MALLA REDDY ENGINEERING COLLEGE
Affiliated to Jawaharlal Nehru Technological University Hyderabad, Hyderabad
Maisammaguda, Dhulapaly, (Post Via Kompally), Secunderabad, Telangana State – 500100

Department of Electrical and Electronics Engineering

LECTURE NOTES

Subject	**EHVAC Transmission**
Subject Code	**70231**
Year / Semester	**IV / II**
Department	**EEE**
Regulation	**MR 17**

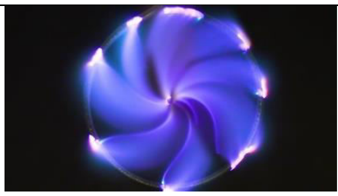
Prepared by,

Dr.T.Rajesh

Professor

Department of EEE





Extra High Voltage Transmission AC Transmission

*Syllabus

2017-18 Onwards (MR-17)	Malla Reddy Engineering College (Autonomous)	B.Tech. VIII Semester		
Code: 70231	EHVAC TRANSMISSION (Professional Elective-V)	L	T	P
Credits: 3		3	-	-

Prerequisites: Power Generation and Distribution, Power Transmission Systems.

Course Objectives: This course deals with the EHVAC transmission and modes of propagation. It also elaborates corona effects, voltage control and travelling wave theory.

MODULE I: Introduction 9 Periods

Necessity of EHV AC transmission – Advantages and problems – Power handling capacity and line losses- Mechanical considerations – Resistance of conductors – Properties of bundled conductors – Bundle spacing and bundle radius - Examples.

Line and ground reactive parameters:
Line inductance and capacitances – sequence inductances and capacitances – modes of propagation – ground return – Examples.

MODULE II: Voltage Gradients of Conductors 10 Periods

Electrostatics – Field of sphere gap – Field of line changes and properties. Charge-potential relations for multi conductors – Surface voltage gradient on conductors – Distribution of voltage gradient on sub-conductors of bundle – Examples.

MODULE III: Corona Effects 10 Periods

A: Power loss and audible noise (AN) – Corona loss formulae – Charge voltage diagram – Generation, characteristics - Limits and measurements of AN – Relation between 1-phase and 3-phase AN levels – Examples.

B: Radio interference (RI) - Corona pulses generation, Properties, Limits – Frequency spectrum

– Modes of propagation – Excitation function – Measurement of RI, RIV and excitation functions – Examples.

MODULE IV: Electro Static Field and Traveling Wave Theory 10 Periods

Electrostatic field: Calculation of electrostatic field of EHVAC lines – Effect on humans, animals and plants – Electrostatic induction in unenergised circuit of double circuit line – Electromagnetic interference - Examples.

Traveling wave expression and solution - Source of excitation - Terminal conditions -Open circuited and short circuited end - Reflection and refraction coefficients - Lumped parameters of distributed lines - Generalized constants - No load voltage conditions and charging current.

MODULE V: Voltage Control 9 Periods

Power circle diagram and its use – Voltage control using synchronous condensers – Cascade connection of shunt and series compensation – Sub synchronous resonance in series capacitor – Compensated lines – Static VAR compensating system.

TEXT BOOKS

1. R.D. Begamudre, **"Extra High Voltage AC Transmission Engineering"**, New Academic Science Ltd., 4th Edition, 2011.
2. S. Rao **"EHVAC and HVDC Transmission & Distribution Engineering"**, Khanna publishers, 2008.

REFERENCES

1. Padiyar.K.R, **"FACTS Controllers in Power Transmission and Distribution"**, New Age International Publishers, 2007.
2. Arrillaga.J **"High Voltage Direct Current Transmission"**, 2nd Edition (London), Peter Peregrines, IEE, 1998.
3. Hingorani H G and Gyugyi. L, **"Understanding FACTS: Concepts and Technology of Flexible AC Transmission Systems",** New York, IEEE Press, 2000.
4. K.R. Padiyar, **"HVDC Power Transmission Systems"**, New Age International (p) Ltd. 2nd Revised Edition, 2012.
5. P. Sarma Maruvada, **"Corona Performance of High-Voltage Transmission Lines"**, Research Studies Press, 2000.

E - RESOURCES

1. http://www.egr.unlv.edu/~eebag/TRANSMISSION%20LINES.pdf
2. http://www.radio-electronics.com/
3. https://electricalnotes.wordpress.com/2011/03/23/what-is-corona-effect/

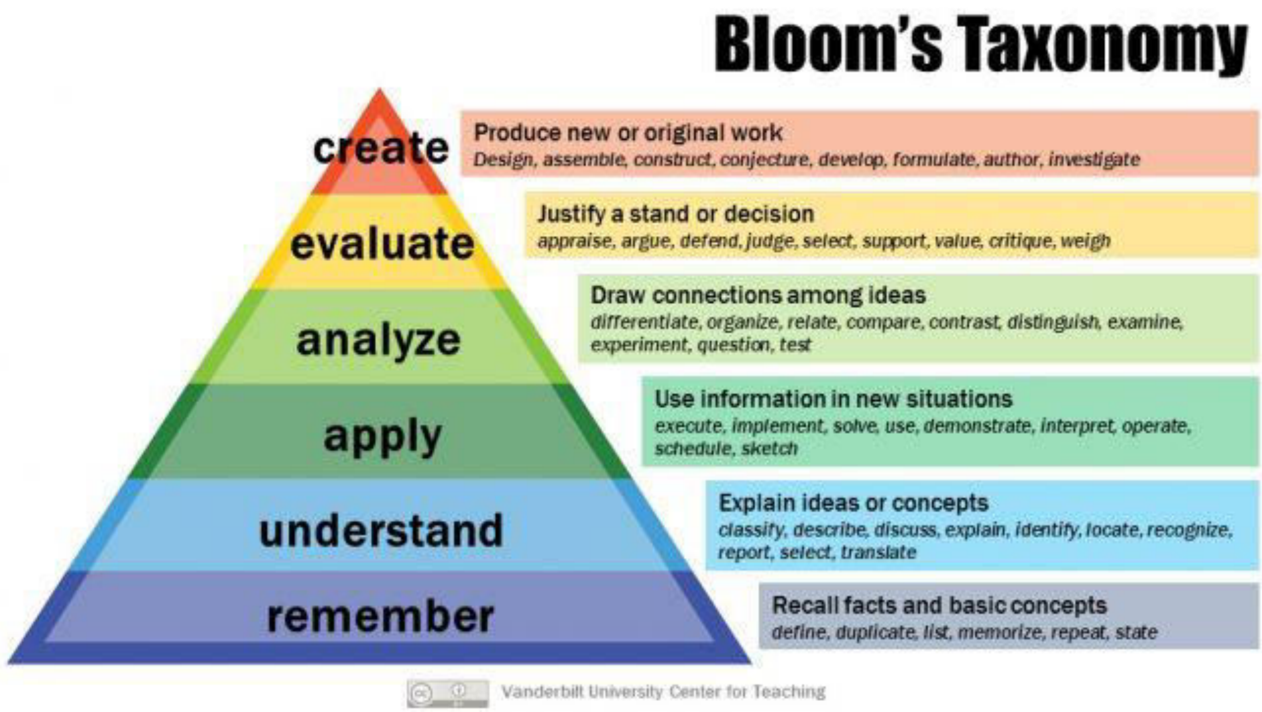
Course Outcomes

At the end of the course, students will be able to

1. Understand the necessity of EHV AC Transmission.
2. Describe the voltage gradients of various conductors.
3. Analyze the power loss & audible noise due to corona.
4. Examine the electrostatic field in EHV AC lines and travelling waves.
5. Evaluate the voltage control by various compensators.

Bloom’s Revised Taxonomy

There are six levels of cognitive learning according to the revised version of Bloom’s Taxonomy. Each level is conceptually different. The six levels are remembering, understanding, applying, analyzing, evaluating, and creating.



Cognitive level / K-level	Meaning
K1 (Remember)	Remember or recognize a term or a concept.
K2 (Understand)	Select an explanation for a statement related to the question topic.
K3 (Apply)	Select the correct application of a concept or technique and apply it to a given context.
K4 (Analyze)	Separate information related to a procedure or technique into its constituent parts for better understanding and distinguish between facts and inferences.
K5 (Evaluate) (Expert Level only)	Make judgements based on criteria and standards. Detect inconsistencies or fallacies within a process or product, determine whether a process or product has internal consistency, and detect the effectiveness of a procedure as it is being implemented.
K6 (Create) (Expert Level only)	Put elements together to form a coherent or functional whole. A typical application is to reorganize elements into a new pattern or structure, devise a procedure for accomplishing some task, or invent a product.

MALLA REDDY ENGINEERING COLLEGE (AUTONOMOUS)

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

VISION & MISSION

VISION OF THE INSTITUTE
To be a premier center of professional education and research, offering quality programs in a socio-economic and ethical ambience.
MISSION OF THE INSTITUTE
• *To impart knowledge of advanced technologies using state-of-the-art infrastructural facilities.* • *To inculcate innovation and best practices in education, training and research.* • *To meet changing socio-economic needs in an ethical ambiance.*
VISION OF THE DEPARTMENT
To become a reputed centre for imparting quality education and research in the field of Electrical and Electronics Engineering with human values, ethics and social responsibility.
MISSION OF THE DEPARTMENT
• To impart quality education and research to undergraduate and postgraduate students in Electrical and Electronics Engineering. • To produce professionally competent and ethically committed engineers to meet changing socio-economic needs. • To impart knowledge of advanced technologies for continual improvement in teaching, learning and research.

MALLA REDDY ENGINEERING COLLEGE (AUTONOMOUS)
DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

COURSE PLAN

1	**Programme /Branch** (or Specialization)	:	B.Tech , EEE
2	**Class**	:	IV Year , II Semester
3	**Course Code**	:	70231
4	**Course Title**	:	EHVAC Transmission
5	**Course Type & Hours**	:	Theory , 48 Hrs.
6	**Course Category & Credits**	:	Professional Elective & 3 Credits
7	**Academic Year**	:	2020-21
8	**Regulation**	:	MR17
9	**Staff In charge**	:	Dr.T.Rajesh, Professor , Department of EEE, E-mail: rajeshpradha@gmail.com
11	**Prerequisites**	:	Electromagnetic Fields, Power Systems, Transmission and Distribution

12 **Course Overview**

Modern power transmission is utilizing voltages between 345 kV and 1150 kV, A.C. Distances of transmission line, bulk powers handled, power loss minimization and economic considerations have increased to such an extent that extra high voltages and ultra-high voltages (EHV and UHV) are necessary. The problems encountered with such high voltage transmission lines exposed are electrostatic fields near the lines, audible noise, radio interference, corona losses, carrier and TV interference, high voltage gradients, heavy bundled conductors, control of voltages at power frequency using shunt reactors, switched capacitors, overvoltage's caused by lightning and switching operations, long air gaps with weak insulating properties for switching surges, ground-return effects, and many more.

This course covers all topics that are considered essential for understanding the operation and design of EHV ac overhead lines. Theoretical analyses of all problems combined with practical application are dealt in this course

13 **Course Objective**

This course enables the students to:

i. Provide In-depth understanding of different aspects of Extra High Voltage AC transmission system design and Analysis.
ii. Calculate the value of Line Inductance and Capacitance of EHVAC transmission system.
iii. Understand the concept of Voltage gradients of conductors.
iv. Develop the empirical formula to determine the Corona loss occurring in EHV AC transmission Line.
v. Determine the interference caused by Corona and to measure its magnitude.
vi. Derive the expression and possible solution for travelling wave and its source of excitation.
vii. Understand various line compensating system.

14 **Text Book**

T1. R. D. Begamudre ,–EHVAC Transmission Engineering‖, New Age International (p) Ltd. 3rd Edition.

T2. K.R. Padiyar, –HVDC Power Transmission Systems‖ New Age International (p) Ltd.2nd revised Edition, 2012.

15 **Reference Book**

R1. S. Rao –EHVAC and HVDC Transmission Engg. Practice‖ Khanna publishers.

R2. Arrillaga.J – High Voltage Direct Current Transmission‖ 2nd Edition (London) peter Peregrines, IEE, 1998.

R3. Padiyar.K.R, – FACTS Controllers in Power Transmission and Distribution‖ New Age Int. Publishers, 2007.

R4. Hingorani H G and Gyugyi. L – Understanding FACTS-Concepts and Technology of Flexible AC Transmission Systems‖ New York, IEEE Press, 2000.

16 **E-Learning Resources**

a) https://www.brainkart.com/article/EHVAC-and-HVDC-Transmission-System_12351/
b) http://alignment.hep.brandeis.edu/Lab/XLine/XLine.html
c) https://www.electronics-tutorials.ws/accircuits/reactive-power.html
d) https://www.thierry-corp.com/plasma/knowledge/corona-discharges/
e) https://electricalnotes.wordpress.com/2011/03/23/what-is-corona-effect/
f) https://electricalnotes.wordpress.com/2012/02/17/effects-of-high-voltage-transmission-lines-on-humans-and-plants/

17 **Course Outcomes**

At the end of the course, students will be able to

1. **Evaluate:** ***Determine*** the resistance, reactive ground parameters and power loss of the line with reference to EHVAC transmission.
2. **Evaluate:** Given the specifications of conductor and electrostatic fields, ***determine*** the voltage gradients for single and multi-conductor arrangements.
3. **Apply:** ***Calculate*** the Corona power loss, Audible Noise and Radio Interference levels for single phase and three phase EHV lines.
4. **Analyze:** ***Calculate*** the electrostatic field of double circuit EHV AC lines and analyze the effect of high electrostatic fields on humans, plants, animals and ***Analyze*** the travelling wave expressions and solutions.
5. **Analyze:** **Analyze** the different reactive power compensation schemes like static VAR compensator, synchronous condensers, shunt and series compensators to control the voltage of EHVAC transmission system.

18 **Program Outcome**

PO 1	**Engineering knowledge**: Apply the knowledge of mathematics, science, engineering fundamentals, and an engineering specialization to the solution of complex engineering problems.
PO 2	**Problem analysis**: Identify, formulate, review research literature and analyze complex engineering problems reaching substantiated conclusions using first principles of mathematics, natural sciences, and engineering sciences.

PO 3	**Design/development of solutions**: Design solutions for complex engineering problems and design system components or processes that meet the specified needs with appropriate consideration for the public health and safety, and the cultural, societal, and environmental considerations.
PO 4	**Conduct investigations of complex problems**: Use research-based knowledge and research methods including design of experiments, analysis and interpretation of data, and synthesis of the information to provide valid conclusions.
PO 5	**Modern tool usage**: Create, select, and apply appropriate techniques, resources, and modern engineering and IT tools including prediction and modeling to complex engineering activities with an understanding of the limitations.
PO 6	**The engineer and society**: Apply reasoning informed by the contextual knowledge to assess societal, health, safety, legal and cultural issues and the consequent responsibilities relevant to the professional engineering practice.
PO 7	**Environment and sustainability**: Understand the impact of the professional engineering solutions in societal and environmental contexts, and demonstrate the knowledge of, and need for sustainable development.
PO 8	**Ethics**: Apply ethical principles and commit to professional ethics and responsibilities and norms of the engineering practice.
PO 9	**Individual and team work**: Function effectively as an individual and as a member or leader in diverse teams, and in multidisciplinary settings.
PO 10	**Communication**: Communicate effectively on complex engineering activities with the engineering community and with society at large, such as, being able to comprehend and write effective reports and design documentation, make effective presentations, and give and receive clear instructions.
PO 11	**Project management and finance**: Demonstrate knowledge and understanding of the engineering and management principles and apply these to one's own work, as a member and leader in a team, to manage projects and in multidisciplinary environments.
PO 12	**Life-long learning**: Recognize the need for, and have the preparation and ability to engage in independent and life-long learning in the broadest context of technological change.

19 **Programme Specific Outcomes (PSOs)**

PSO1	Apply fundamental knowledge to identify, formulate, design and investigate various problems of electrical and electronic circuits, power electronics, power systems and renewable energy systems for specific requirements.
PSO2	Demonstrate proficiency in use of modern software tools & hardware to engage in life-long learning and to successfully adapt in multi-disciplinary environments.
PSO3	Solve ethically and professionally various Electrical Engineering problems in societal and environmental context and communicate effectively.

20. **CO-PO Mapping**

(3/2/1 indicates strength of correlation)

COs	Program Outcomes (Pos)												PSOs		
	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3
1	1	2	-	-	-	-	-	-	-	-	-	-	2	-	-
2	1	2	-	-	-	-	-	-	-	-	-	-	2	-	-
3	1	3	-	-	1	1	1	-	-	-	-	-	1	1	1
4	1	3	-	1	1	2	2	-	-	-	-	-	1	-	2
5	1	3	-	1	-	1	-	-	-	-	-	1	1	-	-

3-Strong, 2-Medium, 1-Weak

21 . Course Outline

UNIT-I LINE AND GROUND REACTIVE PARAMETERS

Hour	Description of Portion to be Covered	Relevant CO Nos	Highest Cognitive Level	Delivery Method	Reference Materials
1	Introduction & Necessity of EHV AC transmission, Advantages	CO1	K1	Lecture	T1,T2
2	Power handling capacity and Line losses	CO1	K3	Lecture	T1,T2
3	Mechanical considerations of transmission line	CO1	K2	Lecture	T1
4	Resistance of conductors, Properties of bundled conductors, Bundle spacing & Bundle radius	CO1	K3	Lecture	T1,R1
5	Problems	CO1	K5	Lecture	T1
6,7	Line inductance and capacitances	CO1	K3	Lecture	T1
8	Sequence inductances and capacitances	CO1	K3	Lecture	T1
9,10	Modes of propagation, Ground return	CO1	K4	Lecture	T1

UNIT-II : VOLTAGE GRADIENTS OF CONDUCTORS

Hour	Description of Portion to be Covered	Relevant CO Nos	Highest Cognitive Level	Delivery Method	Reference Materials
11	Electrostatics Introduction	CO2	K2	Lecture	T1,T2
12	Field of sphere gap	CO2	K3	Lecture	T1
13	Field of line changes and properties	CO2	K3	Lecture	T1
14	Problem Solving	CO2	K5	Lecture	T1
15,16	Charge & potential relations for multi- conductors	CO2	K4	Lecture	T1
17,18	Surface voltage gradient on conductors	CO2	K4	Lecture	T1
19	Problem Solving	CO2	K5	Lecture	T1
20	Distribution of voltage gradient on sub-conductors of bundle	CO2	K3	Lecture	T1
21	Problem Solving	CO2	K5	Lecture	T1

UNIT – III : CORONA EFFECTS – I

Hour	Description of Portion to be Covered	Relevant CO Nos	Highest Cognitive Level	Delivery Method	Reference Materials
22	Power loss and audible noise (AN)	CO3	K2	Lecture	T1
23	Corona loss formulae & charge voltage diagram	CO3	K2	Lecture	T1
24,25	Generation, characteristics, limits and measurements of AN	CO3	K2	Lecture	T1
26	Relation between 1-phase and 3-phase AN level.	CO3	K4	Lecture	T1
27	Problem Solving	CO3	K5	Lecture	T1
28	Radio interference (RI)	CO3	K2	Lecture	T1
29	Corona pulses generation, properties & limits	CO3	K2	Lecture	T1
30	Frequency spectrum & modes of propagation	CO3	K3	Lecture	T1
31,32	Excitation function & measurement of RI, RIV and excitation functions	CO3	K3	Lecture	T1

UNIT – IV: ELECTRO STATIC FIELD AND TRAVELING WAVE THEORY

Hour	Description of Portion to be Covered	Relevant CO Nos	Highest Cognitive Level	Delivery Method	Reference Materials
33	Electrostatic field	CO4	K2	Lecture	T1
34	Calculation of electrostatic field of EHV/AC lines	CO4	K5	Lecture	T1
35	Effect on humans, animals and plants	CO4	K2	Lecture	T1,R2
36,37	Electrostatic induction in unenergized circuit of double-circuit line	CO4	K3	Lecture	T1
38	Electromagnetic interference	CO4	K2	Lecture	T1
39	Traveling wave expression and solution	CO4	K3	Lecture	T1
40	Source of excitation & terminal conditions	CO4	K2	Lecture	T1
41	Open circuited and short-circuited end Reflection and refraction coefficients	CO4	K3	Lecture	T1
42	Lumped parameters of distributed lines & generalized constants	CO4	K3	Lecture	T1
43	No load voltage conditions and charging current.	CO4	K4	Lecture	T1

UNIT – V : VOLTAGE CONTROL

Hour	Description of Portion to be Covered	Relevant CO Nos	Highest Cognitive Level	Delivery Method	Reference Materials
44	Long transmission line Model	CO5	K4	Lecture	T2
45	ABCD Constants	CO5	K5	Lecture	T2
46	Power circle diagram and its use	CO5	K3	Lecture	T2
47	Voltage control using synchronous condensers	CO5	K2	Lecture	R3,R4
48	Cascade connection of shunt and series compensation	CO5	K2	Lecture	R3,R4
49,50	Sub synchronous resonance in series capacitor & compensated lines	CO5	K2	Lecture	R3,R4
51,52	Static VAR compensating system	CO5	K2	Lecture	T2,R3,R4

TOTAL NO. OF HRS. PLANNED: 52

22. Content Beyond Syllabus

a) Introduction to Grid Management (K1)
b) Protection against Over Voltages in HVAC Transmission System (K1)

23. ASSIGNMENT

Assignment No. 1

a) Explain the effect of resistance of the conductor in EHVAC transmission system. **(K2)**
b) Explain in detail the inductance and capacitance of ground return and derive necessary expressions. **(K2)**
c) Explain field of sphere gap with their properties**.(K2)**
d) A point charge Q = 10^{-6} coulomb (1 μC) is kept on the surface of a conducting sphere of radius r = 1 cm, which can be considered as a point charge located at the centre of the sphere. Evaluate the field strength and potential at a distance of 0.5 cm from the surface of the sphere. Also find the capacitance of the sphere, €r=1 **(K5)**
e) Categorize the different expressions for corona loss based on voltage and voltage gradient**.(K4)**

Assignment No. 2

a) Explain in detail the different AN measuring meters with neat diagram. **(K2)**
b) (i) Obtain electrostatic fields of single circuit 3-phase EHV line. **(K3)**
(ii) Describe the difference between primary shock current and secondary shock current.**(K2)**
c) Discuss the effect of electrostatic field on (i) Human beings (ii) Animals (iii) Plant life, (iv) vehicles, (v) Fences **(K6)**
d) Explain in-detail about power circle diagram and its use. **(K2)**
e) Explain in-detail about voltage control using synchronous condensers **(K2)**

Faculty **Course Coordinator** **HOD**

EHV AC Transmission.

Introduction:

The generation and consumption of Electrical energy has been increasing at a tremendous rate throughout the world during the past many decades due to the increase in demand. The increasing need of transmitting power in greater amounts led to a continuous increase in the transmission voltage.

Therefore high voltage tr. lines are used to transmit electric power over long distances. Generally these conductors are made up of copper and/or aluminum.

Let. P → Power to be transmitted
r → Resistance of the conductor
I → Current flowing thro' tr. line.

$$\therefore P_{Loss} = I^2 \cdot r = \left(\frac{P}{V}\right)^2 \cdot r.$$

'P and r' are fixed, less power will be lost if high voltages are used.

Voltage Levels.

a) < 600 V → Low voltage.
b) 600 V to 69 kV → Medium Voltage.
c) 69 kV to 300 kV → High Voltage.
d) 300 kV to 765 kV → EHV
e) > 765 kV → UHV.
↳ India (Raichur to Sholapur).

Necessity of Extra High Voltage (EHV) Transmission | Electricity

Modern trend is to use extra high voltage (EHV) and ultra-high voltage (UHV) for transmission of huge blocks of power over long distances.

The reasons for adopting of EHV/UHV range for transmission purposes are given below:

1. Reduction of Electrical Losses, Increase in Transmission Efficiency, Improvement of Voltage Regulation and Reduction in Conductor Material Requirement:

For transmission of given amount of power over a given distance through the conductors of a given material and at a given power factor as the transmission voltage increases,

(a) Reduction in the current.

Power transmitted $P = \sqrt{3} V_L I_L \cos\phi$.

where,

V → Terminal Voltage

I → Load Current.

$\cos\phi$ → Load Power factor.

$$\therefore I_L = \frac{P}{\sqrt{3} V_L \cos\phi}$$

From the above equation it is inferred that, for constant 'P' and $\cos\phi$, the load current is inversely proportional to the transmission Voltage.

If increase in transmission Voltage, load current gets reduced. As current gets reduced, size of conductor required also reduces for transmitting same amount of power.

(b) Line losses are reduced since line losses are inversely proportional to the transmission voltage.

Power Loss is given by $P_L = 3 I^2 R$.

$$P_L = 3 \cdot \left(\frac{P}{\sqrt{3} V \cos\phi}\right)^2 \cdot R = \frac{P^2 R}{V^2 \cos^2\phi}$$

From the above equation it can be seen that Power loss in a line is inversely Proportional to the square of tr. Voltage.

∴ If $V \uparrow^{es}$ $P_{Loss} \downarrow^{es}$.

(c) Transmission efficiency increases because of reduction in line losses.

$$\text{Transmission Efficiency} = \frac{\text{Output Power}}{\text{Input Power}} \times 100$$

$$= \frac{(\text{Input Power} - \text{Losses})}{\text{Input power}} \times 100$$

$$= \left(1 - \frac{P_{Losses}}{\text{I/p. Power}}\right) \times 100$$

∴ $V \uparrow^{es}$, $I \downarrow^{es}$. so I^2R Losses $\downarrow^{es}$.

η Transmission $\uparrow^{es}$.

(d) Voltage regulation is improved because of reduction of percentage line drop.

and

The voltage drop in tr. Line $= 3 I R$.

when $V\uparrow$ $I\downarrow$, If $V_{drop} \downarrow$. $V_S \simeq V_R$.

∴ Voltage Regulation improved.

$\therefore$ Voltage Regulation $= \dfrac{\text{Voltage Drop}}{\text{Sending Voltage}} \times 100.$

(e) Lesser conductor material is required being inversely proportional to the square of transmission voltage.

W.k.t, $P_{Loss} = 3I^2R = \dfrac{P^2 R}{V^2 \cos^2\phi}$

But $R = \dfrac{\rho l}{a}$, $P_L = \dfrac{P^2}{V^2\cos^2\phi} \cdot \dfrac{\rho l}{a}$

$\therefore a = \dfrac{P^2 \rho \times l}{P_L \cdot V^2 \cdot \cos^2\phi}$

Volume of Conductor Material required } = 3 × area of cond. × length of line

$= 3 \times a \times l.$

$= 3 \times \dfrac{P^2 \rho l}{P_L V^2 \cos^2\phi} \times l$

$\therefore$ Volume $= \dfrac{3P^2 \rho l^2}{P_L V^2 \cos^2\phi}$

Volume of Conductor $\propto \dfrac{1}{V^2}$.

$\therefore$ V ↑es Voluеme of Conductor ↓es . Weight ↓es.

2. Economic considerations have led to the construction of power stations of large capacity and so need of transfer of bulk power over long distances arose. Transmission of bulk power from generating stations to the load centres is technically and economically feasible only at voltages in the EHV/UHV range.

3. Generating stations (Steam-, hydro- and nuclear-power stations) are located in remote areas (far away from load centres) because of the reasons of economy, feasibility and from the point of view of safety and environmental conditions. EHV transmission is, therefore, inevitable for transmission of huge blocks of power over long distances from these power plants to load centres.

4. Flexibility for Future System Growth:
There is flexibility of future system growth.

5. Increase in Transmission Capacity of the Line:

Power transferred is expressed as:

$$P = \frac{V_S \cdot V_R}{X} \sin \delta \qquad ...(13.1)$$

where V_S and V_R are the two terminal voltages, δ is the load angle and X is the line reactance.

Thus the power transmission capacity of a transmission line increases with the increase in transmission voltage. No doubt the cost of transmission line and terminal equipment also increases with the increase in the transmission voltage but in general these costs are proportional to the transmission voltage rather than the square of the transmission voltage. Moreover, there is also a saving in cost due to reduction in energy losses occurring in transmission lines. As a consequence, the total cost of transmission decreases with the increase in transmission voltage, as depicted in Fig. 1.

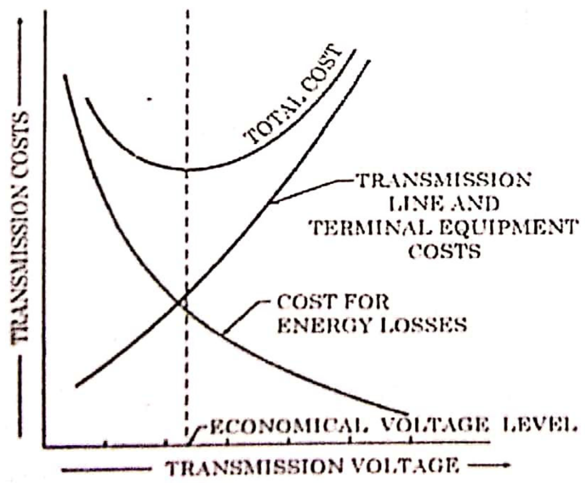


Fig. 13.1

6. Possibility of Interconnections of Power Systems:

It is practically not possible to have interconnections of two or more power systems, which is necessary to achieve sharing of installed reserves and for development of integrated systems and grids, without EHV transmission.

7. Increase of Surge Impedance Loading: (Max. Loading capacity)

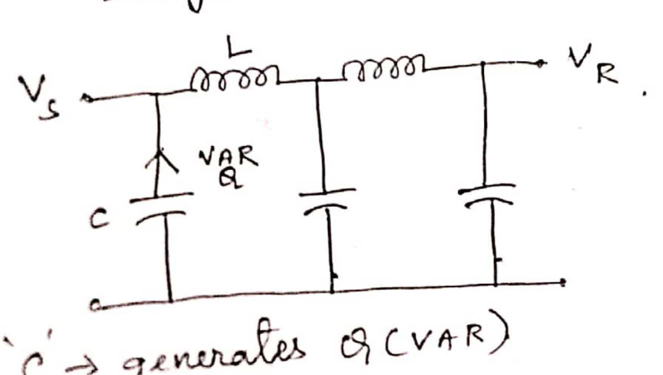
Load carrying capability of a line is usually expressed in terms of "surge impedance loading" (SIL). Surge impedance loading (SIL) is the power that a line carries when each phase is terminated by a load equal to the surge impedance of the line.

For a transmission line, the surge impedance is given as $Z_S = \sqrt{L/C}$ where L and C are respectively the series inductance and shunt capacitance per unit length. The surge impedance loading (SIL), for a transmission line is given as $3V^2/Z_S$ where V is the line-to-neutral voltage.

It is evident that SIL varies as the square of the operating voltage, and, therefore, with the increase in voltage level, SIL itself increases. Thus power transfer capability of the line increases with the increase in voltage level.

The surge impedance of a line can be determined from its conductor configuration. The approximate values of surge impedances for lines with single, double, triple and quadruple conductors are 400, 300, 280 and 260 ohms respectively.

Long tr. Line > 250 km.



'C' → generates Q (VAR)

L → Consumes Q (VAR). when Pure 'R' is connected as Load.

∴ Cap. VAR = Inductive VAR

$$\frac{V^2}{X_C} = I^2 X_L$$

$$\frac{V}{I} = \sqrt{X_C \cdot X_L} \quad \left[X_C = \frac{1}{2\pi f C},\; X_L = 2\pi f L \right]$$

$$\frac{V}{I} = \sqrt{\frac{L}{C}} = Z_S \rightarrow \text{Surge Impedance.}$$

Z_S → chs. impedance of a Loss less line.
↓
(~~VAr MW~~)

SIL → Power delived by the the Line to pure resistive load which is equal in value with Z_S.
↓
(W or MW)

$$SIL = \sqrt{3}\, V_R I_R \cos\phi \quad (\cos\phi \rightarrow 1)$$

$$= \sqrt{3}\, V_R \left(\frac{V_R}{\sqrt{3} Z_S}\right) = \frac{|V_R|^2}{Z_S}$$

For lossless line $V_S = V_R$. (Flat 'V' Profile)

∴ If the line is terminated as Surge Impedance, there are No losses.

∴ V ↑ SIL ↑ ⇒ Power Transfer capacity ↑es.

8. Reduction in Right-Of-Way:

In some countries 'rights-of-way' are paid for at a rate proportional to the total width of the transmission lines. Even in countries where right-of-way is not directly paid, there are usually strong pressures from the public towards fewer and fewer transmission lines.

With the passage of time right-of-way becomes either more costly or difficult to obtain and therefore it is becoming necessary to have fewer transmission lines operating at EHV/UHV. The worth noting point here is that with the increase in operating voltage, number of circuits and requirement of land is reduced considerably.

Advantages of High Voltage Transmission

- The main advantage of high voltage transmission is that large amounts of electricity can be transmitted at relatively low currents. This is why high voltage transmission is used in the first place! High currents require thicker cables since most energy is wasted as heat. Not only is this inefficient, but it's expensive; the cable used on transmission lines isn't cheap, so the smaller the diameter of the cable, the less expensive it is. By using higher voltages, less current is needed, and thus smaller conductors can be used, which economically makes sense.
- Size and volume of conductor required also reduces for transmitting the same amount of power.
- Voltage drop in line ($3I^2R$) reduces and hence voltage regulation of the line is improved.
- Line losses ($3I^2R$) gets reduced which results in the increase in transmission line efficiency.
- Volume of the conductor material decreases
- Power handling capacity of the line increases as we increase the transmission voltage. It is proportional to the square of operating voltage.

- The cost related to tower, insulators and different types of equipment are proportional to voltage rather than the square of voltage. Thus the net capital cost of transmission line decreases as voltage increases. Therefore, a large power can be transmitted with high voltage transmission lines economically.
- The total line installation cost of per MW per km decreases considerably.
- Since, $SIL = \frac{(V^2)}{Z_0}$, SIL itself increases which indicates the power transfer increase.
- The interconnection of power systems on a large scale is possible.
- Reduction in Right of Way.
- No. of circuits and land requirement reduces as voltage increases.
- The operation of EHV AC system is simple, reliable and can be adopted easily.
- The lines can be easily tapped and extended.

Disadvantages of High Voltage Transmission

The major problems in this system are as under.

- Corona loss is a big problem at higher voltages. This may further increase in bad weather conditions.
- It increases radio interference.
- The height of towers and insulation increases with increase in transmission voltage.
- The cost of different types of equipment and switchgear required for transmission increases with increase in transmission voltage.
- The high voltage lines produce electrostatic effects which are injurious to human beings and animals.
- While high voltage alone isn't dangerous, transmission lines are very dangerous, considering the amount of electricity flowing through them. The high voltage allows the electricity to energize the air surrounding the

conductor and causes it to "jump", so even coming close to them is extremely risky. This is why it is never a good idea to approach a downed power line, especially if it's energized. Because high voltage enables the electricity to arc through air, transmission lines must be properly insulated to prevent the electricity from "leaking" onto their pylons.

- Another problem with high voltage transmission is the need for transformers to step voltage up and down as needed. Transformers are expensive, oil-filled, and can weigh more than 300–400 tons. Transformers, like conductors, lose some energy as heat. The oil inside them usually prevents them from overheating, but sometimes cooling fins and/or external fans are needed to maintain the transformer's temperature. To prevent them from becoming overloaded, both the primary (incoming) and secondary (outgoing) lines must be protected by circuit breakers. These also protect the transformers from faults and damaging surges should the line voltage exceed the transformer's insulation rating voltage. All in all, this apparatus is expensive and, like anything else, requires regular maintenance.

Power Handling Capacity:

Power handling capacity (transfer capability) of EHV transmission line solely depends on the current carrying capacity of conductor used in EHV line.

Transfer Capability refers to the amount of electric power that can be passed through a transmission network from one place to another.

So, for calculate the power handling capacity of EHV line, first find out current carrying capacity of that conductor. Current carrying capacity of OH conductor in EHV line depends upon following;

1. Cross-sectional area of that conductor
2. Conductor Material
3. Surrounding temperature (Ambient temp.) of conductor used in EHV line
4. Age of the conductor

Suppose, we have one EHV line of 800kV with power factor of 0.85 lagging, now we will calculate the transfer capability of 800kV EHV line as follows;

P in KW = √3 VI cos(phi)

P in MW = (√3 x V x I x 0.85)/**1000**

P in MW = (√3 x 800 x I x 0.85)/1000

P in MW = 1.178 x I

Let say we use "Moose" ACSR conductor which has total cross-sectional area of 520 Sqmm. Current carrying capacity of Moose conductor is 667 Amp (Aluminium Conductors Steel Reinforced (ACSR) Manufacturer) **At maxim. designed Temperature of 65 degree C.**

Hence power transfer capability of 800kV EHV line is;

P in MW = 1.178 x 667 A

P in MW = 786 MW

Hence the power transfer capability of 800kV EHV line with Moose conductor is 786 MW.

