Power System - II

(Code : EEC501)

Semester V - Electrical Engineering
(Mumbai University)

Strictly as per the Choice Based Credit and Grading System (Revise 2016) of Mumbai University w.e.f. academic year 2018-2019

M. A. Chaudhari
B.E. (Electrical Engineering)
Ex. Head of Department Govt Polytechnic, Pune
Ex. Asst. Director of Technical Education,
Maharashtra state, Pune region
Ex visiting faculty, Govt college of
Engg.(COEP) Pune

S. M. Chaudhari
M.E. (Electrical)
Assistant Professor,
Electrical Engineering Department,
AISSMS IOIT, Pune.
Maharashtra, India.

Miss. Priyanka Mogre
B.E. (Electrical)
Manager, h_2e Power Systems Pune

Mrs. S. S. Landge
M.E. (Electrical)
Assistant Professor,
Electrical Engineering Department,
AISSMS IOIT, Pune.

MO70A Price ₹ 200/-

TechKnowledge™ Publications

(Book Code : MO70A)

Power System – II
(Semester V - Electrical Engineering, Mumbai University)
M. A. Chaudhari, S. M. Chaudhari , Mrs. S. S. Landge, Miss. Priyanka Mogre

First Edition : September 2018
Second Revised Edition : August 2019 **(TechKnowledge Publications)**

Printed at : 37/2, Ashtvinayak Industrial Estate, Near Pari Company,
Narhe, Pune, Maharashtra State India,
Pune - 411041

ISBN : 978-93-89424-24-9

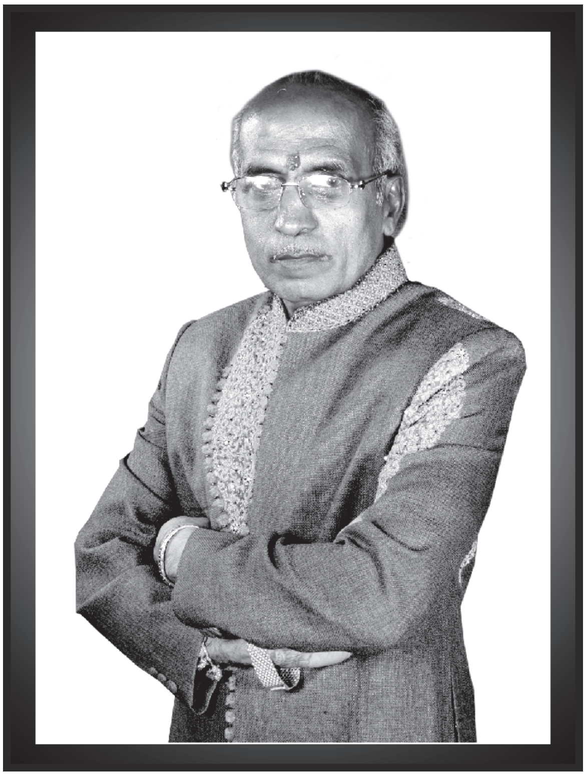
Published by

TechKnowledge Publications

Head Office : B/5, First floor, Maniratna Complex,
Taware Colony, Aranyeshwar Corner,
Pune - 411 009. Maharashtra State, India
Ph : 91-20-24221234, 91-20-24225678.

[EEC501] (FID : MO70) (Book Code : MO70A)

We dedicate this Publication soulfully and wholeheartedly,
in loving memory of our beloved founder director
Late. Shri. Pradeepsheth Lalchandji Lunawat, *who will always*
be an inspiration, a positive force and strong support behind us.



Lt. Shri. Pradeepji L. Lunawat

Soulful Tribute and Gratitude for all Your
Sacrifices, Hardwork and 40 years of Strong Vision.......

(Book Code : MO70A)

Preface

Dear students,

We are extremely happy to come out with this book on **"Power Systems - II"** for you. The topics within the chapters have been arranged in a proper sequence to ensure smooth flow of the subject.

A large number of university questions have been included. So, we are sure that this book will cater all your needs for this subject.

We present this book in the loving memory of **Late Shri Pradeepji Lunawat,** our source of inspiration and a strong foundation of "TechKnowledge Publications". He will always be remembered in our heart and motivate us to achieve our new milestone.

We are thankful to Shri. J S Katre, Shri. Shital Bhandari, Shri. Arunoday Kumar and Shri. Chandroday Kumar for the encouragement and support that they have extended. We are also thankful to staff members of TechKnowledge Publications for their efforts to make this book as good as it is. We have jointly made every possible effort to eliminate all the errors in this book. However if you find any, please let us know, because that will help me to improve further.

We are also thankful to my family members and friends for patience and encouragement.

- Authors

(Book Code : MO70A)

Syllabus

Power System - II

(University of Mumbai)

Course Code	Course Name	Teaching Scheme (Contact Hours)		Credits Assigned		
		Theory	**Tutorial**	**Theory**	**Tutorial**	**Total**
EEC501	**Power System – II (abbreviated as PS - II)**	4	1	4	1	5

Course Code	Course Name	Examination Scheme						
		Theory						
		Internal Assessment			End Sem. Exam	Exam Duration (Hrs.)	Team Work	Total
		Test 1	Test 2	Avg.				
EEC501	Power System – II	20	20	20	80	03	25	125

Course Objectives	To impart knowledge on transmission line operation during fault. To study power system transients and insulation co-ordination.
Course Outcomes	Student will be able • To understand different kind of faults on transmission line. • To analyse symmetrical fault • To analyse symmetrical components and unsymmetrical faults. • To illustrate and analyse power system transients • To understand insulation co-ordination in power system. • To understand and analyse corona on transmission line

Module	Contents	Hours
1.	**Symmetrical Fault Analysis** Introduction to synchronous machine, basic construction, operation and equivalent circuit diagram, short circuit of synchronous machine : no load and loaded machine, transient on a transmission line, selection of Circuit breaker, short circuit MVA, algorithm for SC studies, Z Bus formulation, symmetrical fault analysis using Z bus **(numerical on Z bus formulation up to 3 x 3 matrix).** **(Refer chapter 1)**	14

(Book Code : MO70A)

2.	**Symmetrical Components** Introduction, Symmetrical component transformation, phase shift in star-delta transformers, sequence impedances and sequence network of transmission line, synchronous machine and transformer, power invariance, construction of sequence network of a power system. **(Refer chapter 2)**	07
3.	**Unsymmetrical Fault Analysis** Types of unsymmetrical faults, Analysis of shunt type unsymmetrical faults: single line to ground (SLG) fault, line to line (L-L) fault, double line to ground (LLG) fault, bus impedance matrix method for analysis of shunt type unsymmetrical faults. Analysis of series type unsymmetrical faults: one open conductor faults, two open conductor fault. **(Refer chapter 3)**	07
4.	**Power System Transients** Review of transients in simple circuits, recovery transient due to removal of short circuit, arcing grounds, capacitance switching, current chopping phenomenon. Travelling waves on transmission lines, wave equation, reflection and refraction of waves, typical cases of line terminations, attenuation, Bewely lattice diagram. Lightning phenomenon, mechanism of Lightning stroke, shape of Lightning voltage wave, over voltages due to Lightning, Lightning protection problem, significance of tower footing resistance in relation to Lightning, insulator flashover and withstand voltages, protection against surges, surge arresters, surge capacitor, surge reactor and surge absorber, Lightning arrestors and protective characteristics, dynamic voltage rise and arrester rating. **(Refer chapter 4)**	12
5.	**Insulation Coordination** Volt time curve, basic approach to insulation co-ordination in power system, over voltage protection, ground wires, insulation coordination based on lightning, surge protection of rotating machines and transformers. **(Refer chapter 5)**	03
6.	**Corona** Phenomenon of corona, Disruptive critical voltage, Visual critical voltage, corona loss, factors affecting corona loss, Radio interference due to corona, practical considerations of corona loss, corona in bundled conductor lines, corona ring, corona pulses- their generation and properties in EHV lines, charge voltage (q-v) diagram and corona loss. **(Refer chapter 6)**	05

❑❑❑

(Book Code : MO70A)

Chapter 1 : Symmetrical Fault Analysis 1-1 to 1-57

❑❑❑

CHAPTER

1

Symmetrical Fault Analysis

Syllabus :

Introduction to synchronous machine, basic construction and operation and equivalent circuit diagram, short circuit of synchronous machine : no load and loaded machine, transient on a transmission line, selection of Circuit breaker, short circuit MVA, algorithm for SC studies, Z Bus formulation, symmetrical fault analysis using Z bus **(Numerical on Z bus formulation upto 3 × 3 matrix).**

Syllabus Topic : Introduction to Synchronous Machine (Basic Construction and Operation)

1.1 Introduction to Synchronous Machine (Basic Construction and Operation)

- The construction of alternator (synchronous generator) and synchronous motor is same. In fact the same machine can function as generator or motor. The synchronous machine has the following main parts :
  (a) Stator and stator winding.
  (b) Rotor and rotor winding.
  (c) For some machine additional equipment such as exciter.
- The rotating field system is almost universal, especially for large capacity alternators. This helps to have the windings rigidly braced and insulated for high voltages on a stationary armature.
- The field system has a low voltage and low power winding which can be easily insulated and supplied by two slip rings.
- This also helps to limit the size of the machine. The highest possible speed is 3000 r.p.m. (for f = 50 Hz and P = 2) suitable for steam turbines. Such machines have

smaller diameter rotors longer in size having horizontal mountings to reduce centrifugal forces and wear at the bearings.

– The low speed alternators driven by water wheels or I. C. engines have large diameter rotors vertically mounted. For small capacity machines the mounting is horizontal with a stationary field system also.

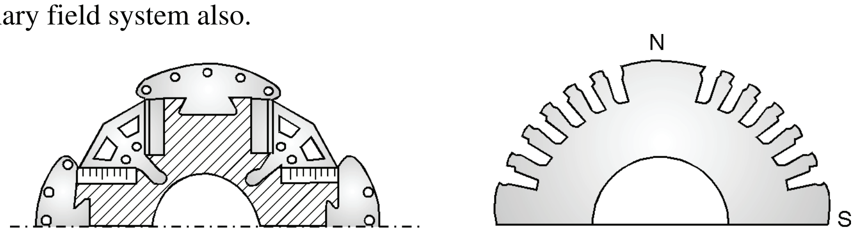


Fig. 1.1.1 : Construction of rotors for turbo alternators

1.1.1 Turbo-Alternators

(a) Stator

– It carries a 3-phase alternating current winding having integral/fraction slots, full pitch or short pitched coils.

– The conductors are transposed and insulated with bitumen-bonded micanite wrapped as a tape, vacuum dried and then impregnated with bitumen under pressure.

– Synthetic resins are used in modern machines replacing bitumen.

– The winding is placed in slots deep inside the semi-enclosed slots punched out in stampings along with ventilation holes, shaft hole and key ways. The stampings made up of low loss alloy steel especially R.C.G.O. steels, as a whole for small capacity machines and in section for high rated machines. The stampings are assembled to form the core under pressure and fitted between non-magnetic end plates.

– The windings of turbo alternators (2-pole machines) are single layer concentric full pitch or double layer short chorded (5/16 pitch).

(b) Rotors

(i) Smooth cylindrical (ii) Salient pole type (See Fig. 1.1.1)

– These are made from solid forgings of alloy steel ultrasonically tested for defects.

– Two-thirds of rotor is milled for teeth. The normal coils are accommodated in slots (number is multiple of four) with flat strips having separators between turns.

Slip-rings are required to convey currents and are made up of copper fitted on micanite and fitted on the haft inside or outside the main bearing.

1.1.2 Salient Pole Machines

- These operate at speeds between 80 r.p.m. and 600 r.p.m. so that the diameter are large to accommodate large number of poles and the lengths are shorter. Stators are identical to turbo alternator except use of multilayer windings in deeper slots and the above limitations.

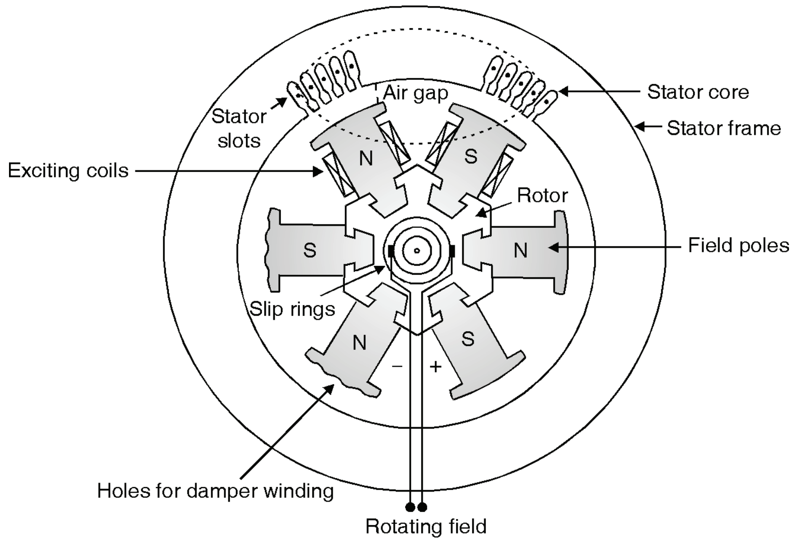


Fig. 1.1.2 : Salient pole type alternator

- The rotors are usually vertically mounted with thrust bearings, especially for water wheel alternators. The poles are carried on the main hub of the rotor shrunk after making them from thick discs.
- The pole structure is laminated. Slots are provided at the top peripheri to house damper or amortisseur winding, useful to start as a motor, decrease hunting and increase stability. The field coils are former wound in sections or as a wheel, from rectangular sections strips.
- Asbestos-rubber insulation is used between turns.

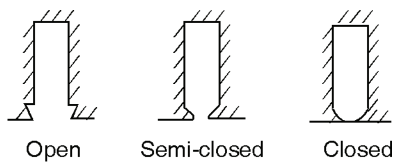


Fig. 1.1.3 : Types of slots

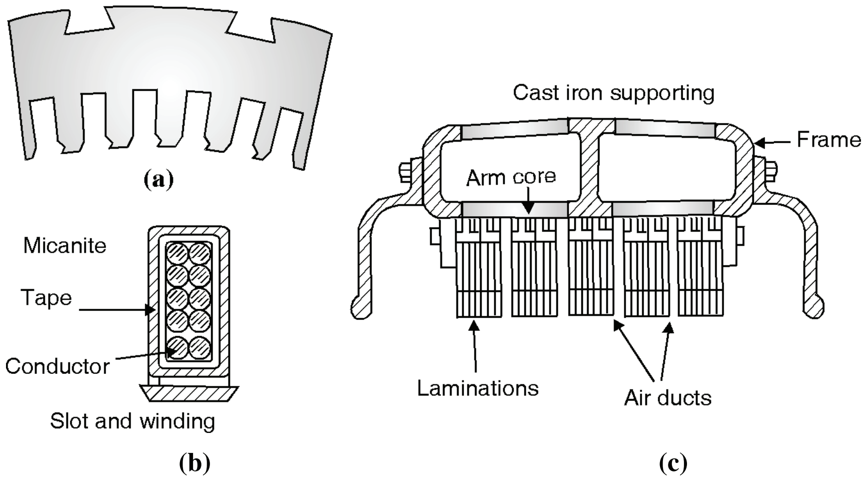


Fig. 1.1.4 : Armature core

☞ **Exciter**

The D.C. exciting current required to produce the necessary magnetic flux in the rotor circuit is obtained from a small D.C. shunt generator of about 125 volt D.C. This generator is called as an **Exciter** and it is generally mounted on the same shaft of the synchronous machine.

1.1.3 Difference between Salient Pole Type and Smooth Cylindrical Type

Sr. No.	Salient pole type	Smooth cylindrical type
1.	Diameter of rotor is more and axial length is small.	Axial length is very large and diameter is small.
2.	Poles are projecting out from the rotor surface.	Poles not projected out but unslotted portion serves as poles.
3.	Due to projected poles the air-gap between stator and rotor is not uniform.	Due to smooth cylindrical rotor portion the air-gap between rotor and stator.
4.	Rotor is mechanically weak.	Rotor is sturdy and strong.
5.	Suitable for low speed low capacity machine.	Suitable for high speed turbo alternators.
6.	Prime-movers are water turbines or I.C. engines used to drive the rotor.	Steam turbines are prime-movers for turbo alternator rotor drives.
7.	For the same rating the size is more than smooth cylindrical type.	For the same rating the size is smaller than projected pole type machine.
8.	Separate damper winding is provided.	Separate winding is not required for damping.

1.2 Armature Reaction in Synchronous Machine

1.2.1 Magnetic Fields in Alternator

The main magnetic field is produced of a rotor whose field winding is excited by a D.C. supply as shown in the following simple sketch.

