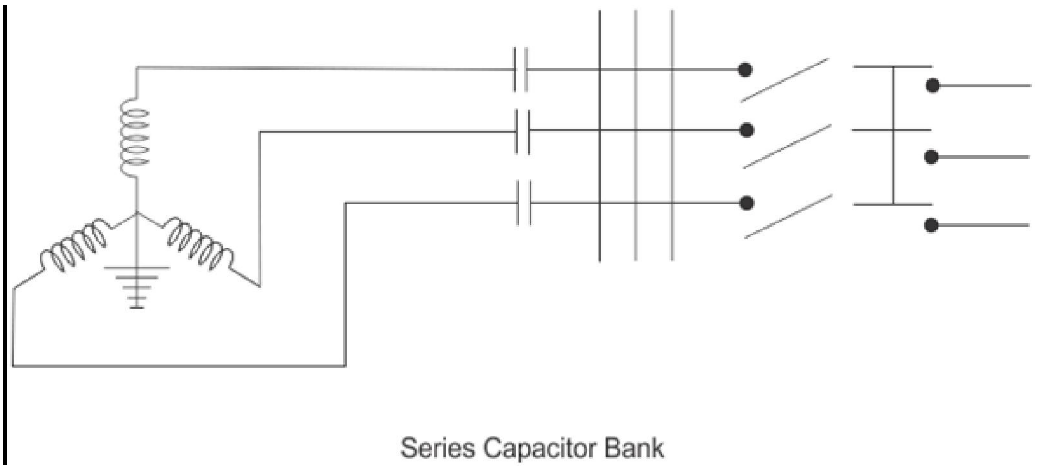
The equipments used to compensate reactive power.
There are mainly two equipments used for this purpose.
(1) Synchronous condensers
(2) Static capacitors or Capacitor Bank

Synchronous condensers, can produce reactive power and the production of reactive power can be regulated. Due to this regulating advantage, the synchronous condensers are very suitable for correcting power factor of the system, but this equipment is quite expensive compared to static capacitors. That is why synchronous condensers, are justified to use only for voltage regulation of very high voltage transmission system. The regulation in static capacitors can also be achieved to some extend by split the total capacitor bank in 3 sectors of ratio 1: 2:2. This division enables the capacitor to run in 1, 2, 1+2=3, 2+2=4, 1+2+2=5 steps. If still further steps are required, the division may be made in the ratio 1:2:3 or 1:2:4. These divisions make the static capacitor bank more expensive but still the cost is much lower them synchronous condensers. It is found that maximum benefit from compensating equipments can be achieved when they are connected to the individual load side. This is practically and economically possible only by using small rated capacitors with individual load not by using synchronous condensers. Static capacitor Bank.

Static capacitor can further be subdivided in to two categories,

(a) Shunt capacitors

(b) Series capacitor



Series Capacitor Bank

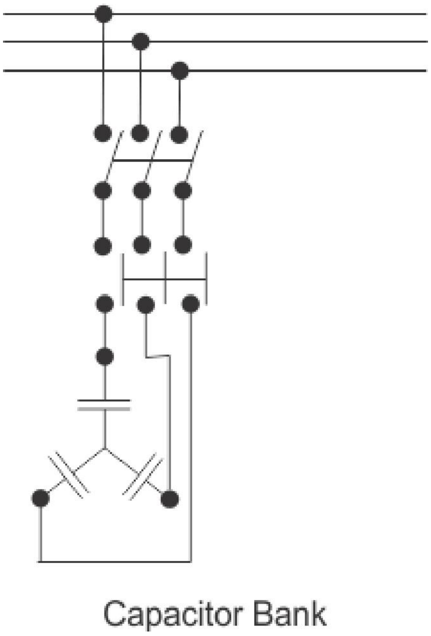


Fig.1.17: Series and Shunt Capacitor bank

These categories are mainly based on the methods of connecting capacitor bank with the system. Among these two categories, shunt capacitors are more commonly used in the power system of all voltage levels. There are some specific advantages of using shunt capacitors such as,

a) It reduces line current of the system.
b) It improves voltage level of the load.
c) It also reduces system Losses.
d) It improves power factor of the source current.
e) It reduces load of the alternator.
f) It reduces capital investment per mega watt of the Load.

All the above mentioned benefits come from the fact, that the effect of capacitor reduces reactive current flowing through the whole system. Shunt capacitor draws almost fixed amount of leading current which is superimposed on the load current and consequently reduces reactive components of the load and hence improves the power factor of the system. series capacitor on the other hand has no control over flow of current. As these are connected in series with load , the load current always passes through the series capacitor bank. Actually, the capacitive reactance of series capacitor neutralizes the inductive reactance of the line hence, reduces, effective reactance of the line. Thereby, voltage regulation of the system is improved. But series capacitor bank has a major disadvantage. During faulty condition, the voltage across the capacitor maybe raised up to 15 times more than its rated value. Thus series capacitor must have sophisticated and elaborate protective equipments. Because of this, use of-series capacitor is confined in the extra high voltage system only.

MODULE II

Corona

When an alternating potential difference is applied across two conductors whose spacing is large as compared to their diameters, there is no apparent change in the condition of atmospheric air surrounding the wires if the applied voltage is low. However, when the applied voltage exceeds a certain value, called critical disruptive voltage, the conductors are surrounded by a faint violet glow called corona.

The phenomenon of corona is accompanied by a hissing sound, production of ozone, power loss and radio interference. Electric power transmission practically deals in the bulk transfer of electrical energy, from generating stations situated many kilometers away from the main consumption centers or the cities. For this reason the long distance transmission cables are of utmost necessity for effective power transfer, which in-evidently results in huge losses across the system. Minimizing those has been a major challenge for power engineers of late and to do that one should have a clear understanding of the type and nature of losses. One of them being the **corona effect in power system**, which has a predominant role in reducing the efficiency of EHV(extra high voltage lines) which we are going to concentrate on, in this article. When an alternating current is made to flow across two conductors of the transmission line whose spacing is large compared to their diameters, then air surrounding the conductors (composed of ions) is subjected to dielectric stress. At low values of supply end voltage, nothing really occurs as the stress is too less to ionize the air outside. But when the potential difference is made to increase beyond some threshold value of around 30 kV known as the **critical disruptive voltage**, then the field strength increases and then the air surrounding it experiences stress high enough to be dissociated into ions making the atmosphere conducting. This results in electric discharge around the conductors due to the flow of these ions, giving rise to a faint luminescent glow, along with the hissing sound accompanied by the liberation of ozone, which is readily identified due to its characteristic odor. This phenomenon of electrical discharge occurring in transmission line for high values of voltage is known as the **corona effect in power system**. If the voltage across the lines is still increased the glow becomes more and more intense along with hissing noise, inducing very high power loss into the system which must be accounted for.

Factors Affecting Corona Effect in Power System

As mentioned earlier, the line voltage of the conductor is the main determining factor for corona in transmission lines, at low values of voltage (lesser than critical disruptive voltage) the stress on the air is too less to dissociate them, and hence no electrical discharge occurs. Since with increasing voltage corona effect in a transmission line occurs due to the ionization of atmospheric air surrounding the cables, it is mainly affected by the conditions of the cable as well as the physical state of the atmosphere. Let us look into these criterion now with greater details :

Atmospheric Conditions for Corona in Transmission Lines

It has been physically proven that the voltage gradient for di-electric breakdown of air is directly proportional to the density of air. Hence in a stormy day, due to continuous air flow the number of ions present surrounding the conductor is far more than normal, and hence its more likely to have electrical discharge in transmission lines on such a day, compared to a day with fairly clear weather. The system has to designed taking those extreme situations into consideration.

Condition of Cables for Corona in Transmission Line.

This particular phenomena depends highly on the conductors and its physical condition. It has an inverse proportionality relationship with the diameter of the conductors. i.e. with the increase in diameter, the effect of corona in power system reduces considerably.

Also the presence of dirt or roughness of the conductor reduces the critical breakdown voltage, making the conductors more prone to corona losses. Hence in most cities and industrial areas having high pollution, this factor is of reasonable importance to counter the ill effects it has on the system.

Spacing between Conductors

As already mentioned, for corona to occur effectively the spacing between the lines should be much higher compared to its diameter, but if the length is increased beyond a certain limit, the dielectric stress on the air reduces and consequently the effect of corona reduces as well. If the spacing is made too large then corona for that region of the transmission line might not occur at all.

Important Terms:

The phenomenon of corona plays an important role in the design of an overhead transmission line. Therefore, it is profitable to consider the following terms much used in the analysis of corona effects:

(i) Critical Disruptive Voltage: It is the minimum phase-neutral voltage at which corona occurs. Consider two conductors of radii r cm and spaced d cm apart. If V is the phase-neutral potential, then potential gradient at the conductor surface is given by:

$$g = \frac{V}{r \ln \frac{d}{r}} \text{ Volts/cm}$$

In order that corona is formed, the value of g must be made equal to the breakdown strength of air. The breakdown strength of air at 76 cm pressure and temperature of 25ºC is 30 kV/cm (max) or 21·2 kV/cm (r.m.s.) and is denoted by g_0. If Vc is the phase-neutral potential required under these conditions, then,

$$g_0 = \frac{V_c}{r \ln \frac{d}{r}}$$

where g_o = breakdown strength of air at 76 cm of mercury and 25ºC

= 30 kV/cm (max) or 21·2 kV/cm (r.m.s.)

∴ Critical disruptive voltage, $V_c = g_0 r \ln \frac{d}{r}$

The above expression for disruptive voltage is under standard conditions i.e. at 76 cm of Hg and 25ºC. However, if these conditions vary, the air density also changes, thus altering the value of g_o.The value of g_o is directly proportional to air density. Thus the breakdown strength of air at a barometric pressure of b cm of mercury and temperature of t°C becomes δg_0 where

δ = air density factor = $\frac{3.92}{273+t}$

Under standard conditions, the value of δ = 1.

Critical disruptive voltage, $V_c = g_0 \delta r \ln\frac{d}{r}$

Correction must also be made for the surface condition of the conductor. This is accounted for by multiplying the above expression by irregularity factor m_o.

Critical disruptive voltage, $V_c = g_0 \delta m_0 r \ln\frac{d}{r}$ kV/phase

where

m_o = 1 for polished conductors

= 0·98 to 0·92 for dirty conductors

= 0·87 to 0·8 for stranded conductors

(ii) Visual critical voltage

It is the minimum phase-neutral voltage at which corona glow appears all along the line conductors.

It has been seen that in case of parallel conductors, the corona glow does not begin at the disruptive voltage Vc but at a higher voltage V_v, called **visual critical voltage**. The phase-neutral effective value of visual critical voltage is given by the following empirical formula

$$V_v = m_v g_0 \delta r (1+\frac{0.3}{\sqrt{\delta r}}) \ln\frac{d}{r} \text{ kV/phase}$$

where m_v is another irregularity factor having a value of 1·0 for polished conductors and 0·72 to 0·82 for rough conductors.

(iii) Power loss due to corona Formation of corona is always accompanied by energy loss which is dissipated in the form of light, heat, sound and chemical action. When disruptive voltage is exceeded, the power loss due to corona is given by:

$$P = 241\times10^{-5}\left(\frac{f+25}{\delta}\right)\sqrt{\frac{r}{d}}(V-V_c)^2 \text{ kw/km/phase}$$

Advantages and Disadvantages of Corona

Corona has many advantages and disadvantages. In the correct design of a high voltage overheadline, a balance should be struck between the advantages and disadvantages.

Below are the Advantages and disadvantages of Corona.

Advantages

- Due to corona formation, the air surrounding the conductor becomes conducting and hence virtual diameter of the conductor is increased. The increased diameter reduces the electro-static stresses between the conductors.
- Corona reduces the effects of transients produced by surges.

Disadvantages

- Corona is accompanied by a loss of energy. This affects the transmission efficiency of the line.
- Ozone is produced by corona and may cause corrosion of the conductor due to chemical action.
- The current drawn by the line due to corona is non-sinusoidal and hence non-sinusoidal Voltage drop occurs in the line. This may cause inductive interference with neighboring Communication lines.

Methods to reduce Corona Discharge Effect

Corona can be avoided

1. **By minimizing the voltage stress and electric field gradient.:** This is accomplished by using utilizing good high voltage design practices, i.e., maximizing the distance between conductors that have large voltage differentials, using conductors with large radii, and avoiding parts that have sharp points or sharp edges.
2. **Surface Treatments:** Corona inception voltage can sometimes be increased by using a surface treatment, such as a semiconductor layer, high voltage putty or corona dope.
3. **Homogenous Insulators:** Use a good, homogeneous insulator. Void free solids, such as properly prepared silicone and epoxy potting materials work well.

4. **If you are limited to using air as your insulator,** then you are left with geometry as the critical parameter. Finally, ensure that steps are taken to reduce or eliminate unwanted voltage transients, which can cause corona to start.
5. **Using Bundled Conductors:** on our 345 kV lines, we have installed multiple conductors per phase. This is a common way of increasing the effective diameter of the conductor, which in turn results in less resistance, which in turn reduces losses.
6. **Elimination of sharp points:** electric charges tend to form on sharp points; therefore when practicable we strive to eliminate sharp points on transmission line components.
7. **Using Corona rings:** On certain new 345 kV structures, we are now installing corona rings. These rings have smooth round surfaces which are designed to distribute charge across a wider area, thereby reducing the electric field and the resulting corona discharges.
8. **Whether:** Corona phenomena much worse in foul weather, high altitude
9. **New Conductor:** New conductors can lead to poor corona performance for a while.
10. **By increasing the spacing between the conductors:** Corona Discharge Effect can be reduced by increasing the clearance spacing between the phases of the transmission lines. However increase in the phase's results in heavier metal supports. Cost and Space requirement increases.
11. **By increasing the diameter of the conductor:** Diameter of the conductor can be increased to reduce the corona discharge effect. By using hollow conductors corona discharge effect can be improved.

Insulators

Electrical Insulator must be used in electrical system to prevent unwanted flow of current to the earth from its supporting points. The **insulator** plays a vital role in electrical system. **Electrical Insulator** is a very high resistive path through which practically no current can flow. In transmission and distribution system, the overhead conductors are generally supported by supporting towers or poles. The towers and poles both are properly grounded. So there must be **insulator** between tower or pole body and current carrying conductors to prevent the flow of current from conductor to earth through the grounded supporting towers or poles.

Insulating Material

The main cause of failure of overhead line insulator, is flash over, occurs in between line and earth during abnormal over voltage in the system. During this flash over, the huge heat produced by arcing, causes puncher in insulator body. Viewing this phenomenon the materials used for electrical insulator, has to posses some specific properties.

Properties of Insulating Material

The materials generally used for insulating purpose is called **insulating material**. For successful utilization, this material should have some specific properties as listed below-

1. It must be mechanically strong enough to carry tension and weight of conductors.
2. It must have very high dielectric strength to withstand the voltage stresses in High Voltage system.
3. It must possesses high Insulation Resistance to prevent leakage current to the earth.
4. The **insulating material** must be free from unwanted impurities.
5. It should not be porous.
6. There must not be any entrance on the surface of electrical insulator so that the moisture or gases can enter in it.
7. There physical as well as electrical properties must be less affected by changing temperature.

There are mainly three **types of insulator** used as **overhead insulator** likewise

1. **Pin Insulator**
2. **Suspension Insulator**
3. **Strain Insulator**

In addition to that there are other two **types of electrical insulator** available mainly for low voltage application i.e. **Stray Insulator** and **Shackle Insulator**.

Pin Insulator

Pin Insulator is earliest developed **overhead insulator**, but still popularly used in power network up to 33KV system. Pin type insulator can be one part, two parts or three parts type, depending upon application voltage. In 11KV system we generally use one part type insulator where whole pin insulator is one piece of properly shaped porcelain or glass. As the leakage path of insulator is through its surface, it is desirable to increase the vertical length of the insulator surface area for lengthening leakage path. In order to obtain lengthy leakage path, one, tower or more rain sheds or petticoats are provided on the insulator body. In addition to that rain shed or petticoats on an insulator serve another purpose. These rain sheds or petticoats are so designed, that during raining the outer surface of the rain shed becomes wet but the inner surface remains dry and non-conductive. So there will be discontinuations of conducting path through the wet pin insulator surface.

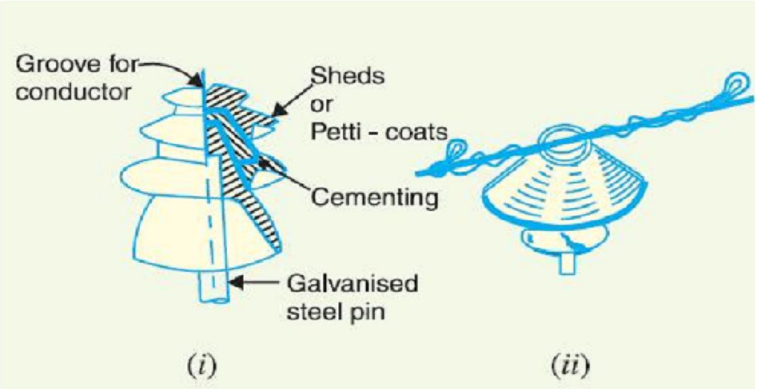


Fig 2.1- Pin Insulator

In higher **voltage** like 33KV and 66KV manufacturing of one part porcelain pin insulator becomes difficult. Because in higher voltage, the thickness of the insulator become more and a quite thick single piece porcelain insulator cannot manufactured practically. In this case we use multiple part pin insulator, where a number of properly designed porcelain shells are fixed together by Portland cement to form one complete insulator unit. For 33KV tow parts and for 66KV three parts pin insulator are generally used.

Designing Consideration of Electrical Insulator

The live conductor attached to the top of the pin insulator is at a potential and bottom of the insulator fixed to supporting structure of earth potential. The insulator has to withstand the potential stresses between conductor and earth. The shortest distance between conductor and earth, surrounding the insulator body, along which electrical discharge may take place through air, is known as flash over distance.

1. When insulator is wet, its outer surface becomes almost conducting. Hence the flash over distance of insulator is decreased. The design of an electrical insulator should be such that the decrease of flash over distance is minimum when the insulator is wet. That is why the upper most petticoat of a pin insulator has umbrella type designed so that it can protect, the rest lower part of the insulator from rain. The upper surface of top most petticoat is inclined as less as possible to maintain maximum flash over voltage during raining.

2. To keep the inner side of the insulator dry, the rain sheds are made in order that these rain sheds should not disturb the voltage distribution they are so designed that their subsurface at right angle to the electromagnetic lines of force.

Suspension Insulator

In higher voltage, beyond 33KV, it becomes uneconomical to use pin insulator because size, weight of the insulator become more. Handling and replacing bigger size single unit insulator are quite difficult task. For overcoming these difficulties, **suspension insulator** was developed. In **suspension insulator** numbers of insulators are connected in series to form a string and the line conductor is carried by the bottom most insulator. Each insulator of a suspension string is called disc insulator because of their disc like shape.

Advantages of Suspension Insulator

(i) Suspension type insulators are cheaper than pin type insulators for voltages beyond 33 kV.

(ii) Each unit or disc of suspension type insulator is designed for low voltage,usually 11 kV. Depending upon the working voltage, the desired number of discs can be connected in series.