Normally for continuous operation the transmission lines used on various voltage are designed to carry or transmit maximum power (customer load is unknown) at the designed maximum conductor temperature of 65 degree C as follows;
At 132 kV with 'Panther' ACSR = 75 MVA
At 220 kV with 'Zebra' ACSR = 200 MVA

At 400 kV with 'Moose' ACSR = 500 MVA

Power Loss

When line resistance is neglected, the Power that can be transmitted depends upon.

a) The magnitude of end voltages (E_s, E_r).
b) Their phase angle difference δ, and.
c) The total positive seq. reactance X/ph.
d) L - The line length.

Thus, $P = \frac{E_s E_r \sin\delta}{L \cdot x}$ —(1)

At unity p.f, $E_s = E_r$,

$$P = \frac{E^2 \sin\delta}{L \cdot x} \quad \text{—(1)}$$

Current $I = \frac{P}{\sqrt{3}E} = \frac{E \sin\delta}{\sqrt{3} L \cdot x}$ —(2) . $\left[P = \sqrt{3} E I, \; I = \frac{P}{\sqrt{3} E} \right.$

and the total power loss in the 3-phases will amount to :

$$p = 3 I^2 r L \quad \text{—(3)}$$

Sub. eqn. (2) in (3) .

$$p = 3\left(\frac{E^2 \sin^2\delta}{3 L^2 x^2}\right) \cdot r \cdot L = \frac{E^2 \sin^2\delta \cdot r}{L x^2} \quad \text{—(4)}$$

Therefore, the percentage power loss is .

$$\% P = \frac{p}{P} \times 100 .$$

$$\% P = \frac{E^2 \sin^2\delta \cdot r}{L x^2} \times \frac{L \cdot x}{E_s E_r \cdot \sin\delta}$$

$$= \sin\delta \cdot \left(\frac{r}{x}\right) \times 100 .$$

$$= 100 . \sin\delta \left(\frac{r}{x}\right) .$$

$\delta = 30^\circ$, $= 100 \cdot \frac{1}{2} \left(\frac{r}{x}\right)$

$$= 50 \left(\frac{r}{x}\right) .$$

The following table shows the percentage Power loss and power handling Capacity of lines at Various Voltage levels for $\delta = 30°$ and without Series-Capacitor Compensation.

Line parameter values   Table-1

Sys. KV	400	750	1000	1200.
r Ω/KM	0.031	0.0136	0.0036	0.0027
x Ω/KM (50 Hz)	0.327	0.272	0.231	0.231
% Power loss (k). $50 \cdot \frac{r}{x}$	$50 \cdot \frac{0.031}{0.327} = 4.76$	2.5	0.78	0.584.

Power Transmitted:

$P = \frac{0.5 E^2}{L \cdot x}$ MW.

Length				
400.	670	2860	6000	8625
600	450	1900	4000	5750.
800	335	1430	3000	4310
1000.	270	1140	2400	3450
1200.	225	950	2000	2875.

Conclusion.

① One 750 KV line can normally carry as much power as four 400KV ckts for equal distance of transmission.

(2) One 1200 kV line can carry the Power of three 750 kV circuits and twelve 400 kV circuits for the Same transmission distance.

(3) Power handling Capacity of line at a given Voltage level decreases with line length, being inversly proportional to the line length 'L'.

(4) If the conductor size is based on Current rating, as line length increases, smaller size conductors will be necessary. This will increase the danger of high voltage effects Caused by Smaller diameter of conductor giving rise to Corona on the Conductors which leads to radio interference and audible noise.

(5) The percentage power loss in transmission remains independent of line length, since it depends on the ratio of conductor resistance to the (+)ve seq. reactance per unit length, and the phase differce 'δ' between E_s and E_r.

(6). From the Values of %p given in the table, it is evident that it decreases as the system voltage is increased.

(7) In comparison to the % power loss at 400 KV, we observe that if the same power is transmitted at 750 KV, the line loss is reduced to (2.5/4.76) = 0.525, at 1000 KV it is 0.78/4.76 = 0.165, and at 1200 KV it is reduced further to 0.124.

Problem:

A power of 12,000 MW is required to be transmitted over a distance of 1000 KM. At voltage levels of 400 KV, 750 KV, 1000 KV, and 1200 KV, determine:

(i) Possible No. of circuits required with equal magnitudes for sending and receiving end voltages with 30° phase differe.

(ii) The currents transmitted; and.

(iii) The total line losses.

Soln:

Syst. KV.	400	750	1000	1200.
x, Ω/KM	0.327	0.272	0.231	0.231
$P = 0.5.\ E^2/L.x$ MW	244.64	1034	2164.5	3116.88
No. of ckts. 12000/P	49	12	6	4.

	400	750	1000	1200
% Power Loss. $\% P_L = 50 . \frac{r}{x}$	4.76	2.5	0.779	0.584.
$\% P_L = \frac{P_L}{P} \times 100$. $P_L = \frac{\% P_L \times P}{100}$.	$\frac{4.76 \times 244.64}{100}$ = 11.644.	25.85	16.86.	18.644.
No. of Ckts. = $\frac{MW}{P} = \frac{12,000}{P}$	$= \frac{12000}{244.64}$ = 49.	$= \frac{12000}{1034}$ = 11.60 ≃ 12.	$= \frac{12000}{2164.5}$ = 5.54 ≃ 6	$= \frac{12000}{3116.88}$ = 3.85 ≃ 4.
Total Power loss. $P_L \times$ No. of Ckts	= 11.644 × 49 = 570.598 MW	= 25.85 × 12 = 310.2 MW	= 16.866 × 6 = 101.19 MW	= 18.21 × 4 = 72.86.

Mechanical Considerations in Line Performance.

* Major problem faced by the designers — Vibrations and oscillations of EHV transmission Conductor.
* Mechanical Engineer - Will recommend the tower dimensions, Phase spacings, Conductor hight, Subconductor spacings, etc. from this the Electrical Engineer has to commence the calculation of R, L, C, electrostatic fields, corona effects and other performance characteristics. Thus, the two should go hand in hand.
* The subconductors in the bundle are seperated by spacers which weakens the outer strands of the conductor during vibrations.
* Three type of Vibrations are recognized as being important for EHV/UHV Conductors, the degree of severity depends on many factors like.

  a) Conductor tension (b) Span length
  c) Conductor size d) Conductor type
  e) terrain of line (f) Wind direction
  g) tower type h) tower height (i) type of spacers and dampers, and (j) the Vegetation in the vicinity.

In general, most severe Vibration conditions are created by winds without turbulence so that hills, buildings and trees help in reducing severity.

The types of vibrations are:

a) Aeolian Vibration.
b) Galloping, and.
c) Wake - Induced oscillations.

a) Aeolian Vibration: $(< 25\ KM/Hr.)$.

· When a Conductor is under tension and a Comparatively steady wind blows (<25 KM/Hr) across it, Small vortices (a column of air moving rapidly round and round in a cylindrical shape). are formed on the leeward side (next side). Called Karman vortices.

· These Vortices detach temselves and when they do alternately from top and bottom they cause a minute vertical force on the Conductor.

The frequency of forces caused to the detachment of the Karman vortices is given by.

$F = 2.065\ V/d$ HZ. (A) when V, d in Km/hr. and cm respectively.

$F = 3.26\ V/d$ HZ (B) when V, d in mph and inches respectively.

where,

V → component of wind velocity normal to the conductor

d → diameter of conductor ~~in cm~~.

The resulting oscillation or vibrational forces cause fatigues (weaken) of Conductor and Supporting Structure and are known as aeolian Vibration.

b) Galloping: (15 – 50) KM/Hr.

It is a very high amplitude, low frequency type of conductor motion, occurs mainly in areas of relatively flat terrain underfreezing rain/icing of conductor.

The flat terrain (15 to 50 km/hr) provides winds that are uniform and a low turbulence. When the conductor is iced, it presents an unsymmetrical cross section. When the wind blows across the surface, there is an aerodynamic lift as well as a drag force due to the direct pressure of the wind.

The two forces gives rise to torsional modes of oscillation and they combine to oscillate the conductor with very large amplitudes sufficient to cause contact of two adjecent phases, which may be 10 to 15 metres apart in the rest position.

Galloping is controlled by using "detuning pendulum" which take the form of weights applied at different locations of the span. Here conductor oscillates at 'f' between 0.1 to 1 Hz.

Galloping is not a problem in hot county like India where temperatures are normally above freezing in winter.

c) Wake - Induced Oscillation : (25-65) KM/hr.

- Similar to aeolian Vibration, and peculiar to bundle conductor.
- Occurs when the wind speed reaches/ ranges between 25 to 65 KM/hr.
- The frequency of oscillation does not exceed 3HZ but may be of sufficient amplitude to cause clashing of adjacent subconductors, which are separated by 50cm.
- This oscillation is caused when one conductor on windward side aerodynamically shields leeward conductor. Oscillations occurs when the bundle tilts 5 to 15° w.r.t to a flat ground surface.
- For the bundle to be stable the following condition should be satisfied.

$$\frac{B}{d} > 15.$$

where, B - Bundle spacing.

d - The diameter of the conductor.

Dampers and Spacers :

When the Wind energy imparted to the Conductor achieves a balance with the energy dissipated by the vibrating Conductor, steady amplitude oscillations occur. By installing proper damping device the amplitude of the oscillation reduces. The damper controls the intensity of wave like properties of travel of the oscillation and provides an equivalent heavy mass which absorbs the energy in the wave. A sketch of stock bridge damper is shown in fig. It uses 2 weights to damp oscillation. For conductors with 2.5cm dia, 5kg is used and for 4.5cm conductor, 14 kg weight is used.

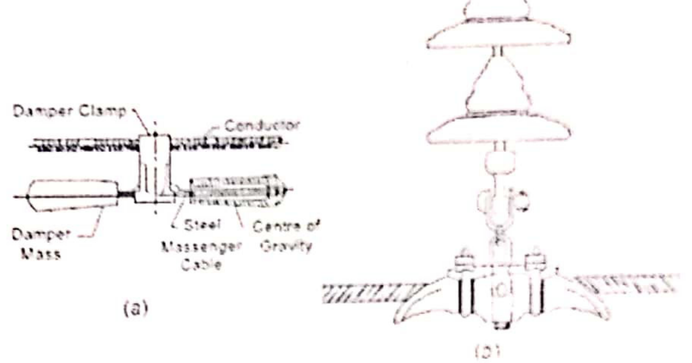


Fig. 2.2 (a) Stockbridge Damper; (b) Suspension Clamp (Courtesy: Electrical Manufacturing Co., Calcutta).

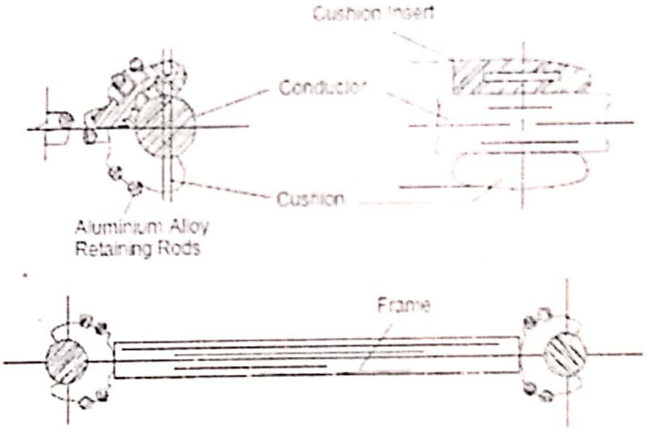


Fig. 2.3 Spacer for two-conductor bundle (Courtesy: EMC, Calcutta)

Spacers are used to keep the conductors apart. Most modern spacers have some flexibility built into them to allow rotation of conductor inside them such as lining the clamps with high strength plastic or rubber washers. Some spacers are specially designed to act as dampers and may also take the form of heavy springs. The selection of the spacers is also determined by the wind speed in the locality. The fig. 2.3. shows a spacer used for bundle conductor.

Resistance of the Conductor:

→ Opposition offered to the flow of current

→ AC resistance – opposition offered by that conductor to the flow of alternating currents through it.

→ DC resistance – opposition offered to the flow of direct current through the conductor.

→ If the distribution of current through the conductor is uniform then effective resistance of the conductor is equal to the D.C resistance of a conductor. It is given by

$$R_{D.C} = \frac{\rho l}{A} \ \Omega.$$

ρ – Resistivity
l – length of the conductor
A – Area of C.S.

→ Conductors used for EHV AC tr. lines are always stranded.

ACSR – Aluminium Conductor Steel Reinforced

ACAR – Aluminium conductor Alloy Reinforced.

Recent development.

AAAC → All Aluminium Alloy Conductor, which consists of alloys of Al, Mg, Si. This has 10% less loss than ACSR. In ACSR, when a steel core is used, because of its permeability and inductance, power-frequency current flows only in the aluminium strands.

In ACAR and AAAC conductors, the cross section is better utilized.

If n_s = No. of strands of aluminium.
d_s = diameter of each strands in metre
ρ_a = specific resistance of Al. (Ω-m). at temp. 't'.

The resistance of stranded conductor per KM is.

$$R = \rho_a \cdot 1.05 \times 10^3 / (\pi d_s^2 n_s / 4)$$

$$= (1337 \rho_a / d_s^2 n_s) \text{ ohms.}$$

The factor 1.05 accounts for the twist or lay whereby the strand length is increased by 5%.

<u>Effect of Resistance of Conductor.</u>

The effect of resistance of e.h.v. lines is manifested in the following forms.

a) Power loss in transmission caused by I^2R heating.

b). Reduced current - Carrying capacity of conductor in high ambient temperature regions.

c) The conductor resistance affects the attenuation of travelling waves due to lightning and switching operations, as well as radio frequency energy generated by corona.

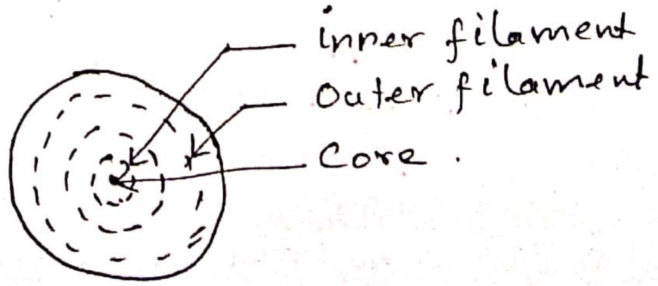
Skin Effect Resistance in round Conductors

Skin Effect: "The tendency of a high-frequency alternating current to flow thro' only the outer layer of a conductor." Here the current density is largest near the surface of the conductor, and decreases with greater depths in the conductor.

* The resistance of O.H.L conductors must be evaluated at frequencies ranging from power frequency (50/60 HZ) to radio frequencies upto 2 MHz or more.

* f ↑es, current tends to flow near the surface, This ↓es the area for current conduction, so, effective resistance ↑es.

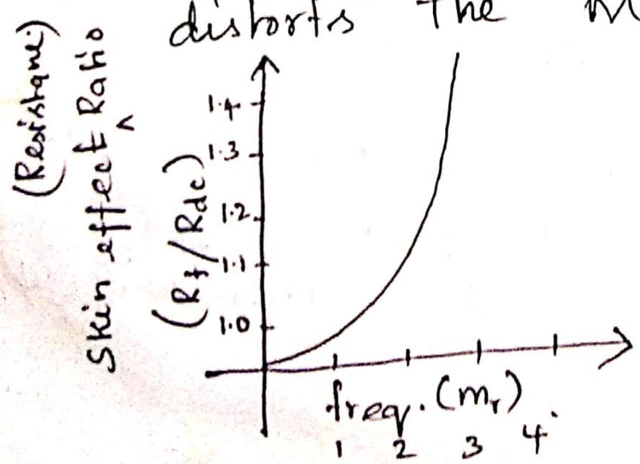
* **Reason:**



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

* The inner filaments of the conductor link larger amounts of flux as the centre is approached which causes an increase in reactance (X_L). The reactance is proportional to frequency so that the impedance to current flow is larger in the inside, thus preventing flow of current. The result is the crowding of the current at the outer filaments of the conductor (skin).

* The increase in resistance of a stranded conductor is more difficult to calculate than that of a single round solid conductor because of the close proximity of the strands which distorts the magnetic field still further.



Temperature rise of Conductors and Current - Carrying Capacity

The relation between the temperature rise and current carrying capacity of EHV AC lines can be given from the heat balance equation and is given by.

Internal heat developed by I^2R + External heat supplied by Solar irradiation = Heat lost by Convection to Air + Heat lost by Radiation

When all the quantities are taken in watts per metre length of conductor then we get,

$$W_i + W_s = W_c + W_r \quad \text{--- (1)}$$

Where,

a) W_i — I^2R heating.

$$W_i = I^2 R_m, \quad R_m = \frac{1+\alpha t}{1+20\alpha} \cdot R_{20}$$

R_m - Resistance of conductor per metre length at the maximum temperature.

α - Temp. resistance Co-eff. in $\Omega/°C$.

R_{20} - Conductor. resistance at 20°C.

b) $W_s = S_a \cdot I_s \cdot d_m$ Watts/metre.

d_m - diameter of conductor in metre.

S_a - The solar absorption Coeff.

I_s - The solar irradiation intensity (W/m^2).

c) $W_c = 18\,\Delta t\,\sqrt{P V_m \cdot d_m}$ Watts/meter

P - Pressure of air in atmosphere

V_m - Wind velocity in m/sec

$\Delta t = (t - t_a)$ - temp. rise in °C above ambient

d). $W_r = 1.79\, e\, d_m \left[\left(\frac{T}{100}\right)^4 - \left(\frac{T_a}{100}\right)^4\right]$

W_r = is the irradiation loss

e - relative emissivity of conductor

T - Conductor Temperature in °K = 273 + t

T_a - Ambient temp in °K = 273 + t_a

Sub. eqn. ⓐ, ⓑ, ⓒ and ⓓ in eqn. ① we get,

$$I^2 R_m + S_a I_s d_m = 18\,\Delta t\,\sqrt{P V_m \cdot d_m} + 1.79\, e\, d_m \left[\left(\frac{T}{100}\right)^4 - \left(\frac{T_a}{100}\right)^4\right]$$

Problem:

A 400KV line in India uses a 2-Conductor bundle with $d_m = 0.0318$ m for each conductor. The phase current is 1000 Amps (500 A/conductor). The area of each conductor is 515.7 mm², $\rho_a = 2.7 \times 10^{-8}$ ohm-m at 20°C, $\alpha = 0.0045\ \Omega/°C$ at 20°. Take the ambient temperature $t_a = 40°C$, atmospheric pressure $P = 1$, wind velocity $V_m = 1$ m/s, e = 0.5 and neglect solar irradiation. Calculate the final temperature of conductor due only to I^2R heating.

<u>given,</u>

- System Voltage = 400 kV
- Distance of Conductor in meter $d_m = 0.0318$ m.
- Phase Current, $I_{ph} = 1000$ A.
  ∴ Current per conductor = I = 500 A.
- Area of each conductor = 515.7 mm^2.
- Specific Resistance $(R_a) = 2.7 \times 10^{-8}$ Ω-m at 20°C.
- Temp. resistance Coeff, $\alpha = 0.0045$ Ω/°C @ 20°C.
- Ambient temperature, $t_a = 40$°C.
- Atmospheric pressure, P = 1
- Wind Velocity, V_m = 1 m/s.
- Relative emissivity of Conductor-surface, e = 0.5

Final Temp. of Conductor only due to I^2R heating, t = ?

<u>Soln:</u>

Resistance of conductor per metre length at the maximum temperature.

$$R_m = \frac{1+\alpha t}{1+20\alpha} \cdot R_{20}$$

$$= \left[\frac{(1+0.0045)t}{1+(0.0045).20}\right] \cdot 2.7\times10^{-8} \cdot \left[\frac{1.05}{515.7\times10^{-6}}\right]$$

$$= 5.0435 \times 10^{-5}(1+0.0045t)\ \Omega/m.$$

∴ I^2R_m heating, $W_i = I^2 R_m$ Watts/metre.

$$W_i = (500)^2 \times [5.0435\times10^{-5}(1+0.0045t)].$$

$$= 12.6086(1+0.0045t)\ \text{watts/m}.$$

Conventional loss in Watts/metre length of conductor.

$$W_c = 18 \times \Delta t \times \sqrt{P \times d_m \times V_m}$$

$$= 18 \times (t - 40^\circ)\sqrt{1 \times 0.0318 \times 1}$$

$$= 3.21\,(t-40) \text{ Watts/m}$$

Radiation loss in watts/metre length of Cond.

$$W_r = 17.9\, e\, d_m \left[\left(\frac{T}{100}\right)^4 - \left(\frac{T_a}{100}\right)^4\right]$$ $T \rightarrow 273 + t$, $T_a = 273 + t_a$.

$$= 17.9 \times 0.5 \times 0.0318 \left[\left(\frac{273+t}{100}\right)^4 - \left(\frac{273+40}{100}\right)^4\right]$$

$$= 0.285\left[\left(\frac{273+t}{100}\right)^4 - 95.98\right]$$

Therefore, from the heat balance equation, we have,

$$W_i + W_s = W_c + W_r$$

$$12.6086(1 + 0.0045t) + 0 = 3.21(t-40) + 0.285\left[\left(\frac{273+t}{100}\right)^4 - 95.98\right] \rightarrow (A)$$

[∵ Solar irradiation Neglected].

On solving eqn. (A) we get (trial and error)

$$t = (44.625)^\circ C$$

$$\simeq 45^\circ C$$

$$\therefore W_i = 12.6086\,(1 + 0.0045\,t)$$
$$= 12.6086\,(1 + 0.0045 \times 45) = 15.1618 \text{ Watts/met}$$

$$W_c = 3.21(t-40)$$
$$= 3.21\,(45-40)$$
$$= 16.05 \text{ Watts/m}$$

And $W_r = 0.285\left[\left(\frac{273+t}{100}\right)^4 - 95.98\right]$

$= 1.79$ watts/m.

Pbm: In the previous examples, calculate the final temperature (or temp. rise) if the solar irradiation adds
(a) 10 watts/m and (b) 1160 W/m^2. giving a contribution of 37 Watts/m to the conductor.

Soln: By going through similar procedure,
a) $t = 45.5^\circ c$ $\Delta t = 5.5^\circ c$
b) $t = 54.1^\circ c$, $\Delta t = 14.1^\circ c$.

Properties of Bundle Conductor.

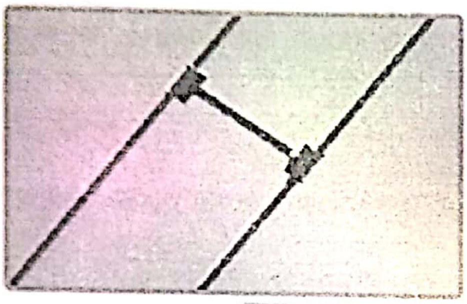
+ In transmission lines we require HV and power for transmission over long distances, so as to meet their high voltage requirements we need to supply huge power.

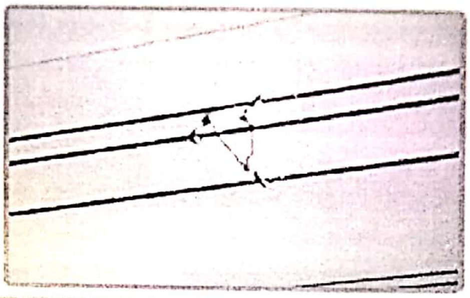
+ But due to high voltage (>230 KV), Corona occurs resulting in huge power. loss and if there is only one conductor per phase then its interaction with communication line is very high and uncontrollable.

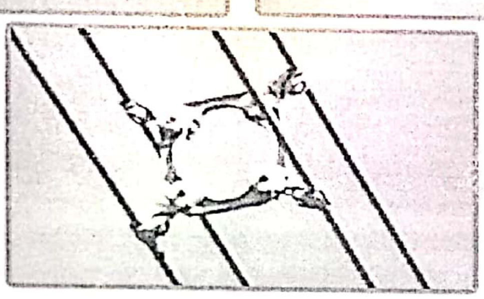
× So, for extra high voltages, there should be. two or more conductors per phase

Properties of Bundled Conductor:

We can often see the transmission lines where instead of a single conductor per phase multiple conductors per phase are being used. A metallic structure called spacers groups the conductors of a phase. These spaces help to maintain a constant distance between the conductors throughout their length, avoid clashing of conductors amongst themselves and also allowing them to be connected in parallel. Each phase can have two, three, or four conductors. The figures below show **bundled conductors** with spacers for the three configurations.







Each conductor joined by the spacer belongs to the same phase, and we will have three such group of conductors in a single circuit transmission or six such groups in double circuit transmission.

A bundle conductor is a conductor made up of two or more sub-conductors and is used as one phase conductor. For voltages greater than 220 kV it is preferable to use more than one conductor per phase which is known as Bundle conductor.

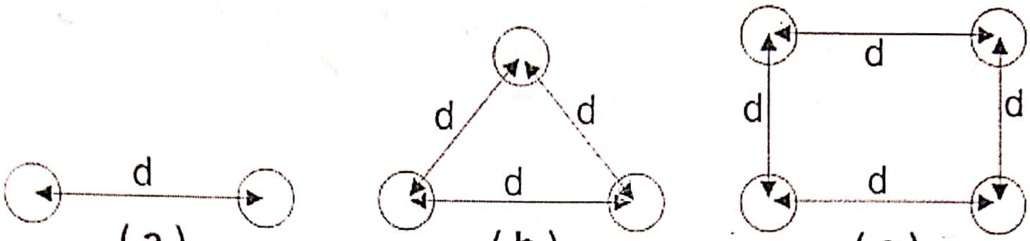
Advantages of Bundled Conductors

1. Bundling of conductors leads to reduction in line inductance.
   We know that inductance of a line is given by

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

   Where, GMD = Geometric mean distance
   GMR = Geometric mean radius

2. For a single conductor of radius r
GMR = 0.7788r
For two conductor bundle as shown in figure



(a) (b) (c)

$$GMR = \sqrt[4]{(0.7788r)(d)(d)(0.7788r)} = 0.8825\sqrt{rd}$$

For three conductor bundle

$$GMR = \sqrt[9]{(0.7788r \times d \times d)^3} = 0.92\sqrt[3]{rd^2}$$

For four conductor bundle

$$GMR = \sqrt[16]{(0.7788r \times d \times d \times \sqrt{2}d)^4} = 1.02\sqrt[4]{rd^3}$$

Hence as we increase the number of conductors the GMR increases and hence L decrease. Now, there are many advantages of reduction in inductance of the line, such as-

- The maximum power transfer capability of the line increases as
  $P = \left(\frac{V_s V_r}{X}\right) Sin\delta$
  Where X = wL ...reactance of line

- The voltage regulation of the line is also increased as the reactance of the line is reduced.

3. On the similar argument for decrease in inductance of line, we can say that the capacitance of the line increases, as capacitance of line to neutral is given by

$$C_n = \frac{2\pi\epsilon_0}{ln\left(\frac{GMD}{GMR}\right)}$$

Now since we have L decreased and C increased the net SIL of the line also increases automatically, and hence the power transfer capability too. Hence using bundled conductors is an effective way of increasing SIL, i.e. Surge Impedance Loading.

4. The most important **advantage of bundled conductors** is its ability to reduce corona discharge. When power is being transferred at very high voltages using a single conductor, the voltage gradient around it is high, and there is a high chance that the corona effect will occur – especially in bad weather conditions. However, using several conductors nearby instead of one conductor, forming a bundled conductor which leads to a reduction of voltage gradient and hence the possibility of corona formation.

   The increase in critical corona voltage depends upon the following-
   - Number of conductors in the group,
   - Clearance between them, and
   - The distance between the groups forming separate phases.

   It has been found out that the optimum spacing between the conductors in a group is of the order of 8-10 times the diameter of each conductor, irrespective of the number of conductors in the bundle.

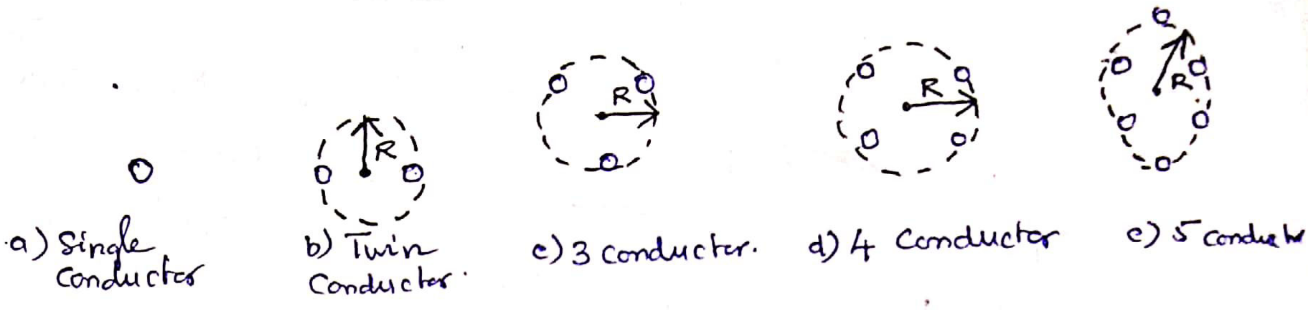
5. Reduction in the formation of corona discharge leads to less power loss and hence improved transmission efficiency of the line.

6. Reduction in communication line interference due to reduction in corona.

7. The ampacity i.e. the current carrying capacity of bundled conductors is much increased in comparison to single large conductor owing to reduced skin effect.

8. As the **bundled conductors** have more effective surface area exposed to air, it has better and efficient cooling and hence better performance compared to a single conductor.

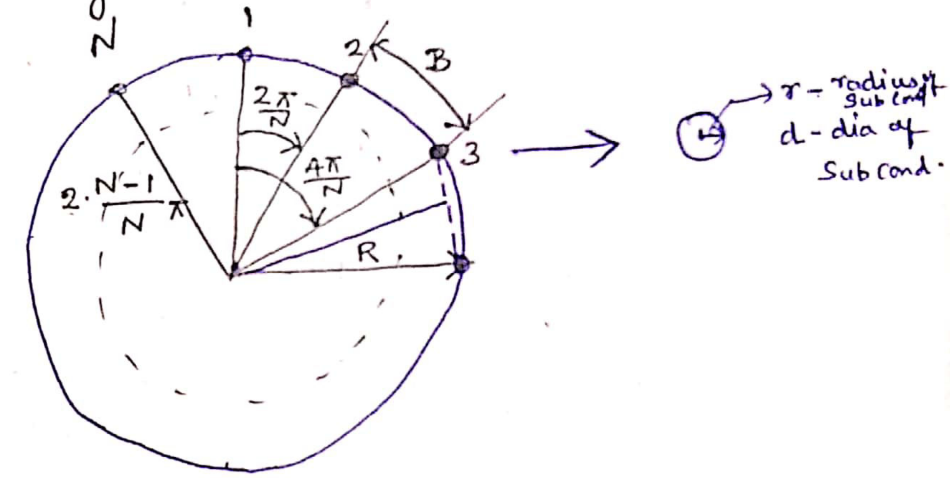
For commercial lines of a system voltage of 1150 - 1200 kV, maximum of 18 subconductors are being used.



B - Bundle spacing

R - Radius of the bundle conductor.

Bundle Spacing and Bundle Radius.



From the above figure.

N - No. of conductor bundles

$\frac{2\pi}{N}$ - Angle sub-tended at the centre by adjacent sub-conductor and is in radians

The figure shows that the sub-conductors of a bundle are uniformly distributed on a circle of radius R. and this is considered because this condition holds good for most of the cases.

using fig.(2). we can write,

$$\frac{B}{2} = R\sin\left(\frac{\pi}{M}\right), \quad R = \frac{B}{2}\Big/\sin\frac{\pi}{N}$$

GMR or Eq. Radius of the bundle.

When a bundle of N- sub conductors is replaced by a single conductor then the radius of this single conductor is GMR or eq. radius.

The expression for GMR or eq. radius is given as.

$$r_{eq} = \left[N.r.R^{N-r}\right]^{\frac{1}{N}}$$

$$= r.\left[N.\left(\frac{R}{r}\right)^{N-1}\right]^{\frac{1}{N}}.$$

$$r_{eq} = R.\left[N.\frac{r}{R}\right]^{1/N}$$

r – Sub.cond. radius.

$$= \frac{r}{r}\left[N.r.R^{N-1}\right]^{1/N}$$

$$= r.\left[N.r.\frac{R^{N-1}}{r^N}\right]^{1/N}$$

$$= r.\left[N.\frac{R^{N-1}}{r^{N-1}}\right]^{1/N}.$$

$$= r\left[N\left(\frac{R}{r}\right)^{N-1}\right]^{1/N}.$$

$$= r\left[N\left(\frac{R}{r}\right)^{N}.\left(\frac{R}{r}\right)^{-1}\right]^{1/N}$$

$$= r\left[N.\left(\frac{R}{r}\right)^{N}\left(\frac{r}{R}\right)^{N}\right]^{1/N}.$$

$$= r.N^{1/N}.\frac{R}{r}.\left(\frac{r}{R}\right)^{1/N}.$$

$$= N^{1/N}.R.\left(\frac{r}{R}\right)^{1/N}.$$

$$= R.\left[N\left(\frac{r}{R}\right)\right]^{1/N}$$

Using fig.(2), and the above equation of r_{eq}. the product of (N-1) mutual distance is given as,

$$= \left[2R\sin\frac{\pi}{N}\right].\left[2R\sin\frac{2\pi}{N}\right]\cdots\left[2R\sin\frac{N-1}{N}\pi\right]$$

$$= (2R)^{N-1}\left(\sin\frac{\pi}{N}\right)\left(\sin\frac{2\pi}{N}\right)\cdots\sin\left(\frac{N-1}{N}.\pi\right).$$

$$\therefore r_{eq} = \left[2.(2R)^{N-1}.\sin\frac{\pi}{N}\sin\frac{2\pi}{N}\cdots\sin\frac{N-1}{N}\pi\right]^{1/N}.$$

For $N = 2$, $r_{eq} = (2 \cdot r \cdot R)^{1/2}$

$N = 3$, $r_{eq} = \left[2^2 \cdot R^2 \cdot r \cdot \sin\frac{\pi}{3} \cdot \sin\frac{2\pi}{3}\right]^{1/3}$

$= (3 \cdot r \cdot R^2)^{1/3}$

For, $N = 4$, $r_{eq} = (4 \cdot r \cdot R^3)^{1/4}$

For, $N = 6$, $r_{eq} = (6 \cdot r \cdot R^5)^{1/6}$.

Problem:

The configuration of some EHV lines for 400KV to 1200KV are given, calculate r_{eq} for each.

(i) 400KV: $N = 2$, $d = 2r = 3.18$ cm, $B = 45$ cm.

(ii) 750KV: $N = 4$, $d = 3.46$ cm, $B = 45$ cm.

(iii) 1000KV: $N = 6$, $d = 4.6$ cm, $B = 12d$.

(iv) 1200KV: $N = 8$, $d = 4.6$ cm, $R = 0.6$ m.

(B - Bundle Spacing, R - Radius of the Bundle Conductor),
N - No. of Bundled conductors.

$r_{eq} = (N \cdot r \cdot R^{N-1})^{1/N}$, $R = \frac{B}{2} / \sin\left(\frac{\pi}{N}\right)$ $= \frac{B}{2 \cdot \sin\left(\frac{\pi}{N}\right)}$

Soln:

(i) System Voltage $= 400$ KV.

No. of Bundled conductor $= N = 2$.

Diameter, $(d) = 2r = 3.18$ cm.

Radius $(r) = \frac{d}{2} = \frac{3.18}{2} = 1.59$ cm.

Bundled Spacing $(B) = 45$ cm.

GMR (or) $r_{eq_{N=2}} = (2rR)^{1/2} = 8.46$ cm $= 0.0846$ m

b) $r_{eq} = (4 \cdot r \cdot R^3)^{1/4} = \left[4 \times 1.73 \times \left(\frac{45}{\sqrt{2}}\right)^3\right]^{1/4}$

$= 21.73\ cm = 0.2173\ m.$

c) $r_{eq} = (6 \cdot r \cdot R^5)^{1/6} = \left[6 \times 2.3 \times (55.2)^5\right]^{1/6}$

$= 43.81\ cm = 0.4381\ m.$

d) $r_{eq} = (8 \cdot r \cdot R^7)^{1/8} = 60 \cdot \left(8 \times \frac{2.3}{60}\right)^{1/8} = 0.920$

$(8 \times 2.3 \times 0.6^7)^{1/8} = 0.920\ m$

$= 51.74\ cm = 0.5174\ m.$

<u>Note:</u> We observe that as the No. of Subconductor increases, the eq. radius of bundle is approaching the bundle radius

Inductance of a Single conductor.

- Ratio of total flux linkage (λ) to the Current.

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

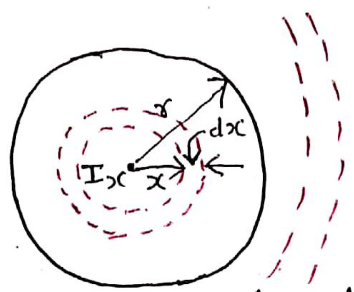
| λ - flux linkage in W-T.

