6 Edition
Revised & Updated

A Handbook on

Electrical Engineering

Contains well illustrated formulae & key theory concepts

for

ESE, GATE, PSUs

& OTHER COMPETITIVE EXAMS

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Director's Message

B. Singh (Ex. IES)

During the current age of international competition in Science and Technology, the Indian participation through skilled technical professionals have been challenging to the world. Constant efforts and desire to achieve top positions are still required.

I feel every candidate has ability to succeed but competitive environment and quality guidance is required to achieve high level goals. At MADE EASY, we help you discover your hidden talent and success quotient to achieve your ultimate goals. In my opinion CSE, ESE, GATE & PSUs exams are tools to enter in to the main stream of Nation serving. The real application of knowledge and talent starts, after you enter in to the working system. Here at MADE EASY you are also trained to become winner in your life and achieve job satisfaction.

MADE EASY alumni have shared their winning stories of success and expressed their gratitude towards quality guidance of MADE EASY. Our students have not only secured All India First Ranks in ESE, GATE and PSUs entrance examinations but also secured top positions in their career profiles. Now, I invite you to become an alumnus of MADE EASY to explore and achieve ultimate goal of your life. I promise to provide you quality guidance with competitive environment which is far advanced and ahead than the reach of other institutions. You will get the guidance, support and inspiration that you need to reach the peak of your career.

I have a true desire to serve the Society and the Nation easing path of the education for the people of India.

After a long experience of teaching Electrical Engineering over a period of time, MADE EASY team realised that there is a need of a good *Handbook* which can provide the crux of Electrical Engineering in a concise form to the student to brush up the formulae and important concepts required for ESE, GATE, PSUs and other competitive examinations. This *handbook* contains all the formulae and important theoretical aspects of Electrical Engineering. It provides much needed revision aid and study guidance before examinations.

B. Singh (Ex. IES)
CMD, MADE EASY Group

A Handbook on

Electrical Engineering

Contents

Chapter 1 :

Power Systems 1-49

I. Supply System...1
II. Line Parameters..3
III. Performance of Transmission Line.... 13
IV. Concept of Corona 21
V. Mechanical Design of Overhead Lines....................................... 23
VI. Balanced and Unbalanced Faults...... 25
VII. Power System Stability......................... 30
VIII. Power System Transients..................... 32
IX. Economic Load Dispatch..................... 37
X. Underground Cable 38
XI. Protective Relays 42
XII. Circuit Breakers....................................... 45
XIII. Generating Power Stations................. 46
XIV. Loads and Load Curves........................ 48

Chapter 2 :

Electrical Machines......... 50-102

I. Transformers.. 50
II. Electromagnetic System...................... 63
III. Basic Concepts in Rotating Electrical Machines................................ 64
IV. D.C. Machines.. 66
V. Polyphase Induction Motors.............. 76
VI. Polyphase Synchronous Machines... 85
VII. Single Phase Induction Machine....... 97
VIII. Special Machines..................................102

Chapter 3 :

Power Electronics 103-161

I. Power Electronics.................................103
II. Thyristor 109
III. Thyristor Commutation Techniques 116
IV. Diode Circuits and Rectifiers............121
V. Phase Controlled Rectifiers 128
VI. Choppers...143
VII. Inverters 149
VIII. AC Voltage Controllers 157
IX. Electric Drives..160

Chapter 4 :

Measurements and Instrumentation................. 162-206

I. Characteristics of Instruments and Measurement Systems.......................162
II. Circuit Components (Resistors, Inductors, Capacitors) 167
III. Galvanometers.....................................169
IV. Analog Meters.......................................171
V. Instrument Transformers...................178
VI. Measurement of Power and Wattmeters 181
VII. Measurement of Resistance.............185
VIII. A.C. Bridges 191
IX. Magnetic Measurements 196
X. Electronic Instruments.......................197
XI. Cathode Ray Oscilloscope 198
XII. High Frequency Measurements 201
XIII. Transducers..202
XIV. Digital Instrumentation 204