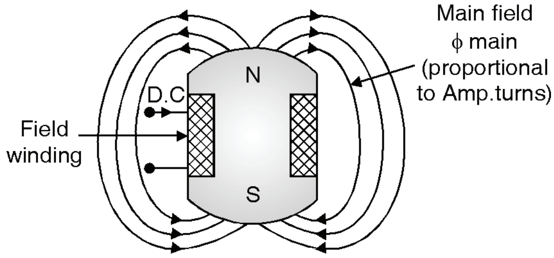
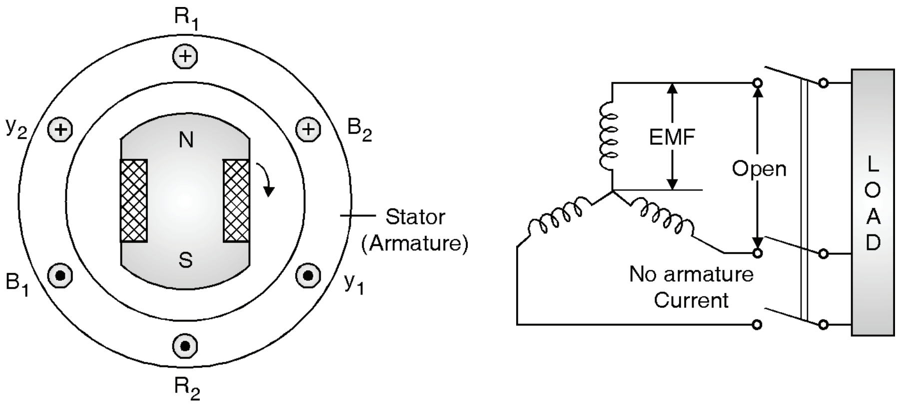


Fig. 1.2.1 : Main magnetic field

1.2.2 No Load Case

– At no-load, when armature (stator) winding is open circuited there is no-armature current and hence no arm flux (i.e. $\phi_a = 0$).

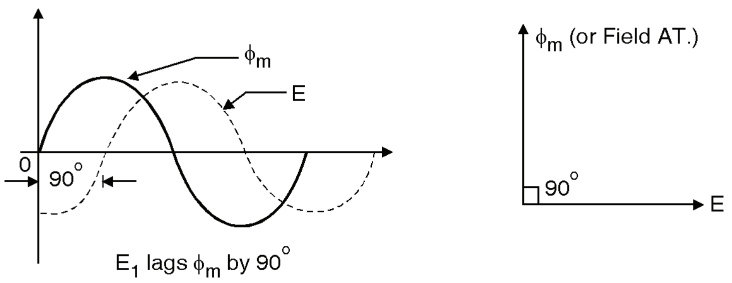
– The main flux induces an emf in the armature windings. The direction of this induced emf (E) is as per the Fleming's right hand rule. It is marked in the Fig. 1.2.2 by ⊕ and ⊙.



(a) Rotor and rotor winding **(b) No load**

Fig. 1.2.2

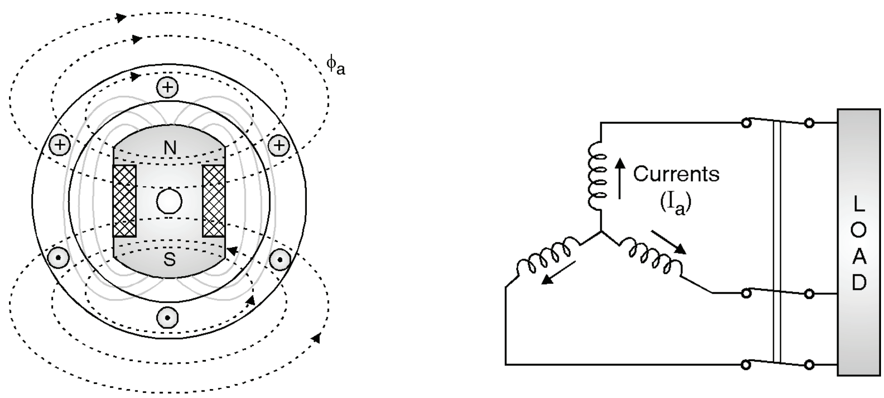
– This EMF (E) lags behind the main flux (ϕ_m) by 90° (Recall transformer theory - the emf E_1 induced due to electromagnetic induction lags ϕ_m by 90°). Similarly in case of alternator also the emf E is induced due to electromagnetic induction and it lags ϕ_m by (90°). This phasor relation is shown in Fig. 1.2.3.



(a) (b)

Fig. 1.2.3

1.2.3 Now take the Case of Alternator On-Load



(a) Armature flux ϕ_a **(b) On load**

Fig. 1.2.4: Alternator loaded (Interaction of two fluxes)

When load is connected, the induced emf E_1 produces the current (I_a) to feed to the load as the circuit is closed.

- The phasor relation of the armature current with the EMF (E_1) depends on **the nature of the load.**
- The load may be resistive, inductive or capacitive and hence load p.f. may be unity, lagging or leadings and hence current (I_a) may be in phase with E for resistive unity p.f. load, it may be lagging or leading to E for lagging / leading p.f. of load.
- I_a will produce its own flux i.e. armature flux ϕ_a (proportional to armature mmf i.e. arm. ampere turns).
- This armature flux (ϕ_a) produced by armature current will interact with the main flux ϕ_m produced by the rotor.

1.2.4 Armature Reaction

- The effect of armature flux ϕ_a on the main flux ϕ_m is called as armature reaction. This effect is different for different nature of p.f. of the load.
- The effect may be cross-magnetising i.e. ϕ_a crosses ϕ_m.
- It may be demagnetising i.e. ϕ_a opposes ϕ_m and hence ϕ_m weakens.
- It may be strong magnetising i.e. ϕ_a is in the same direction as ϕ_m, so both are added and resultant field becomes stronger.

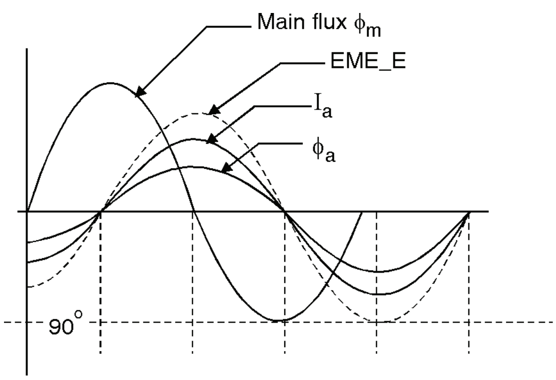
1.2.5 Different Nature of Load Power Factors

Now let us take step by step three different cases of p.f.

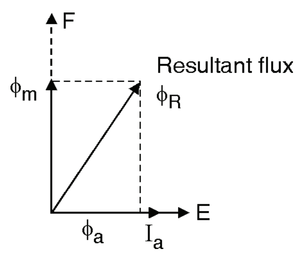
(a) Unity p.f. (b) Zero p.f. lagging (c) Zero p.f. leading

1.2.5.1 Unity p.f. Case

- In this case I_a is in phase with E.
- The phasor relations are
  1. E lag ϕ_m by 90°
  2. I_a is in phase with E
  3. Field Ampere turns i.e. (F) and ϕ_m in phase
  4. Flux produced by I_a is in phase with I_a. i.e. ϕ_a is in phase with I_a.
- These relations are shown in the following waveform and phasor diagrams.
- It is noted from the waveform and vector diagram, that armature flux crosses the main flux and the resultant flux is inclined.
- So for unity p.f. (resistive load) the effect of armature reaction is such that the **main flux ϕ_m is disturbed i.e. distorted. It is a cross magnetizing effect.**



(a) Waveforms



(b) Vector relations

Fig. 1.2.5

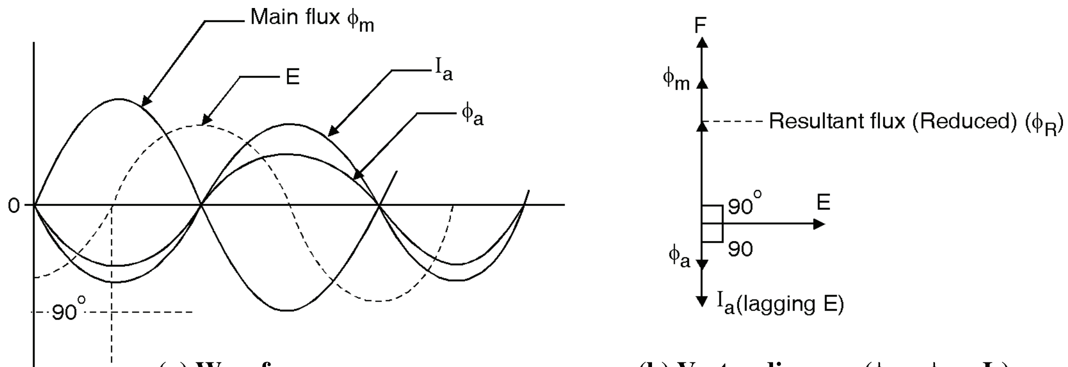
1.2.5.2 Zero Lagging Power Factor Case

– Zero p.f. lagging means the alternator is supplying a load which is purely inductive in nature.

– The phasor relations in this case are ;

1. E lags ϕ_m by 90°
2. I_a lags E by 90°
3. Field AT i.e. F is in phase with ϕ_m
4. ϕ_a is in phase with I_a.

– These relations are shown in the following waveform diagram and phasor diagram.



(a) Waveforms **(b) Vector diagram ($\phi_R = \phi_m - I_a$)**

Fig. 1.2.6

– It is seen from the above diagram that armature flux ϕ_a is in direct opposition to flux ϕ_{main} hence it demagnetizes and hence resultant $\phi_R = \phi_m - \phi_a$.

– Hence in this case the effect of armature reaction is a de-magnetising effect.

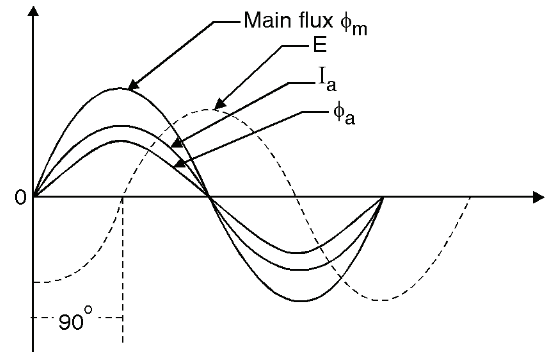
1.2.5.3 Zero Leading Power Factor Case

– Zero p.f. leading means alternator supply power to a purely capacitive load.

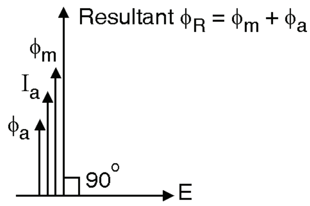
– The phasor relations in this case are ;

1. E lags ϕ_m by 90°
2. I_a leads E by 90°
3. Field AT are in the same phase as ϕ
4. ϕ_a is in phase with I_a.

– These relations are shown in the following waveform and phasor diagrams.



(a) Waveforms



(b) Vector diagram ($\phi_R = \phi_m + \phi_a$)

Fig. 1.2.7

- It is seen from the above diagrams that the armature flux ϕ_a is in the same direction as of ϕ_{main}. Hence it adds in ϕ_m and the resultant flux $\phi_R = \phi_m + \phi_a$ becomes stronger.
- **Hence in this case the effect of armature reaction is strong magnetizing.**

1.2.6 Conclusion

- To conclude the above discussion, it can be said that the effect of armature reaction depends on load as well as nature of p.f. of the load.
- For unity p.f. it is cross-magnetizing

  For lagging p.f. it is de-magnetizing.
- And for leading p.f. it is strong magnetizing.
- The emf(E) of alternator is proportional to flux. Since resultant flux changes the emf changes and hence terminal voltage also changes due to armature reaction effect.

1.2.7 Effect of Armature Reaction on Terminal Voltage (V_T)

1. Terminal voltages slightly changes for unity p.f. load.
2. Decreases for lagging p.f. load.
3. Increases for leading p.f. load.

Thus, for same load current (I_L), if power factor is different than terminal voltage is also different.

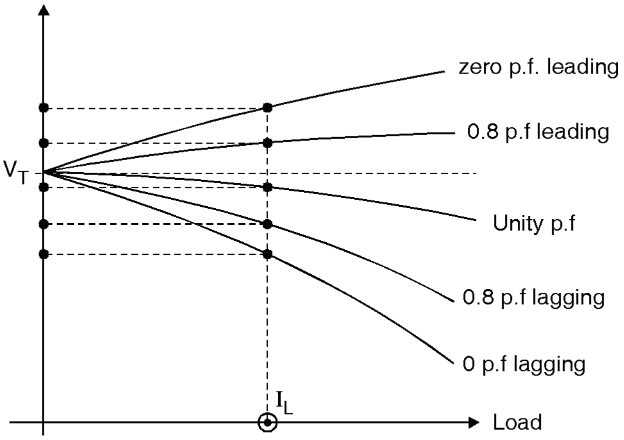


Fig. 1.2.8 : Change in Terminal voltage at load for different p.f.s

Syllabus Topic : Equivalent Circuit Diagram

1.3 The Circuit Model of Synchronous Machine (Equivalent Circuit Diagram)

In this model all the parameters, current and voltages are shown together in the form of an electric circuit model. This is also called as an equivalent circuit.

1.3.1 Concepts of Parameters

When the alternator is loaded, the voltage is lost due to :

(a) Armature (stator) resistance R_a
(b) Armature leakage reactance X_L
(c) Armature reaction reactance X_a.

1.3.1.1 Armature Resistance (R_a)

The armature winding is made of copper and let its resistance per phase be R_a. When alternator is loaded, the current I comes out from the armature winding. Some voltage is lost in the armature itself. This voltage is called as "Armature resistance drop" (IR_a) or ($I_a R_a$ drop). This drop is in phase with the current.

1.3.1.2 Armature Leakage Reactance (X_L)

– The armature current sets up flux and a portion of it does not cross the air-gap but has its path completed in the stator itself. Such a flux is called as "leakage flux".

– Due to this leakage flux an e.m.f. of self induction is set up called as reactance e.m.f. This e.m.f. is ahead to the current by 90°. Thus the armature winding is assumed to possess the leakage reactance. This produces a voltage drop $I \cdot X_L$ (or $I_a X_L$) called as **leakage reactance drop**. This drop is shown 90° ahead to the current in the vector diagram.

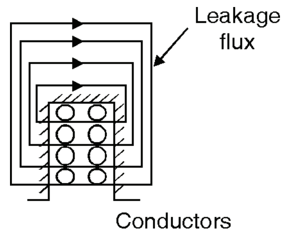


Fig. 1.3.1 : Stator slots

1.3.1.3 Armature Reaction Reactance (X_a)

The main flux is produced by rotor; but when the armature circuit is completed, the armature carries current. This produces its own flux (ϕ_a). It affects the main flux. So that demagnetizing or cross magnetizing or magnetizing effect is produced.(These effects are explained in more details in the previous article.)

– Due to the armature reaction a voltage is dropped = $I \cdot X_a$ (or $I_a X_a$), where X_a is the reactance which when multiplied by I gives the drop of voltage due to armature reaction. The drop $I \cdot X_a$ and $I \cdot X_L$ are similar; thus X_L and X_a can be combined together.

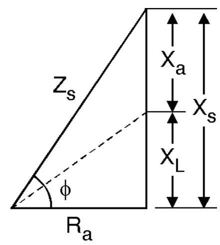


Fig. 1.3.2 : Impedance triangle

1.3.2 Synchronous Reactance (X_S)

– The leakage reactance X_L and the reactance due to armature reaction X_a are combined together and the combination is called as synchronous reactance (X_S).

$$\therefore \quad X_S = X_L + X_a$$

– The effective voltage drop due to the synchronous reactance ($I \cdot X_S$) should be shown leading to the current by 90°.

1.3.3 Synchronous Impedance (Z_S)

– The above fictitious reactance (X_S) when added with R_a, as shown in Fig. 1.3.2 the impedance triangle diagram, the addition is called as synchronous impedance.

$$Z_S = R_a + j X_S \qquad \text{Or} \qquad Z_S = \sqrt{R_a^2 + X_S^2}$$

– The drop due to impedance is called as synchronous impedance drop = $I \cdot Z_S$

It is shown in the equivalent circuit.

1.3.4 Equivalent Circuit of Alternator

When alternator delivers current, voltage drop takes place, i.e. $I_a Z_S$ drop. The synchronous impedance is composed of R_a and X_S.