(iii) If any one disc is damaged, the whole string does not become useless because the damaged disc can be replaced by the sound one.

(iv) The suspension arrangement provides greater flexibility to the line. The connection at the cross arm is such that insulator string is free to swing in any direction and can take up the position where mechanical stresses are minimum.

(v) In case of increased demand on the transmission line, it is found more satisfactory to supply the greater demand by raising the line voltage than to provide another set of conductors. The additional insulation required for the raised voltage can be easily obtained in the suspension arrangement by adding the desired number of discs.

(vi) The suspension type insulators are generally used with steel towers. As the conductors run below the earthed cross-arm of the tower, therefore, this arrangement provides partial protection from lightning.

Disadvantages of Suspension Insulator

1. Suspension insulator string costlier than pin and post type insulator.
2. Suspension string requires more height of supporting structure than that for pin or post insulator to maintain same ground clearance of current conductor.
3. The amplitude of free swing of conductors is larger in suspension insulator system, hence, more spacing between conductors should be provided.

Strain Insulator

When suspension string is used to sustain extraordinary tensile load of conductor it is referred as **string insulator**. When there is a dead end or there is a sharp corner in transmission line, the line has to sustain a great tensile load of conductor or strain. A **strain insulator** must have considerable mechanical strength as well as the necessary electrical insulating properties.

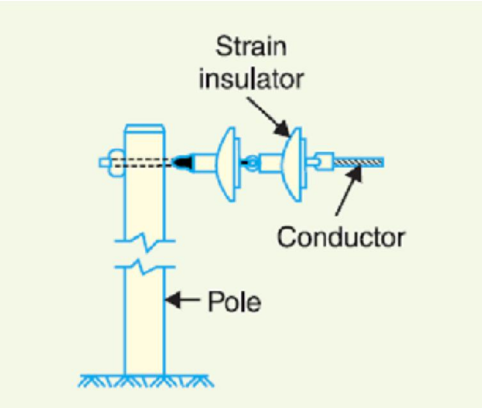


Fig 2.2- Strain Insulator

Shackle Insulator or Spool Insulator

The **shackle insulator** or **spool insulator** is usually used in low voltage distribution network. It can be used both in horizontal and vertical position. The use of such insulator has decreased recently after increasing the using of underground cable for distribution purpose. The tapered hole of the **spool insulator** distributes the load more evenly and minimizes the possibility of breakage when heavily loaded. The conductor in the groove of **shackle insulator** is fixed with the help of soft binding wire.

POTENTIAL DISTRIBUTION OVERA STRING OF SUSPENSION INSULATORS:

A string of suspension insulators consists of a number of porcelain discs connected in series through metallic links. Fig. 2.3(i) shows 3-disc string of suspension insulators. The porcelain portion of each disc is in between two metal links. Therefore, each disc forms a capacitor C as shown in Fig.2.3(ii). This is known as mutual capacitance or self-capacitance. If there were mutual capacitance alone, then charging current would have been the same through all the discs and consequently voltage across each unit would have been the same i.e., V/3 as shown in Fig. 2.3(ii). However, in actual practice, capacitance also exists between metal fitting of each disc and tower or earth. This is known as shunt capacitance C1. Due to shunt capacitance, charging current is not the same through all the discs of the string [See Fig 2.3(iii)]. Therefore, voltage across each disc will be different. Obviously, the disc nearest to the line conductor will have the maximum voltage. Thus referring to Fig 2.3(iii), V_3 will be much more than V_2 or V_1.

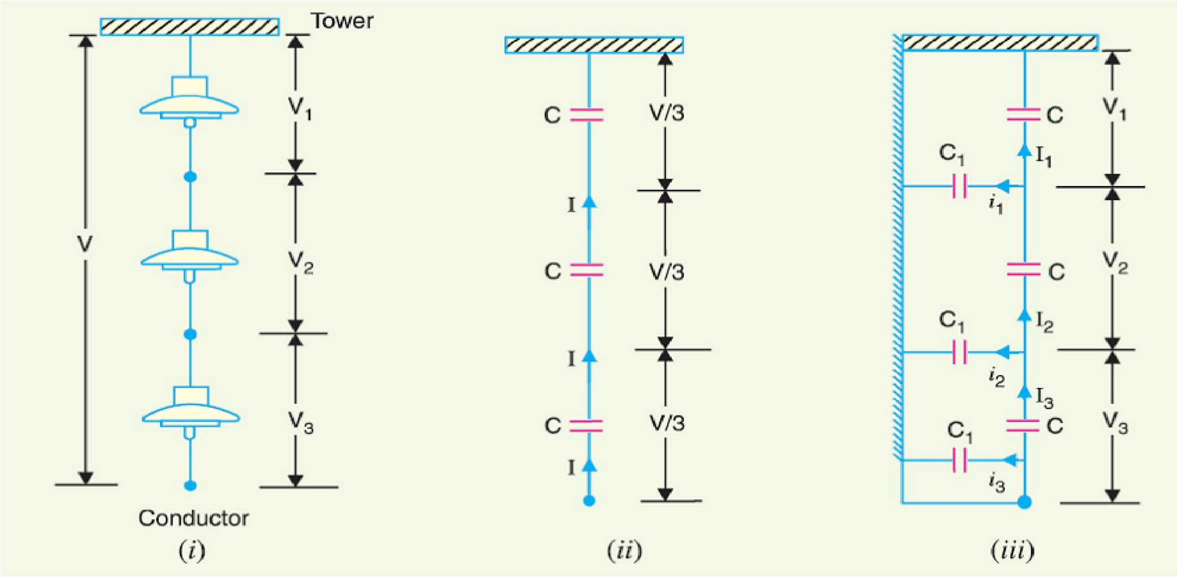
The following points may be noted regarding the potential distribution over a string of suspension insulators:

(i) The voltage impressed on a string of suspension insulators does not distribute itself uniformly across the individual discs due to the presence of shunt capacitance.

(ii) The disc nearest to the conductor has maximum voltage across it. As we move towards the cross-arm, the voltage across each disc goes on decreasing.

(iii) The unit nearest to the conductor is under maximum electrical stress and is likely to be punctured. Therefore, means must be provided to equalize the potential across each unit.

(iv)The presence of stray capacitance causes unequal potential distribution over the string. The end unit of the string (which is the closest to the line) takes maximum potential difference and the upper units have a gradually decreased potential difference until the uppermost unit which has the lowest potential difference. The next proof illustrates this concept.



(i) (ii) (iii)

Fig 2.3- Suspension Insulator string

String Efficiency:

As stated above, the voltage applied across the string of suspension insulators is not uniformly distributed across various units or discs. The disc nearest to the conductor has much higher potential than the other discs. This unequal potential distribution is undesirable and is usually expressed in terms of string efficiency.

The ratio of voltage across the whole string to the product of number of discs and the voltage across the disc nearest to the conductor is known as string efficiency i.e.

$$\text{String Efficiency} = \frac{\text{Voltage across the string}}{n \times \text{Voltage across disc near to conductor}}$$

Where n is the no. of discs in the string.

String efficiency is an important consideration since it decides the potential distribution along the string. The greater the string efficiency, the more uniform is the voltage distribution. Thus 100%

string efficiency is an ideal case for which the voltage across each disc will be exactly the same. Although it is impossible to achieve 100% string efficiency, yet efforts should be made to improve it as close to this value as possible.

Mathematical expression. Fig. 2.3(iii) shows the equivalent circuit for a 3-disc string. Let us suppose that self capacitance of each disc is C. Let us further assume that shunt capacitance C1 is some fraction K of self capacitance i.e., C1 = KC. Starting from the cross-arm or tower, the voltage across each unit is V1,V2 and V3 respectively as shown.

Applying kirchoff's current law to node A

$$I_2 = I_1 + i_1$$

$$V_2 \omega C = V_1 \omega C + V_1 \omega C_1$$

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

$$V_2 = V_1 (1 + K)$$

Applying kirchoff's current law to node B

$$I_3 = I_2 + i_2$$

$$V_3 \omega C = V_2 \omega C + (V_1 + V_2) \omega C_1$$

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

$$V_3 = K V_1 + V_2 (1 + K)$$

$$V_3 = V_1 (1 + 3K + K^2)$$

$$\% stringefficiency = \frac{V}{3 \times V_3} \times 100$$

The following points may be noted from the above mathematical analysis:

(i) If K = 0·2 (Say), then we get, $V_2 = 1{\cdot}2\ V_1$ and $V_3 = 1{\cdot}64\ V_1$. This clearly shows that disc nearest to the conductor has maximum voltage across it; the voltage across other discs decreasing progressively as the cross-arm in approached.

(ii) The greater the value of K (= C1/C), the more non-uniform is the potential across the discs and lesser is the string efficiency.

(iii) The inequality in voltage distribution increases with the increase of number of discs in the string. Therefore, shorter string has more efficiency than the larger one

String Efficiency and methods to improve String Efficiency

The ratio of voltage across the whole string to the product of number of discs and the voltage across the disc nearest to the conductor is known as string efficiency i.e.,

$$\text{String Efficiency} = \frac{\text{Voltage across the string}}{n \times \text{Voltage across disc near to conductor}}$$

where n = number of discs in the string.

String efficiency is an important consideration since it decides the potential distribution along the string. The greater the string efficiency, the more uniform is the voltage distribution. Thus 100% string efficiency is an ideal case for which the voltage across each disc will be exactly the same. Although it is impossible to achieve 100% string efficiency, yet efforts should be made to improve it as close to this value as possible.

Methods of Improving String Efficiency

The maximum voltage appears across the insulator nearest to the line conductor and decreases equalise the potential across the various units of the string i.e. to improve the string efficiency progressively as the cross arm is approached. If the insulation of the highest stressed insulator (i.e. nearest to conductor) breaks down or flash over takes place, the breakdown of other units will take place in succession.

The various methods for improving the string efficiency are:

1. **By using longer cross-arms.** The value of string efficiency depends upon the value of K i.e., ratio of shunt capacitance to mutual capacitance. The lesser the value of K, the greater is the string efficiency and more uniform is the voltage distribution. The value of K can be decreased by reducing the shunt capacitance. In order to reduce shunt capacitance, the distance of conductor from tower must be increased i.e., longer cross-arms should be used. However, limitations of cost and strength of tower do not allow the use of very long cross-arms. In practice, $K = 0{\cdot}1$ is the limit that can be achieved by this method.
2. **By grading the insulators.** In this method, insulators of different dimensions are so chosen that each has a different capacitance. The insulators are capacitance graded i.e. they are

assembled in the string in such a way that the top unit has the minimum capacitance, increasing progressively as the bottom unit (i.e., nearest to conductor) is reached. Since voltage is inversely proportional to capacitance, this method tends to equalise the potential distribution across the units in the string. This method has the disadvantage that a large number of different-sized insulators are required. However, good results can be obtained by using standard insulators for most of the string and larger units for that near to the line conductor.

3. **By using a guard ring.** The potential across each unit in a string can be equalised by using a guard ring which is a metal ring electrically connected to the conductor and surrounding the bottom insulator. The guard ring introduces capacitance between metal fittings and the line conductor. The guard ring is contoured in such a way that shunt capacitance currents i1, i2 etc. are equal to metal fitting line capacitance currents i′1, i′2 etc. The result is that same charging current I flows through each unit of string. Consequently, there will be uniform potential distribution across the units.

Conductor Material

The most common conductor in use for transmission today is aluminum conductor steel reinforced (ACSR). Also seeing much use is all-aluminum-alloy conductor (AAAC). Aluminum is used because it has about half the weight of a comparable resistance copper cable (though larger diameter due to lower fundamental conductivity), as well as being cheaper. Copper was more popular in the past and is still in use, especially at lower voltages and for grounding. Bare copper conductors are light green.

While larger conductors may lose less energy due to lower electrical resistance, they are more costly than smaller conductors. An optimization rule called *Kelvin's Law* states that the optimum size of conductor for a line is found when the cost of the energy wasted in the conductor is equal to the annual interest paid on that portion of the line construction cost due to the size of the conductors. The optimization problem is made more complex by additional factors such as varying annual load, varying cost of installation, and the discrete sizes of cable that are commonly made.

Since a conductor is a flexible object with uniform weight per unit length, the geometric shape of a conductor strung on towers approximates that of a catenary. The sag of the conductor (vertical distance between the highest and lowest point of the curve) varies depending on the temperature and additional load such as ice cover. A minimum overhead clearance must be maintained for safety. Since the temperature of the conductor increases with increasing heat produced by the current through it, it is sometimes possible to increase the power handling capacity (uprate) by changing the conductors for a type with a lower coefficient of thermal expansion or a higher allowable operating temperature.

BUNDLE CONDUCTORS

For higher amounts of current, **bundle conductors** are used for several reasons. Due to the skin effect, for larger conductors, the current capacity does not increase proportional to the cross-sectional area; instead, it is only with the linear dimension. Also, reactance decreases only slowly with size. But the cost and weight do increase with area. Due to this, several conductors in parallel become more economical.

Bundle conductors consist of several parallel cables connected at intervals by spacers, often in a cylindrical configuration. The optimum number of conductors depends on the current rating, but typically higher-voltage lines also have higher current. There is also some advantage due to lower corona loss. American Electric Power is building 765 kV lines using six conductors per phase in a bundle. Spacers must resist the forces due to wind, and magnetic forces during a short-circuit.

Advantages

At extra high voltage, the electric field gradient at the surface of a single conductor is high enough to ionize air, which loses power and generates both audible noise and interference with communication systems. The field surrounding a bundle of conductors is similar to the field that would surround a single, very large conductor—this produces lower gradients which mitigates issues associated with high field strength. When transmitting alternating current, bundle conductors also avoid the reduction in capacity of a single large conductor due to the skin effect. A bundle conductor also has lower reactance, compared to a single conductor. Additionally, bundled conductors cool themselves more efficiently due to the increased surface area of the conductors, further reducing line losses.

MECHANICAL DESIGN OF TRANSMISSION LINE

Sag in Overhead Transmission Line:

While erecting an overhead line, it is very important that conductors are under safe tension. If the conductors are too much stretched between supports in a bid to save conductor material, the stress in the conductor may reach unsafe value and in certain cases the conductor may break due to excessive tension. In order to permit safe tension in the conductors, they are not fully stretched but are allowed to have a dip or sag. The difference in level between points of supports and the lowest point on the conductor is called sag. Following Fig. 8.1 shows a conductor suspended between two equal level supports A and B. The conductor is not fully stretched but is allowed to have a dip. The lowest point on the conductor is O and the sag is S.

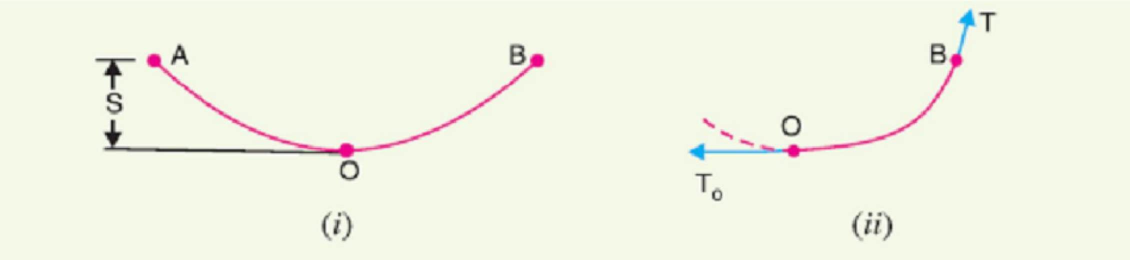


Fig 2.4- Sag in a transmission line

The following points may be noted:

(i) When the conductor is suspended between two supports at the same level, it takes the shape of catenary. However, if the sag is very small compared with the span, then sag-span curve is like a parabola.

(ii) The tension at any point on the conductor acts tangentially. Thus tension T_0 at the lowest Point O acts horizontally as shown in Fig. (ii).

(iii) The horizontal component of tension is constant throughout the length of the wire.

(iv) The tension at supports is approximately equal to the horizontal tension acting at any point on the wire. Thus if T is the tension at the support B, then $T = T_0$.

Conductor sag and tension. This is an important consideration in the mechanical design of overhead lines. The conductor sag should be kept to a minimum in order to reduce the conductor material required and to avoid extra pole height for sufficient clearance above ground level. It is also desirable that tension in the conductor should be low to avoid the mechanical failure of conductor and to permit the use of less strong supports. However, low conductor tension and minimum sag are not possible. It is because low sag means a tight wire and high tension, whereas a low tension means a loose wire and increased sag. Therefore, in actual practice, a compromise in made between the two.

Calculation of Sag: In an overhead line, the sag should be so adjusted that tension in the conductors is within safe limits. The tension is governed by conductor weight, effects of wind, ice loading and temperature variations. It is a standard practice to keep conductor tension less than 50% of its ultimate tensile strength i.e., minimum factor of safety in respect of conductor tension should be 2. We shall now calculate sag and tension of a conductor when (i) supports are at equal levels and (ii) supports are at unequal levels.

When supports are at equal levels. Consider a conductor between two equilevel supports A and B with O as the lowest point as shown in Fig.2.5. It can be proved that lowest point will be at a conductor between two equilevel supports A and B with O as the lowest point as shown in Fig. 2.5. It can be proved that lowest point will be at the mid-span.

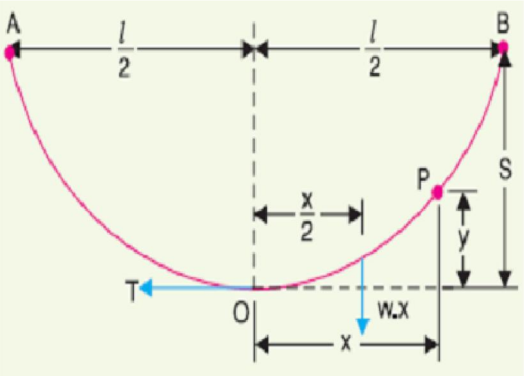


Fig 2.5- Sag Clculation

A conductor between two equilevel supports A and B with O as the lowest point as shown in Fig. 2. It can be proved that lowest point will be at the mid-span.

Let l = Length of span

w = Weight per unit length of conductor

T = Tension in the conductor.

Consider a point P on the conductor. Taking the lowest point O as the origin, let the co-ordinates of point P be x and y. Assuming that the curvature is so small that curved length is equal to its horizontal projection (i.e., OP = x), the two forces acting on the portion OP of the conductor are :

(a) The weight wx of conductor acting at a distance x/2 from O.

(b) The tension T acting at O.

Equating the moments of above two forces about point O, we get,

$$Ty = wx \times \frac{x}{2}$$

$$y = \frac{wx^2}{2T}$$

The maximum dip (sag) is represented by the value of y at either of the supports A & B.