Chapter 5 :

Network Theory 207-241

I. Basic Definitions & Circuits Element ...207
II. Network Laws and Theorems 215
III. Graph Theory 221
IV. Laplace Transform Analysis and Circuit Transients 224
V. Resonance 229
VI. Magnetically Coupled Circuit 232
VII. Two Port Network................................234
VIII. Miscellaneous..237

Contents

Chapter 6 :
Control Systems 242-276

I. Introduction 242
II. Mathematical Modelling 243
III. Transfer function 249
IV. Time Response Analysis of C.S. 254
V. Stability in Time-Domain 261
VI. Industrial Controller 264
VII. Compensator 267
VIII. Frequency Response Analysis 269
IX. State Space Analysis 275

Chapter 7 :
Signals and Systems 277-308

I. Introduction to Signals 277
II. Linear Time Invariant Systems 283
III. Fourier Series 286
IV. Fourier Transform 291
V. Laplace Transform 295
VI. Discrete Time Fourier Transform 298
VII. Z-Transform 299
VIII. Discrete Fourier Transform 302
IX. Digital Filters 303
X. Miscellaneous 306

Chapter 8 :
Analog Electronics 309-370

I. Semiconductor Physics 309
II. Junction Diode Characteristics 317
III. BJT Characteristics 327
IV. Transistor Biasing Circuits 332
V. BJT as an Amplifier 337
VI. Junction Field Effect Transistors 339
VII. Metal Oxide Semiconductor Field Effect Transistor 343
VIII. Transistor Hybrid Model 346
IX. Feedback Amplifiers 348
X. Operational Amplifiers 352
XI. Large Signal Amplifiers 360
XII. The Signal Generators and Wave Shaping Circuits 363

Chapter 9 :
Digital Electronics 371-422

I. Number System and Codes 371
II. Logic Gates 376
III. Boolean Algebra and Reduction Techniques 383
IV. Digital Logic Circuits 387
V. Sequential Circuits 394
VI. Registers 399
VII. Counters 400
VIII. Digital ICs Family 404
IX. DACs and ADCs 411
X. Miscellaneous 418

Chapter 10 :
Electrical Materials 423-449

I. Dielectric Properties of Insulating Materials 423
II. Dielectric Breakdown 431
III. Magnetic Properties of Materials 433
IV. Conductive Materials 438
V. Semiconductors 442
VI. Insulating Materials 443
VII. Structure of Materials 446
VIII. Ceramic Materials 448

Chapter 11 :
Electromagnetic Theory 450-449

I. Vector Calculus 450
II. Cartesian Coordinate System & Vector Calculus 451
III. Electrostatics 457
IV. Magnetostatics 465
V. Time-Varying Electromagnetic Fields 469
VI. Electromagnetic Wave Propagation 472
VII. Transmission Lines 480

Contents

Chapter 12 :

Microprocessors....................484-526

I. Introduction..484
II. Architecture of 8085 485
III. Instruction Set and Data Formats ...492
IV. Interrupts 508
V. Interfacing with Microprocessor 510
VI. Introduction to 8086...........................514
VII. Microcontroller 518

Chapter 13 :

Communication Systems.............................527-546

I. Basics 527
II. Fourier Series, Energy and Signals 528
III. Analog Modulation 530
IV. Pulse Modulation 537
V. Digital Carrier Modulation 540
VI. Random Variables and Noise 543

Chapter 14 :

Computer Fundamentals 547-571

I. Data Representation............................547
II. Computer Architecture.......................548
III. Memory Organization.........................553
IV. Networking Fundamental 562
V. Programming Elements......................563
VI. Operating System Concepts 564

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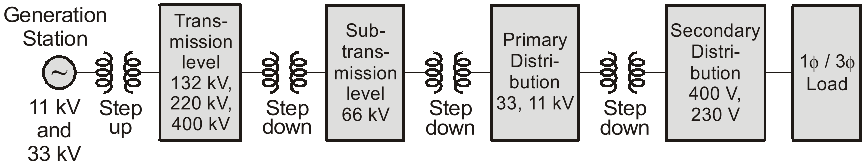
Power Systems

1

I Supply System

Basic Structure of Power System



- Generating stations are interconnected by the lines.
- Transmission lines, when interconnected with each other, becomes transmission networks.
- The combined transmission and distribution network is known as the "power grid".