The synchronous reactance (X_S) = $X_L + X_a$

Thus,

$$Z_S$$

$$\sqrt{(R_a)^2 + (X_S)^2}$$

$$(X_L + X_a)$$

– These parameters can be represented in equivalent circuit of alternator (refer Fig. 1.3.3)

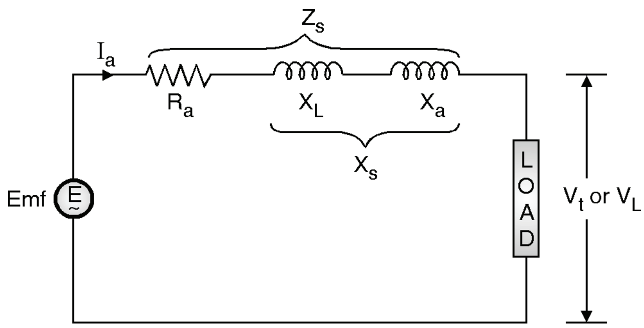


Fig. 1.3.3 : Equivalent circuit of alternator

From equivalent circuit we can write following equation,

$$E \;=\; V_t + j\, I_a X_a + j\, I_a X_L + j\, I_a\, R_a$$

All voltage drops are added to terminal voltage to get emf. See the following phasor diagrams.

1.3.5 Phasor / Vector Diagram on load for Different Power Factors

1. At unity power factor (Fig. 1.3.4)

Current I is in phase with V

IR_a drop in phase with I

$$IX_S \;=\; I\,(X_a + X_L)$$

IX_S drop 90° lead to I

$IZ_S = IR_a + IX_S$ (vectors)

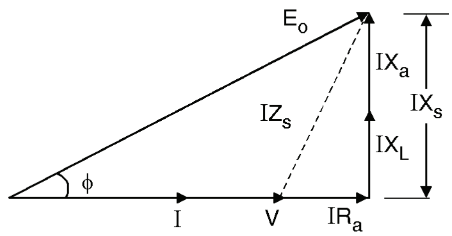


Fig. 1.3.4

$$\dot{E}_o = \dot{V} + I\dot{Z}_S$$

or
$$\dot{V} = \dot{E}_o - I\dot{Z}_S$$

2. For lagging power factor (See Fig 1.3.5)

Current I lags V by ϕ

IR_a in phase with I

procedure of adding is similar as explained in 1st case.

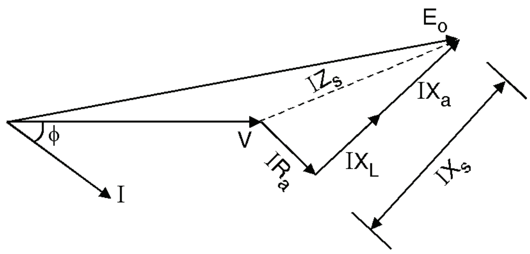


Fig. 1.3.5

3. For leading power factor (Refer Fig. 1.3.6)

I leads V by ϕ. It is observed from the above diagrams that for unity and lagging p.f. loads, the terminal voltage of the alternator reduces with load ($V < E_o$). But for the leading p.f. load, the terminal voltage increases with load ($V > E_o$). This can be seen in the following diagram.

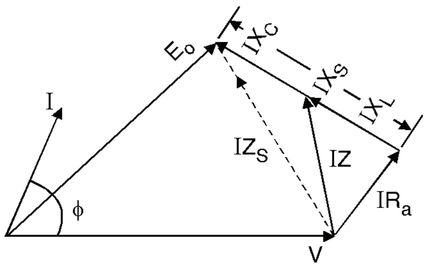


Fig. 1.3.6

Syllabus Topic : Short Circuit of Synchronous Machine

1.4 Short Circuit of Synchronous Machine

➔ (MU - May 15, Dec. 15, Dec. 16)

Q. 1.4.1	Discuss the short circuit of synchronous machine under no load condition. *(Refer section 1.4)*	**May 15, Dec. 16, 10 Marks**
Q. 1.4.2	Discuss the transients on transmission line. *(Refer section 1.4)*	**Dec. 15, 10 Marks**

1.4.1 Short Circuit Currents of Synchronous Machine

– Power system consists of synchronous generation, transformers, lines and loads. In abnormal operation the alternator is subjected to transient condition. These transient occur due to switching operation, sudden changes in load, sudden short circuit etc.

- The short circuit faults in a system develop severe mechanical stresses on armature coil. This produces a large torque which may damage alternator or its prime mover.
- The analysis of synchronous machine under short circuit condition is helpful in predicting possible conditions resulting from abnormal operations.
- In synchronous machine armature and field windings are assumed purely inductive. So the flux linkages in the armature or filed circuit cannot be changed suddenly by application of short circuit to armature winding.
- The current flowing in the armature of synchronous machine under short circuit condition is same as flowing in R-L series circuit. But in R-L series circuit reactance is constant quantity whereas in synchronous machine it is function of time.
- Under no load condition, there is no mmf due to armature reaction.
- When sudden three phase short circuit occur at the terminal of synchronous machine, the current in armature circuit increases suddenly to a large value. As resistance of winding is negligible as compared to its reactance, the current is highly lagging and p.f. is approximately zero.
- This increase in armature current is accompanied by armature reaction.
- As air gap flux cannot change instantaneously, to counter the demagnetization of the armature short circuit current, current appear in the field winding as well as damper winding in direction to help main flux. Thus in initial part of short circuit the equivalent circuit appears as shown in Fig. 1.4.2
- Under steady state condition the armature reaction of synchronous generator produces demagnetizing flux. This effect is indicated as X_a in Fig. 1.4.2.
- The short circuit current in a machine decreases according to winding time constants.
- Damper winding has low leakage inductance and field winding has more. Hence time constant of damper winding to less than field winding.
- During initial part of short circuit the current get induced in damper winding and field winding due to transformer action.
- Hence in the circuit model their reactances X_f and X_{dw} appear in parallel with X_a.
- The damper winding current if first to die out, X_{dw} effectively becomes open circuited. In later stage X_f becomes open circuited.

- The machine reactance thus changes from the parallel combination of X_a, X_f and X_{dw} during initial period of short circuit to X_a and X_f in parallel in the middle period of short circuit and finally to X_a in steady state.
- The reactance of machine in the initial period of short circuit is,

$$X_l + \frac{1}{\left(\frac{1}{X_a} + \frac{1}{X_f} + \frac{1}{X_{d\omega}}\right)} = X_d'' \qquad \text{...(1.4.1)}$$

X_d'' is the subtransient reactance of machine.

- The reactance after damper winding current have diet out it,

$$X_d' = X_l + (X_a \parallel X_f) \qquad \text{...(1.4.2)}$$

X_d' is called as transient reactance of machine.

- The reactance under steady state condition is the synchronous reactance of the machine x_d, obviously $X_d'' < X_d' < X_d$.
- Thus machine offers time varying reactance.

1.4.2 Analysis of Short Circuit Current in Synchronous Machine

- When a short circuit fault occurs at the terminal of synchronous generator, the initial short circuit current is limited by substrasient reactance.
- After few cycles it is controlled by transient reactance.
- Finally it is controlled by steady state reactance and get settled to steady state value. This is shown in Fig. 1.4.1.

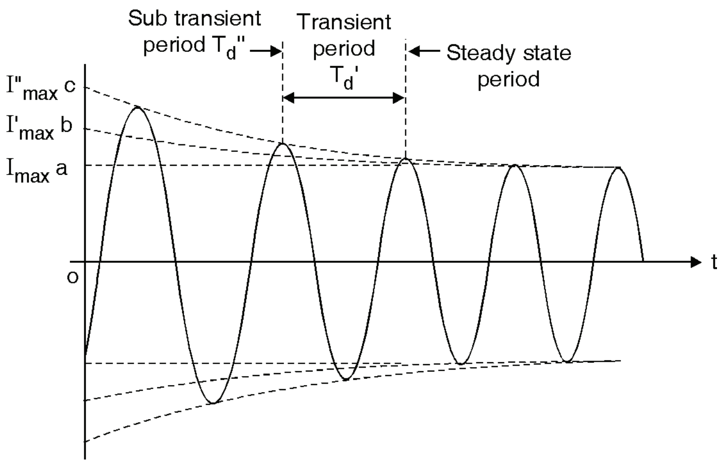
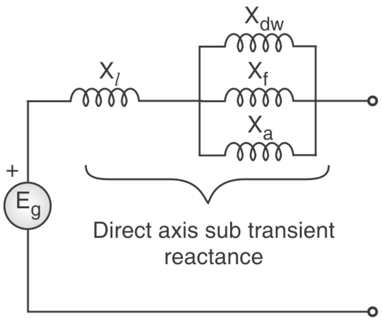


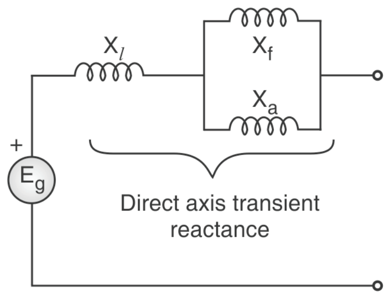
Fig. 1.4.1 : Short circuit oscillogram

- The short circuit period can be divided into three periods.
- Subtransient period lasting only for first few cycles during which the current decay is rapid.
- Transient period covers relatively longer time during which current decrement is moderate. Finally the steady state period.

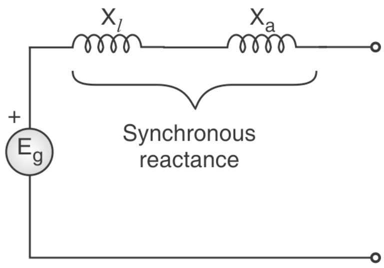
Fig. 1.4.2 should be indicated before analysis of short circuit current in synchronous machine. Equations (1.4.1) and (1.4.2) can be verified from these figs.



(a) Circuit model during subtransient period



(b) Circuit model during transient period



(c) Circuit model during steady state

Fig. 1.4.2 : Short circuit reactance's of synchronous machine

- Subtransient current,

$$I''_{max} = oc = \frac{E_{gmax}}{X''_d} \quad \ldots(1.4.3)$$

- Transient current,

$$I'_{max} = ob = \frac{E_{gmax}}{X'_d} \quad \ldots(1.4.4)$$

– Steady state current,

$$I_{max} = oa = \frac{E_{gmax}}{X_d} \qquad \ldots(1.4.5)$$

– E_{gmax} is maximum voltage from one terminal to neutral on no load.

– Current is sinusoidal over any one cycle. For obtaining rms or effective values the maximum values are divided by $\sqrt{2}$. Hence subtrasient current (rms) is,

$$I'' = \frac{E_g}{X''_d} \qquad \ldots(1.4.6)$$

– Transient current (rms) is,

$$I' = \frac{E_g}{X'_d} \qquad \ldots(1.4.7)$$

– Steady state current (rms) is, $I = \dfrac{E_g}{X_d}$ …(1.4.8)

Where, $E_g = \dfrac{E_{gmax}}{\sqrt{2}}$

Syllabus Topic : No Load and Loaded Machine

1.5 No Load and Loaded Machine

➔ (MU - Dec. 15, May 17)

Q. 1.5.1 Discuss the short circuit of synchronous machine at loaded condition.
(Refer section 1.5) **Dec. 15, May 17, 10 Marks**

– In previous article it was assumed that the machine was operating at no load before occurrence of fault. Now consider that the synchronous machine is loaded when short circuit fault occurs. Fig. 1.5.1 shows a synchronous machine operating under steady state condition and supplying a load current I_o at terminal voltage V_o. E_g is induced emf under loaded condition. X_d is direct axis synchronous reactance of the machine.

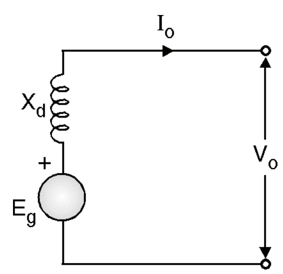


Fig. 1.5.1 : Circuit model of loaded synchronous generator

- When a short circuit occurs at the terminals of machine, a short circuit current starts flowing through it. As it is time dependent it changes from subtransient to transient magnitude.
- The circuit model used for analysis of short circuit current is given in Fig. 1.5.2. Fig. 1.5.2(a) represents the circuit model for subtransient current and Fig. 1.5.2(b) is for transient current.

(a) Model for analysis of subtransient current **(b) Model for analysis of transient current**

Fig. 1.5.2

- The induced emfs during subtransient and transient period are given as,

$$E''_g = V_o + j\, I_o\, X''_d \quad \ldots(1.5.1)$$

$$E'_g = V_o + j\, I_o\, X'_d \quad \ldots(1.5.2)$$

- The voltage E''_g is the voltage behind the subtransient reactance and E'_g is voltage behind the transient reactance. In no load condition I_o is zero. $E''_g = E'_g = E_g$, the no load voltage.
- Equations (1.5.1) and (1.5.2) represents the induced emfs is synchronous generators. In synchronous motor the induced emfs and reactance are similar to that of generator but the direction of current is reversed.
- During short circuit the voltage behind transient and subtransient reactance for synchronous motor is given as,

$$E''_m = V_o - j\, I_o\, X''_d \quad \ldots(1.5.3)$$

$$E'_m = V_o - j\, I_o\, X'_d \quad \ldots(1.5.4)$$

- For a short circuit analysis of interconnected system, the synchronous generator and motor are replaced by their subtransient and transient circuit models. The other components of network are passive hence remains unchanged.

Syllabus Topic : Transient on a Transmission Line

1.6 Transient on Transmission Line

→ (MU - Dec. 15, Dec. 16)

Q. 1.6.1 Discuss the term transient. *(Refer section 1.6)* **Dec. 15, Dec. 16, 5 Marks**

Q. 1.6.2 Discuss the formation of transients on transmission line. *(Refer section 1.6)* **Dec. 16, 10 Marks**

- Transient is an a periodic function of time and doesn't last for a long time. The duration for which they lost is very insignificant compared with the operating time of the system.
- They are very important because depending upon severity of transients, system may result into block out in a city, shunt down of a plant etc.
- The transient behaviour of various circuit is analysed with lumped parameters however in case of transmission limits they must be represented by their actual circuit i.e. distributed parameters.
- For 50 Hz supply and short transmission line :

  Sending end current = Receiving end current

  Change in voltage from sending end to receiving end is smooth. This is not so when transmission line is subjected to transient.
- It is desired to find out expressions for the relation between voltage and current waves travelling over the transmission lines and their velocity of propagation.
- Suppose,

  The wave after time 't' has travelled through distance 'x' assuming lossless lines it is evident that value of voltage and current doesn't change throughout the travel.
- Consider as distance dx which is travelled by the waves in time dt.
- Electrostatic flux associated with the voltage wave and the electromagnetic flux with the current wave. The electrostatic flux is equal to the charge between the conductors of the line up to a distance x is given by

$$q = VCx \quad \ldots(1.6.1)$$

Current in the conductor is determined by

$$I = \frac{dq}{dt} = VC\frac{dx}{dt} \quad \ldots(1.6.2)$$

$\frac{dx}{dt}$; velocity of travelling wave over the line conductor. (Represented by ν)

$$I = VC\nu \quad \ldots(1.6.3)$$

Similarly electromagnetic flux linkages created around the conductors due to the current following in them up to a distance x is given by,

$$\psi = ILx \quad ...(1.6.4)$$

Voltage is the rate at which the flux linkages link around the conductor.

$$V = IL\frac{dx}{dt} = IL\nu \quad ...(1.6.5)$$

Dividing ν by I

$$\frac{V}{I} = \frac{IL\nu}{VC\nu} = \frac{I}{V}\cdot\frac{L}{C} \quad ...(1.6.6)$$

$$\Rightarrow \quad \frac{V^2}{I^2} = \frac{L}{C}$$

$$\Rightarrow \quad \frac{V}{I} = \sqrt{\frac{L}{C}} = Z_n \quad ...(1.6.7)$$

Z_n is designated as surge impedance of the line. It is the natural impedance which is purely a characteristic of the transmission line.

Multiplying I and V

$$VI = VC\nu \cdot IL\nu = VIL\,C\nu^2$$

$$\nu^2 = \frac{1}{LC}$$

$$\nu = \frac{1}{\sqrt{LC}} \quad ...(1.6.8)$$

Syllabus Topic : Short Circuit MVA

1.7 Short Circuit Current and MVA Calculations

➔ (MU - May 15)

Q. 1.7.1 Explain the terms short circuit MVA and symmetrical fault. *(Refer section 1.7)* **May 15, 5 Marks**

- Analysis of symmetrical fault is the determination of the voltage at any point or bus in the power system, the current in any branch and the reactance necessary to limit the fault current to any desired value.
- The analysis is done to decide the ratings of the circuit brakers and current limiting reactors which are used for the protection of system. A precise calculation is not required as the circuit breakers are manufactured in standard sizes such as 250 MVA, 500 MVA, 750 MVA etc.

