UNIT I

STRUCTURE OF ELECTRICAL POWER SYSTEMS

Structure Of Power Systems

For economical and technological reasons (which will be discussed in detail in later chapters), individual power systems are organized in the form of electrically connected areas or regional grids (also called power pools). Each area or regional grid operates technically and economically independently, but these are eventually interconnected to form a national grid (which may even form an international grid) so that each area is contractually tied to other areas in respect to certain generation and scheduling features. India is now heading for a national grid.

The siting of hydro stations is determined by the natural water power sources. The choice of site for coal fired thermal stations is more flexible. The following two alternatives are possible.

1. Power stations may be built close to coal mines (called pit head stations) and electric energy is evacuated over transmission lines to the load centers.

2. Power stations may be built close to the load centers and coal is transported to them from the mines by rail road.

In practice, however, power station siting will depend upon many factors technical, economical and environmental. As it is considerably cheaper to transport bulk electric energy over extra high voltage (EHV) transmission lines than to transport equivalent quantities of coal over rail road, the recent trends in India (as well as abroad) is to build super (large) thermal power stations near coal mines. Bulk power can be transmitted to fairly long distances over transmission lines of 400 kV and above. However, the country's coal resources are located mainly in the eastern belt and some coal fired stations will continue to be sited in distant western and southern regions.

As nuclear stations are not constrained by the problems of fuel transport and air pollution, a greater flexibility exists in their siting, so that these stations are located close to load centers while avoiding high density pollution areas to reduce the risks, however remote, of radioactivity leakage.

In India, as of now, about 75% of electric power used is generated in thermal plants (including nuclear). 23% from mostly hydro stations and 2%. come from renewables and others. Coal is the fuel for most of the steam plants, the rest depends upon oil/natural gas and nuclear fuels.

Electric power is generated at a voltage of 11 to 25 kV which then is stepped up to the transmission levels in the range of 66 to 400 kV (or higher). As the transmission capability of a line is proportional to the square of its voltage, research is continuously being carried out to raise transmission voltages. Some of the countries are already employing 765 kV. The voltages are expected to rise to 800 kV in the near future. In India, several 400 kV lines are already in operation. One 800 kV line has just been built.

For very long distances (over 600 km), it is economical to transmit bulk power by DC transmission. It also obviates some of the technical problems associated with very long distance AC transmission. The DC voltages used are 400 kV and above, and the line is connected to the AC systems at the two ends through a transformer and converting/inverting equipment (silicon controlled rectifiers are employed for this purpose). Several DC transmission lines have been constructed in Europe and the USA. In India two HVDC transmission line (bipolar) have already been commissioned and several others are being planned. Three back to back HVDC systems are in operation.

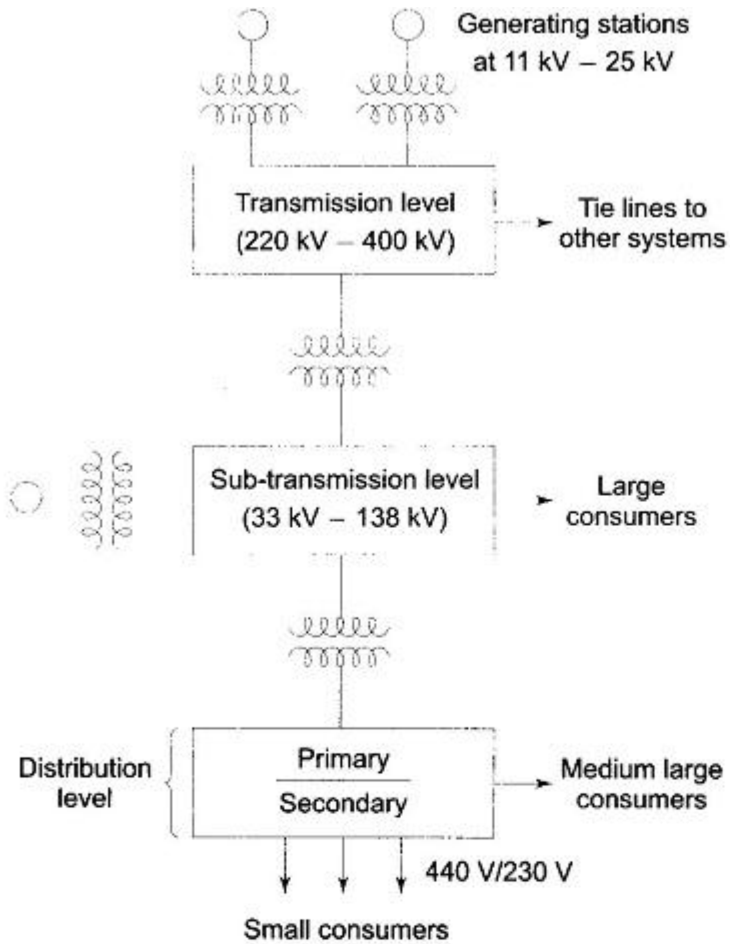


Fig. 1.3 Schematic diagram depicting power system structure

The first stepdown of voltage from transmission level is at the bulk power substation, where the reduction is to a range of 33 to 132 kV, depending on the transmission line voltage. Some industries may require power at these voltage levels. This stepdown is from the transmission and grid level to subtransmission level.

The next stepdown in voltage is at the distribution substation. Normally, two distribution voltage levels are employed:

1. The primary or feeder voltage (11 kV)

2. The secondary or consumer voltage (415 V three phase/230 V single phase).

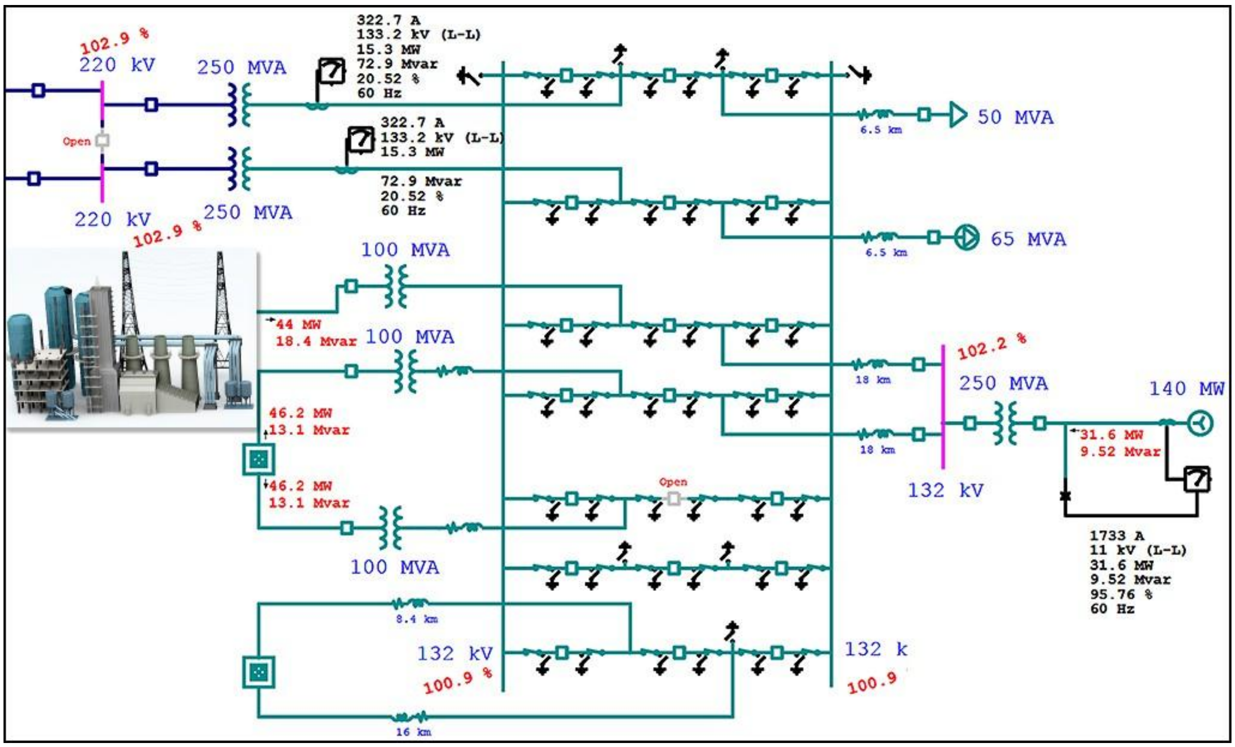
The distribution system, fed from the distribution transformer stations, supplies power to the domestic or industrial and commercial consumers.

Thus, the power system operates at various voltage levels separated by transformer. Figure 1.3 depicts schematically the structure of a power system. Though the distribution system design, planning and operation are subjects of great importance, we are compelled, for reasons of space, to exclude them from the scope of this book.

Single line diagram

Electrical Single-Line Diagram

The ETAP One-Line Diagram is a user-friendly interface for creating and managing the network database used for schematic network visualization.



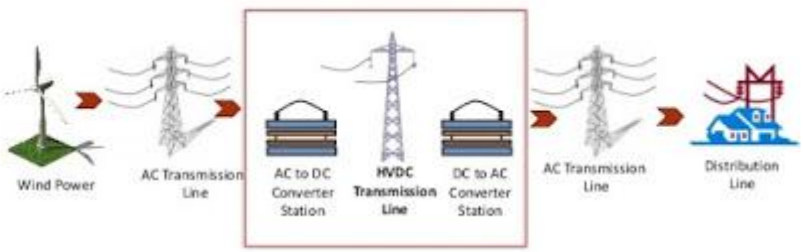
ETAP one-line diagram provides complete bus-breaker connectivity, allowing you to visualize network topology with complete confidence. Applying ground-breaking technologies never before used for power systems software, you can interactively model, monitor, and manage the electrical network as well as execute simulation scenarios and analyze their results in a simple and intuitive manner.

Key Features

- Built-in intelligent graphics
- Autobuild one-line diagram
- Built-in and user-defined templates for substations, protection, etc.
- Datablock templates for visualizing user-defined properties and results
- Bus - Breaker and Bus - Branch representation of electrical networks
- Network nesting
- Integrated 1-phase, 3-phase, & DC systems
- Integrated AC, DC, & grounding systems
- Automatic display of energized & de-energized elements using dynamic continuity check
- Theme manager with standard, phase, layers, voltage, area, & grounding / earthing colors

HVDC – Advantage & Disadvantage

A scheme diagram of HVDC Transmission is shown below for ease in understanding the advantages and disadvantages.



There is a list of advantages of High Voltage DC Power Transmission, HVDC when compared with High Voltage AC Power Transmission, HVAC. They are listed below with detail while comparing with HVAC.

Line Circuit:

The line construction for HVDC is simpler as compared to HVAC. A single conductor line with ground as return in HVDC can be compared with the 3-phase single circuit HVAC line (**Why? Can't we supply power with two phases in HVAC?)**. As because when Line to Earth Fault or Line-Line Fault 3-phase system cannot operate. This is why we compared the a single conductor line with ground as return can be compared with the 3-phase single circuit HVAC line. Thus ***HVDC line conductor is comparatively cheaper while having the same reliability as 3-phase HVAC system.***

Power Per Conductor:

Power Per conductor in HVDC $P_d = V_d I_d$

Power Per Conductor in HVAC $P_a = V_a I_a Cos Ø$

Where I_d and $I_a$are the line current in HVAC and HVDC circuit respectively & $V_d$and V_a are the voltage of line w.r.t ground in HVDC and HVAC respectively.

As crest voltage is same for Insulators of Line, therefore line to ground voltage in HVDC will be root two (1.414) times that of rms value of line to ground voltage in HVAC.

$V_d = 1.414V_a$and $I_d = I_a$ (assumed for comparison purpose)

Therefore,

$P_d / P_a = V_d I_d / V_a I_a Cos Ø$

$= V_d I_d / (V_d/1.414) I_d Cos Ø$

$= 1.414/Cos Ø$

As $Cos Ø <= 1$,

$P_d /P_a > 1$

$P_d > P_a$

Therefore, we see that power per conductor in HVDC is more as compared to HVAC.

Power Per Circuit:

Now, we will compare the power transmission capabilities of 3-phase single circuit line with **Bipolar HVDC Line. (Bipolar HVDC Line have two conductors one with +ive polarity and another with –ive polarity.)**

Therefore, for Bipolar HVDC Line,

$P_d = 2 \times V_d I_d$

While for HVAC Line,

$P_{ac} = 3 \times V_a I_a \mathrm{Cos}Ø$

Hence,

$P_d / P_{ac} = 2V_d I_d / 3V_a I_a \mathrm{Cos}Ø$

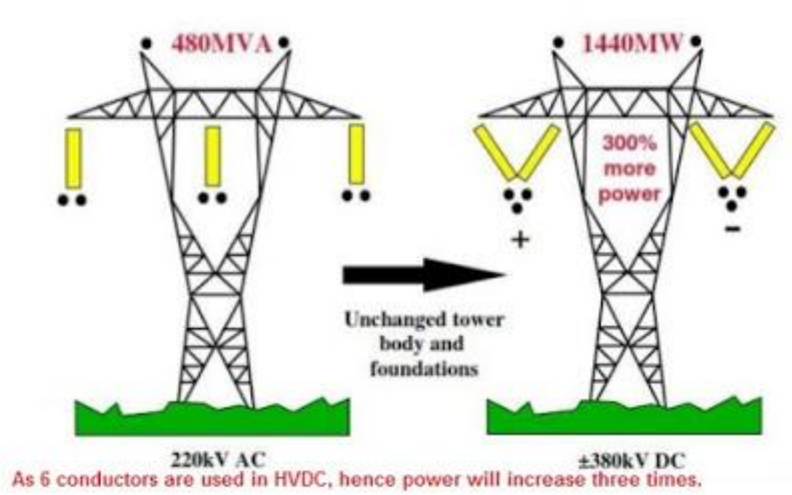
But $V_d = 1.414V_a$ and $I_d = I_a$

$P_d/P_{ac} = (2 \times 1.414) / 3\mathrm{Cos}Ø$

$= 2.828 / 3\mathrm{Cos}Ø \approx 0.9$ (as $\mathrm{Cos}Ø < 1$)

Thus we see that power Transmission Capability of Bipolar HVDC Line is same as 3-phase single circuit HVAC Line. But in case of HVDC, we only need two conductors while in 3-phase HVAC we need three conductors, therefore number of Insulators for supporting conductors on tower will also reduce by 1/3. Hence, HVDC tower is cheaper as compared to HVAC.

Observe the figure below carefully, you will get to know three important points about HVDC
.



No Charging Current:

Unlike HVAC, there is no charging current involved in HVDC which in turn reduces many accessories.

No Skin Effect:

In HVDC Line, the phenomenon of Skin Effect is absent. Therefore current flows through the whole cross section of the conductor in HVDC while in HVAC current only flows on the surface of conductor due to Skin Effect.

No Compensation Required:

Long distance AC power transmission is only feasible with the use of Series and Shunt Compensation applied at intervals along the Transmission Line. For such HVAC line, Shunt Compensation i.e. Shunt Reactor is required to absorb KVARs produced due to the line charging current (because the capacitance of line will dominate during low load / light load condition which is famously known as **Farranty Effect**.) during light load condition and series compensation for stability purpose.

As HVDC operates at unity power factor and there is no charging current, therefore no compensation is required.

Less Corona Loss and Radio Interference:

As we know that, Corona Loss is directly proportional to (f+25) where f is frequency of supply. Therefore for HVDC Corona Loss will be less as f=0. As Corona Loss is less in HVDC therefore Radio Interference will also be less compared to HVAC.
The interesting thing in HVDC is that, Corona and Radio Interference decreases slightly by foul whether condition like snow, rain or fog whereas they increases Corona and hence Radio Interference in HVAC.

Higher Operating Voltage:

High Voltage Transmission Lines are designed on the basis of Switching Surges rather than Lightening Surges as Switching Surges is more dangerous compared to Lightening Surges.
As the level of Switching Surges for HVDC is lower as compared with HVAC, therefore the same size of conductors and Insulators can be used for higher voltage for HVDC when compared with HVAC.

No Stability Problem:

As we know that for two Machine system, power transmitted,
$P = (E1E1Sin\delta)/X$
Where X is inductive reactance of the line, E1 & E2 are the sending and receiving end voltage respectively.

As the length of line increases the value of X increases and hence lower will be the capability of Machine to transmit power from one end to another. Thus, reducing the Steady State Stability Limit. As the Transient Stability Limit is lower than Steady State Stability Limit, thus for longer line Transient Stability Limit becomes very poor.

HVDC do not have any Stability problem in itself as the DC operation is asynchronous operation of Machine.

Now, we will come to disadvantage of HVDC.

Disadvantage of HVDC:

Expensive Converters:

The converters used at both end of line in HVDC are very costly as compared to the equipment used in AC. The converters have very little overload capacity and need reactive power which in turn needs to be supplied locally.

Also Filters are required at the AC side of each converter which also increases the cost.

Voltage Transformation:

Electric Power is used generally at low voltage only. Voltage Transformation is not easier in case of DC.

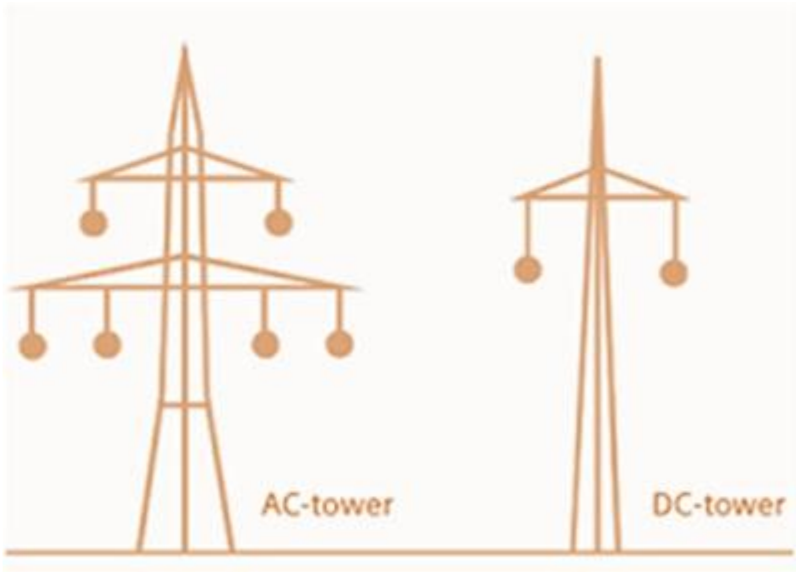
Comparison of AC and DC Transmission

electric Power can either be transmitted by means of AC or DC. Each system has their advantages and disadvantages. Therefore it is very crucial to have a comparative study of their merit and demerits and then decide which method should be adopted to transmit power.

Advantages of DC Transmission:

1) The high voltage DC Transmission has the following advantages over high voltage AC transmission:

2) Power transmission by means of DC requires only two conductors as compared to three conductors required for AC.



3) There is no inductance, capacitance, phase displacement and surge problem in DC transmission.

4) Due to absence of inductance, the voltage drop in DC transmission is less than the AC transmission for same load and receiving end voltage. Because of this DC transmission has better voltage regulation.

5) There is no skin effect in the DC transmission and therefore entire cross-section of the conductor is utilized.

6) For the same voltage, the potential stress on the Insulators are less in DC system as compared to AC system (because in AC insulators had to bear peak voltage which is 1.414 times the RMS voltage.).

7) A DC transmission line has less Corona and hence efficiency is improved.

8) In DC transmission, there is no stability and synchronization problem.

Disadvantages of DC Transmission:

1) DC Power generation is difficult due to commutation problem.

2) Transformer does not work for DC and therefore voltage level of DC cannot be changed for power transmission.

3) DC Switches and Circuit Breakers have their own limitations.

Advantages of AC Transmission:

1) AC power can be generated at high voltage. The maximum voltage at which Electrical Power is generated in India is at 21 kV.

2) AC voltage can be stepped up for power transmission at high voltage. The maximum voltage of Grid in India is 765 kV.

Disadvantages of DC Transmission:

1) AC transmission requires more conductor material as compared to DC transmission.

2) The construction of AC transmission line is more complicated as compared to DC transmission line.

3) Due to Skin Effect in AC transmission, the effective resistance of conductor increases

Kelvin's Law

A transmission line can be designed by taking into consideration various factors out of which economy is the most important factor. The conductor which is to be selected for a give transmission line must be economical. Most of the part of the total line cost is spent for conductor. Thus it becomes vital to select most economic size of conductor.

The most economic design of the line is that for which total annual cost is minimum. Total annual cost is divided into two parts viz. fixed standing charges and running charges. The fixed charges include the depreciation, the interest on capital cost of conductor and maintenance cost. The cost electrical energy wasted due to losses during operation constitutes running charges.

The capital cost and cost of energy wasted in the line is based on size of the conductor. If conductor size is big then due to its lesser resistance, the running cost (cost of energy due to losses) will be lower while the conductor may be expensive. For smaller size conductor, its cost is less but running cost will be more as it will have more resistance and hence greater losses.

The cost of energy loss is inversely proportional to the conductor cross section while the fixed charges (cost of conductor, interest and depreciation charges) are directly proportional to area of cross section of the conductor. Mathematically we have,

Annual interest and depreciation cost = S_1

$$S_1 \ \alpha \ a$$

a is area of cross section of conductor

$$S_1 = K_1 a$$

Annual cost of energy loss in line = S_2

$$S_2 \ \alpha \ 1/a$$

$$S_2 = K_2/a$$

Here K_1 and K_2 are constants

$$S = \text{Total annual cost}$$

$$S = S_1 + S_2$$

$$\therefore \quad S = K_1 a + K_2/a$$

For economical design of line, the cost will be minimum for a particular value of area of cross-section 'a' of the conductor.

Thus for economic design, $dS/da = 0$

$$\therefore \quad \frac{d}{da}\left[K_1 a + \frac{K_2}{a}\right] = 0$$

$K_1 - K_2/a^2 = 0$

$\therefore \quad K_1 = K_2/a^2$

$\therefore \quad K_{1a} = K_2/a$

$\therefore \quad S_1 = S2$

The most economical conductor size, $a = \sqrt{(K_2/K_1)}$

Thus the most economical conductor size is one for which annual cost of energy loss is equal to annual interest and depreciation on the capital investment of the conductor material. This is known as Kelvin's law. The most economical current density can be estimated by using this law as it is not sufficient to determine cross section of the conductor.

Let us find economic current density

Let R = Resistance of the conductor of 1 mm^2 cross section and 1 km length.

I = RMS value of current in the conductor throughout the year

a = Area of cross section of the conductor in mm

w = Weight of conductor of 1 mm^2 cross section in kgf/km

C_1 = Cost of electrical energy wasted in rupees per kWh

C_2 = Cost of conductor in kgf in rupees.

t = Total number of working hours per year

r = Rate of interest and depreciation in percentage on capital cost.

Cost of one km conductor = Rs aw C_2

Annual interest and depreciation on this cost = Rs $(r\ a\ w\ C_2 / 100)$

Annual energy wasted in 1 km of the conductor = $I^2 Rt \times 10^{-3}$ kWh

$= I^2 (\rho l / a)\ t \times 10^{-3}$

Since the l = length of conductor = 1 km

ρ = Specific resistance of conductor material $= I^2 (\rho / a)\ t \times 10^{-3}$

Cost of energy wasted = Rs $(I^2 \rho\ t\ C_1/a)$

The economical cross section is one for which fixed annual charges on conductor material should be equal to cost of energy wasted during the year.

$(I^2 \rho\ t\ C_1/a) \times 10^{-3} = (r\ a\ w\ C_2/ 100)$

$\therefore \quad I^2/a^2 = (10\ r\ w\ C_2) /(\rho\ t\ C_1)$

$\therefore \quad I/a = (10\ r\ w\ C_2)/(\rho\ t\ C_1)$

Economical current density in A / mm^2 , $I = \sqrt{(10\ r\ w\ C_2)/(\rho\ t\ C_1)}$

The graphical representation of Kelvin's law is shown in the Fig.1.

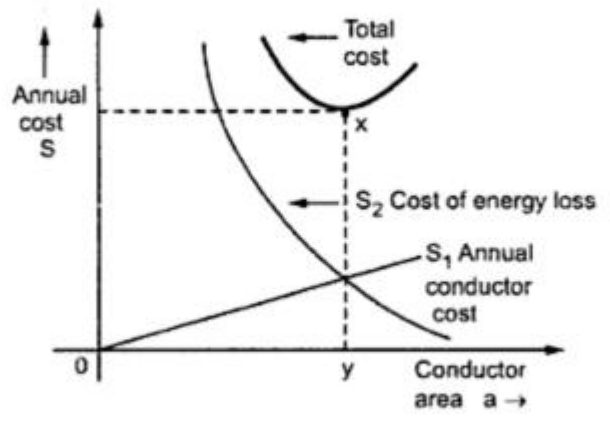


Fig. 1

As the annual conductor cost S_1 is directly proportional to area of cross section of conductor, it is represented by straight line while the cost of energy wasted is inversely proportional to conductor area so it is represented by rectangular hyperbola. The total annual cost S is summation of S_1 and S_2 for that cross section.

The lowercost point x on the total annual cost curve S gives the most economical area of conductor which corresponds to point of intersection of two components of total cost S as S_1 and S_2 as shown in the graph. At this point of intersection, S_1 and S_2 are equal. So most economical area is oy while corresponding minimum cost is xy.

1.1 Limitation of Kelvin's Law

Following are limitations in applying Kelvin's law.

1. The amount of energy loss can not be determined accurately as the load factors of the losses and the load are not same. Also the future load conditions and load factors can not be predicated exactly.

To estimate the energy loss approximately, the load curves are drawn for various types of loads and the load factors is determined. From the load factor, one can get the information of average load current carried by the line during the entire year. The total losses in the year are proportional to the mean value of the square of current during that year. The square root of the mean value of the squares of the line currents throughtout the year is called rms current.

If I_{max} = Maximum full load line current

K_L = Annual load factor of the line = Average load over a period/ Maximum load over the period

= Number of kWh (units) generated per year/ Maximum demand (kW) x 8760 (hrs)

$\therefore$ $K_L = I_{av} / I_m$

K_F = Form factor of load curve = I_{rms}/I_{av}

$\therefore$ $I_{rms} = K_F \cdot I_{av}$

$\therefore$ $I_{rms} = K_F \cdot K_L\ I_m$

The rms current obtained from above expression gives fairly accurate results.

The load factor of the losses is different from the load factor of the load current.

The load factor of the losses is called loss factor λ It is defined as ratio of actual energy loss during a period to the energy loss if maximum current is flowing during the whole period.

2. The cost of energy loss can not be determined exactly. The cost of losses per unit is more than the generating cost per unit.