Effect of System Voltage on Transmission of Power

- Power loss in the line is inversely proportional to the system voltage and power factor both.
- Percentage voltage drop in resistance decreases with the increase in the system voltage.
- Weight of the conductor material for the line will decreases with the increase in supply voltage and power factor.
- Efficiency of transmission, increases with the increase of supply voltage and power factor.
- Higher supply voltages also enhances the system stability.
- The problems encountered with high voltages are the insulation of the equipment, corona, radio and television interference.
- The voltage level of a system is therefore governed by the amount of power to be transmitted and the length of the line.

Voltage Level

- Low voltage → 230 V (1-ϕ), 400 V (3-ϕ)
- High voltage → 11 kV, 33 kV

- Extra high voltage: 66 kV, 132 kV, 220 kV.
- Modern EHV: 400 kV
- Ultra high voltage: 765 kV and above.

Conductor Used for Transmission Line

- Copper conductor
- ACSR : Aluminium conductor steel reinforced.
- ACAR : Aluminium conductor alloy reinforced.
- AAAC : All Aluminium alloy conductor.
- Expanded ACSR conductor: Normally used for EHV lines.
- AAC : All Alluminium conductors.

Types of Conductor

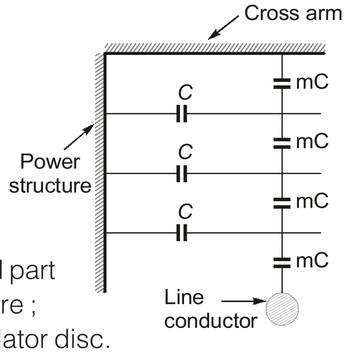
- Solid conductor: It has high skin effect.
- Hollow conductor: Preferred under heavy current, i.e., more than 1000 Amp.
- Stranded conductor.
- Composite standard conductor: used for voltage ≤ 220 kV.
- Bundle conductor: Used for voltage > 275 kV.

Advantage of Bundle Conductor

- Self distance (GMR) increased without change in mutual distance.
- Voltage gradient reduced so corona loss reduce.
- It reduces the interference with nearby communication line.
- Inductance (L) of transmission line reduces and capacitance (C) increases.
- Surge impedance, i.e., $Z_s = \sqrt{\frac{L}{C}}$ decreases.
- Power system stability increases.

Insulators

Over head line insulators provide the required insulation to the line conductors from each other and from the supporting structures electrically. Most commonly used materials are porcelain, toughened glass and steatite,



where, $C \rightarrow$ Capacitance between metal part of the insulator and tower structure ;
$mC \rightarrow$ Capacitance of each insulator disc.
$mC > C$

Note:

☑ The stress experienced by the disc near the power conductor is more than the stress experience by the disc near the cross-arm.

String Efficiency

$$\text{String efficiency} = \frac{\text{Voltage across the whole string}}{n \times (\text{Voltage across the unit adjacent to line conductor})}$$

where, $n \rightarrow$ Number of insulator discs in the string

String efficiency also defined as

$$\%\eta = \frac{\text{Flashover voltage of the string}}{n \times \text{flashover voltage of one string}} \times 100$$

Note:

☑ As the number of disc increases string efficiency decreases.

Methods of Equilising Potential Across Each Disc

- Increase the length of cross arm.
- Capacitance grading or grading of units.
- Use of grading rings or static shielding.