At supports A $x = \frac{l}{2}$ and $y=s$

$$\text{Sag S} = \frac{\text{wl}^2}{8\text{T}}$$

Effect of wind and ice loading- The above formulae for sag are true only in still air and at normal temperature when the conductor is acted by its weight only. However, in actual practice, a conductor may have ice coating and simultaneously subjected to wind pressure. The weight of ice acts vertically downwards i.e., in the same direction as the weight of conductor. The force due to the wind is assumed to act horizontally i.e., at right angle to the projected surface of the conductor. Hence, the total force on the conductor is the vector sum of horizontal and vertical forces as shown in

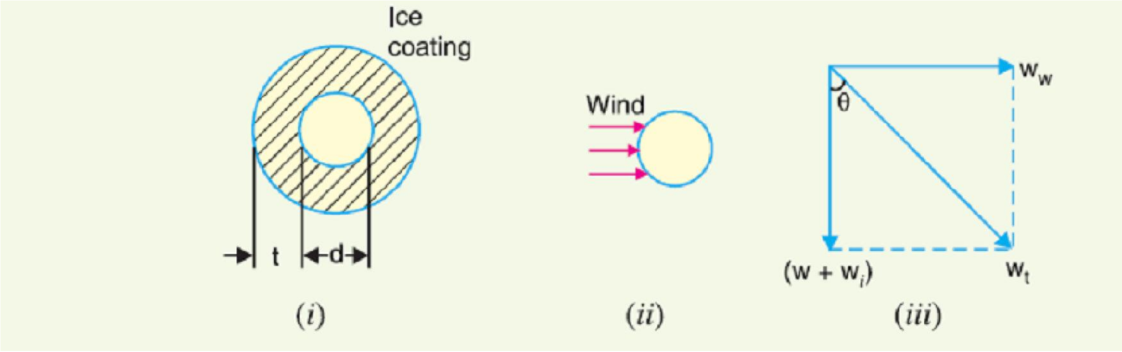


Fig 2.6- Effect of Ice and Wind

Total weight of conductor per unit length is

$$w_t = \sqrt{(w + w_i)^2 + w_w^{\ 2}}$$

Where w = weight of conductor per unit length

= conductor material density × volume per unit length

w_i = weight of ice per unit length

= density of ice * volume of ice per unit length

= density of ice x $\frac{\pi}{4}\left[(d+2t)^2 - d^2\right]\times 1$

w_w = wind force per unit length

= wind pressure per unit area × projected area per unit length

= wind pressure x $\left[(d+2t)\times 1\right]$

Vibration Damper

Aeolian vibrations mostly occur at steady wind velocities from 1 to 7 m/s. With increasing wind turbulences the wind power input to the conductor will decrease. The intensity to induce vibrations depends on several parameters such as type of conductors and clamps, tension, span length, topography in the surrounding, height and direction of the line as well as the frequency of occurrence of the vibration induced wind streams.

In the wake of wind power plants (up to 3 x diameter of the rotor behind the plant) the wind velocity will be reduced up to 0,5 of the velocity of the free wind stream, so that lower wind velocities could be expected more frequently here. That's why the probability of a higher stresses for the conductors caused by wind-induced vibrations will be greater than without wind power plants.

On the other hand the intensity of turbulences will increase which will hinder the arising of vibrations. The both important parameters for inducing vibrations, wind velocity and turbulence intensity, depends on the distance to the rotor and the height of it.

The investigations showed an increasing of damage probability on OHTL due to the wake of wind power plants of the factor 2,5 to 3,5 between one and three rotor diameters behind the plant which will cause an equivalent decreasing of lifetime of conductors and earth wires.

Stringing chart: For use in the field work of stringing the conductors, temperature-sag and temperature tension charts are plotted for the given conductor and loading conditions. Such curves are called stringing charts. These charts are very helpful while stringing overhead lines.

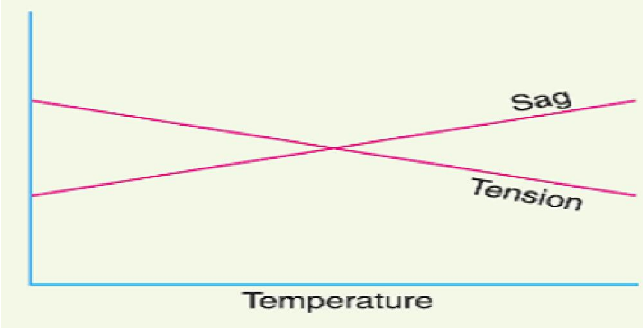


Fig 2.7- Stringing Chart

Sag Template: A Sag Template is a very important tool with the help of which the position of towers on the Profile is decided so that they conform to the limitations of vertical and wind loads on any particular tower, and minimum clearances, as per I.E. Rules, required to be maintained between the line conductor to ground, telephone lines, buildings, streets, navigable canals, power lines, or any other object coming under or near the line.

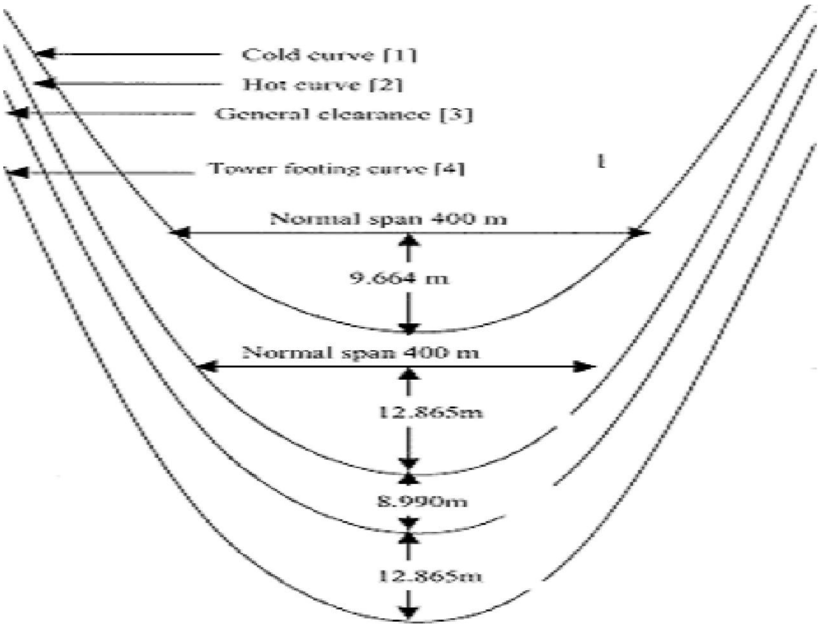


Fig 2.8- Sag Template

A Sag Template is specific for the particular line voltage, the conductor used and the applicable design conditions. Therefore, the correct applicable Sag Template should be used. A Sag Template consists of a set of parabolic curves drawn on a transparent celluloid or a crylic clear sheet duly cut in over the maximum conductor sag curve to allow the conductor curve to be drawn and the lowest points of the conductor sag to be marked on the profile when the profile is placed underneath it.

The set of curves in the sag template consists of:

a) Cold or Uplift Curve’ showing sag of conductor at minimum temperature (minus 2.5ºC) and still wind.

b) Hot or Maximum Sag Curve’ showing maximum sag of conductor at maximum temperature and still wind including sag tolerances allowed (normally 4%), if any, and under maximum ice condition wherever applicable.

c) Ground Clearance Curve’ which is drawn parallel to the ‘Hot or Maximum Sag Curve’ and at a distance equal to the specified minimum ground clearance for the relevant voltage.

d) ‘Tower Footing Curve’ which is drawn parallel to the ‘Ground Clearance Curve’ and separated by a minimum distance equal to the maximum sag at the basic design span.

INSULATED CABLES

Electric power can be transmitted or distributed either by overhead system or by underground cables. The underground cables have several advantages such as less liable to damage through storms or lightning, low maintenance cost, less chance of faults, smaller voltage drop and better general appearance. However, their major drawback is that they have greater installation cost and introduce insulation problems at high voltages compared with the equivalent overhead system. For this reason, underground cables are employed where it is impracticable to use overhead lines. Such locations may be thickly populated areas where municipal authorities prohibit overhead lines for reasons of safety, or around plants and substations or where maintenance conditions do not permit the use of overhead construction. The chief use of underground cables for many years has been for distribution of electric power in congested urban areas at comparatively low or moderate voltages. However, recent improvements in the design and manufacture have led to the development of cables suitable for use at high voltages. This has made it possible to employ underground cables for transmission of electric power for short or moderate distances. In this chapter, we shall focus our attention on the various aspects of underground cables and their increasing use in power system.

Underground Cables:-An underground cable essentially consists of one or more conductors covered with suitable insulation and surrounded by a protecting cover. Although several types of cables are available, the type of cable to be used will depend upon the working voltage and service requirements. In general, a cable must fulfill the following necessary requirements:

(i) The conductor used in cables should be tinned stranded copper or aluminum of high conductivity. Stranding is done so that conductor may become flexible and carry more current.
(ii) The conductor size should be such that the cable carries the desired load current without overheating and causes voltage drop within permissible limits.
(iii) The cable must have proper thickness of insulation in order to give high degree of safety and reliability at the voltage for which it is designed.
(iv) The cable must be provided with suitable mechanical protection so that it may withstand the rough use in laying it.
(v) The materials used in the manufacture of cables should be such that there is complete chemical and physical stability throughout.

Construction of Cables:-Figure shows the general construction of a 3-conductor cable. The various parts are

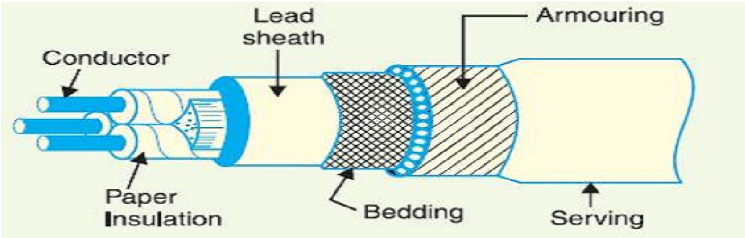


Fig 2.9- Cable

Cores or Conductors. A cable may have one or more than one core (conductor) depending upon the type of service for which it is intended. For instance, the 3 conductor cable shown in Figure is used for 3-phase service. The conductors are made of tinned copper or aluminum and are usually stranded in order to provide flexibility to the cable.

(ii) **Insulation**. Each core or conductor is provided with a suitable thickness of insulation, the thickness of layer depending upon the voltage to be withstood by the cable. The commonly used materials for insulation are impregnated paper, varnished cambric or rubber mineral compound.

(iii) **Metallic sheath**. In order to protect the cable from moisture, gases or other damaging liquids (acids or alkalies) in the soil and atmosphere, a metallic sheath of lead or aluminum is provided over the insulation as shown in Fig.

(iv) **Bedding**. Over the metallic sheath is applied a layer of bedding which consists of a fibrous material like jute or hessian tape. The purpose of bedding is to protect the metallic sheath against corrosion and from mechanical injury due to armouring.

(v) **Armouring**. Over the bedding, armouring is provided which consists of one or two layers of galvanized steel wire or steel tape. Its purpose is to protect the cable from mechanical injury while laying it and during the course of handling. Armouring may not be done in the case of some cables.

(vi) **Serving**. In order to protect armouring from atmospheric conditions, a layer of fibrous material (like jute) similar to bedding is provided over the armouring. This is known as serving.

It may not be out of place to mention here that bedding, armouring and serving are only applied to the cables for the protection of conductor insulation and to protect the metallic sheath from mechanical injury.

Insulating Materials for Cables:-The satisfactory operation of a cable depends to a great extent upon the characteristics of insulation used. Therefore, the proper choice of insulating material for cables is of considerable importance. In general, the insulating materials used in cables should have the following properties:

(i) High insulation resistance to avoid leakage current.

(ii) High dielectric strength to avoid electrical breakdown of the cable.

(iii) High mechanical strength to withstand the mechanical handling of cables.

(iv)Non-hygroscopic i.e., it should not absorb moisture from air or soil. The moisture tends to decrease the insulation resistance and hastens the breakdown of the cable. In case the insulating material is hygroscopic, it must be enclosed in a waterproof covering like lead sheath.

(v) Non-inflammable.

(vi) Low cost so as to make the underground system a viable proposition.

(vii) Unaffected by acids and alkalies to avoid any chemical action. No one insulating material possesses all the above mentioned properties. Therefore, the type of insulating material to be used depends upon the purpose for which the cable is required and the quality of insulation to be aimed at.

The principal insulating materials used in cables are rubber, vulcanized rubber, impregnated paper and polyvinyl chloride.

1. **Rubber**: Rubber may be obtained from milky sap of tropical trees or it may be produced from oil products. It has relative permittivity varying between 2 and 3, dielectric strength is about 30 kV/mm and resistivity of insulation is 1017 cm. Although pure rubber has reasonably high insulating properties, it suffers from some major drawbacks viz., readily absorbs moisture, maximum safe temperature is low (about 38ºC), soft and liable to damage due to rough handling and ages when exposed to light. Therefore, pure rubber cannot be used as an insulating material.

2. Vulcanised India Rubber (V.I.R.). It is prepared by mixing pure rubber with mineral matter such as zinc oxide, red lead etc., and 3 to 5% of sulphur. The compound so formed is rolled into thin sheets and cut into strips. The rubber compound is then applied to the conductor and is heated to a temperature of about 150ºC. The whole process is called vulcanisation and the product obtained is known as vulcanised India rubber. Vulcanised India rubber has greater mechanical strength, durability and wear resistant property than pure rubber. Its main drawback is that sulphur reacts very quickly with copper and for this reason, cables using VIR insulation have tinned copper conductor. The VIR insulation is generally used for low and moderate voltage cables.

3. Impregnated paper. It consists of chemically pulped paper made from wood chippings and impregnated with some compound such as paraffinic or naphthenic material. This type of insulation has almost superseded the rubber insulation. It is because it has the advantages of low cost, low capacitance, high dielectric strength and high insulation resistance. The only disadvantage is that paper is hygroscopic and even if it is impregnated with suitable compound, it absorbs moisture and thus lowers the insulation resistance of the cable.

4. Polyvinyl chloride (PVC). This insulating material is a synthetic compound. It is obtained from the polymerization of acetylene and is in the form of white powder. For obtaining this material as a cable insulation, it is compounded with certain materials known as plasticizers which are liquids with high boiling point. The plasticizer forms a gell and renders the material plastic over the desired range of temperature. Polyvinyl chloride has high insulation resistance, good dielectric strength and mechanical toughness over a wide range of temperatures. It is inert to oxygen and almost inert to many alkalies and acids. Therefore, this type of insulation is preferred over VIR in extreme environmental conditions such as in cement factory or chemical factory. As the mechanical properties (i.e., elasticity etc.) of PVC are not so good as those of rubber, therefore, PVC insulated cables are generally used for low and medium domestic lights and power installations.

Classification of Cables: -Cables for underground service may be classified in two ways according to (i) the type of insulating material used in their manufacture (ii) the voltage for which they are manufactured. However, the latter method of classification is generally preferred, according to which cables can be divided into the following groups:

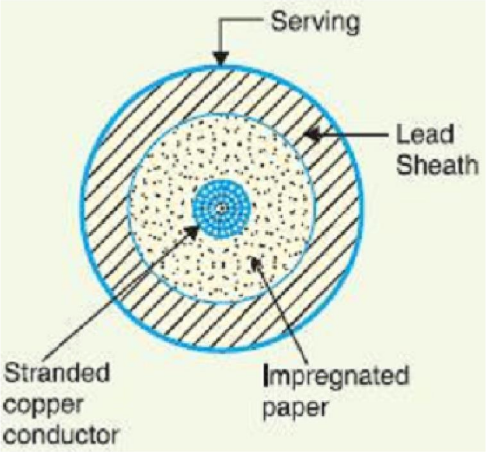


Fig 2.10- Cross section of Cables

(i) Low-tension (L.T.) cables — upto 1000 V

(ii) High-tension (H.T.) cables — upto 11,000 V

(iii) Super-tension (S.T.) cables — from 22 kV to 33 kV

(iv)Extra high-tension (E.H.T.) cables — from 33 kV to 66 kV

(iv) Extra super voltage cables — beyond 132 kV

A cable may have one or more than one core depending upon the type of service for which it is intended. It may be (i) single-core (ii) two-core (iii) three-core (iv) four-core etc. For a 3-phase service, either 3-single-core cables or three-core cable can be used depending upon the operating voltage and load demand. Fig. 11.2 shows the constructional details of a single-core low tension cable. The cable has ordinary construction because the stresses developed in the cable for low voltages (up to 6600 V) are generally small. It consists of one circular core of tinned stranded copper (or aluminium) insulated by layers of impregnated paper. The insulation is surrounded by a lead sheath which prevents the entry of moisture into the inner parts. In order to protect the lead sheath from corrosion, an overall serving of compounded fibrous material (jute etc.) is provided. Single-core cables are not usually armoured in order to avoid excessive sheath losses. The principal advantages of single-core cables are simple construction and availability of larger copper section.

Cable for 3-phase

In practice, underground cables are generally required to deliver 3-phase power. For the purpose, either three-core cable or three single core cables may be used. For voltages upto 66 kV, 3-core cable (i.e., multi-core construction) is preferred due to economic reasons. However, for voltages beyond 66 kV, 3-core-cables become too large and unwieldy and, therefore, single-core cables are used. The following types of cables are generally used for 3-phase service:

1. Belted cables — upto 11 kV
2. Screened cables — from 22 kV to 66 kV
3. Pressure cables — beyond 66 kV

Dielectric Stress in Cable

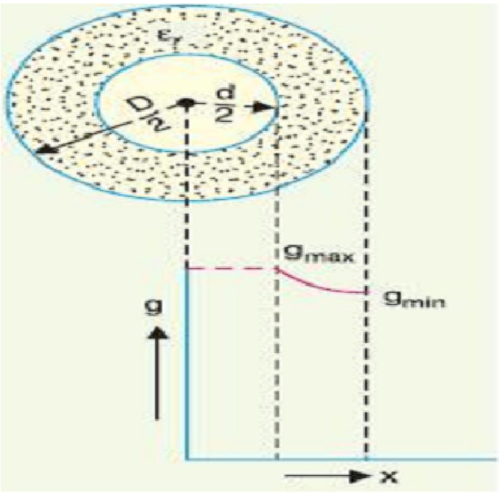


Fig 2.11- Dielectric Stress in Cable

Under operating conditions, the insulation of a cable is subjected to electrostatic forces. This is known as dielectric stress. The dielectric stress at any point in a cable is in fact the potential gradient (or electric intensity) at that point. Consider a single core cable with core diameter d and internal sheath diameter D. The electric intensity at a point x metres from the centre of the cable is

$$E_x = \frac{Q}{2\pi\varepsilon_0\varepsilon_r x} \text{ volts/m}$$

By definition, electric intensity is equal to potential gradient. Therefore, potential gradient g at a point x meters from the Centre of cable is

$$g = E_x$$

$$g = \frac{E}{2\pi\varepsilon_0\varepsilon_r x} \text{ volts/m}$$

Potential difference V between conductor and sheath is

$$V = \frac{Q}{2\pi\varepsilon_0\varepsilon_r}\ln\frac{D}{d} \text{ volts}$$

$$Q = \frac{2\pi\varepsilon_0\varepsilon_r V}{\ln\frac{D}{d}}$$

Substituting the value of Q, we get

$$g = \frac{V}{x\ln\frac{D}{d}} \text{ volts/m}$$

It is clear from the above equation that potential gradient varies inversely as the distance x. Therefore, potential gradient will be maximum when x is minimum i.e., when x = d/2 or at the surface of the conductor. On the other hand, potential gradient will be minimum at x = D/2 or at sheath surface.