Magnetic Field Intensity in a current carrying Conductor.

a) Mag. Field Intensity (H_x) due to the Current Distribution inside the Conductor ($x < r$).

r - radius of the Cond.
I - Current through the conductor of radius 'r'

$H_x \propto \frac{I_x}{x}$



Consider a cylinder with radius $x < r$ and assume uniform current density throughout the conductor.

Mag. Field Intensity (H_x) @ distance 'x' due to the current I_x is given by.

$$H_x = \frac{I \cdot x}{2\pi r^2}$$

$H_x \propto x$.

b) Mag. Field Intensity due to Current distribution outside the conductor ($x > r$).

$$H_x = \frac{I}{2\pi x} \Rightarrow H_x \propto \frac{1}{x}.$$

Inductance due to Internal Flux Linkage.

$$\lambda_{int} = \frac{\mu_0 I}{8\pi} \text{ Wb/m.}$$

(Total internal flux linkage.)

$$L_{int} = \frac{\lambda_{int.}}{I} = \frac{\mu_0}{8\pi} = \frac{4\pi \times 10^{-7}}{8\pi}$$

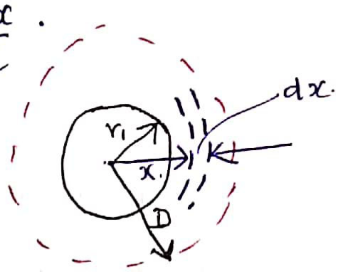
$$= \frac{2}{4} \times 10^{-7}$$

$$= \frac{1}{2} \times 10^{-7} \text{ H/m.}$$

Inductance due to External Flux Linkage.

External Flux Linkage.

$$\lambda_{ext} = \frac{\mu_0 I}{2\pi} \int_{r_1}^{D} \frac{dx}{x}.$$



$$\lambda_{ext} = \frac{\mu_0 I}{2\pi} \ln[x]_{r_1}^{D}$$

$$= \frac{\mu_0 I}{2\pi} \ln\left[\frac{D}{r_1}\right] \text{ Wb/m.}$$

$$= \frac{4\pi \times 10^{-7}}{2\pi} . I . \ln\left[\frac{D}{r_1}\right] \text{ Wb/m.}$$

$$= 2\pi \times 10^{-7} I \ln\left[\frac{D}{r_1}\right] \text{ Wb/m.}$$

Inductance

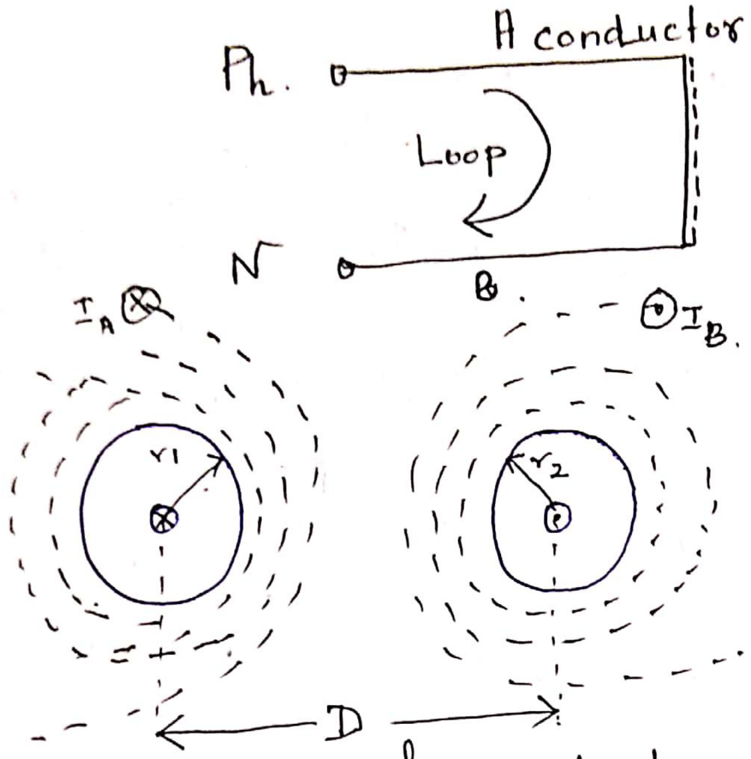
$$L_{ext.} = \frac{\lambda_{ext}}{I} = 2 \times 10^{-7}. \ln\left[\frac{D}{r_1}\right] \text{ H/m.}$$

Overall Flux Linkage $\Big\} = \lambda_{int} + \lambda_{ext}.$

$$= \frac{\mu_0 I}{8\pi} + \frac{\mu_0 I}{2\pi} \int_{r_1}^{D} \frac{dx}{x} = \frac{\mu_0 I}{2\pi}\left[\frac{1}{4} + \int_{r_1}^{D} \frac{dx}{x}\right]$$

Inductance of a single phase Line.

A conductor :



r_1 – Radius of Ph. and
r_2 – Neutral Conductor.

$I_A \rightarrow$ Ph. current
$I_B \rightarrow$ Neutral Current.

$\therefore I_A = -I_B \Rightarrow I_A + I_B = 0$

Sets up Mag. field which reinforce each-other in space between them.

The two ||el conductors form a rectangular loop of one turn through which flux is produced by currents in the two conductors. Since the flux links the loop it possesses inductance.

Inductance of conductor '1' due to internal flux and due to external flux linkage.

* Flux linkage with conductor A due to its own current.

$$= \frac{\mu_0 I_A}{2\pi}\left[\frac{1}{4} + \int_{r_1}^{\alpha} \frac{dx}{x}\right].$$

* Flux linkage with conductor A due to. Current in conductor B.

$$= \frac{\mu_0 I_B}{2\pi}\int_{D}^{\alpha} \frac{dx}{x}.$$

$$= \frac{\mu_0 I_A}{2\pi}\left(\frac{1}{4} + \int_{r_1}^{\infty}\frac{dx}{x}\right) + \frac{\mu_0 I_B}{2\pi}\int_{D}^{\infty}\frac{dx}{x}$$

$$= \frac{\mu_0 I_A}{2\pi}\left[\left(\frac{1}{4} + \int_{r_1}^{\infty}\frac{dx}{x}\right) + I_B\int_{D}^{\infty}\frac{dx}{x}\right]$$

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

$$= \frac{\mu_0}{2\pi}\left[\left(\frac{I_A}{4} + \log_e^{\infty}(I_A + I_B) - I_A\log_e^{r} - I_B\log_e^{D}\right)\right]$$

$$= \frac{\mu_0}{2\pi}\left[\frac{I_A}{4} - I_A\log_e^{r} - I_B\log_e^{D}\right] \quad (\because I_A + I_B = 0)$$

$$I_B = -I_A$$

$$= \frac{\mu_0}{2\pi}\left[\frac{I_A}{4} + I_A\log_e^{D} - I_A\log_e^{r}\right] \text{ Wb-turns/m}$$

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

$$\lambda_A = \frac{\mu_0 I_A}{2\pi}\left[\frac{1}{4} + \log_e\frac{D}{r}\right] \text{ Wb-Turns/m}$$

Inductance of Conductor A, $L_A = \frac{\lambda_A}{I_A}$, $D = d$

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

$$= \frac{4\pi \times 10^{-7}}{2\pi}\left[\frac{1}{4} + \log_e\frac{d}{r}\right] \text{ H/m}$$

$$= 2\times10^{-7}\left[\frac{1}{4} + \log_e\frac{d}{r}\right] \text{ H/m}$$

$$= 10^{-7}\left[\frac{1}{2} + 2\log_e\frac{d}{r}\right] \text{ H/m} \rightarrow (A)$$

Loop Inductance = $2 L_A \cdot H/m$

$$= 10^{-7}\left[1 + 4 \log_e \frac{d}{r}\right] H/m \quad \text{(B)}$$

Note:

eqn. (B) is the inductance of two wire line and is sometimes called loop inductance. However, inductance given by eqn. (A) is the inductance per conductor and is equal to half the loop inductance.

If internal flux is neglected.

$$L_A = 2 \times 10^{-7} \ln\left(\frac{d}{r}\right) H/m.$$

$$= 0.2 \ln(d/r) \mu H/m.$$

If height of the conductor is d/2

$$H = d/2.$$

$$d = 2H$$

$$\therefore L_A = 0.2 \ln\left(\frac{2H}{r}\right) \mu H/m.$$

Expression in Alternate Form.

$$L_A = 10^{-7}\left[\frac{1}{2} + 2 \log_e \frac{d}{r}\right] H/m.$$

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

$$= 2 \times 10^{-7}\left[\log_e e^{1/4} + \log_e \frac{d}{r}\right]$$

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

Conductor located at height H.
$d = 2H$.

If we put $r \cdot e^{-1/4} = r'$ then.

$$L_A = 2 \times 10^{-7} \log_e \frac{d}{r'} H/m \quad \text{— (C)}.$$

The radius r' is the fictitious Conductor assumed to have no internal flux but with the same inductance as the actual conductor of radius r.

$$\therefore \boxed{r' = r.e^{-1/4} = 0.7788\, r}$$

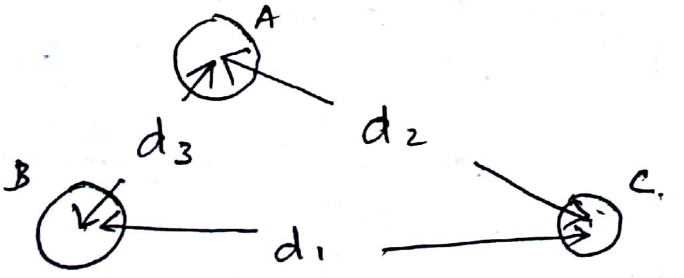
The term $r' = r e^{-1/4}$ is called as geometric mean radius (GMR) of the wire.

Note: Eqn. (c) and (A) gives same Value of Inductance L_A.

The difference is that eqn. (c) omits the term to account for internal flux but compensates for it by using an adjusted value of the radius of the conductor.

$$\text{Loop Inductance} = 2\, L_A$$
$$= 2\left(2 \times 10^{-7} \log_e \frac{d}{r'}\right) \text{ H/m}$$

Inductance of a 3∅ OHL



$I_A + I_B + I_C = 0$

d_1, d_2, d_3 - Spacing bet. conductors

Flux linkage with conductor A due to own current.

$$= \frac{\mu_0 I_A}{2\pi}\left[\frac{1}{4}+\int_r^{\infty}\frac{dx}{x}\right] \quad \text{— (A)}$$

Flux linkage with cond. 'A' due to I_B.

$$= \frac{\mu_0 I_B}{2\pi}\int_{d_3}^{\infty}\frac{dx}{x} \quad \text{— (B)}$$

Flux linkage with cond 'B' due to I_C.

$$= \frac{\mu_0 I_C}{2\pi}\int_{d_2}^{\infty}\frac{dx}{x} \quad \text{— (C)}$$

Total flux linkage with conductor A is.

$$\lambda_A = (A) + (B) + (C).$$

$$= \frac{\mu_0 I_A}{2\pi}\left[\frac{1}{4}+\int_r^{\infty}\frac{dx}{x}\right] + \frac{\mu_0 I_B}{2\pi}\int_{d_3}^{\infty}\frac{dx}{x} + \frac{\mu_0 I_C}{2\pi}\int_{d_2}^{\infty}\frac{dx}{x}$$

$$= \frac{\mu_0}{2\pi}\left[\left(\frac{1}{4}+\int_r^{\infty}\frac{dx}{x}\right)I_A + I_B\int_{d_3}^{\infty}\frac{dx}{x} + I_C\int_{d_2}^{\infty}\frac{dx}{x}\right]$$

$$= \frac{\mu_0}{2\pi}\left[\left(\frac{1}{4}-\log_e r\right)I_A - I_B\log_e d_3 - I_C\log_e d_2 + \log_e \infty\,(I_A+I_B+I_C)\right]$$

As, $I_A+I_B+I_C=0$,

$$\lambda_A = \frac{\mu_0}{2\pi}\left[\left(\frac{1}{4}-\log_e r\right)I_A - I_B\log_e d_3 - I_C\log_e d_2\right] \quad \text{(D)}.$$

(i) Symmetrical spacing.

A, B and 'C' are symmetrically placed at the corners of equilateral Δle of side 'd'

$\therefore d_1 = d_2 = d_3 = d$.

under such conditions eq. (D) becomes:

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

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

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

$$= \frac{\mu_0 I_A}{2\pi}\left[\frac{1}{4} + \log_e \frac{d}{r}\right] \text{ Weber-Turns/m.}$$

Inductor of Conductor A $(L_A) = \frac{\lambda_A}{I_A} = \frac{\mu_0}{2\pi}\left[\frac{1}{4} + \log_e \frac{d}{r}\right]$ H/m

$$= \frac{4\pi \times 10^{-7}}{2\pi}\left[\frac{1}{4} + \log_e \frac{d}{r}\right] \text{ H/m}$$

$$L_A = 10^{-7}\left[0.5 + 2\log_e \frac{d}{r}\right] \text{ H/m} \rightarrow (E)$$

(ii) Unsymmetrical Spacing:

When 3ø lines are not equidistance from each other, the conductor spacing is said to be unsymmetrical. under such conditions, the flux linkages and inductance of each phase are not the same. The different inductance in each phase results in unequal voltage drop in the three phases even if the currents in the conductors are balanced. Therefore the voltage at the receiving end will not be the same for all phases. In order that the voltage drops are equal in all conductors, we generally interchange the positions of the conductors at regular intervals and it is called as Transposition.

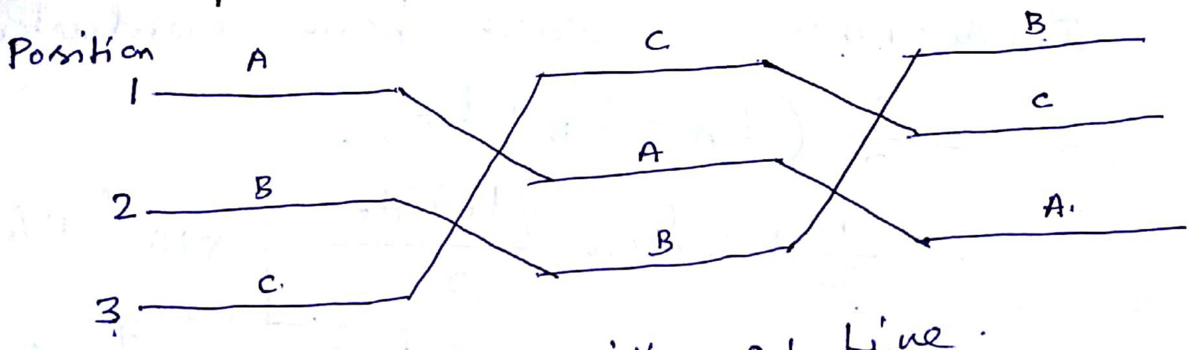


Fig: Transposition of Line.

Each Section – 1m of Length.

Let us further assume balanced condition.

$I_A + I_B + I_C = 0$, let the Currents be,

$$\left.\begin{aligned} I_A &= I(1+j0) \\ I_B &= I(-0.5 - j0.866) \\ I_C &= I(-0.5 + j0.866) \end{aligned}\right\} \Rightarrow (F)$$

$$(D) \Rightarrow \lambda_A = \frac{\mu_0}{2\pi}\left[\left(\frac{1}{4} - \log_e r\right)I_A - I_B \log_e d_3 - I_C \log_e d_2\right]$$

Sub (F) in (D) and reducing we get,

$$\lambda_A = \frac{\mu_0 I}{2\pi}\left[\frac{1}{4} + \log_e \frac{\sqrt{d_2 d_3}}{r} + j\,0.866 \log_e \frac{d_3}{d_2}\right]$$

$$L_A = \frac{\lambda_A}{I_A} = \frac{\lambda_A}{I} = \frac{\mu_0}{2\pi}\left[\frac{1}{4} + \log_e \frac{\sqrt{d_2 d_3}}{r} + j0.866 \log_e \frac{d_3}{d_2}\right]$$

$$L_A = 10^{-7}\left[\frac{1}{2} + 2\log_e \frac{\sqrt{d_2 d_3}}{r} + j\,1.732 \log_e \frac{d_3}{d_2}\right] \text{ H/m.}$$

$|||^{ly}$ $L_B = 10^{-7}\left[\frac{1}{2} + 2\log_e\frac{\sqrt{d_3 d_1}}{r} + j1.732\log_e\frac{d_1}{d_3}\right]$ H/m.

$L_C = 10^{-7}\left[\frac{1}{2} + 2\log_e\frac{\sqrt{d_1 d_2}}{r} + j1.732\log_e\frac{d_2}{d_1}\right]$ H/m.

Inductance of each line conductor,

$= \frac{1}{3}(L_A + L_B + L_C).$

$= \left[\frac{1}{2} + 2\log_e\frac{\sqrt[3]{d_1 d_2 d_3}}{r}\right] \times 10^{-7}$ H/m.

$= \left[0.5 + 2\log_e\frac{\sqrt[3]{d_1 d_2 d_3}}{r}\right] \times 10^{-7}$ H/m

→ (G).

Compare (E) and (G) (Symmetrical and Unsymmetrical)

The two cases will be equal if $d = \sqrt[3]{d_1 d_2 d_3}$

d – equivalent equilateral spacing of unsymmetrically transposed line.

Self and Mutual GMD.

* Used for simplifying Inductance calculation mainly for multiconductor arrangement.

(i) Self GMD (D_s). or GMR.

Inductance/conductor/m $= 2\times10^{-7}\left(\frac{1}{4} + \log_e\frac{d}{r}\right)$

$= \left(2\times10^{-7}\times\frac{1}{4}\right) + 2\times10^{-7}\log_e\frac{d}{r}.$

Internal flux linkage.

If we replace 

Solid Conductor → eq. hollow Cylinder with thin walls.
↓
Current is confined to the Conductor surface and Internal conductor flux linkage would be zero.

THE GMR CONCEPT ⇒

So the first term $\left(2\times10^{-7}\times\frac{1}{4}\right)$ is eliminated.

The radius of the eq. hallow 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.

∴ The GMR of Conductor $= r' = 0.7788 \cdot r$.

(GMR depends on the size and shape of the conductor and is independent of the spacing between the conductor)

(ii) **Mutual - GMD** - Geometrical mean of the distance from one Conductor to the other.

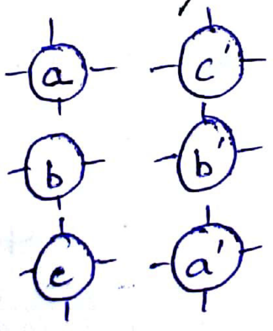
a) Mutual GMD [Two Conductor] (D_m).

D_m = Spacing between the Conductor $= d$

b) Mutual GMD [3 ϕ, Single Circuit Line].

$$D_m = (d_1 d_2 d_3)^{1/3}$$

c). For 3 ϕ Double ckt. line.



GMR (Self).

$$D_{S_1} = (D_{aa} \cdot D_{aa'}\ D_{a'a}\ D_{a'a'})^{1/4}$$

$$D_{S_2} = (D_{bb}\ D_{bb'}\ D_{b'b}\ D_{b'b'})^{1/4}.$$

$$D_{S_2} = (D_{cc}\ D_{cc'}\ D_{c'c}\ D_{c'c'})^{1/4}$$

Eq. GMR $D_s = \sqrt[3]{D_{S_1}\, D_{S_2}\, D_{S_3}}$

$D_{aa} = D_{a'a'} = D_{bb} = D_{b'b'} = D_{cc} = D_{c'c'} = 0.7788\, r.$

Mutual GMD

Between phases (A) and (B) $\Rightarrow D_{AB} = (D_{ab}\, D_{ab'}\, D_{a'b}\, D_{a'b'})^{1/4}$

(B) (C) $\Rightarrow D_{BC} = (D_{bc}\, D_{bc'}\, D_{b'c}\, D_{b'c'})^{1/4}$

(C) (A) $\Rightarrow D_{CA} = (D_{ca}\, D_{ca'}\, D_{c'a}\, D_{c'a'})^{1/4}$

Eq. Mutual GMD $= D_m = \sqrt[3]{D_{AB} \cdot D_{BC} \cdot D_{CA}}$.

Inductance Formula in Terms of GMD.

(i) Single phase:

$$L/\text{cond}/m = 2\times10^{-7} \log_e \frac{D_m}{D_s}$$

$D_s = 0.7788 \cdot r$, D_m = spacing between conductor.

(ii) Single ckt. 3ϕ line:

$$L/ph/m = 2\times10^{-7} \log_e \frac{D_m}{D_s}$$

$D_s = 0.7788r$; $D_m = (d_1\, d_2\, d_3)^{1/3}$,

(iii) Double ckt. 3ϕ line.

$$L/ph/m = 2\times10^{-7} \log_e \frac{D_m}{D_s}$$

$D_s = (D_{S1} \cdot D_{S2} \cdot D_{S3})^{1/3}$; $D_m = (D_{AB} \cdot D_{BC} \cdot D_{CA})^{1/3}$

Problem:

(1) A single ph. line has two parallel conductors 2 metres apart. The diameter of each conductor is 1.2 cm. Calculate the loop inductance per KM of the line.

Soln:

$d = 2m = 200$ cm

$r = 1.2/2 = 0.6$ cm

Loop Inductance/m. length $= 10^{-7}\left(1 + 4 \log_e \frac{d}{r}\right)$ H.

$= 10^{-7}\left(1 + 4 \cdot \log_e \frac{200}{0.6}\right)$

$= 24.23 \times 10^{-7}$ H.

Loop inductance/Km = $24.23 \times 10^{-7} \times 1000$
$= 24.23 \times 10^{-3}$ H
$= 2.423$ mH.

② Fig. shows the three conductors of the 3ϕ line placed at the corners of an equilateral Δle of each side 2m. Here conductor spacing d = 2m and conductor radius $r = 1.24/2 = 0.62$ cm.

Soln:

$L/ph/m = 10^{-7}(0.5 + 2\log_e d/r)$ H.

$= 10^{-7}(0.5 + 2\log_e \frac{200}{0.62})$ H.

$= 12 \times 10^{-7}$ H.

$L/ph/km = 12 \times 10^{-7} \times 1000.$

$= 1.2 \times 10^{-3}$ H $= 1.2$ mH

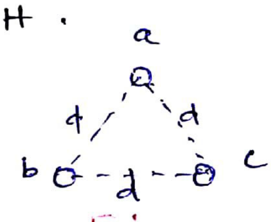
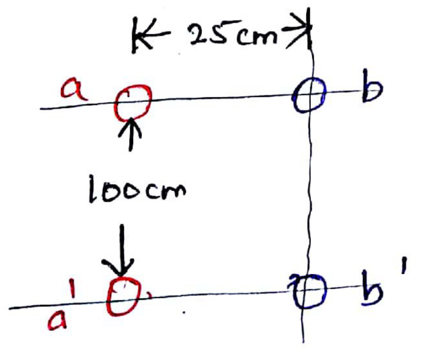


Fig.

③ Fig. shows the arrangement of double ckt. 1ϕ line. Conductor a, a' ~~form~~ 1 connection and conductor b, b' ~~form~~ the return connection. The conductor radius, $r = \frac{1}{2} = 0.5$ cm

Soln:

GMR of conductor $= 0.7788 r$.
$= 0.7788 \times 0.5 = 0.389$ cm.



Self GMD : GMR

$D_{S_1} = \sqrt[4]{D_{aa} D_{aa'} D_{a'a} D_{a'a'}}$

$= \sqrt[4]{(0.389 \times 100)^2}$

$= 6.23$ cm.

$D_{S_2} = \sqrt[4]{D_{bb} D_{bb'} D_{b'b} D_{b'b'}}$

$= 6.23$ cm.

$D_S = \sqrt[2]{6.23 \times 6.23} = 6.23$ cm.

~~Mutual Inductance~~:

Mutual GMD between 'a' and 'b'

$$D_m = \sqrt[4]{D_{ab} \cdot D_{ab'} \cdot D_{a'b} \cdot D_{a'b'}}$$

$$= \sqrt[4]{25 \cdot 103 \cdot 103 \cdot 25}$$

$$= 50.74 \text{ cm}$$

$\because D_{ab'} = D_{a'b}$

$= \sqrt{25^2 + 100^2}$

$= 103$ cm

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

$$= 2 \times 10^{-7} \log_e \frac{50.74}{6.23}$$

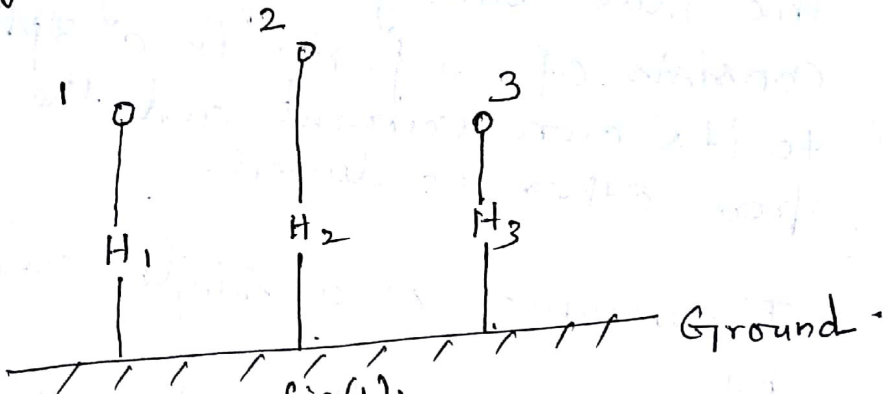
$$= 0.42 \times 10^{-6} H.$$

$\therefore$ Loop Inductance/Km $= 2 \times 0.42 \times 10^{-6} \times 1000$

$= 0.84$ mH.

Expression for Inductance of multiconductor lines used in EHVAC transmission.

Let us consider a system of several conductors located at non uniform heights above the ground as shown in figure(1).



fig(1).

Now the conductors are in air, but their images also exist below the ground with same height as that of conductors from the ground point as shown in fig(2)

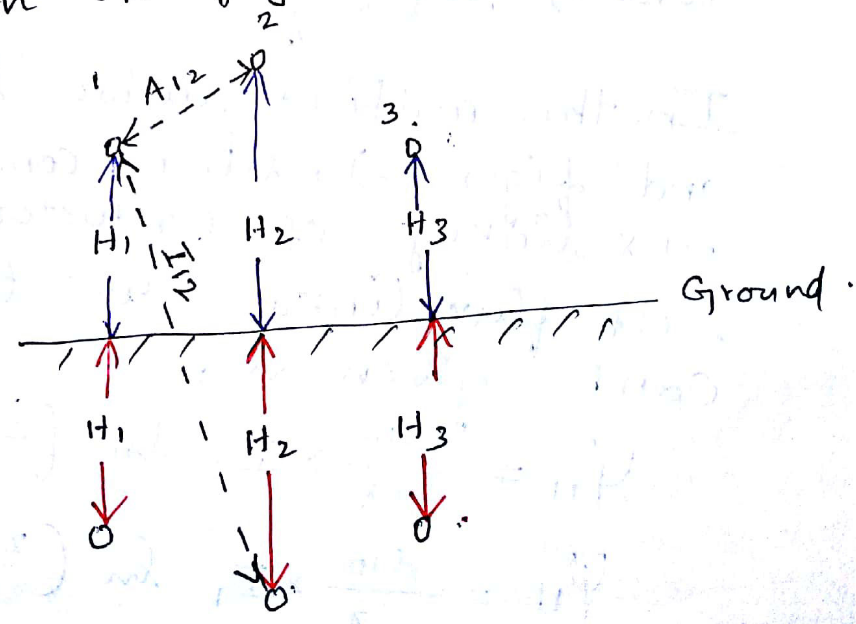


fig.(2).

It canbe seen in fig(2) that the actual conductors in air have their replica below ground. These image conductors carry equal current as those of their corresponding actual conductor but in reverse direction.

The flux linkage of any conductor, say '1' consists of 3 parts in a 3phase line, due to its own current and the contribution from other conductors.

Inductance of a single conductor is given by,

$$L = 2 \times 10^{-7} \ln \frac{d}{r'} \ H/m.$$

$$= 0.2 \ln \left(\frac{d}{r'}\right) \ mH/Km.$$

$d = 2H$

$$= 0.2 \ln \left(\frac{2H}{r'}\right) \ mH/KM.$$

$r' = r_{eq}$
$= 0.7788 \times r$
$= D_s$.

where, $\ln\left(\frac{2H}{r'}\right) \rightarrow$ Maxwell's coeff.

In the multi conductor lines of fig.(1) and figure(2), let us consider the flux linkage of conductor-1. The self flux linkage due to its own current can be given as,

$$\psi_{11} = \frac{\mu_0}{2\pi} \times I_1 \ln\left(\frac{2H}{r'}\right)$$

$$\psi_{11} = \frac{\mu_0}{2\pi} \times I_1 \ln\left(\frac{2H}{D_s}\right).$$

D_s - GMR.

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Now, the flux linkage of conductor-1 only due to the current flowing in conductor-2 will have concentric flux lines about conductor-2 and the flux lines which will link conductor 1 will be beyond the arieal distane i.e., A_{12}.

* IIIly the flux linkage of conductor-1 only due to the current flowing in the image of conductor-2 i.e $(-I_2)$ is considered, then the flux lines which link the ~~arieal~~ aerial conductor-1 will be flowing beyond the distance I_{12}.

Hence in phase-1 the total flux linkage due to the current of conductor 2 or ph-2 is given as,

$$\psi_{12} = \frac{\mu_0}{2\pi}\left[I_2 \int_{A_{12}}^{\infty} \frac{dx}{x} - I_2 \int_{I_{12}}^{\infty} \frac{dx}{x}\right]$$

$$= \frac{\mu_0}{2\pi} I_2 \ln\left[\frac{I_{12}}{A_{12}}\right]$$

where, $\ln\left[\frac{I_{12}}{A_{12}}\right]$ is the mutual Maxwell's coeff. (P_{12}) between the conductor.

$$\therefore P_{ij} = \ln\left[\frac{I_{ij}}{A_{ij}}\right] \quad \text{where } i = j$$

The flux linkage matrix for a system in which 'n' conductors are present is given as,

$$[\psi_n] = \frac{\mu_0}{2\pi}[P]_{nn}[I]_n$$

$$[\psi_n] = [L]_{nn} \cdot [I]_n.$$

where,

ψ_n = Flux linkage matrix.
$= [\psi_1, \psi_2 \cdots \psi_n]$.

L_{nn} = Inductance Matrix $= 0.2[P]_{nn}$
$= \frac{\mu_0}{2\pi}[P]_{nn}$.

I_n = Current matrix.
$= [I_1, I_2 \cdots, I_n]$

$[P]_{nn}$ = Maxwell's Coefficient matrix

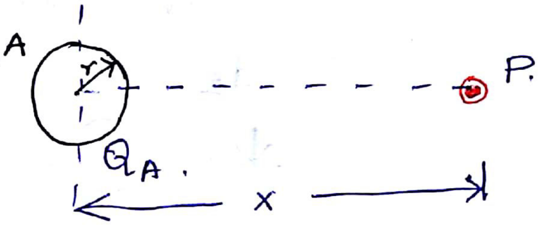
$$P_{ii} = \ln\left[\frac{2H}{r_{eq}}\right].$$

$$P_{ij} = P_{ji} = \ln\left[\frac{I_{ij}}{A_{ij}}\right] \text{ where } i \neq j.$$

In the inductance matrix $[L]_{nn}$, the self inductances are represented by diagonal elements and the mutual inductances are represented by the off-diagonal elements.

Capacitance of Transmission Line.

Electric Potential at a point due to a charge is the workdone in bringing a unit positive charge from infinity to that point.



The concept of electric potential is extremely important for the determination of capacitance in a circuit.

(i) Potential at a charged Single Conductor.

* Consider a long straight cylinderical conductor 'A' of radius 'r' metres.
* Let the conductor operates at such a potential (V_A) that charge Q_A coulombs per metre (C/m) exists on the conductor.
* The electric field intensity (E) at distance 'x' from the centre of the conductor in air is given by.

$$E = \frac{Q_A}{2\pi x \epsilon_0} \quad V/m.$$

Q_A - Charge per metre length

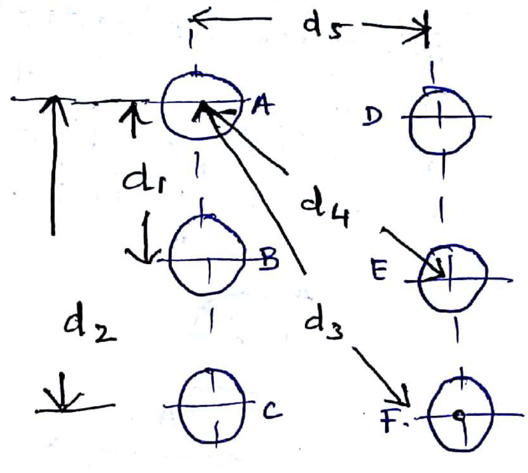
ϵ_0 - permittivity of free space.

As $x \to \infty$, $E \to 0$

Therefore the P.d between conductor 'A' and infinity distant neutral plane is given by,

$$V_A = \int_r^{\infty} \frac{Q_A}{2\pi x \epsilon_0} dx = \frac{Q_A}{2\pi \epsilon_0} \int_r^{\infty} \frac{dx}{x}$$

(ii) Potential at a Conductor in a group of charged conductor.



Potential at 'A' due to its own Charge (Q_A)

$$= \int_{r}^{\infty} \frac{Q_A}{2\pi x \epsilon_0} dx.$$

Potential at 'A' due to charge Q_B.

$$= \int_{d_1}^{\infty} \frac{Q_B}{2\pi x \epsilon_0} dx.$$

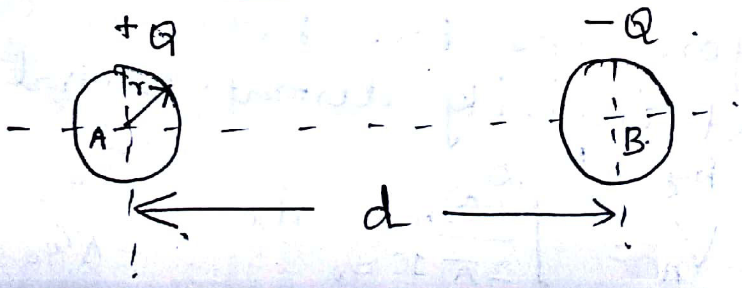
duce to Q_C.

$$= \int_{d_2}^{\infty} \frac{Q_C}{2\pi x \epsilon_0} dx.$$

V_A = (i) + (ii) + (iii) + ...

$$= \frac{1}{2\pi \epsilon_0} \left[Q_A \ln \frac{1}{r} + Q_B \ln \frac{1}{d_1} + Q_C \ln \frac{1}{d_2} + \dots \right]$$

Capacitance of 1ϕ 2 wire Line.



Total p.d between Conductor A and neutral "infinite" plane is.

$$V_A = \int_r^\infty \frac{Q}{2\pi x \epsilon_0}\,dx + \int_d^\infty \frac{-Q}{2\pi x \epsilon_0}\,dx.$$

$$= \frac{Q}{2\pi\epsilon_0}\left[\ln\frac{\infty}{r} - \log\frac{\infty}{d}\right] = \frac{Q}{2\pi\epsilon_0}\ln\frac{d}{r}\,V.$$

$$V_B = \frac{-Q}{2\pi\epsilon_0}\ln\frac{d}{r}\,V.$$

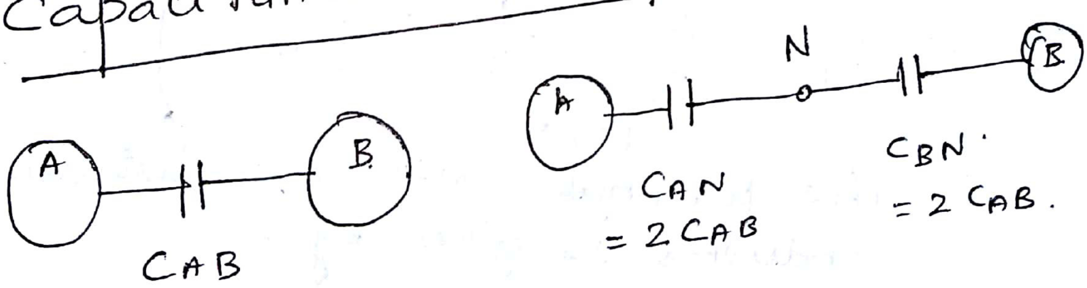
Since both the potentials are w.r.t the same neutral plane.

$$V_{AB} = 2V_A = \frac{2Q}{2\pi\epsilon_0}\ln\frac{d}{r}\,V.$$

$$\text{Capacitance, } C_{AB} = \frac{Q}{V_{AB}} = \frac{Q}{\frac{2Q}{2\pi\epsilon_0}\cdot\ln\frac{d}{r}}$$

$$C_{AB} = \frac{\pi\epsilon_0}{\ln\frac{d}{r}}\ F/m.$$

Capacitance to Neutral.