3. The cost of conductor and rates of interest are changing continuously.
4. If economical conductor size is selected then voltage drop may be beyond the acceptable limits.
5. The economical size size of conductor may not have the enough mechanical strength.
6. The cost of conductor also includes to some extent cost of insulation which changes with change in cross section of conductor. The cost of insulation is difficult to express in terms of cross section of conductor.
7. Due to problem of corona, leakage currents, the economic size of conductor can not be used at extra voltages.
8. Due to change in rates of interest and depreciation continuously, even if other parameters are same, application of Kelvin's law will give economical conductor size different at different time and in different countries.
9. In case of cables, the current carried safely depends on accepted temperature rise. In addition to copper loss, there is dielectric loss in metallic sheath all the time independent of whether current is carried by cable or not. These losses are difficult to consider these losses while applying Kelvin's law.

In case of overhead lines, the problem of temperature rise is not much dominent than in case of cables. The I^2R losses are the major losses in overhead lines. So kelvin's law gives fairly acceptable results for lines upto 33 kV.

For cables, the economic conductor size as obtained from Kelvin's law is to be considered from the point of view of acceptable temperature rise. So the practically selected conductor size and size obtained from Kelvin's law will be different and the different in cost will no be considerable. So small deviations from most economic conductor size can be always made practically.

10. The conductor size of the two systems having same load demand should also be same. But the cost of energy, interests and depreciation rates which are independent of resistance, voltage drop, temperature rise may be different in the two systems may give different economic cross section of the conductor after applying Kelvin's law

Economic Choice Of Conductor Size - Kelvin's Law

As economy is one of the most important factors while designing any transmission line, the **cost of required conductor material** is a considerable part. Thus, it becomes vital to **select a proper size of the conductor**. The most economic design of a transmission line is for which the total annual cost is minimum. Total annual cost can be divided into two parts, viz. annual charges on capital outlay and running charges. Annual charges on capital outlay include depreciation, interest on the capital cost, maintenance cost etc.. The cost of energy lost during the operation is counted in running charges. Regarding this, there are two important points that must be noted -

- if the cross-sectional area of the conductor is decreased, the total capital cost of the conductor decreases but the line losses increase (resistance increases with the decrease in the conductor size, hence, I^2R loss increases)
- whereas, if the cross-sectional area of the conductor is increased, the line losses decrease but the total capital cost increases.

Therefore, it is important to find the most **economical size of the conductor**. **Kelvin's law** helps in finding this.
[Also read: Economic choice of transmission voltage]

Kelvin's Law For Finding Economic Size Of A Conductor

Let, area of cross-section of conductor = a
annual interest and depreciation on capital cost of the conductor = C_1
annual running charges = C_2

Now, annual interest and depreciation cost is directly proportional to the area of conductor.
i.e., $C_1 = K_1 a$
And, annual running charges are inversely proportional to the area of conductor.
$C_2 = K_2/a$
Where, K_1 and K_2 are constants.

Now, Total annual cost = $C = C_1 + C_2$

$$C = K_1 a + K_2/a$$

For C to be minimum, the differentiation of C w.r.t a must be zero. i.e. dC/da = 0.
Therefore,

$$\frac{dC}{da} = \frac{d}{da}\left[K_1 a + \frac{K_2}{a}\right] = 0$$

$$\therefore \quad K_1 - \frac{K_2}{a^2} = 0$$

$$\therefore \quad K_1 = \frac{K_2}{a^2}$$

$$\therefore \quad K_1 a = \frac{K_2}{a}$$

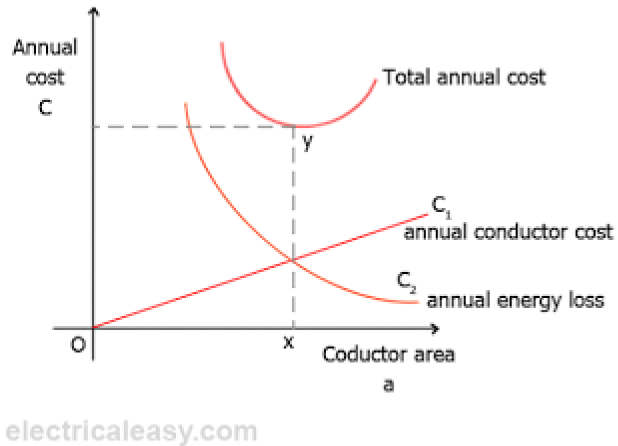
$$\therefore \quad C_1 = C_2$$

*"The **Kelvin's law** states that the most economical size of a conductor is that for which annual interest and depreciation on the capital cost of the conductor is equal to the annual cost of energy loss."*

From the above derivation, the economical cross-sectional area of a conductor can be calculated as,

$$a = \sqrt{(K_2/K_1)}$$

Graphical Illustration Of Kelvin's Law



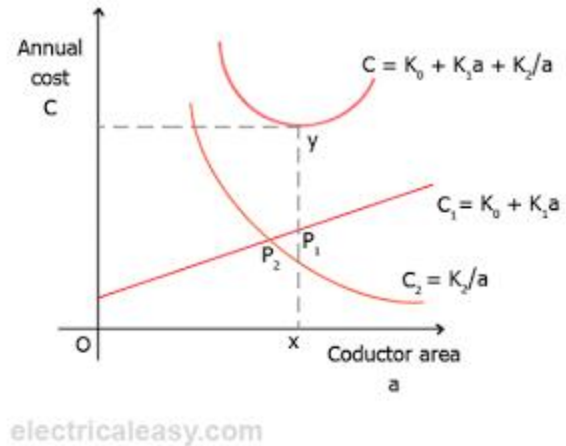
As the annual cost of conductor is directly proportional to size of the conductor, it is shown by the straight line C_1 in the figure. Annual cost of energy loss is shown by the curve C_2. The total annual cost curve is obtained by adding the curve C_1 and C_2. The lowermost point on total annual cost curve gives the most **economical size of the conductor** which corresponds to the intersection point of curve C_1 and C_2. So, here, the most economical area of cross-section of the conductor is represented by ox and the corresponding minimum cost is represented by xy.

Limitations Of Kelvin's Law

Although Kelvin's law holds good theoretically, there is often considerable difficulty while applying it in practice. The limitations of this law are:

1. It is quite difficult to estimate the energy loss in the line without actual load curves which are not available at the time of estimation.
2. Interest and depreciation on the capital cost cannot be determined accurately.
3. The conductor size determined using this law may not always be practicable one because it may not have sufficient mechanical strength.
4. This law does not take into account several factors like safe current carrying capacity, corona lossetc.
5. The economical size of a conductor may cause the voltage drop beyond the acceptable limits.

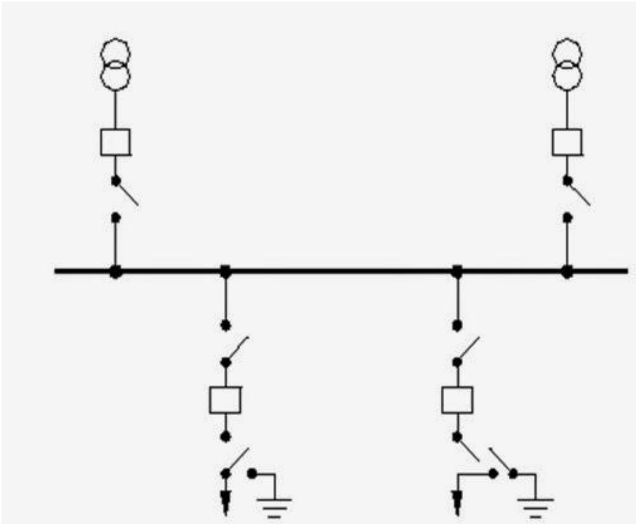
Modified Kelvin's Law



The actual Kelvin's law does not count the cost of supporting structures, erection, insulators etc.. It only accounts for the capital cost of conductor and corresponding interest and depreciation. Also, for underground cables, the cost of insulation and laying is not considered in the actual Kelvin's law. To account for these costs and to get practically fair results, the initial investment needs to be divided into two parts, viz (i) one part which is independent of conductor size and (ii) other part which is directly proportional to the conductor size. For an overhead line, insulator cost is almost constant and the cost of supporting structure and their erection is partly constant and partly proportional to the conductor size. So, according to the modified Kelvin's law, the annual charge on capital outlay is given as, $C_1 = K_0 + K_1a$. where, K_0 is an another constant. The differentiation of total cost C w.r.t. to the area of conductor (a) comes to be same as derived above under the heading Kelvin's law.
*The **modified statement of Kelvin's law** suggests that the most economical conductor size is that for which the annual cost of energy loss is equal to the annual interest and depreciation for that part of capital cost which is proportional to the conductor size.*

TYPES OF BUS BAR SYSTEM

1 Single Busbar System
Single busbar system is as shown below in figure



Single Busbar System

a. Merits

1. Low Cost
2. Simple to Operate
3. Simple Protection

b. Demerits

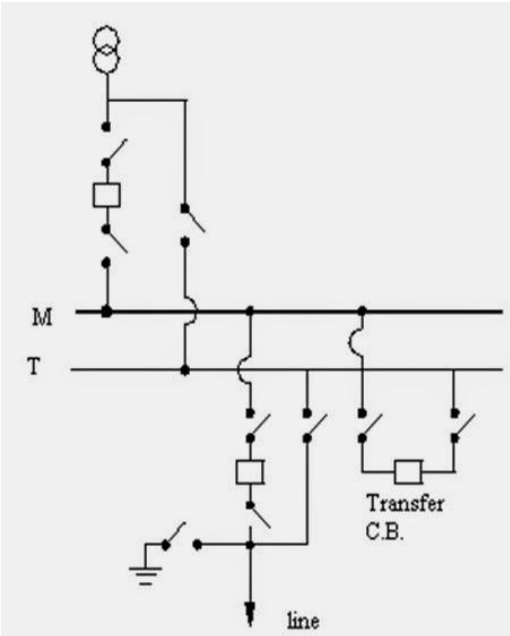
1. Fault of bus or any circuit breaker results in shut down of entire substation.
2. Difficult to do any maintenance.
3. Bus cannot be extended without completely deenergizing substations.

c. Remarks

1. Used for distribution substations up to 33kV.
2. Not used for large substations.
3. Sectionalizing increases flexibility.

2 Main & Transfer Bus bar System

Main & Transfer Bus is as shown below in figure



a. Merits

1. Low initial & ultimate cost
2. Any breaker can be taken out of service for maintenance.
3. Potential devices may be used on the main bus.

b. Demerits

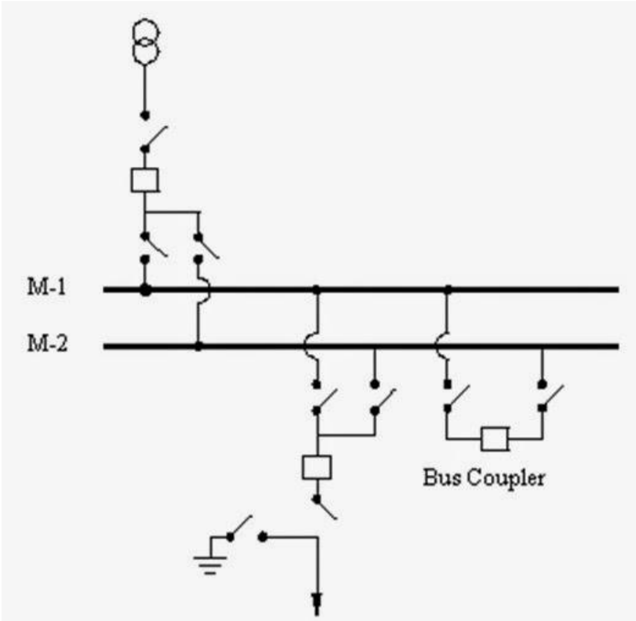
1. Requires one extra breaker coupler.
2. Switching is somewhat complex when maintaining a breaker.
3. Fault of bus or any circuit breaker results in shutdown of entire substation.

c. Remarks

1. Used for 110kV substations where cost of duplicate bus bar system is not justified.

3 Double Bus bar Single Breaker system

Double Bus Bar with Double Breaker is as shown below in figure



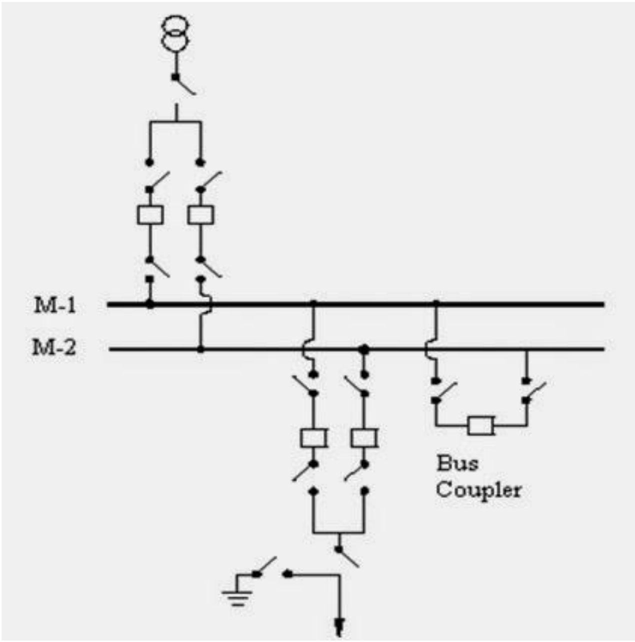
a. Merits
1. High flexibility
2. Half of the feeders connected to each bus

b. Demerits
1. Extra bus-coupler circuit breaker necessary.
2. Bus protection scheme may cause loss of substation when it operates.
3. High exposure to bus fault.
4. Line breaker failure takes all circuits connected to the bus out of service.
5. Bus couplers failure takes entire substation out of service.

c. Remarks
Most widely used for 66kV, 132kv, 220kV and important 11kv, 6.6kV, 3.3kV

Substations.

4 Double Bus bar with Double breaker System
Double Bus Bar with Double breaker system is as shown below in figure



a. Merits

1. Each has two associated breakers
2. Has flexibility in permitting feeder circuits to be connected to any bus
3. Any breaker can be taken out of service for maintenance.
4. High reliability

b. Demerits

1. Most expensive
2. Would lose half of the circuits for breaker fault if circuits are not connected to both the buses.

c. Remarks

1. Not used for usual EHV substations due to high cost.

UNIT II

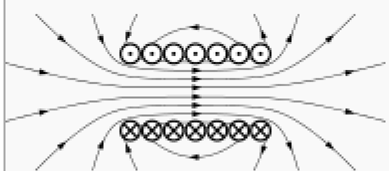
ELECTRICAL DESIGN OF TRANSMISSION LINES

Resistance, inductance and capacitance calculations in single and three phase transmissions lines –stranded and bundled conductors

Electrical resistance and conductance

"Resistive" redirects here. For the term used when referring to touchscreens, see resistive touchscreen.

Electromagnetism



Electricity
Magnetism

Electrostatics[show]

Magnetostatics[show]

Electrodynamics[show]

Electrical network[hide]

Electric current
Electric potential
Voltage
Resistance
Ohm's law
Series circuit
Parallel circuit
Direct current
Alternating current

Electromotive force
Capacitance
Inductance
Impedance
Resonant cavities
Waveguides

Covariant formulation[show]

Scientists[show]

v
t
e

The **electrical resistance** of an electrical conductor is a measure of the difficulty to pass an electric current through that conductor. The inverse quantity is **electrical conductance**, and is the ease with which an electric current passes. Electrical resistance shares some conceptual parallels with the notion of mechanical friction. The SI unit of electrical resistance is the ohm (Ω), while electrical conductance is measured in siemens (S).

An object of uniform cross section has a resistance proportional to its resistivity and length and inversely proportional to its cross-sectional area. All materials show some resistance, except for superconductors, which have a resistance of zero.

The resistance (R) of an object is defined as the ratio of voltage across it (*V*) to current through it (*I*), while the conductance (G) is the inverse:

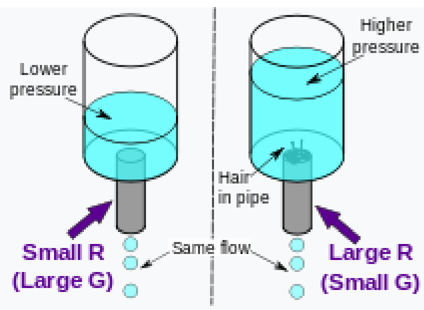
For a wide variety of materials and conditions, *V* and *I* are directly proportional to each other, and therefore *R* and *G* are constant(although they can depend on other factors like temperature or strain). This proportionality is called Ohm's law, and materials that satisfy it are called *ohmic* materials.

In other cases, such as a diode or battery, *V* and *I* are *not* directly proportional. The ratio V/I is sometimes still useful, and is referred to as a "chordal resistance" or "static resistance",[1][2] since it corresponds to the inverse slope of a chord between the origin and an *I*–*V*curve. In other situations, the derivative may be most useful; this is called the "differential resistance".

Contents

[hide]

Introduction[edit]



The hydraulic analogy compares electric current flowing through circuits to water flowing through pipes. When a pipe (left) is filled with hair (right), it takes a larger pressure to achieve the same flow of water. Pushing electric current through a large resistance is like pushing water through a pipe clogged with hair: It requires a larger push (electromotive force) to drive the same flow (electric current).

In the hydraulic analogy, current flowing through a wire (or resistor) is like water flowing through a pipe, and the voltage drop across the wire is like the pressure drop that pushes water through the pipe. Conductance is proportional to how much flow occurs for a given pressure, and resistance is proportional to how much pressure is required to achieve a given flow. (Conductance and resistance are reciprocals.)

The voltage *drop* (i.e., difference between voltages on one side of the resistor and the other), not the voltage itself, provides the driving force pushing current through a resistor. In hydraulics, it is similar: The pressure *difference* between two sides of a pipe, not the pressure itself, determines the flow through it. For example, there may be a large water pressure above the pipe, which tries to push water down through the pipe. But there may be an equally large water pressure below the pipe, which tries to push water back up through the pipe. If these pressures are equal, no water flows. (In the image at right, the water pressure below the pipe is zero.)

The resistance and conductance of a wire, resistor, or other element is mostly determined by two properties:

- geometry (shape), and
- material

Geometry is important because it is more difficult to push water through a long, narrow pipe than a wide, short pipe. In the same way, a long, thin copper wire has higher resistance (lower conductance) than a short, thick copper wire.

Materials are important as well. A pipe filled with hair restricts the flow of water more than a clean pipe of the same shape and size. Similarly, electrons can flow freely and easily through a copper wire, but cannot flow as easily through a steel wire of the same shape and size, and they essentially cannot flow at all through an insulator like rubber, regardless of its shape. The difference between copper, steel, and rubber is related to their microscopic structure and electron configuration, and is quantified by a property called resistivity.

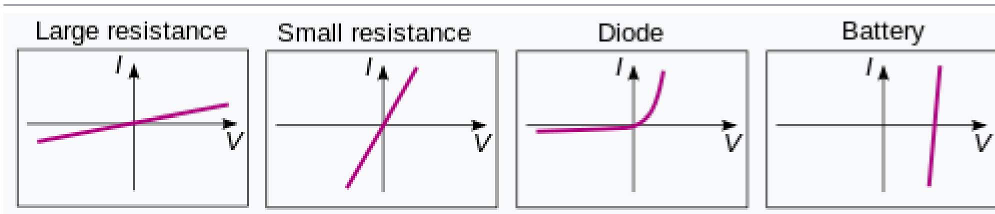
In addition to geometry and material, there are various other factors that influence resistance and conductance, such as temperature; see below.

Conductors and resistors[edit]

A 6.5 MΩ resistor, as identified by its electronic color code (blue–green–black-yellow-red). An ohmmeter could be used to verify this value.

Substances in which electricity can flow are called conductors. A piece of conducting material of a particular resistance meant for use in a circuit is called a resistor. Conductors are made of high-conductivity materials such as metals, in particular copper and aluminium. Resistors, on the other hand, are made of a wide variety of materials depending on factors such as the desired resistance, amount of energy that it needs to dissipate, precision, and costs.

Ohm's law[edit]



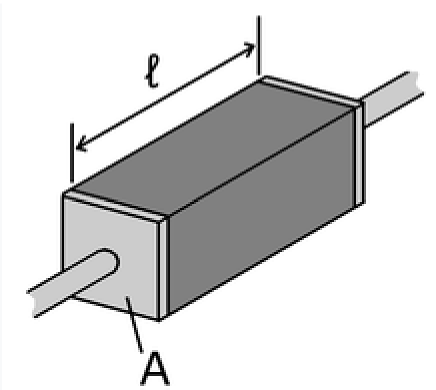
The current-voltage characteristics of four devices: Two resistors, a diode, and a battery. The horizontal axis is voltage drop, the vertical axis is current. Ohm's law is satisfied when the graph is a straight line through the origin. Therefore, the two resistors are *ohmic*, but the diode and battery are not.

Main article: Ohm's law

Ohm's law is an empirical law relating the voltage *V* across an element to the current *I* through it:

(*I* is directly proportional to *V*). This law is not always true: For example, it is false for diodes, batteries, and other devices whose conductance is not constant. However, it is true to a very good approximation for wires and resistors (assuming that other conditions, including temperature, are held constant). Materials or objects where Ohm's law is true are called *ohmic*, whereas objects that do not obey Ohm's law are *non-ohmic*.

Relation to resistivity and conductivity[edit]



A piece of resistive material with electrical contacts on both ends.

Main article: Electrical resistivity and conductivity

The resistance of a given object depends primarily on two factors: What material it is made of, and its shape. For a given material, the resistance is inversely proportional to the cross-sectional area; for example, a thick copper wire has lower resistance than an otherwise-identical thin copper wire. Also, for a given material, the resistance is proportional to the length; for example, a long copper wire has higher resistance than an otherwise-identical short copper wire. The resistance R and conductance G of a conductor of uniform cross section, therefore, can be computed as where is the length of the conductor, measured in metres [m], *A* is the cross-sectional area of the conductor measured in square metres[m²], σ (sigma) is the electrical conductivity measured in siemens per meter ($S\cdot m^{-1}$), and ρ (rho) is the electrical resistivity (also called *specific electrical resistance*) of the material, measured in ohm-metres (Ω·m). The resistivity and conductivity are proportionality constants, and therefore depend only on the material the wire is made of, not the geometry of the wire. Resistivity and conductivity are reciprocals: . Resistivity is a measure of the material's ability to oppose electric current.

This formula is not exact, as it assumes the current density is totally uniform in the conductor, which is not always true in practical situations. However, this formula still provides a good approximation for long thin conductors such as wires.

Another situation for which this formula is not exact is with alternating current (AC), because the skin effect inhibits current flow near the center of the conductor. For this reason, the *geometrical* cross-section is different from the *effective* cross-section in which current actually flows, so resistance is higher than expected. Similarly, if two conductors near each other carry AC current, their resistances increase due to the proximity effect. At commercial power frequency, these effects are significant for large conductors carrying large currents, such as busbars in an electrical substation,[3] or large power cables carrying more than a few hundred amperes.

What determines resistivity

The resistivity of different materials varies by an enormous amount: For example, the conductivity of teflon is about 10^{30} times lower than the conductivity of copper. Why is there such a difference? Loosely speaking, a metal has large numbers of "delocalized" electrons that are not stuck in any one place, but free to move across large distances, whereas in an insulator (like teflon), each electron is tightly bound to a single molecule, and a great force is required to pull it away. Semiconductors lie between these two extremes. More details can be found in the article: Electrical resistivity and conductivity. For the case of electrolyte solutions, see the article: Conductivity (electrolytic).

Resistivity varies with temperature. In semiconductors, resistivity also changes when exposed to light. See below.

Measuring resistance

An instrument for measuring resistance is called an ohmmeter. Simple ohmmeters cannot measure low resistances accurately because the resistance of their measuring leads causes a voltage drop that interferes with the measurement, so more accurate devices use four-terminal sensing.

Typical resistances

Component	Resistance (Ω)

1 meter of copper wire with 1 mm diameter	0.02[4]
1 km overhead power line (*typical*)	0.03[5]
AA battery (*typical internal resistance*)	0.1[6]
Incandescent light bulb filament (*typical*)	200–1000[7]
Human body	1000 to 100,000[8

Capacitance

Capacitance is the ability of a body to store an electric charge. There are two closely related notions of capacitance: *self capacitance*and *mutual capacitance*. Any object that can be electrically charged exhibits *self capacitance*. A material with a large self capacitance holds more electric charge at a given voltage, than one with low capacitance. The notion of *mutual capacitance* is particularly important for understanding the operations of the capacitor, one of the three fundamental electronic components (along with resistors and inductors).

The capacitance is a function only of the geometry of the design (e.g. area of the plates and the distance between them) and the permittivity of the dielectric material between the plates of the capacitor. For many dielectric materials, the permittivity and thus the capacitance, is independent of the potential difference between the conductors and the total charge on them.

The SI unit of capacitance is the farad (symbol: F), named after the English physicist Michael Faraday. A 1 farad capacitor, when charged with 1 coulomb of electrical charge, has a potential difference of 1 volt between its plates.[1] The inverse of capacitance is called elastance.

Self-capacitance

In electrical circuits, the term *capacitance* is usually a shorthand for the *mutual capacitance* between two adjacent conductors, such as the two plates of a capacitor. However, for an isolated conductor there also exists a property called *self-capacitance*, which is the amount of electric charge that must be added to an isolated conductor to raise its electric potentialby one unit (i.e. one volt, in most measurement systems).[2] The reference point for this potential is a theoretical hollow conducting sphere, of infinite radius, with the conductor centered inside this sphere.

Mathematically, the *self-capacitance* of a conductor is defined by where

q is the charge held by the conductor,

dS is an infinitesimal element of area,

r is the length from dS to a fixed point *M* within the plate.