Maximum potential gradient is

$$g_{\max} = \frac{2V}{d\ln\frac{D}{d}} \text{ volts/m}$$

Minimum potential gradient is

$$g_{\min} = \frac{2V}{D\ln\frac{D}{d}} \text{ volts/m}$$

$$\frac{g_{\max}}{g_{\min}} = \frac{D}{d}$$

The variation of stress in the dielectric is shown in Fig.14. It is clear that dielectric stress is maximum at the conductor surface and its value goes on decreasing as we move away from the conductor. It may be noted that maximum stress is an important consideration in the design of a cable. For instance, if a cable is to be operated at such a voltage that maximum stress is 5 kV/mm, then the insulation used must have a dielectric strength of at least 5 kV/mm, otherwise breakdown of the cable will become inevitable.

Most Economical Size of Conductor

It has already been shown that maximum stress in a cable occurs at the surface of the conductor. For safe working of the cable, dielectric strength of the insulation should be more than the maximums tress. Rewriting the expression for maximum stress, we get,

$$g_{\max} = \frac{2V}{d \ln \frac{D}{d}} \text{ volts/m}$$

The values of working voltage V and internal sheath diameter D have to be kept fixed at certain values due to design considerations. This leaves conductor diameter d to be the only variable. For given values of V and D, the most economical conductor diameter will be one for which $g_{\max}$ has a minimum value. The value of $g_{\max}$ will be minimum when $d \ln D/d$ is maximum i.e.

$$\frac{d}{dd}\left[d \ln \frac{D}{d}\right] = 0$$

$$\frac{D}{d} = e = 2.718$$

Most economical conductor diameter is

$$d = \frac{D}{2.718}$$

and the value of $g_{\max}$ under this condition is

$$g_{\max} = \frac{2V}{d} \text{ volts/m}$$

Grading of Cables

The process of achieving uniform electrostatic stress in the dielectric of cables is known as grading of cables. It has already been shown that electrostatic stress in a single core cable has a maximum value ($g_{\max}$) at the conductor surface and goes on decreasing as we move towards the sheath. The maximum voltage that can be safely applied to a cable depends upon $g_{\max}$ i.e., electrostatic stress at the conductor surface. For safe working of a cable having homogeneous dielectric, the strength of dielectric must be more than $g_{\max}$. If a dielectric of high strength is used for a cable, it is useful only near the conductor where stress is maximum. But as we move away from the conductor, the electrostatic stress decreases, so the dielectric will be unnecessarily over strong. The unequal stress distribution in a cable is undesirable for two reasons. Firstly, insulation of greater thickness is required which increases the cable size. Secondly, it may lead to the breakdown of insulation. In order to overcome above disadvantages, it is necessary to have a uniform stress distribution in cables. This can be achieved by distributing the stress in such a way that its value is increased in the outer layers of dielectric. This is known as grading of cables. The following are the two main methods of grading of cables:

(i) Capacitance grading (ii) Intersheath grading

Capacitance Grading:

The process of achieving uniformity in the dielectric stress by using layers of different dielectrics is known as capacitance grading.

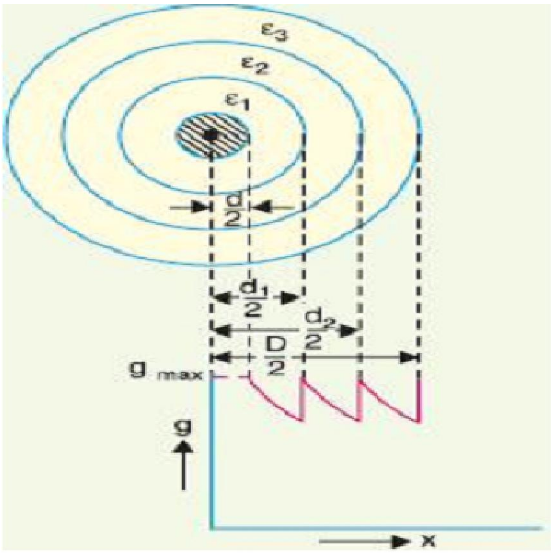


Fig 2.12- Capacitance grading

In capacitance grading, the homogeneous dielectric is replaced by a composite dielectric. The composite dielectric consists of various layers of different dielectrics in such a manner that relative permittivity > r of any layer is inversely proportional to its distance from the center. Under such conditions, the value of potential gradient any point in the dielectric is constant and is independent of its distance from the center. In other words, the dielectric stress in the cable is same everywhere and the grading is ideal one. However, ideal grading requires the use of an infinite number of dielectrics which is an impossible task. In practice, two or three dielectrics are used in the decreasing order of permittivity, the dielectric of highest permittivity being used near the core. The capacitance grading can be explained beautifully by referring to the above Figure. There are three dielectrics of outer diameter d_1, d_2 and D and of relative permittivity >1, >2 and >3 respectively. If the permittivity are such that >1 > 2 > 3 and the three dielectrics are worked at the same maximum stress, then

$$\varepsilon_1 d = \varepsilon_2 d_1 = \varepsilon_3 d_2$$

$$V_1 = \frac{g_{\max}}{2} d \ln \frac{d_1}{d}$$

$$V_2 = \frac{g_{\max}}{2} d_1 \ln \frac{d_2}{d_1}$$

$$V_3 = \frac{g_{\max}}{2} d_2 \ln \frac{D}{d_2}$$

Total p.d. between core and earthed sheath is

$$V = V_1 + V_2 + V_3$$

$$V = \frac{g_{\max}}{2} \left[d \ln \frac{d_1}{d} + d_1 \ln \frac{d_2}{d_1} + d_2 \ln \frac{D}{d_2} \right]$$

Intersheath Grading: In this method of cable grading, a homogeneous dielectric is used, but it is divided into various layers by placing metallic inters heaths between the core and lead sheath. The inter sheaths are held at suitable potentials which are in between the core potential and earth potential. This arrangement improves voltage distribution in the dielectric of the cable and consequently more uniform potential gradient is obtained.

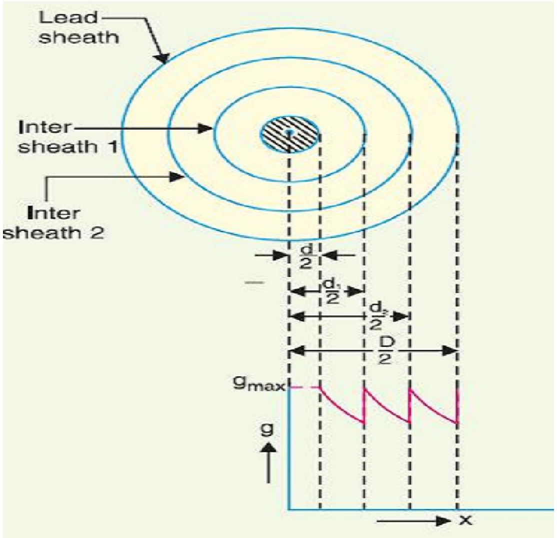


Fig 2.13- Intersheath grading

Consider a cable of core diameter d and outer lead sheath of diameter D. Suppose that two intersheaths of diameters d_1 and d_2 are inserted into the homogeneous dielectric and maintained at some fixed potentials. Let V_1, V_2 and V_3 respectively be the voltage between core and intersheath 1, between inter sheath 1 and 2 and between inter sheath 2 and outer lead sheath. As there is a definite potential difference between the inner and outer layers of each inter sheath, therefore, each sheath can be treated like a homogeneous single core cable Maximum stress between core and inter sheath 1 is

$$g_{1max} = \frac{V_1}{\frac{d}{2}\log_e \frac{d_1}{d}}$$

$$g_{2max} = \frac{V_2}{\frac{d_1}{2}\log_e \frac{d_2}{d_1}}$$

$$g_{3max} = \frac{V_3}{\frac{d_2}{2}\log_e \frac{D}{d_2}}$$

Since the dielectric is homogeneous, the maximum stress in each layer is the same i.e.,

$$g_{1\max} = g_{2\max} = g_{3\max} = g_{\max}$$

$$\frac{V_1}{\frac{d}{2}\ln\frac{d_1}{d}} = \frac{V_2}{\frac{d_1}{2}\ln\frac{d_2}{d_1}} = \frac{V_2}{\frac{d_2}{2}\ln\frac{D}{d}}$$

As the cable behaves like three capacitors in series, therefore, all the potentials are in phase i.e. Voltage between conductor and earthed lead sheath is

$$V = V_1 + V_2 + V_3$$

Inter sheath grading has three principal disadvantages. Firstly, there are complications in fixing the sheath potentials. Secondly, the inter sheaths are likely to be damaged during transportation and installation which might result in local concentrations of potential gradient. Thirdly, there are considerable losses in the inter sheaths due to charging currents. For these reasons, inter sheath grading is rarely used.

Measurement of capacitance of 3-core cables

In three-core cables, capacitance does not have a single value, but can be lumped as shown in below figure.

Capacitance between each core and sheath = C_s

Capacitance between cores = C

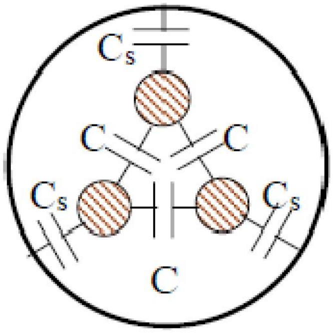


Fig 2.14- Cable Capacitance

These can be separated from measurements as described in the following section.

(a) Strap the 3 cores together and measure the capacitance between this bundle and the sheath as shown in figure.

Measured value = C_{m1} = 3 Cs

This gives the capacitance to the sheath as Cs = $\frac{C_{m1}}{3}$

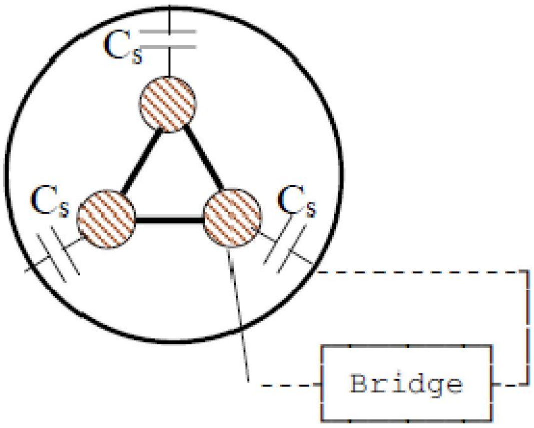


Fig 2.15- Capacitance Measurement

(b) Connect 2 of the cores to the sheath and measure between the remaining core and the sheath.

Measured value $C_{m2} = 2C + C_s$

i.e. $C = (C_{m2} - C_s)/2 = (3C_{m2} - C_{m1})/6$

Which gives the capacitance between the conductors.

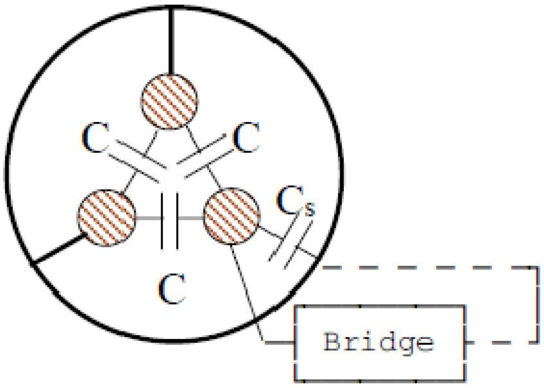


Fig 2.16-Capacitance Measurement

The effective capacitance to neutral Co of any of the cores may be obtained by considering the star equivalent. This gives

$$C_0 = C_s + 3C = \frac{1}{3}C_m 1 + 3\frac{3C_m^2 - C_m^1}{6}$$

$$C_0 = \frac{3}{2}C_m^2 - \frac{1}{6}C_m^1$$

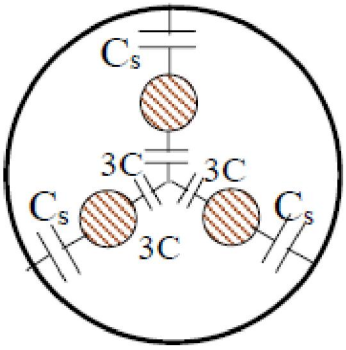


Fig 2.17-Calculation of C_0

In the breakdown of actual 3-core belted cables, it is generally observed that charring occurs at those places where the stress is tangential to the layers of paper. Thus for the insulation to be effective, the tangential stresses in paper insulation should be preferably avoided. This can usually be accomplished only screening each core separately (or by having individual lead sheaths for each of the cores), so that the cable in effect becomes 3 individual cables laid within the same protective covering.

MODULE III

LOAD FLOW STUDIES

Load flow studies are important in planning and designing future expansion of power systems. The load flow gives us the sinusoidal steady state of the entire system – voltages, real and reactive power generated and absorbed and line losses. Generally, load flow studies are limited to the transmission system, which involves bulk power transmission.

Through the load flow studies we can obtain the voltage magnitudes and angles at each bus in the steady state. This is rather important as the magnitudes of the bus voltages are required to be held within a specified limit. Once the bus voltage magnitudes and their angles are computed using the load flow, the real and reactive power flow through each line can be computed. Also based on the difference between power flow in the sending and receiving ends, the losses in a particular line can also be computed. Furthermore, from the line flow we can also determine the over and under load conditions. Load flow studies throw light on some of the important aspects of the system operation, such as: violation of voltage magnitudes at the buses, overloading of lines, overloading of generators, stability margin reduction, indicated by power angle differences between buses linked by a line, effect of contingencies like line voltages, emergency shutdown of generators, etc. Load flow studies are required for deciding the economic operation of the power system. They are also required in transient stability studies. Hence, load flow studies play a vital role in power system studies.

CLASSIFICATION OF BUSES

For load flow studies it is assumed that the loads are constant and they are defined by their real and reactive power consumption. It is further assumed that the generator terminal voltages are tightly regulated and therefore are constant. The main objective of the load flow is to find the voltage magnitude of each bus and its angle when the powers generated and loads are pre-specified. To facilitate this we classify the different buses of the power system as listed below.

1. ***Load Buses***: In these buses no generators are connected and hence the generated real power P_{Gi} and reactive power Q_{Gi} are taken as zero. The load drawn by these buses are defined by real power $-P_{Li}$ and reactive power $-Q_{Li}$ in which the negative sign accommodates for the

power flowing out of the bus. This is why these buses are sometimes referred to as P-Q bus. The objective of the load flow is to find the bus voltage magnitude $|V_i|$ and its angle δ_i.

2. ***Voltage Controlled Buses***: These are the buses where generators are connected. Therefore the power generation in such buses is controlled through a prime mover while the terminal voltage is controlled through the generator excitation. Keeping the input power constant through turbine-governor control and keeping the bus voltage constant using automatic voltage regulator, we can specify constant P_{Gi} and $|V_i|$ for these buses. This is why such buses are also referred to as P-V buses.
3. ***Slack or Swing Bus***: Usually this bus is numbered 1 for the load flow studies. This bus sets the angular reference for all the other buses. Since it is the angle difference between two voltage sources that dictates the real and reactive power flow between them, the particular angle of the slack bus is not important. However it sets the reference against which angles of all the other bus voltages are measured. For this reason the angle of this bus is usually chosen as 0°. Furthermore it is assumed that the magnitude of the voltage of this bus is known.

Now consider a typical load flow problem in which all the load demands are known. Even if the generation matches the sum total of these demands exactly, the mismatch between generation and load will persist because of the line I^2R losses. Since the I^2R loss of a line depends on the line current which, in turn, depends on the magnitudes and angles of voltages of the two buses connected to the line, it is rather difficult to estimate the loss without calculating the voltages and angles. For this reason a generator bus is usually chosen as the slack bus without specifying its real power. It is assumed that the generator connected to this bus will supply the balance of the real power required and the line losses.

REAL AND REACTIVE POWER INJECTED IN A BUS

For the formulation of the real and reactive power entering a bus, we need to define the following quantities. Let the voltage at the i^{th} bus be denoted by

$$V_i = |V_i|\angle\delta_i = |V_i|(\cos\delta_i + j\sin\delta_i) \tag{3.1}$$

Also let us define the self admittance at bus-*i* as

$$Y_{ii} = |Y_{ii}|\angle\theta_{ii} = |Y_{ii}|(\cos\theta_{ii} + j\sin\theta_{ii}) = G_{ii} + jB_{ii} \tag{3.2}$$

Similarly the mutual admittance between the buses *i* and *j* can be written as

$$Y_{ij} = |Y_{ij}|\angle\theta_{ij} = |Y_{ij}|(\cos\theta_{ij} + j\sin\theta_{ij}) = G_{ij} + jB_{ij} \tag{3.3}$$

Let the power system contains a total number of *n* buses. The current injected at bus-*i* is given as

$$\begin{aligned} I_i &= Y_{i1}V_1 + Y_{i2}V_2 + \cdots + Y_{in}V_n \\ &= \sum_{k=1}^{n} Y_{ik}V_k \end{aligned} \tag{3.4}$$

It is to be noted we shall assume the current entering a bus to be positive and that leaving the bus to be negative. As a consequence the power and reactive power entering a bus will also be assumed to be positive. The complex power at bus-*i* is then given by

$$\begin{aligned} P_i - jQ_i &= V_i^* I_i = V_i^* \sum_{k=1}^{n} Y_{ik}V_k \\ &= |V_i|(\cos\delta_i - j\sin\delta_i)\sum_{k=1}^{n} |Y_{ik}V_k|(\cos\theta_{ik} + j\sin\theta_{ik})(\cos\delta_k + j\sin\delta_k) \\ &= \sum_{k=1}^{n} |Y_{ik}V_iV_k|(\cos\delta_i - j\sin\delta_i)(\cos\theta_{ik} + j\sin\theta_{ik})(\cos\delta_k + j\sin\delta_k) \end{aligned} \tag{3.5}$$

Note that

$$\begin{aligned} &(\cos\delta_i - j\sin\delta_i)(\cos\theta_{ik} + j\sin\theta_{ik})(\cos\delta_k + j\sin\delta_k) \\ &\quad = (\cos\delta_i - j\sin\delta_i)[\cos(\theta_{ik} + \delta_k) + j\sin(\theta_{ik} + \delta_k)] \\ &\quad = \cos(\theta_{ik} + \delta_k - \delta_i) + j\sin(\theta_{ik} + \delta_k - \delta_i) \end{aligned}$$

Therefore substituting in (3.5) we get the real and reactive power as

$$P_i = \sum_{k=1}^{n} |Y_{ik} V_i V_k| \cos(\theta_{ik} + \delta_k - \delta_i) \tag{3.6}$$

$$Q_i = -\sum_{k=1}^{n} |Y_{ik} V_i V_k| \sin(\theta_{ik} + \delta_k - \delta_i) \tag{3.7}$$

PREPARATION OF DATA FOR LOAD FLOW

Let real and reactive power generated at bus-*i* be denoted by P_{Gi} and Q_{Gi} respectively. Also let us denote the real and reactive power consumed at the i^{th} bus by P_{Li} and Q_{Li} respectively. Then the net real power injected in bus-*i* is

$$P_{i,inj} = P_{Gi} - P_{Li} \tag{3.8}$$

Let the injected power calculated by the load flow program be $P_{i,calc}$. Then the mismatch between the actual injected and calculated values is given by

$$\Delta P_i = P_{i,inj} - P_{i,calc} = P_{Gi} - P_{Li} - P_{i,calc} \tag{3.9}$$

In a similar way the mismatch between the reactive power injected and calculated values is given by

$$\Delta Q_i = Q_{i,inj} - Q_{i,calc} = Q_{Gi} - Q_{Li} - Q_{i,calc} \tag{3.10}$$

The purpose of the load flow is to minimize the above two mismatches. It is to be noted that (3.6) and (3.7) are used for the calculation of real and reactive power in (3.9) and (3.10). However since the magnitudes of all the voltages and their angles are not known a priori, an iterative procedure must be used to estimate the bus voltages and their angles in order to calculate the mismatches. It is expected that mismatches ΔP_i and ΔQ_i reduce with each iteration and the load flow is said to have converged when the mismatches of all the buses become less than a very small number.