Remember:

☑ For static shielding the capacitance from the shield to the K_{th} link from the top

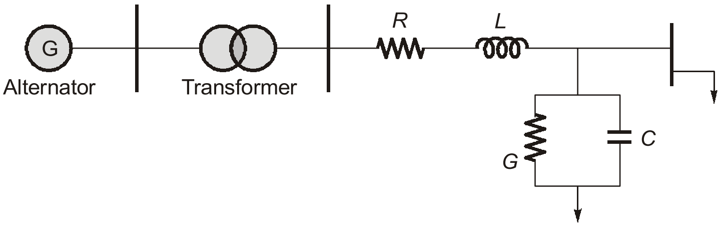
$$C_K = \frac{KC}{n-K} \qquad (\because n = \text{number of disc})$$

Types of Insulator

- **Pin type insulator:** Pin type insulator operate satisfactory upto 25 kV.
- **Multipine type insulator:** Operates upto 33 kV
- **Suspension type insulator:** A suspension insulator is designed to operate at 11 kV.
- **Strain type insulator:** Strain type insulator mechanically strong. It is used when direction of transmission line changes across river crossing and at the dead end of the transmission line.
- **Shackle type:** Shackle type insulator are used in low tension cable. These insulator can be operated either horizontally or vertically.

II Line Parameters

Transmission line is a carrier on which bulk amount of power from a remote generating station to the operative areas is being carried out.



Transmission line is

- series combination of resistance (R) and inductance (L) and
- Parallel combination of shunt conductance (G) and capacitance (C).

Note:

- The line parameter of transmission line is calculated in per unity or per km and are constant for entire line length.
- The shunt conductance is caused by leakage current.
- In transmission line if $G = 0$ means leakage current is assume to be zero.
- Power loss in the conductor is only due to series resistance.
- Power transmission capacity of the line is mainly governed by the series inductance.

- **Resistance of a conductor,** $R_{\text{eff}} = \dfrac{\text{Power loss in conductor}}{I^2}$ ohms

  where, $R_{\text{eff}} \rightarrow$ Effective resistance of the conductor

- **D.C. Resistance of a Conductor,** $R_{dc} = \rho \dfrac{l}{A}$ ohms

  where, $\rho \rightarrow$ Resistivity of conductor, Ω-m ; $l \rightarrow$ Length of conductor, metre ; $A \rightarrow$ Cross-sectional area, m^2

Note:

☑ The effective resistance is equal to the dc resistance of the conductor only if the current is uniformly distributed throughout the cross-sectional area of the conductor (i.e. for DC only).

Skin Effect

If DC is passed in a conductor, the current density is uniform over the cross-section of the conductor but when an alternating current flows through a conductor, the distribution tends to become non uniform. There is a tendency of the current to crowd near the surface of the conductor. This phenomenon is called "skin effect". The effective conductor resistance increases in AC as compared to DC which causes larger power loss.

Remember:

☑ Skin effect increases with increase in frequency, conductor diameter and permeability.

Proximity Effect

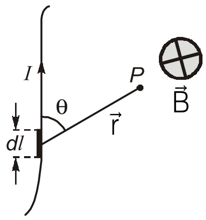
When two or more conductors are in proximity, their electromagnetic field interact with each other, with the result that the current in each of them is redistributed such that the greater current density is concentrated in that part of the strand most remote from the interfering conductor. In each case, a reduced current rating results from the apparent increase of resistance.

Remember:

☑ Proximity effect is more pronounced in case of cable, large conductors and high frequencies.

Magnetic Flux Density

Biot-savart's law



- Magnetic flux at any point produced by a current carrying element

$$d\vec{B} = \frac{\mu}{4\pi}\frac{I\vec{dl}\times(\vec{r})}{r^3}$$

where, $dB \rightarrow$ Infinitesimal flux density at point P

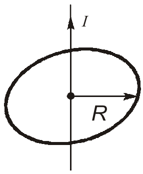
$I \rightarrow$ Current in element ; $dl \rightarrow$ Length of element

$\theta \rightarrow$ Angle between current direction and radius vector to P

$r \rightarrow$ Radius vector ; $\mu \rightarrow$ Permeability of medium

- Magnetic flux density B at any point to an infinite conductor.

$$B = \frac{\mu I}{2\pi R}$$



where, R = Radial distance of the point from the conductor.