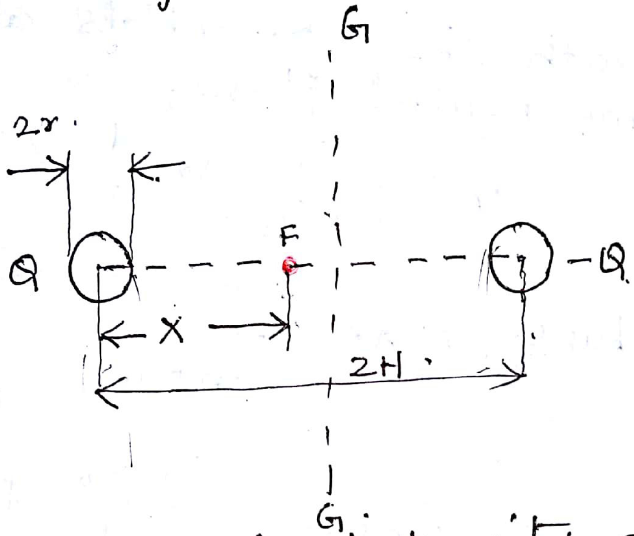


$$C_N = C_{AN} = C_{BN} = 2.C_{AB}$$

$$= \frac{2\pi\epsilon_0}{\ln\frac{d}{r}}\ F/m.$$

Line Capacitance Calculation:

- Consider two conductors of equal radius, with their centres 2H apart, as shown in fig. 8.
- Charge on conductors +Q and −Q. (Coulombs/metre).
- A unit positive test charge is located at point F at a distance 'x' from the centre of the conductor on the left side.



Electric field intensity at pt. F is given by

$$E_F = \frac{Q}{2\pi \epsilon_0}\left(\frac{1}{x} + \frac{1}{2H-x}\right)$$

The potential difference between two conductors is given by

$$V = \frac{Q}{2\pi\epsilon_0}\int_{r}^{2H-r}\left(\frac{1}{x} + \frac{1}{2H-x}\right)dx = \frac{Q}{\pi\epsilon_0}\ln\left(\frac{2H-r}{r}\right)$$

If, $2H \gg r \Rightarrow V = \frac{Q}{\pi\epsilon_0}\ln\frac{2H}{r}$.

By Symmetry, the mid-plane G-G will be at $\frac{1}{2}V$ (0.5V) and the p.d between the (+)ve conductor and (G-G) is $V_g = \frac{V}{2}$.

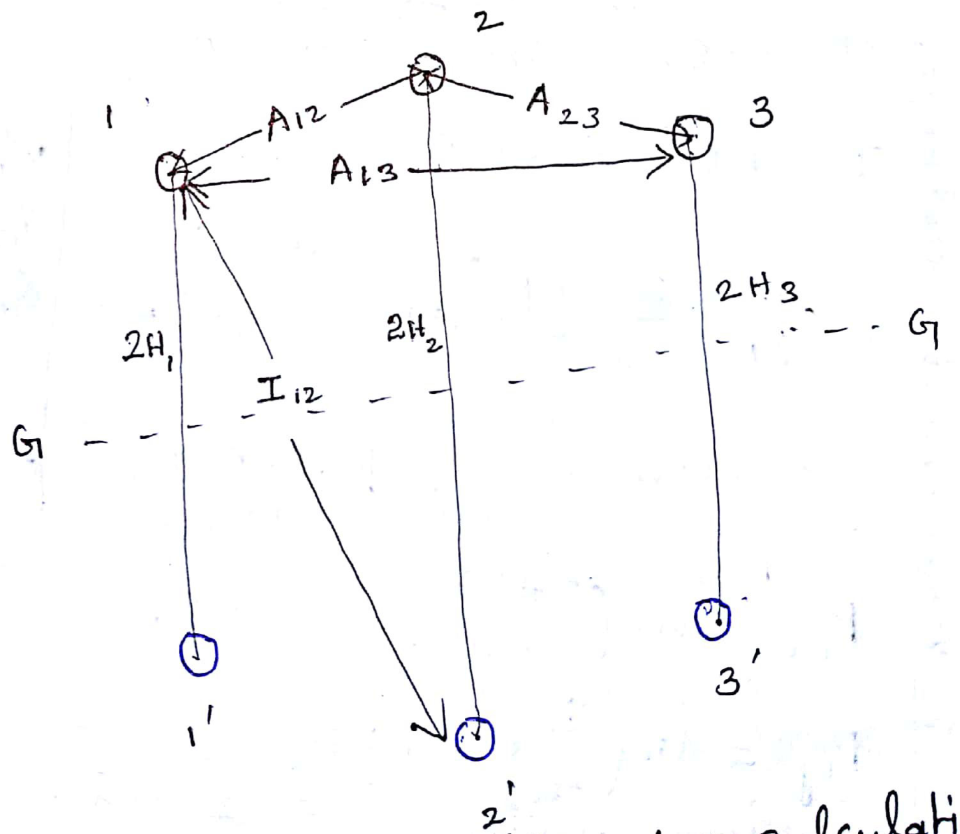
$$V_g = \frac{Q}{2\pi\epsilon_0} \ln \frac{2H}{r}$$

$$= \frac{Q}{2\pi\epsilon_0} \ln. \frac{\text{Dist. of Conductor from (-)ve Charge}}{\text{Dist. of Conductor from (+)ve Charge}}$$

$\ln \frac{2H}{r} \Rightarrow$ Maxwell's potential coeff.
(same type in inductance calculation).

$\therefore$ Self potential Coeff. $P_{ii} = \ln \frac{2H}{r}$.

Mutual potential coeff between phases are determined by placing the conductors and their images with proper charge.



Multiconductor line for calculation of Maxwell's potential coeff.

The potential of conductor '1' due to the charges Q_2 and $-Q_2$ of conductor 2 and its image will be.

$$V_{12} = \frac{Q_2}{2\pi\epsilon_0} \ln \frac{\text{Distance from } -Q_2}{\text{Distance from } +Q_2}$$

$$= \frac{Q_2}{2\pi\epsilon_0} \ln\left(\frac{I_{12}}{A_{12}}\right) = \frac{Q_2}{2\pi\epsilon_0} \cdot P_{12}.$$

For a system of 'n' conductors (Phases or poles) above ground, the potentials of conductors will be,

$$V_1 = \frac{Q_1}{2\pi\epsilon_0} \ln \frac{2H_1}{r} + \frac{Q_2}{2\pi\epsilon_0} \ln \frac{I_{12}}{A_{12}} + \cdots + \frac{Q_n}{2\pi\epsilon_0} \ln \frac{I_{1n}}{A_{1n}}$$

$$\vdots$$

$$V_n = \frac{Q_1}{2\pi\epsilon_0} \ln \frac{I_{n1}}{A_{n1}} + \frac{Q_2}{2\pi\epsilon_0} \ln \frac{I_{n2}}{A_{n2}} + \cdots + \frac{Q_n}{2\pi\epsilon_0} \ln \frac{2H_n}{r}.$$

In Matrix form:

$$[V]_n = [P]_{nn} \left[\frac{Q}{2\pi\epsilon_0}\right]_n.$$

where,
$V_n = [V_1, V_2 \cdots V_n]_t$
$Q_n = [Q_1, Q_2, \cdots Q_n]_t$

The elements of potential Coeff:

$P_{ii} = \ln\left(\frac{2H_i}{r}\right)$ → Self

$P_{ij} = \ln\left(\frac{I_{ij}}{A_{ij}}\right)$, $i \neq j$ → Mutual
$i, j = 1, 2 \cdots n$

Capacitance Matrix

$$[C]_{nn} = 2\pi\epsilon_0 [P]^{-1}_{nn} = 2\pi\epsilon_0 [M].$$

If Internal flux are neglected,
$[L][C] = \mu_0\epsilon_0 [U] = \frac{1}{\vartheta^2}[U]$.
$[U]$ → unit matrix
ϑ = velocity of light = 3×10^8 km/s.

Pbm:

A 345KV line has an ACSR blue bird Conductor 1.762 inches (0.04477 m) in diameter with an eq. radius (req) for inductance calculation of 0.0181 m. The height of line is 13m. calculate the inductance per km length of conductor and the error caused by neglecting the internal flux linkage.

Soln:

Given that,

3-phase Line, Line Voltage, V = ~~345~~ kV.

Height, H = 13m, Spacing, ~~S = 12m~~.

Conductor diameter, d = 0.04477 m
= 1.762 inches.

$r_{eq} = r' = 0.0181$ m ~~inches~~.

To Calculate,

a) L/Km ?

b) Error caused by neglecting the internal flux linkage E = ?

a) $L_A = 2\times10^{-7} \ln \frac{d}{r'}$ H/m.

$= 0.2 \ln\left(\frac{2H}{r'}\right)$ mH/KM.

$= 0.2 \ln\left(\frac{2\times13}{0.0181}\right)$

$= 1.454$ mH/KM.

b) When flux linkage is neglected.

$L = 0.2 \ln(2H/r)$.

$r = \frac{d}{2} = \frac{0.04477}{2} = 0.022385$

$L = 0.2 \ln\left(\frac{2\times13}{0.022385}\right) = 1.411$ mH/KM.

The error caused by neglecting the internal flux linkage is given by.

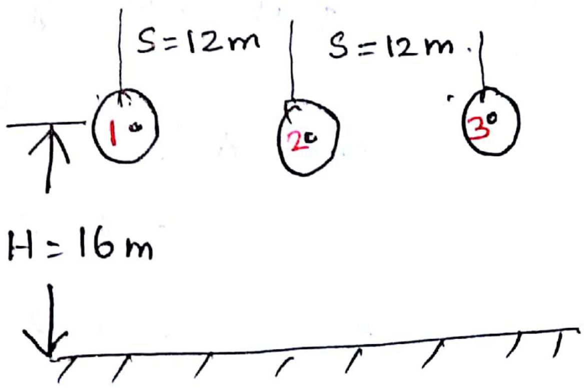
Error, E = Difference between the inductance per KM of length when internal flux linkage is considered and the inductor per KM of length when internal flux linkage is neglected.

= 1.454 − 1.411
= 0.043
Error. = 4.3%.

(2) The dimension of a 3-ph, 400 KV horizontal line are: H = 16m, S = 12m phase separation, Conductor 2 x 3.18 cm dia, and B = 45.72m. Calculate:

(i) The matrix of inductance per KM, for. untransposed configuration, and.

(ii) The same when there is complete. transposition.



Soln:

Given that.

3 ∅ line.
V = 400 K.V.
H = 16 m.
S = 12 m.

Conductor dia d = 2x3.18cm.

r = 3.18cm.

B = 45.72 cm.

we have.

$$r_{eq} = \sqrt{r \cdot B} = \sqrt{3.18 \times 10^{-2} \times 45.72 \times 10^{-2}}$$
$$= 0.12\, m.$$

a). For untransposed configuration, the matrix of inductance per KM is given as.

$$[L]_{ut} = 0.2 \begin{bmatrix} P_{11} & P_{12} & P_{13} \\ P_{21} & P_{22} & P_{23} \\ P_{31} & P_{32} & P_{33} \end{bmatrix}.$$

$$P_{ii} = \ln\left[\frac{2H}{r_{eq}}\right]$$

$$P_{ij} = P_{ji} = \ln\left[\frac{I_{ij}}{A_{ij}}\right] \text{ where } i \neq j$$

<u>Self</u> $P_{ii} = P_{11} = P_{22} = P_{33} = \ln\left[\frac{2H}{r_{eq}}\right]$.

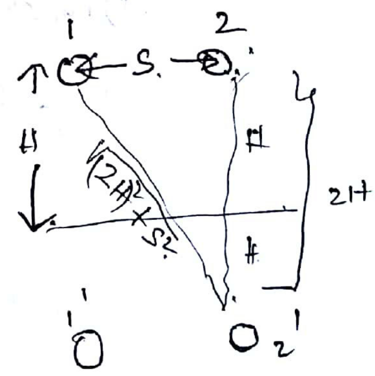
$$= \ln\left[\frac{2 \times 16}{0.12}\right].$$

$$= 5.586.$$

$$P_{12} = P_{21} = P_{23} = P_{32} = \ln\left(\frac{\sqrt{4H^2 + S^2}}{S}\right)$$

$$= \ln\left(\frac{\sqrt{(4 \times 16^2) + 12^2}}{12}\right)$$

$$= 1.047$$



$$= \sqrt{4H^2 + S^2}.$$

$$P_{13} = P_{31} = \ln\left(\frac{\sqrt{4H^2 + 4S^2}}{2S}\right)$$

$$= \ln\left(\frac{\sqrt{4 \times 16^2 + 4 \times 12^2}}{2 \times 12}\right).$$

$$= 0.51.$$

Therefore Matrix of inductance /KM, for untransposed configuration.

$$[L]_{ut} = 0.2 \begin{bmatrix} 5.586 & 1.047 & 0.5 \\ 1.047 & 5.586 & 1.047 \\ 0.5 & 1.047 & 5.586 \end{bmatrix}.$$

$$= \begin{bmatrix} 1.117 & 0.2094 & 0.1 \\ 0.2094 & 1.117 & 0.2094 \\ 0.1 & 0.2094 & 1.117 \end{bmatrix} mH/KM$$

b). The 3ø will divide the completely transposed line in three equal positions. i.e., one third of the line for each phases.

The matrix of inductance per KM for complete transposition is given as

$$[L]_t = \begin{bmatrix} L_s & L_m & L_m \\ L_m & L_s & L_m \\ L_m & L_m & L_s \end{bmatrix}$$

Where,

$$L_s = 0.2. \left[\frac{L_{11} + L_{22} + L_{33}}{3}\right]$$

$$= 0.2 \left[\frac{5.586 + 5.586 + 5.586}{3}\right].$$

$$= 1.1172 \ mH/KM.$$

$$L_m = 0.2\left(\frac{L_{12} + L_{23} + L_{31}}{3}\right) = \frac{0.2(1.047 + 1.047 + 0.5)}{3.}$$

$$= 0.173 \ mH/KM.$$

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$$[L]_t = \begin{bmatrix} 1.1172 & 0.173 & 0.173 \\ 0.173 & 1.1172 & 0.173 \\ 0.173 & 0.173 & 1.1172 \end{bmatrix}$$

(3) Calculate the Capacitance matrix of the 3ϕ, 400kV line shown in previous problem.

a) For Untransposed Configuration the Matrix of Maxwell's Coeff

$$[P]_{ut} = \begin{bmatrix} 5.863 & 1.0664 & 0.525 \\ 1.0664 & 5.863 & 1.0664 \\ 0.525 & 1.0664 & 5.863 \end{bmatrix}$$

Its inverse is

$$|M|_{ut} = [P]^{-1}_{ut} = \begin{bmatrix} 0.176 & -0.298 & -0.0104 \\ -0.0298 & 0.1805 & -0.0298 \\ -0.0104 & -0.0298 & 0.176 \end{bmatrix}$$

The resulting Capacitance Matrix will be

$$|C| = 2\pi\varepsilon_0 [M] = \frac{10^{-9}}{18}[M], \text{ F/m}$$

$$|C|_{ut} = \begin{bmatrix} 9.77 & -1.65 & -0.58 \\ -1.65 & 10.02 & -1.65 \\ -0.58 & -1.65 & 9.77 \end{bmatrix}$$

b) For the completely transposed line.

$$[C] = \begin{bmatrix} C_s & C_m & C_m \\ C_m & C_s & C_m \\ C_m & C_m & C_s \end{bmatrix}$$ with $C_s = 9.85$ nF/km, $C_m = -1.29$ nF/km

Sequence Inductances and Capacitance.

- Used for analyzing 3-phase problem
- to solve very extensive Network problems.
- to obtain mutually independent qty from the original phase quantities that have mutual interaction.

Inductance transformation to Sequence Qtys.

A fully transposed 3ϕ AC line, the flux linkage equation is.

$$L_{3\phi} = \frac{\Psi_{3\phi}}{I_{3\phi}}.$$

$$\Psi_3 = [L]_{33} [I]_3 \quad \text{—— (1)}$$

The inductance Matrix is symmetric for a transposed line for which the Symmetrical-Components theory will be used.

For zero-seq, the currents in the 3ϕ are equal and in phase so that $I_1 = I_2 = I_3 = I_0$. The resulting flux linkage is.

$$\Psi_0 = \begin{vmatrix} L_s & L_m & L_m \\ L_m & L_s & L_m \\ L_m & L_m & L_s \end{vmatrix} \begin{vmatrix} 1 \\ 1 \\ 1 \end{vmatrix} I_0 = \begin{vmatrix} 1 \\ 1 \\ 1 \end{vmatrix} [L_s \; 2L_m] I_0$$

Consequently, the inductance offered to Zero-seq. Currents is

$$\boxed{L_0 = L_s + 2L_m} \quad \text{—— (2).}$$

When (+)ve Seq. Currents are impressed,

$I_1 = I_m \sin\omega t$, $I_2 = I_m \sin(\omega t - 120^\circ)$ and $I_3 = I_m \sin(\omega t + 120^\circ)$.

$$\psi_1 = \begin{bmatrix} L_s & L_m & L_m \\ L_m & L_s & L_m \\ L_m & L_m & L_s \end{bmatrix} \begin{bmatrix} \sin\omega t \\ \sin(\omega t - 120^\circ) \\ \sin(\omega t + 120^\circ) \end{bmatrix} I_m$$

$$= \begin{bmatrix} \sin\omega t \\ \sin(\omega t - 120^\circ) \\ \sin(\omega t + 120^\circ) \end{bmatrix} (L_s - L_m) I_m.$$

Hence the inductance offered to (+)ve Seq. is

$$\boxed{L_1 = L_s - L_m} \quad \text{—— (3)}$$

$|||^{ly}$, for Negative sequence currents, the inductance is also

$$\boxed{L_2 = L_s - L_m} \quad \text{—— (4)}$$

Sequence Capacitance

In $|||^{lr}$ manner, we can evaluate the Zero, (+)ve and (−)ve sequence Capacitance.

$$C = \frac{q}{V}.$$

$$Q = C \cdot V$$

$$= \left\{2\pi\varepsilon_0 [P]^{-1}\right\} \cdot V.$$

$$= C \cdot V.$$

Zero-Seq.

Voltage $[V_0] = [1 \;\; 1 \;\; 1]\, V$

$$\boxed{C_0 = C_s + 2C_m} \quad \text{—— (5)}$$

(+)ve Sequence

Voltage $[V_+] = [\sin\omega t, \sin(\omega t - 120°), \sin(\omega t + 120°)]$

and $\boxed{C_1 = C_s - C_m}$ —— (6)

(−)ve seq.

$\boxed{C_2 = C_s - C_m}$ —— (7).

From the above equations, it is observed that,

(i) Zero seq. inductance (L_0) is higher than the self inductance while (+)ve and (−)ve seq inductances (L_1, L_2) are lower than L_s.

$$L_0 > L_s \; ; \; L_1; L_2 < L_s.$$

(ii) The converse holds for Capacitance. Since, C_m is a (−)ve qty (X)

$$C_0 < C_s \text{ and } C_1; C_2 > C_s.$$

(iii) From above equations, the self and mutual inductances can be found from the seq. inductance.

From eqn. (2) and (3).

(2) ⇒ $L_0 = L_s + 2L_m \longrightarrow L_s = L_0 - 2L_m$. (A)

(3) ⇒ $L_1 = L_s - L_m \longrightarrow L_m = L_s - L_1$ (B).

(B) in (A). we get. $L_s = L_0 - 2L_s + 2L_1$

$3L_s = L_0 + 2L_1$

$\boxed{L_s = \frac{1}{3}(L_0 + 2L_1)}$ $\boxed{L_m = \frac{1}{3}(L_0 - L_1)}$

(iv). IIIly $\boxed{C_s = \frac{1}{3}(C_0 + 2C_1)}$, $\boxed{C_m = \frac{1}{3}(C_0 - C_1)}$.

Sequence L, C from phase Quantities. (Matrix Diagonalization).

Referring to Symmetrical Component theory, the Phase quantities are transformed to Symmetrical Components by,

$$\begin{vmatrix} V_0 \\ V_1 \\ V_2 \end{vmatrix} = \frac{1}{3}\begin{vmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{vmatrix}\begin{vmatrix} V_a \\ V_b \\ V_c \end{vmatrix} \quad \text{——— (1).}$$

where $\alpha = 1\angle 120^\circ$.

$$\begin{vmatrix} V_a \\ V_b \\ V_c \end{vmatrix} = \begin{vmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{vmatrix}\begin{vmatrix} V_0 \\ V_1 \\ V_2 \end{vmatrix} \quad \text{——— (2).}$$

in (1) and (2) $T = \begin{vmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{vmatrix}$ and $T^{-1} = \frac{1}{3}\begin{vmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{vmatrix}$

If we now carry out the multiplications $[T]^{-1}[L][T]$ and $[T]^{-1}[C][T]$ for a completely transposed line, the result is:

$$|T|^{-1}|L||T| = \frac{1}{3}\begin{vmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{vmatrix} \times \begin{vmatrix} L_s & L_m & L_m \\ L_m & L_s & L_m \\ L_m & L_m & L_s \end{vmatrix} \times \begin{vmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{vmatrix}$$

$$= \begin{vmatrix} L_s + 2L_m & & \\ & L_s - L_m & \\ & & L_s - L_m \end{vmatrix} \quad \text{——— (3)}$$

III ly

$$|T|^{-1}|C||T| = \begin{vmatrix} C_s + 2C_m & & \\ & C_s - C_m & \\ & & C_s - C_m \end{vmatrix} \quad \text{——— (4).}$$

This procedure is convenient for de-coupling mutually interacting quantities and then combining them suitably.
Applied for steady state conditions and use phasor algebra.

For a general problem encountered with E.H.V. transmission lines, they are given the generic name "Modes of Propagation"

Line Parameters for Modes of Propagation

From the previous section,

$\alpha = 1\angle 120^\circ = -0.5 + j0.866 \rightarrow$ Complex No.

This is not convenient when solving equations encountered with wave propagation on the phase or pole conductors which are characterized by a) Velocity of propagation. b) Attenuation and c) Surge Impedance.

(A) Diagonalization Procedure

Inductance Matrix of transposed line.

$$L = \begin{vmatrix} L_s & L_m & L_m \\ L_m & L_s & L_m \\ L_m & L_m & L_s \end{vmatrix}$$

The following steps have to be followed for diagonalization.

Step-1 : By using chs. eqn. $[\lambda|U| - |L|] = 0$ calculate the eigen values (λ) or the chs. roots of the given matrix.

i.e; $\lambda|U| - |L| = 0 \Rightarrow \begin{vmatrix} \lambda - L_s & -L_m & -L_m \\ -L_m & \lambda - L_s & -L_m \\ -L_m & -L_m & \lambda - L_s \end{vmatrix} = 0$

$$\lambda^3 - 3L_s\lambda^2 + 3(L_s^2 - L_m^2)\lambda - (L_s^3 - 3L_sL_m^2 + 2L_m^3) = 0$$

$$(\lambda - L_s - 2L_m)(\lambda - L_s + L_m)^2 = 0$$

The 3 eigen values are,

$\lambda_1 = L_s + 2L_m$, $\lambda_2 = L_s - L_m$, $\lambda_3 = L_s - L_m$.

Step-2:

For each of these eigen values in turn, we evaluate the eigen vector. $[x]$, which is a column matrix, according to the equation.

$$\{|U|\lambda_n - |L|\}[x] = 0$$

$$[\lambda_1 |U| - |L|]\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$

a) Here $\lambda_1 = L_s + 2L_m$.

$$\Rightarrow \begin{bmatrix} L_s+2L_m-L_s & -L_m & -L_m \\ -L_m & L_s+2L_m-L_s & -L_m \\ -L_m & -L_m & L_s+2L_m-L_s \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$

$$\Rightarrow L_m \begin{vmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{vmatrix}\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$

i.e., $2x_1 - x_2 - x_3 = 0$

$-x_1 + 2x_2 - x_3 = 0$

$-x_1 - x_2 + 2x_3 = 0$

If we consider, $x_1 = 1$ then we get,

$x_2 = 1$ and $x_3 = 1$.

$$\text{Eigen vectors } [X] = \begin{vmatrix} X_1 \\ X_2 \\ X_3 \end{vmatrix} = \begin{vmatrix} 1 \\ 1 \\ 1 \end{vmatrix}$$

$$\text{In Normalized form} = \frac{1}{\sqrt{3}}\begin{vmatrix} 1 \\ 1 \\ 1 \end{vmatrix}.$$

b) eigen value $\lambda_2 = L_s - L_m$, find eigen vector.

$$[\lambda_2 |U| - |L|] \begin{bmatrix} y_1 \\ y_2 \\ y_3 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$

$$\Rightarrow \begin{vmatrix} L_s - L_m - L_s & -L_m & -L_m \\ -L_m & L_s - L_m - L_s & -L_m \\ -L_m & -L_m & L_s - L_m - L_s \end{vmatrix} \begin{vmatrix} y_1 \\ y_2 \\ y_3 \end{vmatrix} = \begin{vmatrix} 0 \\ 0 \\ 0 \end{vmatrix}$$

$$\Rightarrow -L_m \begin{vmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{vmatrix} \begin{vmatrix} y_1 \\ y_2 \\ y_3 \end{vmatrix} = \begin{vmatrix} 0 \\ 0 \\ 0 \end{vmatrix}$$

i.e., $y_1 + y_2 + y_3 = 0$
$y_1 + y_2 + y_3 = 0$
$y_1 + y_2 + y_3 = 0$

$\Rightarrow$ if we consider $y_1 = 1$ then $y_2 + y_3 = -1$.

But in this case y_2 and y_3 will have infinite No. of choices. Let us consider $y_2 = 0$ and this gives as $y_3 = -1$.

The resulting eigenvector and normalized form are

$$\begin{vmatrix} 1 \\ 0 \\ -1 \end{vmatrix} \text{ and } \frac{1}{\sqrt{2}} \begin{vmatrix} 1 \\ 0 \\ -1 \end{vmatrix}.$$

c) As the eigen values λ_2 and λ_3 are equal the equations obtained for the components of the eigen vector will also be same.

$z_1 + z_2 + z_3 = 0$, i.e., Let us consider $z_1 = 1$ and then considering $z_3 = 1$, Hence we obtain $z_2 = -2$.

The corresponding eigen vectors and normalized form $\Rightarrow \begin{bmatrix} 1 \\ -2 \\ 1 \end{bmatrix}, \begin{bmatrix} \frac{1}{\sqrt{6}} \\ -2/\sqrt{6} \\ 1/\sqrt{2} \end{bmatrix}$

The inverse transformation matrix or eigen vector matrix can now be written as:

$$[T]^{-1} = \begin{vmatrix} x_1 & x_2 & x_3 \\ y_1 & y_2 & y_3 \\ z_1 & z_2 & z_3 \end{vmatrix}$$

Note: Consider the normalized form,

$$[T^{-1}] = \begin{vmatrix} \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} \\ \frac{1}{\sqrt{2}} & 0 & \frac{-1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & \frac{-2}{\sqrt{6}} & \frac{1}{\sqrt{6}} \end{vmatrix}$$

Now the transformation Matrix will be,

$$|T| = \begin{vmatrix} \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{6}} \\ \frac{1}{\sqrt{3}} & 0 & \frac{-2}{\sqrt{6}} \\ \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{6}} \end{vmatrix}$$

When we evaluate the diagonal matrix. obtained will be.

$$|T|^{-1}|L||T| = \begin{vmatrix} L_s+2L_m & & \\ & L_s-L_m & \\ & & L_s-L_m \end{vmatrix}$$

Here the obtained diagonal elements will be equal to the eigen values and these values are also equal to the sequence inductance presented to the voltage and current.

However these inductances will be now called the inductances for three modes of propagation of electromagnetic energy of the waves generating them.

(B) Interpretation of Eigen vector.

a) Eigen vector corresponding to the first eigen value $\lambda_1 = L_s + 2L_m$ is [1 1 1].

Interpretation:

The travel of all quantities on the three conductors (V, I, Q and Energy) are all equal and same polarity on three conductors.

In this mode of propagation, the return current flow through the ground and attenuation of energy etc. are high because of ground resistance. It is called as Line to Ground mode.

b). $\lambda_2 = L_s - L_m$, EV = [1, 0, -1].

Propagation takes place in the outer-phase conductors only with centre phase being idle.

Here ground is not involved in propagation so that the attenuation is lower than in the line to ground mode.

The second mode is called the Line-Line Mode or Phase-Phase Mode.

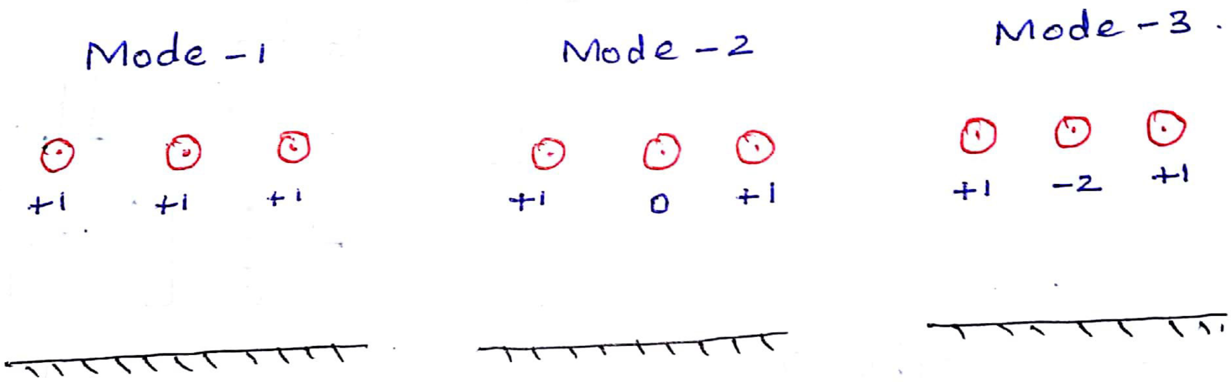
c). $\lambda_3 = L_s - L_m$, EV = [1, -2, 1]

Here the outer phase form the 'GO' for the current and the centre phase the 'RETURN'.

Here also the system is closed, +1 and +1 charges on the outer and -2 on the centre phase. Therefore Ground is not involved in the propagation. This is called as Line to Line mode of 2nd kind or inter-phase mode.

So, the mutually-interacting quantities are resolved into three independent modes of propagation in a manner identical to symmetrical component analysis of which we are familiar, the behaviour of all quantities in each mode can be analysed and the phase quantities are finally obtained by Inverse procedure.

The three modes are pictorially represented as shown in figure.



Concept of Modes of propagation is very useful for. (Advantages)

a) design of carrier equipment for speech. and protection.

b) Propagation of switching and lightning. surge on the line which causes overvoltage

[c] Velocities of Propagation for the modes in Transposed Lines.

w.k.t, $[L][C] = \frac{1}{g^2}[U] = \mu_0 \epsilon_0 [U]$

where g = Velocity of e.m. wave propagation, which is equal to velocity of light.

$$\frac{1}{g^2} = \mu_0 \epsilon_0 \implies \boxed{g = \frac{1}{\sqrt{\mu_0 \epsilon_0}}}$$

$$[T]^{-1}[L][C][T] = \{|T|^{-1}|L||T|\}\{[T]^{-1}[C][T]\} = \frac{1}{g^2}|U|$$

$$= \begin{bmatrix} L_s+2L_m & & \\ & L_s-L_m & \\ & & L_s-L_m \end{bmatrix}\begin{bmatrix} C_s+2C_m & & \\ & C_s-C_m & \\ & & C_s-C_m \end{bmatrix}$$

$$= \frac{1}{g^2}\begin{bmatrix} 1 & & \\ & 1 & \\ & & 1 \end{bmatrix}$$

This gives,

$$(L_s+2L_m)(C_s+2C_m) = L_0 C_0 = \frac{1}{g^2}.$$

$$(L_s-L_m)(C_s-C_m) = L_1 C_1 = 1/g^2.$$

This shows that the velocity of propagation of waves in all 3 modes are equal to the Velocity of Light. This is the case when ground return inductance is not taken into account.

Problem:

The [L] and [C] matrices for the 400 KV horizontal line were worked in previous examples. Diagonalize the Capacitance Matrix of untransposed line.

Soln:

$$C_{ut} = \begin{vmatrix} 9.77 & -1.65 & -0.58 \\ -1.65 & 10.02 & -1.65 \\ -0.58 & -1.65 & 9.77 \end{vmatrix} \text{ nF/KM.}$$

Step-1

$$\lambda[U] - [C] = \begin{vmatrix} \lambda-9.77 & 1.65 & -0.58 \\ -1.65 & \lambda-10.02 & -1.65 \\ -0.58 & -1.65 & \lambda-9.77 \end{vmatrix}$$

$$\lambda^3 - 29.65\lambda^2 + 285.46\lambda - 896.67 = 0.$$

Eigen Values, $\lambda_1 = 11.9755$; $\lambda_2 = 10.35$; $\lambda_3 = 7.2345$

[The chs. roots are distinct].

Step-2

$$\{\lambda_1[U] - [C]\}[x] = \begin{vmatrix} 2.2055 & 1.65 & 0.58 \\ 1.65 & 1.955 & 1.65 \\ 0.58 & 1.65 & 2.2055 \end{vmatrix} \begin{vmatrix} x_1 \\ x_2 \\ x_3 \end{vmatrix} = 0$$

By choosing $x_1 = 1$, We obtain the Components of First eigenvector to be $x_1 = 1$, $x_2 = -1.6887$ and $x_3 = 1.00127 \simeq 1$

$$\therefore \text{ Normalized Form} = \begin{bmatrix} \overset{x_1}{0.454} & \overset{x_2}{-0.7665} & \overset{x_3}{0.454} \end{bmatrix}.$$

Step-3

$\{\lambda_2[U] - [C]\}[y] = 0.$, $\lambda_2 = 10.35$

$$\text{Normalized form} = \begin{bmatrix} \overset{y_1}{0.7071}, & \overset{y_2}{0}, & \overset{y_3}{-0.7071} \end{bmatrix}$$

Step-4

$\{\lambda_3[U] - [C]\}[z] = 0$, $\lambda_3 = 7.2345$

Normalized Form = [0.542, 0.6422, 0.542].

Step-5

$$[T]^{-1} = \begin{vmatrix} 0.454 & -0.7655 & 0.454 \\ 0.7071 & 0 & -0.7071 \\ 0.542 & 0.6422 & 0.542 \end{vmatrix}$$ and

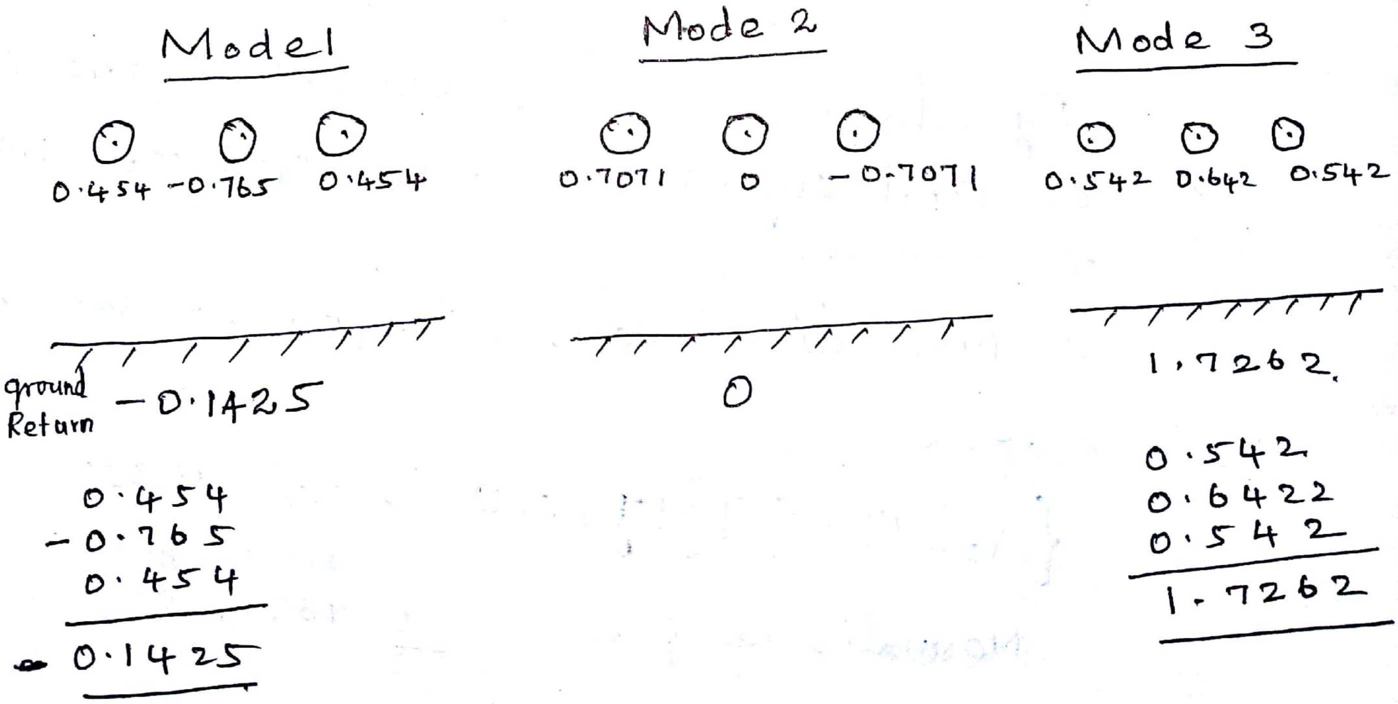
$$[T^{t}] = \begin{vmatrix} 0.454 & 0.7071 & 0.542 \\ -0.7655 & 0 & 0.6422 \\ 0.454 & -0.7071 & 0.542 \end{vmatrix}$$

Step-6

$$[T]^{-1}[C][T] = \begin{vmatrix} 11.954 & & \\ & 10.36 & \\ & & 7.234 \end{vmatrix} \text{ nF/km.}$$

which is nearly the matrix of eigen values.