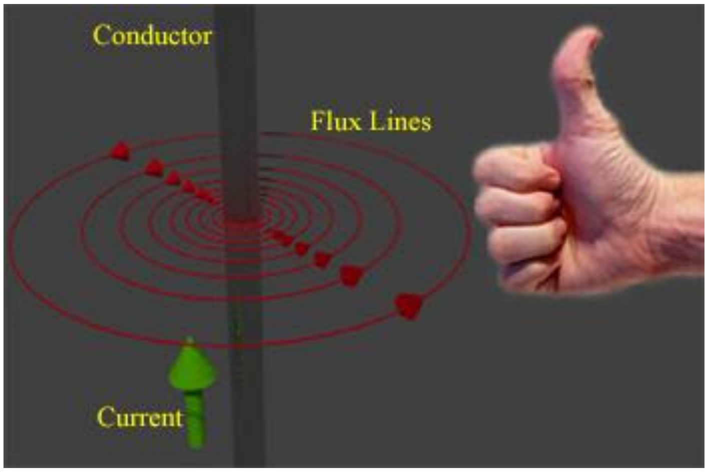
Using this method, the self-capacitance of a conducting sphere of radius *R* is:[3]

Example values of self-capacitance are:

- for the top "plate" of a van de Graaff generator, typically a sphere 20 cm in radius: 22.24 pF,
- the planet Earth: about 710 μF.[4]

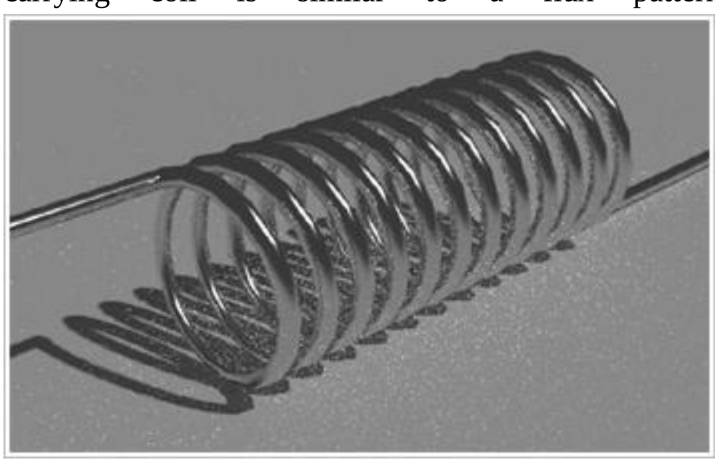
The inter-winding capacitance of a coil is sometimes called self-capacitance,[5] but this is a different phenomenon. It is actually mutual capacitance between the individual turns of the coil and is a form of stray, or parasitic capacitance. This self-capacitance is an important consideration at high frequencies. It changes the impedance of the coil and gives rise to parallel resonance. In many applications this is an undesirable effect and sets an upper frequency limit for the correct operation of the circuit

Definition of Inductance

If a changing flux is linked with a coil of a conductor there would be an emf induced in it. The property of the coil of inducing emf due to the changing flux linked with it is known as **inductance of the coil**. Due to this property all electrical coil can be referred as **inductor**. In other way, an inductor can be defined as an energy storage device which stores energy in form of magnetic field. 

Theory of Inductor

A current through a conductor produces a magnetic field surround it. The strength of this field depends upon the value of current passing through the conductor. The direction of the magnetic field is found using the right hand grip rule, which shown. The flux pattern for this magnetic field would be number of concentric circle perpendicular to the detection of current. Now if we wound the conductor in form of a coil or solenoid, it can be assumed that there will be concentric circular flux lines for each individual turn of the coil as shown. But it is not possible practically, as if concentric circular flux lines for each individual turn exist, they will intersect each other. However, since lines of flux cannot intersect, the flux lines for individual turn will distort to form complete flux loops around the whole coil as shown. This flux pattern of a current carrying coil is similar to a flux pattern of a bar magnet as shown.



Now if the current through the coil is changed, the magnetic flux produced by it will also be changed at same rate. As the flux is already surrounds the coil, this changing flux obviously links the coil. Now according to Faraday's law of electromagnetic induction, if changing flux links with a coil, there would be an induced emf in it. Again as per Lenz's law this induced emf opposes every cause of producing it. Hence, the induced emf is in opposite of the applied voltage across the coil.

Definition of Self Inductance

Whenever, current flows through a circuit or coil, flux is produced surround it and this flux also links with the coil itself. Self induced emf in a coil is produced due to its own changing flux and changing flux is caused by changing current in the coil. So, it can be concluded that self-induced emf is ultimately due to changing current in the coil itself. And self inductance is the property of a coil or solenoid, which causes a self-induced emf to be produced, when the current through it changes.

Explanation of Self Inductance of a Coil

Whenever changing flux, links with a circuit, an emf is induced in the circuit. This is Faraday's laws of electromagnetic induction. According to this law, $e = -N\frac{d\phi}{dt} \cdots\cdots\cdots\cdots\cdots (1)$ Where, e is the induced emf. N is the number of turns. (dφ/dt) is the rate of change of flux leakage with respect to time. The negative sign of the equation indicates that the induced emf opposes the change flux linkage. This is according to Len'z law of induction. The flux is changing due to change in current of the circuit itself. The produced flux due to a current, in a circuit, always proportional to that current. That means, $\phi = Ki$ Where, i is the current in the circuit and K is the proportional constant. $Now,\ \frac{d\phi}{dt} = K\frac{di}{dt} \cdots\cdots\cdots\cdots\cdots (2)$ Now, from equation (1) and (2) we get, $e = -NK\frac{di}{dt}$ The above equation can also be rewritten as $-e = L\frac{di}{dt} \cdots\cdots\cdots\cdots (3)$

Where, L (= NK) is the constant of proportionality and this L is defined as the self inductance of the coil or solenoid. This L determines how much emf will be induced in a coil for a specific rate of change of current through it.

Now, from equation (1) and (3), we get, $L\frac{di}{dt} = N\frac{d\phi}{dt} \Rightarrow Ldi = Nd\phi$ Integrating, both sides we get, $\int Ldi = \int Nd\phi \Rightarrow Li = N\phi \Rightarrow L = \frac{N\phi}{i} \cdots\cdots\cdots\cdots (4)$ From the above expression, inductance can be also be defined as, "If the current I through an N turn coil produces a flux of Ø Weber, then its self-inductance would be L".

A coil can be designed to have a specific value of self-inductance (L). In the view of self-inductance, a coil or solenoid is referred as an inductor. Now, if cross-sectional area of the core of the inductor(coil) is A and flux density in the core is B, then total flux inside the core of inductor is AB.

Therefore, equation (4) can be written as $L = \frac{NAB}{i}$ Now, $B = \mu_o\mu_r H$ Where, H is magnetic

field strength, μ_o and μ_r are permeability of free space and relative permeability of the core respectively. Now, H = mmf/unit length = Ni/l Where l is the length of the coil. Therefore,
$$L = \frac{NA\mu_o\mu_r Ni}{li} = \frac{A\mu_o\mu_r N^2}{l}$$

Self Inductance Formula
$$L = \frac{A\mu_o\mu_r N^2}{l}$$

Video presentation on theory of Inductor

Unit of Inductance

$e = -L\frac{di}{dt}$ Which we derived at equation (3). Where, L is known is the self induction of the circuit. In the above **equation of inductance**, if e = 1 Volt and (di / dt) is one ampere per second, then L = 1 and its unit is Henry. That means, if a circuit, produces emf of 1 Volt, due to the rate of change of current through it, one ampere per second then the circuit is said to have one henry self-inductance. This henry is **unit of inductance**.

Mutual Inductance

Inductance due to the current, through the circuit itself is called self inductance. But when a current flows through a circuit nearer to another circuit, then flux due to first circuit links to secondary circuit. If this flux linkage changes with respect to time, there will be an induced emf in the second circuit. Similarly, if current flows through second circuit, it will produced flux, and if this current changes, the flux will also change. This changing flux will link with first coil. Due to this phenomenon emf will be induced in the first coil. This phenomenon is known as mutual inductance. If current i_1 flows through circuit 1 then emf $e_2$is induced in the nearby circuit is given by, $e_2 = -M\frac{di_1}{dt}\ Volt$ Where, M is the mutual inductance. If current i_2 flows through circuit 2, then emf e_1 is induced in the nearby circuit 1 is given by,
$$e_1 = -M\frac{di_2}{dt}\ Volt$$

Defination of Mutual Inductance

Mutual inductance may be defined as the ability of one circuit to produce an emf in a nearby circuit by induction when current in the first circuit changes. In reverse way second circuit can also induce emf in the first circuit if current in the second circuit changes.

Coefficient of Mutual Inductance

Let's consider two nearby coils of turns N_1 and N_2 respectively. Let us again consider, current i_1 flowing through first coil produces φ_1. If this whole of the flux links with second coil, the weber-turn in the second coil would be $N_2\varphi_1$ due to current i_1 in the first coil. From this, it can be said, $(N_2\varphi_1)/i_1$ is the weber-turn of the second coil due to unit current in the first coil. This term is defined as co-efficient of mutual inductance. That means, mutual inductance between two coils or circuits is defined as the weber-turns in one coil or circuit due to 1 A current in the other coil or circuit.

Formula or Equation of Mutual Inductance

Now we have already found that, mutual inductance due to current in first coil is, $M = \frac{N_2\phi_1}{i_1}$ Again, if self inductance of first coil or circuit is L_1, then,

$$L_1 i_1 = N_1\phi_1 \Rightarrow \frac{L_1}{N_1} = \frac{\phi_1}{i_1}$$

$$M = \frac{N_2 L_1}{N_1} \cdots\cdots\cdots\cdots\cdots (5)$$

Similarly, coefficient of mutual inductance due to current i_2 in the second coil is, $M = \frac{N_1\phi_2}{i_2}$ Now, if self inductance of the second coil or circuit is, L_2,

$$L_2 i_2 = N_2\phi_2$$

$$\Rightarrow \frac{L_2}{N_2} = \frac{\phi_2}{i_2}$$

$$Therefore,\ M = \frac{N_1 L_2}{N_2} \cdots\cdots\cdots\cdots\cdots (6)$$

Now, multiplying (5) and (6), we get,

$$M \times M = \frac{N_2 L_1}{N_1} \times \frac{N_1 L_2}{N_2}$$

$$\Rightarrow M^2 = L_1 L_2 \Rightarrow M = \sqrt{L_1 L_2}$$

This is an ideal case, when the whole changing flux of one coil, links to another coil. The value of M practically not equal to $\sqrt{(L_1 L_2)}$ as because the whole flux of one coil does not link with other, rather, a part of the flux of one coil, links with another coil. Hence practically,

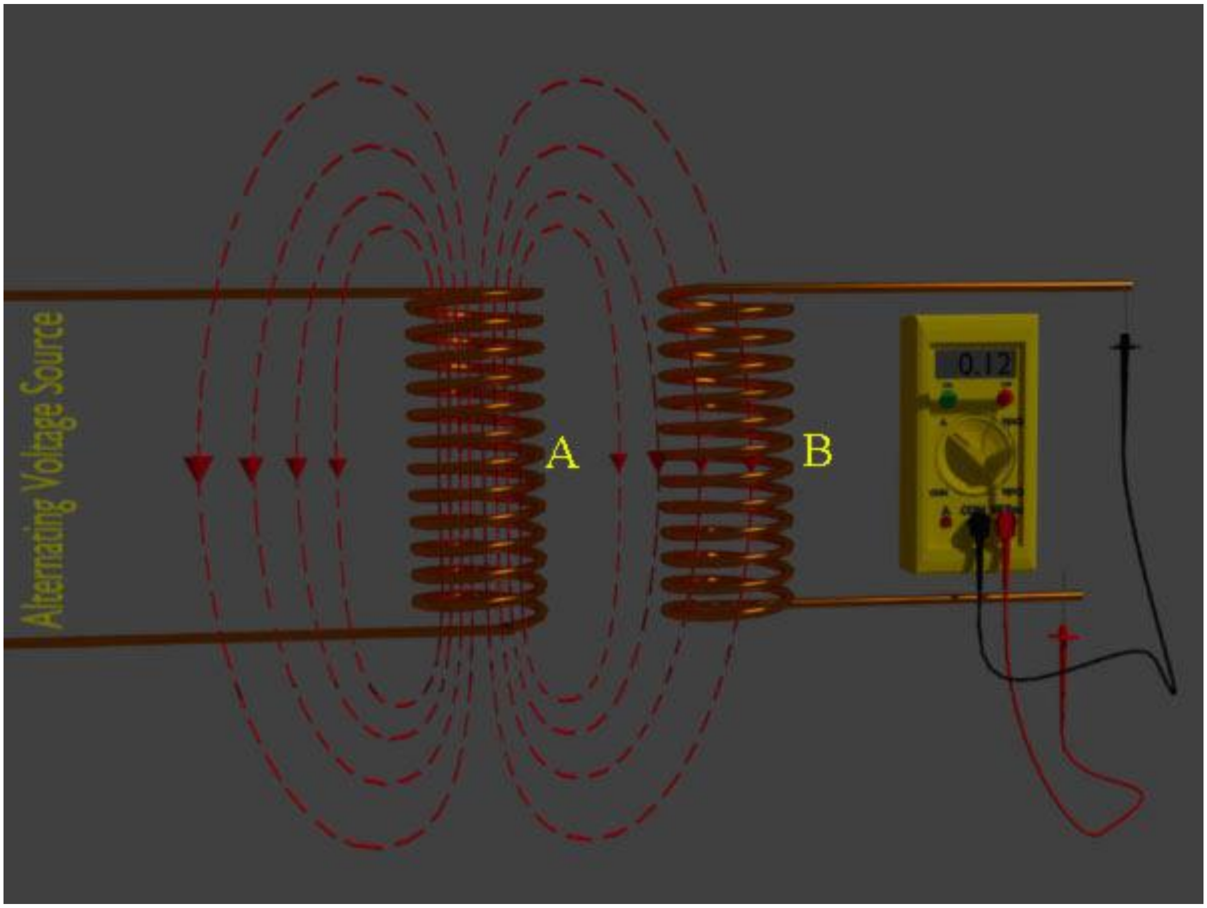
$$M \neq \sqrt{L_1 L_2}$$

$$and\ \frac{M}{\sqrt{L_1 L_2}} = K\ (\neq 1)$$

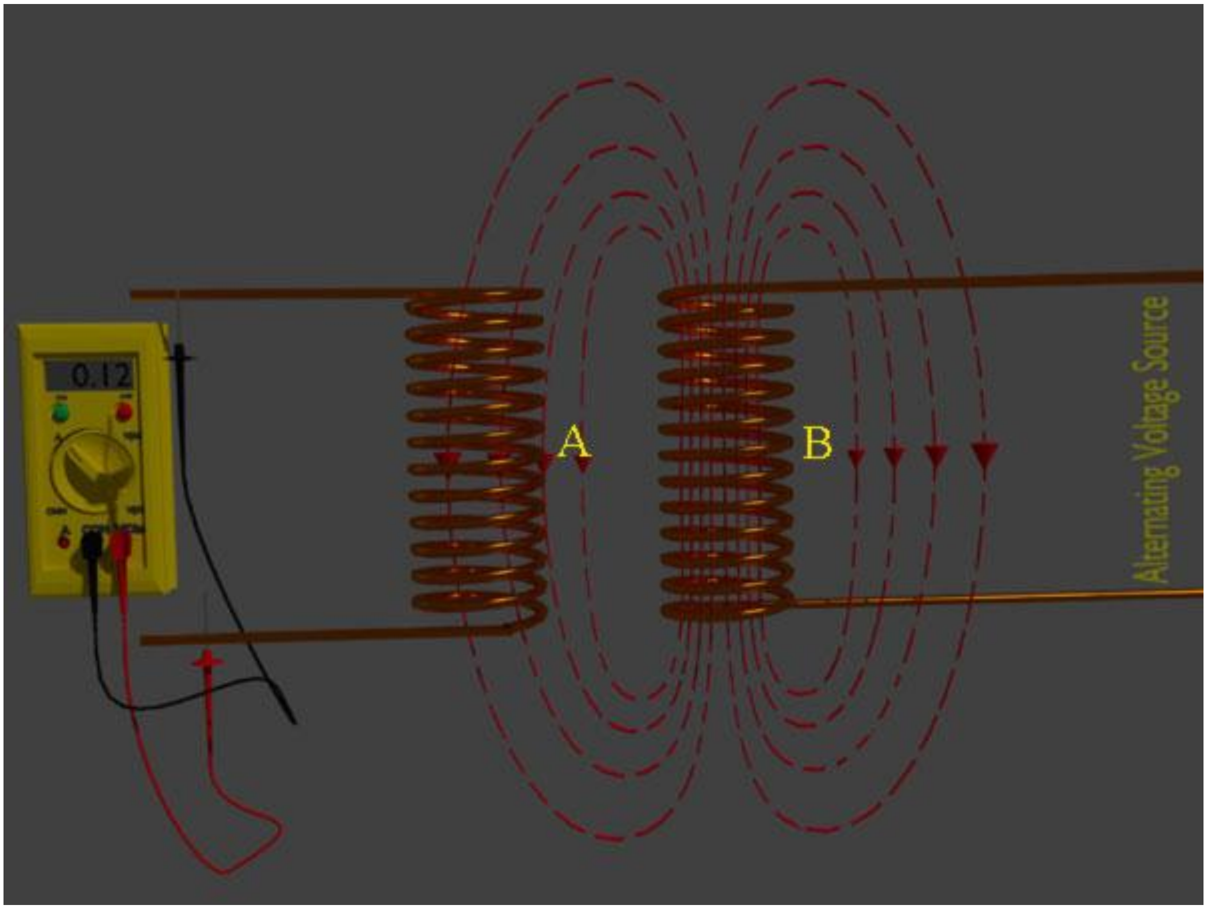
This k is known as coefficient of coupling and this is the ratio of actual coefficient of mutual inductance to ideal (maximum) coefficient of mutual inductance. If flux of one coil is entirely links with other, then value of K will be one. This is an ideal case. This is not possible, but when K nearly equal to unity, that means, maximum flux of one coil links to other, the coils are said to be tightly coupled or closely coupled. But when no flux of one coil links with other, the value of K becomes zero (K = 0), then the coils are said to be very loosely coupled or isolated.

Mutual Inductance of two Solenoids or Coils

Let us assume two solenoids or coils A and B respectively.



Coil A is connected with an alternating voltage source, V. Due to alternating source connected to coil A, it will produce an alternating flux as shown. Now, if we connect on sensitive voltmeter across coil B, we will find a non zero reading on it. That means, some emf is induced in the coil B. This is because, apportion of flux produced by coil A, links with coil B and as the flux changes in respect of time, there will be an induced emf in the coil B according to Faraday's law of electromagnetic induction. This phenomenon is called mutual induction. That means, induction of emf in one coil due to flux of other coil is mutual induction.



Similarly, if the alternating voltage source was connected to coil B and induced voltage is measured by connecting voltmeter across coil A, the voltmeter gives a non-zero reading. That means, in this case the emf will be induced in coil A due to flux linkage from coil B. Let us consider coil A and B have turns N_1 and N_2. If the entire flux of coil A links with coil B, then weber-turns of the coil B due to unit current of coil A, would be $(N_2\varphi_1)/i_1$, where, $\varphi_1$and i_1 is flux and current of coil A. As per definition this is nothing but mutual inductance of coil A and B, M.

That is, $M = \frac{N_2\phi_1}{i_1}$ Similarly, if the current and flux of the coil B are i_2 and φ_2.

$$Then,\ M = \frac{N_1\phi_2}{i_2}$$

Inductances in Series

Let's coil or inductance A and B are connected in series. The self inductance of coil A , is $L_A$and that of coil B is L_B. Now again consider, M is the mutual inductance between them. There may be two conditions.

1. The direction of flux produced by both coil will be in same direction. In that case, the flux of coil B links will be coil A, will be in same direction with the flux produced by coil A, itself. Hence, the effective inductance of coil A will be $L_A + M$. At the same time, the flux of coil A, links with coil B will be in the same direction with the

self flux of coil B. Hence, the effective inductance of coil B will be $L_B + M$. Hence total effective inductance of the series connected inductors A and B will be nothing but, $L_A + M + L_B + M = L_A + L_B + 2M$

2. Now, if the direction of instantaneous flux at coil A and B are in opposite, then flux of coil B linking with coil A, will be in opposite direction of flux produced by coil A itself. So, effective inductance of coil A will be $L_A - M$. In the same way, the flux of coil A which links with coil B will be in opposite direction of the self flux of coil B. Hence, effective inductance of coil B will be, $L_B - M$. So, total inductance in series in this case will be, $L_A - M + L_B - M = L_A + L_B - 2M$ So, general form of equivalent inductance of two inductors in series in, $L_A + L_B \pm 2M$

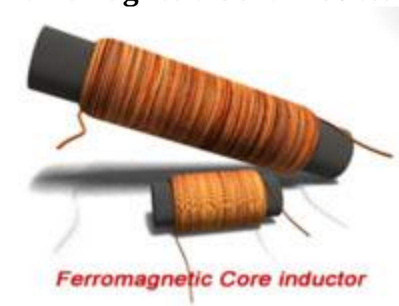
Types of Inductor

There are many types of inductors; all differ in size, core material, type of windings, etc. so they are used in wide range of applications. The maximum capacity of the inductor gets specified by the type of core material and the number of turns on coil.

Depending on the value, **inductors** typically exist in two forms, fixed and variable. The number of turns of the fixed coil remains the same. This type is like resistors in shape and they can be distinguished by the fact that the first color band in fixed inductor is always silver. They are usually used in electronic equipment as in radios, communication apparatus, electronic testing instruments, etc.

The number of turns of the coil in variable inductors, changes depending on the design of the inductor. Some of them are designed to have taps to change the number of turns. The other design is fabricated to have a many fixed inductors for which, it can be switched into parallel or series combinations. They often get used in modern electronic equipment. Core or heart of inductor is the main part of the inductor. Some types of inductor depending on the material of the core will be discussed.

Ferromagnetic Core Inductor or Iron-core Inductors

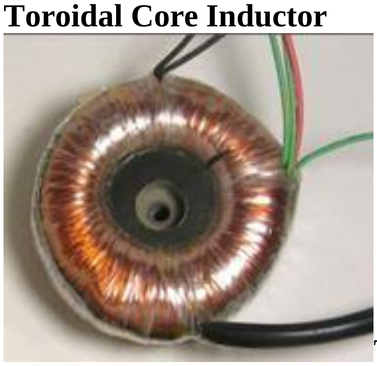


This type uses ferromagnetic materials such as ferrite or iron in manufacturing the inductor for increasing the inductance. Due to the high magnetic permeability of these materials, inductance can be increased in response of increasing the magnetic field.
At high frequencies it suffers from core loses, energy loses, that happens in ferromagnetic cores.

Air Core Inductor

Air cored inductor is the type where no solid core exists inside the coils. In addition, the coils that wound on nonmagnetic materials such as ceramic and plastic, are also considered as air cored. This type does not use magnetic materials in its construction.
The main advantage of this form of **inductors** is that, at high magnetic field strength, they have a minimal signal loss. On the other hand, they need a bigger number of turns to get the same inductance that the solid cored inductors would produce. They are free of core losses because they are not depending on a solid core.

Toroidal Core Inductor



Toroidal Inductor constructs of a circular ring-formed magnetic core that characterized by it is magnetic with high permeability material like iron powder, for which the wire wounded to get inductor. It works pretty well in AC electronic circuits'

application.
The advantage of this type is that, due to its symmetry, it has a minimum loss in magnetic flux; therefore it radiates less electromagnetic interference near circuits or devices. Electromagnetic interference is very important in electronics that require high frequency and low power.

Laminated Core Inductor

This form gets typified by its stacks made with thin steel sheets, on top of each other designed to be parallel to the magnetic field covered with insulating paint on the surface; commonly on oxide finish. It aims to block the eddy currents between steel sheets of stacks so the current keeps flowing through its sheet and minimizing loop area for which it leads to great decrease in the loss of energy. Laminated core inductor is also a low frequency inductor. It is more suitable and used in transformer applications.

Powdered Iron Core

Its core gets constructed by using magnetic materials that get characterized by its distributed air gaps. This gives the advantage to the core to store a high level of energy comparing to other types. In addition, very good inductance stability is gained with low losses in eddy current and hysteresis. Moreover, it has the lowest cost alternative.

Another Classification of Inductor

Coupled Inductor
It happens when inductors are related to each other by electromagnetic induction. Generally it gets used in applications as transformers and where the mutual inductance is required.

RF Inductor
Another name is radio frequency of RF inductors. This type operates at high frequency ranges. It is characterized by low current rating and high electrical resistance. However, it suffers from a proximity effect, where the wire resistance increases at high frequencies. Skin

effect, where the wire resistance to high frequency is greater than the electrical resistance of current direct.

Multi-Layer Inductor
Here the wounded wire is coiled into layers. By increasing the number of layers, the inductance increases, but with increasing of the capacitance between layers.

Molded Inductor
The material for which it stands from is molded on ceramic or plastic. Molded inductors are typically available in bar and cylindrical shapes with a variety option of windings.

Choke
The main purpose of it is to block high frequencies and pass low frequencies. It exists in two types; RF chokes and power chokes.

Applications of Inductors
In general there are a lot of applications due to a big variety of inductors. Here are some of them. Generally the inductors are very suitable for radio frequency, suppressing noise, signals, isolation and for high power applications.
More applications summarized here:

1. Energy Storage
2. Sensors
3. Transformers
4. Filters
5. Motors

Skin and Proximity Effects of AC Current
When an AC current flows through a conductor, outer filament of that conductor carries more current as compared to the filament closer to its center. This results in higher resistance to AC than to DC and is know as skin effect. Proximity effect, the alternating flux in a conductor is caused by the current of the other nearby conductor.

Beginner

Recommended Level

Introduction to Skin and Proximity Effects

Skin Effect: When a DC current flows through a conductor, current is uniformly distributed across the section of the conductor. On the other hand, when an AC current flows through a conductor, outer filament of that conductor carries more current as compared to the filament closer to its center. This results in higher resistance to AC than to DC and is known as **skin**

effect. This is due to more flux linkage per ampere to inner filaments as compared to outer side of the conductor.

This effect is more significant for bigger size conductors and for higher frequencies. Current density will decrease exponentially with respect to the depth of conductor from outside.

Consider an AC current that flows in copper conductor coils connected in winding.

Then, the penetration depth is given by

δcu=2μ0ωσcu−−−−−−−√δcu=2μ0ωσcu

Where,

ωω

$= 2\pi f$; σ_{cu} = conductivity of copper.

If the diameter of conductor is less than the value of depth of penetration, then the skin effect will be low.

Proximity Effect: The alternating flux in a conductor is caused by the current of the other nearby conductor. This flux produces a circulating current or eddy current in the conductor which results an apparent increase in the resistance of the wire and; thus, more power losses in the windings. This phenomenon is **proximity effect**.

Proximity effect can be reduced by selecting the core and number of turns that optimizes the number of layers.. An increased number of layers decreases the losses after the first selection. Foil winding layers reduces the losses more effectively as compared to round wires on a single layer. Interleaving the winding also reduces the proximity effect. Interleaving decreases the effective number of layers in each section of winding and; thus, the resulting field build up more uniformly than rising gradually in between.

Current produced is basically due to the saturation of core that contains PWM current having significant harmonic distortions. This can also lead to the increase of copper losses basically in multiple layers and non-interleaved windings as against the impedance of single layers which is almost negligible for such cases.