- Also the system impedances are never known accurately. Hence accurate calculation is virtually impossible.
- Following things are assumed during short circuit analysis,
  (i) As compared to fault currents, load currents are considered negligible.
  (ii) Shunt capacitance of transmission line is neglected.
  (iii) Shunt elements in the transformer model are neglected. The transformer is represented as reactance in series as its resistance is very small in comparison with its reactance.
  (iv) Resistance of system is neglected and only inductive reactance is considered. A transmission line is represented by series reactance.
  (v) The emf of all the generators are assumed to be equal to $1 \angle 0°$ per unit. It indicates that the system voltage is at its nominal value at the time of occurrences of fault. The selection of zero phase for one source is arbitrary and convenient. By assuming all sources in phase and of same magnitude, prefault load current is neglected.
  (vi) The effect of DC component is considered by using correction factor.
- Generator reactance's are normally taken as their subtransient values. But if transient currents are to be determined then transient reactances are used. The fault analysis is done by network reduction techniques. (Thevenin's theorem).
- Three phase symmetrical fault is the balanced nature of fault. The system is also balanced. Hence only condition applied to one phase is equally applicable to remaining two phases. The steps involved in three phase symmetrical fault analysis are,
  (i) Draw one line diagram of the complete network indicating each component, its ratings voltage, resistance and reactance.
  (ii) Choose common base kVA or MVA. Convert all the resistances and reactance's in per unit values as referred to common base kVA or MVA.
  (iii) Convert one line diagram to impedance or reactance diagram. Indicate reactance's / impedance in per unit in this diagram.
  (iv) Reduce the impedance / reactance diagram by network reduction technique (Thevenins theorem) keeping the identity of fault point.
  (v) Find the reactance of the system as seen from the fault point. (Thevenin's Reactance)
  (vi) Calculate the fault current and fault MVA in per unit. Convert per unit values to actual values.

Calculation of Fault Current and MVA

– Short circuit current or per unit fault current.

$$I_{SC,\ p.u.} = \frac{\text{p.u. voltage at fault point}}{\text{p.u.} \times \text{Equivalent}} \quad \text{...(1.7.1)}$$

$$\text{Per unit fault MVA} = \sqrt{3} \times \text{Per unit fault current} \times \text{Per unit source voltage} \quad \text{...(1.7.2)}$$

OR

$$\text{Fault MVA} = \frac{\text{Base MVA}}{\text{p.u.} \times \text{Equivalent}} \times \text{MVA (lagging)} \quad \text{...(1.7.3)}$$

$$\text{Fault current,} \quad I_{SC} = \frac{\text{Base MVA} \times 10^3}{\sqrt{3} \times \text{Base kV}} \times I_{SC}\text{, p.u.} \quad \text{...(1.7.4)}$$

Syllabus Topic : Z-Bus Formulation

1.8 Z-Bus Formation

➔ (MU - May 15, May 17)

Q. 1.8.1 Discuss the Z bus formation technique.
(Refer Section 1.8) **May 15, May 17, 10 Marks**

– Load flow computations are done using bus admittance matrix (Y_{bus}) however for short circuit studies (faults calculation) bus impedance matrix (Z_{bus}) is preferable.

– In short circuit studies all three sequence components and sequence networks are involved. A direct solution is possible and no iterations are required.

Bus Impedance Matrix in Fault Calculation

– The symmetrical fault current at any bus in a power system is easily obtained from bus impedance matrix [Z_{BUS}]. It is necessary that [Z_{BUS}] should be obtained by inversion of bus admittance matrix [Y_{BUS}].

– The [Y_{BUS}] for a simple three bus system is given as,

$$\begin{bmatrix} Y_{11} & Y_{12} & Y_{13} \\ Y_{21} & Y_{22} & Y_{23} \\ Y_{31} & Y_{32} & Y_{33} \end{bmatrix} \quad \text{...(1.8.1)}$$

$$[Z_{BUS}] = [Y_{BUS}]^{-1} = \begin{bmatrix} Z_{11} & Z_{12} & Z_{13} \\ Z_{21} & Z_{22} & Z_{23} \\ Z_{31} & Z_{32} & Z_{33} \end{bmatrix} \quad \text{...(1.8.2)}$$

- The symmetrical fault current at bus-1 is given by $(1/Z_{11})$ p.u. Here it is assumed that the prefault bus voltage is 1.0 p.u. Similarly symmetrical fault currents at bus-2 and bus-3 are given by $(1/Z_{22})$ p.u. and $(1/Z_{33})$ p.u. respectively.
- The prefault voltage at these buses is 1.0 p.u.
- For a large system this method is not accepted as it need inversion of very large matrix. Also for any change in the network, the full $[Y_{BUS}]$ is to be rebuilt and needs full inversion. These problems can be overcome by $[Z_{BUS}]$ building algorithm method.
- Determination of fault current by formulating impedance matrix using network theory.

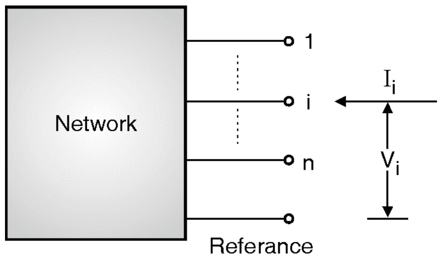


Fig. 1.8.1 : General n port network

Fig. 1.8.1 shows in bus passive linear network. Voltage at various ports is given as,

$$\begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_i \\ \vdots \\ V_n \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{21} & \cdots & Z_{1n} \\ Z_{21} & Z_{22} & \cdots & Z_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ Z_{i1} & Z_{i2} & \cdots & Z_{in} \\ \cdots & \cdots & \cdots & \cdots \\ Z_{n1} & Z_{n2} & \cdots & Z_{nn} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_i \\ \vdots \\ I_n \end{bmatrix}$$

$$V_{bus} = [Z_{bus}]\, I_{bus}$$

Where, V_{bus} - $(n \times 1)$ matrix $\rightarrow$ bus voltage

I_{bus} - $(n \times 1)$ matrix $\rightarrow$ bus current

Z_{bus} - $(n \times n)$ matrix $\rightarrow$ bus impedance

Various elements of $[Z_{bus}]$ can be calculated as,

$$Z_{ik} = \left.\frac{V_i}{I_k}\right|_{I_1 = I_2 = \ldots\ldots = I_n = 0\ ;\ I_k \neq 0}$$

Means all the ports except k^{th} port are open circuited. k^{th} port is terminated in current source of strength I_k.

Syllabus Topic : Algorithm for SC Studies

1.9 Algorithm of Short Circuit Studies

→ (MU-May 16)

Q. 1.9.1 Discuss the algorithm for short circuit studies.
(Refer section 1.9) **May 16, 10 Marks**

- An algorithm is described below in terms of modifying an existing bus impedance matrix designated as $[Z_{bus}]_{old}$ the new modified matrix is designated as $[Z_{bus}]_{new}$.
- When a new element having self impedance Z_s is added, a new bus may be created (if the new element is a tree branch) or a new bus may not be created (if the new element is a link).
- Each of these two cases can be subdivided into two cases so that Z_s may be added in the following ways :
  1. Adding Z_s from a new bus to reference.
  2. Adding Z_s from a new but to an old bus.
  3. Adding Z_s from an old bus to reference.
  4. Adding Z_s between two old buses.

☞ Types 1 Modification

Addition of three branch Z_s from new bus q to reference.

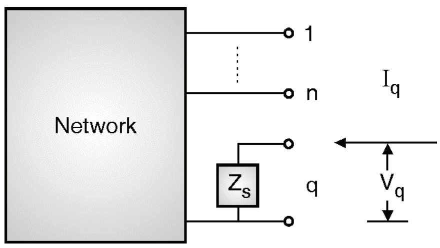


Fig. 1.9.1

Branch Z_s is connected between reference bus and a new bus q. For this new bus.

$$V_q = Z_s I_q$$

Complete set of equation becomes,

$$\begin{bmatrix} V_1 \\ \vdots \\ V_i \\ \vdots \\ V_n \\ V_q \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{21} & \cdots & Z_{1n} & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ Z_{i1} & Z_{i2} & \cdots & Z_{in} & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ Z_{n1} & Z_{n2} & \cdots & Z_{nn} & 0 \\ 0 & 0 & \cdots & 0 & Z_s \end{bmatrix} \begin{bmatrix} I_1 \\ \vdots \\ I_i \\ \vdots \\ I_n \\ I_q \end{bmatrix}$$

$[Z_{bus}]_{old}$ is $n \times n$ matrix

Addition of new branch : Implies addition of $(n + 1)^{th}$ row and $(n + 1)^{th}$ column

Also, $Z_{iq} = Z_{qi} = 0$ for $i = 1, 2, 3 \ldots.i, \ldots.n$

$Z_{qq} = Z_s$

$[Z_{bus}]_{new}$ can, therefore be written as,

$$[Z_{bus}] = \left[\begin{array}{c|c} & 0 \\ [Z_{bus}]_{old} & \vdots \\ & 0 \\ \hline 0 \cdots\cdots 0 & Z_s \end{array}\right]$$

Type 2 Modification

Addition of tree branch Z_s from a New bus q to old bus k.

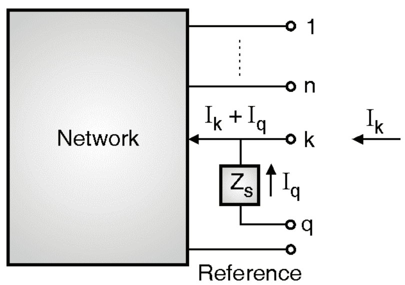


Fig. 1.9.2

$$\begin{aligned} V_q &= Z_s I_q + V_k \\ &= Z_s I_q + Z_{k1} I_1 + Z_{k2} I_2 + \ldots. + Z_{kk} (I_k + I_q) + \ldots\ldots. + Z_{kn} I_n \\ &= Z_{k1} I_1 + Z_{k2} I_2 + \ldots.. + Z_{kk} I_k + \ldots.. + Z_{kn} I_n + (Z_{kk} + Z_s) I_q \end{aligned}$$

Equation of V_1 can be written as :

(new current as k^{th} bus is $I_k + I_q$)

$$\begin{aligned} V_1 &= Z_{11}\, I_1 + Z_{12}\, I_2 + \ldots + Z_{1k}\,(I_k + I_q) + \ldots\ldots + Z_{1n}\, I_n \\ &= Z_{11}\, I_1 + Z_{12}\, I_2 + \ldots + Z_{1k}\, I_k + \ldots\ldots + Z_{1n}\, I_n + Z_{1k}\, I_q \end{aligned}$$

Equation of $V_2, V_3, \ldots, V_n$ can be modified as ;

$$\begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_i \\ \vdots \\ V_n \\ V_q \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{21} & \cdots & Z_{1k} & \cdots & Z_{1n} & Z_{1k} \\ Z_{21} & Z_{22} & \cdots & Z_{2k} & \cdots & Z_{2n} & Z_{2k} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ Z_{k1} & Z_{k2} & \cdots & Z_{kk} & \cdots & Z_{kn} & Z_{kk} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ Z_{n1} & Z_{n2} & \cdots & Z_{nk} & \cdots & Z_{nn} & Z_{nk} \\ Z_{k1} & Z_{k2} & \cdots & Z_{kk} & \cdots & Z_{nn} & (Z_{kk} + Z_s) \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_k \\ \vdots \\ I_n \\ I_q \end{bmatrix}$$

$[Z_{bus}]_{new}$ is $(n + 1) \times (n + 1)$ matrix

$$[Z_{bus}]_{new} = \left[\begin{array}{c|c} & Z_{1k} \\ & Z_{2k} \\ [Z_{bus}]_{old} & \cdots \\ & Z_{kk} \\ \hline Z_{k1}\ Z_{k2} \cdots Z_{kk} \cdots Z_{nn} & Z_{kk} + Z_s \end{array}\right]$$

☞ Type 3 Modification

Addition of a link Z_s between an old bus k and reference.

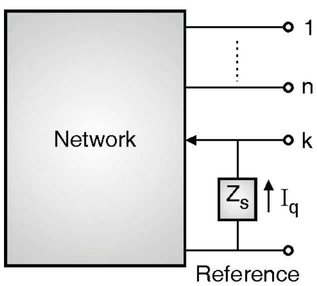


Fig. 1.9.3

This case is an extension to type 2 modification.

Initially,

Let Z_s bc connected between new bus q and old bus k and then let the new bus q be connected to reference bus so that $V_q = 0$. New set of equations →

$$\begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ \vdots \\ V_n \\ \hline 0 \end{bmatrix} = \left[\begin{array}{ccc|c} & & & Z_{1k} \\ & & & Z_{2k} \\ & [Z_{bus}]_{old} & & \cdots \\ & & & \cdots \\ & & & Z_{nk} \\ \hline Z_{k1} & Z_{k2} \cdots & Z_{kn} & Z_{kk} + Z_s \end{array}\right] \begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ \vdots \\ I_n \\ \hline I_q \end{bmatrix}$$

If I_q is eliminated from the above equation, the last row and last column of the impedance matrix are eliminated.

We have,

$$[Z_{bus}]_{new} = [Z_{bus}]_{old} - \frac{1}{Z_{kk} + Z_s} \begin{bmatrix} Z_{1k} \\ Z_{2k} \\ \vdots \\ Z_{nk} \end{bmatrix} [Z_{k1} \ Z_{k2} \ \cdots \ Z_{kn}]$$

☞ **Type 4 modification**

Addition of link Z_s between two old Buses i and k.

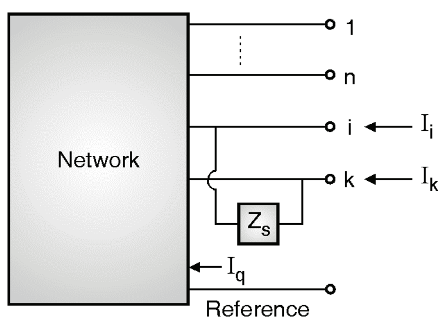


Fig. 1.9.4

$$V_1 = Z_{11} I_1 + Z_{12} I_2 + \ldots + Z_{1i} (I_i + I_q) + Z_{1j} I_j + Z_{1k} (I_k - I_q) + \ldots\ldots + Z_{1n} I_n$$

Rearranging,

$$V_1 = Z_{11} I_1 + Z_{12} I_2 + \ldots + Z_{in} I_n + (Z_{1i} - Z_{1k}) I_q$$

It is to be noted that,

$$V_k = Z_s I_q + V_i$$

Or

$$= Z_{k1} I_1 + Z_{k2} I_2 + \ldots + Z_{ki} (I_i + I_q) + Z_{kj} I_j + Z_{kk} (I_k - I_q) + \ldots\ldots$$

$$= Z_s I_q + Z_{i1} I_1 + Z_{i2} I_2 + \ldots + Z_{ii} (I_i + I_q) + Z_{ij} I_j + Z_{ik} (I_k - I_q) + \ldots\ldots$$

Rearranging,

$$0 = (Z_{i1} + Z_{k1}) I_1 + \ldots + (Z_{ii} - Z_{ki}) I_i + (Z_{ij} - Z_{kj}) I_j$$
$$+ (Z_{ik} - Z_{kk}) I_k + (Z_{ik} - Z_{kk}) I_k + \ldots\ldots + (Z_s + Z_{1i} - Z_{ik} - Z_{ki} + Z_{kk}) I_q$$

Similar equations can be written for $V_2, V_3, \ldots V_n$.

Equation can be represented in the following form;

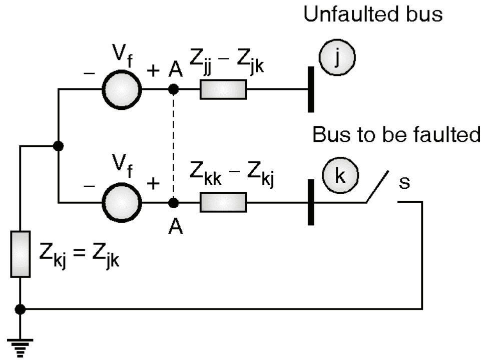
$$\left[\begin{array}{c} V_1 \\ V_2 \\ \vdots \\ \vdots \\ V_n \\ \hline 0 \end{array}\right] = \left[\begin{array}{c|c} & Z_{1i} - Z_{1k} \\ & Z_{2i} - Z_{2k} \\ [Z_{bus}]_{old} & \cdots \\ & \cdots \\ & \cdots \\ \hline Z_{i1} - Z_{k1} & Z_s + Z_{i1} + Z_{kk} - 2Z_{ik} \end{array}\right] \left[\begin{array}{c} I_1 \\ I_2 \\ \vdots \\ \vdots \\ I_n \\ \hline I_q \end{array}\right]$$

$$[Z_{bus}]_{new} = [Z_{bus}]_{old} - \frac{1}{Z_s + Z_{i1} + Z_{kk} - 2Z_{ik}} \begin{bmatrix} Z_{1i} & Z_{1k} \\ Z_{2i} & Z_{2k} \\ & \vdots \\ & \vdots \\ Z_{ni} & - Z_{nk} \end{bmatrix} [(Z_{i1}\ \ Z_{k1})\ \cdots\ (Z_{in} - Z_{kn})]$$

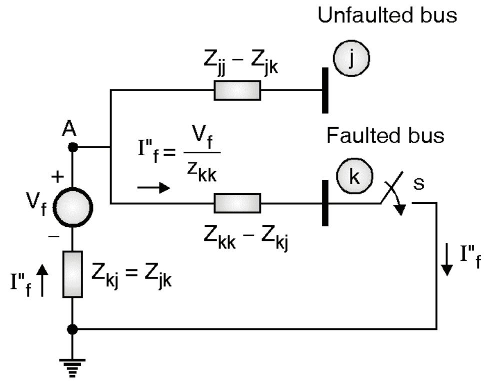
Syllabus Topic : Symmetrical Fault Analysis Using Z BUS

1.10 Symmetrical Fault Analysis Using Z BUS

- The Thevenin's equivalent circuit is helpful for symmetrical fault analysis. The Z_{BUS} matrix elements can be used to construct the Thevenin's equivalent circuit between any pair of buses in a network.
- Fig. 1.10.1 shows a Thevenin's equivalent circuit. In this circuit bus (k) is the fault bus and bus (i) is unfaulted.
- The impedances are corresponding to the elements of Z_{BUS}. All the prefault bus voltages are same as V_f of fault bus.
- Load current bus are neglected here.
- The two points marked have the same potential. Hence they can be jointed together to get obtain the equivalent circuit of Fig. 1.10.1(b) with a single voltage source.
- When switch S is open, there is no short circuit and no current flows in any branch of the network.