Note:

The direction of the flux density is normal to the plane containing the conductor and radius vector R.

Amperes's law , $\oint H.dl = I_{\text{enclosed}}$

where, $H \rightarrow$ Magnetic field intensity
$I \rightarrow$ R.M.S. value of current enclosed by an amperian loop.

Relation Between Magnetic Flux Density and Magnetic Field Intensity

$$\boxed{B = \mu H\,,\ \ \mu = \mu_0\ \mu_r}$$

where, $\mu_0 \rightarrow 4\pi \times 10^{-7}$ H/m = Permeability of free space
$\mu_r \rightarrow$ Relative permeability of the medium
= 1 (for non magnetic material)

Inductance

Inductance of an inductor is the ratio of its total magnetic flux linkages to the current I through the inductor.

$$\boxed{L = \frac{N\Psi_m}{I} = \frac{\lambda}{I}} \text{ Henry}$$

where, $\Psi_m \rightarrow$ Magnetic flux linkages through a single turn
$N \rightarrow$ Total number of turns ; $\lambda \rightarrow$ Total magnetic flux linkages

Above formulae is valid for a medium in which the permeability is constant.

Remember:

The permeability of ferrous medium is not constant. For such cases the inductance is defined as the ratio of infinitesimal change in flux linkage to the infinitesimal change in current producing it

$$L = \frac{d\lambda}{dI} \text{ Henry}$$

- Flux linkages within the conductor : $\Psi_{\text{int}} = \frac{\mu I}{8\pi}$ Wb-T/m

  where, $\Psi_{\text{int}} \rightarrow$ Total internal flux linkages ; $I \rightarrow$ R.M.S. value of current.

$$\Psi_{\text{int}} = 0.5I \times 10^{-7} \text{ Wb-T/m}$$

- Inductance of the conductor, contributed by flux within the conductor:

$$\boxed{L_{\text{int}} = 0.5 \times 10^{-7} \text{ H/m}} \quad \text{as} \quad \boxed{L_{\text{int}} = \frac{\Psi_{\text{int}}}{I}}$$

- Flux linkages outside the conductor

$$\Psi_{12} = \frac{\mu I}{2\pi} \ln\left(\frac{D_2}{D_1}\right) \text{ Wb-T/m}$$

for μ_r = 1 : $\Psi_{12} = 2 \times 10^{-7} \ln\left(\frac{D_2}{D_1}\right)$ Wb-T/m

where $\Psi_{12} \rightarrow$ Total flux linkages between points 1 and 2

- Inductance of the conductor, contributed by flux between points 1 and 2:

$$\boxed{L_{12} = 2\times 10^{-7}\ln\left(\frac{D_2}{D_1}\right)\ \text{H/m}}$$

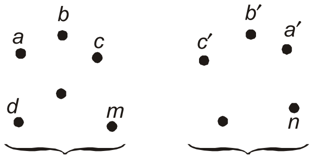
- Inductance of a single phase two wire line: $\boxed{L = 4\times 10^{-7}\ln\left(\frac{D}{r'}\right)}$ H/m

where, $D \rightarrow$ Distance between two solid conductors of same radii r

$r' \rightarrow$ Radius of fictitious conductor = 0.7788 r

Inductance of Composite Conductor Lines

Conductor M consists of m similar parallel sub-conductors and conductor N consists of n similar parallel sub-conductors.