Leakage Flux in Windings

We have discussed earlier that leakage flux is represented by the leakage inductance in series with the supply for a transformer model. The leakage flux lines follows the three dimensional path as shown below.

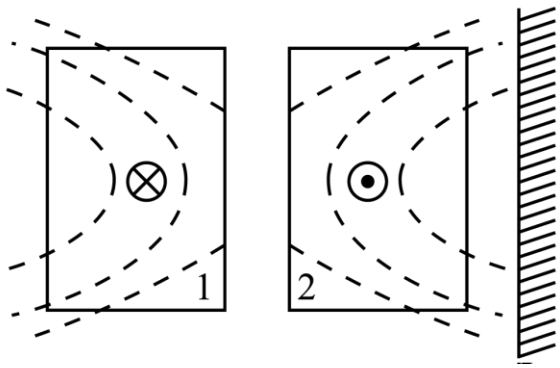


Figure 1. Leakage Flux 3D for a Concentric Winding

Depending on the configuration of its winding, we can determine the value of it based on certain assumptions.

Consider the magnetic path is linear. Then the leakage flux configuration for the concentric winding will be as shown below. Magnetic field intensity will vary with the distance from the limb of transformer.

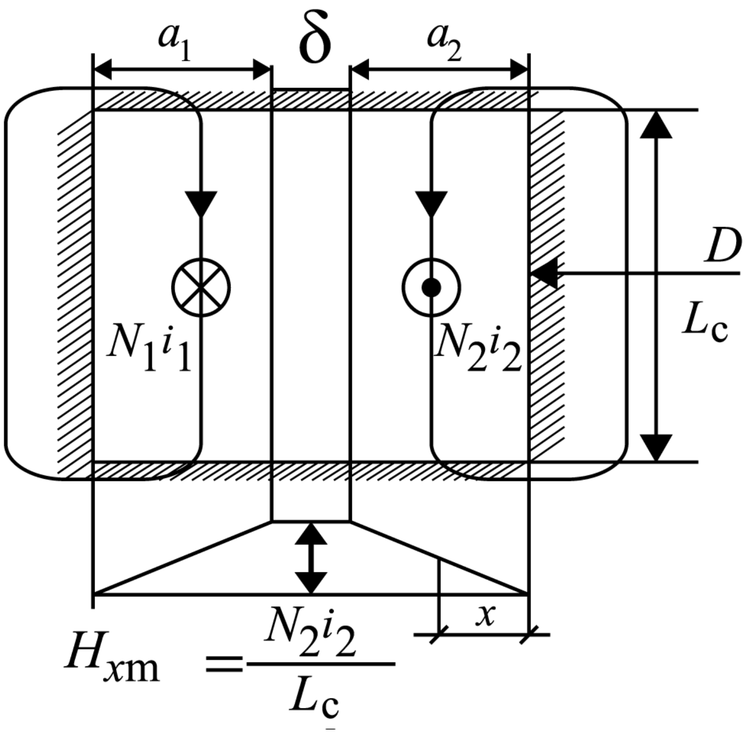


Figure 2. Concentric Winding of a Transformer

It is assumed that flux of each winding is filling their own volume with half of the space in between these two windings.

From the figure and basic equations for H field,

HxmLc=N2I2xa2HxmLc=N2I2xa2

Now, for the distance $a_2 < x < a_2 + \delta$

Hxm=(N2I2)LCxa2≈(N2I2)LC≈−(N1I1)LCHxm=(N2I2)LCxa2≈(N2I2)LC≈−(N1I1)LC

(Due to ampere-turns balance)

Magnetic energy stored by the secondary winding is given by

E2=RcfW2=Rcf12L2li22E2=RcfW2=Rcf12L2li22

R_{cf} is the Rogowski's coefficient which is used to correct the magnetic field path effect which is assumed linear. Its value should be greater than 1.

⇒⇒

Leakage inductance for secondary winding is,

L2l=(Rcf22W2)i22=2Rcfi22(12)μ0∫a2+δ20Hx2π(D+2x)LCdxL2l=(Rcf22W2)i22=2Rcfi22(12)μ0∫0a2+δ2Hx2π(D+2x)LCdx

⇒L2l=(Rcf2μ0N22πD2avgar2)LC⇒L2l=(Rcf2μ0N22πD2avgar2)LC

Where,

D2avg=D+3a22D2avg=D+3a22

and

ar2=a23+δ2ar2=a23+δ2

Similarly,

L1l=(Rcf1μ0N12πD1avgar1)LCL1l=(Rcf1μ0N12πD1avgar1)LC

Where,

D1avg=D+(a2+d)+3a12D1avg=D+(a2+d)+3a12

which is a high-voltage winding place away from the core as compared to a low-voltage winding number 2.

Similar analysis can be done to find out the leakage inductance for alternate winding in different chamber of transformer or bi-concentric winding. But, nowadays finite element 3D analysis is carried out for the calculation of more precise value of leakage inductance.

Foil Windings and Layers

Foil windings are used to reduce the effective copper loss. They are vertical section of conducting plates which are symmetrically placed on both sides of the transformer. These windings have low eddy current losses for the magnetic field parallel to the foil. These are insulated from the conductors with varnish or insulation sheets. Filling factor for foil winding is dependent on the thickness of insulation. The major difficulty in manufacturing of foil winding is the labor for placing the foil winding to the transformer coils.

Filling factor is the ratio of cross-sectional area of the conductor and the window area of the core. Cross-sectional area of the conductor is given by the product of the number of turns and the wire cross-section area of a conductor.

Foil winding is especially popular for small transformers due to its simplicity. Finite element analysis can be used to analyze the eddy current loss distribution within the foil winding.

Power Loss in a Transformer Winding

Number of windings on the primary and secondary sides of the transformer is decided based on the voltage per turn. Next, we have to choose the proper current density of the primary and secondary windings for finding out the area requirement for the windings. The current density is dependent on the local heating and efficiency. It is important to decide the proper value of the current density for the design of windings as the load for maximum efficiency and copper losses is dependent on this choice. It is different for small-sized and big-sized transformers.

Area of the conductor = Current in that winding / Current density for that winding.

ap=Ipδpap=Ipδp

as=Isδsas=Isδs

Let the specific copper loss per kilogram for copper conductor be ρ_c.

Volume of the conductor in primary = V_P

Volume of the conductor in secondary = V_S

Total volume of the conductors ≈ $V_P + V_S = V_t \approx$ constant

The copper loss in primary = $\rho_c \delta_p^2 V_P$ and the copper loss in secondary = $\rho_c \delta_s^2 V_S$

Hence, the total copper loss

$$P_{tc} = \rho_c \delta_P^2 V_P + \rho_c \delta_S^2 (V_t - V_P)$$

Differentiating it with V_P and equating it to zero to get the condition for the minimum loss. We can get the same value of current density for the both conductors. However, current density for outer winding is somewhat larger than its inner winding due to better cooling condition.

Interleaving the Windings

This interleaving scheme is applicable to transformer but not to inductors. If the design of transformer winding is altered in such a way that one winding layer lies within another layer using the same wire. For instance, a four layer winding with pattern (P1, P2, S1, S2) changed to (P1, S1, P2, S2) or (S1, P1, P2, S2) or (P1, S1, S2, P2).

Interleaving can reduce the ohmic and eddy current losses by a factor of two. Also, the current-handling capacity of winding can be increased by a factor of

2–√2

. **Concept of Self-GMD and Mutual-GMD**

The use of self geometrical mean distance (abbreviated as self-GMD) and mutual geometrical mean distance (mutual-GMD) simplifies the inductance calculations, particularly relating to multi conductor arrangements. The symbols used for these are respectively Ds and Dm. We shall briefly discuss these terms.

(i) Self-GMD (Ds)

In order to have concept of self-GMD (also sometimes called Geometrical mean radius; GMR), consider the expression for inductance per conductor per metre already derived in Art. Inductance/conductor/m

$$= 2 \times 10^{-7}\left(\frac{1}{4} + \log_e \frac{d}{r}\right)$$

$$= 2 \times 10^{-7} \times \frac{1}{4} + 2 \times 10^{-7} \log_e \frac{d}{r}$$

In this expression, the term $2 \times 10^{-7} \times (1/4)$ is the inductance due to flux within the solid conductor. For many purposes, it is desirable to eliminate this term by the introduction of a concept called self-GMD or GMR. If we replace the original solid conductor by an equivalent hollow cylinder with extremely thin walls, the current is confined to the conductor surface and internal conductor flux linkage would be almost zero. Consequently, inductance due to internal flux would be zero and the term $2 \times 10^{-7} \times (1/4)$ shall be eliminated. The radius of this equivalent hollow cylinder must be sufficiently smaller than the physical radius of the conductor to allow room for enough additional flux to compensate for the absence of internal flux linkage. It can be proved mathematically that for a solid round conductor of radius r, the self-GMD or GMR = 0·7788 r. Using self-GMD, the eq. (i) becomes :

Inductance/conductor/m = $2 \times 10\text{-}7 \log_e d/ D_s$ *

Where

D_s = GMR or self-GMD = 0·7788 r

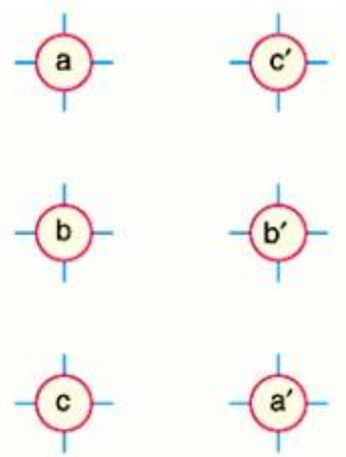
It may be noted that self-GMD of a conductor depends upon the size and shape of the conductor and is independent of the spacing between the conductors.

(ii) Mutual-GMD

The mutual-GMD is the geometrical mean of the distances form one conductor to the other and, therefore, must be between the largest and smallest such distance. In fact, mutual-GMD simply represents the equivalent geometrical spacing.

(a) The mutual-GMD between two conductors (assuming that spacing between conductors is large compared to the diameter of each conductor) is equal to the distance between their centres i.e. D_m = spacing between conductors = d

(b) For a single circuit 3-φ line, the mutual-GMD is equal to the equivalent equilateral spacing i.e., $(d_1\, d_2\, d_3)^{1/3}$.



(c) The principle of geometrical mean distances can be most profitably employed to 3-φ double circuit lines. Consider the conductor arrangement of the double circuit shown in Fig. Suppose the radius of each conductor is r.

Self-GMD of conductor = $0{\cdot}7788\, r$

Self-GMD of combination aa' is

$$D_{s1} = (**D_{aa} \times D_{aa'} \times D_{a'a'} \times D_{a'a})^{1/4}$$

Self-GMD of combination bb' is

$$D_{s2} = (D_{bb} \times D_{bb'} \times D_{b'b'} \times D_{b'b})^{1/4}$$

Self-GMD of combination cc' is

$$D_{s3} = (D_{cc} \times D_{cc'} \times D_{c'c'} \times D_{c'c})^{1/4}$$

Equivalent self-GMD of one phase

$$D_s = (D_{s1} \times D_{s2} \times D_{s3})^{1/3}$$

The value of Ds is the same for all the phases as each conductor has the same radius.

Mutual-GMD between phases A and B is

$$D_{AB} = (D_{ab} \times D_{ab'} \times D_{a'b} \times D_{a'b'})^{1/4}$$

Mutual-GMD between phases B and C is

$$D_{BC} = (D_{bc} \times D_{bc'} \times D_{b'c} \times D_{b'c'})^{1/4}$$

Mutual-GMD between phases C and A is

$$D_{CA} = (D_{ca} \times D_{ca'} \times D_{c'a} \times D_{c'a'})^{1/4}$$

Equivalent mutual-GMD, $D_m = (D_{AB} \times D_{BC} \times D_{CA})^{1/3}$

It is worthwhile to note that mutual GMD depends only upon the spacing and is substantially independent of the exact size, shape and orientation of the conductor.

Inductance Formulas in Terms of GMD

The inductance formulas developed in the previous articles can be conveniently expressed in terms of geometrical mean distances.

(i) Single phase line

$$\text{Inductance/conductor/m} = 2 \times 10^{-7} \log_e \frac{D_m}{D_s}$$

where $D_s = 0{\cdot}7788\, r$ and D_m = Spacing between conductors = d

(ii) Single circuit 3-φ line

$$\text{Inductance/phase/m} = 2 \times 10^{-7} \log_e \frac{D_m}{D_s}$$

where $D_s = 0{\cdot}7788\, r$ and $D_m = (d_1\, d_2\, d_3)^{1/3}$

(iii) Double circuit 3-φ line

$$\text{Inductance/phase/m} = 2 \times 10^{-7} \log_e \frac{D_m}{D_s}$$

where $D_s = (D_{s1}\, D_{s2}\, D_{s3})^{1/3}$ and $D_m = (D_{AB} \times D_{BC} \times D_{CA})^{1/3}$

Unsymmetrical Spacing

Let us assume that the three conductors each of radius r of 3-phase line are placed along the corners of triangle as shown in figure below. Suppose phase conductors placed at corners A, B and C are carrying current I_A, I_B and I_C respectively. If the load is assumed to be balanced then $I_A+I_B+I_C = 0$ Now, we will calculate the inductance of phase conductor placed at corner A. Obviously for that, we need to calculate the total flux linkage of conductor A. If you observe the figure carefully, you will notice that phase conductor placed at corner A will link to the magnetic flux of conductor B and conductor C. Is it? We missed one thing. Phase conductor A will also link to its own magnetic flux. Correct? You will definitely say, YES.

Flux Linkage of conductor A due to its own current

$Ø_1 = (\mu_0 I_A / 2\pi)\,[1/4 + \int_r^{\infty} dx/x]$

$= (\mu_0 I_A / 2\pi)\,[0.25 - \log r]$

Flux Linkage of conductor A due to current I_B

$Ø_2 = (\mu_0 I_B / 2\pi) \int_{d1}^{\infty} dx/x$

$= -(\mu_0 I_B / 2\pi) \log d_1$

Flux Linkage of conductor A due to current I_C

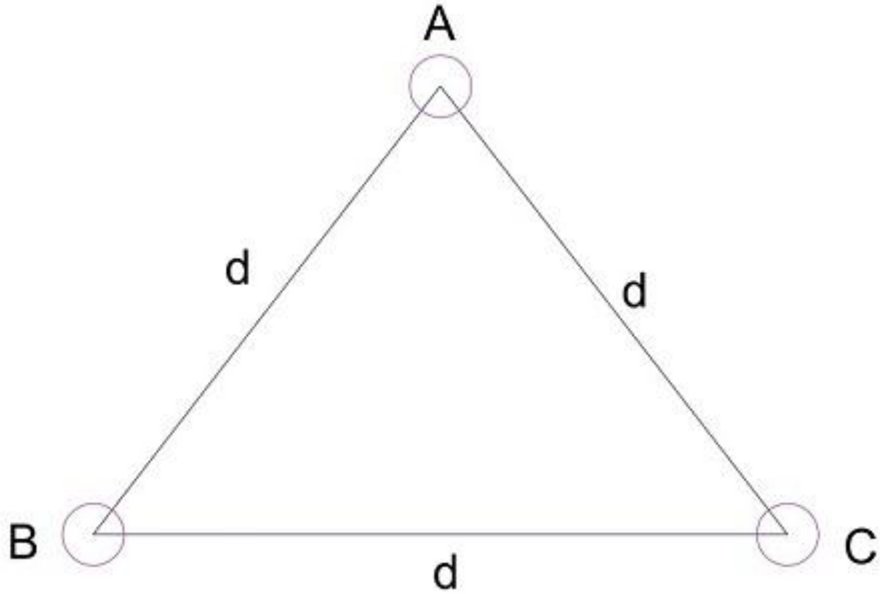
$Ø_3 = (\mu_0 I_C / 2\pi) \int_{d3}^{\infty} dx/x$

$= -(\mu_0 I_C / 2\pi)\log d_3$

Thus, total flux linkage $Ø = Ø_1 + Ø_2 + Ø_3$

$= (\mu_0 / 2\pi)[(0.25-\log r)I_A - I_B \log d_1 - I_C \log d_3]$

The above equation gives the total flux linkage of phase conductor A. Similarly, the flux linkage of phase conductor B and C can be calculated.
Now we assume that the three conductors are symmetrically spaced as shown in figure below.



Symmetrical Spacing

The total flux linkage of conductor A

$Ø = (\mu_0 / 2\pi)[(0.25\text{-}\log r)I_A – I_B\log d_1 – I_C\log d_3]$

But $d_1 = d_2 = d_3 = d$, hence

$Ø = (\mu_0 / 2\pi)[(0.25\text{-}\log r)I_A – I_B\log d – I_C\log d]$

$= (\mu_0 / 2\pi)[(0.25\text{-}\log r)I_A – \log d(I_B + I_C)]$

But $I_B + I_C = -I_A$

$Ø = (\mu_0 / 2\pi)[(0.25\text{-}\log r)I_A + I_A\log d]$

$= (\mu_0 I_A / 2\pi)[0.25 + \log (d / r)]$

Therefore Inductance of Conductor A, L_A

$= Ø / I_A$ H/m

$= (\mu_0 / 2\pi)[0.25 + \log (d / r)]$

As the conductors are symmetrically spaced from each other therefore the flux linkage of each conductor will be same. Due to this, the inductance of each phase conductor will be same. Therefore for symmetrical spacing of 3-phase line conductors,

$L_A = L_B = L_C$

Effect of Unsymmetrical Spacing of Conductors

The flux linkage of each phase conductors for unsymmetrical spacing are not same. Due to this the inductance of the three phase conductors will be different. Because of this, there will be unequal voltage drop in the three phases even though the currents in phase conductors are balanced. Thus the voltage at the receiving end will not be same for the three phases. To have equal voltage drop in phase conductors, we normally interchange the positions of conductors at equal interval along the line. This interchanging is known as Transposition of line.

Inductance of Three-Phase Lines with Symmetrical Spacing

Consider the three-phase line shown in Fig. 1.6. Each of the conductors has a radius of *r* and their centers form an equilateral triangle with a distance *D* between them. Assuming that the

$$I_a + I_b + I_c = 0 \tag{1.23}$$

currents are balanced, we have

Consider a point *P* external to the conductors. The distance of the point from the phases a, b and c are denoted by D_{pa}, $D_{pb}$and D_{pc}respectively.

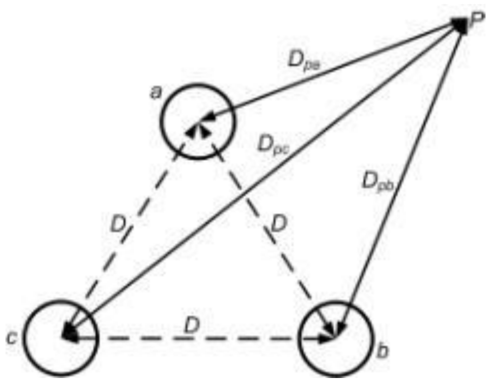


Fig. 1.6 Three-phase symmetrically spaced conductors and an external point P.

Let us assume that the flux linked by the conductor of phase-a due to a current I_a includes the internal flux linkages but excludes the flux linkages beyond the point *P* . Then from (1.18) we

$$\lambda_{apa} = \left(\frac{1}{2} + 2\ln\frac{D_{pa}}{r}\right) I_a = 2\times10^{-7} I_a \ln\frac{D_{pa}}{r'} \tag{1.24}$$

get

The flux linkage with the conductor of phase-a due to the current I_b , excluding all flux beyond

$$\lambda_{apb} = 2\times10^{-7} I_b \ln\frac{D_{pb}}{D} \tag{1.25}$$

the point *P* , is given by (1.17) as

Similarly the flux due to the current I_c is

$$\lambda_{apc} = 2\times10^{-7} I_c \ln \frac{D_{pc}}{D} \tag{1.26}$$

Therefore the total flux in the phase-a conductor is

$$\lambda_a = \lambda_{apa} + \lambda_{apb} + \lambda_{apc} = 2\times10^{-7}\left(I_a \ln \frac{D_{pa}}{r'} + I_b \ln \frac{D_{pb}}{D} + I_c \ln \frac{D_{pc}}{D} \right)$$

$$\lambda_a = 2\times10^{-7}\left(I_a \ln \frac{1}{r'} + I_b \ln \frac{1}{D} + I_c \ln \frac{1}{D} + I_a \ln D_{pa} + I_b \ln D_{pb} + I_c \ln D_{pc} \right) \tag{1.27}$$

The above expression can be expanded as

From (1.22) we get

$$I_b + I_c = -I_a$$

$$\lambda_a = 2\times10^{-7}\left(I_a \ln \frac{1}{r'} - I_a \ln \frac{1}{D} + I_b \ln \frac{D_{pb}}{D_{pa}} + I_c \ln \frac{D_{pc}}{D_{pa}} \right) \tag{1.28}$$

Substituting the above expression in (1.27) we get

Now if we move the point *P* far away, then we can approximate D_{pa} □ D_{pb} □ D_{pc}.. Therefore

$$\lambda_a = 2\times10^{-7}\left(I_a \ln \frac{1}{r'} - I_a \ln \frac{1}{D} \right) = 2\times10^{-7} I_a \ln \frac{D}{r'} \tag{1.29}$$

their logarithmic ratios will vanish and we can write (1.28) as

$$L_a = 2\times10^{-7}\ln\frac{D}{r'} \qquad (1.30)$$

Hence the inductance of phase-a is given as

Note that due to symmetry, the inductances of phases b and c will be the same as that of phase-a given above, i.e., $L_b = L_c =$

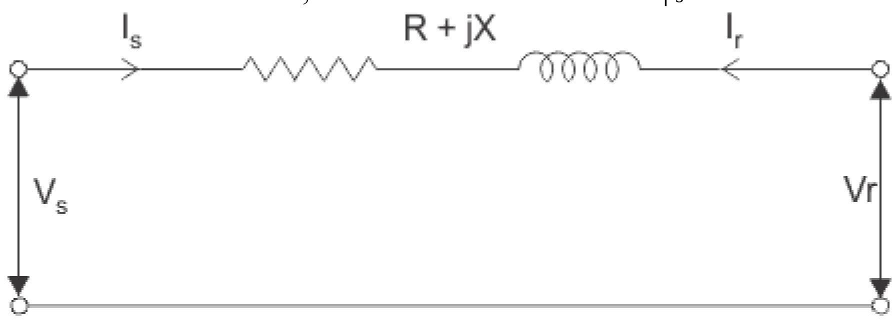
UNIT III

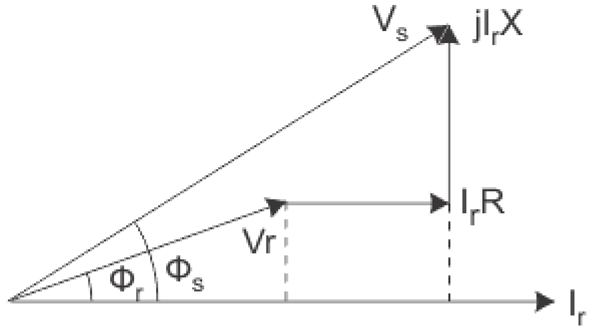
PERFORMANCE OF TRANSMISSION LINES

Equivalent circuit for short, medium and long transmission lines

Short Transmission Line

The transmission lines which have length less than 50 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.





As the shunt capacitance of the line is neglected, hence sending end current and receiving end current is same, i.e. $I_s = I_r$.c

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 the 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 dentition of voltage regulation of power transmission line,

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

$$= \frac{I_r.R.cos\varphi_r + I_r.X.sin\varphi_r}{V_r} X\ 100\ \%$$

$$\text{per unit regulation} = \frac{I_r.R}{V_r} cos\varphi_r + \frac{I_r.X}{V_r} sin\varphi_r = v_r cos\varphi_r + v_X sin\varphi_r$$

Here, v_r and v_x are the per unit resistance and reactance of the **short transmission line**respectively. 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 ,

$$V_s = AV_r + BI_r \quad \cdots\cdots\cdots\cdots\cdots\cdots (1)$$

$$I_s = CV_r + DI_r \quad \cdots\cdots\cdots\cdots\cdots\cdots (2)$$

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

$$D = \frac{I_s}{I_r}\bigg|_{V_r = 0}$$

dimension of admittance. 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

⇒ 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,

$$\% \text{ voltage regulation} = \frac{V_s / A - V_r}{V_r} \times 100 \%$$

equivalent circuit Definition of EQUIVALENT CIRCUIT

1. **:** an electric circuit made up of the basic elements resistance, inductance, and capacitance in a simple arrangement such that its performance would duplicate that of a more complicated circuit or network

Voltage Control Methods in Power System

Voltage ratings of the various buses in the power system which includes generating station buses, switching substation buses, receiving substation buses and distribution substation buses should be within the permissible limits for satisfactory operation of all electrical equipments. The task of voltage control is closely associated with fluctuating load conditions and corresponding requirements of reactive power compensation. Therefore several voltage control methods are employed in power system to keep the voltage levels within the desirable limits. In this article some of the voltage control methods in power system are discussed.

- Excitation control and voltage regulators at the generating stations:
- Use of tap changing transformers at sending end and receiving end of the transmission lines

- Switching in shunt reactors during low loads or while energizing long EHV lines
- Switching in shunt capacitors during high loads or low power factor loads
- use of series capacitors in long EHV transmission lines and distribution lines in case of load fluctuations
- Use of tap changing transformers in industries, substations, distribution substations
- use of static shunt compensation having shunt capacitors and thyristorized control for step-less control of reactive power
- Use of synchronous condensers in receiving end substations for reactive power compensation

All the above methods are suitably applied at different parts of the power system to maintain the voltage levels within the limits

Excitation Control and Voltage Regulation in generating Stations:

The induced emf of synchronous generator (E) depends upon the excitation current (field current). The terminal voltage V of synchronous generators are given by$V = E – IX$ The generators have excitation and automatic voltage regulation systems (AVR). The function of this systems are:

- To control the load under steady state operating conditions for operating near steady state stability limit
- To regulate voltage under fault conditions (faults in the grid system beyond generator protection zone)
- To enable sharing of reactive power. The reactive power shared by a generator depends upon its excitation level The terminal voltage of the synchronous generator is held within the permissible limits by automatic voltage regulators (AVR) systems

Voltage Control by Tap changing in transformers:

The voltage control of transmission and distribution systems is obtained basically by tap-changing Tap changers are either on-load or off load tap changers. By changing the turns ratio of the transformer the voltage ratio and the secondary voltage is changed and voltage control is obtained. Tap changing is widely used voltage control method employed at every voltage level

The voltage control of the range + 15 to -15 % can be achieved by tap changing transformers

Off load tap changing voltage control:

Adjustment of voltage ratio can be made by off-circuit tap changing. These adjustments are usually for seasonal load variations of special operational requirement of local substations and adjusting the voltage in distribution transformer at consumer end.