(a) before the fault



(b) during the fault

Fig. 1.10.1 : Thevenin's equivalent between buses (j) and (k)

- Closing of switch S corresponds to fault on bus (k). Hence current flows in the circuit towards bus (k). This current is,

$$I''_f = \frac{V_f}{Z_{kk}}$$

- It induces a voltage drop $(Z_{jk} / Z_{kk}) V_f$ in the direction from reference node towards bus (j). Hence voltage at bus (j) during the fault is,

$$V_f - (Z_{jk} / Z_{kk}) V_f$$

- In this way by substituting appropriate values for the impedance in the equivalent circuit of Fig. 1.10.1(b), the bus voltage of the system before and after the occurrence of fault can be calculated.
- If switch S is closed in Fig. 1.10.1(b), it reflects the voltage of bus (j) with respect to reference while the fault is on bus (k). Thus, if 3 phase short circuit fault occurs at bus (k) of large system, we can calculate the fault current and voltage at any unfaulted buses by inserting the proper impedances into elementary circuits shown in Fig. 1.10.1.

Syllabus Topic : Selection of Circuit Breaker

1.11 Selection of Circuit Breakers

➔ (Mu-May 17)

Q. 1.11.1 What are the various factors affecting the selection of circuit breaker ?
(Refer section 1.11) **May 17, 5 Marks**

- A circuit breaker is an requirement which can
  (i) Make or break a circuit either manually or by remote control under normal conditions
  (ii) Break a circuit automatically under fault conditions.
  (iii) Make a circuit either manually or by remote control under fault conditions
- A typical circuit breaker operating time is given in Fig. 1.11.1
- On occurrence of the fault, the protective devices get activated.
- There is a time difference between the determination of over current in circuit by protective relay and the initial trip command. The time is the detection time.
- The contacts of the circuit breakers are held together by spring mechanism and, with the trip command, the spring mechanism releases the contacts.
- When two current carrying contacts part, a voltage instantly appears at the contacts and a large voltage gradient appears in the medium between the two contacts.

– This voltage gradient ionizes the medium thereby maintaining the flow of current. This current generates extreme heat and light that is called electric arc.

– Different mechanisms are used for elongating the arc such that it can be cooled and extinguished.

– Therefore the circuit breaker has to withstand fault current from the instant of initiation of the fault to the time the arc is extinguished.

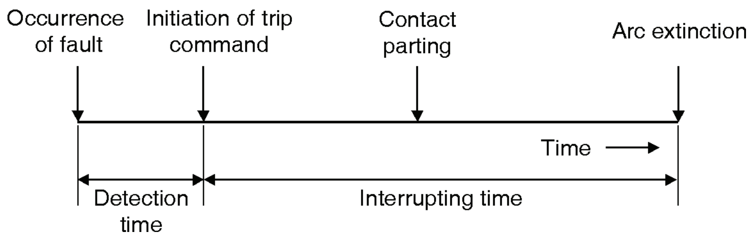


Fig. 1.11.1 : Typical circuit breaker operating time

– Major duties are imposed on circuit breaker when there is a fault on the system in which it is connected.

– The three phase faults are scare but give highest SC. MVA. For selection of circuit breaker maximum possible S.C. MVA to be interrupted w.r.t. type of fault, its location and generating capacity is to be found, as its essential for circuit breaker to be capable to interrupt it.

– Two factors are of utmost importance for the selection of circuit breakers

– These are

1. The maximum instantaneous current that a breaker must withstand and
2. The total current when the breaker contacts part.

– In a high power circuit breaker selection, the subtransient current is multiplied by a factor of 1.6 to determine the rms value of the current the circuit breaker must withstand. This current is called the **momentary current.**

– The **interrupting current** of a circuit breaker is lower than the momentary current and will depend upon the speed of the circuit breaker. The interrupting current may be asymmentrical since some dc component may still continue to decay.

Circuit Breaker speed	Multiplying factor
8 cycles or slower	1.0
5 cycles	1.1
3 cycles	1.2
2 cycles	1.4

- Breakers are usually classified by their nominal voltage, continuous current rating, rated maximum voltage, K-factor which is the voltage range factor, rated short circuit current at maximum voltage and operating time.
- The K-factor is the ratio of rated maximum voltage to the lower limit of the range of the operating voltage. The maximum symmetrical interrupting current of a circuit breaker is given by K times the rated short circuit current.

Syllabus Topic : Numerical on Z bus Formulation up to 3 × 3 Matrix

1.12 Problems

Ex. 1.12.1

A three phase 5,000 kVA, 11 kV alternator has a substransient reactance of 8%. A three phase short circuit occurs at its terminals. Determine the fault current and fault MVA.

Soln. :

Alternator's percentage reactance is based on its own voltage and kVA ratings.

$$\text{Base current } I_B = \frac{\text{Base kVA}}{\sqrt{3} \times \text{Base kV}} = \frac{5000}{\sqrt{3} \times \text{Base kV}} = \frac{5000}{\sqrt{3} \times 11}$$

$$= 262.5 \text{ amp.}$$

$$\text{Per unit fault current} = \frac{\text{p.u. voltage}}{\text{p.u. reactance}} = \frac{1}{0.08}$$

$$= 12.5 \angle -90° \text{ A.}$$

$$\text{Fault current, } I_{SC} = I_{SC} \cdot \text{p.u.} \times I_B = 12.5 \times 262.5$$

$$= 3281.25 \text{ A.}$$

$$\text{Fault MVA} = \sqrt{3} \times I_{SC} \times \text{Source voltage}$$

$$= \sqrt{3} \times 3281.25 \times 11000$$

$$= 62.5 \text{ MVA}$$

Ex. 1.12.2

A 3 phase 10 MVA, 6.6 kV alternator with a reactance of 7% is connected to a feedback of series impedance (0.12 + j 0.48) Ω / ph / km. The transformer is rated at 3 MVA, 6.6 kV / 33 kV and has a reactance of 5 %. Determine the fault current supplied by the generator operating under no load with a voltage of 6.9 kV when a three phase symmetrical fault occurs at a point 15 km along the feeder.

Soln. :

One line diagram for the given system is,

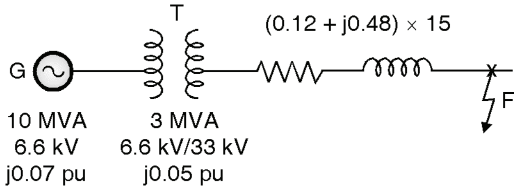


Fig. P. 1.12.2

$$\text{Let the base kVA} = 10{,}000 \text{ kVA}$$

$$\text{Base kV on generator side} = 6.6 \text{ kV}$$

$$\text{Base kV on load side (feeder side)} = 33 \text{ kV}$$

$$\text{Per unit reactance of generator} = j0.07 \text{ p.u.}$$

$$\text{Per unit reactance of transformer} = j0.05 \times \frac{5000}{3000} = j0.0833 \text{ p.u.}$$

$$\text{Total impedance of the line} = (0.12 + j\,0.48) \times 15$$

$$= 1.8 + j\,7.2 = 7.42 \angle 76° \ \Omega$$

$$\text{Per unit impedance} = \frac{7.42 \angle 76° \times 10000}{(33)^2 \times 1000} = 0.0681 \angle 76°$$

$$= 0.016 + j\,0.066 \text{ p.u.}$$

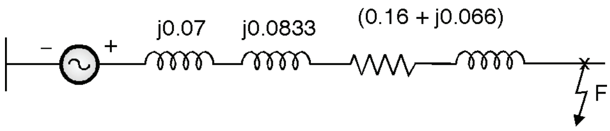


Fig. P. 1.12.2(a) : Reactance Diagram

Total per unit impedance upto fault point

$$Z_{eq,\,p.u.} = j0.07 + j0.0833 + (\,0.16 + j0.066\,)$$

$$= 0.16 + j\,0.2193$$

$$= 0.271 \angle 53.88° \text{ p.u.}$$

$$\text{Per unit fault current, } I_{SC,\ p.u.} = \frac{\text{Per unit voltage}}{\text{Per unit impedance}} = \frac{6.9 / 6.6}{0.271 \angle 53.88}$$

$$= 3.858 \angle -53.88° \text{ p.u.}$$

$$\text{Base current} = I_B = \frac{\text{Base kVA}}{\sqrt{3} \times \text{Base kV}} = \frac{10{,}000}{\sqrt{3} \times 33}$$

$$= 174.95 \text{ A.}$$

$$\therefore \quad \text{Fault current } I_{SC} = I_{SC,\ pu} \times I_B = 3.858 \angle -53.88° \times 174.95$$

$$= 674.97 \angle -53.88 = 674.97 \text{ A.}$$

Ex. 1.12.3

Two three phase 11 kN a generators of capacities 10 MVA and 6 MVA and subtransient reactances of 8% and 4% respectively operate in parallel. The generating station is connected to transmission line of 200 km length through a step up transformer of capacity 5 MVA and having percentage reactance of 2.5%. The resistance and reactance of transmission line per km of its length are 0.025 Ω and 0.1 Ω respectively and it operate at 66 kV. Calculate the short circuit MVA for a three phase fault at the receiving end of the transmission line and at the sending end.

Soln. :

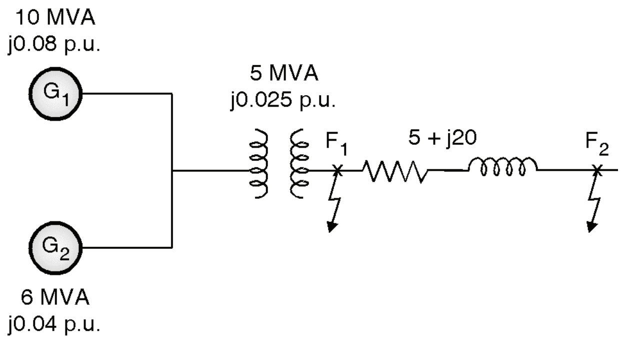


Fig. P. 1.12.3 : One line diagram

$$\text{Base kVA} = 10{,}000$$

$$\text{Base kV on generator side} = 11 \text{ kV}$$

$$\text{Base kV on transmission line side} = 66 \text{ kV}$$

$$\text{Per unit reactance of generator } G_1 = j0.08$$

$$\text{Per unit reactance of generator } G_2 = j0.04 \times \frac{10{,}000}{6000} = j0.067$$

$$\text{Per unit reactance of transformers} = j0.025 \times \frac{10{,}000}{6{,}000} = j0.042$$

$$\text{Per unit reactance of line} = 200\,(0.025 + j0.1) \times \frac{10{,}000}{66^2 \times 1000}$$

$$= 5 + j\,20 \times \frac{10{,}000}{66^2 \times 1000}$$

$$= 0.011 + j\,0.0459 \text{ p.u.}$$

Reactance diagram of given system is,

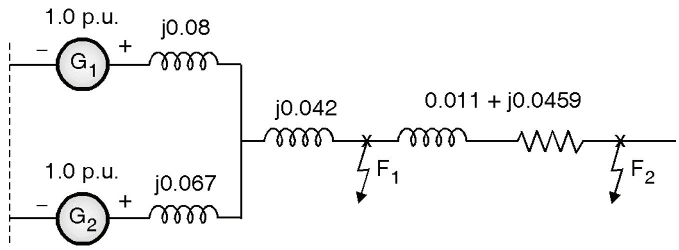


Fig. P. 1.12.3(a)

Reactance diagram can be reduced as :

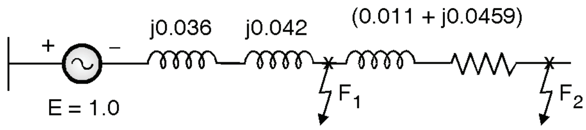


Fig. P. 1.12.3(b)

For a three phase fault at sending end (F_1) of transmission line.

The total reactance up to fault point $F_1 = j0.036 + j\,0.042 = j0.078$

$$\text{Short circuit MVA} = \frac{\text{Base MVA}}{\text{Per unit reductnace}} = \frac{10{,}000 \times 10^{-3}}{j0.078}$$

$$= 128.21$$

For three phase fault at receiving end side (F_2),

Total impedance upto fault point is,

$$= j0.036 + j\,0.042 + 0.011 + j\,0.0459$$

$$= 0.011 + j0.1239$$

$$= 0.127 \angle 84.9°$$

$$\therefore \text{Short circuit MVA} = \frac{10}{0.124} = 80.64$$

Ex. 1.12.4

Determine the required MVA rating of the circuit breaker CB for the system shown in Fig. P. 1.12.4. consider the grid as infinite bus. Choose 6 MVA as base.

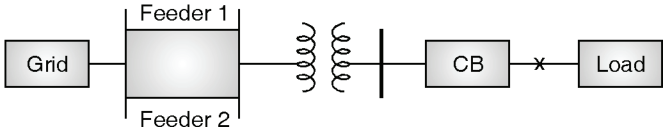


Fig. P. 1.12.4

Transformer : 3 phase, 33/11 kV, 6 MVA, 0.01 + j0.07 p.u. impedance
Load : 3 phase, 11 kV, 5000 kVA, 0.85 lag, j0.2 pu impedance
Impedance of each feeder : 9.5 + j7

Soln. :

Base MVA : 6

$$\text{Per unit impedance of transformer} = 0.01 + j0.07$$

$$\text{Per unit impedance of feeder} = (9.5 + j7) \times \frac{6}{33^2}$$

$$= 0.052 + j0.0385$$

$$\text{Per unit impedance of load} = j0.2 \times \frac{6 \times 10^6}{5000 \times 10^3} = j0.24$$

Single line diagram of the above system is,

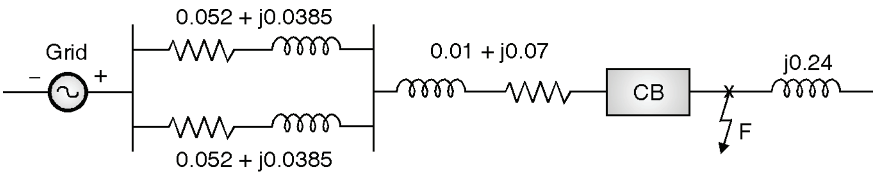


Fig. P. 1.12.4(a)

$$\text{Equivalent impedance upto fault point} = [(0.052 + j0.0385) \parallel (0.052 + j0.0385)] + 0.01 + j0.07$$

$$= 0.026 + j0.01925 + 0.01 + j0.07$$

$$= 0.036 + j0.08925$$

$$= 0.09623 \angle 68.03^\circ \text{ p.u.}$$

$$\text{Short circuit rating of CB} = \frac{\text{Base MVA}}{Z_{eq,\,pu}} = \frac{6}{0.09623}$$

$$= 62.35 \text{ MVA}$$

Ex. 1.12.5

Fig. P.1.12.5 shows a generating station feeding power to a 132 kV system. Determine the total fault current, fault level and fault current supplied by each alternator for a three phase fault at the receiving end bus. The line is 200 km long.