The figure shows the distribution of currents in the three modes. We note that in only one mode ground is not involved in the propagation.



Diagonalization of $[L]_{ut}$

$$[L][C] = \frac{1}{g^2}[U].$$

$$\{[T]^{-1}[L][T]\}\{[T^{-1}][C][T]\} = \frac{1}{g^2}[U]$$

$$[T]^{-1}[L][T] = \frac{1}{g^2}\{[T]^{-1}\cdot[C][T]\}^{-1}$$

$$= \frac{1}{g^2}\cdot[\lambda]^{-1}.$$

The three eigen values of L are.

$$\mu_1 = \frac{1}{g^2 \times \lambda_1}, \quad \mu_2 = \frac{1}{g^2 \times \lambda_2}, \quad \mu_3 = \frac{1}{g^2 \times \lambda_3}.$$

where g - velocity of Light = 3×10^5 Km/sec.

Problem:

The eigen values of the capacitance matrix are 11.954×10^{-9} F/KM, 10.36×10^{-9} F/KM and 7.234×10^{-9} F/KM. Find the eigen values of Inductance matrix.

Soln.

$$\mu_1 = \frac{1}{g^2 \times \lambda_1} = \frac{1}{(3\times10^5)^2 \times 11.954 \times 10^{-9}} = \frac{1}{1076} = 0.93 \text{ mH/}$$

$$\mu_2 = \frac{1}{g^2 \times \lambda_2} = \frac{1}{(3\times10^5)^2 \times 10.36 \times 10^{-9}} = \frac{1}{932.4} = 1.0725 \frac{\text{m}}{\text{K}}$$

$$\mu_3 = \frac{1}{g^2 \times \lambda_3} = \frac{1}{(3\times10^5)^2 \times 7.234 \times 10^{-9}} = \frac{1}{651} = 1.536 \frac{\text{mH}}{\text{K}}$$

Ground Return

Under balanced operating conditions of a transmission line, ground-return current do not flow. However many situations occur in practice when ground currents have important effect on system performance. Some of these are

a) Short circuit current due to 1 L-G, 2 L-G faults.

b) Switching operations and Lightning Phenomena;

c) Propagation of waves on conductors

d) Radio Interference.

The ground-return resistance increases with frequency of the current while the inductance decreases with frequency. In all cases involving ground, the soil is inhomogeneous and stratified in several layers with different values of electrical conductivity.

UNIT – III

Corona Effects

Corona Discharge (also known as **the Corona Effect**) is an electrical discharge caused by the ionization of a fluid such as air surrounding a conductor that is electrically charged. The corona effect will occur in high voltage systems unless sufficient care is taken to limit the strength of the surrounding electric field.

Corona discharge can cause an audible hissing or cracking noise as it ionizes the air around the conductors. This is common in high voltage electric power transmission lines. The corona effect can also produce a violet glow, production of ozone gas around the conductor, radio interference, and electrical power loss.

Corona Effect

The corona effect occurs naturally due to the fact that air is not a perfect insulator – containing many free electrons and ions under normal conditions. When an electric field is established in the air between two conductors, the free ions and electrons in the air will experience a force. Due to this effect, the ions and free electrons get accelerated and moved in the opposite direction.

The charged particles during their motion collide with one another and also with slow-moving uncharged molecules. Thus the number of charged particles increases rapidly. If the electric field is strong enough, a dielectric breakdown of air will occur and an arc will form between the conductors.

Electric power transmission deals with the bulk transfer of electrical energy, from generating stations situated many kilometers away from the main consumption centers or the cities. For this reason, the long-distance transmission conductors are of utmost necessity for effective power transfer – which in-evidently results in huge losses across the system.

Minimizing these energy losses has been a major challenge for power engineers. Corona discharge can significantly reduce the efficiency of EHV (Extra High Voltage) lines in power systems.

Two factors are important for corona discharge to occur:

1. Alternating electrical potential difference must be supplied across the line.

2. The spacing of the conductors, must be large enough compared to the line diameter.

When an alternating current is made to flow across two conductors of a transmission line whose spacing is large compared to their diameters, the air surrounding the conductors (composed of ions) is subjected to dielectric stress.
At low values of the supply voltage, nothing occurs as the stress is too small to ionize the air outside. But when the potential difference increases beyond some threshold value (known as the **critical disruptive voltage**), the field strength becomes strong enough for the air surrounding the conductors to dissociated into ions – making it conductive. This critical disruptive voltage occurs at approximately 30 kV.

The ionized air results in electric discharge around the conductors (due to the flow of these ions). This gives rise to a faint luminescent glow, along with the hissing sound accompanied by the liberation of ozone.

This phenomenon of electric discharge occurring in high voltage transmission lines is known as **the corona effect**. If the voltage across the lines continues to increase, the glow and hissing noise becomes more and more intense – inducing a high power loss into the system.

Factors Affecting Corona Loss

- **Atmospheric Conditions**

  We have proved that the voltage gradient for dielectric breakdown of air is directly proportional to the density of air. Hence in a stormy day, due to continuous air flow, the number of ions present surrounding the conductor is far more than normal, and hence it's more likely to have electrical discharge in transmission lines on such a day, compared to a day with the fairly clear weather. The system has to be designed considering those extreme situations.

- **Condition of Conductors**

This particular phenomenon depends highly on the conductors and its physical condition. It has an inverse proportionality relationship with the diameter of the conductors. i.e., with the increase in diameter, the effect of corona on power system reduces considerably. Also, the presence of dirt or roughness of the conductor reduces the critical breakdown voltage, making the conductors more prone to corona losses. Hence in most cities and industrial areas having high pollution, this factor is of reasonable importance to counter the ill effects it has on the system.

- **Spacing Between Conductors**

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

Reducing Corona Discharge

Corona discharge always results in power loss. Energy is lost in the form of light, sound, heat, and chemical reactions. Although these losses are individually small, over time they can add up to significant power loss in high voltage networks.

Corona discharge can be reduced by:

- **Increasing the conductor size:** A larger conductor diameter results in a decrease in the corona effect.
- **Increasing the distance between conductors:** Increasing conductor spacing decreases the corona effect.
- **Using bundled conductors:** Bundled conductors increase the effective diameter of the conductor – hence reducing the corona effect.

- **Using corona rings:** The electric field is stronger where there is a sharp conductor curvature. Because of this corona discharge occurs first at the sharp points, edges, and corners. Corona rings reduce the corona effect by 'rounding out' conductors (i.e. making them less sharp). They are used at the terminals of very high voltage equipment (such as at the bushings of high voltage transformers). A corona ring is electrically connected to the high voltage conductor, encircling the points where the corona effect is most likely to occur. This encircling significantly reduces the sharpness of the surface of the conductor – distributing the charge across a wider area. This in turn reduces corona discharge.

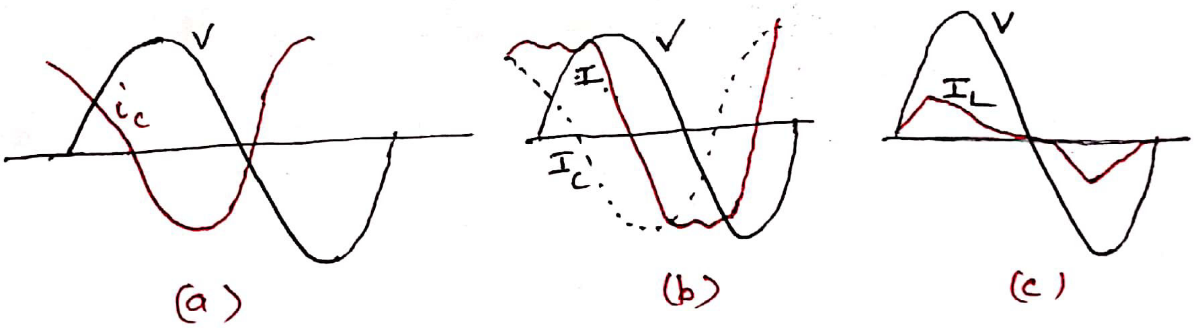
Corona loss:

* Avg. Corona loss for 345KV to 750KV lines – 1 to 20 KW/KM in fair weather
* In foul weather conditions, the losses can go upto 300KW/KM.

Yearly Average loss:

(2 - 10) KW/KM for 400Km lines
(20 - 40) KW/KM for 800 KM lines

Corona Current:



(a) When no corona is present, current is sinusoidal. The current leads/lags voltage by 90°

(b) When corona is present, it calls for a loss component and a typical waveform of the total current is shown in fig (b).

(c) When the two components are separated, the resulting inphase component has a waveform which is not sinusoidal.

$P_c = 3 \times$ L-G voltage $\times$ in-ph. component of current.

Corona loss Formula (P_c)

P_c is the function of,

a) Corona inception voltage 'V_0'
b) Actual voltage of the conductor 'V'
c) The excess voltage, $(V - V_0)$
(d) Conductor surface voltage (E). gradient
(e) Corona-inception gradient, (E_0)
(f) Frequency (f).
(g) Conductor size, (d); No. of cond/bundle 'N'
(h) atmospheric conditions, (chiefly rate of rainfall) 'P'
(i) Conductor surface condition.

I. Based on voltage:

(i) Linear relationship: (Skilling's formula).

$$P_c \propto (V - V_0).$$

(ii) Quadratic relationship

a) Peek's Formula $P_c \propto (V-V_0)^2$

b) Rayan/Henline Formula, $P_c \propto V \cdot (V-V_0)^2$

c) Peterson's Formula, $P_c \propto V^2 \cdot F \cdot (V/V_0)^2$.

$F \rightarrow$ Experimental Factor.

(iii) Cubic Relationship.

a) Foust and Menger Formula, $P_c \propto V^2$

b) Prinz's Formula, $P_c \propto V^2 (V-V_0)$.

(B) Based on Voltage Gradients.

a) Nigol and Cassan Formula, $P_c \propto E^2 \cdot \ln(E/E_0)$

b) Project EHV formula, $P_c \propto V \cdot E^m, m=5$

Corona loss formula for 3ϕ EHV Lines in KW/KM.

(i) Nigol and Cassan formula.

$$P_c = K \cdot f \cdot r^3 \cdot \theta \cdot E^2 \cdot \ln\left(\frac{E}{E_0}\right), \text{ KW/KM, 3-ph.}$$

where,

f - freq. in HZ; r – radius of Conductor (cm) ~~surface~~

θ - Angular position in radians of Conductor surface where the Voltage gradient exceeds the critical Corona-inception gradient,

E - Effective surface gradient at operating Voltage V, KV/cm, r.m.s.

E_0 - Corona-inception gradient for given weather and Conductor surface Condition, KV/cm

K - a Constant which depends upon weather and Conductor surface conditions.

(2) Anderson, Baretsky, McCarthy Formula.

An equation for Corona loss in rain giving the excess loss above the fair weather loss in KW/3-ph KM is:

$$P_c = P_{FW} + 0.3606\ k.V.r^2.\ ln(1+10\rho).\sum_{1}^{3N} E^5$$

where,

P_{FW} = total fair weather loss in KW/KM,
- 1 to 5 KW/km for 500 KV
- 3 to 20 KW/km for 700 KV

K = 5.35×10^{-10} for 500 to 700 KV lines.
= 7.04×10^{-10} for 400 KV lines.

V = Conductor voltage in KV, L-L, r.m.s.

E = Surface voltage gradient on the underside of the conductor, KV/cm, peak,

ρ = rain rate in mm/hour. ρ = 10% → Heavy snow. ρ = 2.5% → Medium snow. ρ = 0.5% → Light snow.

r = radius of conductor, cm.

N = No. of conductors in bundle of each phase

PEEKS FORMULA

$$P_c = 5.16 \times 10^{-3}.\ f.\ \sqrt{r/2H}\ V^2(1 - V_0/V)^2,\ KW/Km.$$

H – height above ground (m).

V, V_0 — KV, r.m.s

r – radius of conductor (m).

δ – Air density

Voltage Gradient $(E) = \frac{V}{rK}\left(ln\left(\frac{2H}{r}\right)\right)$ and

$(E_0) = 21.4\,\delta(1 + 0.0301/\sqrt{r\delta})$

Problem:

For $r = 1cm$, $H = 5m$, $f = 50Hz$, Calculate Corona loss P_c according to Peek's formula when $E = 1.1\,E_0$ and $\delta = 1$.

Soln:

$E_0 = 21.4\delta(1 + 0.0301/\sqrt{r.\delta})$

$= 21.4 \times 1(1 + 0.0301/\sqrt{0.01})$

$= 27.84$ kV/cm.

$E = 1.1 \times E_0$

$= 30.624$ kV/cm

$\sqrt{r/2H} = 0.0316.$

$V = E.r.\ln(2H/r) = 211.4$ KV (L-L).

$= 30.624 \times 1 \times \ln\left(\frac{2 \times 500}{1}\right).$

$\left[V_0 = \frac{V}{1.1}\right].$

$= 211.4$ KV

a) $P_c = 5.16 \times 10^{-3} . f . \sqrt{r/2H} . V^2(1 - V_0/V)^2$ KW/km.

$= 5.16 \times 10^{-3} \times 50 \times 0.0316 \times 211.4^2(1 - 1/1.1)^2.$

$= 2.954$ KW/KM.

b) Corona loss

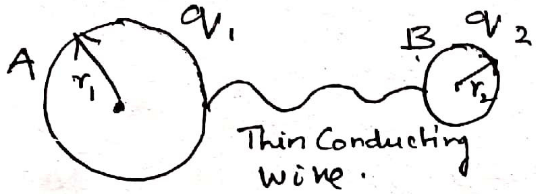
$i_c = \frac{P_c}{V} = \frac{2.954}{211.54} = 0.013964.$ ~~0.030916~~

$= 30.916 \times 10^{-3}$ Amp/KM.

$= 30.916$ mA/KM.

Corona Concept

Two spheres – Connected by a Wire
– Now @ Same Voltage.



$$V_1 = V_2 = \frac{q_1}{4\pi\epsilon_0 r_1} = \frac{q_2}{4\pi\epsilon_0 r_2}$$

$$\frac{q_1}{r_1} = \frac{q_2}{r_2}$$

$$\frac{4\pi r_1^2 \sigma_1}{r_1} = \frac{4\pi r_2^2 \sigma_1}{r_2}$$

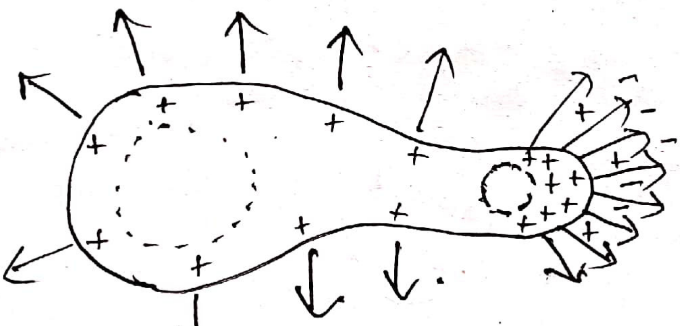
$$r_1\sigma_1 = r_2\sigma_1 \quad | \; \sigma - \text{ch. density}$$

$$r\sigma = K$$

If $r \downarrow$ $\sigma \uparrow$ (more).

More Charge density, it ionises anything surrounding it.

$$\Leftarrow (X) \boxed{\sigma = \frac{K}{r}} \Rightarrow \sigma \propto \frac{1}{r}.$$



irregular shape Conductor.

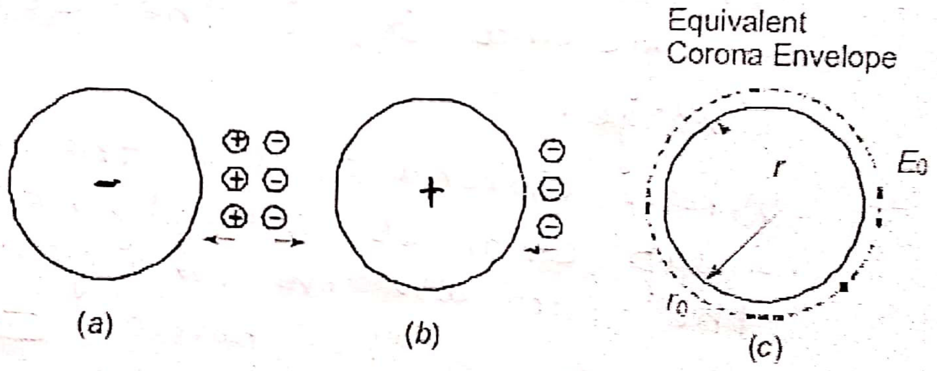
⟹ Largest curvature more the No. of Charges
↓
More Elect. Field
↓
ionizes the air surrounding it
means
↓ splits the molecules into (+)ve (−)ve
↓
(+)ve ions repelled and (−)ve charges are attracted by (+)ve Charges and neutralization takes place. So, the charges may get reduced to to discharge.

CHARGE-VOLTAGE (q – V) DIAGRAM AND CORONA LOSS

Increase in Effective Radius of Conductor and Coupling Factors

The partial discharge of air around a line conductor is the process of creation and movement of charged particles and ions in the vicinity of a conductor under the applied voltage and field.

We shall consider a simplified picture for conditions occurring when first the voltage is passing through the negative half-cycle and next the positive half-cycle, as shown in figure



In Figure (a), free electrons near the negative conductor when repelled can acquire sufficient energy to form an electron avalanche. The positive ions (a neutral molecule which has lost an electron) are attracted towards the negative conductor while the electrons drift into lower fields to attach themselves to neutral atoms or molecules of Nitrogen and Oxygen to form negative ions. Some recombination could also take place. The energy imparted for causing initial ionization by collision is supplied by the electric field.

During the positive half cycle, the negative ions are attracted towards the conductor, but because of local conditions not all ions drift back to the conductor. A space charge is left behind and the hysteresis effect gives rise to the energy loss. Furthermore, because of the presence of charged particles, the effective charge of the conductor ground electrode system is increased giving rise to an increase in effective capacitance. This can be interpreted in an alternative manner by assuming that the conductor diameter is effectively increased by the conducting channel up to a certain extent where the electric field intensity decreases to a value equal to that required for further ionization, namely, the corona-inception gradient, Figure (c)

Charge - Voltage Diagram with Corona.

* When Corona is absent the capacitance of a Conductor is based on the physical radius of the metallic conductor. The Q-V relation is a straight line OA as shown in figure. and $C = \frac{Q_0}{V_0}$

where V_0 is the corona inception voltage and Q_0 is the Corresponding Charge.

* When Corona occurs, the Q-V relationship changes steeply, because of the increase in charge. This is shown as the portion AB which is nearly a straight line.

* When the voltage is decreased after reaching a maximum V_m there is a hysteresis effect. and the q-V relation follows the path BD. Here the charge decreases after reaching maximum corona inception voltage.

* The slope of BD almost equals 'c' i.e., OA showing that the space charge cloud near the conductor has been absorbed into the conductor and charges far enough away from the conductor are not ~~entirely~~ pulled back.

* Area OABD – Represent energy loss. (for one half cycle).

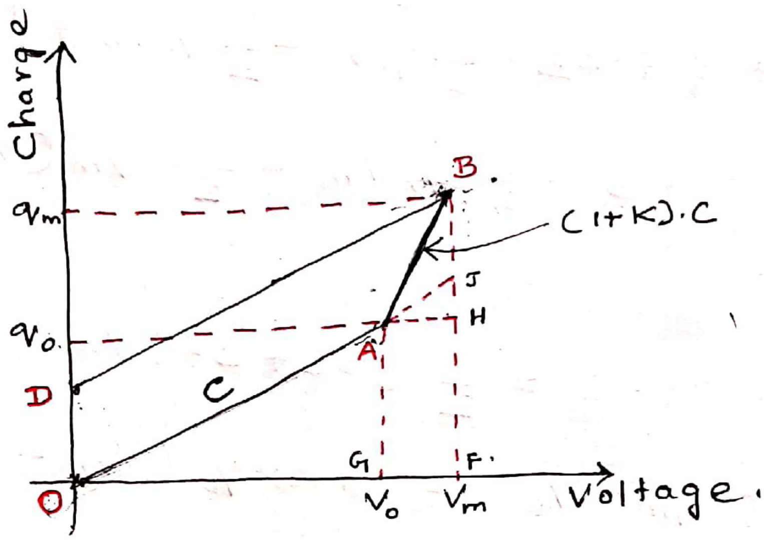


Fig: Charge - Voltage diagram of corona.

Let,

V_o - Corona inception Voltage
q_o - Corona -iception charge
V_m - Maximum corona - inception Voltage.
q_m - Maximum Corona - inception Charge.
C - Capacitance of conductor.
K - experimental factor = 0.7.

$$\text{Area OABD} = (\text{Area DOFB}) - (\text{Area OAG}) - (\text{Area GAHF}) - (\text{Area AHB})$$

$$= (\text{Area DOFB}) - \frac{1}{2} q_o V_o - q_o (V_m - V_o) - \frac{1}{2} (q_m - q_o)(V_m - V_o).$$

$$= \text{Area DOFB} - \frac{1}{2} q_o V_o - q_o (V_m - V_o) - \frac{1}{2} \left[q_m (V_m - V_o) - q_o (V_m - V_o) \right].$$

$$= \text{Area DOFB} - \frac{1}{2} q_o V_o - q_o (V_m - V_o). - \frac{1}{2} q_m (V_m - V_o) + \frac{1}{2} q_o (V_m - V_o).$$

$$= \text{Areaa DOFB} - \frac{1}{2} q_o V_o - \frac{1}{2} q_o (V_m - V_o). - \frac{1}{2} q_m (V_m - V_o)$$

$= \text{Area of DOFB} - \frac{1}{2}q_0V_0 - \frac{1}{2}q_0V_m + \frac{1}{2}q_0V_0 - \frac{1}{2}q_m(V_m - V_0)$

$= \text{Area DOFB} - \frac{1}{2}q_0V_m - \frac{1}{2}q_m(V_m - V_0)$. — (1)

Note:

$\text{Area DOFB} = \frac{1}{2}(DO + BF)V_m$ — (A)

$BH = q_m - q_0 = (1+K)q_0(V_m - V_0)/V_0$.

$JH = q_0(V_m - V_0)/V_0$.

and $BF = q_m = q_0 + (1+K)q_0(V_m - V_0)/V_0$. — (i)

$\therefore DO = BJ = BH - JH = Kq_0(V_m - V_0)/V_0$ — (ii)

Sub (i) and (ii) in (A).

$\text{Area DOFB} = Kq_0(V_m - V_0)V_m/V_0 + \frac{1}{2}q_0V_m^2/V_0$ — (A).

Sub. (A) in (1), we get,

$\text{Area OABD} = \frac{1}{2}K \cdot q_0 \cdot (V_m - V_0)(V_m + V_0)/V_0$.

$= \frac{1}{2}KC(V_m^2 - V_0^2)$.

∴ For a unipolar waveform, energy loss is equal to for 1 full cycle.

$W_{ac} = KC(V_m^2 - V_0^2)$.

The corresponding power loss will be.

$P_c = fW_{ac} = fKC(V_m^2 - V_0^2)$

If the maximum voltage is close to the corona inception voltage (V_0), we can write,

$V_m^2 - V_0^2 = (V_m + V_0)(V_m - V_0) = 2V_m(V_m - V_0)$

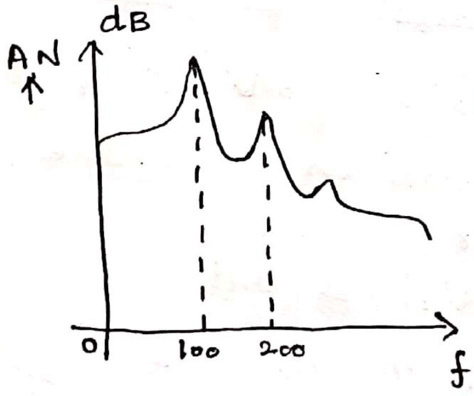
So that, $\boxed{P_c = 2fKCV_m(V_m - V_0)}$.

Audible Noise :

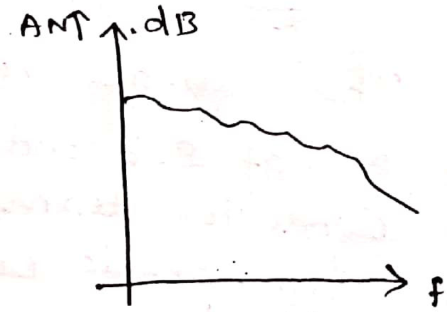
* When Corona is present on the conductors, e.h.v lines generates audible noise which is high during foul weather conditions. The noise varies from low frequency low frequency to about 20 KHz.

* Corona discharges generate (+)ve and (-)ve ions which are attracted and repelled by the periodic reversal of polarity of the alternatively AC excitation.

* Their movement gives rise to sound-pressure waves at frequencies twice the power frequency and its multiples. The noise has a pure tone superimposed on the broad band noise.



A.C Line



D.c Line.

* DC lines exhibits only broad band noise, unlike AC lines noise generated by DC lines is nearly equal in both fair and foul weather conditions.

Dis advantage :

* Psycho-acoustics : leading to insanity due to loss of sleep at night to inhabitants residing close to e.h.v lines.

Limits for Audible Noise:

Tests performed from a 500kV lines gave the following results.

When,

AN is less than 52.5 dB(A) – No complaints.

52.5 (dB)A to 59.0 dB(A) – Few complaints.

Greater than 59.0 dB(A) – Many complaints.

Here, the notation (A) denotes that noise is measured on a meter on a filter designated as A – Weighting Network.

Factors on which the AN depends upon.

a) The surface voltage gradient on conductor.
b) No. of subconductors in a bundle,
c) Conductor diameter
d) atmospheric conditions and.
e) Aerial distance from the line conductors to the point where noise is to be evaluated.

Measurement of Audible Noise (AN):

AN is caused by changes in air pressure or other transmission Medium so that it is described by Sound Pressure Level (SPL)

Unit of SPL = 20×10^{-6} Newton/m^2
(or).
20 micro Pascal
[2×10^{-5} micro bar].

$$SPL(dB) = 10 \log_{10}(SPL / 20 \times 10^{-6} \text{ Pascals}).$$

This is termed as Acoustic Power Level.

a) MicroPhone:

- It is used to measure audible noise.
- Very simple in construction.
- Its manufacturing should confirm the standards like ANSI, I.E.C or I.S.I etc.
- Types:

(i) Air Condenser Microphones.
- Stable
- Exhibit highest frequency response.

(ii) ceramic Microphones
- Most rugged

(iii) Electret Microphone.
- requires polarization Voltage so that the power supply (Battery) will also be exposed to rain and must be protected suitably.

Since AN level from a transmission line is much lower than, say, aircraft or ignition noise, 1 inch 'dm' microphones are used. Sometimes ½ inch Microphones which is of more sensitive than 1 inch is also used. Therefore size is not a deciding factor.

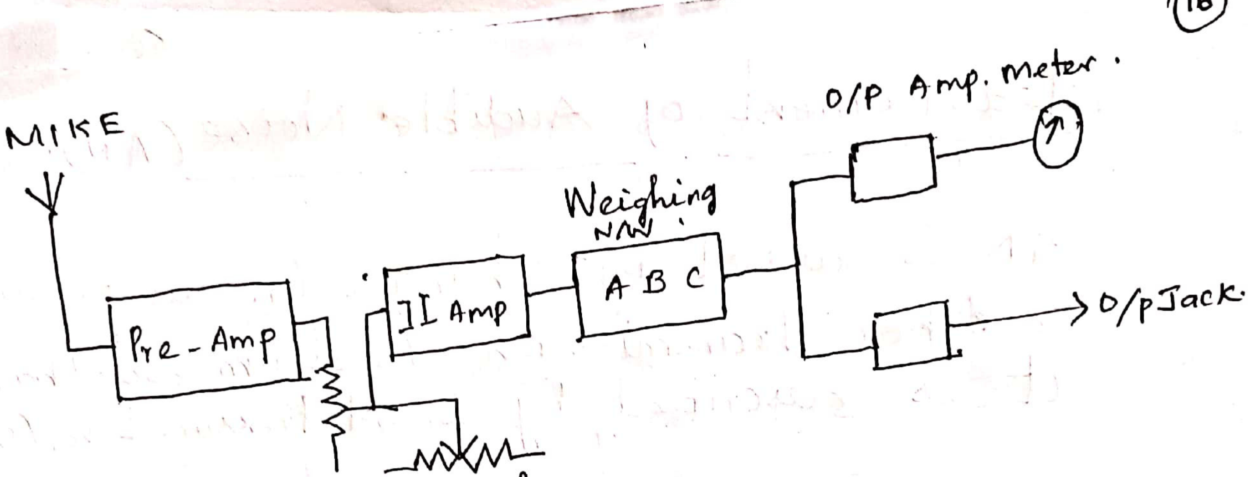
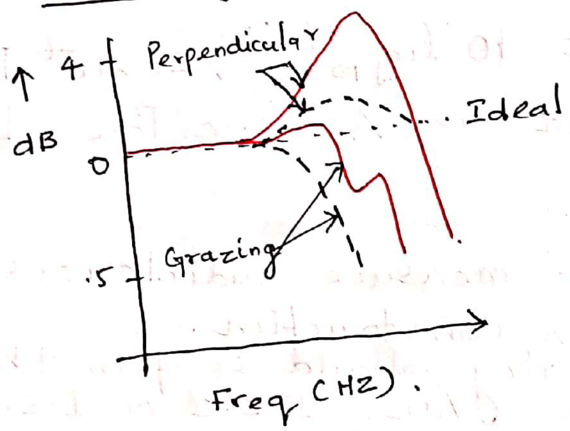


Fig: Block diagram of AN Measuring circuit.

Frequency Response:



b) Weighting Networks

* Weighting Networks are filters to measure sound in terms of sound pressure by varying frequency sensitivities.
* Types: 5 types → (A – E) Sound pr. levels.

'A' Weighted N/W – designed to have same response as the human ear (40 dB)
- Prefered by labour relations dept.
- least susceptible to wind gust.

'B' Weighted N/W – Response to moderated sound pr. levels upto 70 dB.

'C' Weighted N/W – Flat response up to 16 KHZ.
- Employed to hight pressure ~~sound~~ sound level response of about 100 dB.

D-Weighted N/W : Used to measure the aircraft noise levels with in the range of 3-4 KHZ .

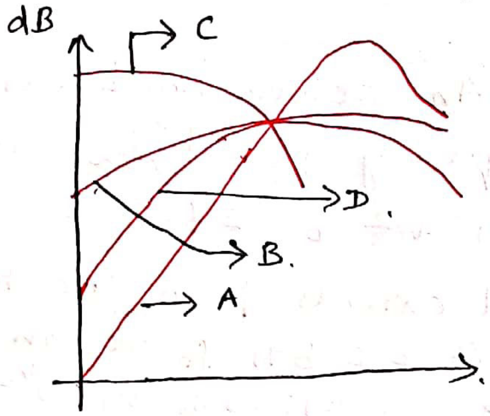


Fig: Freq. response of Weighting N/W .

(c) Octave Band

* It is a frequency spectrum analyser used to measure discrete freq. Components.
* These discrete - frequency components or line spectra are measured on octave bands by selective filters.

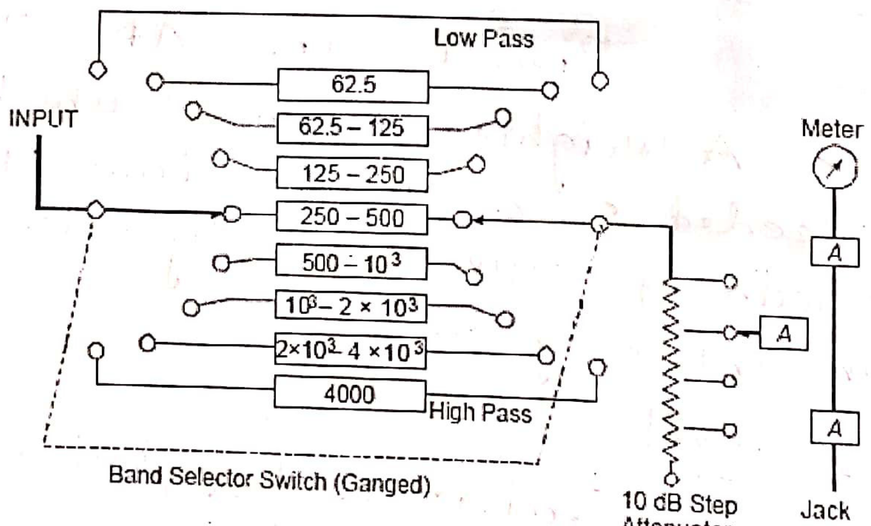


Fig. 5.9 Octave band AN meter circuit.

The octave band consist of a centre freq. f_0. Let f_1 and f_2 be the upper and lower freq. of bands.

Then $f_0 = \sqrt{f_1 f_2}$. An octave band extends from the lower frequency $f_2 = f_0/\sqrt{2}$ to the upper frequency $f_1 = \sqrt{2} f_0 = 2 f_2$.

A 3rd octave band extends from the lower frequency $f_3 = f_0/(2)^{1/6} = 0.891 f_0$ to an upper frequency $f_4 = (2)^{1/6} \cdot f_0 = 1.1225 f_0 = (2)^{1/3} f_3$.

Formulae for AN

* AN from a line is subjected to variation with atmospheric condition. This means that there is no one quantity or AN level that can be considered as the audible noise level of a line.

* All designers accept two levels L_{50} level and L_5 level.

L_{50} Level

This is the AN level measured on a 'A' weighted Network which is exceeded 50% of the time during periods of rain, usually extending over an entire year.

L_5 level

Similar to L_{50}, but exceeded only 5% of total time. This level is used for describing the noise levels in heavy rains

Formulas used for Calculating AN levels.

Conditions for using this formulas.

a) Applicable for bundle conductors up to 16 - sub conductors.

b) Subconductor diameters range (2 cm to 6.5 cm)

c) The AN calculated is the L_{50} level in rain.

d) Transmission voltages are 230 kV to 1500 kV, 3φ Line AC.

Refer fig, the AN level of each phase at the measuring point M is with i = 1, 2, 3 ....

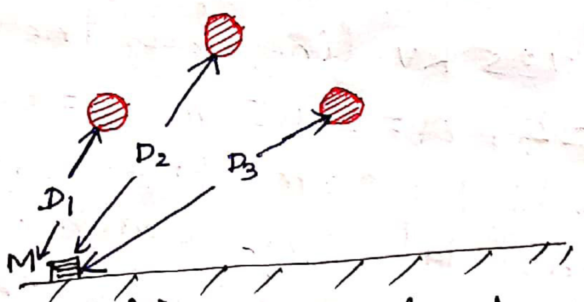


Fig. Calculation of AN level of line by B.P.A Formula.

For N<3, the formula is,

$$AN(i) = 120 \log_{10} E_{am}(i) + 55 \log_{10} d - 11.4 \log_{10} D(i) - 115.4 \, dB(A). \quad \to (1)$$

where,

$E_{am}(i)$ = Avg. maximum surface voltage gradient on bundle belonging to i in kV/cm, r.m.s.

d = diameter of subconductor in cm.

N = No. of subconductor in bundle.

and D(i) = Aerial distance from phase i to the location of the microphone in metres.