On-Load tap changing voltage control:

Such an arrangement of on-load tap changing is employed for changing the turn-ratio of the transformer to regulate the system voltage while the transformer is delivering load.

Voltage Control by Shunt reactors:

Shunt reactors are provided at sending end and receiving end of the long EHV and UHV transmission lines. They are switched in when the line is to be charged or during line is on low load

When the line is on no load or low load, shunt capacitance predominates and receiving end voltage is higher than the sending end voltage. This phenomenon is called *Ferranti effect*.

The receiving end voltage of 400kV, 1000 km long line may be as high as 800kV. The shunt capacitance of such lines is neutralized by switching in the shunt reactor. During high loads, the series inductive reactance of the line produces IX_L drop and the receive end voltage drops, the shunt reactors are switched off Shunt treactors may be connected to the low voltage tertiary winding of a transformer via a suitable circuit breaker, EHV shunt reactors may be connected to the transmission line without any circuit breaker.

Voltage Control by Shunt Capacitors:

Shunt capacitors are usually switched in during high loads. Static shunt capacitors are installed near the load terminals, in industries, substations, … Most of the industrial loads (induction motors, transformers, welding sets, furnaces) draws inductive current of poor power factor (0.3 to 0.6 lag). The shunt capacitors provide leading VARs there by the total KVA loading of substation transformer and the current is reduced. Thereby IXl_L drop in the line is reduced and voltage regulation is improved. shunt capacitors are switched in when KVA demand on the distribution line goes up and voltage on the bus comes down. Switching in shunt capacitor should improve the bus voltage if the compensation is effective

Voltage Control by Static Shunt Compensation:

A step-less variable compensation is possible by thyristorized control of shunt capacitor and reactors. During heavy loads, the thyristors of the capacitor control are made to conduct for longer duration in each cycle. During low loads, the thyristors in reactor circuit are made to conduct for longer duration in each cycle. Thus a step-less variation of shunt compensation is achieved by means of static shut compensation

Voltage Control by Synchronous Condensers:

Synchronous condensers are over excited synchronous motors installed in the power system to deliver the reactive power. These synchronous phase modifiers are located near the load improves the voltage profile of the power system. The main advantage of synchronous phase modifiers are the ability to deliver the reactive power can be adjusted unlike static shunt capacitors.

Voltage Control by Series Capacitors:

In Extra High Voltage (EHV) or Ultra High Voltage System (UHV) systems series capacitors are connected in series with the transmission line to reduce the effect of inductive reactance XL between the sending end and receiving end of the line. One of the major drawbacks of series capacitors is that high over voltages are produced across the capacitor terminals under short circuit condition. Series capacitors are usually employed for increasing the power transfer capability of the transmission line and not for voltage regulation

Voltage Control by Flexible AC transmission (FACT) devices:

very long high power transmission lines have high series reactance X_L and shut capacitance. It is difficult to control the voltage, power flow and stability by conventional manner. FACT devices play key role in high power interconnected systems. In every intermediate substation in transmission network FACT devices are installed

- Controllable Series Capacitor banks
- Controllable shunt compensation (SVS)

Thyristors are controlled by feedback control system. Voltage power flow and voltage angle is controlled

Series and Shunt Compensation

The methods available for the injection of both are static compensation and synchronous compensation.

Static compensation involves capacitors and reactors where as synchronous compensation involves synchronous phase modifier.

Shunt compensation:

At buses where reactive power demand increases, bus voltage can be controlled by connecting capacitor banks in parallel to a lagging load.

Capacitor banks supply part of or full reactive power of load, thus reducing magnitude of the source current necessary to supply load. Consequently the voltage drop between the sending end and the load gets reduced, power factor will be improved and increased active power output will be available from the source.

Depending upon load demand, capacitor banks may be permanently connected to the system or can be varied by switching ON or OFF the parallel connected capacitors either manually or automatically.

Following figure shows the single line diagram of a transmission line and its phasor diagram before the addition of the shunt capacitor and its phasor diagram.

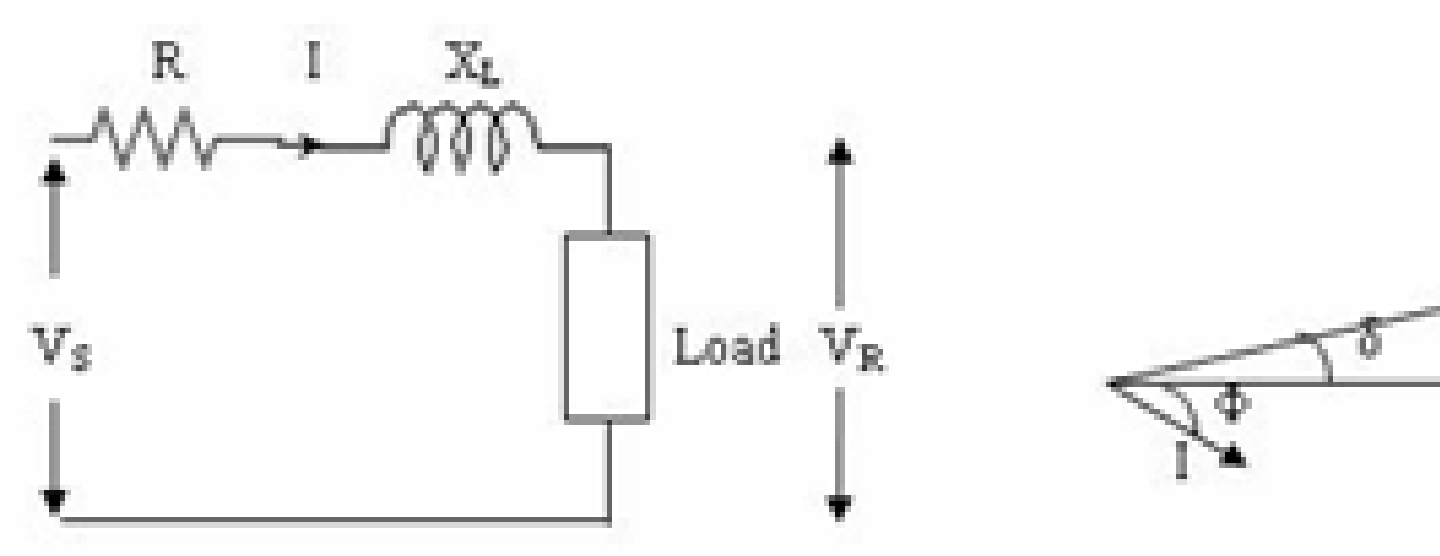


Figure: Single line diagram of an uncompensated transmission line and its phasor diagram

Voltage drop in the line with lagging power factor can be approximated as

VD = *IRR* + *IX X L* V

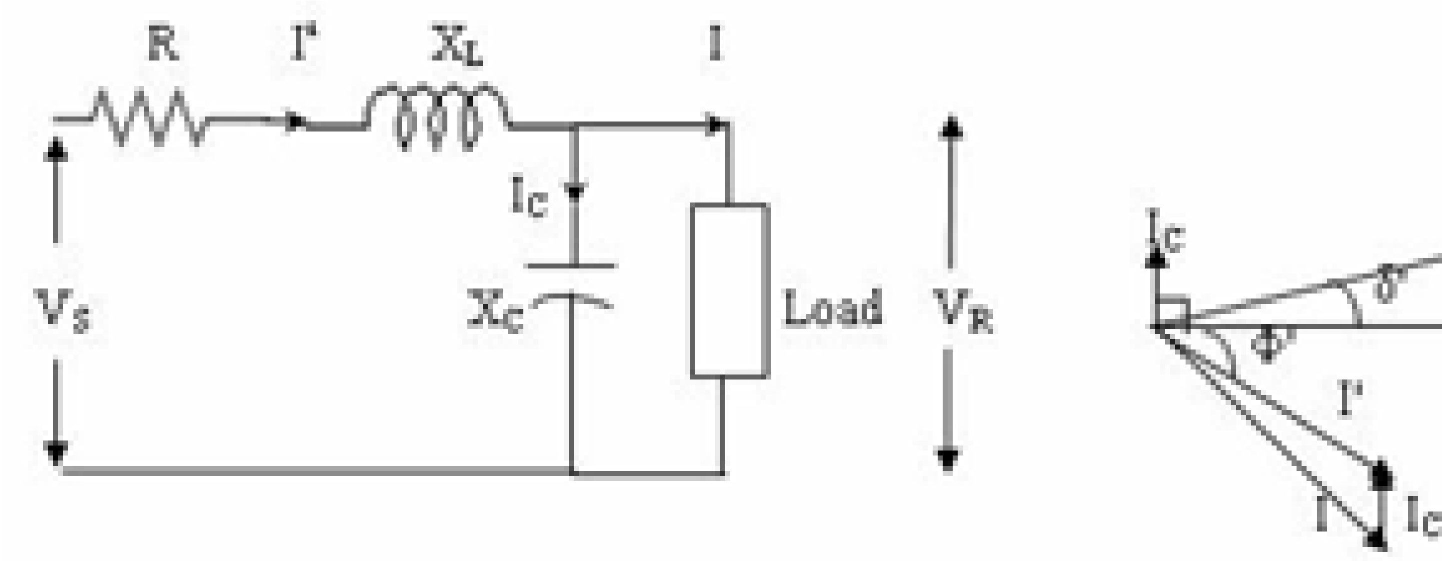


Figure: Single line diagram of a shunt compensated transmission line and its phasor diagram

Voltage drop can be approximated as:

$VD = I_R R + I_X X_L - I_C X_L$.

The difference between the voltage drops is the voltage rise due to installation of the capacitor and can be expressed as: $VR = I_C X_L$.

The usage of shunt capacitor banks suffers from the following drawbacks:

1. Shunt capacitors do not affect current or power factor beyond their point of application.
2. The reactive power supplied by the shunt capacitor banks is directly proportional to the bus voltage.
3. When the reactive power required is less on light loads, capacitor bank output will be high. This disadvantage can be eliminated by connecting a number of capacitors in parallel and then capacitance can be varied by switching ON or OFF depending upon load requirement.

Series compensation

When the line has high value of reactance to resistance ratio, the inductive reactance of the transmission line can be decreased by introducing series capacitors which results in low voltage drop.

When a load with lagging power factor is connected at the end, voltage drop in the line is: VD = I (R cos φ + XLsin φ)

If a capacitance 'C' with reactance X_c is connected in series with the line, then the reactance will be reduced to (X_L- X_c) and hence the voltage drop is reduced. Further the reactive power taken by the line is also reduced.

In the following figure, the equivalent circuit of the line with series compensation and its phasor diagram are presented.

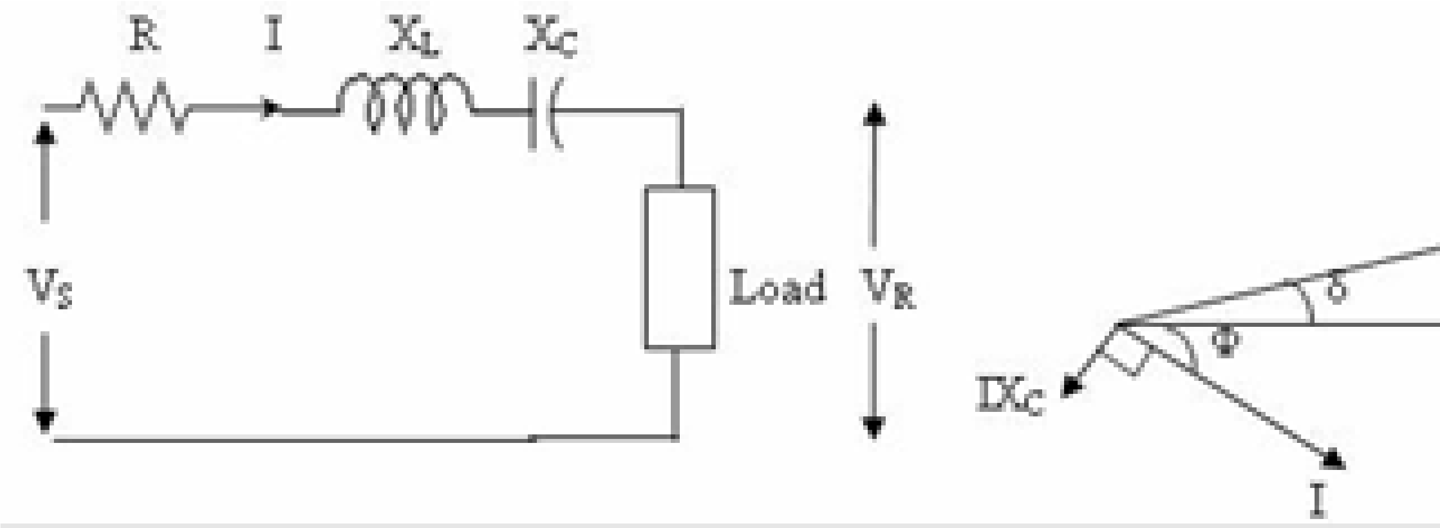


Figure: Single line diagram of a series compensated transmission line and its phasor diagram.

It can be observed from the phasor diagram that line voltage drop is:

VD = I (Rcos φ + (X_L - X_C)sin φ)

Thus the use of series capacitors is to reduce the voltage drop in the lines with low power factor and improve the voltage at the receiving end particularly with low power factor loads.

For variable load conditions, the voltage can be controlled by switching in suitable series capacitors in the line.

Under short circuit condition, the produced high voltage may damage the capacitor and so series capacitor has to be protected using a spark gap with a high speed contactor.

The use of series compensation introduces few problems like Subsynchronous resonance, Ferroresonance and high recovery voltage.

Tags :GATE EEGATE EEPower Systems

Transmission Line in Power System

What is Transmission Line?

Transmission line is the long conductor with special design (bundled) to carry bulk amount of generated power at very high voltage from one station to another as per variation of the voltage level.

Type of Transmission Line

In transmission line determination of voltage drop, transmission efficiency, line loss etc. are important things to design. These values are affected by line parameter R, L and C of the transmission line. Length wise transmission lines are three types.

Short Transmission Line

- Length is about 50 km.
- Voltage level is up to 20 kV
- Capacitance effect is negligible
- Only resistance and inductance are taken in calculation capacitance is neglected.

Medium Transmission Line

- Length is about 50km to 150km
- Operational voltage level is from 20 kV to 100 kV
- Capacitance effect is present
- Distributed capacitance form is used for calculation purpose.

Long Transmission Line

- Length is more than 150 km

- Voltage level is above 100 kV
- Line constants are considered as distributed over the length of the line.

What is the Transmission Efficiency?

Transmission efficiency is defined as the ration of receiving end power P_R to the sending end power P_S and it is expressed in percentage value.

$$\% \, \eta T = \frac{P_R}{P_S} \times 100 = \frac{V_R I_R \cos\theta_R}{V_S I_S \cos\theta_S} \times 100$$

$\cos\theta_s$ is the sending end power factor.
$\cos\theta_R$ is the receiving end power factor.
V_s is the sending end voltage per phase.
V_R is the receiving end voltage per phase.

What is Transmission Line Voltage Regulation

Voltage regulation of transmission line is defined as the ratio of difference between sending and receiving end voltage to receiving end voltage of a transmission line between conditions of no load and full load. It is also expressed in percentage.

$$\% \, VR = \frac{V_S - V_R}{V_R} \times 100$$

Where, V_s is the sending end voltage per phase and V_R is the receiving end voltage per phase.

UNIT IV

CABLES AND INSULATORS

Underground cables: types, advantages & disadvantages

Underground cables are used for power applications where it is impractical, difficult, or dangerous to use the overhead lines. They are widely used in densely populated urban areas, in factories, and even to supply power from the overhead posts to the consumer premises.

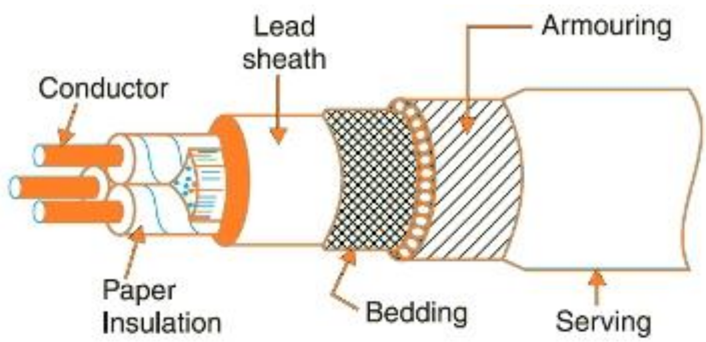


Figure 1: Basic construction of an underground cable|image: 3.bp.blogspot.com

The underground cables have several advantages over the overhead lines; they have smaller voltage drops, low chances of developing faults and have low maintenance costs. However, they are more expensive to manufacture, and their cost may vary depending on the construction as well as the voltage rating.

Types of underground cables

The underground cables are classified in two ways; by the voltage capacity, or by the construction.

By Voltage

LT cables: Low-tension cables with a maximum capacity of 1000 V

HT Cables: High-tension cables with a maximum of 11KV

ST cables: Super-tension cables with a rating of between 22 KV and 33 KV

EHT cables: Extra high-tension cables with a rating of between 33 KV and 66 KV

Extra super voltage cables: with maximum voltage ratings beyond 132 KV

By Construction

Belted cables: Maximum voltage of 11KVA

Screened cables: Maximum voltage of 66 KVA

Pressure cables: Maximum voltage of more than 66KVA

Low and medium voltage cables

Belted cables

The cores in the belted underground cables are not circular and are insulated by impregnated paper. The cores are generally stranded and may be of non-circular shape to make better use of available space. In a 3 phase cable, the three cores are grouped together and then belted with the paper belt.

The gaps between the conductors and the paper insulation are filled with fibrous material such as the jute. This makes the cable to have a circular cross-sectional shape. A lead sheath is used to cover the belt hence protect it from moisture and provide mechanical strength. The lead sheath is then covered with a single or multiple layers of an armoring material and finally an outer cover.

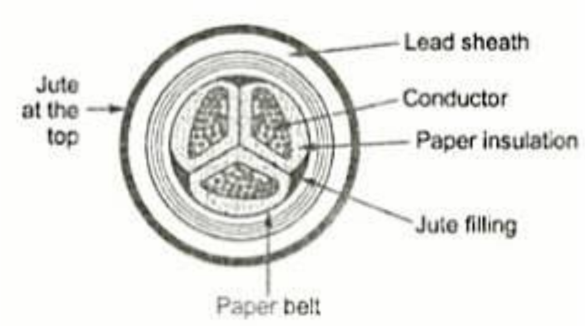


Figure 2: A typical belted 3 core cable image 4.bp.blogspot.com

Disadvantages:

Since the electrical field in the three core cables is tangential, the paper insulation and the fibrous materials are subjected to the tangential electrical stresses. This stresses weakens the fibrous material as well as the resistance and dielectric strength for the insulation along the tangential path.

The weakening of the insulation may lead to the formation of air spaces in the insulation. Under high voltages the air may be ionized and cause deterioration and breakdown of insulation. For this reason, the belted cables are only suitable for voltages up to 11KVa and not higher.

Due to the large diameter of the paper belt, bending the cable may lead to the formation of wrinkles and gaps.

The screened cables

There are two types of screened cables; the H type and the S.L type.

H-type cables

In a typical 3-core cable, each of the three cores is insulated by impregnated paper and covered by perforated aluminium foil or other metallic screen. The arrangement of the cores is designed to allow each of the three metallic screens to make contact with each other. The three cores are then wrapped around using a conduction belt made of copper woven fabric tape.

The H-type screened cable does not have an insulating belt; however, it has the lead sheath, followed by bedding, armoring and a then a serving. The core screens in the cable are all electrically connected to both the conducting belt and the lead sheath. This ensures that they are at the earth potential and all the electrical stresses are therefore purely radial, hence reduced dielectric losses.

Advantages of H-type cables

Metallic screens improve the heat dissipation of the cable

No formation of air pockets and voids in the dielectric, hence a high breakdown strength and less dielectric losses

Disadvantages H-type cables : the cables are only suitable for low and medium voltages of up to 33KV, but can reach 66KVA at times.

S.L Type screened cable

The S.L type cables construction is almost like that of the H-type, however, each of the insulated cores is covered separately with its own lead sheath. Unlike the H-type, the S.L screened cable does not have an overall sheath, however it has the armoring and serving.

Advantages of S.L type Screened cables:

The use of separate sheaths reduces chances of core-to-core breakdown

Easy to bend the cable

Disadvantages of S.L type Screened cables

Thinner lead sheaths are used hence need for greater care in manufacturing and handling

Only suitable for low and medium voltages of up to 33KV

Pressures cables

These are high power cables used for voltages above 66KV. The cable construction is different from the above two and majority uses a cooling gas or oil.

Benefits of using underground cables:

Suitable for congested urban areas where overhead lines may be difficult or impossible to install

Low maintenance

Small voltage drops

Fewer faults

Not susceptible to shaking and shorting due to vibrations, wind, accidents, etc.

Not easy to steal, make illegal connections or sabotage

Poses no danger to wildlife or low flying aircraft.

Disadvantages of underground cables

More expensive

Difficult in identifying and repairing broken cables

Damage to cables or electrocution may occur to people digging the ground and if they are unaware of the cable’s existence

insulation resistance – dielectric stresses and grading

CONSTRUCTION OF STATOR INSULATION SYSTEMS 9 Figure 2.2: Stator core and windings of a few megawatt motor, showing the intricacy of the end-windings Up to about 50 MW a “coil-type” form-winding is used, in which a multiturn loop of conductors with insulation is prefabricated ready to be inserted so that the two long parallel sections (legs) fit into two stator slots and the remainder protrudes from the ends of the stator. This is quite simple to construct as one end of the stator then has no extra connections needed; the connections are just continuations of the coils. For larger ratings it is impracticable to fit so thick and rigid a coil into the stator, and it is desirable to have transposition of the subconductors of each turn (described in the next paragraph) to reduce losses. The windings for machines of such high power rating are therefore fabricated in single bars for insertion in the stator: this is a “bar-type” or “Roebels-bar” construction. It is then necessary at each end to make connections between individual conductors, which is complicated still further if channels for direct cooling are present. Stator conductors Within a coil or bar, there are several mutually insulated conductors — about ten, as a very rough idea. A high-power machine has high currents: if each winding turn were a single copper wire, this wire’s cross-section would be so great as to 10 CHAPTER 2. STATOR INSULATION SYSTEMS turn insulation main insulation semicon layer slot wedge conductors stator iron (a) Cross-section looking axially, of the insulation system within the slot of a quite low-power machine (no stranding, indirect cooling). There would typically be two separate coils in the slot, stacked vertically. insulation conductor binding tape main and turn insulation stress−grading end slot semiconductor stator iron (b) Cross-section looking radially, of insulation around the slot to end transition region. The insulation itself continues in the slot, but the slot semiconductor changes to the higher-resistivity non-linear end-winding stress-grading, with some overlap Figure 2.3: Diagrams of the construction of a simple stator insulation system cause unacceptable skin effect and eddy current losses. Several smaller conductors, the “strands” or sub-conductors, are therefore connected in parallel to form a larger conductor. The strands in a bar-type winding are arranged to change position regularly (transposition) in order to minimise differences in the induced voltages that could arise from different magnetic conditions in different parts of the slot. Strands in a coil-type winding usually do not need this transposition as the smaller machine size results in less distance between different strands; an inverted turn at the end-winding can be used to swap inner and outer parts between the two slots that a coil occupies. “Turns” of parallel strands are then connected in series to form whole coils, which are themselves connected to form whole windings. The set of conductors and insulation that is put in each stator slot is conventionally of rectangular cross-section with rounded edges, constrained by cross-section demands of the iron between the slots and by the practicalities of making the winding. Often a stator slot contains an arm of each of two coils, stacked radially. The open top of the slot cannot be closed by metal on account of electric shorting between laminations and induced voltage along such a metal strip. To hold the bars or coils in place, insulating slot-wedges are slid along the outside of the slot. The corners of conventional bars result in a non-uniform electric field in and 2.1. CONSTRUCTION OF STATOR INSULATION SYSTEMS 11 around the insulation and therefore in some over- or under-stressed regions. Some recent development has been made of fundamentally different insulation systems, based on circular-section conductors of cable-insulation design, but this has not become at all widely used. Stator insulation geometry Strand insulation can be very thin, as the expected voltages between strands in the same turn are small ($\approx$ 10V). It must however be mechanically strong against erosion, and able to withstand high temperatures. At points where the strands have a transposition, extra insulation is often needed to fill the gaps. Turn insulation must be able to withstand the voltage of some hundreds of volts between turns in normal operation. It must be also to withstand the much higher voltages that can result from transients coming to the generator terminals from outside; a high frequency signal is distributed very disproportionately much over the first turns of the winding next to the terminals, due to the high inductance of the slot part of the windings. Since the 1970s many manufacturers have used a strengthened strand insulation to obviate the need for turn insulation. To insulate the outside of the turn insulation from the stator-core’s earth potential a further layer, the “groundwall” or “main” insulation, is used. This is the thickest insulation layer, as near the phase terminals it must be able to insulate the full phase to earth voltage, often many kilovolts. Although the groundwall thickness could be varied along a winding from a small amount at the neutral point to the necessarily greater thickness near the phase terminal, this is avoided for simplicity of geometry; a life-lenght prolongation trick facilitated by this is the reversal of the connection of a winding so that the previously higher-stressed parts of groundwall are stressed less than the other end, so prolonging the insulation’s life. For machines operating at more than about 6 kV the groundwall insulation in the slot region is covered with a semiconductive (poor conductor, 0.1-10 kΩ/sq1) compound, usually with carbon-black as the conductive component. This is sufficiently conductive to ensure that cavities between the bar and the stator will not be exposed to high enough electric fields to cause partial discharges (PDs) but suf- ficiently resistive that the laminations of the stator iron will not be shorted out. The laminations are the thin sheets of iron that are stacked together along the axis of the machine, to form the magnetic circuit; they are electrically insulated from each other by a thin layer, to prevent the induced electric field within the machine from driving large eddy currents through the iron. Although the voltages between

Grading Of Cables

Grading of cable is the process of achieving uniform distribution of dielectric stress or voltage gradient in a dielectric of cable.

Voltage gradient or dielectric stress is maximum at the surface of the conductor and minimum at the inner surface of a sheath. Put in another way, the dielectric stress decreases from the surface of conductor to the sheath. This non – uniform distribution of dielectric stress leads to insulation break down in the cable. To avoid this insulation break down, it is required to distribute the dielectric stress equally throughout the dielectric. The uniform distribution of dielectric stress is achieved by grading the cables.