For the load flow studies we shall consider the system of Fig. 3.1, which has 2 generator and 3 load buses. We define bus-1 as the slack bus while taking bus-5 as the P-V bus. Buses 2, 3 and 4 are P-Q buses. The line impedances and the line charging admittances are given in Table 3.1. Based on this data the Y_{bus} matrix is given in Table 3.2. This matrix is formed using the same procedure as given in Section 3.1.3. It is to be noted here that the sources and their internal impedances are not considered while forming the Y_{bus} matrix for load flow studies which deal only with the bus voltages.

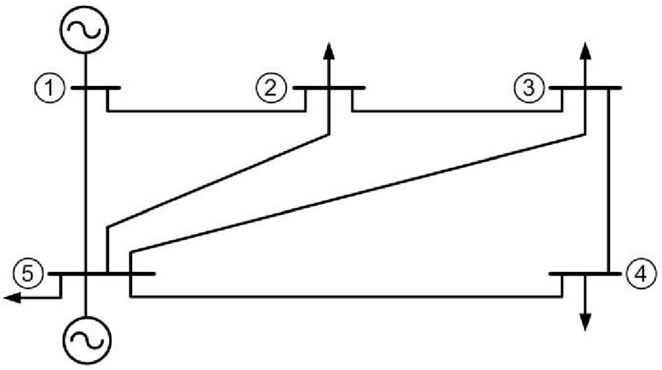


Fig. 3.1 The simple power system used for load flow studies.

Table 3.1 Line impedance and line charging data of the system of Fig. 3.1.

Line (bus to bus)	Impedance	Line charging ($Y/2$)
1-2	$0.02 + j0.10$	$j0.030$
1-5	$0.05 + j0.25$	$j0.020$
2-3	$0.04 + j0.20$	$j0.025$
2-5	$0.05 + j0.25$	$j0.020$
3-4	$0.05 + j0.25$	$j0.020$
3-5	$0.08 + j0.40$	$j0.010$
4-5	$0.10 + j0.50$	$j0.075$

Table 3.2 Y_{bus} matrix of the system of Fig. 3.1.

	1	**2**	**3**	**4**	**5**
1	2.6923 – *j*13.4115	– 1.9231 + *j*9.6154	0	0	– 0.7692 + *j*3.8462
2	– 1.9231 + *j*9.6154	3.6538 – *j*18.1942	– 0.9615 + *j*3.8077	0	– 0.7692 + *j*3.8462
3	0	– 0.9615 + *j*3.8077	2.2115 – *j*11.0027	– 0.7692 + *j*3.8462	– 0.4808 + *j*2.4038
4	0	0	– 0.7692 + *j*3.8462	1.1538 – *j*5.6742	– 0.3846 + *j*1.9231
5	– 0.7692 + *j*3.8462	– 0.7692 + *j*3.8462	– 0.4808 + *j*2.4038	– 0.3846 + *j*1.9231	2.4038 – *j*11.8942

The bus voltage magnitudes, their angles, the power generated and consumed at each bus are given in Table 3.3. In this table some of the voltages and their angles are given in boldface letters. This indicates that these are initial data used for starting the load flow program. The power and reactive power generated at the slack bus and the reactive power generated at the P-V bus are unknown. Therefore each of these quantities are indicated by a dash (–). Since we do not need these quantities for our load flow calculations, their initial estimates are not required. Also note from Fig. 3.1 that the slack bus does not contain any load while the P-V bus 5 has a local load and this is indicated in the load column.

Table 3.3 Bus voltages, power generated and load – initial data.

Bus no.	Bus voltage		Power generated		Load	
	Magnitude (pu)	Angle (deg)	P (MW)	Q (MVAr)	P (MW)	P (MVAr)
1	1.05	0	–	–	0	0
2	**1**	**0**	0	0	96	62
3	**1**	**0**	0	0	35	14
4	**1**	**0**	0	0	16	8
5	1.02	**0**	48	–	24	11

LOAD FLOW BY GAUSS-SEIDEL METHOD

The basic power flow equations (3.6) and (3.7) are nonlinear. In an n-bus power system, let the number of P-Q buses be n_p and the number of P-V (generator) buses be n_g such that $n = n_p + n_g + 1$. Both voltage magnitudes and angles of the P-Q buses and voltage angles of the P-V buses are unknown making a total number of $2n_p + n_g$ quantities to be determined. Amongst the known quantities are $2n_p$ numbers of real and reactive powers of the P-Q buses, $2n_g$ numbers of real powers and voltage magnitudes of the P-V buses and voltage magnitude and angle of the slack bus. Therefore there are sufficient numbers of known quantities to obtain a solution of the load flow problem. However, it is rather difficult to obtain a set of closed form equations from (3.6) and (3.7). We therefore have to resort to obtain iterative solutions of the load flow problem.

In the Gauss-Seidel load flow we denote the initial voltage of the i^{th} bus by $V_i^{(0)}$, $i = 2, \ldots, n$. This should read as the voltage of the i^{th} bus at the 0^{th} iteration, or initial guess. Similarly this voltage after the first iteration will be denoted by $V_i^{(1)}$. In this Gauss-Seidel load flow the load buses and voltage controlled buses are treated differently. However in both these type of buses we use the complex power equation given in (3.5) for updating the voltages. Knowing the real and reactive power injected at any bus we can expand (3.5) as

$$P_{i,inj} - jQ_{i,inj} = V_i^* \sum_{k=1}^{n} Y_{ik} V_k = V_i^* \left[Y_{i1} V_1 + Y_{i2} V_2 + \cdots + Y_{ii} V_i + \cdots + Y_{in} V_n \right] \tag{3.11}$$

We can rewrite (3.11) as

$$V_i = \frac{1}{Y_{ii}} \left[\frac{P_{i,inj} - jQ_{i,inj}}{V_i^*} - Y_{i1} V_1 - Y_{i2} V_2 - \cdots - Y_{in} V_n \right] \tag{3.12}$$

In this fashion the voltages of all the buses are updated.

Algorithm for GS method

1. Prepare data for the given system as required.

2. Formulate the bus admittance matrix Y_{BUS}. This is generally done by the rule of inspection.

3. Assume initial voltages for all buses, 2,3,…n. In practical power systems, the magnitude of the bus voltages is close to 1.0 p.u. Hence, the complex bus voltages at all (n-1) buses (except slack bus) are taken to be 1.0<0.This is normally referred as the flat start solution.

4. Update the voltages. In any k+1 iteration, the voltages are given by

$$V_i = \frac{1}{Y_{ii}} \left[\frac{P_{i,inj} - jQ_{i,inj}}{(V_i^K)^*} - \sum_{j=1}^{i-1} Y_{ij} V_j^{k+1} - \sum_{j=i+1}^{n} Y_{ij} V_j^k \right] \quad \text{for i=2,3,......n}$$

Here note that when computation is carried out for bus-i, updated values are already available for buses 2,3…....(i-1) in the current (k+1) iteration. Hence these values are used. For buses (i+1)…..n, values from previous, k^{th} iteration are used.

5. Continue the iteration till $\left|\Delta V_i^{k+1}\right| = \left|V_i^{k+1} - V_i^k\right| < \varepsilon$ for i=2,3,......n Where,ε is the tolerance value. Generally it is customary to use a value of 0.0001 pu.

6. Compute slack bus power after voltages have converged [assuming bus 1 is slack bus].

$$S_1^* = P_1 - jQ_1 = V_1^* \left(\sum_{j=1}^{n} Y_{1j} V_j \right)$$

7. Compute all line flows.

8. The complex power loss in the line is given by S_{ik} + S_i. The total loss in the system is calculated by summing the loss over all the lines.

Updating Load Bus Voltages

Let us start the procedure with bus-2. Since this is load bus, both the real and reactive power into this bus is known. We can therefore write from (3.12)

$$V_2^{(1)} = \frac{1}{Y_{22}}\left[\frac{P_{2,inj} - jQ_{2,inj}}{V_2^{*(0)}} - Y_{21}V_1 - Y_{23}V_3^{(0)} - Y_{24}V_4^{(0)} - Y_{25}V_5^{(0)}\right] \tag{3.13}$$

From the data given in Table 3.3 we can write

$$V_2^{(1)} = \frac{1}{Y_{22}}\left[\frac{-0.96 + j0.62}{1} - 1.05Y_{21} - Y_{23} - Y_{24} - 1.02Y_{25}\right]$$

It is to be noted that since the real and reactive power is drawn from this bus, both these quantities appear in the above equation with a negative sign. With the values of the Y_{bus} elements given in Table 3.2 we get $V_2^{(1)} = 0.9927\angle -2.5959°$.

The first iteration voltage of bus-3 is given by

$$V_3^{(1)} = \frac{1}{Y_{33}}\left[\frac{P_{3,inj} - jQ_{3,inj}}{V_3^{*(0)}} - Y_{31}V_1 - Y_{32}V_2^{(1)} - Y_{34}V_4^{(0)} - Y_{35}V_5^{(0)}\right] \tag{3.14}$$

Note that in the above equation since the update for the bus-2 voltage is already available, we used the 1st iteration value of this rather than the initial value. Substituting the numerical data we get $V_3^{(1)} = 0.9883\angle -2.8258°$. Finally the bus-4 voltage is given by

$$V_4^{(1)} = \frac{1}{Y_{44}}\left[\frac{P_{4,inj} - jQ_{4,inj}}{V_4^{*(0)}} - Y_{41}V_1 - Y_{42}V_2^{(1)} - Y_{44}V_3^{(1)} - Y_{45}V_5^{(0)}\right] \tag{3.15}$$

Solving we get $V_4^{(1)} = 0.9968\angle -3.4849°$.

Updating P-V Bus Voltages

It can be seen from Table 3.3 that even though the real power is specified for the P-V bus-5, its reactive power is unknown. Therefore to update the voltage of this bus, we must first estimate the reactive power of this bus. Note from Fig. 3.11 that

$$Q_{i,inj} = -\operatorname{Im}\left[V_i^* \sum_{k=1}^{n} Y_{ik} V_k\right] = -\operatorname{Im}\left[V_i^* \left\{Y_{i1}V_1 + Y_{i2}V_2 + \cdots + Y_{ii}V_i + \cdots + Y_{in}V_n\right\}\right] \tag{3.16}$$

And hence we can write the k^{th} iteration values as

$$Q_{i,inj}^{(k)} = -\operatorname{Im}\left[V_i^{*(k-1)}\left\{Y_{i1}V_1 + Y_{i2}V_2^{(k)} + \cdots + Y_{ii}V_i^{(k-1)} + \cdots + Y_{in}V_n^{(k-1)}\right\}\right] \tag{3.17}$$

For the system of Fig. 3.1 we have

$$Q_{5,inj}^{(1)} = -\operatorname{Im}\left[V_1^{*(0)}\left\{Y_{51}V_1 + Y_{52}V_2^{(1)} + Y_{53}V_3^{(1)} + Y_{54}V_4^{(1)} + Y_{55}V_5^{(0)}\right\}\right] \tag{3.18}$$

This is computed as 0.0899 per unit. Once the reactive power is estimated, the bus-5 voltage is updated as

$$V_5^{(1)} = \frac{1}{Y_{55}}\left[\frac{P_{5,inj} - jQ_{5,inj}^{(1)}}{V_5^{*(0)}} - Y_{51}V_1 - Y_{52}V_2^{(1)} - Y_{53}V_3^{(1)} - Y_{54}V_4^{(0)}\right] \tag{3.19}$$

It is to be noted that even though the power generation in bus-5 is 48 MW, there is a local load that is consuming half that amount. Therefore the net power injected by this bus is 24 MW and consequently the injected power $P_{5,inj}$ in this case is taken as 0.24 per unit. The voltage is calculated as $V_4^{(1)} = 1.0169\angle -0.8894°$. Unfortunately however the magnitude of the voltage obtained above is not equal to the magnitude given in Table 3.3. We must therefore force this voltage magnitude to be equal to that specified. This is accomplished by

$$V_{5,corr}^{(1)} = |V_5| \times \frac{V_5^{(1)}}{\left|V_5^{(1)}\right|} \tag{3.20}$$

This will fix the voltage magnitude to be 1.02 per unit while retaining the phase of − 0.8894°. The corrected voltage is used in the next iteration.

Convergence of the Algorithm

As can be seen from Table 3.3 that a total number of 4 real and 3 reactive powers are known to us. We must then calculate each of these from (3.6) and (3.7) using the values of the voltage magnitudes and their angle obtained after each iteration. The power mismatches are then calculated from (3.9) and (3.10). The process is assumed to have converged when each of ΔP_2, ΔP_3, ΔP_4, ΔP_5, ΔQ_2, ΔQ_3 and ΔQ_4 is below a small pre-specified value. At this point the process is terminated.

Sometimes to accelerate computation in the P-Q buses the voltages obtained from (3.12) is multiplied by a constant. The voltage update of bus-*i* is then given by

$$V_{i,acc}^{(k)} = (1-\lambda)V_{i,acc}^{(k-1)} + \lambda V_i^{(k)} = V_{i,acc}^{(k-1)} + \lambda\left\{V_i^{(k)} - V_{i,acc}^{(k-1)}\right\} \tag{3.21}$$

where λ is a constant that is known as the *acceleration factor*. The value of λ has to be below 2.0 for the convergence to occur. Table 3.4 lists the values of the bus voltages after the 1st iteration and number of iterations required for the algorithm to converge for different values of λ. It can be seen that the algorithm converges in the least number of iterations when λ is 1.4 and the maximum number of iterations are required when λ is 2. In fact the algorithm will start to diverge if larger values of acceleration factor are chosen. The system data after the convergence of the algorithm will be discussed later.

Table 3.4 Gauss-Seidel method: bus voltages after 1st iteration and number of iterations required for convergence for different values of λ.

λ	Bus voltages (per unit) after 1st iteration				No of iterations for convergence
	V_2	V_3	V_4	V_5	
1	$0.9927\angle -2.6°$	$0.9883\angle -2.83°$	$0.9968\angle -3.48°$	$1.02\angle -0.89°$	28
2	$0.9874\angle -5.22°$	$0.9766\angle -8.04°$	$0.9918\angle -14.02°$	$1.02\angle -3.39°$	860
1.8	$0.9883\angle -3.7°$	$0.9785\angle -6.8°$	$0.9903\angle -11.12°$	$1.02\angle -3.52°$	54
1.6	$0.9893\angle -3.17°$	$0.9807\angle -5.67°$	$0.9909\angle -8.65°$	$1.02\angle -2.74°$	24
1.4	$0.9903\angle -3.64°$	$0.9831\angle -3.62°$	$0.9926\angle -6.57°$	$1.02\angle -2.05°$	14
1.2	$0.9915\angle -3.11°$	$0.9857\angle -3.68°$	$0.9947\angle -3.87°$	$1.02\angle -1.43°$	19

SOLUTION OF A SET OF NONLINEAR EQUATIONS BY NEWTON-RAPHSON METHOD

In this section we shall discuss the solution of a set of nonlinear equations through Newton-Raphson method. Let us consider that we have a set of n nonlinear equations of a total number of n variables $x_1, x_2, \ldots, x_n$. Let these equations be given by

$$\begin{aligned} f_1(x_1,\cdots,x_n) &= \eta_1 \\ f_2(x_1,\cdots,x_n) &= \eta_2 \\ &\vdots \\ f_n(x_1,\cdots,x_n) &= \eta_n \end{aligned} \tag{3.22}$$

where f_1, …, f_n are functions of the variables x_1, x_2, …, x_n. We can then define another set of functions g_1, …, g_n as given below

$$\begin{gathered} g_1(x_1,\cdots,x_n)=f_1(x_1,\cdots,x_n)-\eta_1=0 \\ g_2(x_1,\cdots,x_n)=f_2(x_1,\cdots,x_n)-\eta_2=0 \\ \vdots \\ g_n(x_1,\cdots,x_n)=f_n(x_1,\cdots,x_n)-\eta_n=0 \end{gathered} \tag{3.23}$$

Let us assume that the initial estimates of the n variables are $x_1^{(0)}$, $x_2^{(0)}$, …, $x_n^{(0)}$. Let us add corrections $\Delta x_1^{(0)}$, $\Delta x_2^{(0)}$, …, $\Delta x_n^{(0)}$ to these variables such that we get the correct solution of these variables defined by

$$\begin{gathered} x_1^*=x_1^{(0)}+\Delta x_1^{(0)} \\ x_2^*=x_2^{(0)}+\Delta x_2^{(0)} \\ \vdots \\ x_n^*=x_n^{(0)}+\Delta x_n^{(0)} \end{gathered} \tag{3.24}$$

The functions in (3.23) then can be written in terms of the variables given in (3.24) as

$$g_k(x_1^*,\cdots,x_n^*)=g_k\left(x_1^{(0)}+\Delta x_1^{(0)},\cdots,x_n^{(0)}+\Delta x_n^{(0)}\right),\quad k=1,\ldots,n \tag{3.25}$$

We can then expand the above equation in Taylor's series around the nominal values of $x_1^{(0)}$, $x_2^{(0)}$, …, $x_n^{(0)}$. Neglecting the second and higher order terms of the series, the expansion of g_k, k = 1, …, n is given as

$$g_k(x_1^*,\cdots,x_n^*)=g_k\left(x_1^{(0)},\cdots,x_n^{(0)}\right)+\Delta x_1^{(0)}\left.\frac{\partial g_k}{\partial x_1}\right|^{(0)}+\Delta x_2^{(0)}\left.\frac{\partial g_k}{\partial x_2}\right|^{(0)}+\cdots+\Delta x_n^{(0)}\left.\frac{\partial g_k}{\partial x_n}\right|^{(0)} \tag{3.26}$$

where $\left.\partial g_k/\partial x_i\right|^{(0)}$ is the partial derivative of g_k evaluated at $x_2^{(0)}$, …, $x_n^{(0)}$.