For $N \geq 3$, the formula becomes.

$$AN(i) = 120 \log_{10} E_{am}(i) + 55 \log_{10} d - 11.4 \log_{10} D(i) + 26.4 \log_{10} N - 128.4, \; dB(A) \quad -(2)$$

When all dimensions are in metre units,

$$N<3: \; AN(i) = 120 \log E_m(i) + 55 \log d_m - 11.4 \log D(i) + 234.6, \; dB(A).$$

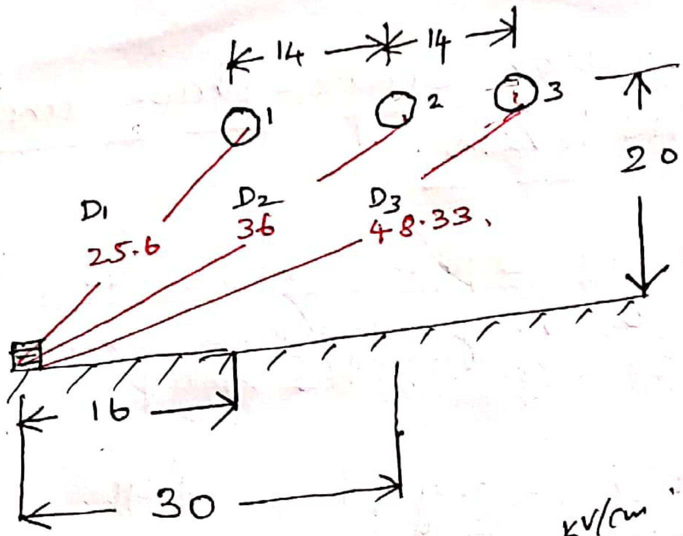
$$N \geq 3: \; AN(i) = 120 \log E_m(i) + 55 \log d_m - 11.4 \log D(i) + 26.4 \log N + 221.6, \; dB(A)$$

After calculating the AN levels of each phase, the rule for addition of the three levels follows equation,

$$AN = 10 \log_{10} \sum_{i=1}^{3} 10^{0.1 AN(i)}, \; dB(A).$$

Problem:

A 735 KV line has the following details: $N=4$, $d = 3.05$ cm, B = bundle spacing = 45.72 cm, phase separation $S = 14$ m in height $H = 20$ m, horizontal configuration. By the Mangoldt formula, the maximum conductor surface voltage gradients are 20 KV/cm and 18.4 KV/cm for the centre and outer phases, respectively. Calculate SPL or AN in dB(A) at a distance of 30 m along ground from the centre phase (line centre). Assume that the microphone is kept at ground level.



Phase 1. $E_m = 18.4$ kV/cm, $D_1 = 25.6$.

$AN_1 = 120 \log_{10} 18.4 + 55 \log_{10} 3.05 - 11.4 \log_{10} 25.6$
$+ 26 \log_{10} 4 - 128.4$.

$= 120 \log 18.4 - 11.4 \log_{10} 25.6 - 85.87$

$= 151.78 - 16.05 - 85.87 = 49.86$ dB(A)

Phase 2. $E_m = 20$, $D_2 = 36$.

$AN_2 = 120 \log_{10} 20 - 11.4 \log 36 - 85.87$

$= 52.5$ dB(A

Phase 3 $E_m = 18.4$, $D_3 = 48.33$.

$AN_3 = 120\ 18.4 - 11.4 \log 48.33 - 85.87$

$= 46.71$ dB(A).

$\therefore$ Total $AN_T = 10 \log_{10} \sum_{i=1}^{3} 10^{0.1 AN(i)}$, dB(A).

$= 10 \log_{10} (10^{4.986} + 10^{5.25} + 10^{4.671})$

$= 10 \log (32.15 \times 10^4)$

$= 55$ dB(A)

This is within the range of low-complaint region according to the perry criterion which is 52.5 to 59 dB(A)

Relation between single-phase and 3-phase AN levels.

Measurement of 3 phase noise level in EHV AC lines is very expensive when compared to 1ϕ. The 3ϕ experimental setup is very costly.

The AN level from any phase at the measuring point 'M' consists of a constant part and a variable part which can be seen from previous eqn of AN.

Let us consider a 1ϕ EHV AC transmission line with ~~less~~ more than 3 subconductors. Now, the audible noise measured at point N is given as.

$$AN(i) = 120 \log V(i) - 11.4 \log D(i) + 55 \log d + 26.4 \log N - 128.4 \text{ dB(A)}.$$

where, $i = 1, 2, 3$.

For $(i) = 1$

$$AN_1 = 120 \log V_1 - 11.4 \log D_1 + 55 \log d + 26.4 \log N - 128.4 \text{ dB}.$$

$$= 120 \log V_1 - 11.4 \log D_1 + (55 \log d + 26.4 \log N - 128.4).$$

$$AN_1 = 120 \log V_1 - 11.4 \log D_1 + K.$$

For $(i) = 2$.

$$AN_2 = 120 \log V_2 - 11.4 \log D_2 + (55 \log d + 26.4 \log N - 128.4 \text{ dB})$$

$$= 120 \log V_2 - 11.4 \log D_2 + K.$$

For (i) = 3.

$AN_3 = 120 \log V_3 - 11.4 \log D_3 + K$.

Let the outer phases have the same Voltages.

i.e., $V_1 = V_3$.

$\therefore AN_3 = 120 \log V_1 - 11.4 \log D_3 + K$.

The centre phase gradient be written as .

$V_2 = (1+m) V_1$

and

$K_2 = \frac{D_2}{D_1}$ and $K_3 = \frac{D_3}{D_1}$

The total AN levels of the 3 phases obtained after combining 3 individual phase is.

$$AN_T = 10 \log_{10} \sum_{i=1}^{3} 10^{0.1 AN(i)}$$

$$= 10 \log_{10} \left[10^{0.1(AN_1 + AN_2 + AN_3)} \right]$$

$$= 10 \log_{10} \left[10^{0.1 AN_1 + 0.1 AN_2 + 0.1 AN_3} \right]$$

$$= 10 \log_{10} \left[10^{0.1K} \cdot 10^{12 \log V_1} \left(10^{-1.14 \log D_1} + 10^{-1.14 \log D_3} + 10^{-1.14 \log D_2 + 12 \log (1+m)} \right) \right]$$

$$= K + 120 \log V_1 - 11.4 \log D_1 + 10 \log \left[1 + K_3^{-1.14} + (1+m)^{12} \cdot K_2^{-1.14} \right] \quad \text{—(1)}$$

For a single phase line with the same surface voltage gradient V_2 as the centre-phase conductor of the 3ϕ configuration, and at a distance D_2, the noise level is.

$$AN_S = K + 120 \log V_1 - 11.4 \log D_1 + 10 \log_{10} \left[(1+m)^{12} \cdot K_2^{-1.14} \right] \quad \text{—(2)}$$

Therefore, the difference in AN levels of equation (1) − (2) is:

$$AN_T - AN_S = 10 \log_{10} \frac{1 + K_3^{-1.14} + K_2^{-1.14}(1+m)^{12}}{K_2^{-1.14}(1+m)^{12}} \quad (3)$$

This is the decible adder which will convert the 1ϕ AN level to that of a 3ϕ line.

Detailed Derivation.

$$A_T = 10 \log_{10} \sum_{i=1}^{3} 10^{0.1 AN(i)} := 10 \log_{10} 10^{[0.1AN_1 + 0.1AN_2 + 0.1AN_3]}$$

$$A_T = 10 \log_{10} 10^{[0.1(K+120\log V_1 - 11.4\log \hat{S}_1) + 0.1(K + 120 \log V_2 - 11.4 \log \hat{S}_2) + 0.1(K + 120 \log V_3 - 11.4 \log \hat{S}_3)]}$$

$$= 10 \log_{10} 10^{[0.1(K+120\log V_1 - 11.4\log \hat{S}_1) + 0.1(K + 120 \log (1+m) V_1 - 11.4 \log \hat{S}_2) + 0.1(K + 120 \log V_1 - 11.4 \log \hat{S}_3)]}$$

$$= 10 \log_{10} \left[10^{0.1K} \cdot 10^{12\log V_1} \left\{10^{-1.14\log S_1} + 10^{-1.14\log S_3} + 10^{-1.14\log S_2 + 12\log(1+m)}\right\}\right]$$

$$= 10 \log_{10} \left[10^{0.1K} \cdot 10^{12\log V_1} \left\{10^{-1.14\log S_1} + 10^{-1.14\log K_3 S_1} + 10^{-1.14 \log K_2 S_1 + 12\log(1+m)}\right\}\right].$$

$$= 10 \log \left[10^{0.1K} \cdot 10^{12\log V_1} \cdot 10^{-1.14\log S_1} \left\{1 + 10^{-1.14\log K_3} + 10^{-1.14\log K_2} \cdot 10^{12\log(1+m)}\right\}\right].$$

$$= [K + 120\log V_1 - 1.14\log S_1] + 10\log\left[1 + 10^{\log K_3^{-1.14}} + 10^{\log K_2^{-1.14}} \cdot 10^{\log(1+m)^{12}}\right]$$

$$= [K + 120\log V_1 - 1.14\log S_1] + 10\log\left[1 + K_3^{-1.14} + K_2^{-1.14}(1+m)^{12}\right]$$

Problem.

Using eqn.(1) compute AN_T for the 735KV line of previous example problem

Soln:

$$\text{Eqn.}(1) \Rightarrow AN_T = K + 120\log V_1 - 11.4\log D_1 + 10\log\left[1 + K_3^{-1.14} + (1+m)^{12} K_2^{-1.14}\right]$$

$$K = 55\log d + 26.4\log N - 128.4$$

$$\boxed{K = -85.87}$$

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

$$\frac{V_2}{V_1} = (1+m) = \frac{20}{18.4} = 1.087$$

$$\boxed{1+m = 1.087}$$

$$\boxed{120\log V_1 = 151.88} \; ; \; \boxed{11.4\log D_1 = 16.05}$$

$$K_2 = \frac{D_2}{D_1} = \frac{36}{25.6} = 1.406$$

$$K_3 = \frac{D_3}{D_1} = \frac{48.33}{25.6} = 1.888$$

$$\therefore 1 + K_3^{-1.14} + K_2^{-1.14}(1+m)^{12} = 3.33$$

$$AN_T = -85.87 + 151.8 - 16.05 + 10\log 3.33$$

$$AN_T = 55.1 \text{ dB(A)}$$

Problem.

Using eqn.(3), compute the decibel adder to convert the 1ϕ AN level of the Centre phase to the 3ϕ AN level of. Previous problem

Soln:

$$AN_T - AN_S = 10 \log_{10} \frac{1 + K_3^{-1.4} + K_2^{-1.14} (1+m)^{12}}{K_2^{-1.14} (1+m)^{12}}$$

$$= 10 \log \frac{3.33}{1.844} = 10 \log 1.8054$$

$$= 2.566.$$

The AN level of the centre phase was 52.5 dB(A) at 30m from the conductor along ground. This will be the level of 1ϕ line with the same surface voltage gradient and distance to the location of. Microphone.

$$\therefore AN_T = AN_S + 2.566$$

$$= 52.5 + 2.566.$$

$$= 55.07 \text{ dB(A)}$$

Corona Pulse: Generation and Properties.

Corona Discharge — Two Types.

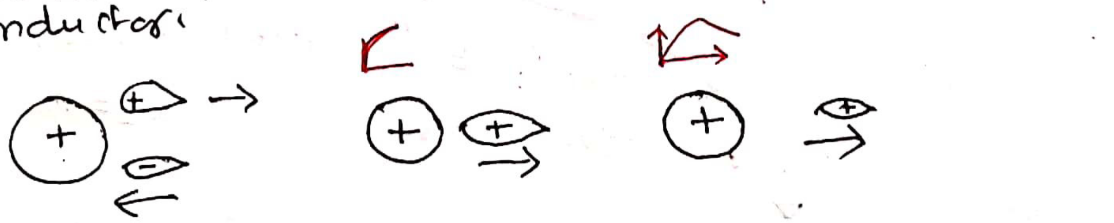
(i) Pulseless or Glow Corona } Both give rise to energy loss

(ii) Pulse Type or streamer. }

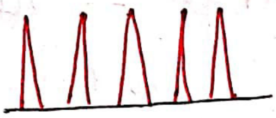
↓ give rise radio interference in the range of 0.5 MHz to 1.6 MHz | Affect radio receptions.

When a conductor is (+)ve with respect to ground, an electron avalanche moves rapidly into the conductor (leaving the heavy positive-ion charge cloud close to the conductor, which drifts away). The rapid movement of electrons and motion of positive ions gives the steep front of the pulse, while the further drift of the (+)ve ion cloud will form the tail of the pulse.

It is clear that the presence of positive charges near the (+)ve conductor lowers the field to an extent that the induced current in the conductor nearly vanishes. As soon as the (+)ve ions have drifted far enough due to wind or neutralized by other agencies such as free electrons by recombination, the electric field in the vicinity of the conductor regains sufficiently high electric field in the visinity of the conductor regains sufficiently high value for pulse formation to repeat itself. Thus, a train of pulses results from a point in Corona on the conductor.



Thus, a train of pulses results from a point in corona on the conductor.

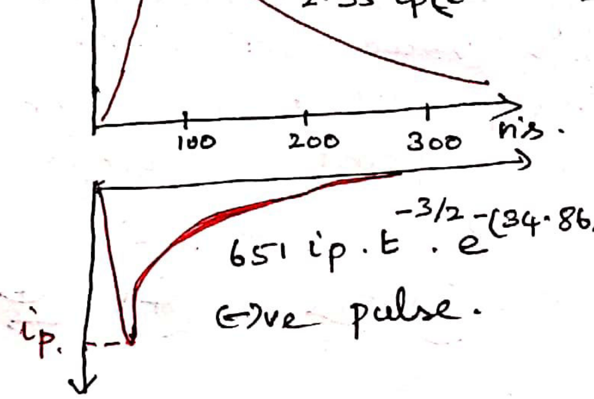


Pulse train.

The situation when the conductor is negative w.r.t ground is the reverse of that described above. The electron avonche moves away from the conductor while the positive-ion cloud moves towards the (-)vly charged conductor. However, since the heavy (+)ve ions are moving into progressively higher electric fields, their motion is very rapid which gives rise to a much sharper pulse than a positive pulse. Similarly, the lighter electrons move rapidly away from the conductor and the electric field near the conductor regains its original value for the next pulse generation quicker than for (+)ve case.

Therefore, (-)ve pulses are smaller in amplitude, have much smaller rise and fall times but much higher repetion rates than positive pulses.

Positive and Negative Corona Pulse.



$2.35\, i_p (e^{-0.0105t} - e^{-0.03465t})$

$i_+ = K_+ i_p (e^{-\alpha t} - e^{-\beta t})$

$651\, i_p \cdot t^{-3/2} \cdot e^{-(34.86/t + 0.01215t)}$.

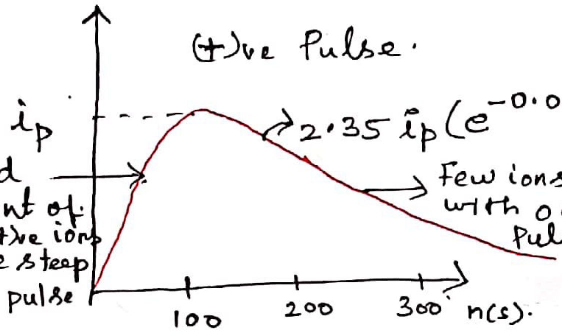
$i_- = K_- i_p t^{-3/2} \cdot e^{-\gamma/t - \delta t}$.

Corona Pulse

Corona Discharge.

- → Pulseless or Glow corona } Both give rise to energy loss.
- → Pulse Type or Streamer } Both give rise to energy loss.
  - ↓ give rise to RI in the range of 0.5 MHz to 1.6 MHz.

Positive and Negative Corona pulse

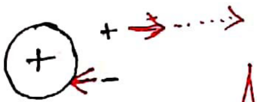


$2.35\, i_p (e^{-0.0105t} - e^{-0.03465t}) \Rightarrow i_+ = k_+ i_p (e^{-\alpha t} - e^{-\beta t})$

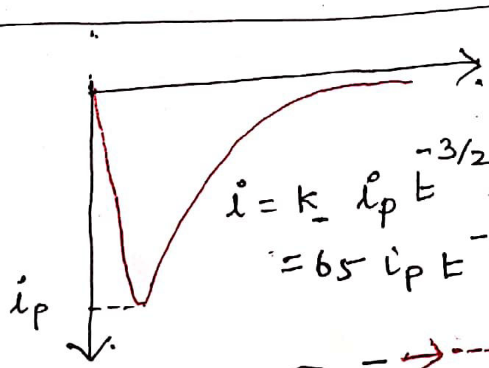
The rapid movement of e^-s and (+)ve ions gives the steep front of pulse.

Few ions drift away to lower levels to combine with other molecules forming the tail of pulse.

Repetition:
1 pulse during fair weather
10 pulses during rain.
↑ Pulse train is formed if moisture content is more.

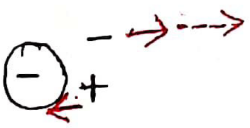


Pulse train.



$i = k_- i_p t^{-3/2} e^{-\gamma/t - \delta t}$

$= 65\, i_p t^{-3/2} e^{-(34.86/t + 0.01215t)}$



* Negative pulses are smaller in amplitude, rise time and fall times but much higher repetition rates than (+)ve pulses.
* less significant from the point of view of RI.

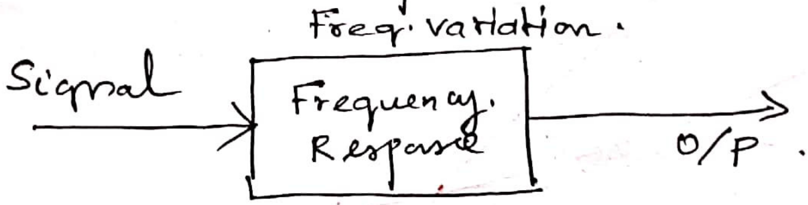
Pulse train

Type	Time to crest	Time to 50% on Tail	Peak Value of Current	Repetition Rate Pulses per second: A.C	D.C
(+)ve	50 ns	200 ns	100 mA	Power freq	1000
(-)ve	20 ns	50 ns.	10 mA	100	10,000

... energy ...
is uniform.

Frequency Spectrum:

The Frequency spectrum of radio noise measured from long lines usually corresponds to the Fourier amplitude spectrum of single pulse.



Bode plot, Polor Plot

Positive pulse. Nature $i_+ = K_+ \, i_p \, (e^{-\alpha t} - e^{-\beta t})$.

$$F(j\omega) = \int_{-\infty}^{\infty} f(t) . e^{-j\omega t} . dt.$$

$$f(t) = K \, i_p (e^{-\alpha t} - e^{-\beta t}).$$

The fourier integral ~~of~~ for a double-exponential puse is

$$F(j\omega) = \int_0^{\infty} K \, i_p (e^{-\alpha t} - e^{-\beta t}) . e^{-j\omega t} . dt.$$

$$= K i_p . \left[\frac{1}{(\alpha + j\omega)} - \frac{1}{(\beta + j\omega)} \right]$$

$$= K i_p \left[\frac{(\beta + j\omega) - (\alpha + j\omega)}{(\alpha + j\omega)(\beta + j\omega)} \right].$$

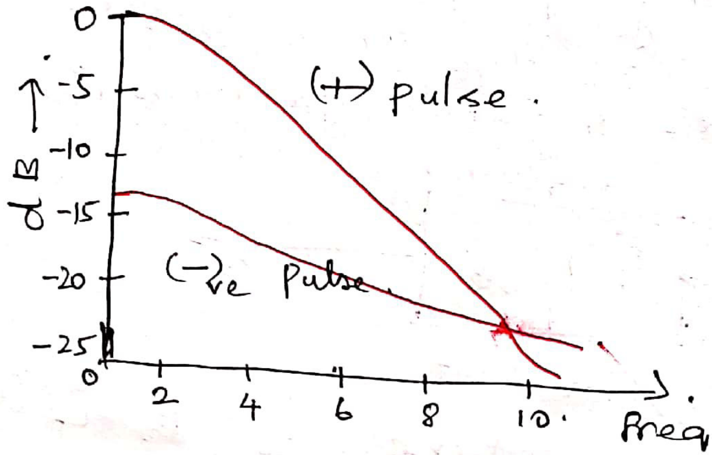
$$F(j\omega) = K i_p \left[\frac{(\beta - \alpha)}{(\alpha + j\omega)(\beta + j\omega)} \right]$$

$$F(j\omega) = |A(j\omega)| \angle \phi(j\omega).$$

The Amplitude is:

$$|A(\omega)| = K i_p . (\beta - \alpha) / \sqrt{(\alpha^2 + \omega^2)(\beta^2 + \omega^2)}$$

Bode frequency plot of (+)ve and (-)ve Corona pulses.



$$|A(\omega)| = \frac{K i_p \cdot (\beta - \alpha)}{\sqrt{(\alpha^2+\omega^2)(\beta^2+\omega^2)}}.$$

At low frequencies, i.e., $\omega << \alpha$ and β,

$$|A(\omega)| = \frac{K i_p (\beta - \alpha)}{\sqrt{(\alpha^2)(\beta^2)}} = \frac{K i_p (\beta-\alpha)}{\alpha \cdot \beta}.$$

At high frequencies i.e., $\omega >> \alpha$ and β.

$$|A(\omega)| = \frac{K i_p (\beta-\alpha)}{\sqrt{\omega^2 \cdot \omega^2}} = \frac{K i_p (\beta-\alpha)}{\omega^2}.$$

using the above information draw the Bode magnitude plot.

Values of α and β are.

(+)ve pulse : $\alpha = 10.5 \times 10^6$, $\beta = 34.65 \times 10^6$.

(-)ve pulse : $\alpha = 38.3 \times 10^8$, $\beta = 83 \times 10^6$.

Table, shows details of calculation of amplitude Vs frequency from 0 to 10 MHz by taking the reference (0 dB) at $f=0$ for the (+)ve pulse. At $f=0$ the amplitude of (−)ve pulse freq. spectrum is 13.5 dB below that for (+)ve pulse, for equal peak amplitude.

f =	0	0.5	1	1.5	2	4	6	8	10	MHz.
(+)ve	0	−4	−1.47	−2.9	−4.4	−10	−15	−19	−22	dB.
(−)ve	−13.5	−13.54	−13.64	−13.8	−14	−15.4	−17.3	−19.2	−21.1	dB

These are plotted in freq. response graph, shown in previous fig.

<u>Derivation</u>: $F(j\omega) = \int_{-\infty}^{\infty} f(t).e^{-j\omega t}.dt.$

$$f(t) = K i_p (e^{-\alpha t} - e^{-\beta t}).$$

$$F(j\omega) = \int_0^{\infty} K i_p (e^{-\alpha t} - e^{-\beta t}).e^{-j\omega t}.dt.$$

$$= K i_p \int_0^{\infty} \left[e^{-(\alpha+j\omega)} - e^{-(\beta+j\omega)}\right] dt.$$

$$= K i_p \left[\int_0^{\infty} e^{-(\alpha+j\omega)}.dt - \int_0^{\infty} e^{-(\beta+j\omega)}.dt.\right]$$

$$= K i_p \left\{\left[\frac{-e^{-(\alpha+j\omega)t}}{(\alpha+j\omega).}\right]_0^{\infty} - \left[\frac{-e^{-(\beta+j\omega)t}}{(\beta+j\omega)}\right]_0^{\infty}\right\}$$

$$= K i_p \left\{\left[0 - \left(-\frac{1}{\alpha+j\omega}\right)\right] - \left[0 - \left(-\frac{1}{\beta+j\omega}\right)\right]\right\}$$

$$F(j\omega). = K i_p \left[\frac{1}{\alpha+j\omega} - \frac{1}{\beta+j\omega}\right] = K i_p \left[\frac{(\beta-\alpha.)}{(\alpha+j\omega)(\beta+j\omega)}\right]$$

Limits for RI Fields.

RI level is governed not only by the amplitude and wave shape of a single pulse, but also by the repetitive nature of pulses in a train.

RI resulting from a transmission line is a man-made phenomenon and as such its regulation should be similar to other man-made sources of noise like AN, automobile ignition noise, aircraft noise, R-f heating equipment etc., In order to make environment eco-friendly, designer's have set limits to radio interference whose nature can be described through S/N ratio (signal to Noise). It is the duty of the designer to keep the Noise level from a line below a limiting value at the edge of right-of-way (ROW) of the corridor.

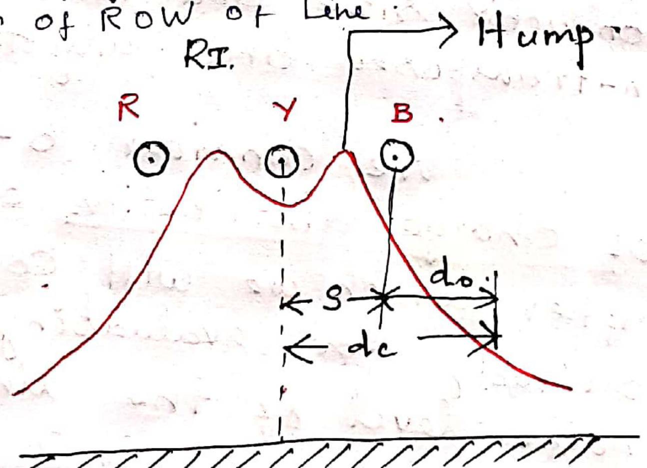
RI Limits in various countries of the world.

	Country	Distance from Line	RI Limit	Frequency.	Remarks
1)	Switzerland	20m from outermost phase	200 μV/m (46 dB above 1 μV/m)	500KHz	Dry weather 10°C.
2	Poland	20 m from outer phase	750 μV/m (57.5 dB	500KHz. ± 10KHz	Air Humidity < 80%. Temp 5°C.
3	U.S.S.R	100 m from outer phase.	40 dB.	500KHz	80% of the year limit should not be exceeded

Lateral Profile of Radio Interference and Modes of Propagation.

Generally, the design of tr. line with reference to RI depends on various factors like choice of conductor size, No. of subconductors in bundle, line height and phase spacing. The lateral decrement of radio noise measured at ground level as one move's away from the line has a double hump characteristics within the space between the conductors and then decreases monotonically as the meter is moved away from the outer phase.

Fig: Lateral profile of RI at ground level for fixing width of ROW of Line



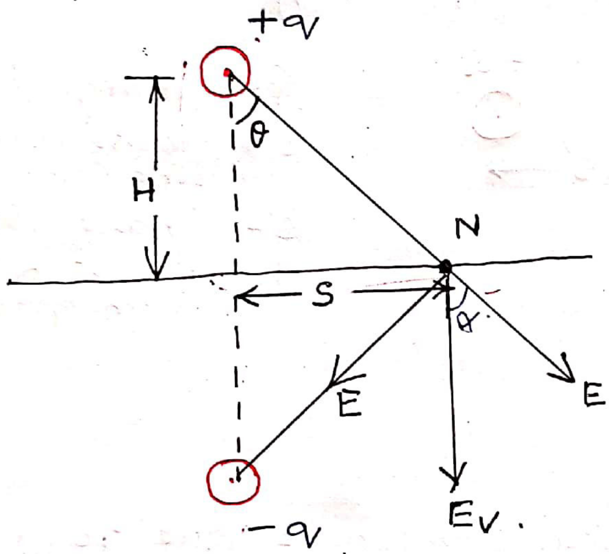
No receiver should be located within the distance d_o from the outer phase or d_c from the line centre. It becomes essential to measure/calculate at design stages the lateral Profile very accurately from a proposed line inorder to advice the regulatory bodies on the location of receivers. In practice many complaints are heard from the public who experience interference to radio broadcasts if the line is located too close to their homesteads when the power company routes an e.h.v lines wrongly. In such cases, it is the engineer's duty to recommend remedies. ~~and~~

The lateral profile is dissected in to several components which belong to different modes of propagation for radiofrequency energy on the multi-conductor line. This is the basis for determining the expected noise profile from a chosen conductor size and line configuration in un-transposed and fully transposed condition.

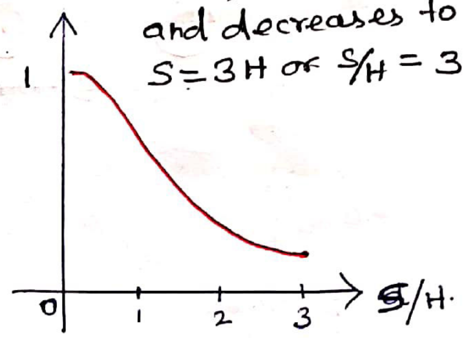
We consider 6-preliminary cases of charge distribution on the line conductors after which we will combine these suitably for evaluating the total noise level of the line. In all these cases, the problem is to find (calculate) the field strength at the location of a noise meter when the r-f charge distribution is known. Here we consider the vertical component of ground level, field intensity and horizontal component of magnetic field intensity. F).

Case 1: Single conductor above ground

Consider a single conductor at radio frequency above a perfectly conducting ground surface as shown in figure.



F=1, when S=0 (below the conductor) and decreases to 0.1 at S=3H or S/H = 3.



F-graph.

Let,
+Q – charge in coulombs/meter.
–Q – image charge
H – be the ht. of charge from ground Level.
S – be the lateral distance from conductor on ground surface.

The vertical component of electric field strength at point 'N' at a lateral distance of 's' meters due to charges (Q, –Q) is given as,

$$E_V = 2 \times \frac{Q}{2\pi\epsilon_0} \times \frac{H}{H^2+S^2}$$

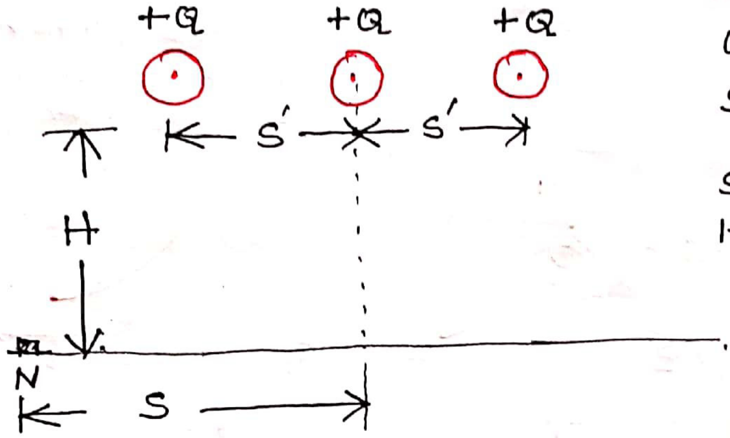
$$= 2 \times \frac{Q}{2\pi\epsilon_0} \times \frac{H}{H^2\left(1+\frac{S^2}{H^2}\right)}$$

$$= \frac{Q}{\pi\epsilon_0} \cdot \frac{1}{H\left(1+\frac{S^2}{H^2}\right)} = \frac{Q}{\pi\epsilon_0 H} \cdot \frac{1}{\left(1+\left(\frac{S}{H}\right)^2\right)}$$

The factor $\frac{1}{1+(S/H)^2}$ is dimensionless → Field Factor (F).

Case 2: 3-Phase AC line charge. (+Q, +Q, +Q)

On a perfectly transposed line, the line-to-ground mode carries equal charge Q of same polarity.



Q - Charge in C/m.
S - Noise meter dist. from line Centre.
S' - Phase Spacing.
H - Height of the charge from ground.

Now, the vertical component due to first charge Q is given as,

$$E_{V_1} = 2 \times \frac{Q}{2\pi\varepsilon_0} \cdot \frac{H}{H^2+(S-S')^2}$$

$$= \frac{Q}{\pi\varepsilon_0} \cdot \frac{H}{H^2\left[1+\frac{(S-S')^2}{H^2}\right]}$$

$$= \frac{Q}{\pi\varepsilon_0 H} \cdot \frac{1}{1+\left(\frac{S-S'}{H}\right)^2}$$

IIIly for the 2nd and 3rd charges, we have,

$$E_{V_2} = \frac{Q}{\pi\varepsilon_0 H} \cdot \frac{1}{1+\left(\frac{S}{H}\right)^2}$$

$$E_{V_3} = \frac{Q}{\pi\varepsilon_0 H} \cdot \frac{1}{1+\left(\frac{S+S'}{H}\right)^2}$$

Hence total vertical components is given as,

$$E_V = E_{V_1} + E_{V_2} + E_{V_3}.$$

$$E_V = \frac{Q}{\pi \varepsilon_0 H} \cdot \left[\frac{1}{1+\left(\frac{S-S'}{H}\right)^2} + \frac{1}{1+\left(\frac{S}{H}\right)^2} + \frac{1}{1+\left(\frac{S+S'}{H}\right)^2} \right]$$

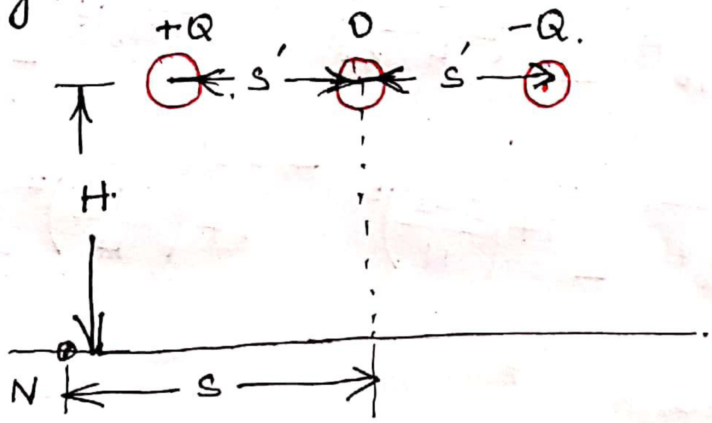
$$E_V = \frac{Q}{\pi \varepsilon_0 H} \cdot F_F.$$

$$F_F = \frac{E_V}{\left(\frac{Q}{\pi \varepsilon_0 H}\right)} = \frac{\left(\frac{Q}{\pi \varepsilon_0 H}\right)\left[\frac{1}{1+\left(\frac{S-S'}{H}\right)^2} + \frac{1}{1+(S/H)^2} + \frac{1}{1+\left(\frac{S+S'}{H}\right)^2}\right]}{\left(\frac{Q}{\pi \varepsilon_0 H}\right)}.$$

$$F_F = \frac{1}{1+\left(\frac{S-S'}{H}\right)^2} + \frac{1}{1+(S/H)^2} + \frac{1}{1+\left(\frac{S+S'}{H}\right)^2}.$$

Case 3: Three phase A.C line with charges. (Q, 0, −Q).

Consider a transposed line carrying charges (Q, 0, −Q) on first, second and third conductors respectively as shown in figure.



Let,
Q − Charge C/m.
S − Noisemeter dist from the centre conductor.
S' − Phase spacing.
H − height of charge from ground.

Now,
The vertical component due to +Q on 1st cond. is given by.

$$EV_1 = 2 \times \frac{Q}{2\pi \varepsilon_0} \cdot \frac{H}{H^2 + (S-S')^2}$$

$$EV_1 = \frac{Q}{\pi \varepsilon_0} \cdot \frac{1}{H\left[1+\left(\frac{S-S'}{H}\right)^2\right]}$$

The vertical component due to second charge Q=0 on second conductor, is given as,

$$E_{V_2} = 2 \times \frac{Q}{2\pi \epsilon_{0}} \cdot \frac{H}{H^2+S^2}$$

$$= \frac{Q}{\pi \epsilon_{0}} \cdot \frac{H}{H^2+S^2} = \frac{0}{\pi \epsilon_{0}} \cdot \frac{H}{H^2+S^2} = 0.$$

IIIly the vertical component due to charge −Q on the 3rd conductor is given as.

$$E_{V_3} = 2 \times \frac{-Q}{2\pi \epsilon_0} \cdot \frac{H}{H^2+(S+S')^2}.$$

$$= \frac{-Q}{\pi \epsilon_0 H} \cdot \frac{1}{\left[1+\left(\frac{S+S'}{H}\right)^2\right]}$$

$$E_V = E_{V_1} + E_{V_2} + E_{V_3}.$$

$$= \frac{Q}{\pi \epsilon_0 H} \cdot \left[\frac{1}{1+\left(\frac{S-S'}{H}\right)^2}\right] + 0 + \frac{-Q}{\pi \epsilon_0 H} \cdot \left[\frac{1}{1+\left(\frac{S+S'}{H}\right)^2}\right]$$

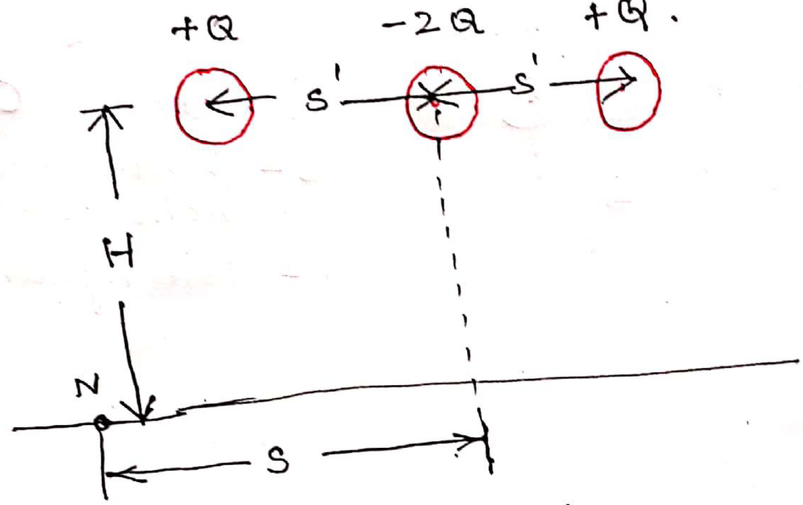
$$= \frac{Q}{\pi \epsilon_0 H} \cdot \left[\frac{1}{1+\left(\frac{S-S'}{H}\right)^2} - \frac{1}{1+\left(\frac{S+S'}{H}\right)^2}\right]$$

$$\therefore E_V = \frac{Q}{\pi \epsilon_0 H} \cdot F_f .$$

$$F_f = \frac{E_V}{\left(\frac{Q}{\pi \epsilon_0 H}\right)} = \frac{\frac{Q}{\pi \epsilon_0 H} \cdot \left[\frac{1}{1+\left(\frac{S-S'}{H}\right)^2} - \frac{1}{1+\left(\frac{S+S'}{H}\right)^2}\right]}{\frac{Q}{\pi \epsilon_0 H}}.$$

$$F_f = \frac{1}{1+\left(\frac{S-S'}{H}\right)^2} - \frac{1}{1+\left(\frac{S+S'}{H}\right)^2}.$$

Case 4 : Three Phase A.C Lines with charges $(+Q, -2Q, +Q)$



$$E_{V_1} = \frac{Q}{\pi \varepsilon_0 H} \cdot \frac{1}{\left[1+\left(\frac{S-s'}{H}\right)^2\right]}$$

$$E_{V_2} = \frac{-2Q}{\pi \varepsilon_0 H} \cdot \frac{1}{\left[1+\left(\frac{S}{H}\right)^2\right]}$$

$$E_{V_3} = \frac{Q}{\pi \varepsilon_0 H} \cdot \frac{1}{\left[1+\left(\frac{S+s'}{H}\right)^2\right]}$$

Total vertical component is given as.

$$E_V = E_{V_1} + E_{V_2} + E_{V_3}.$$

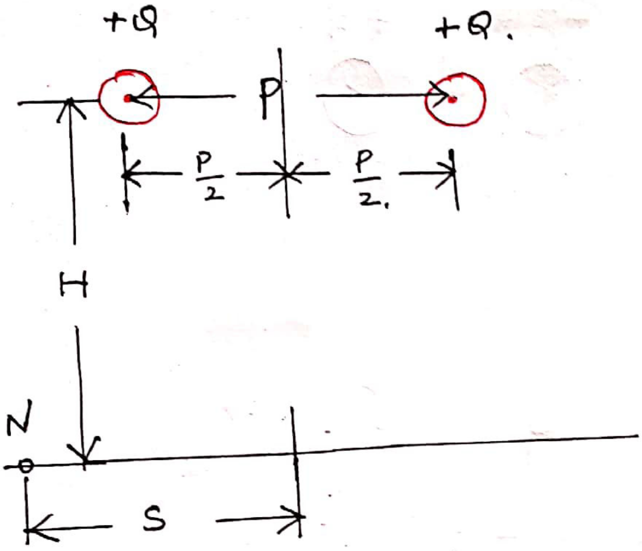
$$= \frac{Q}{\pi \varepsilon_0 H} \cdot \left[\frac{1}{1+\left(\frac{S-s'}{H}\right)^2} - \frac{2}{\left[1+\left(\frac{S}{H}\right)^2\right]} + \frac{1}{\left[1+\left(\frac{S+s'}{H}\right)^2\right]}\right]$$

The field factor is given as,

$$E_V = \frac{Q}{\pi \varepsilon_0 H} \cdot F_f.$$

$$\therefore F_f = \frac{1}{1+\left(\frac{S-s'}{H}\right)^2} - \frac{2}{1+\left(\frac{S}{H}\right)^2} + \frac{1}{1+\left(\frac{S+s'}{H}\right)^2}$$

Case 5 : Bi Polar D.C Line with charges (+Q , +Q).