There are two methods of grading of cables. They are,

1. Capacitance grading and

2. Inter sheath grading

Capacitance grading:

Capacitance grading is the process of using various layers of dielectrics with each dielectric having their own permittivity. The permittivity values should be in decreasing order from the surface of the conductor to the sheath of a cable. The product of permittivity of dielectric and radius from centre of the conductor to the particular layer of a dielectric should be constant at every layer of a dielectric.

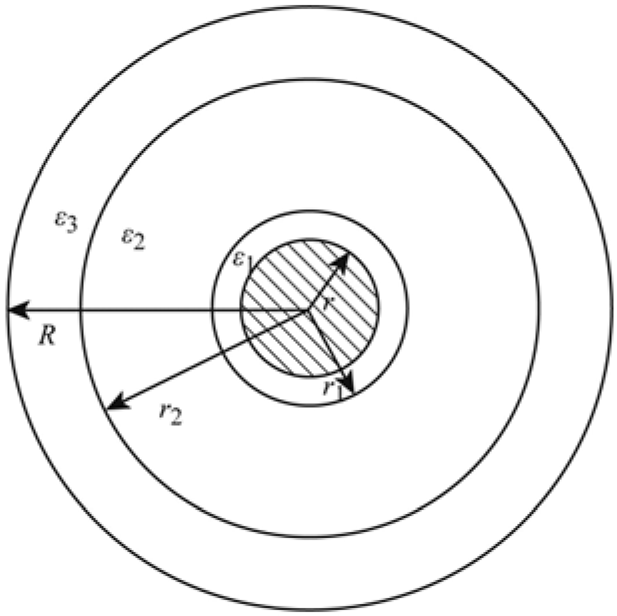


Figure 1

Figure 1 is the capacitance graded cable. Here, the radius of the conductor is *r*. Three dielectric layers are used in this cable. Consider the permittivity of first dielectric layer is ε_1, the distance from the surface of the conductor to first layer is r_1, the permittivity of second dielectric is ε_2, the distance from the surface of the conductor to second layer is r_2, the permittivity of third dielectric is ε_3, the distance from the surface of the conductor to third layer is *R*.

The relative permittivity values and their distances are $\varepsilon_1 > \varepsilon_2 > \varepsilon_3$ and $r_1 < r_2 < R$. The uniform dielectric stress can be achieved by maintaining the product of permittivity and radius of each dielectric as same, $\varepsilon_1 r_1 = \varepsilon_2 r_2 = \varepsilon_3 R$. The uniform dielectric stress cannot be achieved by capacitance grading alone. By capacitance grading alone an infinite number of dielectrics will be needed to achieve uniform dielectric stress. But it is not practically possible.

Inter sheath grading:

In this grading of a cable, a homogeneous dielectric is used. This homogenous dielectric is divided into several layers. Mechanical inter sheaths are placed in between sheaths and conductors. The inter sheaths are then held at adequate potentials which are placed in between conductor potential and earth potential. However, fixing of potentials at inter sheaths is a difficult task.

Dielectric loss

Dielectric loss quantifies a dielectric material's inherent dissipation of electromagnetic energy (e.g. heat).[1] It can be parameterized in terms of either the **loss angle** δ or the corresponding **loss tangent** tan δ. Both refer to the phasor in the complex plane whose real and imaginary parts are the resistive (lossy) component of an electromagnetic field and its reactive (lossless) counterpart.

Electromagnetic field perspective

For time varying electromagnetic fields, the electromagnetic energy is typically viewed as waves propagating either through free space, in a transmission line, in a microstrip line, or through a waveguide. Dielectrics are often used in all of these environments to mechanically support electrical conductors and keep them at a fixed separation, or to provide a barrier between different gas pressures yet still transmit electromagnetic power. Maxwell’s equations are solved for the electric and magnetic field components of the propagating waves that satisfy the boundary conditions of the specific environment's geometry.[2] In such electromagnetic analyses, the parameters permittivity ε, permeability μ, and conductivity σ represent the properties of the media through which the waves propagate. The permittivity can have real and imaginary components (the latter excluding σ effects, see below) such that

.

If we assume that we have a wave function such that

,

then Maxwell's curl equation for the magnetic field can be written as:

where ε'' is the imaginary component of permittivity attributed to *bound* charge and dipole relaxation phenomena, which gives rise to energy loss that is indistinguishable from the loss due to the *free* charge conduction that is quantified by σ. The component ε' represents the familiar lossless permittivity given by the product of the *free space* permittivity and the *relative* real permittivity, or $\varepsilon' = \varepsilon_0\varepsilon'_r$. The **loss tangent** is then defined as the ratio (or angle in a complex plane) of the lossy reaction to the electric field **E** in the curl equation to the lossless reaction:

.

For dielectrics with small loss, this angle is $\ll 1$ and $\tan\delta \approx \delta$. After some further calculations to obtain the solution for the fields of the electromagnetic wave, it turns out that the power decays with propagation distance z as

, where:

- P_o is the initial power,
- ,
- ω is the angular frequency of the wave, and
- λ is the wavelength in the dielectric.

There are often other contributions to power loss for electromagnetic waves that are not included in this expression, such as due to the wall currents of the conductors of a transmission line or waveguide. Also, a similar analysis could be applied to the magnetic permeability where

,

with the subsequent definition of a **magnetic loss tangent**

.

The electric loss tangent can be similarly defined: [3]

,

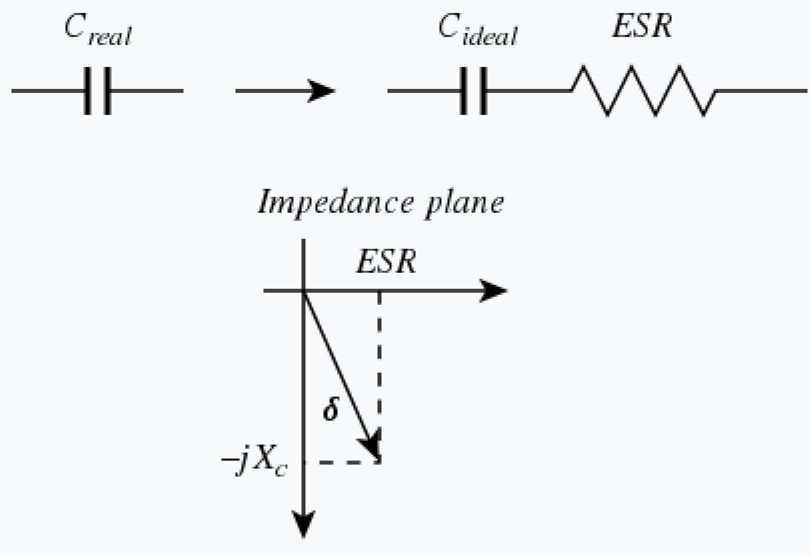
upon introduction of an effective dielectric conductivity (see relative permittivity#Lossy medium).

Discrete circuit perspective

For discrete electrical circuit components, a capacitor is typically made of a dielectric placed between conductors. The lumped element model of a capacitor includes a lossless ideal capacitor in series with a resistor termed the equivalent series resistance (ESR), as shown in the figure below.[4] The ESR represents losses in the capacitor. In a low-loss capacitor the ESR is very small (the conduction is low leading to a high resistivity), and in a lossy capacitor the ESR can be large. Note that the ESR is *not* simply the resistance that would be measured across a capacitor by an ohmmeter. The ESR is a derived quantity representing the loss due to both the dielectric's conduction electrons and the bound dipole relaxation phenomena mentioned above. In a dielectric, one of the conduction electrons or the dipole relaxation typically dominates loss in a particular dielectric and manufacturing method. For the case of the conduction electrons being the dominant loss, then

,

where C is the lossless capacitance.



A real capacitor has a lumped element model of a lossless ideal capacitor in series with an equivalent series resistance (ESR). The loss tangent is defined by the angle between the capacitor's impedance vector and the negative reactive axis.

When representing the electrical circuit parameters as vectors in a complex plane, known as phasors, a capacitor's **loss tangent** is equal to the tangent of the angle between the capacitor's impedance vector and the negative reactive axis, as shown in the adjacent diagram. The loss tangent is then

.

Since the same AC current flows through both *ESR* and X_c, the loss tangent is also the ratio of the resistivepower loss in the ESR to the reactive power oscillating in the capacitor. For this reason, a capacitor's loss tangent is sometimes stated as its *dissipation factor*, or the reciprocal of its *quality factor Q*, as follows

.

Thermal characteristics

Constant pressure to develop new and improved electronics equipment drives innovation in semiconductor devices. Thermal management and electrical integrity are two key challenges that must be addressed in order to meet customer demand for higher performance, smaller packaging, lower power consumption, and lower cost.

IC Products

Figure 9 The distribution of Thermal resistance（θja）

1. All values are calculated by simulating the test method using a wind tunnel according to the JEDEC standard. Air velocity of 0 m/s represents natural convection under still air in the wind tunnel specified in the JEDEC standard.
2. Thermal characteristics are affected by environmental conditions such as the density of the copper pattern on the test board, etc.

Discretes Products

Transient thermal resistance

Transient thermal resistance rth(t) of 2SK3740

Heat is generated at channels by power loss and then conducted from channelo atmosphere via the die, the die attach material, and the heat sink.

Safe operating area（SOA* or ASO**）

* SOA = Safe Operating Area
** ASO = Area of Safe Operating

Please use discrete devices within a safe operating area specified in data sheet.

There are five constraints to the safe operating area

- Current Limit … Line A
- Voltage Limit … Line B
- Power Dissipation Limit … Line C
- RDS(on) Limit … Line D
- Second breakdown Limit … Line E

Second breakdown may occur in some transistors.

Capacitance of Three Core Cables

In three core cables, capacitance play an important role because in such cables capacitances exist between the cores as well as each core and the sheath. These capacitances are dominating as the dielectric constant of the dielectric used in cables is much more than the air. The capacitances are shown in the Fig. 1.

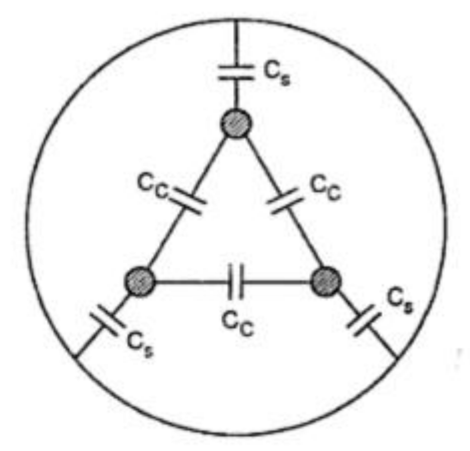


Fig. 1

The core to core capacitances are denoted as Cc while core to sheath capacitance are denoted as Cs.

The core to core capacitances Cc are in delta and can be represented in the equivalent star as shown in the Fig. 2.

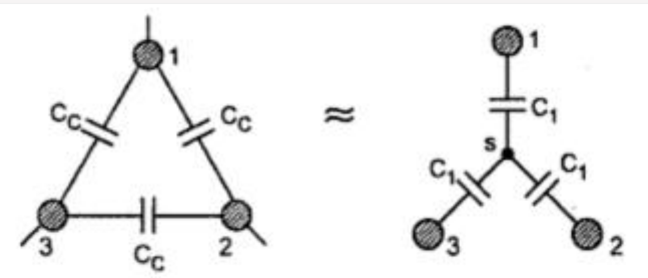


Fig. 2

The impedance between core 1 and the star point, Z_1 can be obtained as,

$$Z_1 = \frac{Z_{12} \times Z_{13}}{Z_{12} + Z_{13} + Z_{23}} \quad \text{...From delta-star conversion}$$

Now $$Z_{12} = Z_{13} = Z_{23} = \frac{1}{\omega C_C}$$

$\therefore$ $$Z_1 = \frac{\frac{1}{\omega C_C} \times \frac{1}{\omega C_C}}{\frac{3}{\omega C_C}} = \frac{1}{3} \cdot \frac{1}{\omega C_C}$$

And $$Z_1 = \frac{1}{\omega C_1} \quad \text{... in equivalent star}$$

$\therefore$ $$\frac{1}{\omega C_1} = \frac{1}{3} \cdot \frac{1}{\omega C_C}$$

$\therefore$ $$C_1 = 3\ C_C$$

If star point is assumed to be at earth potential and if sheath is also earthed then the capacitance of each conductor to neutral is,

$$\boxed{C_N = C_s + C_1 = C_s + 3\,C_C}$$

If V_{ph} is the phase voltage then charging current per phase is,

$$I = \frac{V_{ph}}{\text{Capacitive reactance per phase}}$$

$$= \frac{V_{ph}}{X_{CN}} = \frac{V_{ph}}{\frac{1}{\omega C_N}}$$

$$\therefore \quad \boxed{I = \omega C_N V_{ph} \text{ A}}$$

1.1 Measurement of C_s and C_c

The total capacitance is not easy to calculate but by actual practical measurement C_s and C_c can be determined.

Practical measurement involves two cases :

Case 1 : The core 2 and 3 are connected to sheath.

Thus the C_c between cores 2 and 3 and C_s between cores 2, 3 and sheath get eliminated as shown in the Fig. 3.

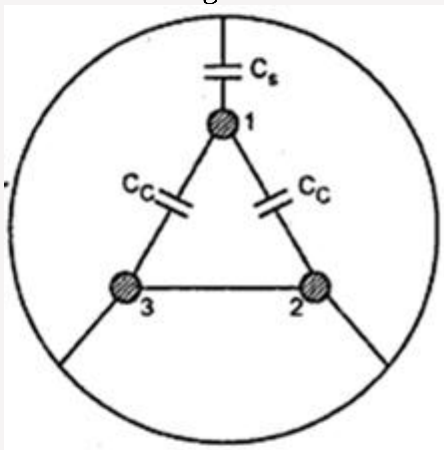


Fig. 3

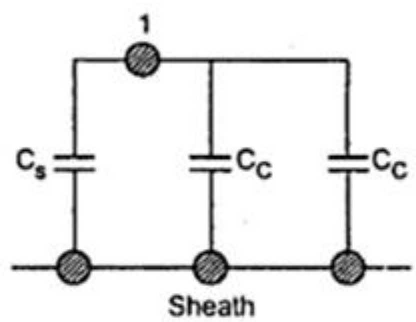


Fig. 4

All the three capacitances are now in parallel across core 1 and the sheath.

The capacitance of core 1 with sheath is measured practically and denoted by C_a.

$C_a = C_s + 2C_c$ ....(1)

Case 2 : All the three cores are bundled together.

This eliminates all the core-core capacitances. This is shown in the Fig. 5.

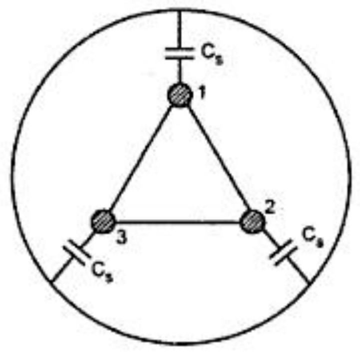


Fig. 5

The capacitances C_s are in parallel between the common core and sheath.

This capacitance is practically measured and denoted as C_b.

$C_b = 3 C_s$ ....(2)

Solving (1) and (2) simultaneously,

$C_a = (C_b/3) + 2C_c$

$C_c = (C_a/2)-(C_b/2)$ and $C_s = C_b/3$

Thus both the capacitances can be determined.

$C_N = C_s + 3C_c = (C_b/3) + 3((C_a/2) - (C_b/2))$

$$\therefore \quad \boxed{C_N = \frac{3C_a}{2} - \frac{C_b}{6}}$$

1.2 Capacitance of Three Core Cable

There is one empirical formula to calculate the capacitance of a three core belted cable, stated by Simon. It is applicable for the circular conductors. The formula gives the capacitance of a three core cable to neutral per phase per kilometer length of the cable. The formula is given as,

Where ε_r = Relative permittivity of the dielectric

d = Conductor diameter

t = Belt Insulation thickness

T = Conductor insulation thickness

The formula can be used when the test results are not available. This gives approximate value of the capacitance. If ε_r is not given, it can be assumed to be 3.5. It must be remembered that all the values of d, t and T must be used in the same units while using the formula.

Example : A three core cable has core diameter 0f 2 cm and core to core distance of 4 cm. The dielectric material has relative permittivity of 5. Compute the capacitance of this cable per phase per km. Thickness of the conductor insulation is 1 cm and that of belt insulation is 0.5 cm.

Solution : d = 2 cm , ε_r = 5, T = 1 cm, t = 0.5 cm

Use the empirical formula as the test results are not given.

$$
\begin{aligned}
C_N &= \frac{0.0299\ \varepsilon_r}{ln\left[1+\frac{T+t}{d}\left\{3.84-1.7\frac{t}{T}+0.52\frac{t^2}{T^2}\right\}\right]}\ \mu F/km \\
&= \frac{0.0299\times 5}{ln\left[1+\frac{1+0.5}{2}\left\{3.84-\frac{17\times 0.5}{1}+\frac{052\times(0.5)^2}{(1)^2}\right\}\right]} \\
&= \frac{0.0299\times 5}{ln\left[1+0.75\ \{3.84-0.85+0.13\}\right]} = \frac{0.0299\times 5}{ln[3.34]} = \mathbf{0.1239}\ \ \mu F/km
\end{aligned}
$$

Types of Electrical Insulator | Overhead Insulator

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

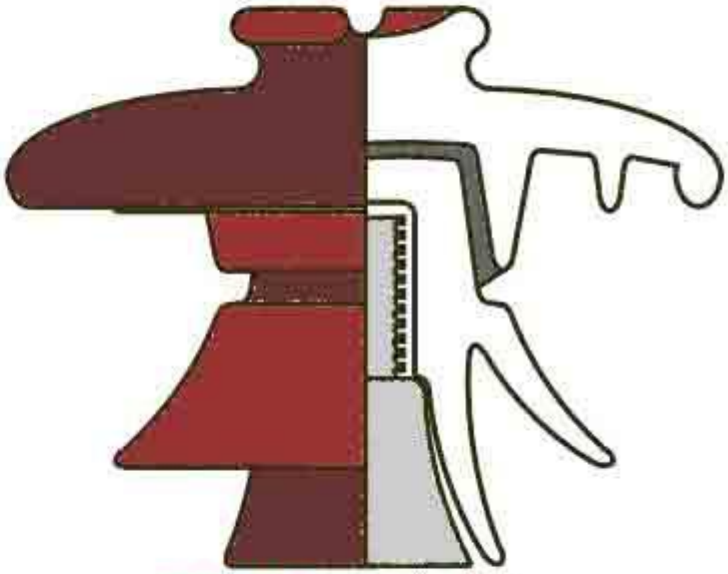
1. **Pin Insulator**
2. **Suspension Insulator**
3. **Strain Insulator**

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

Pin Insulator

Pin Insulator is earliest developed **overhead insulator**, but still popularly used in power network up to 33 KV system. Pin type insulator can be one part, two parts or three parts type, depending upon application voltage. In 11 KV 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, tow 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. 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 can not 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.



33KV Pin Insulator

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.

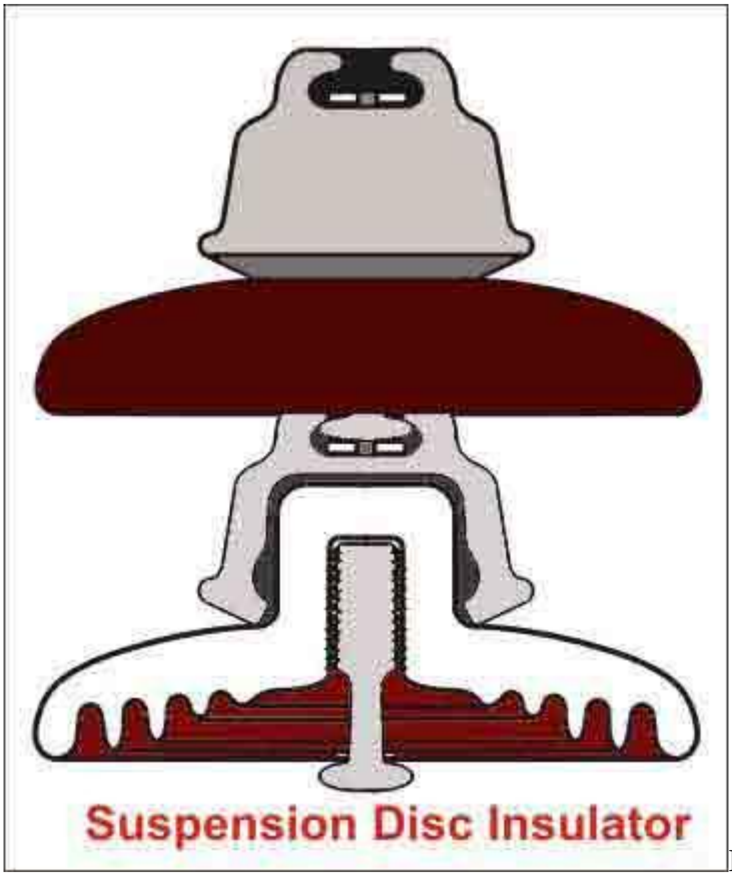
1. When insulator is wet, its outer surface becomes almost conducting. Hence the flash over distance of insulator is decreased. The design of an electrical insulator should be such that the decrease of flash over distance is minimum when the insulator is wet. That is why the upper most petticoat of a 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.

Post Insulator

Post insulator is more or less similar to Pin insulator but former is suitable for higher voltage application. **Post insulator** has higher numbers of petticoats and has greater height. This type of insulator can be mounted on supporting structure horizontally as well as vertically. The insulator is made of one piece of porcelain but has fixing clamp arrangement are in both top and bottom end. The main differences between pin insulator and post insulator are,

SL	Pin Insulator	Post Insulator
1	It is generally used up to 33KV system	It is suitable for lower voltage and also for higher voltage
2	It is single stag	It can be single stag as well as multiple stags
3	Conductor is fixed on the top of the insulator by binding	Conductor is fixed on the top of the insulator with help of connector clamp
4	Two insulators cannot be fixed together for higher voltage application	Two or more insulators can be fixed together one above other for higher voltage application
4	Metallic fixing arrangement provided only on bottom end of the insulator	Metallic fixing arrangement provided on both top and bottom ends of the insulator

Suspension Insulator

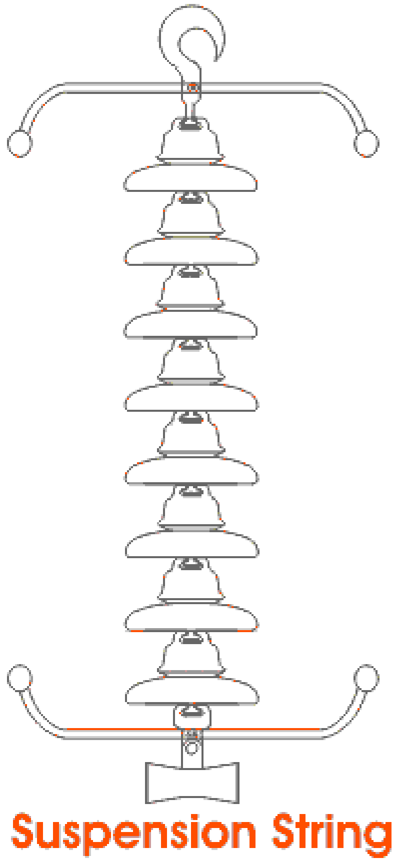


In higher voltage, beyond 33KV, it becomes uneconomical to use pin insulator because size, weight of the insulator become more. Handling and replacing bigger size single unit insulator are quite difficult task. For overcoming these difficulties, **suspension insulator** was developed. In **suspension 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

1. Each suspension disc is designed for normal voltage rating 11KV (Higher voltage rating 15KV), so by using different numbers of discs, a suspension string can be made suitable for any voltage level.
2. If any one of the disc insulators in a suspension string is damaged, it can be replaced much easily.

3. Mechanical stresses on the suspension insulator is less since the line hanged on a flexible



suspension string.

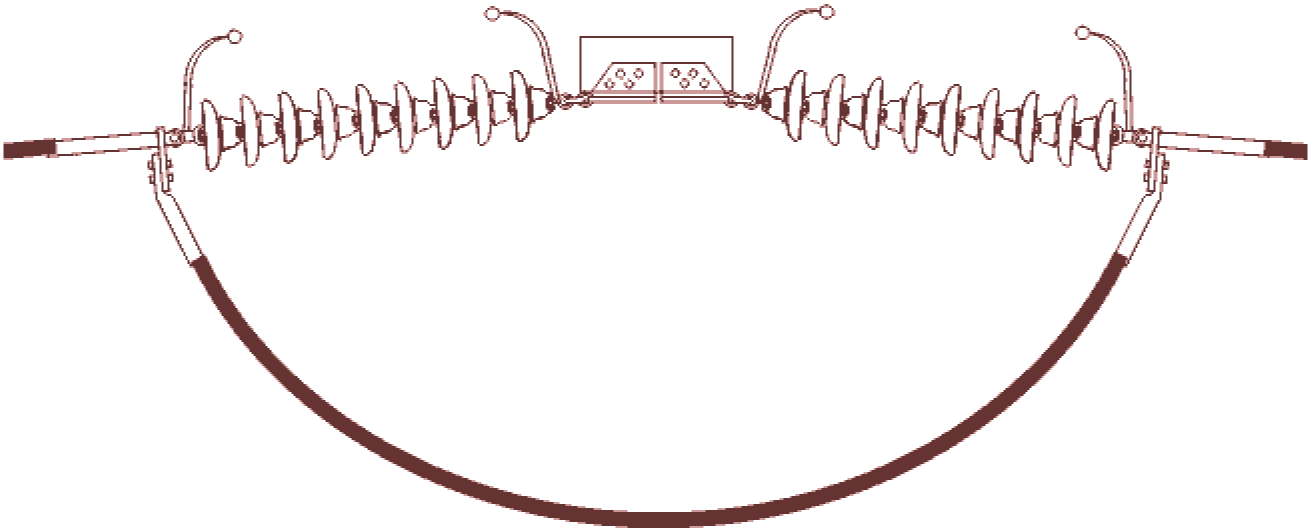
4. As the current carrying conductors are suspended from supporting structure by suspension string, the height of the conductor position is always less than the total height of the supporting structure. Therefore, the conductors may be safe from lightening.