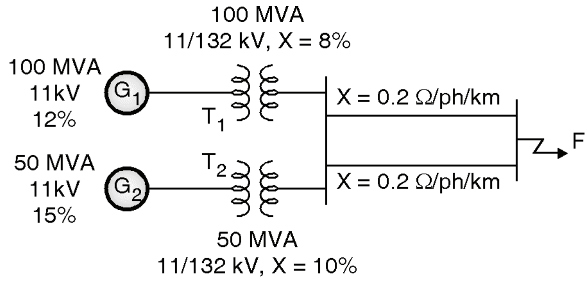


Fig. P. 1.12.5

Soln. :

$$\text{Base MVA} = 100$$

$$\text{Base kV for generator side} = 11 \text{ kV}$$

$$\text{Base kV for feeder side} = 132 \text{ kV}$$

$$\text{Per unit reactance of generator } G_1 = j0.12 \text{ p.u.}$$

$$\text{Per unit reactance of generator } G_2 = j0.15 \times \frac{100}{50} = j0.3$$

$$\text{Per unit reactance of transformer } T_1 = j0.08 \times \frac{100}{100} = j0.08$$

$$\text{Per unit reactance of transfer } T_2 = j0.1 \times \frac{100}{50}$$

$$= j0.2$$

$$\text{Per unit reactance of each line} = j0.2 \times 200 \times \frac{MVA_B}{(kV_B)^2} = j0.2 \times 200 \times \frac{100}{(132)^2}$$

$$= j0.229 \text{ p.u.}$$

Reactance diagram :

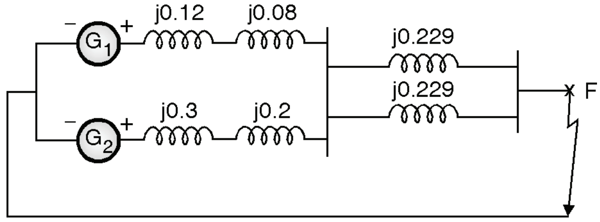


Fig. P. 1.12.5(a)

Reactance diagram is reduced as :

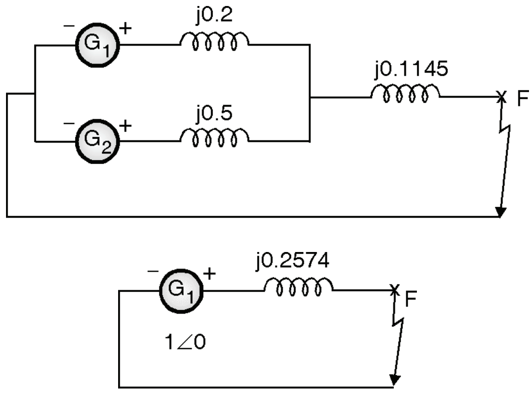


Fig. P. 1.12.5(b)

$$\text{Fault level} = \frac{\text{Base MVA}}{X_{eq,\ pu}}$$

$$= \frac{100}{0.2574}$$

$$= 388.5 \text{ MVA}$$

$$\text{Total fault current} = \frac{\text{Fault level in MVA} \times 1000}{\sqrt{3} \times \text{Base kVon feeder side}}$$

$$= \frac{388.5 \times 1000}{\sqrt{3} \times 132}$$

$$= 1699.2 \text{ A}$$

$$\begin{array}{c}\text{Total fault current}\\ \text{supplied by two generation}\end{array} = \begin{array}{c}\text{Total fault current}\\ \text{on feeder side}\end{array} \times \text{Transformation ratio}$$

$$= 1699.2 \times \frac{132}{11} = 20{,}390.96 \text{ A.}$$

$$\text{Fault current supplied by } G_1 = \frac{20{,}390.96 \times j0.5}{j0.5 + j0.2} = 14{,}564.9 \text{ A.}$$

$$\text{Fault current supplied} = \frac{20{,}390.96 \times j0.2}{j0.5 + j0.2} = 5825.98 \text{ A.}$$

Ex. 1.12.6

A 50 MVA generator with 10 % reactance and a 100 MVA generator with 8% reactance (on their own bases) are connected as shown in Fig. P. 1.12.6. The fault level on bus 1 is to be restricted to 1000 MVA. Calculate on 100 MVA base (i) reactance of bus bar reactor X (ii) fault level of bus 2 and (iii) MVA ratings of circuit breaker C.

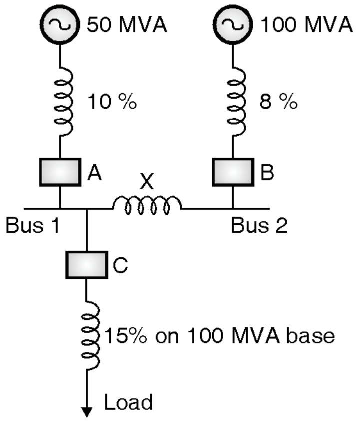


Fig. P. 1.12.6

Soln. :

$$\text{The base MVA} = 100$$

$$\text{Per unit reactance of 50 MVA Generator} = \frac{10}{100} \times \frac{100}{50} = 0.2$$

$$\text{Per unit reactance of 100 MVA generator} = \frac{8}{100} \times \frac{100}{100} = 0.08$$

$$\text{Per unit reactance of feeder} = \frac{15}{100} = 0.15$$

(i) When fault occurs on bus 1, reactance of 100 MVA generator in series with busbar reactor act in parallel with reactance of 50 MVA generator.

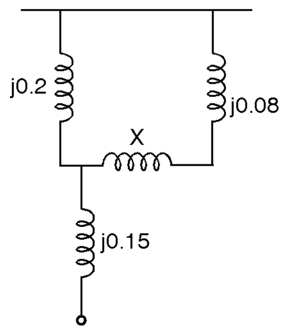


Fig. P. 1.12.6(a)

$\therefore$ Per unit reactance between fault point and the neutral bus

$$= j\,\frac{0.2 \times (X + 0.08)}{0.2 + 0.04 + X}$$

$$= j\frac{0.2X + 0.06}{0.24 + X}$$

$$\text{Short circuit MVA} = \frac{\text{Base MVA}}{\text{Per unit reactance}}$$

$$\therefore 1000 = \frac{100}{(0.2\,X + 0.016)/0.24 + X}$$

$$= \frac{100\,(0.24 + X)}{0.2\,X + 0.016}$$

$$200\,X + 16 = 24 + 100\,X$$

$$\therefore X = 0.08 \text{ p.u.}$$

(ii) When fault occurs on bus 2, reactance of 50 MVA generator in series with bus bar reactor acts in parallel with reactance of 100 MVA generator. So per unit reactance between fault point and the neutral bus

$$= j\frac{(0.2 + X) \times 0.08}{(0.2 + X) + 0.08}$$

$$= j\frac{(0.2 + 0.08) \times 0.08}{0.2 + 0.08 + 0.08}$$

$$= j\,0.0622 \text{ p.u.}$$

$$\text{Fault MVA} = \frac{\text{Base MVA}}{\text{Per unit reactance}}$$

$$= \frac{100}{0.0622} = 1607.14 \text{ MVA}$$

(iii) Per unit reactance from neutral bus to fault point :

$$X_{eq,\,pu} = j\left[0.15 + \frac{0.2(0.08 + 0.08)}{0.2 + 0.08 + 0.08}\right]$$

$$= j\left[0.15 + \frac{0.032}{0.36}\right] = j0.2388 \text{ p.u.}$$

$$\text{MVA ratings of circuit breaker C} = \frac{\text{Base MVA}}{X_{eq,\,p.u.}} = \frac{100}{j0.2388} = 418.61 \text{ MVA}$$

Ex. 1.12.7

In the power system circuit as shown in Fig. P. 1.12.7. The current limiting reactor X is to be chosen such that the feeder breaker rating does not exceed 50 MVA. The system data is, feeder transformer reactance : 8 % on 50 MVA base. The generator sources A, B, C have individual fault level of 1000 MVA with respect to generator breaker open. Ignore prefault current and assume 1.0 p.u. voltage throughout before fault. Assume common base of 100 MVA.

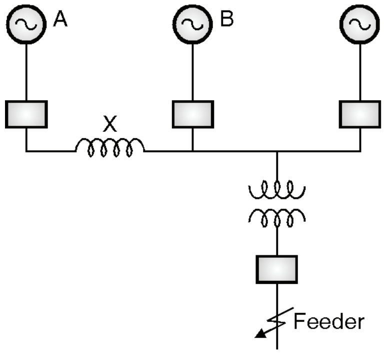


Fig. P. 1.12.7

Soln. : Common base MVA = 100

$$\text{Per unit reactance of transformer} = \frac{8}{100} \times \frac{100}{50} = 0.16 \text{ p.u.}$$

$$\text{Per unit reactance of each generator} = \frac{\text{Base MVA}}{\text{Short circuit MVA}} = \frac{100}{1000} = 0.1 \text{ p.u.}$$

Reactance diagram is :

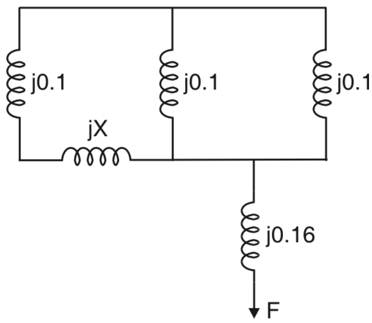


Fig. P. 1.12.7(a)

When fault occurs at point F, the reactance of generator B and C and series combination of reactance of generator A and busbar reactor act in parallel. Their combined reactance is,

$$= j\,[0.1 \parallel 0.1 \parallel (0.1 + X)] = j\,[0.05 \parallel (0.1 + X)]$$

$$= j\left[\frac{0.05 \times (0.1 + X)}{0.05 + 0.1 + X}\right] = j\left[\frac{0.05\,X + 0.005}{0.15 + X}\right]$$

This reactance is in series with transformer reactance. So per unit reactance between fault point and neutral bus

$$X_{eq,\,p.u.} = j\left[\frac{0.05\,X + 0.005}{0.15 + X}\right] + j0.16$$

$$= j\left[\frac{0.029 + 0.21\,X}{0.15 + X}\right]$$

$$\text{Short circuit MVA} = \frac{\text{Base MVA}}{X_{eq,\,p.u.}}$$

$$500 = \frac{100\,(0.15 + X)}{0.029 + 0.21\,X}$$

$$X = \frac{100 \times 0.15 - 500 \times 0.029}{500 \times 0.21 - 100} = 0.1 \text{ p.u.}$$

$$X = 10\ \%$$

Ex. 1.12.8

A 25 MVA 13.8 kV generator with $X_d'' = 15\ \%$ is connected through a transformer to a bus which supplies four identical motors as shown in Fig. P. 1.12.8. The sub transient reactance X_d of each motor is 20% on a base of 5 MVA, 6.9 kV. The three phase rating of transformer is 25 MVA, 13.8/6.9 kV with a leakage reactance of 10% the bus voltage at the motors is 6.9 kV when a three phase fault occurs at point P. For the fault specified determine (a) the subtransient current in the fault, (b) the subtransient current in breaker A.

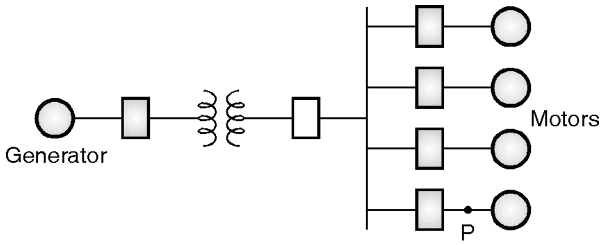


Fig. P. 1.12.8

Soln. :

Base MVA = 25 MVA

Base kV on generator side = 13.8 kV

Base kV on load side = 6.9 kV

Per unit reactance of generator = 0.15 p.u.

Per unit reactance of transformer = 0.1 p.u.

$$\text{Per unit reactance of each motor} = \frac{20}{100} \times \frac{6.9^2}{6.9^2} \times \frac{25}{5} = 1 \text{ p.u.}$$

(i) Reactance diagram for given system is :

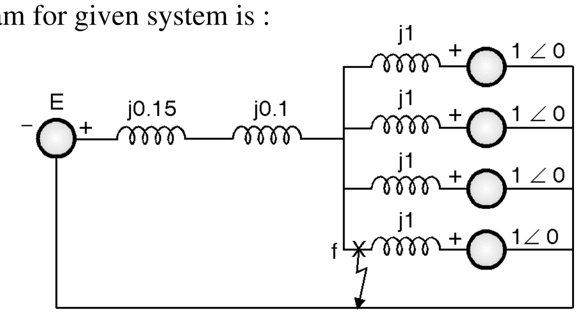
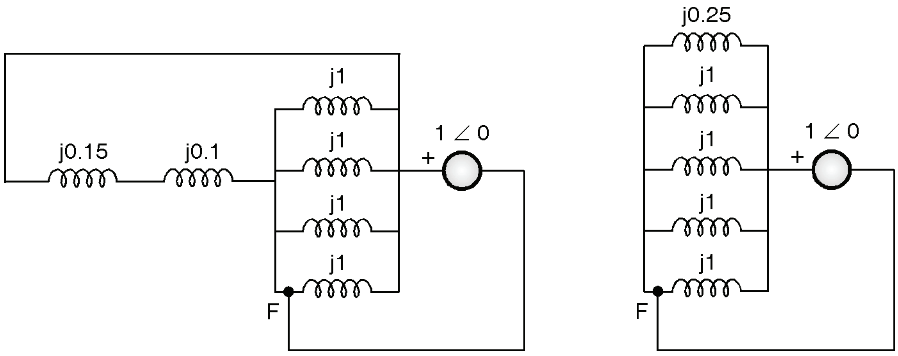


Fig. P. 1.12.8(a)

The system being initially on no load. The generator and motor induced emfs are identical. So the reactance diagram can be reduced to that shown in Fig. P. 1.12.8(a) and then to Fig. P. 1.12.8(b).



(b) **(c)**

Fig. P. 1.12.8

$$X_{eq,\,p.u.} = 4 \times \frac{1}{j\,1} + \frac{1}{j\,0.25} = -\,j0.125$$

$$I_{SC} = \frac{1\angle 0}{0.125} = 8 \text{ p.u.}$$

$$\text{Base current in 6.9 kV circuit} = \frac{25 \times 1000}{\sqrt{3} \times 6.9}$$

$$= 2091.8 \text{ A.}$$

$$\text{Total} \quad I_{SC} = 2091.8 \times 8$$

$$= 16{,}734.79 \text{ A.}$$

(ii) From Fig. P. 1.12.8(c) current through circuit breaker is,

$$I_{SC}\,(A) = 3 \times \frac{1}{j1} + \frac{1}{j0.25} = -\,j7$$

$$\text{Total current in breaker A} = 2091.8 \times 7$$

$$= 14642.6 \text{ A.}$$

Ex. 1.12.9

Fig. P. 1.12.9 shows a single line diagram of power system network. The breaking capacity of breaker A is 100 MVA. Find out the per unit value of reactor R. Also find the per unit value of reactor R. Also find out the breaking capacity of breaker B.

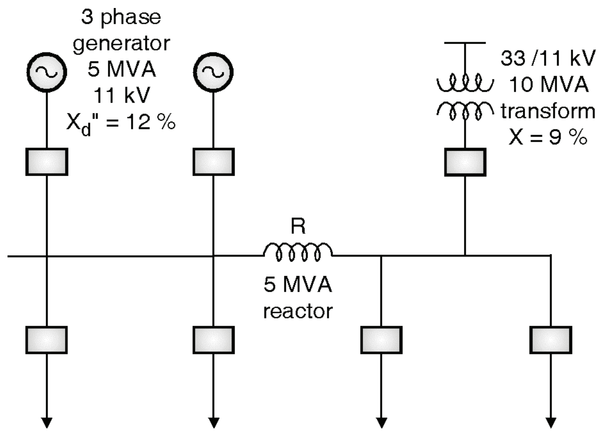


Fig. P. 1.12.9

Soln. :

Let the base MVA is = 10 MVA

(i) Per unit reactance of each generator $= j\dfrac{12}{100} \times \dfrac{10}{5} = j0.24$

Per unit reactance of transformer = j0.09 (given)

Let X is the per unit reactance of reactor.