Equation (3.26) can be written in vector-matrix form as

$$\begin{bmatrix} \partial g_1/\partial x_1 & \partial g_1/\partial x_2 & \cdots & \partial g_1/\partial x_n \\ \partial g_2/\partial x_1 & \partial g_2/\partial x_2 & \cdots & \partial g_2/\partial x_n \\ \vdots & \vdots & \ddots & \vdots \\ \partial g_n/\partial x_1 & \partial g_n/\partial x_2 & \cdots & \partial g_n/\partial x_n \end{bmatrix}^{(0)} \begin{bmatrix} \Delta x_1^{(0)} \\ \Delta x_2^{(0)} \\ \vdots \\ \Delta x_n^{(0)} \end{bmatrix} = \begin{bmatrix} 0 - g_1\left(x_1^{(0)},\cdots,x_n^{(0)}\right) \\ 0 - g_2\left(x_1^{(0)},\cdots,x_n^{(0)}\right) \\ \vdots \\ 0 - g_n\left(x_1^{(0)},\cdots,x_n^{(0)}\right) \end{bmatrix} \tag{3.27}$$

The square matrix of partial derivatives is called the Jacobian matrix J with $J^{(0)}$ indicating that the matrix is evaluated for the initial values of $x_2^{(0)}$, …, $x_n^{(0)}$. We can then write the solution of (3.27) as

$$\begin{bmatrix} \Delta x_1^{(0)} \\ \Delta x_2^{(0)} \\ \vdots \\ \Delta x_n^{(0)} \end{bmatrix} = \left[J^{(0)}\right]^{-1} \begin{bmatrix} \Delta g_1^{(0)} \\ \Delta g_2^{(0)} \\ \vdots \\ \Delta g_n^{(0)} \end{bmatrix} \tag{3.28}$$

Since the Taylor's series is truncated by neglecting the 2nd and higher order terms, we cannot expect to find the correct solution at the end of first iteration. We shall then have

$$\begin{aligned} x_1^{(1)} &= x_1^{(0)} + \Delta x_1^{(0)} \\ x_2^{(1)} &= x_2^{(0)} + \Delta x_2^{(0)} \\ &\vdots \\ x_n^{(1)} &= x_n^{(0)} + \Delta x_n^{(0)} \end{aligned} \tag{3.29}$$

These are then used to find $J^{(1)}$ and $\Delta g_k^{(1)}$, $k = 1, \ldots, n$. We can then find $\Delta x_2^{(1)}$, …, $\Delta x_n^{(1)}$ from an equation like (3.28) and subsequently calculate $x_2^{(1)}$, …, $x_n^{(1)}$. The process continues till Δg_k, $k = 1, \ldots, n$ becomes less than a small quantity.

LOAD FLOW BY NEWTON-RAPHSON METHOD

Let us assume that an n-bus power system contains a total number of n_p P-Q buses while the number of P-V (generator) buses be n_g such that $n = n_p + n_g + 1$. Bus-1 is assumed to be the slack bus. We shall further use the mismatch equations of ΔP_i and ΔQ_i given in (3.9) and (3.10) respectively. The approach to Newton-Raphson load flow is similar to that of solving a system of nonlinear equations using the Newton-Raphson method: at each iteration we have to form a

Jacobian matrix and solve for the corrections from an equation of the type given in (3.27). For the load flow problem, this equation is of the form

$$J\begin{bmatrix} \Delta\delta_2 \\ \vdots \\ \Delta\delta_n \\ \dfrac{\Delta|V_2|}{|V_2|} \\ \vdots \\ \dfrac{\Delta|V_{1+n_p}|}{|V_{1+n_p}|} \end{bmatrix} = \begin{bmatrix} \Delta P_2 \\ \vdots \\ \Delta P_n \\ \Delta Q_2 \\ \vdots \\ \Delta Q_{1+n_p} \end{bmatrix} \tag{3.30}$$

where the Jacobian matrix is divided into submatrices as

$$J = \begin{bmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{bmatrix} \tag{3.31}$$

It can be seen that the size of the Jacobian matrix is $(n + n_p - 1) \times (n + n_p - 1)$. For example for the 5-bus problem of Fig. 3.1 this matrix will be of the size (7×7). The dimensions of the submatrices are as follows:

J_{11}: $(n - 1) \times (n - 1)$, J_{12}: $(n - 1) \times n_p$, J_{21}: $n_p \times (n - 1)$ and J_{22}: $n_p \times n_p$

The submatrices are

$$J_{11} = \begin{bmatrix} \dfrac{\partial P_2}{\partial \delta_2} & \cdots & \dfrac{\partial P_2}{\partial \delta_n} \\ \vdots & \ddots & \vdots \\ \dfrac{\partial P_n}{\partial \delta_2} & \cdots & \dfrac{\partial P_n}{\partial \delta_n} \end{bmatrix} \tag{3.32}$$

$$J_{12} = \begin{bmatrix} |V_2|\dfrac{\partial P_2}{\partial |V_2|} & \cdots & |V_{1+n_p}|\dfrac{\partial P_2}{\partial |V_{1+n_p}|} \\ \vdots & \ddots & \vdots \\ |V_2|\dfrac{\partial P_n}{\partial |V_2|} & \cdots & |V_{1+n_p}|\dfrac{\partial P_n}{\partial |V_{1+n_p}|} \end{bmatrix} \tag{3.33}$$

$$J_{21} = \begin{bmatrix} \dfrac{\partial Q_2}{\partial \delta_2} & \cdots & \dfrac{\partial Q_2}{\partial \delta_n} \\ \vdots & \ddots & \vdots \\ \dfrac{\partial Q_{1+n_p}}{\partial \delta_2} & \cdots & \dfrac{\partial Q_{1+n_p}}{\partial \delta_n} \end{bmatrix} \tag{3.34}$$

$$J_{22} = \begin{bmatrix} |V_2|\dfrac{\partial Q_2}{\partial |V_2|} & \cdots & |V_{1+n_p}|\dfrac{\partial Q_2}{\partial |V_{1+n_p}|} \\ \vdots & \ddots & \vdots \\ |V_2|\dfrac{\partial Q_{1+n_p}}{\partial |V_2|} & \cdots & |V_{1+n_p}|\dfrac{\partial Q_{1+n_p}}{\partial |V_{1+n_p}|} \end{bmatrix} \tag{3.35}$$

Load Flow Algorithm

The Newton-Raphson procedure is as follows:

Step-1: Choose the initial values of the voltage magnitudes $|V|^{(0)}$ of all n_p load buses and $n - 1$ angles $\delta^{(0)}$ of the voltages of all the buses except the slack bus.

Step-2: Use the estimated $|V|^{(0)}$ and $\delta^{(0)}$ to calculate a total $n - 1$ number of injected real power $P_{calc}{}^{(0)}$ and equal number of real power mismatch $\Delta P^{(0)}$.

Step-3: Use the estimated $|V|^{(0)}$ and $\delta^{(0)}$ to calculate a total n_p number of injected reactive power $Q_{calc}{}^{(0)}$ and equal number of reactive power mismatch $\Delta Q^{(0)}$.

Step-3: Use the estimated $|V|^{(0)}$ and $\delta^{(0)}$ to formulate the Jacobian matrix $J^{(0)}$.

Step-4: Solve (3.30) for $\Delta\delta^{(0)}$ and $\Delta|V|^{(0)}\div|V|^{(0)}$.

Step-5: Obtain the updates from

$$\delta^{(1)} = \delta^{(0)} + \Delta\delta^{(0)} \tag{3.36}$$

$$|V|^{(1)} = |V|^{(0)}\left[1 + \frac{\Delta|V|^{(0)}}{|V|^{(0)}}\right] \tag{3.37}$$

Step-6: Check if all the mismatches are below a small number. Terminate the process if yes. Otherwise go back to step-1 to start the next iteration with the updates given by (3.36) and (3.37).

Formation of the Jacobian Matrix

We shall now discuss the formation of the submatrices of the Jacobian matrix. To do that we shall use the real and reactive power equations of (3.6) and (3.7). Let us rewrite them with the help of (3.2) as

$$P_i = |V_i|^2 G_{ii} + \sum_{\substack{k=1 \\ k\neq i}}^{n} |Y_{ik}V_iV_k| \cos(\theta_{ik} + \delta_k - \delta_i) \tag{3.38}$$

$$Q_i = -|V_i|^2 B_{ii} - \sum_{\substack{k=1 \\ k\neq i}}^{n} |Y_{ik}V_iV_k| \sin(\theta_{ik} + \delta_k - \delta_i) \tag{3.39}$$

A. Formation of J_{11}

Let us define J_{11} as

$$J_{11} = \begin{bmatrix} L_{22} & \cdots & L_{2n} \\ \vdots & \ddots & \vdots \\ L_{n2} & \cdots & L_{nn} \end{bmatrix} \tag{3.40}$$

It can be seen from (3.32) that M_{ik}'s are the partial derivatives of P_i with respect to δ_k. The derivative P_i (3.38) with respect to k for $i \neq k$ is given by

$$L_{ik} = \frac{\partial P_i}{\partial \delta_k} = -|Y_{ik}V_iV_k| \sin(\theta_{ik} + \delta_k - \delta_i), \quad i \neq k \tag{3.41}$$

Similarly the derivative P_i with respect to k for $i = k$ is given by

$$L_{ii} = \frac{\partial P_i}{\partial \delta_i} = \sum_{\substack{k=1 \\ k \neq i}}^{n} \left| Y_{ik} V_i V_k \right| \sin\left(\theta_{ik} + \delta_k - \delta_i\right)$$

Comparing the above equation with (3.39) we can write

$$L_{ii} = \frac{\partial P_i}{\partial \delta_i} = -Q_i - \left| V_i \right|^2 B_{ii} \tag{3.42}$$

B. Formation of J_{21}

Let us define J_{21} as

$$J_{21} = \begin{bmatrix} M_{22} & \cdots & M_{2n} \\ \vdots & \ddots & \vdots \\ M_{n_p 2} & \cdots & M_{n_p n} \end{bmatrix} \tag{3.43}$$

From (3.34) it is evident that the elements of J_{21} are the partial derivative of Q with respect to δ. From (3.39) we can write

$$M_{ik} = \frac{\partial Q_i}{\partial \delta_k} = -\left| Y_{ik} V_i V_k \right| \cos\left(\theta_{ik} + \delta_k - \delta_i\right), \quad i \neq k \tag{3.44}$$

Similarly for $i = k$ we have

$$M_{ii} = \frac{\partial Q_i}{\partial \delta_i} = \sum_{\substack{k=1 \\ k \neq i}}^{n} \left| Y_{ik} V_i V_k \right| \cos\left(\theta_{ik} + \delta_k - \delta_i\right) = P_i - \left| V_i \right|^2 G_{ii} \tag{3.45}$$

The last equality of (3.45) is evident from (3.38).

C. Formation of J_{12}

Let us define J_{12} as

$$J_{12} = \begin{bmatrix} N_{22} & \cdots & N_{2n_p} \\ \vdots & \ddots & \vdots \\ N_{n2} & \cdots & N_{nn_p} \end{bmatrix} \tag{3.46}$$

As evident from (3.33), the elements of J_{21} involve the derivatives of real power P with respect to magnitude of bus voltage $|V|$. For $i \neq k$, we can write from (3.38)

$$N_{ik} = |V_k| \frac{\partial P_i}{\partial |V_k|} = |Y_{ik} V_i V_k| \cos(\theta_{ik} + \delta_k - \delta_i) = -M_{ik} \quad i \neq k \tag{3.47}$$

For $i = k$ we have

$$\begin{aligned} N_{ii} &= |V_i| \frac{\partial P_i}{\partial |V_i|} = |V_i| \left[2|V_i| G_{ii} + \sum_{\substack{k=1 \\ k \neq i}}^{n} |Y_{ik} V_k| \cos(\theta_{ik} + \delta_k - \delta_i) \right] \\ &= 2|V_i|^2 G_{ii} + \sum_{\substack{k=1 \\ k \neq i}}^{n} |Y_{ik} V_i V_k| \cos(\theta_{ik} + \delta_k - \delta_i) = 2|V_i|^2 G_{ii} + M_{ii} \end{aligned} \tag{3.48}$$

D. Formation of J_{22}

For the formation of J_{22} let us define

$$J_{22} = \begin{bmatrix} O_{22} & \cdots & O_{2n_p} \\ \vdots & \ddots & \vdots \\ O_{n_p 2} & \cdots & O_{n_p n_p} \end{bmatrix} \tag{3.49}$$

For $i \neq k$ we can write from (3.39)

$$O_{ik} = |V_i| \frac{\partial Q_i}{\partial |V_k|} = -|V_i| |Y_{ik} V_i V_k| \sin(\theta_{ik} + \delta_k - \delta_i) = L_{ik}, \quad i \neq k \tag{3.50}$$

Finally for $i = k$ we have

$$\begin{aligned} O_{ii} &= |V_i| \frac{\partial Q_i}{\partial |V_k|} = |V_i| \left[-2|V_i| B_{ii} - \sum_{\substack{k=1 \\ k \neq i}}^{n} |Y_{ik} V_k| \sin(\theta_{ik} + \delta_k - \delta_i) \right] \\ &= -2|V_i|^2 B_{ii} - \sum_{\substack{k=1 \\ k \neq i}}^{n} |Y_{ik} V_i V_k| \sin(\theta_{ik} + \delta_k - \delta_i) = -2|V_i|^2 B_{ii} - L_{ii} \end{aligned} \tag{3.51}$$

We therefore see that once the submatrices J_{11} and J_{21} are computed, the formation of the submatrices J_{12} and J_{22} is fairly straightforward. For large system this will result in considerable saving in the computation time.

TAP-CHANGING AND REGULATING TRANSFORMERS

Transformers which provide a small adjustment of voltage magnitude, usually in the range o f ± 10%, and others which shift the phase angle of the line voltages are important components of a power system. Some transformers regulate both the magnitude and phase angle.

Almost all transformers provide taps on windings to adjust the ratio of transformation by changing taps when the transformer is deenergized. A change in tap can be made while the transformer is energized and such transformers a recalled load-tap-changing (LTC) transformers or tap-changing-under-load (TCUL) transformers. The tap changing is automatic and operated by motors which respond to relays set to hold the voltage at the prescribed level. Special circuits allow the change to be made without interrupting the current.

A type of transformer designed for small adjustments of voltage rather than large changes in voltage levels is called a regulating transformer Each of the three windings to which taps are made is on the same magnetic core as the phase winding whose voltage is 90° out of phase with the voltage from neutral to the point connected to the center of the tapped winding. For instance, the voltage

to neutral V_{an} is increased by a component ΔV_{an} which is in phase or 180° out

of phase with ΔV_{bc}.

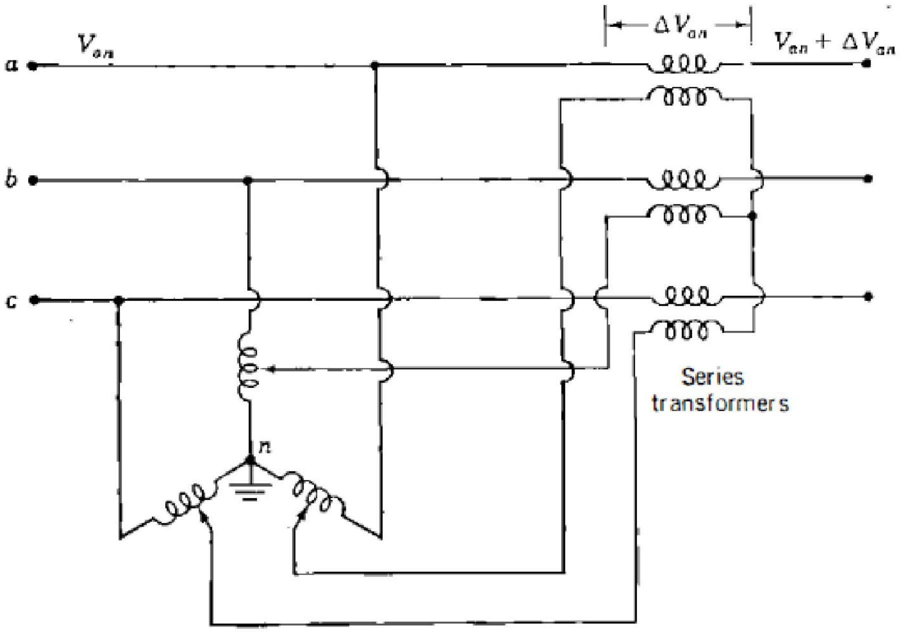


Fig. 3.2 Regulating t/f for control of voltage magnitude

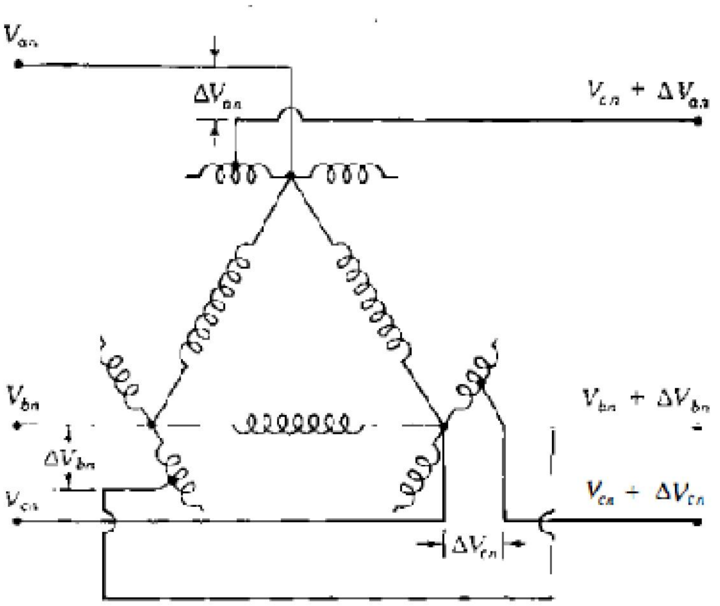


Fig 3.3 Regulating t/f for control of phase angle

PHASE-SHIFTING TRANSFORMER

The voltage drop in a transmission line is simulated in a line drop compensator, which senses the remote secondary voltage and adjusts the voltage taps. The voltage taps, however, do not change the phase angle of the voltages appreciably. A minor change due to change of the transformer impedance on account of tap adjustment and the resultant power flow through it can be ignored. The real power control can be affected through phase-shifting of the voltage. A phase-shifting transformer changes the phase angle without appreciable change in the voltage magnitude; this is achieved by injecting a voltage at right angles to the corresponding line-to-neutral voltage.