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

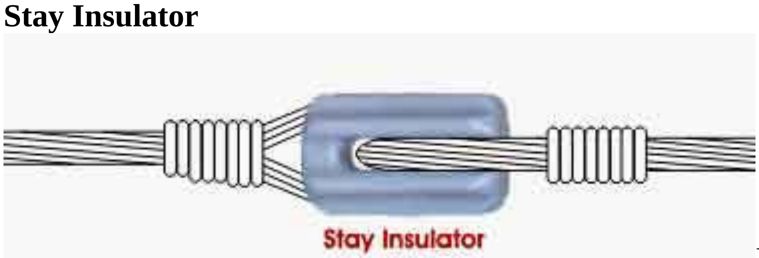
When suspension string is used to sustain extraordinary tensile load of conductor it is referred as **string insulator**. When there is a dead end or there is a sharp corner in transmission line, the line has to sustain a great tensile load of conductor or strain. A **strain insulator** must have considerable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



STRAIN INSULATOR

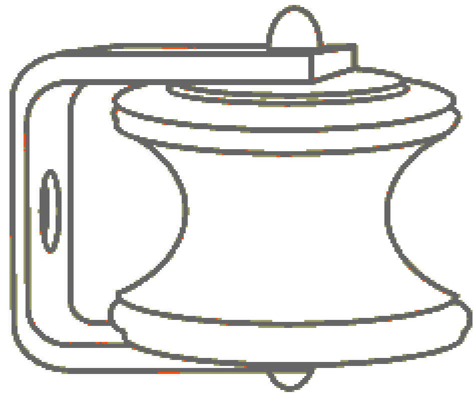
Rated System Voltage	Number of disc insulator used in strain type tension insulator string	Number of disc insulator used in suspension insulator string
33KV	3	3
66KV	5	4
132KV	9	8
220KV	15	14

Stay Insulator



For low voltage lines, the stays are to be insulated from ground at a height. The insulator used in the stay wire is called as the **stay**

insulator and is usually of porcelain and is so designed that in case of breakage of the insulator



Shackle or Spool Insulator

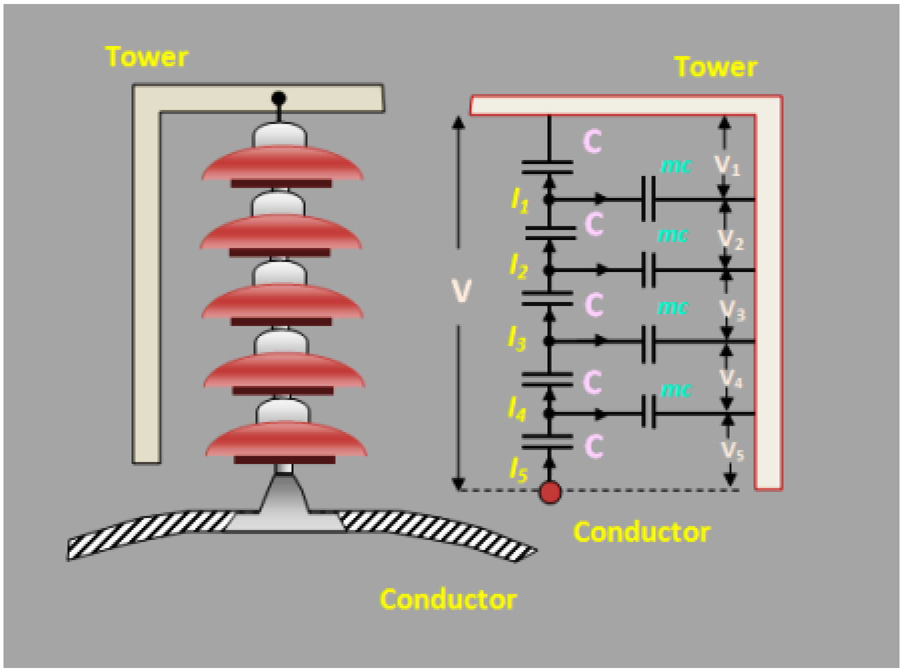
the guy-wire will not fall to the ground.

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

Voltage Distribution Over Suspension Insulator | String Efficiency

In these topics, it is discussed the voltage distribution over suspension insulator string. Let, there are 5 nos. disc insulators which are connected in series through metallic link and suspense from line tower which is shown in the figure. From the figure, it is seen that porcelain portion of each disc is in between two metal links.



Therefore each disc forms a capacitor **C** as shown in fig. It is known as mutual capacitance or self-capacitance. And capacitance also exists between metal fitting of each disc and tower or earth. This is known as shunt capacitance **mc**. Due to the shunt capacitance, the charging current is not the same though all the disc of string. Hence, the voltage across each disc will be different. And voltage across to the nearest conductor will have the maximum voltage. The reference to Fig. V5 will be much than V4 or V3 or V2 or V1

String Effeciency and methods to improve String Effeciency
Posted on September 25, 2011 by k10blogger

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., $Stringeffeciency = \frac{VolatgeacrossString}{n \times Voltageacrossdiscnearesttoconductor}$
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 volatge 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 progressively as the crossarm 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. This necessitates to equalise the potential across the various units of the string i.e. to improve the string efficiency.
The various methods for this purpose 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 i_1, i_2 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.

UNIT V

MECHANICAL DESIGN OF TRANSMISSION LINES

Sag and Tension- Sag calculation for equal and unequal level supports

Calculation of Sag & Tension

Calculation of sag and tension in transmission line depend on the span of the conductor. Span having equal level supports is called level span, whereas when the level of the supports is not at an equal level is known as unequal level span. The calculation of conductor at an equal level shown below

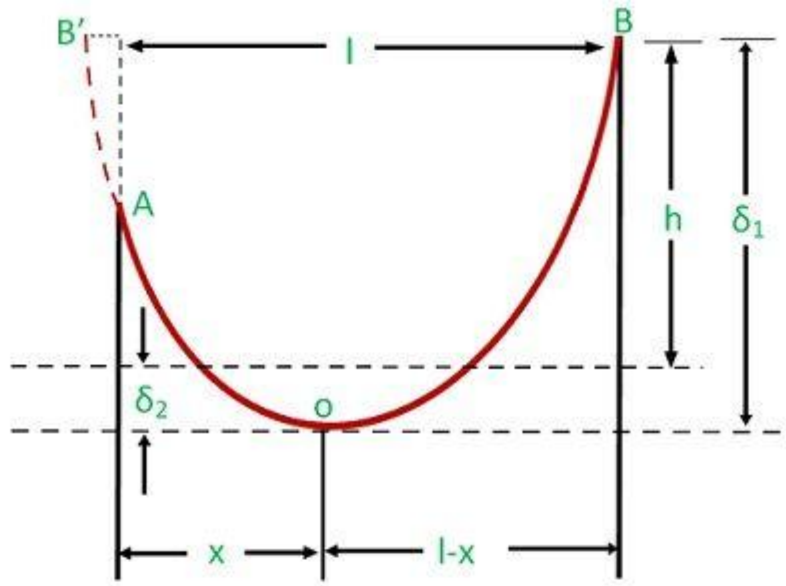
consider a conductor AOB suspended freely between level supports A and B at the same level.The lowest point of the conductor is O. Let the shape of the conductor be a parabola.

l – span length
w- weight per unit length of the conductor
δ – conductor sag
H – tension in the conductor at the point of maximum deflection O
T_B – tension in the conductor at the point of support B.

Consider OB is the equilibrium tension of the conductor and force acting on it are the horizontal tension H at O. The weight (w.OB) of the conductor OB acting vertically downwards through the center of gravity at a distance l/4 from B, and the tension T_B at the support B.

$$H\delta = (w.OB)l/4$$

Since OB is approximately equal to the l/2



Supports at unequal levels.

Take moments about B

$$H.\delta = w.\frac{l}{2} \times \frac{l}{4}$$

$$\delta = \frac{wl^2}{8H}$$

l – span length
w- weight per unit length of the conductor
δ – conductor sag
H – tension in the conductor at the point of maximum deflection O
T_B – tension in the conductor at the point of support B.

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Take moments about B

$$H.\delta = w.\frac{l}{2} \times \frac{l}{4}$$

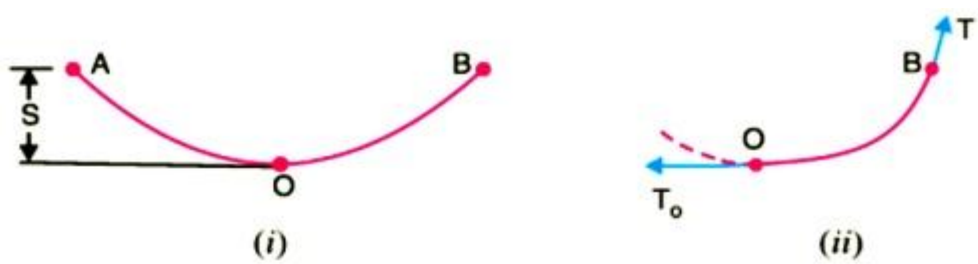
$$\delta = \frac{wl^2}{8H}$$

Calculation of Sag and Tension at an unequal level supports

In hilly areas or sloping grounds, the supports are not usual at the same level. For the calculation of sag and tension at unequal supports level consider a conductor AOB. The portion of OA and OB may be treated as catenaries of half span x and l-x respectively shown in the figure below

MECHANICAL DESIGN OF 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. 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. The following points may be noted



(i) When the conductor is suspended between two supports at the same level, it takes the shap e 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_O 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 $T = T_O$

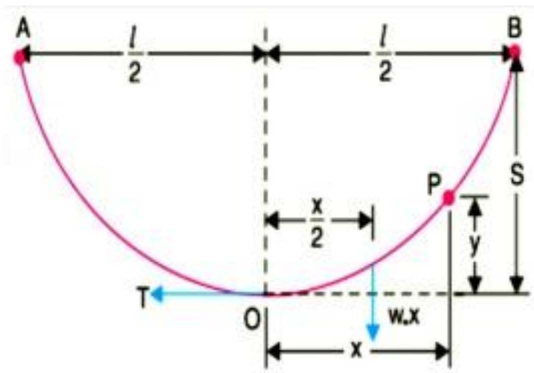
Conductor Sag And Tension

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.

2. 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.8.2. 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. It can be proved that lowest point will be at the mid-span.



a conductor between two equilevel supports A and B with O as the lowest point as shown in Fig. 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 w_x 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,

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

or $$y = \frac{w x^2}{2T}$$

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

At support A, $x = l/2$ and $y = S$

$$\therefore \quad \text{Sag,} \quad S = \frac{w(l/2)^2}{2T} = \frac{w l^2}{8T}$$

(ii) When supports are at unequal levels. In hilly areas, we generally come across conductors suspended between supports at unequal levels. Fig.3 shows a conductor suspended between two supports A and B which are at different levels. The lowest point on the conductor is O .

Let

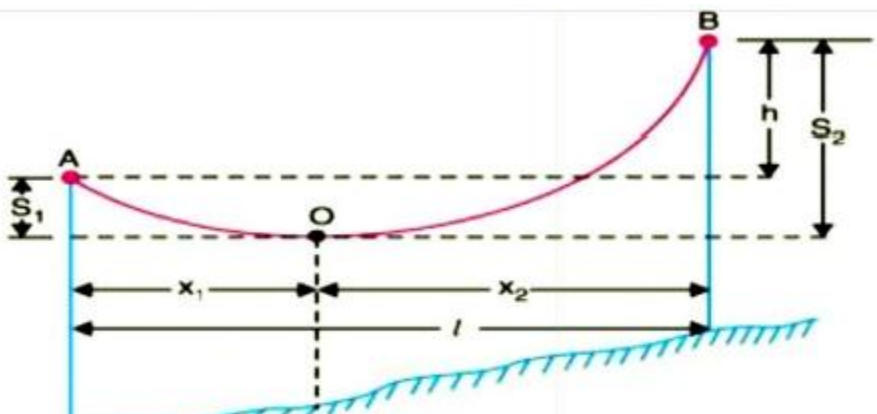
l = Span length

h = Difference in levels between two supports

x_1 = Distance of support at lower level (i.e., A) from O

x_2 = Distance of support at higher level (i.e. B) from O

T = Tension in the conductor



If w is the weight per unit length of the conductor, then,

$$\text{Sag } S_1 = \frac{w x_1^2}{2T}$$

and $$\text{Sag } S_2 = \frac{w x_2^2}{2T}$$

Also $$x_1 + x_2 = l$$

Now $$S_2 - S_1 = \frac{w}{2T}[x_2^2 - x_1^2] = \frac{w}{2T}(x_2 + x_1)(x_2 - x_1)$$

$\therefore$ $$S_2 - S_1 = \frac{w\,l}{2T}(x_2 - x_1) \qquad [\because x_1 + x_2 = l]$$

But $$S_2 - S_1 = h$$

$\therefore$ $$h = \frac{w\,l}{2T}(x_2 - x_1)$$

or $$x_2 - x_1 = \frac{2\,Th}{w\,l} \qquad ...(ii)$$

Solving exps. (*i*) and (*ii*), we get,

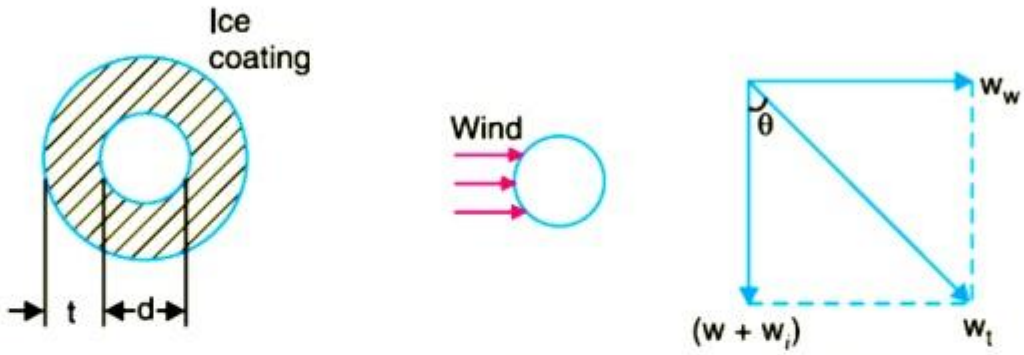
$$x_1 = \frac{l}{2} - \frac{T\,h}{w\,l}$$

$$x_2 = \frac{l}{2} + \frac{T\,h}{w\,l}$$

Having found x_1 and x_2, values of S_1 and S_2 can be easily calculated.

3. 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



(*i*) (*ii*) (*iii*)

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

Wi = weight of ice per unit length

= density of ice * volume of ice per unit length

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

$$= \text{density of ice} \times \pi\, t\,(d+t)^*$$

w_w = wind force per unit length

= wind pressure per unit area projected area per unit length

$$= \text{wind pressure} \times [(d+2t) \times 1]$$

When the conductor has wind and ice loading also, the following points may be noted :

i)The conductor sets itself in a plane at an angle to the vertical where

$$\tan\theta = \frac{w_w}{w + w_i}$$

ii)The sag in the conductor is given by

$$S = \frac{w_t\, l^2}{2T}$$

Hence S represents the slant sag in a direction making an angle to the vertical. If no specific mention is made in the problem, then slant slag is calculated by using the above formula.

iii)The vertical sag = $S\cos\theta$

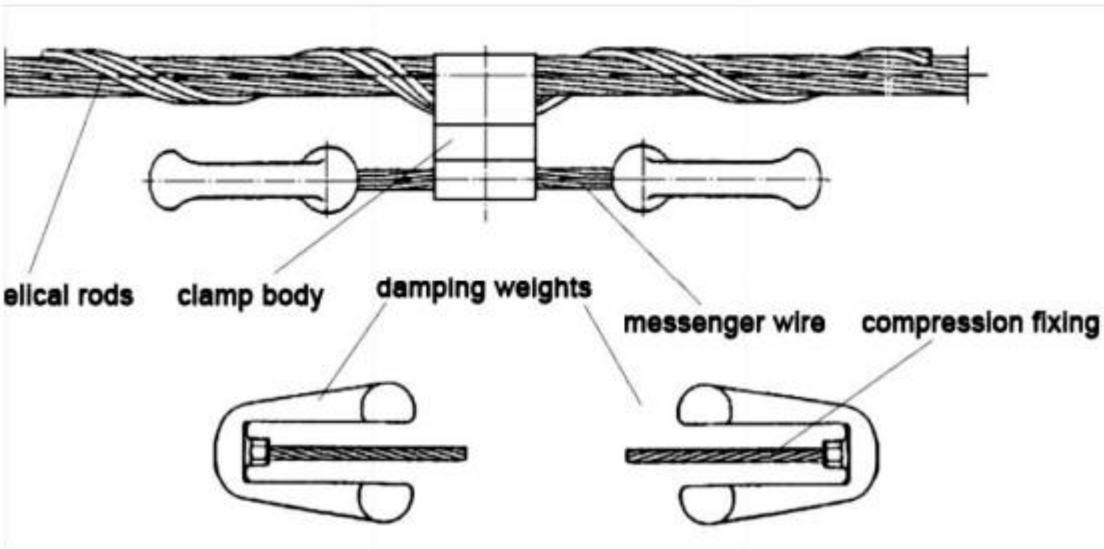
4. VIBRATION DAMPER

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.

Vibration Damping

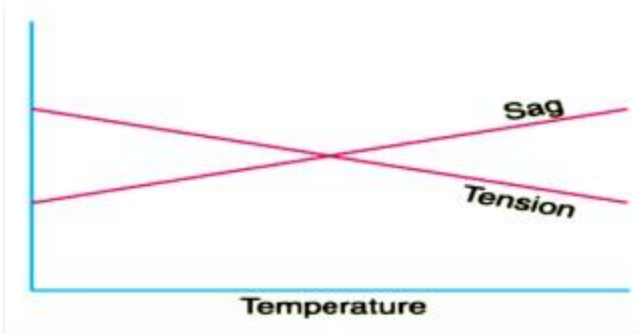
The knowledge of the mechanical self- damping of conductors is an important parameter for the energy balance calculation. The impedance and the efficiency of the vibration damper have been measured in relationship to frequency and used as input data for the energy balance.



The velocity of the damper clamp shall be remain under the limit of 10 cm/s. The vibration dampers are tested at this vibrating velocity in an endurance test. They must stand at least 100 million vibrations without damages. If the velocity of the damper clamp remains beneath the value of 10 cm/s the bending stresses remain in the endurance range so that damages could not be expected.

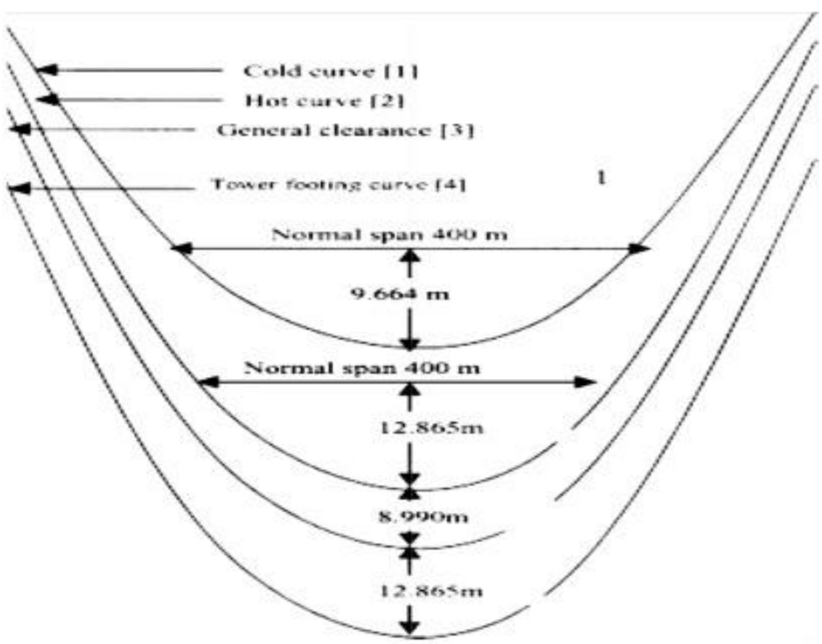
5. STRINGING CHART

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 (see Fig). These charts are very helpful while stringing overhead lines.



6. 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.



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

Corona

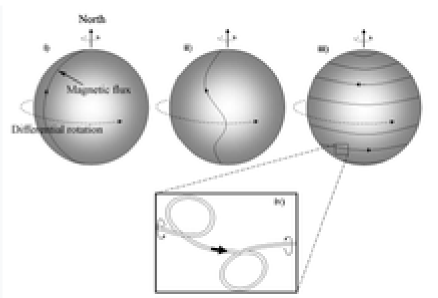
corona characteristics

A **corona** (Latin, 'crown') is an aura of plasma that surrounds the sun and other stars. The Sun's corona extends millions of kilometres into space and is most easily seen during a total solar eclipse, but it is also observable with a coronagraph. The word "corona" is a Latin word meaning "crown", from the Ancient Greek κορώνη (korōnè, "garland, wreath").

The high temperature of the Sun's corona gives it unusual spectral features, which led some in the 19th century to suggest that it contained a previously unknown element, "coronium". Instead, these spectral features have since been explained by highly ionized iron (Fe-XIV). Bengt Edlén, following the work of Grotrian (1939), first identified the coronal spectral lines in 1940 (observed since 1869) as transitions from low-lying metastable levels of the ground configuration of highly ionised metals (the green Fe-XIV line at 5303 Å, but also the red line Fe-X at 6374 Å). These high stages of ionisation indicate a plasma temperature in excess of 1,000,000 kelvins,[1] much hotter than the surface of the sun.

Light from the corona comes from three primary sources, from the same volume of space. The K-corona (K for *kontinuierlich*, "continuous" in German) is created by sunlight scattering off free electrons; Doppler broadening of the reflected photospheric absorption lines spreads them so greatly as to completely obscure them, giving the spectral appearance of a continuum with no absorption lines. The F-corona (F for Fraunhofer) is created by sunlight bouncing off dust particles, and is observable because its light contains the Fraunhofer absorption lines that are seen in raw sunlight; the F-corona extends to very high elongation angles from the Sun, where it is called the zodiacal light. The E-corona (E for emission) is due to spectral emission lines produced by ions that are present in the coronal plasma; it may be observed in broad or forbidden or hot spectral emission lines and is the main source of information about the corona's composition.[2]

Physical features



A drawing demonstrating the configuration of solar magnetic flux during the solar cycle

The sun's corona is much hotter (by a factor from 150 to 450) than the visible surface of the Sun: the photosphere's average temperature is 5800 kelvins compared to the corona's one to three million kelvins. The corona is 10^{-12} times as dense as the photosphere, and so produces about one-millionth as much visible light. The corona is separated from the photosphere by the relatively shallow chromosphere. The exact mechanism by which the corona is heated is still the subject of some debate, but likely possibilities include induction by the Sun's magnetic field and magnetohydrodynamic waves from below. The outer edges of the Sun's corona are constantly being transported away due to open magnetic flux and hence generating the solar wind.

The corona is not always evenly distributed across the surface of the sun. During periods of quiet, the corona is more or less confined to the equatorial regions, with coronal holes covering the polar regions. However, during the Sun's active periods, the corona is evenly distributed over the equatorial and polar regions, though it is most prominent in areas with sunspot activity. The solar cycle spans approximately 11 years, from solar minimum to the following minimum. Since the solar magnetic field is continually wound up due to the faster rotation of mass at the sun's equator (differential rotation), sunspot activity will be more pronounced at solar maximum where the magnetic field is more twisted. Associated with sunspots are coronal loops, loops of magnetic flux, upwelling from the solar interior. The magnetic flux pushes the hotter photosphere aside, exposing the cooler plasma below, thus creating the relatively dark sun spots.

Since the corona has been photographed at high resolution in the X-ray range of the spectrum by the satellite Skylab in 1973, and then later by Yohkoh and the other following space instruments, it has been seen that the structure of the corona is quite varied and complex: different zones have been immediately classified on the coronal disc.[3][4][5] The astronomers usually distinguish several regions,[6] as described below.

Active regions

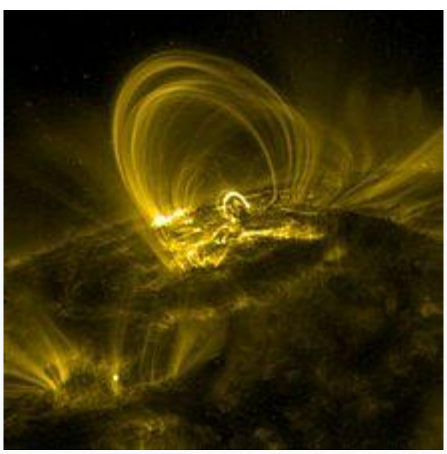
Active regions are ensembles of loop structures connecting points of opposite magnetic polarity in the photosphere, the so-called coronal loops. They generally distribute in two zones of activity, which are parallel to the solar equator. The average temperature is between two and four million kelvins, while the density goes from 10^9 to 10^{10} particle per cm^3.

Illustration depicting solar prominences and sunspots

Active regions involve all the phenomena directly linked to the magnetic field, which occur at different heights above the Sun's surface:[6]sunspots and faculae, occur in the photosphere, spicules, Hα filaments and plages in the chromosphere, prominences in the chromosphere and transition region, and flares and coronal mass ejections happen in the corona and chromosphere. If flares are very violent, they can also perturb the photosphere and generate a Moreton wave. On the contrary, quiescent prominences are large, cool dense structures which are observed as dark, "snake-like" Hα ribbons (appearing like filaments) on the solar disc. Their temperature is about 5000–8000 K, and so they are usually considered as chromospheric features.

In 2013, images from the High Resolution Coronal Imager revealed never-before-seen "magnetic braids" of plasma within the outer layers of these active regions.[7]

*Coronal loops****[edit]***
Main article: Coronal loop



TRACE 171Å coronal loops

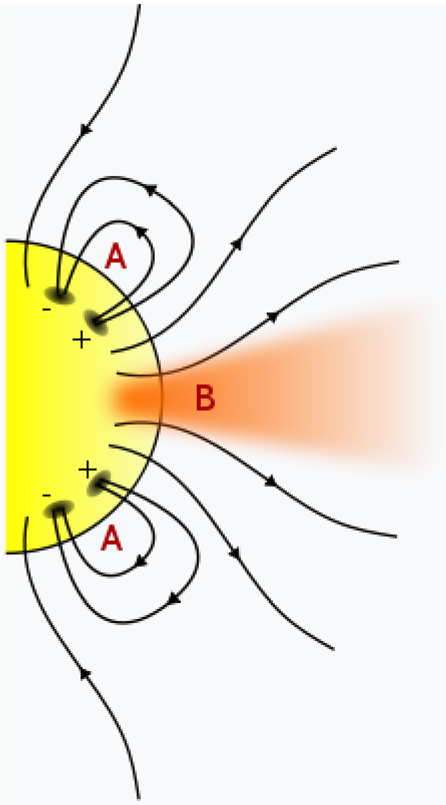
Coronal loops are the basic structures of the magnetic solar corona. These loops are the closed-magnetic flux cousins of the open-magnetic flux that can be found in coronal hole (polar) regions and the solar wind. Loops of magnetic flux well-up from the solar body and fill with hot solar plasma.[8] Due to the heightened magnetic activity in these coronal loop regions, coronal loops can often be the precursor to solar flaresand coronal mass ejections (CMEs).