The reactance diagram is,

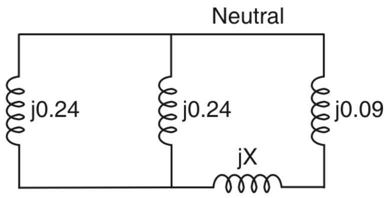


Fig. P. 1.12.9(a)

The reactances of generation are in parallel. So their combined reactance is j0.24/2 = j0.12 p.u. This reactance is in parallel with reactance of transformer in series with reactance reactor i.e. j(0.09 + X). The per unit reactance between fault point and the neutral bus is,

$$= j0.12 \parallel j(0.09 + X)$$

$$= j\frac{0.12\,(X + 0.09)}{0.12 + X + 0.09}$$

$$= j\frac{0.12\,X + 0.0108}{0.21 + X}$$

$$\text{Since short circuit MVA} = \frac{\text{Base MVA}}{\text{Per unit reactace}}$$

$$100 = \frac{10}{\frac{0.12\,X + 0.0108}{0.21 + X}}$$

$$100 = \frac{10\,(0.21 + X)}{0.12\,X + 0.0108}$$

$$12\,X + 1.08 = 2.1 + 10\,X$$

$$\therefore \quad X = \frac{2.1 - 1.08}{2}$$

$$\therefore \quad X = 0.51 \text{ p.u.}$$

$$\text{Actual value of reactance of reactor} = \frac{0.51 \times 11^2}{10} = 6.171\ \Omega$$

(ii)

$$\text{Breaking capacity of breaker B} = \frac{\text{Base MVA}}{\text{Per unit reactance } X_{p.u.}}$$

$$X_{eq,\,p.u.} = j\,\frac{0.12\,(x + 0.09)}{0.12 + x + 0.09}$$

$$= j\,\frac{0.12\,(6.171 + 0.09)}{0.12 + 6.171 + 0.09}$$

$$X_{eq,\,p.u.} = j\,\frac{0.7513}{6.381} = j\,0.1177$$

$$\therefore \text{Breaking capacity of breaker B} = \frac{10}{0.1177}$$

$$B = 84.96 \text{ MVA}$$

Ex. 1.12.10

A synchronous generator and a synchronous motor each rated 25 MVA, 11 kN having 15% subtransient reactance are connected through transformer and a line as shown in Fig P. 1.12.10. The transformers are rated 25 MVA, 11/66 kV and 66/11 kV with leakage reactance of 10% each. The line has a reactance of 10% on a base of 25 MVA, 66kV. The motor is drawing 15 MW at 0.8 power factor leading and a terminal voltage of 10.6 kV when a symmetrical three phase fault occurs at the motor terminals. Find the subtransient current in the generator, motor and fault.

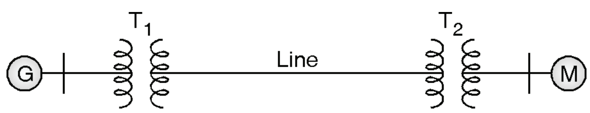


Fig. P. 1.12.10

Soln. :

The reactance's of all the components of power system are specified for the base MVA of 25 MVA. Keeping these values as it is, the reactance diagram is,

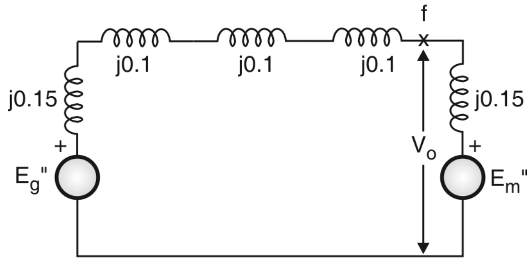


Fig. P. 1.12.10(a)

Considering 11 kV as base voltage,

$$\text{Prefault voltage, } V_o = \frac{10.6}{11} = 0.9636 \angle 0° \text{ p.u.}$$

$$\text{Prefault current} = \frac{15/25}{0.9636 \times 0.8} \angle \cos^{-1} 0.8$$

$$= 0.7783 \angle 36.86° \text{ p.u.}$$

Generator voltage behind subransient reactance,

$$E_g'' = 0.9636 \angle 0° + j\, 0.45 \times 0.7783 \angle 36.86°$$

$$= 0.9636 + j0.45 \angle 90° \times 0.7783 \angle 36.86$$

$$= 0.9636 + 0.3502 \angle 136.86°$$

$$= 0.7081 + j0.2395$$

$$= 0.7475 \angle 18.68° \text{ p.u.}$$

Motor voltage behind subtransient reactance.

$$E_m'' = 0.9636 \angle 0° - (j\, 0.15 \times 0.7783 \angle 36.86°)$$

$$= 0.9636 - (0.15 \angle 90° \times 0.77\,83 \angle 36.86°)$$

$$= 0.9636 - 0.1167 \angle 136.86°$$

$$= 1.0488 - j0.0798$$

$$= 1.052 \angle -4.35° \text{ p.u.}$$

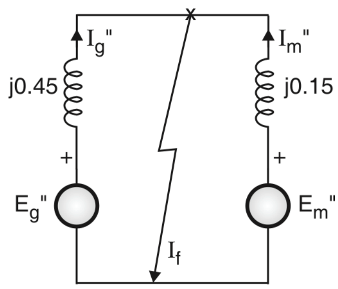


Fig. P. 1.12.10(b)

The equivalent circuit during fault is,

$$I_g'' = \frac{0.7475 \angle 18.68°}{j0.45}$$

$$I_g'' = 1.661 \angle -71.32° \text{ p.u.}$$

$$I''_m = \frac{1.052 \angle -4.35°}{j0.15}$$

$$I''_m = 7.013 \angle -94.35° \text{ p.u.}$$

Total fault current $I_f = I''_g + I''_m$

$$= 0.5319 - j1.574 - 0.532 - 6.993$$

$$\therefore \quad I_f = -j8.567$$

$$\text{Base current} = \frac{25 \times 10^6}{\sqrt{3} \times 11 \times 10^3} = 1{,}312.2 \text{ A.}$$

$$\therefore \quad I''_g = 1.661 \angle -71.32° \times 1312.2$$

$$= 2{,}179.56 \angle -71.32° \text{ A.}$$

$$I''_m = 7.013 \angle -94.35° \times 1312.2$$

$$= 9202.5 \angle -94.35° \text{ A.}$$

$$I_f = 8.567 \angle 90° \times 1312.2$$

$$= 11{,}241.62 \angle 90° \text{ A.}$$

Ex. 1.12.11

A four bus sample power system is shown in Fig. P. 1.12.11. Calculate the fault current at bus no. 4 for three phase solid fault occurring at that bus various data are given below. Assume prefault voltage as 1.0 p.u. and prefault current to be zero.

G_1 = 11.2 kV, 100 MVA, X'_{g_1} = 0.08 p.u.

Line from 1 - 2 = 0.2 p.u.

Line from 1 - 3 = 0.2 p.u

Line from 1 - 4 = 0.1 p.u,

Line from 2 - 3 = 0.1 p.u.

Line from 2 - 4 = 0.1 p.u.

G_2 = 11.2 kV, 100 MVA, X'_{g_2} = 0.08 p.u.

T_1 = 11/110 kV, 100 MVA, X_{T_1} = 0.06 p.u.

T_2 =11/110 kV, 100 MVA, X_{T_2} = 0.06 p.u.

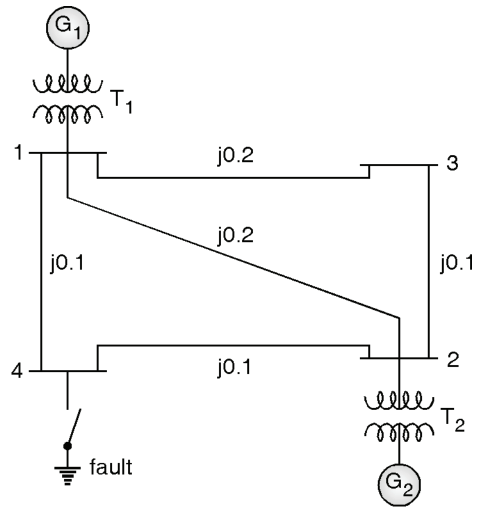


Fig. P. 1.12.11

Soln. :

The reactance diagram for the given system is,

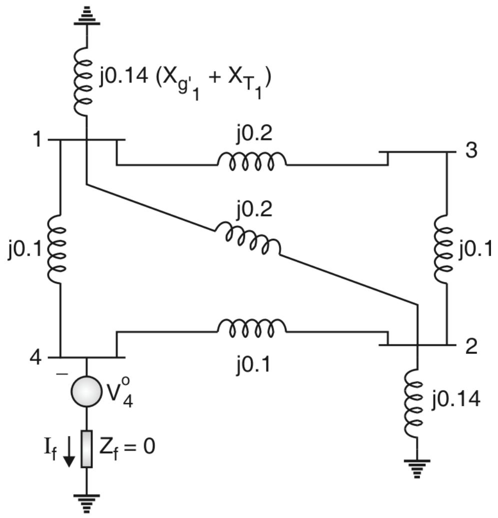


Fig. P. 1.12.11(a)

The fault current I_f can be calculated by reducing the network as,

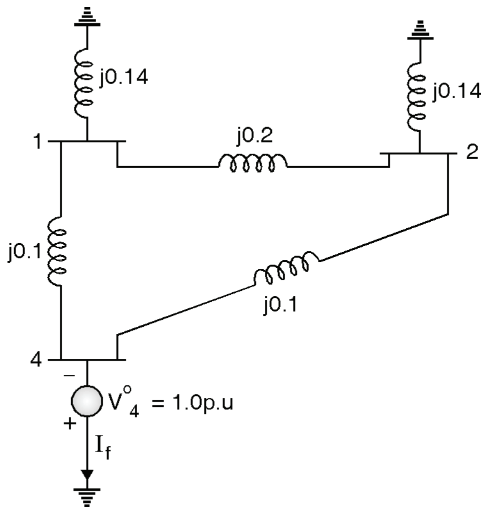


Fig. P. 1.12.11(b)

This circuit shown in Fig. P. 1.12.11(b) can be reduced as

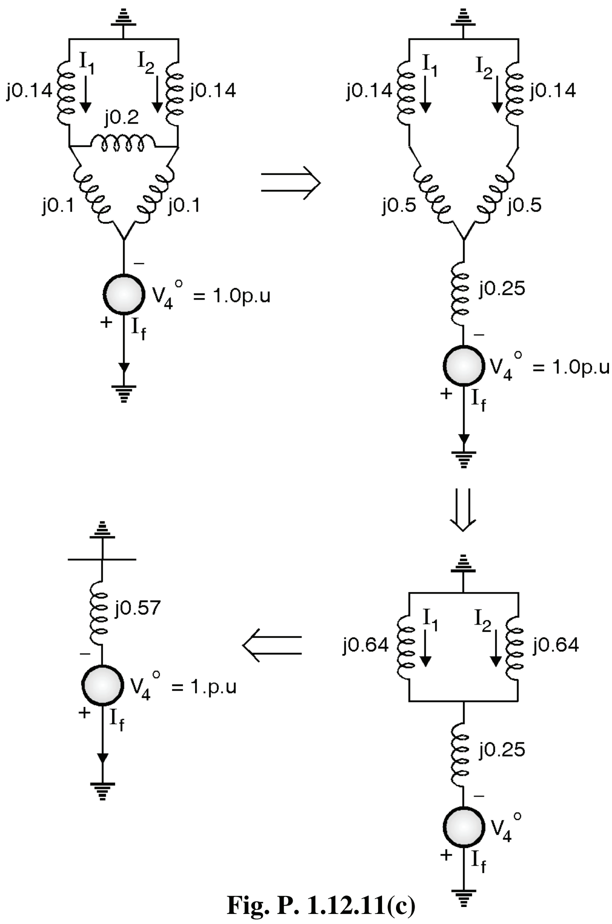


Fig. P. 1.12.11(c)

$$\therefore \text{ Fault current} \quad I_f = \frac{1.0}{j\,0.57}$$

$$= -j\,1.754 \text{ p.u.}$$

We can find current supplied by G_1 and G_2 using current division rule.

$$\text{Fault current supplied by } G_1 = I_1 = I_f \times \frac{j0.64}{j1.28}$$

$$\therefore I_1 = -j1.754 \times \frac{j0.64}{j1.28}$$

$$I_1 = -j0.877 \text{ p.u.}$$

Similarly

$$I_2 = -j\,1.754 \times \frac{j0.64}{j1.28}$$

$$I_2 = -j0.877 \text{ p.u.}$$

$$\text{Bus current} = \frac{100 \times 10^6}{\sqrt{3} \times 11.2 \times 10^3} = 5154.9 \text{ A.}$$

$\therefore$ Total fault current at bus number 4 is = 1.754 × 5154.9 = 9.041.72 A.

Ex. 1.12.12

A 33 kV line has a resistance of 4Ω and reactance of 16 Ω respectively. The line is connected to generating station bus bars through a 6000 kVA step up transformer which has a reactance of 6 %. The station has two generators rated 10,000 kVA with 10% reactance and 500 kVA with 5% reactance. Calculate the fault current and short circuit kVA when a 3 phase fault occurs at the h.v. terminals of transformers and at the load end of line.

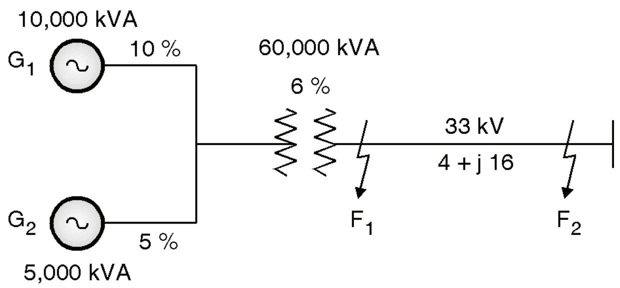


Fig. P. 1.12.12

Soln. :

As the kV rating of generator is not given in problem and voltage ratio of transformer is also not given, assume kV rating of generator 11 kV and transformer ratio 11 kV : 33 kV

Base kVA = 10,000

Base kV on generator side = 11 kV

Base kV on transmission line side = 33 kV

(i) Per unit reactance of generator G_1 = j 0.1 p.u.

(ii) Per unit reactance of Generator $G_2 = j\,0.05 \times \frac{10000}{5000} \times \frac{11^2}{11^2} = j\,0.1$ p.u.

(iii) Per unit reactance of transformer $= j\,0.06 \times \frac{10000}{6000} \times \frac{11^2}{11^2} = j\,0.1$ p.u.

(iv) Per unit reactance of line $= (4 + j6) \times \frac{10000}{33^2 \times 1000} = 0.037 \times j\,0.059$ p.u.

Reactance diagram

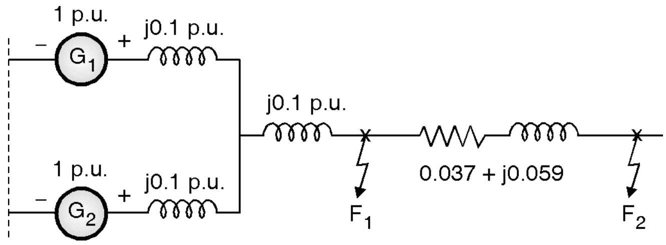


Fig. P. 1.12.12(a)

Reactance diagram can be reduced as,

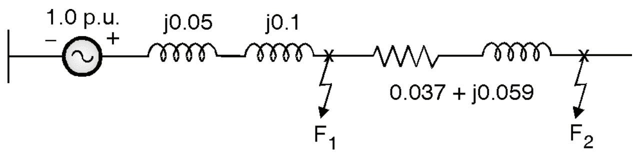


Fig. P. 1.12.12(b)

(i) For 3 phase fault at hv side of transformer.

Total reactance upto fault point $F_1 = j\,0.05 + j\,0.1 = j\,0.15$p.u.

$$\therefore \text{ Fault current } = I_f = \frac{1.00}{j\,0.15}$$

$$= 6.667 \text{ p.u.}$$

$$\text{Actual fault current} = 6.667 \times \frac{10000}{11}$$

$$= 6060.606 \text{ A.}$$

$$\text{Short circuit kVA} = \frac{\text{Base kVA}}{\text{per unit reactance upto foult point}}$$

$$= \frac{10000}{j\,0.15} = 66{,}666.67 \text{ kVA}$$

$$= 66.67 \text{ MVA}$$

(ii) For a three phase fault at load end.

Total reactance upto fault point

$$F_2 = j\,0.05 + j\,0.1 + 0.037 + j\,0.059$$

$$= 0.037 + j\,0.209$$

$$= 0.2122 \angle 79.96 \text{ p.u.}$$

$$\text{Fault current} = I_f = \frac{1.00}{0.2122} = 4.713 \text{ p.u.}$$

$$\text{Actual fault current} = 4.71 \times \frac{10000}{11} = 4281.82 \text{ A.}$$

$$\text{Short circuit kVA} = \frac{10000}{0.2122}$$

$$= 47125.35 \text{ kVA} = 47.125 \text{ MVA}$$

Ex. 1.12.13 **MU-May 16, 10 Marks**

An 11 kV 100 MVA alternator having sub transient reactance of 0.25 is supplying a 50 MVA motor having transient reactance of 0.2 pu through a transmission line. The line reactance is 0.05 pu on a base of 100 MVA. The motor is drawing a 100 MW at 0.8 PF leading with terminal voltage of 10.95 kV when a three phase fault occurs at generator terminals. Calculate total current in generator and motor under fault.