(Single phase line having composite conductors)

If line current is I, then each strand of conductor M carries a current I/m and each strand of conductor N carries a current of $-I/n$ (the conductor N being the return conductor).

$$L_M = 2\times 10^{-7}\times \ln\frac{\left[(D_{aa'}D_{ab'}\ldots D_{an})(D_{ba'}D_{bb'}\ldots D_{bn})\ldots(D_{ma'}D_{mb'}\ldots D_{mn})\right]^{1/mn}}{\left[(D_{aa}\,D_{ab}\ldots D_{am})(D_{ba}\,D_{bb}\ldots D_{bm})\ldots(D_{ma}\,D_{mb}\ldots D_{mm})\right]^{1/m^2}}\ \text{H/m}$$

where, $L_M \rightarrow$ inductance of conductor M

$$\boxed{L = 2\times 10^{-7}\ln\left(\frac{\text{GMD}}{\text{GMR}}\right)}$$

Remember:

- GMD = mn^{th} root of the product of mn distances (known as the geometric mean distance between conductor M and conductor N and denoted by D_m).
- GMR = $(m^2)^{th}$ root of the product of m^2 distances these being the distances from each sub-conductor of conductor M to every other sub-conductor of conductor M (including D_{aa}, D_{bb}....D_{mm}).
- GMR = Geometric mean radius (denoted by D_s), which depends on radius of conductors and does not effected by unequal spacing of conductors.
- D_{aa} = 0.7788 times the radius of sub-conductor 'a'.

Inductance of 3-ϕ Line With Equivalent Spacing.

Assuming balanced currents, i.e., $(I_a + I_b + I_c = 0)$

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

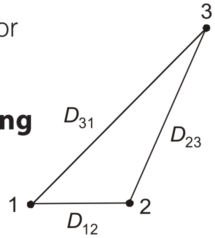
where, $L_a \rightarrow$ Inductance of phase

$D \rightarrow$ Distance between any two phases

$r' \rightarrow 0.7788r$ = Radius of fictitious conductor

$\rightarrow$ 0.7788 times the radius of conductor

$L_a \rightarrow L_b = L_c$ (Because of symmetry)

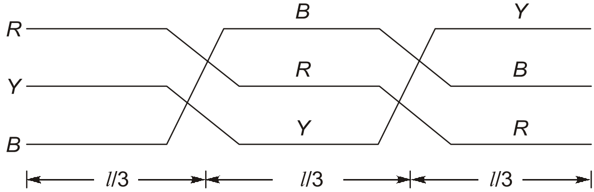


Inductance of 3-ϕ line with unsymmetrical spacing

In this case the lines are transposed.

Transposition of transmission line

- Whenever 3ϕ unsymmetrical line running parallel and neighbour to the communication line it cause interference in the communication line.
- In order to eliminate the communication interference transposition of line is recommended.
- Change the position of power conductor at regular interval with equidistance for a given line length, so that the position of power conductor is replaced by its successive phase conductor.



Advantages of Transposition

- Net resultant flux ϕ_r which link with communication line become zero.
- GMD/phase equal.
- L/phase equal.
- I/phase equal.
- Flux per phase equal.

Note:

☑ Transposition of transmission line is an old technique. The radio interference is eliminated by completely insulating any one of the phases.

Inductance of Phase-1

$$L_1 = 2\times 10^{-7}\ln\left(\frac{D_{eq}}{r'}\right)\ \text{H/m}$$

where, $L_1 \rightarrow$ inductance of phase 1

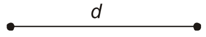
$D_{eq} \rightarrow \sqrt[3]{D_{12}D_{23}D_{31}}$ = Equivalent spacing

= Geometric mean of the distance of the line.

Inductance of Bundled Conductor Lines

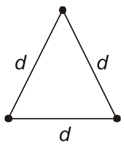
- *For a two conductor (duplex) arrangement*

$$D_s^b = \sqrt[4]{(D_s.d)^2} = \sqrt{D_s\cdot d}$$



- *For a three conductor (tripex) arrangement*

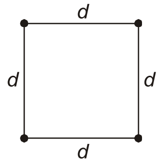
$$D_s^b = \sqrt[9]{(D_s\cdot d\cdot d)^3} = \sqrt[3]{D_s\cdot d^2}$$