The Solar plasma that feed these structures is heated from under 6000 K to well over 10^6 K from the photosphere, through the transition region, and into the corona. Often, the solar plasma will fill these loops from one point and drain to another, called foot points (siphon flow due to a pressure difference,[9] or asymmetric flow due to some other driver).

When the plasma rises from the foot points towards the loop top, as always occurs during the initial phase of a compact flare, it is defined as chromospheric evaporation. When the plasma rapidly cools and falls toward the photosphere, it is called chromospheric condensation. There may also be symmetric flow from both loop foot points, causing a build-up of mass in the loop structure. The plasma may cool rapidly in this region (for a thermal instability), its dark filaments obvious against the solar disk or prominences off the Sun's limb.

Coronal loops may have lifetimes in the order of seconds (in the case of flare events), minutes, hours or days. Where there is a balance in loop energy sources and sinks, coronal loops can last for long periods of time and are known as *steady state* or *quiescent* coronal loops. (example).

Coronal loops are very important to our understanding of the current *coronal heating problem*. Coronal loops are highly radiating sources of plasma and are therefore easy to observe by instruments such as *TRACE*. An explanation of the coronal heating problem remains as these structures are being observed remotely, where many ambiguities are present (i.e. radiation contributions along the LOS). *In-situ* measurements are required before a definitive answer can be had, but due to the high plasma temperatures in the corona, *in-situ*measurements are, at present, impossible. The next mission of the NASA Solar Probe Plus will approach the Sun very closely allowing more direct observations.



Coronal arches connecting regions of opposite magnetic polarity (A) and the unipolar magnetic field in the coronal hole (B)

Large-scale structures

Large-scale structures are very long arcs which can cover over a quarter of the solar disk but contain plasma less dense than in the coronal loops of the active regions.

They were first detected in the June 8, 1968 flare observation during a rocket flight.[10]

The large-scale structure of the corona changes over the 11-year solar cycle and becomes particularly simple during the minimum period, when the magnetic field of the Sun is almost similar to a dipolar configuration (plus a quadrupolar component).

Interconnections of active regions

The **interconnections of active regions** are arcs connecting zones of opposite magnetic field, of different active regions. Significant variations of these structures are often seen after a flare.[*citation needed*]

Some other features of this kind are helmet streamers—large cap-like coronal structures with long pointed peaks that usually overlie sunspots and active regions. Coronal streamers are considered as sources of the slow solar wind.[11]

*Filament cavities**[edit]***

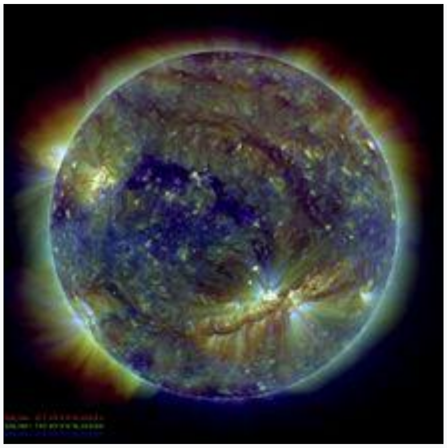


Image taken by the Solar Dynamics Observatory on Oct 16 2010. A very long filament cavity is visible across the Sun's southern hemisphere.

Filament cavities are zones which look dark in the X-rays and are above the regions where Hαfilaments are observed in the chromosphere. They were first observed in the two 1970 rocket flights which also detected *coronal holes*.[10]

Filament cavities are cooler clouds of gases (plasma) suspended above the Sun's surface by magnetic forces. The regions of intense magnetic field look dark in images because they are empty of hot plasma. In fact, the sum of the magnetic pressure and plasma pressure must be constant everywhere on the heliosphere in order to have an equilibrium configuration: where the magnetic field is higher, the plasma must be cooler or less dense. The plasma pressure can be calculated by the state equation of a perfect gas , where is the particle number density, the Boltzmann constant and the plasma temperature. It is evident from the equation that the plasma pressure lowers when the plasma temperature decreases with respect to the surrounding regions or when the zone of intense magnetic field empties. The same physical effect renders sunspots apparently dark in the photosphere.

Bright points

Bright points are small active regions found on the solar disk. X-ray bright points were first detected on April 8, 1969 during a rocket flight.[10]

The fraction of the solar surface covered by bright points varies with the solar cycle. They are associated with small bipolar regions of the magnetic field. Their average temperature ranges from 1.1×10^6 K to 3.4×10^6 K. The variations in temperature are often correlated with changes in the X-ray emission.[12]

Coronal holes

Coronal holes are the Polar Regions which look dark in the X-rays since they do not emit much radiation.[13] These are wide zones of the Sun where the magnetic field is unipolar and opens towards the interplanetary space. The high speed solar wind arises mainly from these regions.

In the UV images of the coronal holes, some small structures, similar to elongated bubbles, are often seen as they were suspended in the solar wind. These are the coronal **plumes**. More exactly, they are long thin streamers that project outward from the Sun's north and south poles.[14]

The quiet Sun[edit]

The solar regions which are not part of active regions and coronal holes are commonly identified as the **quiet Sun**.

The equatorial region has a faster rotation speed than the polar zones. The result of the Sun's differential rotation is that the active regions always arise in two bands parallel to the equator and their extension increases during the periods of maximum of the solar cycle, while they almost disappear during each minimum. Therefore, the quiet Sun always coincides with the equatorial zone and its surface is less active during the maximum of the solar cycle. Approaching the minimum of the solar cycle (also named butterfly cycle), the extension of the quiet Sun increases until it covers the whole disk surface excluding some bright points on the hemisphere and the poles, where there are the coronal holes.

Variability of the corona

A portrait as diversified as the one already pointed out for the coronal features is emphasized by the analysis of the dynamics of the main structures of the corona, which evolve in times very different among them. Studying the coronal variability in its complexity is not easy because the times of evolution of the different structures can vary considerably: from seconds to several months. The typical sizes of the regions where coronal events take place vary in the same way, as it is shown in the following table.

Coronal event	Typical time-scale	Typical length-scale (Mm)
Active region flare	10 to 10,000 seconds	10–100
X-ray bright point	minutes	1–10
Transient in large-scale structures	from minutes to hours	~100
Transient in interconnecting arcs	from minutes to hours	~100
Quiet Sun	from hours to months	100–1,000

Coronal hole	several rotations	100–1,000

Flares

On August 31, 2012 a long filament of solar material that had been hovering in the Sun's outer atmosphere, the corona, erupted at 4:36 p.m. EDT

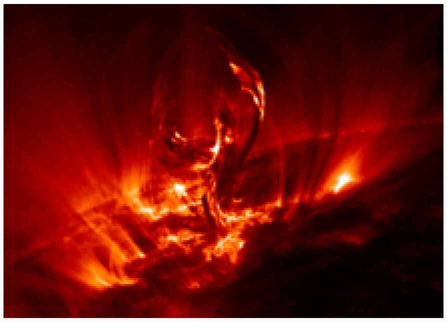
Flares take place in active regions and are characterized by a sudden increase of the radiative flux emitted from small regions of the corona. They are very complex phenomena, visible at different wavelengths; they involve several zones of the solar atmosphere and many physical effects, thermal and not thermal, and sometimes wide reconnections of the magnetic field lines with material expulsion.

Flares are impulsive phenomena, of average duration of 15 minutes, and the most energetic events can last several hours. Flares produce a high and rapid increase of the density and temperature.

An emission in white light is only seldom observed: usually, flares are only seen at extreme UV wavelengths and into the X-rays, typical of the chromospheric and coronal emission.

In the corona, the morphology of flares, is described by observations in the UV, soft and hard X-rays, and in Hα wavelengths, and is very complex. However, two kinds of basic structures can be distinguished: [15]

- **Compact flares**, when each of the two arches where the event is happening maintains its morphology: only an increase of the emission is observed without significant structural variations. The emitted energy is of the order of $10^{22} – 10^{23}$ J.
- **Flares of long duration**, associated with eruptions of prominences, transients in white light and *two-ribbon flares*:[16] in this case the magnetic loops change their configuration during the event. The energies emitted during these flares are of such great proportion they can reach 10^{25} J.



Filament erupting during a solar flare, seen at EUV wavelengths (TRACE)

As for temporal dynamics, three different phases are generally distinguished, whose duration are not comparable. The durations of those periods depend on the range of wavelengths used to observe the event:

- **An initial impulsive phase**, whose duration is on the order of minutes, strong emissions of energy are often observed even in the microwaves, EUV wavelengths and in the hard X-ray frequencies.
- **A maximum phase**
- **A decay phase**, which can last several hours.

Sometimes also a phase preceding the flare can be observed, usually called as "pre-flare" phase.

Transients

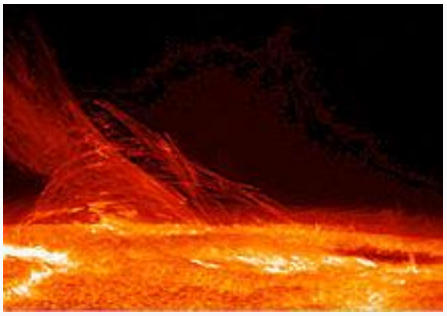
Accompanying solar flares or large solar prominences, **"coronal transients"** (also called coronal mass ejections) are sometimes released. These are enormous loops of coronal material that travel outward from the Sun at over a million kilometers per hour, containing roughly 10 times the energy of the solar flare or prominence that accompanies them. Some larger ejections can propel hundreds of millions of tons of material into space at roughly 1.5 million kilometers an hour.

Stellar coronae

Coronal stars are ubiquitous among the stars in the cool half of the Hertzsprung–Russell diagram.[17] These coronae can be detected using X-ray telescopes. Some stellar coronae, particularly in young stars, are much more luminous than the Sun's. For example, FK Comae Berenices is the prototype for the FK Com class of variable star. These are giants of spectral types G and K with an unusually rapid rotation and signs of extreme activity. Their X-ray coronae are among the most luminous ($L_x \geq 10^{32}$ erg·s^{-1} or 10^{25}W) and the hottest known with dominant temperatures up to 40 MK.[17]

The astronomical observations planned with the Einstein Observatory by Giuseppe Vaiana and his group[18] showed that F-, G-, K- and M-stars have chromospheres and often coronae much like our Sun. The *O-B stars*, which do not have surface convection zones, have a strong X-ray emission. However these stars do not have coronas, but the outer stellar envelopes emit this radiation during shocks due to thermal instabilities in rapidly moving gas blobs. Also A-stars do not have convection zones but they do not emit at the UV and X-ray wavelengths. Thus they appear to have neither chromospheres nor coronae.

Physics of the corona



Taken by Hinode on Jan 12 2007 this image reveals the filamentary nature of the corona.

The matter in the external part of the solar atmosphere is in the state of plasma, at very high temperature (a few million kelvins) and at very low density (of the order of 10^{15} particle/m^3). According to the definition of plasma, it is a quasi-neutral ensemble of particles which exhibits a collective behaviour.

The composition is the same as the one in the Sun's interior, mainly hydrogen, but completely ionized, thence protons and electrons, and a small fraction of the other atoms in the same percentages as they are present in the photosphere. Even heavier metals, such as iron, are partially ionized and have lost most of the external electrons. The ionization state of a chemical element depends strictly on the temperature and is regulated by the Saha equation. Historically, the presence of the spectral lines emitted from highly ionized states of iron allowed determination of the high temperature of the coronal plasma, revealing that the corona is much hotter than the internal layers of the chromosphere.

The corona behaves like a gas which is very hot but very light at the same time: the pressure in the corona is usually only 0.1 to 0.6 Pa in active regions, while on the Earth the atmospheric pressure is about 100 kPa, approximately a million times higher than on the solar surface. However it is not properly a gas, because it is made of charged particles, basically protons and electrons, moving at different velocities. Supposing that they have the same kinetic energy on average (for the equipartition theorem), electrons have a mass roughly 1800 times smaller than protons, therefore they acquire more velocity. Metal ions are always slower. This fact has relevant physical consequences either on radiative processes (that are very different from the photospheric radiative processes), or on thermal conduction. Furthermore, the presence of electric charges induces the generation of electric currents and high magnetic fields. Magnetohydrodynamic waves (MHD waves) can also propagate in this plasma,[19] even if it is not still clear how they can be transmitted or generated in the corona.

Radiation

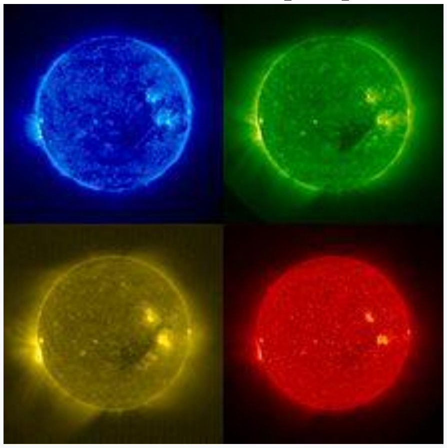
The corona emits radiation mainly in the X-rays, observable only from space.

The plasma is transparent to its own radiation and to that one coming from below, therefore we say that it is **optically-thin**. The gas, in fact, is very rarefied and the photon mean free-path overcomes by far all the other length-scales, including the typical sizes of the coronal features.

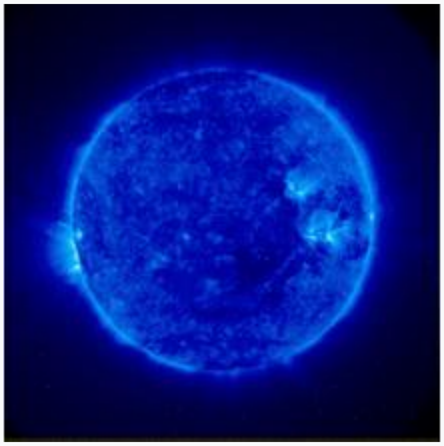
Different processes of radiation take place in the emission, due to binary collisions between plasma particles, while the interactions with the photons, coming from below; are very rare.

Because the emission is due to collisions between ions and electrons, the energy emitted from a unit volume in the time unit is proportional to the squared number of particles in a unit volume, or more exactly, to the product of the electron density and proton density.[20]

Thermal conduction[edit]



A mosaic of the extreme ultraviolet images taken from STEREO on December 4, 2006. These false color images show the Sun's atmospheres at a range of different temperatures. Clockwise from top left: 1 million degrees C (171 Å—blue), 1.5 million °C (195 Å—green), 60,000–80,000 °C (304 Å—red), and 2.5 million °C (286 Å—yellow).



STEREO – First images as a slow animation

In the corona thermal conduction occurs from the external hotter atmosphere towards the inner cooler layers. Responsible for the diffusion process of the heat are the electrons, which are much lighter than ions and move faster, as explained above.

When there is a magnetic field the thermal conductivity of the plasma becomes higher in the direction which is parallel to the field lines rather than in the perpendicular direction.[21] A charged particle moving in the direction perpendicular to the magnetic field line is subject to the Lorentz force which is normal to the plane individuated by the velocity and the magnetic field. This force bends the path of the particle. In general, since particles also have a velocity component along the magnetic field line, the Lorentz force constrains them to bend and move along spirals around the field lines at the cyclotron frequency.

If collisions between the particles are very frequent, they are scattered in every direction. This happens in the photosphere, where the plasma carries the magnetic field in its motion. In the corona, on the contrary, the mean free-path of the electrons is of the order of kilometres and even more, so each electron can do a helicoidal motion long before being scattered after a collision. Therefore, the heat transfer is enhanced along the magnetic field lines and inhibited in the perpendicular direction.

In the direction longitudinal to the magnetic field, the thermal conductivity of the corona is[21]

where is the Boltzmann constant, is the temperature in kelvins, the electron mass, the electric charge of the electron,

the Coulomb logarithm, and

the Debye length of the plasma with particle density . The Coulomb logarithm is roughly 20 in the corona, with a mean temperature of 1 MK and a density of 10^{15} particles/m^3, and about 10 in the chromosphere, where the temperature is approximately 10kK and the particle density is of the order of 10^{18} particles/m^3, and in practice it can be assumed constant.

Thence, if we indicate with the heat for a volume unit, expressed in J m^{-3}, the Fourier equation of heat transfer, to be computed only along the direction of the field line, becomes

.

Numerical calculations have shown that the thermal conductivity of the corona is comparable to that of copper.

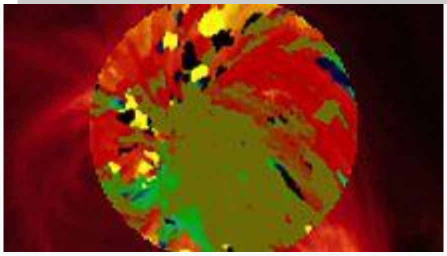
Coronal seismology

Coronal seismology is a new way of studying the plasma of the solar corona with the use of magnetohydrodynamic (MHD) waves. Magnetohydrodynamics studies the dynamics of electrically conducting fluids—in this case the fluid is the coronal plasma. Philosophically, coronal seismology is similar to the Earth's seismology, the Sun's helioseismology, and MHD spectroscopy of laboratory plasma devices. In all these approaches, waves of various kinds are used to probe a medium. The potential of coronal seismology in the estimation of the coronal magnetic field, density scale height, fine structure and heating has been demonstrated by different research groups.

Coronal heating problem

Unsolved problem in physics:

Why is the Sun's Corona so much hotter than the Sun's surface? (more unsolved problems in physics)



A new visualisation technique can provide clues to the coronal heating problem.

The coronal heating problem in solar physics relates to the question of why the temperature of the Sun's corona is millions of kelvins higher than that of the surface. The high temperatures require energy to be carried from the solar interior to the corona by non-thermal processes, because the second law of thermodynamics prevents heat from flowing directly from the solar photosphere (surface), which is at about 5800 K, to the much hotter corona at about 1 to 3 MK (parts of the corona can even reach 10 MK).

Between the photosphere and the corona, is the thin region through which the temperature increases known as the transition region. It ranges from only tens to hundreds of kilometers thick. Energy cannot be transferred from the cooler photosphere to the corona by conventional heat transfer as this would violate the second law of thermodynamics. An analogy of this would be a light bulb raising the temperature of the air surrounding it to something greater than its glass surface. Hence, some other manner of energy transfer must be involved in the heating of the corona.

The amount of power required to heat the solar corona can easily be calculated as the difference between coronal radiative losses and heating by thermal conduction toward the chromosphere through the transition region. It is about 1 kilowatt for every square meter of surface area on the Sun's chromosphere, or 1/40000 of the amount of light energy that escapes the Sun.

Many coronal heating theories have been proposed,[22] but two theories have remained as the most likely candidates: wave heating and magnetic reconnection (or nanoflares).[23] Through most of the past 50 years, neither theory has been able to account for the extreme coronal temperatures.

The NASA mission Solar Probe + is intended to approach the Sun to a distance of approximately 9.5 solar radii to investigate coronal heating and the origin of the solar wind.

In 2012, high resolution (<0.2″) soft X-ray imaging with the High Resolution Coronal Imager aboard a sounding rocket revealed tightly wound braids in the corona. It is hypothesized that the reconnection and unravelling of braids can act as primary sources of heating of the active solar corona to temperatures of up to 4 million kelvins. The main heat source in the quiescent corona (about 1.5 million kelvins) is assumed to originate from MHD waves.[24]

Competing heating mechanisms		
Heating Models		
Hydrodynamic	**Magnetic**	
	DC (*reconnection*)	**AC (*waves*)**
• No magnetic field • Slow rotating stars	• B-field stresses • Reconnection events • Flares-nanoflares • *Uniform heating rates*	• Photospheric foot point *shuffling* • MHD wave propagation • High Alfvén wave flux • *Non-uniform heating rates*
•	**Competing theories**	

Wave heating theory

The wave heating theory, proposed in 1949 by Evry Schatzman, proposes that waves carry energy from the solar interior to the solar chromosphere and corona. The Sun is made of plasma rather than ordinary gas, so it supports several types of waves analogous to sound waves in air. The most important types of wave are magneto-acoustic waves and Alfvén waves.[25] Magneto-acoustic waves are sound waves that have been modified by the presence of a magnetic field, and Alfvén waves are similar to ultra low frequency radio wavesthat have been modified by interaction with matter in the plasma. Both types of waves can be launched by the turbulence of granulation and super granulation at the solar photosphere, and both types of waves can carry energy for some distance through the solar atmosphere before turning into shock waves that dissipate their energy as heat.

One problem with wave heating is delivery of the heat to the appropriate place. Magneto-acoustic waves cannot carry sufficient energy upward through the chromosphere to the corona, both because of the low pressure present in the chromosphere and because they tend to be reflected back to the photosphere. Alfvén waves can carry enough energy, but do not dissipate that energy rapidly enough once they enter the corona. Waves in plasmas are notoriously difficult to understand and describe analytically, but computer simulations, carried out by Thomas Bogdan and colleagues in 2003, seem to show that Alfvén waves can transmute into other wave modes at the base of the corona, providing a pathway that can carry large amounts of energy from the photosphere through the chromosphere and transition region and finally into the corona where it dissipates it as heat.

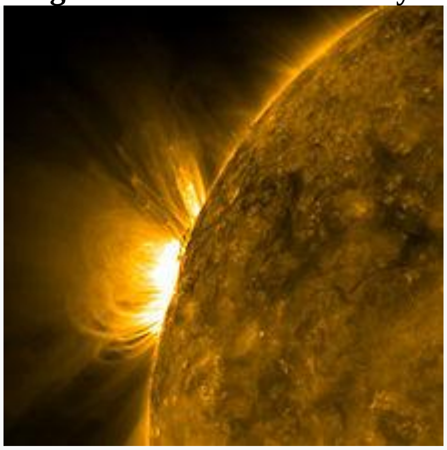
Another problem with wave heating has been the complete absence, until the late 1990s, of any direct evidence of waves propagating through the solar corona. The first direct observation of waves propagating into and through the solar corona was made in 1997 with the Solar and Heliospheric Observatory space-borne solar observatory, the first platform capable of observing the Sun in the extreme ultraviolet (EUV) for long periods of time with stable photometry. Those were magneto-acoustic waves with a frequency of about 1 millihertz (mHz, corresponding to a 1,000 second wave period), that carry only about 10% of the energy required to heat the corona. Many observations exist of localized wave phenomena, such as Alfvén waves launched by solar flares, but those events are transient and cannot explain the uniform coronal heat.

It is not yet known exactly how much wave energy is available to heat the corona. Results published in 2004 using data from the TRACE spacecraft seem to indicate that there are waves in the solar atmosphere at frequencies as high as 100 mHz (10 second period). Measurements of the temperature of different ions in the solar wind with the UVCS instrument aboard SOHO give strong indirect evidence that there are waves at frequencies as high as 200 Hz, well into the range of human hearing. These waves are very difficult to detect under normal circumstances, but evidence collected during solar eclipses by teams from Williams College suggest the presences of such waves in the 1–10 Hz range.

Recently, Alfvénic motions have been found in the lower solar atmosphere [26] [27] and also in the quiet Sun, in coronal holes and in active regions using observations with AIA on board the Solar Dynamics Observatory.[28] These Alfvénic oscillations have significant power, and seem to be connected to the chromospheric Alfvénic oscillations previously reported with the Hinode spacecraft .[29]

Solar wind observations with the WIND (spacecraft) have recently shown evidence to support theories of Alfvén-cyclotron dissipation, leading to local ion heating.[30]

Magnetic reconnection theory



Arcing active region by Solar Dynamics Observatory

The magnetic reconnection theory relies on the solar magnetic field to induce electric currents in the solar corona.[31] The currents then collapse suddenly, releasing energy as heat and wave energy in the corona. This process is called "reconnection" because of the peculiar way that magnetic fields behave in plasma (or any electrically conductive fluid such as mercury or seawater). In a plasma, magnetic field lines are normally tied to individual pieces of matter, so that the topology of the magnetic field remains the same: if a particular north and south magnetic pole are connected by a single field line, then even if the plasma is stirred or if the magnets are moved around, that field line will continue to connect those particular poles. The connection is maintained by electric currents that are induced in the plasma. Under certain conditions, the electric currents can collapse, allowing the magnetic field to "reconnect" to other magnetic poles and release heat and wave energy in the process.

Magnetic reconnection is hypothesized to be the mechanism behind solar flares, the largest explosions in our solar system. Furthermore, the surface of the Sun is covered with millions of small magnetized regions 50–1,000 km across. These small magnetic poles are buffeted and churned by the constant granulation. The magnetic field in the solar corona must undergo nearly constant reconnection to match the motion of this "magnetic carpet", so the energy released by the reconnection is a natural candidate for the coronal heat, perhaps as a series of "microflares" that individually provide very little energy but together account for the required energy.

The idea that nanoflares might heat the corona was proposed by Eugene Parker in the 1980s but is still controversial. In particular, ultraviolet telescopes such as TRACE and SOHO/EIT can observe individual micro-flares as small brightenings in extreme ultraviolet light,[32] but there seem to be too few of these small events to account for the energy released into the corona. The additional energy not accounted for could be made up by wave energy, or by gradual magnetic reconnection that releases energy more smoothly than micro-flares and therefore doesn't appear well in the TRACE data. Variations on the micro-flare hypothesis use other mechanisms to stress the magnetic field or to release the energy, and are a subject of active research in 2005.

Spicules (type II)

For decades, researchers believed spicules could send heat into the corona. However, following observational research in the 1980s, it was found that spicule plasma did not reach coronal temperatures, and so the theory was discounted.

As per studies performed in 2010 at the *National Center for Atmospheric Research* in Colorado, in collaboration with the *Lockheed Martin's Solar and Astrophysics Laboratory*(LMSAL) and the *Institute of Theoretical Astrophysics* of the University of Oslo, a new class of spicules (TYPE II) discovered in 2007, which travel faster (up to 100 km/s) and have shorter lifespans, can account for the problem. These jets insert heated plasma into the Sun's outer atmosphere.

Thus, a much greater understanding of the Corona and improvement in the knowledge of the Sun's subtle influence on the Earth's upper atmosphere can be expected henceforth. The Atmospheric Imaging Assembly on NASA's recently launched Solar Dynamics Observatory and NASA's Focal Plane Package for the Solar Optical Telescope on the Japanese Hinode satellite which was used to test this hypothesis. The high spatial and temporal resolutions of the newer instruments reveal this coronal mass supply.

These observations reveal a one-to-one connection between plasma that is heated to millions of degrees and the spicules that insert this plasma into the corona.