Q - Charge Q/m.
S - Dist. of noise meter from pole centre.
P - Pole spacing.

$$E_{V_1} = \frac{Q}{\pi \varepsilon_0 H} \frac{1}{\left[1+\left(\frac{S-P/2}{H}\right)^2\right]}$$

$$E_{V_2} = \frac{Q}{\pi \varepsilon_0 H} \cdot \frac{1}{\left[1+\left(\frac{S+P/2}{H}\right)^2\right]}$$

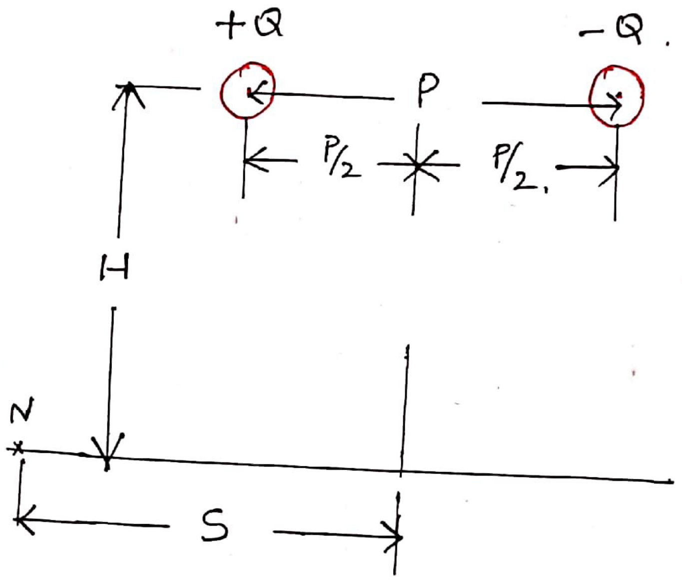
$$E_V = E_{V_1} + E_{V_2}$$

$$= \frac{Q}{\pi \varepsilon_0 H}\left[\frac{1}{\left[1+\left(\frac{S-P/2}{H}\right)^2\right]} + \frac{1}{\left[1+\left(\frac{S+P/2}{H}\right)^2\right]}\right]$$

$$E_V = \frac{Q}{\pi \varepsilon_0 H} \cdot \left[F_f \right].$$

$$\therefore F_f = \frac{1}{\left[1+\left(\frac{S-P/2}{H}\right)^2\right]} + \frac{1}{\left[1+\left(\frac{S+P/2}{H}\right)^2\right]}$$

Case 6: Bi-Polar D.C Line with charges (+Q, −Q).



$$E_{V_1} = \frac{Q}{\pi \varepsilon_0 H} \cdot \left[\frac{1}{1+\left(\frac{S-P/2}{H}\right)^2} \right]$$

$$E_{V_2} = \frac{-Q}{\pi \varepsilon_0 H} \cdot \left[\frac{1}{1+\left(\frac{S+P/2}{H}\right)^2} \right].$$

$$E_V = E_{V_1} + E_{V_2}$$

$$= \frac{Q}{\pi \varepsilon_0 H} \left[\frac{1}{1+\left(\frac{S-P/2}{H}\right)^2} - \frac{1}{1+\left(\frac{S+P/2}{H}\right)^2} \right]$$

$$E_V = \frac{Q}{\pi \varepsilon_0 H} F_f .$$

$$F_f = \frac{1}{1+\left(\frac{S-P/2}{H}\right)^2} - \frac{1}{1+\left(\frac{S+P/2}{H}\right)^2}$$

Conclusion:

① +q.
② +q, +q, +q.
⑤ +q, +q

For cases 1, 2 and 5 where the charges on the conductors are of the same polarity, the vertical component of electric field decreases from a maximum under line centre monotonically as the meter is moved along the ground away from the line.

∴ Ev evaluating

For <u>cases 3 and 6</u> with charge distributions $(+Q, 0, -Q)$ and $(+Q, -Q)$, we observe that field is zero at the line centre, reaches maximum value ~~at~~ and then decreases monotonically.

The combination of field profiles of <u>case 2 and 3 (or 5 and 6)</u> yield the characteristic <u>double hump</u>.

For <u>case 4</u> with the charge distribution $(+q, -2q, +q)$ the field commences at a high value under line centre, reaches zero, and then after increasing to a maximum value. ~~decreases~~ monotonically.

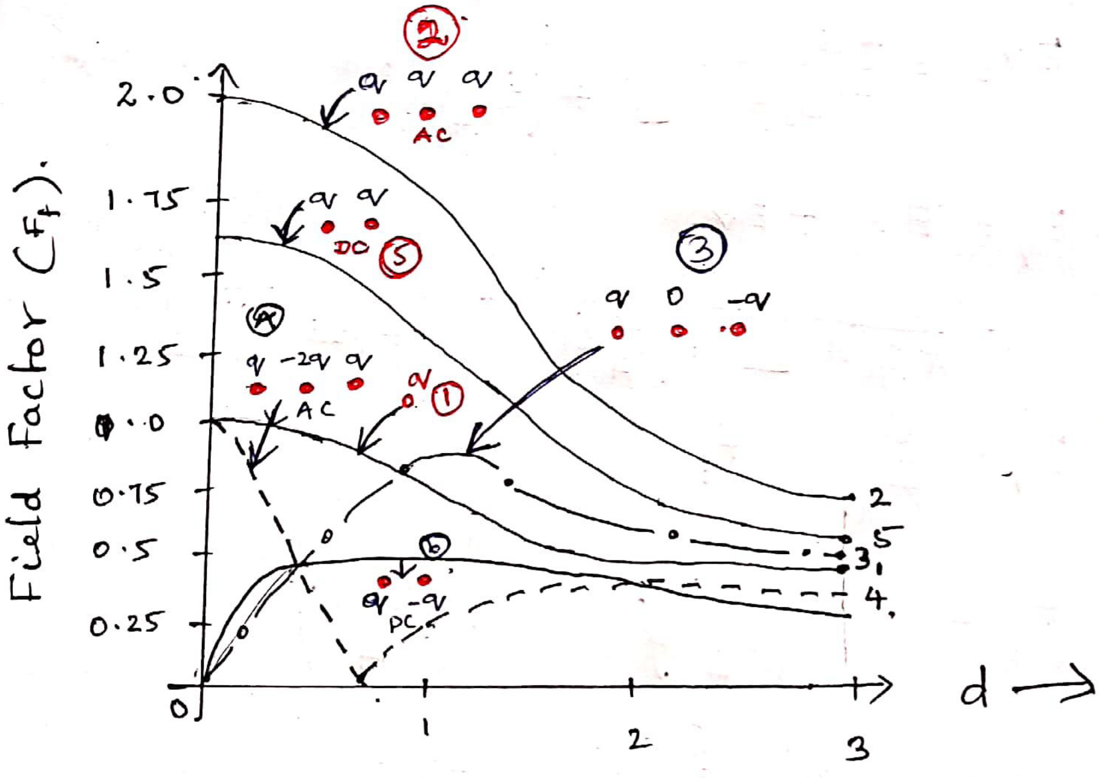


Fig: Plot of field factors for charge distributions

The CIGRE Formula:

Based on all RI data gathered over a number of years and from lines of various configurations, the CIGRE and IEEE evolved an empirical formula relating most important line and atmospheric parameters with the radio noise level. This is known as CIGRE Formula.

$$RI_i(dB) = 3.5 g_m + 6d - 33 \log_{10}(D_i/20) - 30$$

where,

d (diameter) = 2r

g_m - Max. Surface voltage gradient.

D_i - Aerial distance from conductor to the point where RI is to be evaluated.

Restrictions of CIGRE Formula. (It applies when).

a) the value of g_m and d are in. cm, g_m in kV/cm.

b) the aerial distance D_i is in metres and $D_i > 20m$;

c) freq. 'f' = 0.5 MHz.

d) No. of Sub-conductors $N \leq 4$. This is true of lines up to 765 KV;

e) the ratio of Bundle spacing 'B' to the conductor diameter lies between 12 and 20;

f) the weather condition is avg. fair weather;

g) the RI level has a dispersion of ± 6 dB

Rules for Addition of RI levels of 3ϕ - Single circuit line.

a) If one of the RI level is atleast 3dB higher than the rest, then this is the RI level of the line.

b) Otherwise the RI level of line is
RI = (Avg. of the two highest + 1.5) dB.

c) At 1 MHz, the RI level is 6 dB lower.

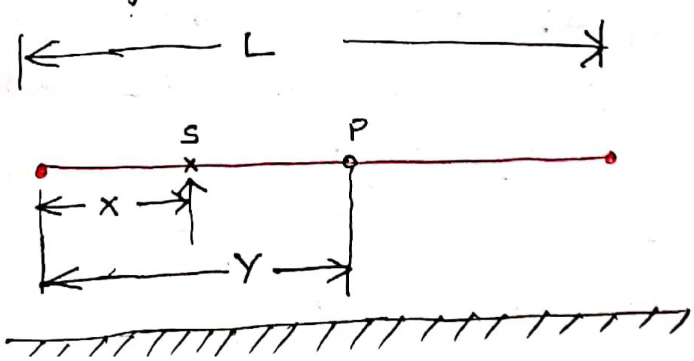
d) For evaluating the RI level in rain, add 17 dB.

RI Excitation Function:

In EHVAC transmission, the increase of voltage level increases the usage of number of bundled conductors in bundle, further which restricts the usage of CIGRE formula at higher levels.

In order to predict the RI levels at designing stage, a rational method is evolved by varying parameters like d, N, B, H and configuration of line, weather variables etc. While evaluating a rational method for prediction of RI levels, the most important concept resulted is an excitation function (or) generating function at given radio frequency in unit bandwidth. The measurement of excitation function is achieved by conducting experiments on short lengths of conductors strung inside a cylindrical (or) rectangular cage (or) from short out door over head experimental lines.

Consider the fig. which shows a source of corona at 's' located at a distance 'x' from one end of a line of length L. Here excitation function is used to predict RI levels with given dimensions and conductor geometry. The corona source at 's' on the conductor generates an excitation function I measured in $\mu A/\sqrt{m}$.



Under rain, a uniform energy or power per unit bandwidth is generated so that in a differential length dx, the power generated is (E. dx). In this method, we calculate the RI level under rain first and deduct 17 dB to obtain Fair-weather RI. This power will split equally in two directions and travel along the line to reach the point P at a distance (y-x) from the soure 'S'. In doing so, it will attenuate to a value $e^{-2\alpha(y-x)}$, where a = attenuation factor. Therefore, the total energy received at 'P' due to all sources to the left of P will be.

$$E_L = \int_0^L \frac{1}{2} (E \cdot dx) \cdot e^{-2\alpha(y-x)}$$

$$= \frac{E}{4a} (1 - e^{-2ay}).$$

Similarly, the energy received at 'P' due to all sources to its right will be.

$$E_R = \int \frac{E}{4a} (1 - e^{-2a(L-y)}).$$

For a line of finite length, repeated reflections occur from the ends, but for a very long lines these are not of consequence. Also, unless the point 'P' is located very close to the ends, the exponential terms can be neglected.

Therefore, the total r-f energy received at 'P' will be, $E_P = E/2a$.

which shows that all points on a long line receive the same r-f energy when the corona gen. is uniform.

Let,

I - be the current.

Measurement of RI, RIV and Excitation Function.

The interference to AM broadcast in the frequency range 0.5 MHZ to 1.6 MHZ is measured in terms of three quantities:

a) Radio Interference Field Intensity (RI). (μV/m)

b) Radio Influence Voltage (RIV), μV.

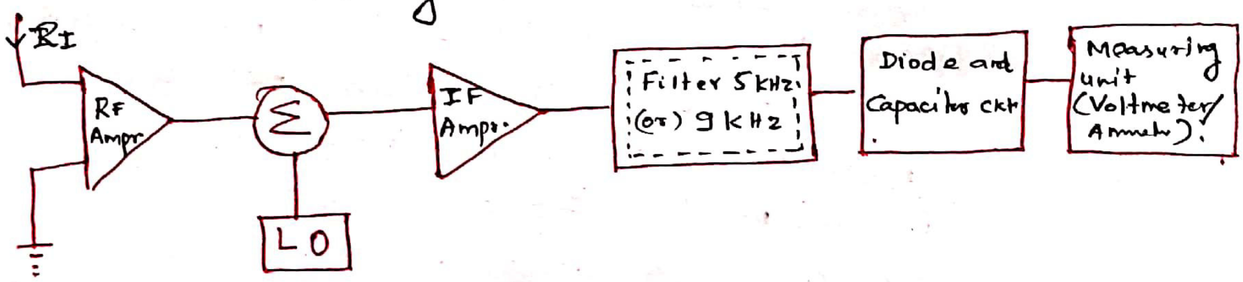
c) Excitation Function, μA/√m.

Radio Noise Meter

- It is used to measure the radio noise levels adjacent to transmission lines.

The block diagram of a radio noise meter is shown in figure. The various components in the BD are listed as follows.

1. RF Amplifier
2. Mixer and local oscillator.
3. IF amplifier.
4. Filter.
5. Diode
6. Measuring unit.



1. RF Amplifier

It measures the radio interference caused by the corona with the help of an antenna and simplifies to radio frequencies.

2. Mixer and local oscillators:

The local oscillator mixes the various radio frequencies with sine waves using non-linear component to produce original radio frequencies. Along with these, radio frequencies are also generated which are removed by using filters.

3. IF Amplifier.

The radio frequencies measured by local oscillators are fed to IF amplifier, which further converts radio frequencies to measurable frequencies.

4. Filters:

The filters are provided to the next of IF amplifier in order to restrict the harmonics generated in transmission lines. These filters have a bandwidth of 5KHz (or) 9KHz.

5. Diodes:

The diodes sense the output at filters and makes them to flow in unidirectional and charges the capacitor connected in series with diode through internal resistance R_c.

6. Measuring unit:

It includes measuring meters like ammeters (or) voltmeters, which can be used to measure voltage across capacitor either by reading current discharged through resistance (R_d). (or) by connecting voltmeter across the resistance R_d.

Radio Influence Voltage Measurement.

The schematic arrangement for radio interference voltage is shown in fig.

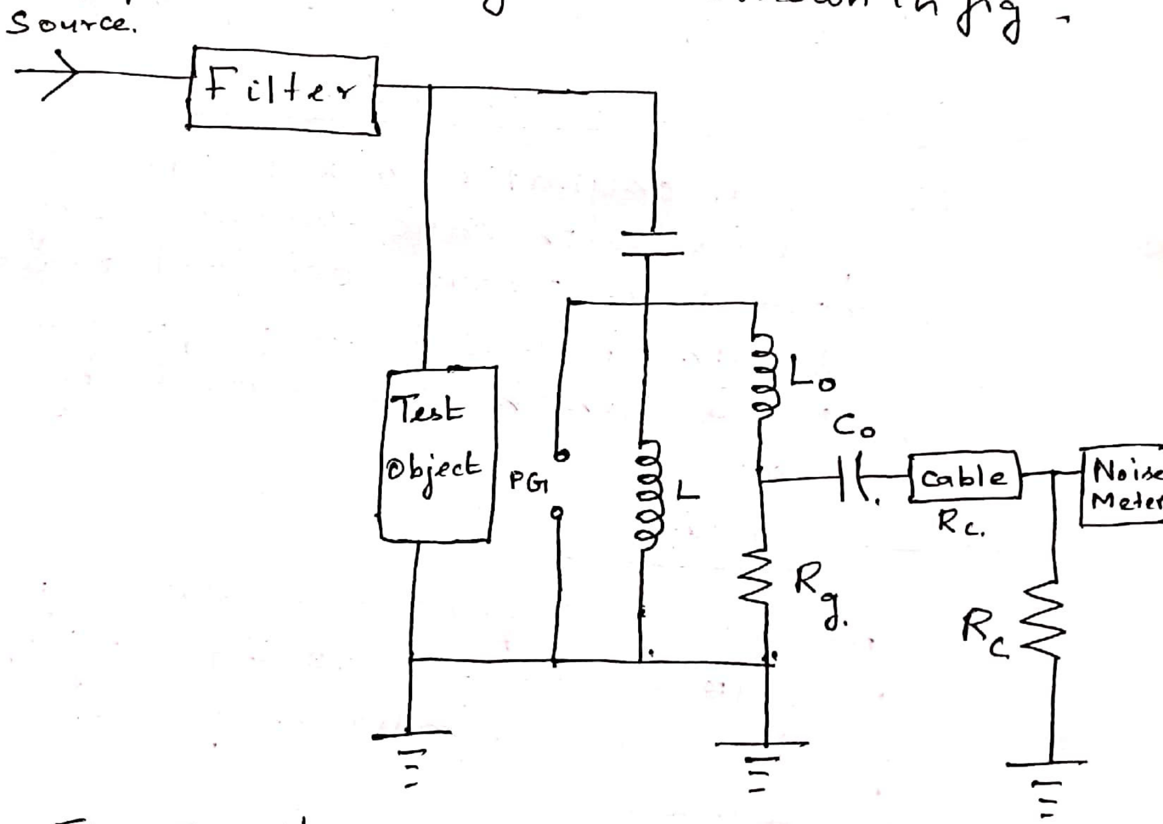
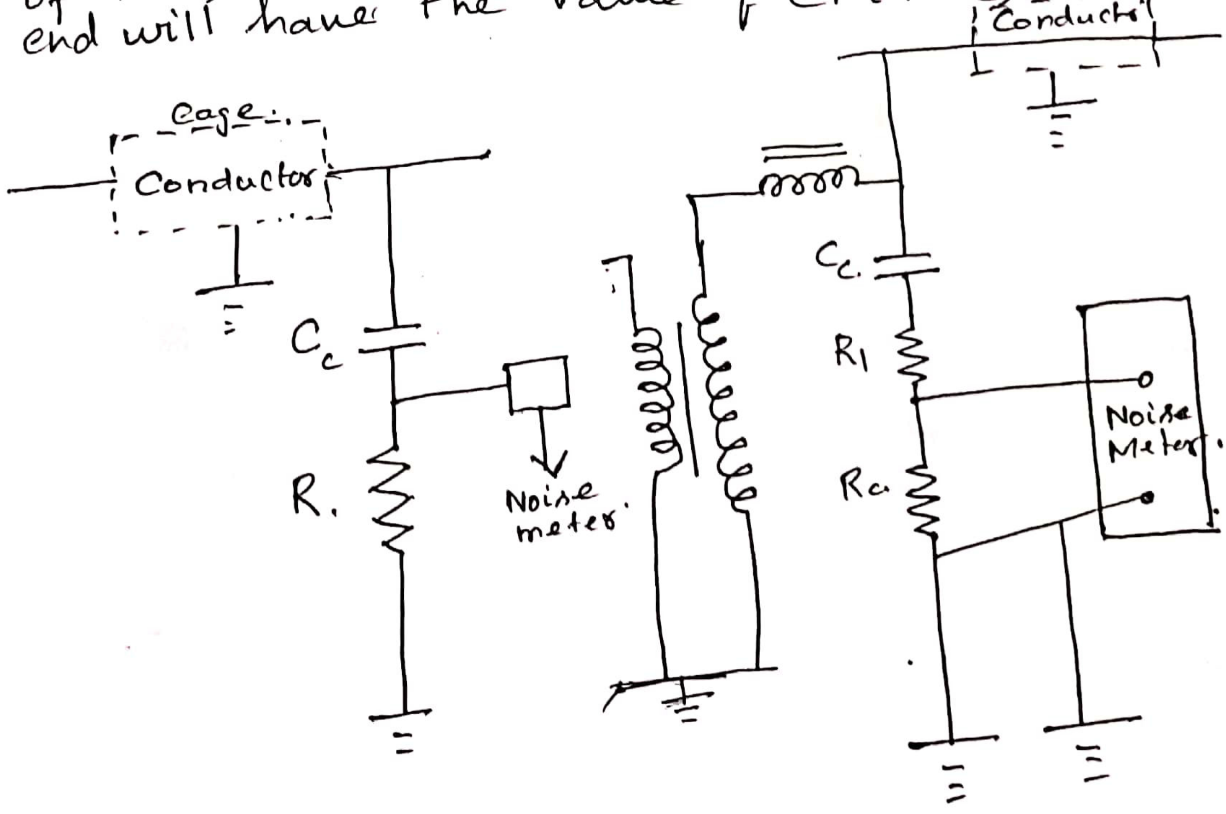


Fig: Circuit for measuring RIV.

The test object (insulator string with gaurd rings) is energized with a high voltages source at power frequency (or) impulse, which further produces r-f energy by partial discharge. However, in order to prevent the flow of r-f energy into source, a filter is provided across it, further causing the r-f energy to flow, to measuring circuit. A coupling capacitor of about 500 p.f to 200 p.f. is arranged at ground level along with a small inductance (L). The capacitor also exhibits a reactance of 6.36 MΩ to 1.59 MΩ. Further, the value of inductance should be chosen such that it yields votage drop less than 5 Volts.

Measurement of Excitation Function.

The discharge of corona injection of Currents into transmission lines at radio frequencies leading to generation of excitation function, which is measured on short lengths of Conductors strung inside "cages". The schematic arrangement of cage set-up for measuring excitation function is shown in fig. In order to measure, a conductor is strung with strain insulator at both ends offering high impedance of 1MHZ. The conductor is also terminated with a coupling capacitor (C_c) at one end in series with resistance R_1 and R_c. However the (C_c) has negligible resistance at radio-frequency. Because of this, the termination at the measuring end will have the value of (R_1+R_c).



EHVAC TRANSMISSION

UNIT – V

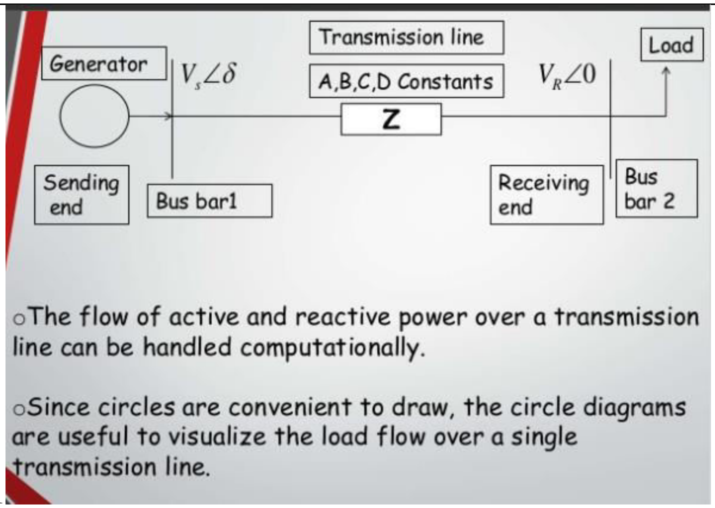
NOTES

Unit-V

1.Explain in-detail about power circle diagram and its use.

A **circle diagram** is a graphical representation of the performance of an electrical machine. It is commonly used to illustrate the performance of transformers, alternators, synchronous motors, and induction motors.

1



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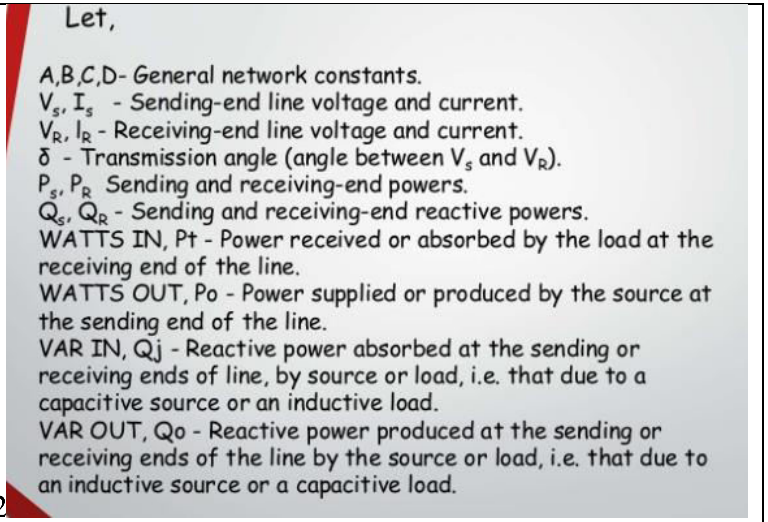

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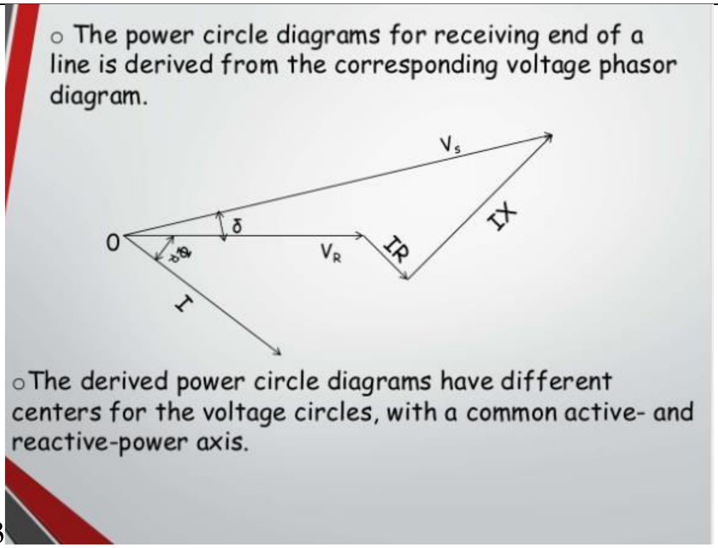

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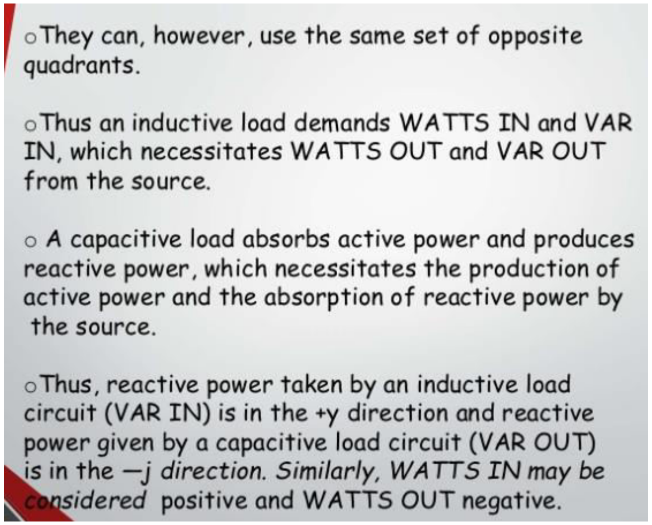


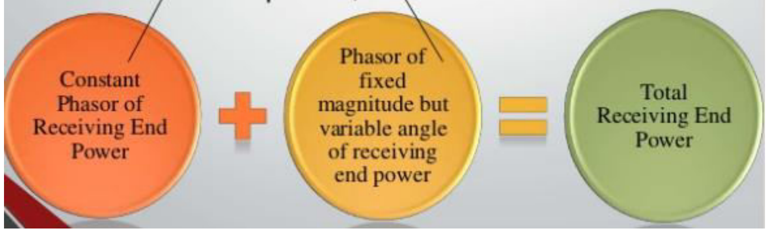
S_R = Total Receiving end power

$$= -\frac{A}{B} V_R^2 \angle(\beta-\alpha) + \frac{V_s V_R}{B} \angle(\beta-\delta)$$

- S_R is in MVA(three phase)
- V_s V_R Are in kV (line).

$$-\frac{A}{B} V_R^2 \angle(\beta-\alpha) + \frac{V_s V_R}{B} \angle(\beta-\delta)$$

- From the above equation, it is clear that



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- The loci for S_R would be circle drawn from the tip of constant phasor as centre.

- Hence the centre of receiving-end circle is located at the tip of the phasor

$$-\frac{A}{B} V_R^2 \angle(\beta-\alpha)$$

- Hence the horizontal coordinates of the centre..

$$-\frac{A}{B} V_R^2 \angle \mathrm{Cos}\,(\beta-\alpha) \quad \text{(MW)}$$

And the vertical coordinates of the centre..

$$-\frac{A}{B} V_R^2 \angle \sin\,(\beta-\alpha) \quad \text{(MVAR)}$$

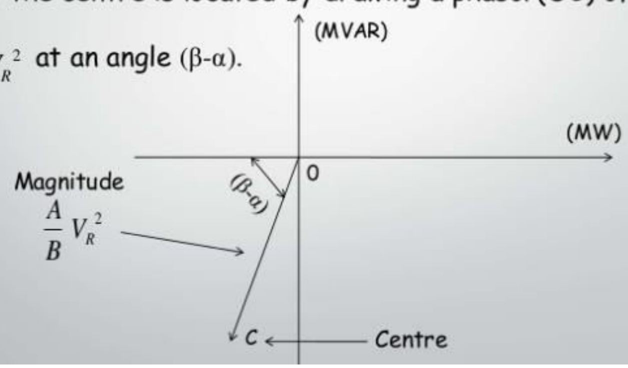
6

- The radius of the receiving end circle is..

$$\frac{V_s V_R}{B}$$

Steps for drawing receiving-end circle diagram:

1) First the centre is located by drawing a phasor(OC) of $-\frac{A}{B} V_R^2$ at an angle (β-α).



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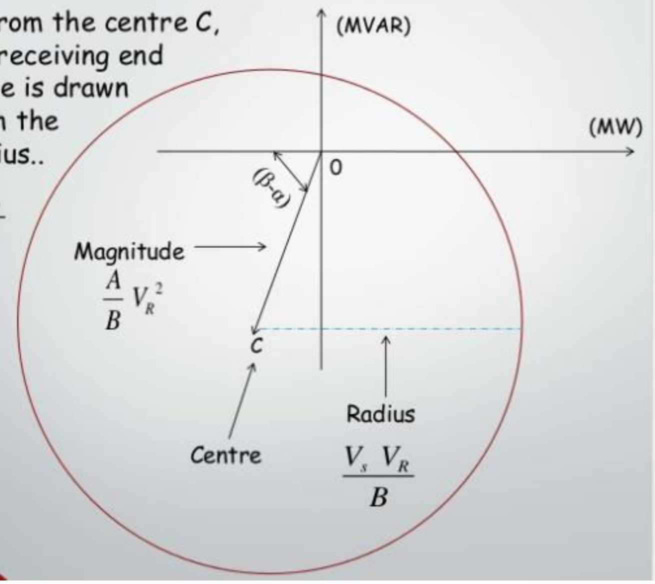
2) From the centre C, the receiving end circle is drawn with the radius..

$$\frac{V_s V_R}{B}$$



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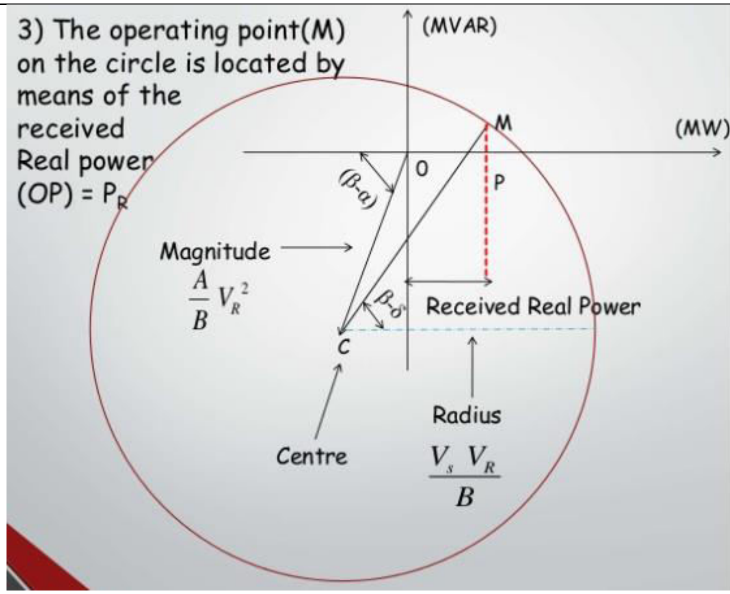
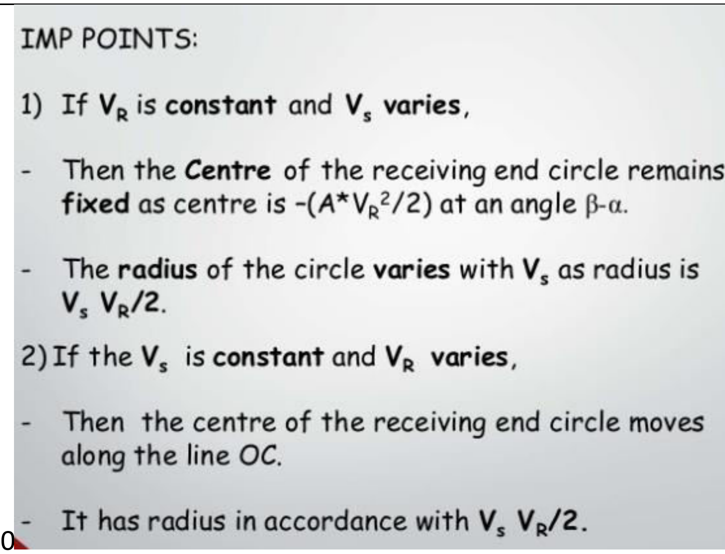
9 

10 

Importance of circle diagram:
It provides us with the power output, power factor, speed, slip, torque, efficiency, and copper loss of the induction motor in a graphical representation. The **diagram** is also easier to remember and understand compared to the theoretical and mathematical description.

2. Explain in detail sub synchronous resonance problems and counter measures.

5. Explain the phenomena of sub-synchronous resonance and its remedies. (Same Answer)

The SSR Phenomena:

A power system is mainly consisting of an electrical system and mechanical system. These two systems are coupled at the rotor of the alternator. The electrical system consists of an alternator and an external transmission line network. The mechanical system consists of one or more turbines connected in cross compound or tandem. The generator rotor is coupled with the main turbine shaft while the exciter may either be driven by same shaft or independently driven.