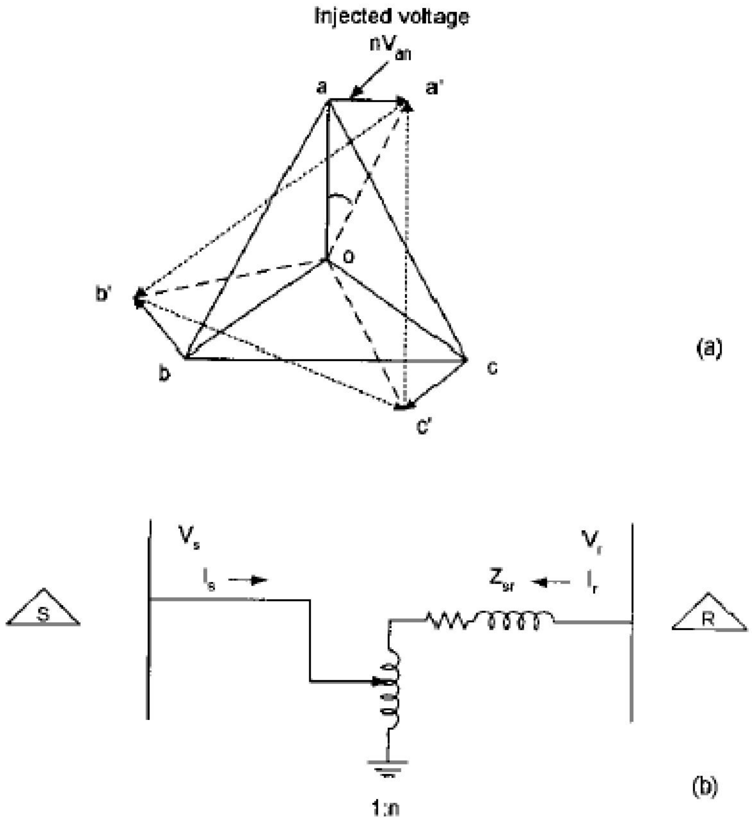


Fig. 3.4 (a) Voltage injection vector diagram of a phase shifting transformer; (b) schematic diagram of phase-shifting transformer.

Consider the equivalent circuit representation of Fig. 13. Let the regulating transformer be represented by an ideal transformer with a series impedance or admittance. Since it is an ideal transformer, the complex power input equals the complex power output, and for a voltage adjustment tap changing transformer we have already shown that

$$I_s = n^2 y V_s - n y V_r$$

where n is the ratio of the voltage adjustment taps (or currents). Also,

$$I_r = y(V_r - n V_s)$$

EFFECTS OF REGULATING TRANSFORMERS

The transformer with the higher tap setting is supplying most of the reactive power to the load. The real power is dividing equally between the transformers. If both transformers have the same impedance, they would share both the real and reactive power equally if they had the same turns ratio. When two transformers are in parallel, we can vary the distribution of reactive power between the transformers by adjusting the voltage-magnitude ratios. When two paralleled transformers of equal kilovolt amperes do not share the Kilovolt amperes equally because their impedances differ, the kilovolt amperes may be more nearly equalized by adjustment of the voltage-magnitude ratios through tap changing.

MODULE IV

ECONOMIC OPERATION OF POWER SYSTEM

INTRODUCTION

One of the earliest applications of on-line centralized control was to provide a central facility, to operate economically, several generating plants supplying the loads of the system. Modern integrated systems have different types of generating plants, such as coal fired thermal plants, hydel plants, nuclear plants, oil and natural gas units etc. The capital investment, operation and maintenance costs are different for different types of plants.

The operation economics can again be subdivided into two parts.

i) Problem of economic dispatch, which deals with determining the power output of each plant to meet the specified load, such that the overall fuel cost is minimized.

ii) Problem of optimal power flow, which deals with minimum – loss delivery, where in the power flow, is optimized to minimize losses in the system. In this chapter we consider the problem of economic dispatch.

During operation of the plant, a generator may be in one of the following states:

i) Base supply without regulation: the output is a constant.

ii) Base supply with regulation: output power is regulated based on system load.

iii) Automatic non-economic regulation: output level changes around a base setting as area control error changes.

iv) Automatic economic regulation: output level is adjusted, with the area load and area control error, while tracking an economic setting.

Regardless of the units operating state, it has a contribution to the economic operation, even though its output is changed for different reasons. The factors influencing the cost of generation are the generator efficiency, fuel cost and transmission losses. The most efficient generator may not give minimum cost, since it may be located in a place where fuel cost is high. Further, if the plant is located far from the load centers, transmission losses may be high and running the plant may become uneconomical. The economic dispatch problem basically determines the generation of different plants to minimize total operating cost. Modern generating plants like nuclear plants, geo-thermal plants etc, may require capital investment of millions of rupees. The economic dispatch is however determined in terms of fuel cost per unit power generated and does not include capital investment, maintenance, depreciation, start-up and shut down costs etc.

PERFORMANCE CURVES

INPUT-OUTPUT CURVE

This is the fundamental curve for a thermal plant and is a plot of the input in British thermal units (Btu) per hour versus the power output of the plant in MW as shown in Fig.4.1

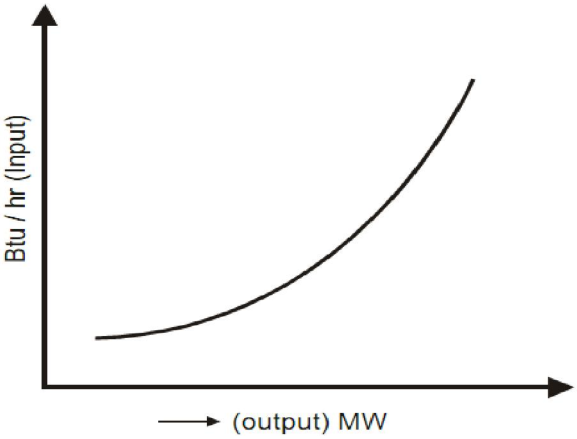


Fig.4.1: Input output curve

HEAT RATE CURVE

The heat rate is the ratio of fuel input in Btu to energy output in KWh. It is the slope of the input – output curve at any point. The reciprocal of heat – rate is called fuel – efficiency. The heat rate curve is a plot of heat rate versus output in MW. A typical plot is shown in Fig .

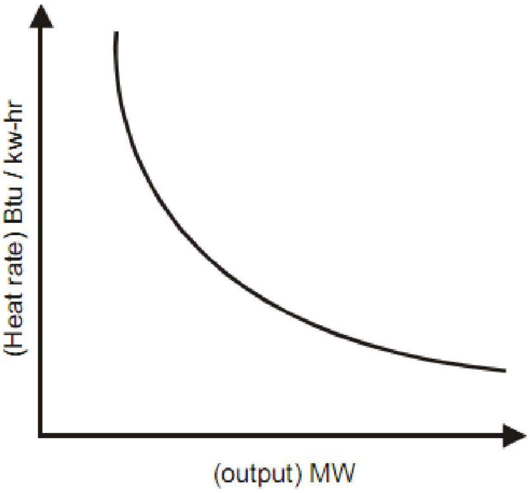


Fig.4.2: Heat Rate Curve

INCREMENTAL FUEL RATE CURVE

The incremental fuel rate is equal to a small change in input divided by the corresponding change in output.

Incremental fuel rate =ΔInput/ΔOutput

The unit is again Btu / KWh. A plot of incremental fuel rate versus the output is shown in Fig.4.3

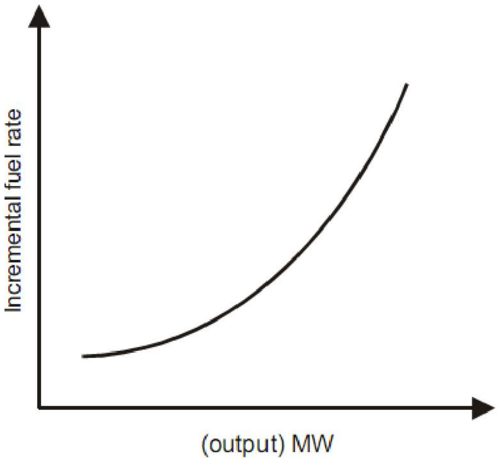


Fig 4.3: Incremental Fuel Rate Curve

Incremental cost curve

The incremental cost is the product of incremental fuel rate and fuel cost (Rs / Btu or $/Btu). The curve in shown in Fig.4.4. The unit of the incremental fuel cost is Rs / MWh or $ /MWh.

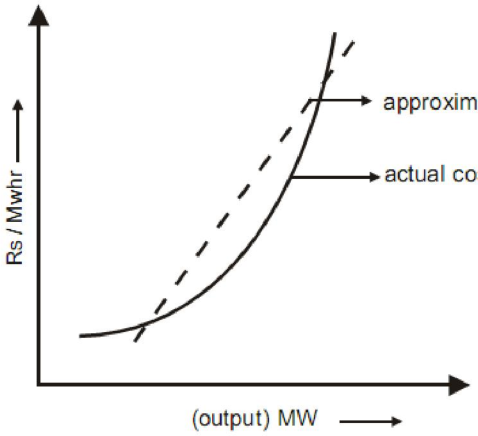


Fig. 4.4: Incremental Cost curve

In general, the fuel cost F_i for a plant, is approximated as a quadratic function of the

generated output $P_{Gi.}$

$$F_i = a_i + b_i P_{Gi} + c_i P_{Gi}^2 \text{Rs/h}$$

The incremental fuel cost is given by

$$\frac{dF_i}{dP_{Gi}} = b_i + 2c_i P_{Gi} \quad \text{Rs/MWh}$$

The incremental fuel cost is a measure of how costly it will be produce an increment of power. The incremental production cost, is made up of incremental fuel cost plus the incremental cost of labour, water, maintenance etc. which can be taken to be some percentage of the incremental fuel cost, instead of resorting to a rigorous mathematical model. The cost curve can be approximated by a linear curve. While there is negligible operating cost for a hydel plant, there is a limitation on the power output possible. In any plant, all units normally operate between P_{Gmin}, the minimum loading limit, below which it is technically infeasible to operate a unit and P_{Gmax}, which is the maximum output limit.

ECONOMIC GENERATION SCHEDULING NEGLECTING LOSSES AND GENERATOR LIMITS

In an early attempt at economic operation it was decided to supply power from the most efficient plant at light load conditions. As the load increased, the power was supplied by this most efficient plant till the point of maximum efficiency of this plant was reached. With further increase in load, the next most efficient plant would supply power till its maximum efficiency is reached. In this way the power would be supplied by the most efficient to the least efficient plant to reach the peak demand. Unfortunately however, this method failed to minimize the total cost of electricity generation. We must therefore search for alternative method which takes into account the total cost generation of all the units of a plant that is supplying a load.

The simplest case of economic dispatch is the case when transmission losses are neglected. The model does not consider the system configuration or line impedances. Since losses are neglected, the total generation is equal to the total demand P_D.

Consider a system with n_g number of generating plants supplying the total demand P_D. If F_i is the cost of plant *i* in Rs/h, the mathematical formulation of the problem of economic scheduling can be stated as follows:

Minimize $$F_T = \sum_{i=1}^{n_g} F_i$$

Such that $$\sum_{i=1}^{n_g} P_{Gi} = P_D$$

Where F_T= total cost

P_{Gi}= generation of plant i

P_D= total demand

This is a constrained optimization problem, which can be solved by Lagrange's Method.

LAGRANGE METHOD FOR SOLUTION OF ECONOMIC SCHEDULE

The problem is restated below:

Minimize $F_T = \sum_{i=1}^{n_g} F_i$

Such that $P_D - \sum_{i=1}^{n_g} P_{Gi} = 0$

The augmented cost function is given by

$$L = F_T + \lambda(P_D - \sum_{i=1}^{n_g} P_{Gi})$$

The minimum is obtained when

$$\frac{\partial L}{\partial P_{Gi}} = 0 \quad \text{and} \quad \frac{\partial L}{\partial \lambda} = 0$$

$$\frac{\partial L}{\partial P_{Gi}} = \frac{\partial F_T}{\partial P_{Gi}} - \lambda = 0$$

$$\frac{\partial L}{\partial \lambda} = P_D - \sum_{i=1}^{n_g} P_{Gi} = 0$$

The second equation is simply the original constraint of the problem. The cost of a plant F_i depends only on its own output P_{Gi}, hence

$$\frac{\partial F_T}{\partial P_{Gi}} = \frac{\partial F_i}{\partial P_{Gi}} = \frac{dF_i}{dP_{Gi}}$$

Using the above,

$$\frac{\partial L}{dP_{Gi}} = \frac{dF_i}{dP_{Gi}} - \lambda = 0 \qquad i = 1, 2, \text{-----------}, n_g$$

We can write $b_i + 2c_i P_{Gi} = \lambda$ $\qquad i = 1, 2, \text{-----------}, n_g$

The above equation is called the co-ordination equation. Simply stated, for economic generation scheduling to meet a particular load demand, when transmission losses are neglected and generation limits are not imposed, all plants must operate at equal incremental production costs, subject to the constraint that the total generation be equal to the demand.

ECONOMIC SCHEDULE INCLUDING LIMITS ON GENERATOR (NEGLECTING LOSSES)

The power output of any generator has a maximum value dependent on the rating of the generator. It also has a minimum limit set by stable boiler operation. The economic dispatch problem now is to schedule generation to minimize cost, subject to the equality constraint.

$$\sum_{i=1}^{n_g} P_{Gi} = P_D$$

and the inequality constraint

$$P_{Gi(\min)} \le P_{Gi} \le P_{Gi(\max)} \qquad i = 1, 2, \ldots\ldots\ldots n_g$$

The procedure followed is same as before i.e. the plants are operated with equal incremental fuel costs, till their limits are not violated. As soon as a plant reaches the limit (maximum or minimum) its output is fixed at that point and is maintained a constant. The other plants are operated at equal incremental costs.

ECONOMIC DISPATCH INCLUDING TRANSMISSION LOSSES

When transmission distances are large, the transmission losses are a significant part of the generation and have to be considered in the generation schedule for economic operation. The mathematical formulation is now stated as

Minimize $\qquad F_T = \sum_{i=1}^{n_g} F_i$

Such that $\qquad \sum_{i=1}^{n_g} P_{Gi} = P_D + P_L$

Where $\qquad P_L$ is the total loss

The Lagrange function is now written as

$$L = F_T + \lambda(P_D - \sum_{i=1}^{n_g} P_{Gi} - P_L)$$

The minimum point is obtained when

$$\frac{\partial L}{\partial P_{Gi}} = \frac{\partial F_T}{\partial P_{Gi}} - \lambda(1 - \frac{\partial P_L}{\partial P_{Gi}}) = 0 \qquad i=1,2,\ldots\ldots\ldots.n_g$$

$$\frac{\partial L}{\partial \lambda} = P_D - \sum_{i=1}^{n_g} P_{Gi} - P_L = 0 \qquad \text{(same as the constraint)}$$

Since $$\frac{\partial F_T}{\partial P_{Gi}} = \frac{dF_i}{dP_{Gi}}$$

$$\frac{dF_i}{dP_{Gi}} + \lambda \frac{dP_L}{dP_{Gi}} = \lambda$$

$$\lambda = \frac{dF_i}{dP_{Gi}} \left(\frac{1}{1 - \frac{dP_L}{dP_{Gi}}} \right)$$

The term $\frac{1}{1 - \frac{dP_L}{dP_{Gi}}}$ is called the penalty factor of plant *i*, L_i. The coordination equations including losses are given by

$$\lambda = \frac{dF_i}{dP_{Gi}} L_i \qquad i=1,2,\ \ldots\ldots\ldots\ldots,n_g$$

The minimum operation cost is obtained when the product of the incremental fuel cost and the penalty factor of all units is the same, when losses are considered.

A rigorous general expression for the loss P_L is given by

$$P_L = \sum_m \sum_n P_{Gm} B_{mn} P_{Gn}$$

Where B_{mn} is called loss coefficient, depends on load composition.

For a two plant system

$$P_L = B_{11}P_{G1} + 2P_{G1}B_{12}P_{G2} + B_{22}P_{G2} \qquad \text{as } B_{12}=B_{21}$$

AUTOMATIC LOAD DISPATCH

Economic load dispatching is that aspect of power system operation wherein it is required to distribute the load among the generating units actually paralleled with the system in such a manner as to minimize the cost of supplying the minute to minute requirements of the system. In a large interconnected system it is humanly impossible to calculate and adjust such generations and hence the help of digital computer system along with analogue devices is sought and the whole process is carried out automatically; hence called automatic load dispatch. The objective of automatic load dispatch is to minimise the cost of supplying electricity to the load points while ensuring security of supply against loss of generation and transmission capacity and also maintaining the voltage and frequency of the system within specified limits. Since the interconnection is growing bigger and bigger in size with time, the control engineer has to make adjustments to various parameters in the system. Hence automatic control of load dispatch problem is required. The chosen control system is invariably based on a digital computer working on-line.

The components for automatic load dispatching are

Computer-The computer predicts the load and suggests economic loading. It transmits information to machine controller.

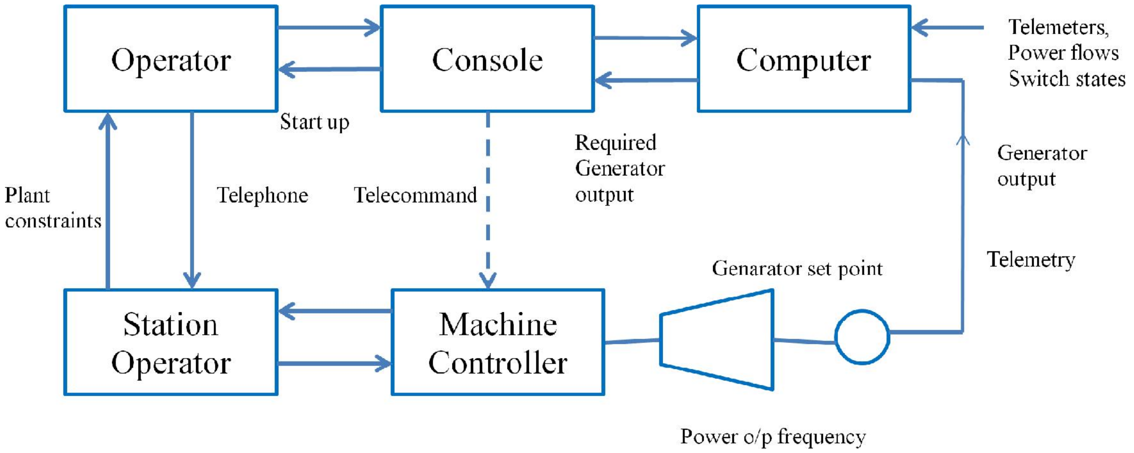


Fig.4.5: Schematic diagram of automatic load dispatching components

Data Input: The computer receives a lot of data from the telemetering system and from the paper tape. Telemetering data comes to the computer either as analog signals representing line power flows, plant outputs or as signal bits indicating switch or isolator positions. Paper tape stores all the basic data required e.g. the system parameters, load predictions, security constraints, etc.

Console: It is the component through which the operator can converse with the computer. He can obtain certain information required for some action to be taken under emergency condition or he can put data into it if needed. The console has the facilities of security checking and load flows for the network calculations.

Machine Controller: The computer sends information regarding the optimal generation to the machine controller at regular intervals which in turn implements them. Control on each machine is applied by a closed loop system which uses a measure of actual power generated and which operates through a conventional speeder motor. These are referred to as controller power loops. In the power frequency loop an error signal proportional to the difference between the derived and actual frequency and power is developed. A summed error signal is formed from these two components and is converted in the motor controller to a train of pulses that are applied to a speed governor reference setting motor called the speeder motor. The duration and amplitude of these pulses are fixed but the pulse rate is made proportional to the summed error signal. The pulses are applied as raise or lower command to the speeder motor in accordance with the error signal and thus the output of the generator is increased or decreased accordingly.