- *For a four-conductor (quadruplex) arrangement*

$$D_s^b = \sqrt[16]{(D_s\cdot d\cdot d\cdot d\sqrt{2})^4}$$

$$= 1.09\times\sqrt[4]{D_s\cdot d^3}$$



where, D_s^b = Geometric mean radius of bundled conductor

D_s = Geometric mean radius of each sub-conductor of bundle

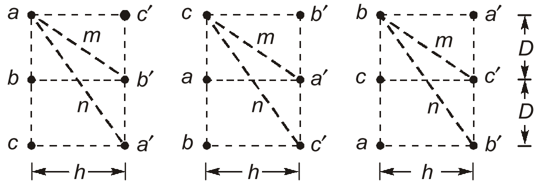
d = Spacing between the sub-conductors of a bundle

Remember:

☑ Inductance of bundled conductor line is less than the inductance of the line with one conductor per phase.

☑ GMD depends only on the distance between the conductors and is independent of radius of conductors.

Inductance of Double Circuit 3-ϕ Line



Section-I Section-II Section-III

Inductance per phase per metre length

$$L = 2\times 10^{-7}\ \ln\left[2^{1/6}\left(\frac{D}{r'}\right)^{1/6}\cdot\left(\frac{m}{n}\right)^{1/3}\right]\ \text{H/phase/m}$$

Mutual Inductance

Mutual inductance is defined as the flux linkages of one circuit due to the current in the second circuit per-ampere of current in the second circuit. If the current I_2 produces λ_{12} flux linkages with circuit 1. The mutual inductance is

$$\boxed{M_{12} = \frac{\lambda_{12}}{I_2}} \text{ Henry}$$

Electrical Field and Potential Difference

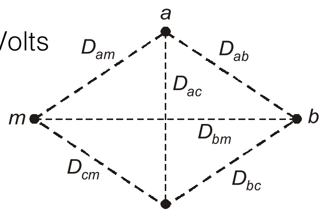
- The lines of electric flux originate on the positive charges on one conductor and terminate on the negative charges on the other conductor.
- If a long straight cylindrical conductor has a uniform charge throughout its length and is isolated from other charges.
- Electric field intensity E at any point, $E = \dfrac{q}{2\pi \in x}$ V/m

  where, $q \rightarrow$ Charge on conductor per unit length
  $\in \rightarrow$ Permittivity of the medium
  $x \rightarrow$ Distance from conductor to the point under consideration.
- The potential difference between two points

$$V_{xy} = \frac{q}{2\pi \in} \ln\left(\frac{D_y}{D_x}\right) \text{ Volts}$$

where, $D_x, D_y \rightarrow$ Distance of point x and y from charge q
$q \rightarrow$ Charge per unit length

- The potential difference between two conductor of an array of parallel conductors



(An array of *m* charged conductors)

$$V_{ab} = \frac{1}{2\pi \in}\left[q_a \ln\frac{D_{ab}}{r_a} + q_b \ln\frac{r_b}{D_{ba}} + q_c \ln\frac{D_{cb}}{D_{ca}} + \cdots + q_m \ln\frac{D_{mb}}{D_{ma}}\right]$$

Capacitance

Capacitance of Two Wire Line

$$\boxed{C_{ab} = \frac{\pi\varepsilon}{\ln\left(\dfrac{D}{r}\right)}} \text{ F/m}$$

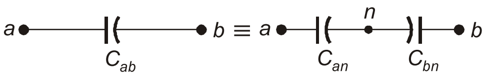
where, $C_{ab} \rightarrow$ Line to line capacitance
$q \rightarrow$ Charge per unit length; $r \rightarrow$ Radius of conductor a and b

If the conductor have different radii , $r = \sqrt{r_a \cdot r_b}$

where, $r_a, r_b \rightarrow$ Radius of conductor 'a' and conductor 'b' respectively.

Line to neutral capacitance

$$\boxed{C_{an} = C_{bn} = 2C_{ab}}$$



Charging Current

- The current caused by the alternate charging and discharging of the line due to alternating voltage is called **charging current** of the line.

Note:

☑ Charging current flows in a line even when the line is open circuited and affects the voltage drop, efficiency and power factor of the line.