The electrical and mechanical system are mutually coupled such that the mechanical energy is converted in to electrical energy or the electrical energy converted to mechanical energy. When a power system is disturbed from its equilibrium state, giving rise to interchange of energies

- between the masses in the mechanical system
- between inductances and the capacitances in the electrical system
- between mechanical and electrical systems, which are coupled through the rotor of the alternator

The SSR phenomena pertains to the **interchange of energy between the electrical and the mechanical systems which are coupled through the rotor of the alternator**. As the energy is interchanged between these two systems, their frequencies of oscillation are the natural frequencies of their respective systems. The natural frequencies of oscillation of each system will from their respective modes of oscillation. For a given **electrical system** the number of modes of oscillation will depend upon the number of circuit configuration that can be made through switching. For a given **mechanical system** the number of modes are finite and depend upon the number of masse used.

The natural frequencies of the mechanical system normally range from 0.5 to 55 Hz for a 60 Hz system, but for the hydro generator sets these are quite low (10 Hz or below).The natural frequencies of the electrical system are very high for all practical purposes it can be said that the electrical system natural frequencies are below 60 Hz. Since these various frequencies of oscillations are below the synchronous frequency (60 Hz) they are termed as Sub synchronous Oscillations and the phenomena as **Sub synchronous Resonance (SSR).**

Mainly SSR is the resonance between a series-capacitor-compensated electric system and the mechanical spring-mass system of a turbine-generator at subsynchronous frequencies, that is, at frequencies that are less than the synchronous frequency.

4. Develop the A,B,C,D constant expressions for a long distance transmission line.

Long Transmission Line

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

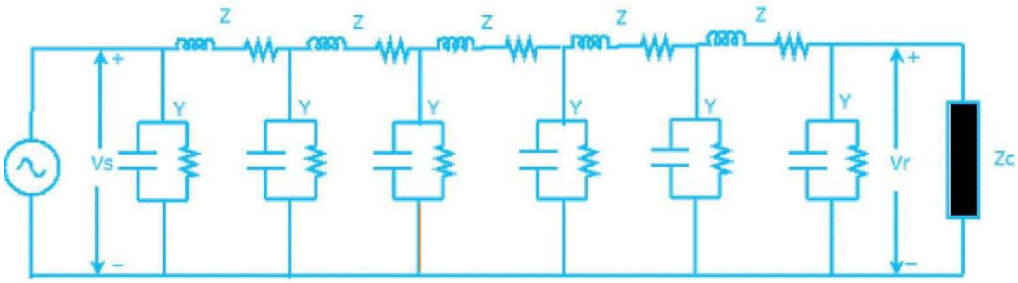


Fig.1.14: Long line model

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

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

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

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

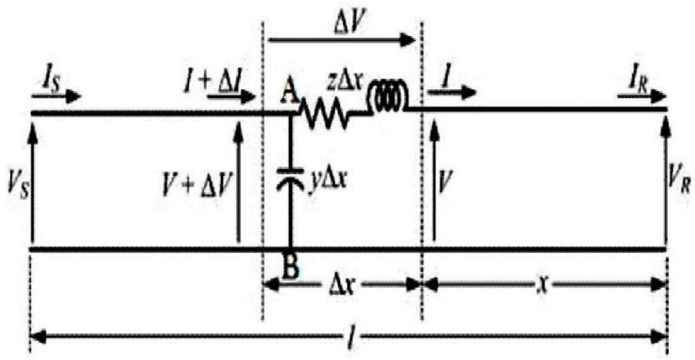


Fig.1.15: Modeling of long transmission line

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

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

V+ΔV = voltage leaving the element Δx.

I+ΔI = current leaving the element Δx.

ΔV = voltage drop across element Δx.

zΔx = series impedence of element Δx

yΔx = shunt admittance of element Δx

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

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

$\Delta V = Iz\Delta x$

Now to determine the current ΔI, we apply KCL to node A.
$\Delta I = (V+\Delta V)y\Delta x = V\, y\Delta x + \Delta V\, y\Delta x$ (1)

Since the term ΔV yΔx is the product of 2 infinitely small values, we can ignore it for the sake of easier calculation.

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

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

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

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

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

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

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

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

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

$dV/dx = \sqrt{(yz)}\, A_1\, e^{x\sqrt{yz}} - \sqrt{(yz)} A_2 e^{-x\sqrt{yz}}$ (5)

Now comparing equation (1) with equation (5)

$$I = \frac{dV}{dX} = \sqrt{\frac{y}{z}}\, A_1 e^{-x\sqrt{YZ}} \qquad (6)$$

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

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

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

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

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

Now at x=0, V= V_R and I= I_R. Substituting these conditions to equation (7) and (8) respectively. $V_R = A_1 + A_2$ (9)

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

Solving equation (9) and (10), We get values of A_1 and A_2 as, $A_1 = (V_R + Z_C I_R)/2$

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

Now applying another extreme condition at x=l, we have $V = V_S$ and $I = I_S$. Now to determine V_S and I_S we substitute x by l and put the values of A_1 and A_2 in equation (7) and (8) we get

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

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

By trigonometric and exponential operators we know $\sinh \delta l = (e^{\delta l} - e^{-\delta l})/2$

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

Therefore, equation(11) and (12) can be re-written as $V_S = V_R \cosh \delta l + Z_C\, I_R \sinh \delta l$

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

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

$A = \cosh \delta l$

$B = Z_C \sinh \delta l$

$C = \sinh \delta l / Z_C$

$D = \cosh \delta l$

5. Explain in-detail about voltage control using synchronous condensers.

A synchronous condenser is a synchronous machine running without mechanical load. By controlling the field excitation it can be made to either absorb or generate reactive power. With a voltage regulator, it can automatically made to adjust the reactive power output to maintain a constant terminal voltage. It is basically an over-excited synchronous motor running on no-load. Synchronous condensers are also called as **synchronous phase modifiers**. A synchronous condenser is located near the load end and can inject or absorb reactive power. And, thus, a synchronous phase modifier improves the voltage profile.

The voltage at the receiving end of a transmission line can be controlled by installing specially designed synchronous motors called **synchronous condensers** at the receiving end of the line. The Voltage Control by Synchronous Condenser supplies leading reactive power (kVAR) to the line depending upon the excitation of the motor. This wattless leading kVA partly or fully cancels the lagging kVA reactive power (kVAR) of the line, thus controlling the voltage drop in the line. In this way, voltage at the receiving end of a transmission line can be kept constant as the load on the, system changes.

For simplicity, consider a short transmission line where the effects of capacitance are neglected. Therefore, the line has only resistance and inductance. Let V_1 and V_2 be the per phase sending end and receiving end voltages respectively. Let I_2 be the load current at a lagging power factor of cos Φ_2.

1.Without synchronous condenser:

Fig.1(i) shows the transmission line with resistance R and inductive reactance X per phase. The load current I2 can be resolved into two rectangular components viz Ip in phase with V2 and Iq at right angles to V2 [See Fig.1(ii)] Each component will produce resistive and reactive drops ; the resistive drops being in phase with and the reactive drops in quadrature leading with the corresponding currents. The vector addition of these voltage drops to V2 gives the sending end voltage V1.

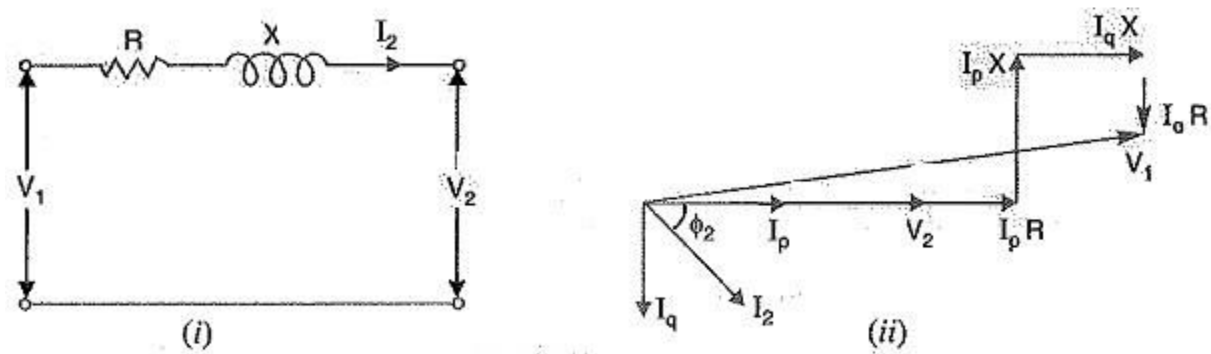


Fig. (1)

2.With synchronous condenser:

Now suppose that a synchronous condenser taking a leading current Im is connected at the receiving end of the line. The vector diagram of the circuit becomes as shown in Fig. 2. Note that since Im and Iq are in direct opposition and that Im must be greater than Iq, the four drops due to these two currents simplify to :

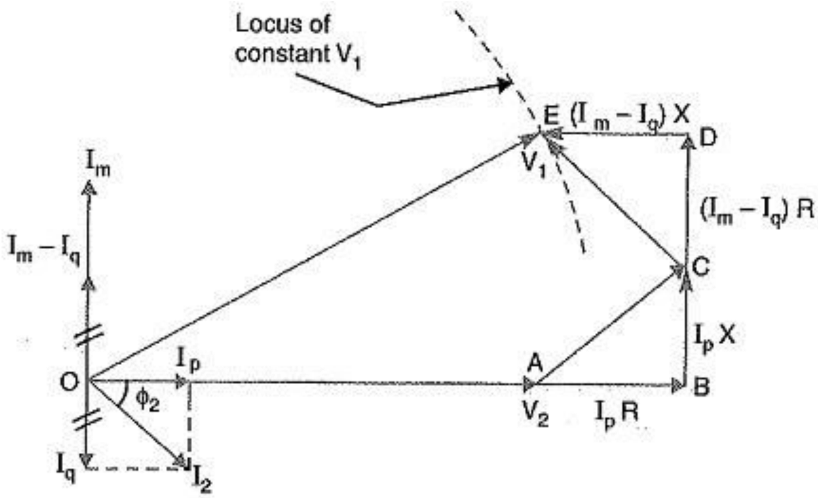


Fig. (2)

$(I_m - I_q)\, R$ in phase with I_m

$(I_m - I_q)\, X$ in quadrature leading with I_m

From the vector diagram, the relation between V1 and V2 is given by

$$OE^2 = (OA + AB - DE)^2 + (BC + CD)^2$$
$$V_1^2 = [V_2 + I_p R - (I_m - I_q)\, X]^2 + [I_p X + (I_m - I_q)\, R]^2$$

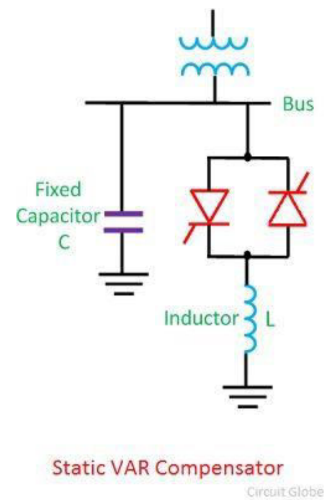
From this equation, the value of Im can be calculated to obtain any desired ratio of V1/V2 for a given load current and power factor.

6. Explain the voltage control of transmission system using Static VAR Compensators.

A static VAR compensator is a parallel combination of controlled reactor (absorbers) and fixed shunt capacitor (generators) shown in the figure below. The term "static" is used to indicate that SVCs, un like synchronous condensers, have no moving or rotating parts The thyristor switch assembly in the SVC controls the reactor. The firing angle of the thyristor controls the voltage across the inductor and thus the current flowing through the inductor. In this way, the reactive power draw by the inductor can be controlled.

The SVC is capable of step less adjustment of reactive power over an unlimited range without any time delay. It improves the system stability and system power factor. Most commonly used SVC scheme are as follows.

1. Thyristor controlled reactor (TCR)
2. Thyristor-switched capacitor (TSC)
3. Self Reactor (SR)
4. Thyristor controlled reactor – Fixed capacitor (TCR-FC)
5. Thyristor-switched capacitor – Thyristor controlled reactor (TSC-TCR)



Characteristic of an ideal SVS:

From the viewpoint of power system operation, an SVS is equivalent to a shunt capacitor and a shunt inductor, both of which can be adjusted to control voltage and reactive power at its terminals (or a nearby bus) in a prescribed manner (see Figure 11.39).

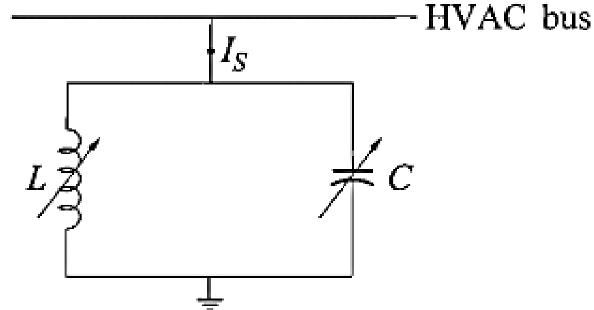


Figure 11.39 Idealized static var system

Ideally, an SVS should hold constant voltage (assuming that this is the desired objective), possess unlimited var generation/absorption capability with no active and reactive power losses and provide instantaneous response. The performance of the SVS can be visualized on a graph of controlled ac bus voltage (V) plotted against the SVS reactive current (I_S). The V/I characteristic of an ideal SVS is shown in Figure 11.40. It represents the steady-state and quasi steady-state characteristics of the SVS.

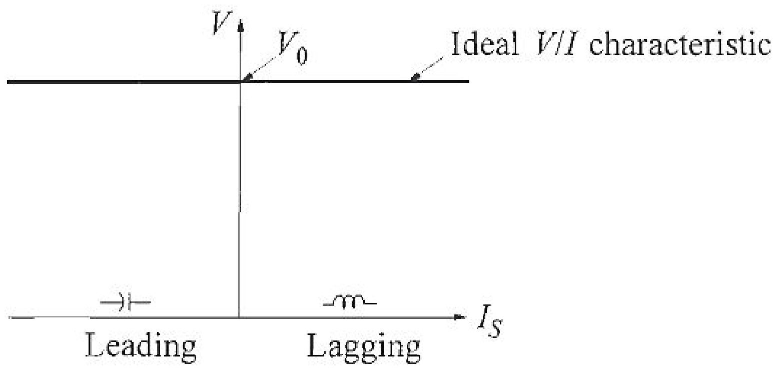


Figure 11.40 *V/I* characteristic of ideal compensator

Characteristic of a realistic SVS:

We consider an SVS composed of a controllable reactor and a fixed capacitor. The resulting characteristics are sufficiently general and are applicable to a wide range of practical SVS configurations.

Figure 11.41 illustrates the derivation of the characteristic of an SVS consisting of a controllable reactor and a fixed capacitor. The composite characteristic is derived by adding the individual characteristics of the components. The characteristic shown in Figure 11.41(a) is representative of the characteristics of practical controllable reactors.

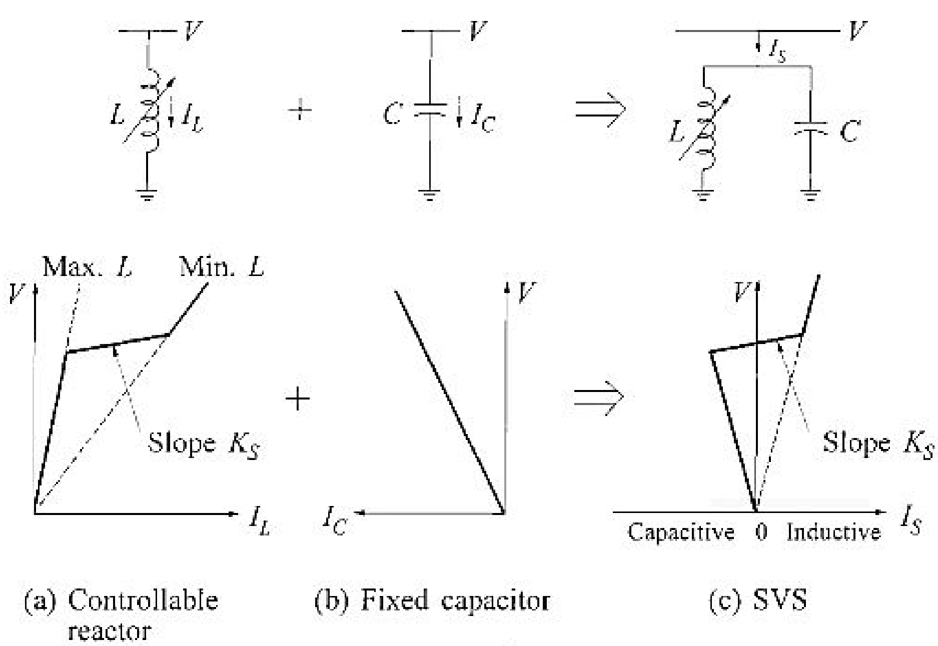
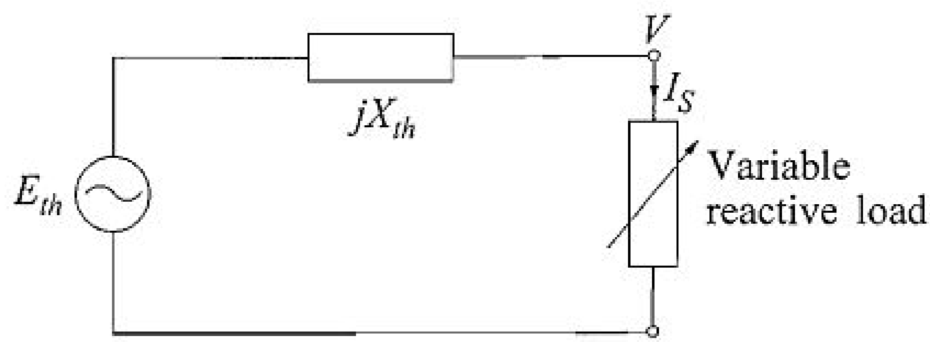


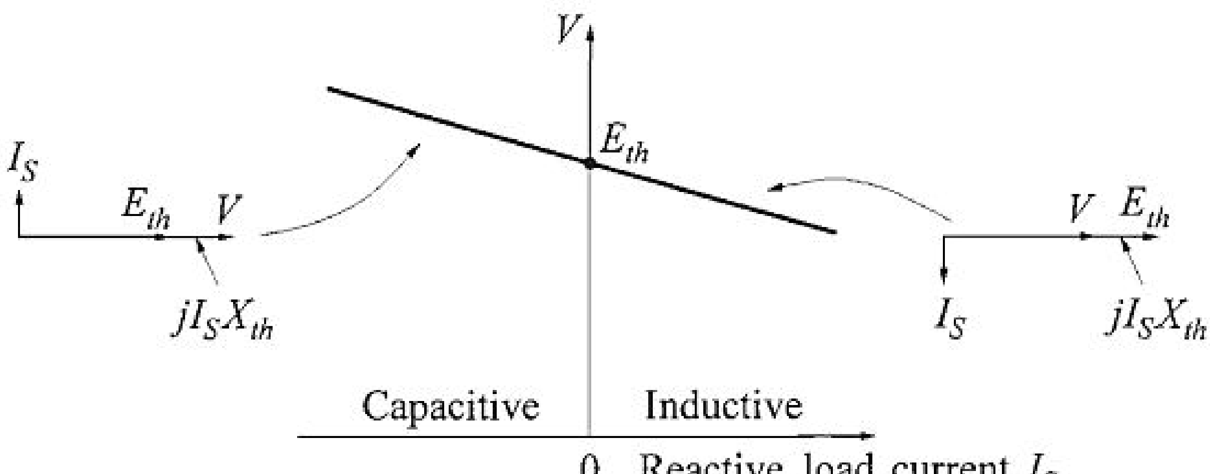
Figure 11.41 Composite characteristics of an SVS

Power system characteristic:

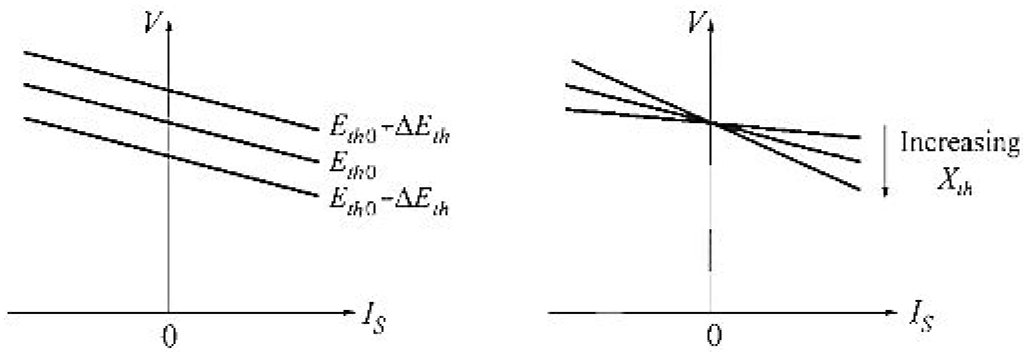
In order to examine how the SVS performs when applied to a power system, the characteristics of the SVS and the power system need to be examined together. The system *V/I* characteristic may be determined by considering the Thevenin equivalent circuit as viewed from the bus whose voltage is to be regulated by the SVS. This is illustrated in Figure 11.42. The Thevenin impedance in Figure 11.42(a) is predominantly an inductive reactance. The corresponding voltage versus reactive current characteristic is shown in Figure 11.42(b). The voltage V increases linearly with capacitive load current and decreases linearly with inductive load current.



(a) Thevenin equivalent circuit of HVAC network



(b) Voltage-reactive current characteristic



(c) Effect of varying source voltage E_{th}

(d) Effect of varying system reactance X_{th}

Figure 11.42 Power system voltage versus reactive current characteristic [38]

For each network condition, an equivalent circuit such as that shown in Figure 11.42(a) can be defined. Figures 11.42(c) and (d) show how the network *V/I* characteristic is affected by changes in source voltage E_{th} and the system equivalent reactance X_{th}, respectively.

6. Shunt and Series Compensation

Voltage level control is accomplished by controlling the generation, absorption and reactive power flow at all levels in the system.

1. Shunt Capacitors:

Shunt capacitors banks are used to supply reactive power at both transmission and distribution levels, along lines or sub-stations and loads. Capacitors are either directly connected to a bus bar or to the tertiary winding of a main transformer. They may be switched on and off depending on the changes in load having a lagging power factor, the capacitors supply reactive power.

Shunt capacitors are extensively used in industrial and utility systems at all voltage levels. By developing higher power density, lower cast improved capacitors and an increase in energy density by a factor of 100 is possible. These present a constant impedance type of load and the capacitive power output varies with the square of voltage.

$$K_{Var},V_2 = K_{Var},V_1[V_2/V_1]^2$$

Where Kvar, V1 is output at voltage V_1

Kvar, V2 is output at voltage V_2

As the voltage reduces, so does the reactive power output, when it is required the most. This is called the destabilizing effect of power capacitors. Capacitors can be switched in certain discrete steps and do no not provide a stepless control. As a reactive power demand increases voltage falls.

Advantages:

1. These are less costly.
2. Flexibility of installation and operation.
3. Power factor improvement.
4. Efficiency of transmission and distribution of power is high.
5. Single or multiple banks industrial distribution at low and medium voltage substation.
6. Essential elements of SVC & Facts controllers and HVDC transmission.
7. Reactive power compensation

Disadvantages:

1. They cannot be overloaded.
2. The reactive power supplied by static capacitors tends to decrease in case of voltage dip on the bus because KVAR α V^2

Problems Associated with shunt capacitors:

- Switching inrush currents at higher frequencies and switching over voltage.
- Harmonic resonance problems.
- Limited overvoltage withstands capacity.
- Limited of harmonic current loadings
- Possibility of self-excitation of motors when improperly applied as power factor improperly applied as power factor improvement capacitors switched with motor.

Applications:

- improve power factor
- improve feeder voltage control

2.Series capacitors

It is connected in series to compensate the inductive reactance of line. This reduces the transfer reactance between the fuses to which the lines is connected. It increases maximum power that can be transmitted and reduce reactive power loss. The reactive power produced by the series capacitor increases with increase in power transfer, a series capacitor is self regulating in this regard.

Under fault conditions, the voltage across the capacitor rises and unlike a shunt capacitor, a series capacitor experiences many time its rated voltage due to fault currents.

A Zinc oxide varistor in parallel with the capacitor may be adequate to limit this voltage**.**

For locations with high fault currents a parallel fast acting triggered gap is introduced which operates for more severe faults. When the spark gap triggers it is followed by closure of the bypass breaker.

The drainage reactor limits the frequency and magnitude of the current through the capacitor when the gap sparks.

The schematic diagram of a series capacitor installation is shown in figure.

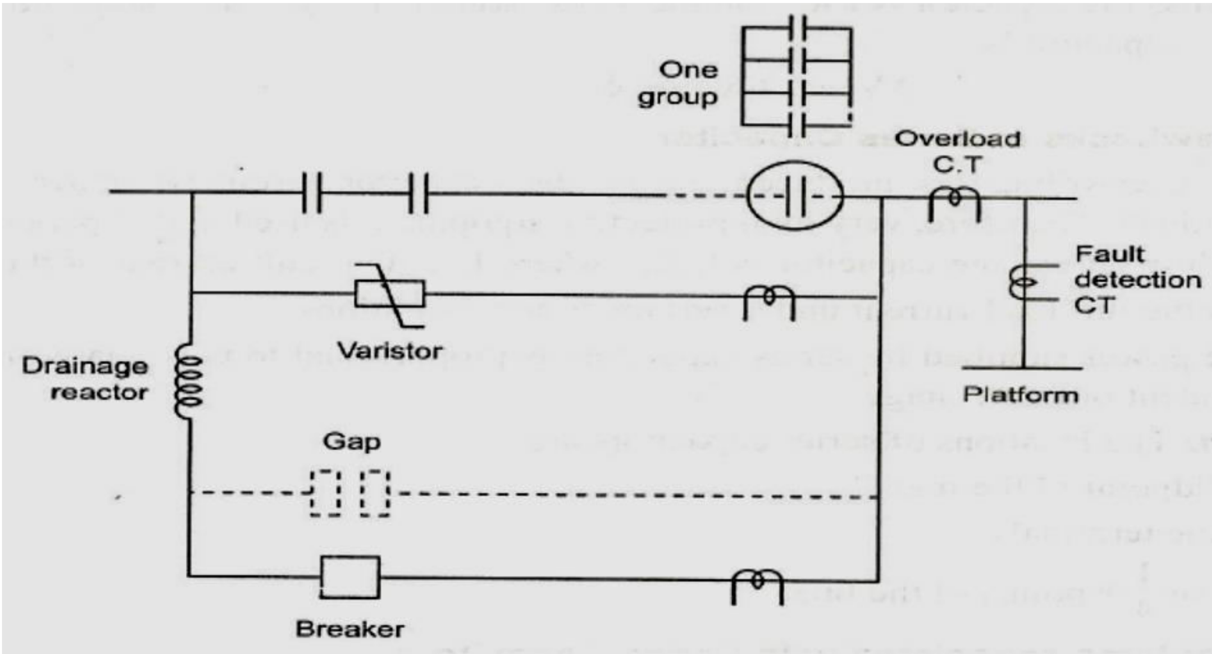


Figure 5.3 Series capacitor

Phasor diagram when series capacitor is connected on a line.

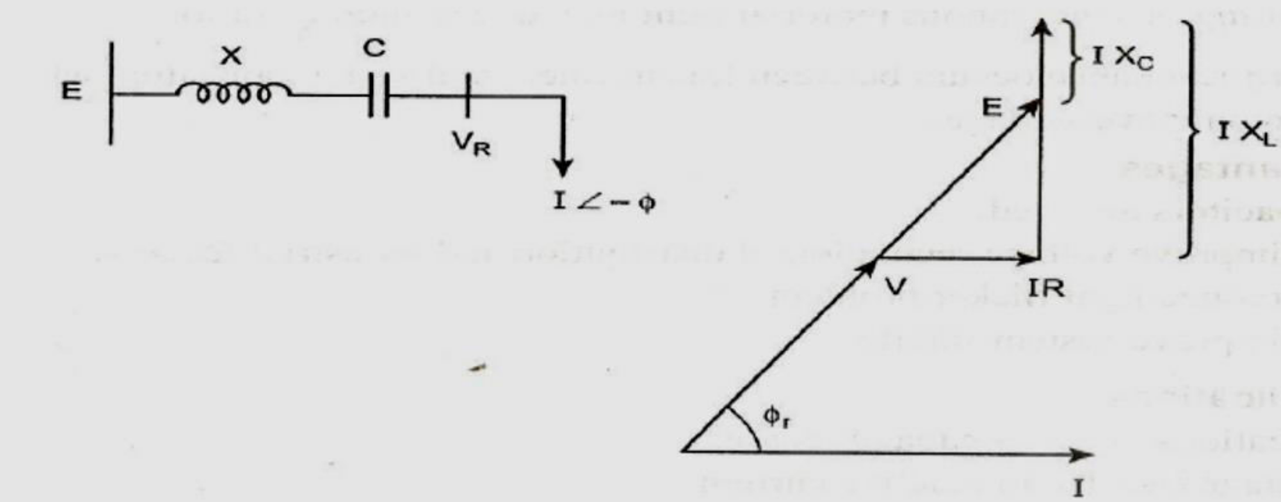


Figure 5.4 Phasor diagram Series capacitor

The voltage drop Across the line is

$$IR \cos \phi_r + I (X_L - X_c) \sin \phi_r$$

It is clear from the vector diagram diagram shown in figure that the voltage drop produced by an inductive load can be reduced particularly when the line has a high X/R ratio.

In practice X_c may be so chosen that the factor (X_L-X_c) $\sin\phi r$ becomes negative and numerically equal to R $\cos\phi r$ so that the voltage drop becomes zero. The ratio X_c/X_L pressed as a percentage is usually referred to as the percentage compensation.

If I is the full load current, and X_c is the capacitive reactance of the series capacitor, then the drop across the capacitor is IX_c and the VAR rating is $I^2 X_c$. The voltage boost produced by the series capacitor is $V= IX_c \sin\phi r$.

Drawbacks of series capacitor:

1. High over-voltage is produced across the capacitor terminals under short curcuit conditions. Therefore, very high protective equipment is used. E.g., spark gap.
2. The drop across the capacitor is if Xc, where if is the fault current of the order of 20 times the full load current under certain circuit conditions. Reactive power supplies capacitor is proportional to the square of line current and independent of line voltage.

Location:

The location of series capacitors au:
1.Midpoint of the line.
2.Line luminal
3.1/3 or ¼ th point of the line.

Problems associated with series capacitors:

- ✓ Locking of synchronous motor during stating .
- ✓ Hunting of synchronous motor at light load due to high R/x ratio
- ✓ Ferro resonance occurs between transformers and series capacitors which produces harmonic over voltages.

Advantages:

Series capacitors are used

- ✓ To improve voltage regulation of distribution and industrial feeders
- ✓ To reduce light flicker problems
- ✓ To improve system stability

Applications:

The applications of series capacitors are

- ✓ Voltage rise due to reactive current
- ✓ By passing the capacitor during faults and reinsertion after fault clearing

3.Shunt reactors:

The shunt reactor au used to reduce (or) limit rise due to circuit (or) light load, shunt reactor absorbs reactive power are usually used for EHV lines longer than and when the far end line is opened, the large source inductive reactance will cause a rise in voltage at the receiving end of the line. Ferranti effete will cause a feather rise in receiving end voltage. During heavy loads some of the reactors may have to be disconnected.

Advantages:

- ✓ Shunt reactors of sufficient size is permanently connected to the line to limit fundamental. Frequency temporary over voltages
- ✓ To limit switching transients
- ✓ To maintain normal voltage under light load conditions
- ✓ During heavy load conditions, some of the reactors are disconnected by using switching reactors and circuit breakers.

Location:

Shunt reactors added to maintain normal voltage under light load may be connected to EHV bus as shown in fig 5.5.

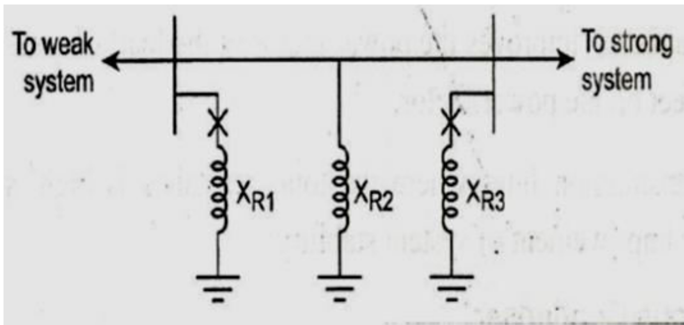


Figure 5.5 Shunt reactors connected to EHV bus

Shunt reactors connected to EHV bus:

X_{R1}, X_{R3} – switchable reactors.

X_{R2} – permanently connected reactor

shunt reactors connected to the tertiary windings of adjacent transformers as shown in fig 5.6

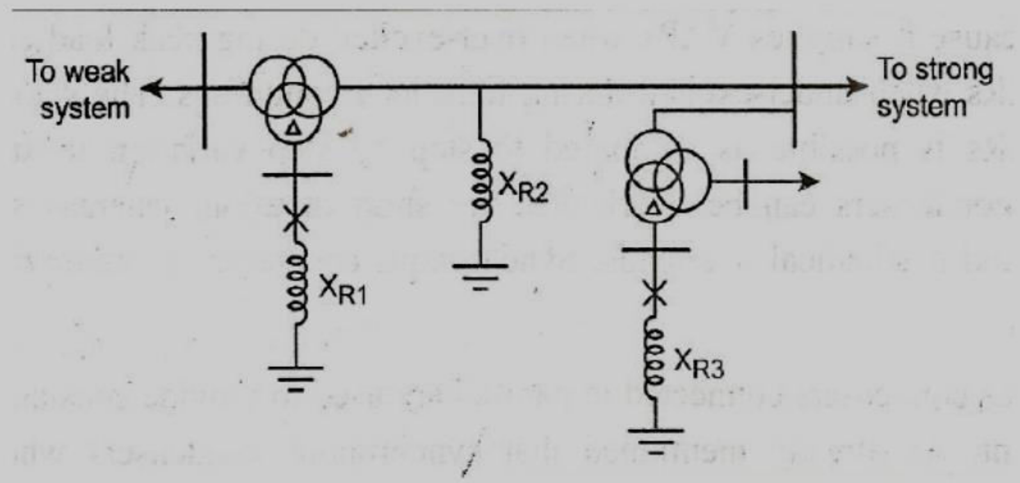


Figure 5.6 Shunt reactors connected to tertiary winding of transformers.

In short transmission lines, no need connecting shunt reactors permanently, so switchable reactors may be connected to EHV bus or tertiary winding of transformers but in some applications, tapped reactors with on load tap changer is used in fig 5.7

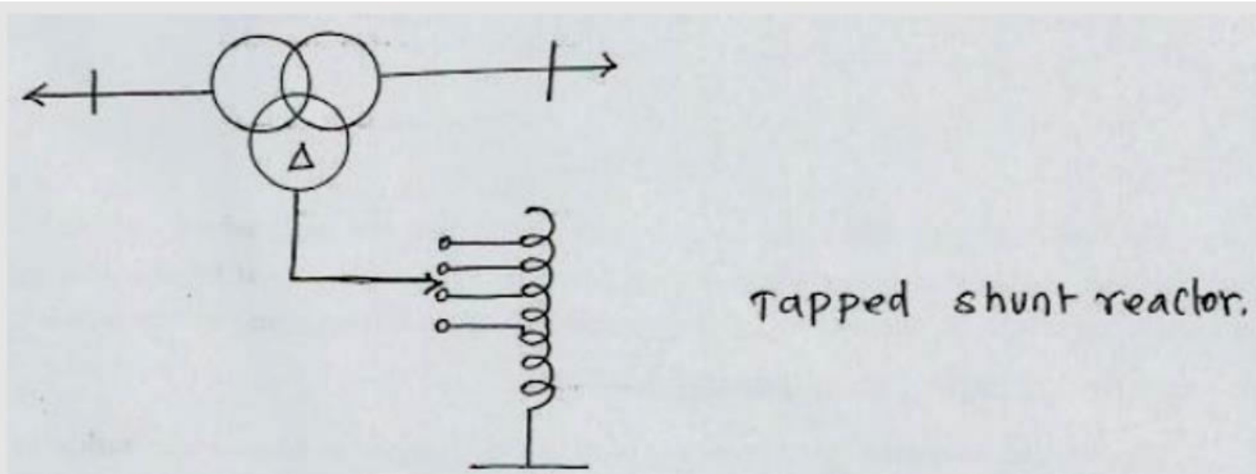


Figure 5.7 Tapped reactors with on load tap changer

Comparison between series & shunt capacitors:

- The voltage boost due to a shunt capacitor is evenly distributed over the transmission line whereas the change in voltage between the two ends of a series capacitor where it is connected in sudden. The voltage drop along the line is unaffected.

- For the same voltage, the reactive power capacity of a shunt capacitor is greater than that of a series capacitor.
- The shunt capacitor improves the power factor of the load whereas the series capacitor has little effect on the power factor.
- For long transmission lines where the total reactance is high, series capacitors are effective for improvement of system stability.