HYDROTHERMAL SCHEDULING LONG AND SHORT TERMS-

Long-Range Hydro-Scheduling:

The long-range hydro-scheduling problem involves the long-range forecasting of water availability and the scheduling of reservoir water releases (i.e., "drawdown") for an interval of time that depends on the reservoir capacities. Typical long-range scheduling goes anywhere from 1 week to 1 yr or several years. For hydro schemes with a capacity of impounding water over several seasons, the long-range problem involves meteorological and statistical analyses.

Short-Range Hydro-Scheduling

Short-range hydro-scheduling (1 day to 1 wk) involves the hour-by-hour scheduling of all generation on a system to achieve minimum production cost for the given time period. In such a scheduling problem, the load, hydraulic inflows, and unit availabilities are assumed known. A set of starting conditions (e.g., reservoir levels) is given, and the optimal hourly schedule that minimizes a desired objective, while meeting hydraulic steam, and electric system constraints, is sought. Hydrothermal systems where the hydroelectric system is by far the largest component may be scheduled by economically scheduling the system to produce the minimum cost for the thermal system. The schedules are usually developed to minimize thermal generation production costs, recognizing all the diverse hydraulic constraints that may exist.

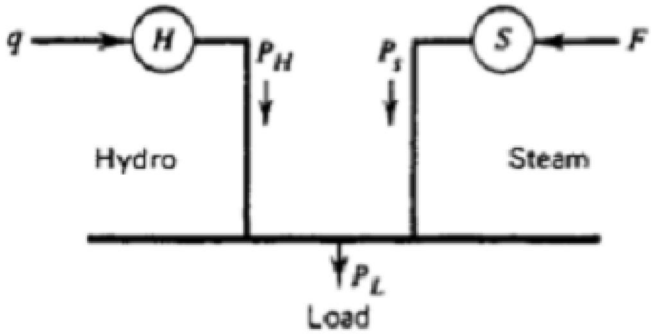


Fig. 4.6: Hydro Scheduling

The hydroplant can supply the load by itself for a limited time. That is, for any time period j,

$$P_{Hj}^{\max} \geq P_{loadj} \qquad \text{j=1,2,.........j}_{\max}$$

The energy available from the hydroplant is insufficient to meet the load.

$$\sum_{j=1}^{j_{\max}} P_{Hj} n_j \leq \sum_{j=1}^{j_{\max}} P_{loadj} n_j \qquad n_j \text{ is the no of hours in period j}$$

$$\sum_{j=1}^{j_{\max}} n_j = T_{\max} = \text{Total Interval}$$

Steam plant energy required is

$$\sum_{j=1}^{j_{\max}} P_{loadj} n_j - \sum_{j=1}^{j_{\max}} P_{Hj} n_j = E$$

$$\text{Where } E = \sum_{j=1}^{N_s} P_{sj} n_j \qquad N_s \text{ is the no of periods the steam plant is on}$$

$$\sum_{j=1}^{N_s} n_j \leq T_{\max}$$

So the scheduling problem and the constraint are

$$\text{Min } F_T = \sum_{j=1}^{N_s} F(P_{sj}) n_j$$

$$\text{Subject to } \sum_{j=1}^{N_s} P_{sj} n_j - E = 0$$

Lagrange function is $$L = \sum_{j=1}^{N_s} F(P_{sj}) n_j + \alpha \left(E - \sum_{j=1}^{N_s} P_{sj} n_j \right)$$

$$\frac{\partial L}{\partial P_{sj}} = \frac{dF(P_{sj})}{dP_{sj}} - \alpha = 0 \qquad \text{for j=1,2,...............N}_s$$

$$\frac{dF(P_{sj})}{dP_{sj}} = \alpha$$

So steam plant should be run at constant incremental cost for the entire period it is on. Let this optimum value of steam-generated power be P_s^*, which is the same for all time intervals the steam unit is on.

The total cost over the interval is

$$F_T = \sum_{j=1}^{N_s} F(P_s^*) n_j = F(P_s^*) \sum_{j=1}^{N_s} n_j = F(P_s^*) T_s$$

T_s is the total run time for the steam plant

The total cost $\quad F_T = (a + bP_s^* + cP_s^{*2}) T_s$

Also $\quad \sum_{j=1}^{N_s} P_{sj} n_j = \sum_{j=1}^{N_s} P_s^* n_j = P_s^* T_s = E$

So $\quad T_s = \frac{E}{P_s^*}$

$$F_T = (a + bP_s^* + cP_s^{*2})(\frac{E}{P_s^*})$$

Minimizing F_T , we get $P_s^* = \sqrt{\frac{a}{c}}$

So the unit should be operated at its maximum efficiency point (P_s^*) long enough to supply the energy needed, E. Optimal hydrothermal schedule is as shown below:

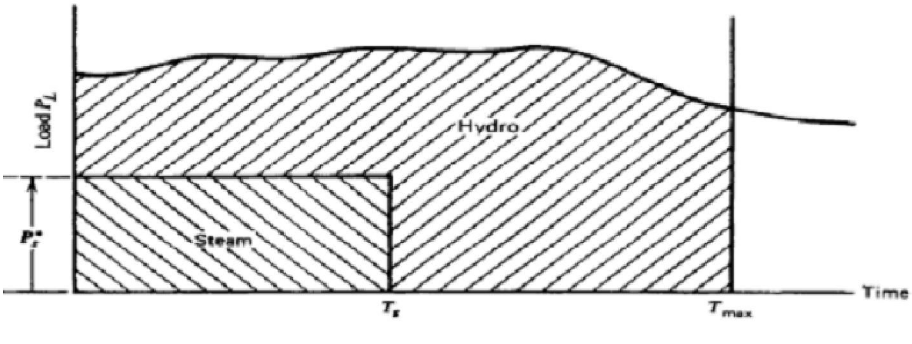


Fig.4.7: Optimal Hydrothermal Scheduling

FACTS

The large interconnected transmission networks are susceptible to faults caused by lightning discharges and decrease in insulation clearances. The power flow in a transmission line is determined by Kirchhoff's laws for specified power injections (both active and reactive) at various nodes. While the loads in a power system vary by the time of the day in general, they are also subject to variations caused by the weather (ambient temperature) and other unpredictable factors. The generation pattern in a deregulated environment also tends to be variable (and hence less predictable).

The factors mentioned in the above paragraph point to the problems faced in maintaining economic and secure operation of large interconnected systems. The probles are eased if sufficient margins (in power transformer) can be maintained. The required safe operating margin can be substantially reduced by the introduction of fast dynamic control over reactive and active power by high power electronic controllers. This can make the AC transmission network flexible to adapt to the changing conditions caused by contingencies and load variations. Flexible AC Transmission System (FACTS) is used as Alternating current transmission systems incorporating power electronic-based and other static controllers to enhance controllability and increase power transfer capability. The FACTS controller is used as a power electronic based system and other static equipment that provide control of one or more AC transmission system parameters like voltage, current, power, impedance etc.

Benefits of utilizing FACTS devices: The benefits of utilizing FACTS devices in electrical transmission systems can be summarized as follows:

1. Better utilization of existing transmission system assets.
2. Increased transmission system reliability and availability.
3. Increased dynamic and transient grid stability and reduction of loop flows.
4. Increased quality of supply for sensitive industries.

FACTs controllers: Structures & Characteristics of following FACTs Controllers

The FACTS controllers can be classified as—

1. Shunt connected controllers
2. Series connected controllers
3. Combined series-series controllers
4. Combined shunt-series controller

Static Var Compensator (SVC)

Static Var compensator is a static Var generator whose output is varied so as to maintain or control specific parameters (e.g. voltage or reactive power of bus) of the electric power system. In its simplest form it uses a thyristor controlled reactor (TCR) in conjunction with a fixed capacitor (FC) or thyristor switched capacitor (TSC). A pair of anti parallel thyristors is connected in series with a fixed inductor to form a TCR module while the thyristors are connected in series with a capacitor to form a TSC module. An SVC can control the voltage magnitude at the required bus thereby improving the voltage profile of the system. The primary task of an SVC is to maintain the voltage of a particular bus by means of reactive power compensation (obtained by varying the firing angle of the thyristors). It can also provide increased damping to power oscillations and enhance power flow over a line by using auxiliary signals such as line active power, line reactive power, line current, and computed internal frequency. Static VAR Compensator (SVC) is a shunt connected FACTS controller whose main functionality is to regulate the voltage at a given bus by controlling its equivalent reactance. Basically it consists of a fixed capacitor (FC) and a thyristor controlled reactor (TCR).

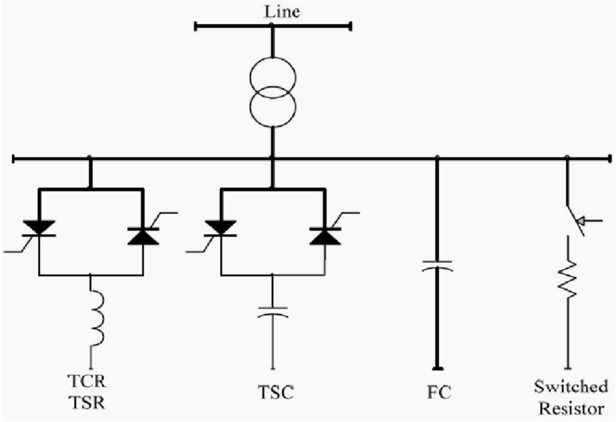


Fig.4.8: Static Var Compensator

Thyristor Controlled Series Capacitor (TCSC)

A TCSC is a capacitive reactance compensator, which consists of a series capacitor bank shunted by a thyristor controlled reactor in order to provide a smoothly variable series capacitive reactance. Even through a TCSC in the normal operating range in mainly capacitive, but it can also be used in an inductive mode. The power flow over a transmission line can be increased by controlled series compensation with minimum risk of sub-synchronous resonance (SSR).TCSC is a second generation FACTS controller, which controls the impedance of the line in which it is connected by varying the firing angle of the thyristors. A TCSC module comprises a series fixed capacitor that is connected in parallel to a thyristor controlled reactor (TCR). A TCR includes a pair of anti-parallel thyristors that are connected in series with an inductor. In a TCSC, a Metal Oxide Varistor (MOV) along with a bypass breaker is connected in parallel to the fixed capacitor for overvoltage protection. A complete compensation system may be made up of several of these modules. TCSC controllers use thyristor-controlled reactor (TCR) in parallel with capacitor segments of series capacitor bank. The combination of TCR and capacitor allow the capacitive reactance to be smoothly controlled over a wide range and switched upon command to a condition where the bi-directional thyristor pairs conduct continuously and insert an inductive reactance into the line. TCSC is an effective and economical means of solving problems of transient stability, dynamic stability, steady state stability and voltage stability in long transmission lines. A TCSC is a series controlled capacitive reactance that can provide continuous control of power on the ac line over a wide range.

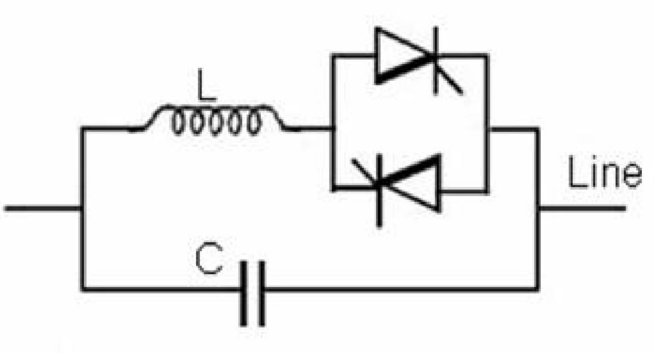


Fig.4.9: Thyristor Controlled Series Capacitor

Static Synchronous Series Compensator (SSSC)

A SSSC is a static synchronous generator operated without an external electric energy source as a series compensator whose output voltage is in quadrature with, and controllable independently of the line current for the purpose of increasing or decreasing the overall reactive voltage drop across the line and thereby controlling the transmitted electric power. The SSSC may include transiently rated energy source or energy absorbing device to enhance the dynamic behaviour of the power system by additional temporary real power compensation, to increase or decrease momentarily, the overall real voltage drop across the line.

A SSSC incorporates a solid state voltage source inverter that injects an almost sinusoidal voltage of variable magnitude in series with a transmission line. The SSSC has the same structure as that of a STATCOM except that the coupling transformer of an SSSC is connected in series with the transmission line. The injected voltage is mainly in quadrature with the line current. A small part of injected voltage, which is in phase with the line current, provides the losses in the inverter. Most of injected voltage, which is in quadrature with the line current, emulates a series inductance or a series capacitance thereby altering the transmission line series reactance. This reactance, which can be altered by varying the magnitude of injected voltage, favourably influences the electric power flow in the transmission line.

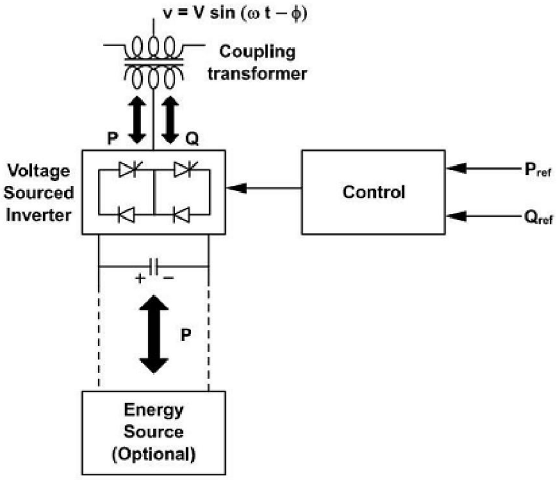


Fig.4.10: Static Synchronous Series Compensator

SSSC is a solid-state synchronous voltage source employing an appropriate DC to AC inverter with gate turn- off thyristor. It is similar to the STATCOM, as it is based on a DC capacitor fed VSI that generates a three - phase voltage, which is then injected in a transmission line through a transformer connected in series with the system. In SSSC, the resonance phenomenon has been removed. So SSSC is having more superior performance as compare to TCSC. The main control objective of the SSSC is to directly control the current, and indirectly the power, flowing through the line by controlling the reactive power exchange between the SSSC and the AC system. The main advantage of this controller over a TCSC is that it does not significantly affect the impedance of the transmission system and, therefore, there is no danger of having resonance problem.

Static Synchronous Compensator (STATCOM)

A STATCOM is a static synchronous generator operated as a shunt connected static var compensator whose capacitive or inductive output current can be controlled independent of the ac system voltage. A STATCOM is a solid state switching converter capable of generating or absorbing independently controllable real and reactive power at its output terminals, when it is fed from an energy source or an energy storage device of appropriate rating. A STATCOM incorporate a voltage source inverter (VSI) that produces a set of three phase ac output voltages, each of which is in phase with, and coupled to the corresponding ac system voltage via a relatively small reactance. This small reactance is usually provided by the per phase leakage reactance of the coupling transformer. The VSI is driven by a dc storage capacitor. By regulating the magnitude of the output voltage produced, the reactive power exchange between STATCOM and the ac system can be controlled. The Static Synchronous Compensator (STATCOM) is a power electronic-based Synchronous Voltage Generator (SVG) that generates a three-phase voltage from a dc capacitor in synchronism with the transmission line voltage and is connected to it by a coupling transformer.

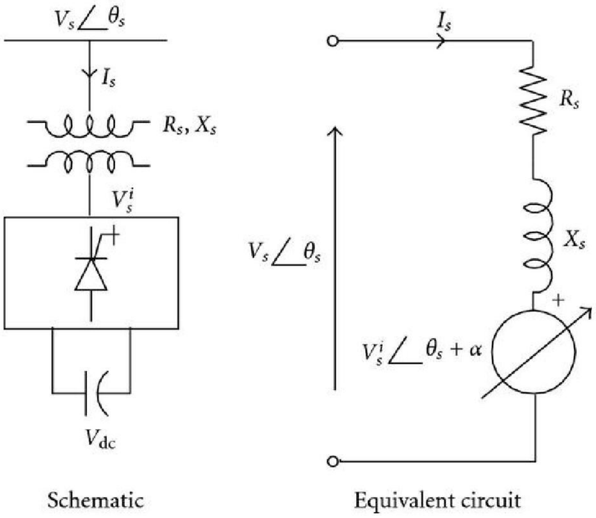


Fig.4.11: Static Synchronous Compensator

By controlling the magnitude of the STATCOM voltage the reactive power exchange between the STATCOM and the transmission line and hence the amount of shunt compensation can be controlled. In STATCOM, the resonance phenomenon has been removed. So STATCOM is having more superior performance as compared to SVC.

Unified Power Flow Controller (UPFC)

The UPFC, by means of angularly unconstrained series voltage injection, is able to control, concurrently or selectively, the transmission line voltage, impedance, and angle or, alternatively, the real and reactive power flow in the line. The UPFC may also provide independently controllable shunt reactive compensation.

The UPFC is the most versatile and powerful FACTS device. UPFC is also known as the most comprehensive multivariable flexible ac transmission system (FACTS) controller. Simultaneous control of multiple power system variables with UPFC poses enormous difficulties. In addition, the complexity of the UPFC control increases due to the fact that the controlled and the variables interact with each other. The Unified Power Flow Controller (UPFC) is used to control the power flow in the transmission systems by controlling the impedance, voltage magnitude and phase angle. This controller offers advantages in terms of static and dynamic operation of the power system. The basic structure of the UPFC consists of two voltage source inverter (VSI); where one converter is connected in parallel to the transmission line while the other is in series with the transmission line. The UPFC consists of two voltage source converters; series and shunt converter, which are connected to each other with a common dc link. Series converter or Static Synchronous Series Compensator (SSSC) is used to add controlled voltage magnitude and phase angle in series with the line, while shunt converter or Static Synchronous Compensator (STATCOM) is used to provide reactive power to the ac system, beside that, it will provide the dc power required for both inverter. Each of the branch consists of a transformer and power electronic converter. These two voltage source converters share a common dc capacitor. The energy storing capacity of this dc capacitor is generally small. Therefore, active power drawn by the shunt converter should be equal to the active power generated by the series converter. The reactive power in the shunt or series converter can be chosen independently, giving greater flexibility to the power flow control. The coupling transformer is used to connect the device to the system.

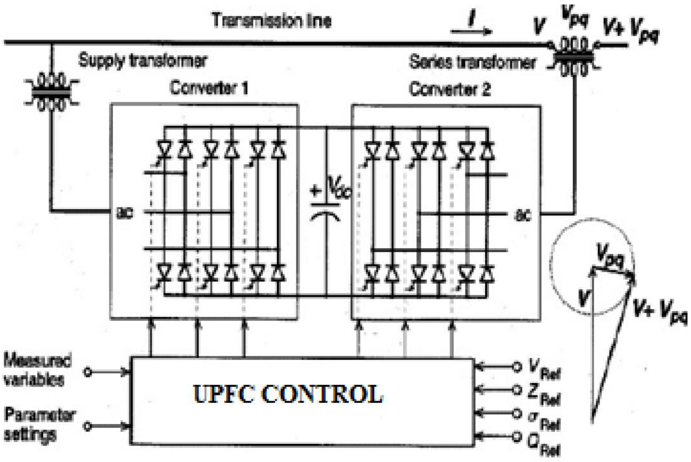


Fig.4.11: Unified Power Flow Controller

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