Charging Current for 1-ϕ line

$$I_C = j\omega C_{an} V_{an} \text{ A/m / Phase}$$

where, $V_{an} \rightarrow$ Potential difference between conductor a and neutral

$\omega \rightarrow$ Frequency of alternating voltage

Capacitance of 3-ϕ line with equilateral spacing

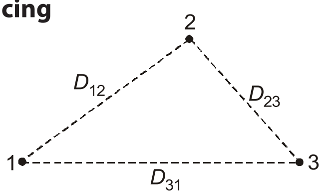
$$\boxed{C_n = \frac{0.02412}{\log\left(\frac{D}{r}\right)}} \ \mu\text{F/km} \quad \text{or} \quad \boxed{C_n = \frac{2\pi \in}{\ln\left(\frac{D}{r}\right)}}$$

where, $C_n \rightarrow$ Line to neutral capacitance ; $D \rightarrow$ Spacing between conductors ; $r \rightarrow$ Radius of each conductor

Charging current per phase, $I_C = j\omega C_n V_{an}$

Capacitance of 3-ϕ line with asymmetrical spacing

$$\boxed{C_n = \frac{2\pi \in}{\ln\left(\frac{D_{eq}}{r}\right)}} \ \mu\text{F/km}$$



where, $\boxed{D_{eq} = \sqrt[3]{D_{12} D_{23} D_{31}}}$

Capacitance of bundled conductor lines

$$\boxed{C_n = \frac{2\pi \in}{\ln\left(\frac{D_{eq}}{D_{sc}^b}\right)}} \ \mu\text{F/km}$$

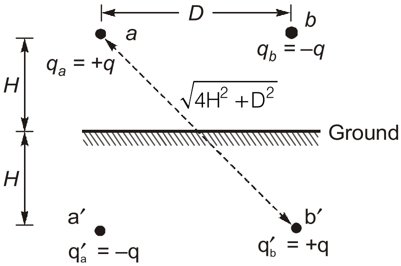
Self GMD of Bundle Conductors

- For a two conductor bundle, $D_{sc}^b = \sqrt{rd}$
- For a three conductor bundle, $D_{sc}^b = \sqrt[9]{(r \times d \times d)^3} = \sqrt[3]{rd^2}$
- For a four conductor bundle, $D_{sc}^b = \sqrt[16]{(r \times d \times d \times \sqrt{2}d)^4} = 1.09\sqrt[4]{rd^3}$

Effect of Ground on Line Capacitance (Method of Images)

The presence of ground alters the electric field of a line and hence affect the line capacitance.

For 1-ϕ line:

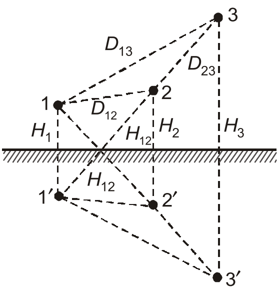


$$C_{ab} = \frac{\pi\varepsilon}{\ln\left(\dfrac{D}{r\left(1+\dfrac{D^2}{4H^2}\right)^{0.5}}\right)} \text{ F/m}$$

where, $H \rightarrow$ Height of conductor from ground

$$C_{an} = 2C_{ab} = \frac{2\pi\varepsilon}{\ln\left(\dfrac{D}{r'}\right)} \text{ F/m} \; ; \qquad r' = r\sqrt{1+\left(\frac{D}{2H}\right)^2}$$

For 3-ϕ line



Conductors of a 3-phase line with image charges

$$C_n = \frac{2\pi\varepsilon}{\ln\left(\dfrac{D_{eq}}{r}\right) - \ln\left[\dfrac{\sqrt[3]{H_{12}H_{23}H_{31}}}{\sqrt[3]{H_1H_2H_3}}\right]}$$

where, H_1, H_2, H_3, and H_{12}, H_{23}, H_{31} are shown in figure.
C_n is in μF/km.

Note:

☑ Presence of ground increases the line capacitance by small amount.