Soln. :

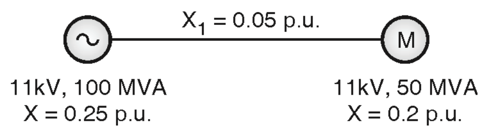


Fig. P. 1.12.13

Considering base MVA = 100 MVA and

Base kV = 11 kV

P.U. reactance of generator and transmission line remains same as it is specified for base MVA of 100 MVA.

$$\text{Reactance of motor} = 0.2 \times \frac{11^2}{11^2} \times \frac{100}{50} = j0.4 \text{ p.u.}$$

Reactance diagram is

Considering 11 kV base

Prefault voltage,

$$V_0 = \frac{10.95}{11} = 0.9955 \angle 0° \text{ p.u}$$

$$\text{Prefault current} = \frac{100/100}{0.9955 \times 0.8} \angle \cos^{-1} 0.8$$

$$= 1.2555 \angle 36.86° \text{ p.u.}$$

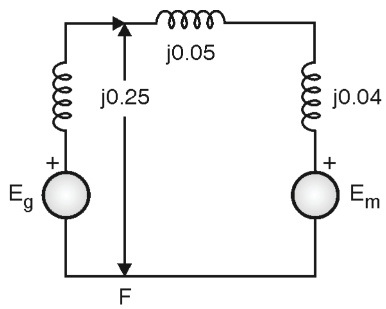


Fig. P. 1.12.13(a)

Generator voltage behind subtransient reactance

$$E_g = 0.9955 \angle 0° + j\, 0.1506 \angle 90° \times 1.2555 \angle 36.86°$$

$$= 0.9955 + 0.1883 \angle 126.86°$$

$$= 0.9955 - 0.1129 + j0.1506$$

$$= 0.8826 + j0.1506 = 0.8953 \angle 9.68° \text{ p.u.}$$

Motor voltage behind subtransient reactance

$$E_m = 0.9955 \angle 0° [- 0.09 \angle 90° \times 1.2555 \angle 36.86°]$$

$$= 0.9955 - 0.1129 \angle 126.86°$$

$$= 0.9955 - 0.0677 - j0.0903$$

$$= 0.9278 - j0.0903$$

$$= 0.9322 \angle - 5.56°$$

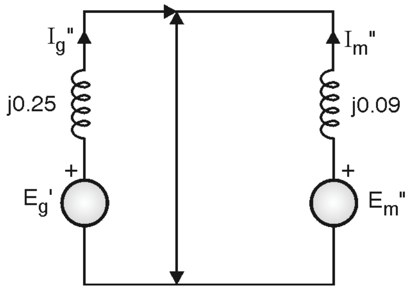


Fig. P. 1.12.13(b)

Equivalent circuit during fault

$$I_g'' = \frac{0.8953 \angle 9.68°}{j0.25}$$

$$I_g'' = 3.5812 \angle - 80.32° \text{ p.u.}$$

$$I_m'' = \frac{0.9322 \angle - 5.56°}{j0.09}$$

$$I_m'' = 10.3578 \angle - 95.56° \text{ p.u.}$$

Total fault current

$$I_f = 3.5812 \angle - 80.32 + 10.35478 \angle - 95.56°$$

$$I_f = - j3.5302 + 0.6022 - 10.0354 - j10.3091$$

$$= - 9.4332 - j13.8393$$

$$I_f = 16.7485 \angle 55.72°$$

$$\text{Base current} = \frac{100 \times 10^6}{\sqrt{3} \times 11 \times 10^3} = 5248.64 \text{ Amp.}$$

$$\therefore \quad I_g'' = 3.5812 \angle - 80.32° \times 5248.64$$

$$= 18,796.43 \angle - 80.32° \text{ Amp}$$

$$I_m'' = 10.3578 \angle - 95.56° \times 5248.64$$

$$= 54364.36 \angle - 93.56° \text{ Amp}$$

1.13 Transients in Series R-L Circuit

– Consider a series R-L circuit shown in Fig. 1.13.1. A three phase short circuit fault takes place in such circuit. The assumptions made while studying the transient behaviour of such circuit are,

(i) The series R-L circuit is fed from constant voltage source.

(ii) Short circuit takes place when system is unloaded.

(iii) Circuit is represented by a lumped RL series circuit.

- This circuit is equivalent to a transmission line with negligible line capacitance.
- Assume that the short circuit takes place at t = 0. α controls the instant on the voltage wave when short circuit occurs.

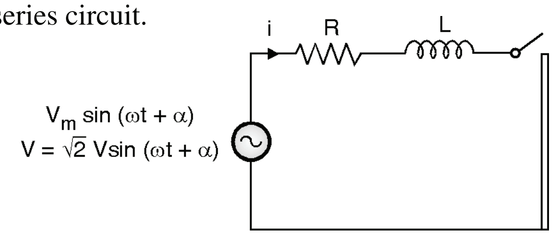


Fig. 1.13.1 : Series R-L circuit

Applying KVL to the circuit,

$$V = iR + L\frac{di}{dt} \qquad \ldots(1.13.1)$$

$$\therefore \quad L\frac{di}{dt} + iR = V_{max} \sin(\omega t + \alpha) \qquad \ldots(1.13.2)$$

$$\therefore \quad i = \frac{V_{max}}{\sqrt{R^2 + \omega^2 L^2}} \sin(\omega t + \alpha - \theta)$$

$$i = \frac{V_{max}}{Z} \sin(\omega t + \alpha - \theta) \qquad \ldots(1.13.3)$$

Where, $Z = (R^2 + \omega^2 L^2)^{1/2}, \angle \theta = \tan^{-1} \frac{\omega L}{R}$

The initial condition is,

$$L\frac{di}{dt} + Ri = 0$$

$$\therefore i = A \cdot e^{-\frac{Rt}{L}}$$

Complete solution of Equation (1.13.3) is,

$$i = \frac{V_{max}}{Z} \sin(\omega t + \alpha - \theta) + A \cdot e^{-Rt/L} \qquad \ldots(1.13.4)$$

At t = 0, $\quad i = 0$

$$\therefore 0 = \frac{V_{max}}{Z} \sin(\alpha - \theta) + A \qquad \therefore \; A = \frac{-V_{max}}{Z} \sin(\alpha - \theta)$$

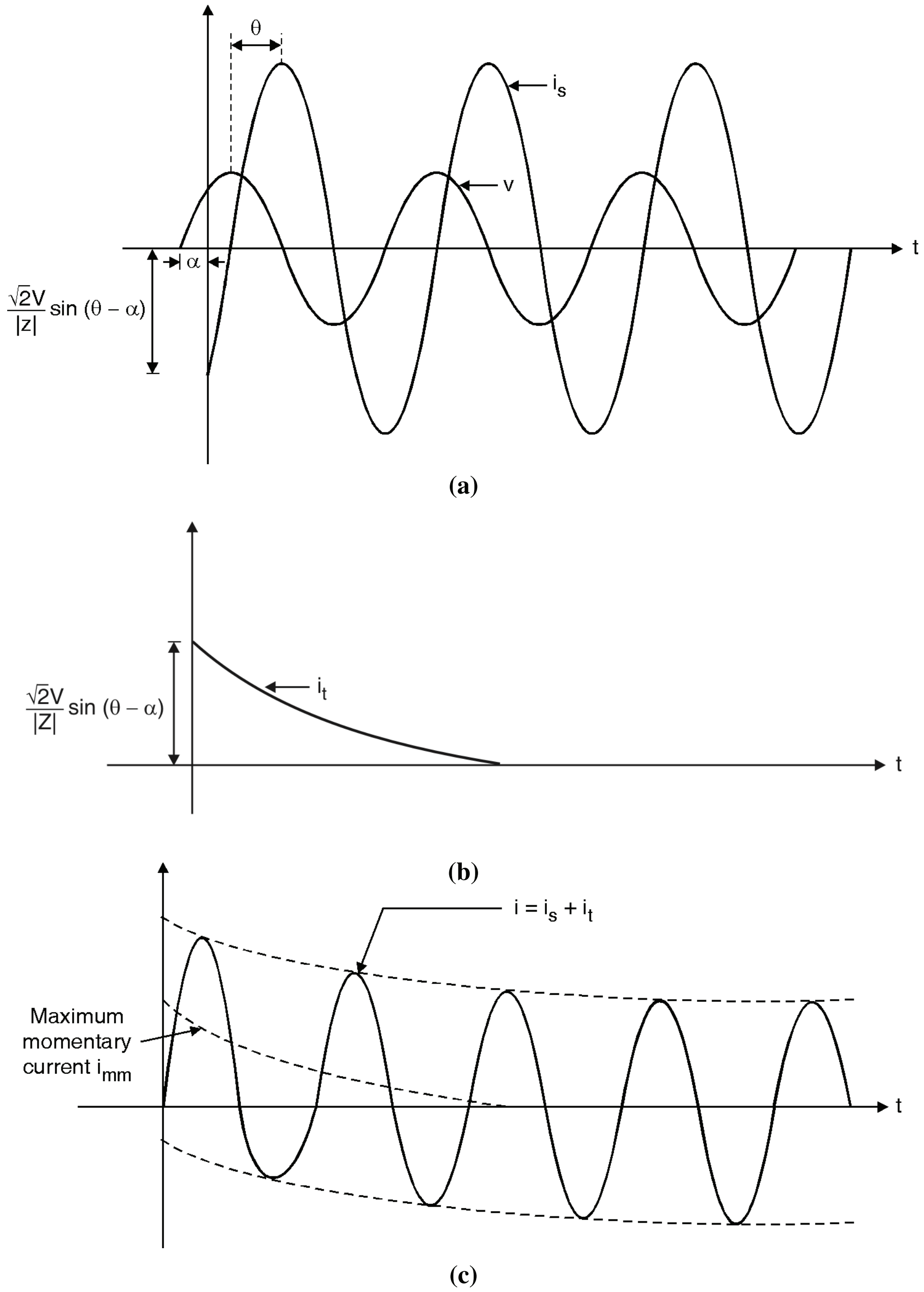
Hence Equation (1.13.4) becomes,

$$i = \frac{V_{max}}{Z} \sin(\omega t + \alpha - \theta) - \frac{V_{max}}{Z} \sin(\alpha - \theta) \cdot e^{-\frac{Rt}{L}}$$

$$i = \frac{\sqrt{2}\, V}{Z} \sin(\omega t + \alpha - \theta) + \frac{\sqrt{2}\, V}{Z} \sin(\theta - \alpha) \cdot e^{-\frac{Rt}{L}}$$

$$i = i_s + i_t$$

where, $i_s = \frac{\sqrt{2}\,V}{Z} \sin(\omega t + \alpha - \theta)$ is a steady state current or symmetrical short circuit current



(c)

Fig. 1.13.2 : Waveform of (a) i_s , (b) i_t , (c) i

$$i_t = \frac{\sqrt{2}\,V}{Z} \sin(\theta - \alpha) \cdot e^{(-R/L)\,t}$$

= is transient current or DC offset current. It delays corresponding of time constant (L/R)

- This plots of i_s, i_t and i are shown in Fig. 1.13.2. The DC offset current causes the total short circuit current to be unsymmetrical till the transient decays.
- i_{mm} is the maximum momentary short circuit current and corresponds to the first peak. If the decay of transient current in this short time is neglected.

$$i_{mm} = \frac{\sqrt{2}\,V}{|Z|} \sin(\theta - \alpha) + \frac{\sqrt{2}\,V}{|Z|} \qquad \ldots(1.13.5)$$

- As series RL circuit corresponds to transmission line, its resistance is small and $\theta \simeq 90°$.

$$\therefore \quad i_{mm} = \frac{\sqrt{2}\,V}{|Z|} \cos\alpha + \frac{\sqrt{2}\,V}{|Z|} \qquad \ldots(1.13.6)$$

- If short circuit occurs when the voltage is going through zero i.e. $\alpha = 0$ then,

$$i_{mm} = 2\frac{\sqrt{2}\,V}{|Z|} \qquad \ldots(1.13.7)$$

- It is twice the maximum value of symmetrical short circuit current. This is called as Doubling effect.

Exercise

Q. 1 Draw the waveforms for fault current for a 3-phase fault on alternator terminals. Explain the sub-transient, transient and steady state reactance. What is their significance in fault calculation ? **(Section 1.4.2)** **(7 Marks)**

Q. 2 Write a brief note on selection of circuit breaker. **(Section 1.11)** **(7 Marks)**

Q. 3 Explain the phenomena of sudden three phase short circuit at the generator terminal on no load condition and define subtransient, transient and steady state reactances of synchronous generator. **(Section 1.4)** **(7 Marks)**

Q. 4 Derive expression of current when there is a sudden three phase short circuit at the other end of unloaded transmission line. Assume a constant voltage source is connected at sending end and neglect line capacitance. **(Section 1.13)** **(7 Marks)**

1.14 University Questions and Answers

➔ May 2015

Q. 1(a) Explain the terms short circuit MVA and symmetrical fault.
(Ans. : Refer section 1.7) **(5 Marks)**

Q. 4(a) Discuss the short circuit of synchronous machine under no load condition. *(Ans. : Refer section 1.4)* **(10 Marks)**

Q. 4(b) Discuss the Z bus formation technique. *(Ans. : Refer section 1.8)* **(10 Marks)**

➔ Dec. 2015

Q. 1(d) Discuss the term transient. *(Ans. : Refer section 1.6)* **(5 Marks)**

Q. 2(a) Discuss the short circuit of synchronous machine at loaded condition. *(Ans. : Refer section 1.5)* **(10 Marks)**

Q. 2(b) Discusses the transients on transmission line. *(Ans. : Refer section 1.4)* **(10 Marks)**

➔ May 2016

Q. 2(a) Discuss the algorithm for short circuit studies. *(Ans. : Refer section 1.9)* **(10 Marks)**

Q. 2(b) An 11 kV 100 MVA alternator having sub transient reactance of 0.25 is supplying a 50 MVA motor having transient reactance of 0.2 pu through a transmission line. The line reactance is 0.05 pu on a base of 100 MVA. The motor is drawing a 100 MW at 0.8 PF leading with terminal voltage of 10.95 kV when a three phase fault occurs at generator terminals. Calculate total current in generator and motor under fault. *(Ans. : Refer Example 1.12.13)* **(10 Marks)**

➔ Dec. 2016

Q. 1(d) Discuss the term transient. *(Ans. : Refer section 1.6)* **(5 Marks)**

Q. 2(a) Discuss the short circuit of synchronous machine at no load condition. *(Ans. : Refer section 1.4)* **(10 Marks)**

Q. 2(b) Discuss the formation of transients on transmission line. *(Ans. : Refer section 1.6)* **(10 Marks)**

➔ May 2017

Q. 1(D) What are the various factors affecting the selection of circuit breaker ? *(Ans. : Refer section 1.11)* **(5 Marks)**

Q. 2(a) Discuss the short circuit of synchronous machine at loaded condition. *(Ans. : Refer section 1.5)* **(10 Marks)**

Q. 2(b) Discuss the z-bus formation technique. *(Ans. : Refer section 1.8)* **(10 Marks)**

Chapter Ends...

❑❑❑

CHAPTER 2 Symmetrical Components

Syllabus :

Introduction, symmetrical component transformation, phase shift in star-delta transformers, sequence impedances and sequence network of transmission line, synchrounous machine and transformer, power invariance, construction of sequence network power system.

Syllabus Topic : Introduction

2.1 Introduction

- More commonly occurring faults in power system are line to ground fault or line to line fault. These faults are called as unsymmetrical faults as system becomes unbalanced during such faults.
- Under unbalanced condition analysis is done on a three phase basis.
- A more convenient method used for analysis of unbalanced faults is symmetrical component method.
- In this method the three phase unbalanced voltages and currents are transformed into three sets of balanced voltages and currents called symmetrical components.
- This method resolves the unbalanced system of impedances into three equivalent single phase systems having independent impedances. The three independent impedance systems can be suitably connected to represent all types of fault conditions.

2.1.1 Applications of Symmetrical Components

1. Symmetrical component method converts three unbalanced phases into three independent sources. This simplifies asymmetric fault analysis.

2. Symmetrical components expands one line diagram to show positive sequence, negative sequence and zero sequence impedances of generator, transformers and lines. It simplifies analysis of unbalanced conditions such as single line to ground short circuit fault.
3. Physically in three phase winding a positive sequence set of currents produces a normal rotating field, negative sequence produces a field with opposite rotation and zero sequence produces a field that oscillates but not rotates. These effects can be detected physically with sequence filters. Hence it becomes the basis for design of protective relays which used negative sequence voltages and currents as a reliable indicator of fault condition.

2.2 Synthesis of Unsymmetrical Phasors from their Symmetrical Components

- Symmetrical component are expressed in phase sequence, the order in which the phase quantities go through a maximum. There may be a positive phase sequence, a negative phase sequence and zero or uniphase sequence component.

☞ **Positive Phase Sequence**

- In this phase sequence the phase or line currents or voltages attains a maximum in the same cyclic order as in normal supply. Assuming conventional counter clockwise rotation positive sequence phasors are shown in Fig. 2.2.1.
- A balanced system corresponding to normal condition contains a positive phase sequence only. It is the condition for three phase fault.

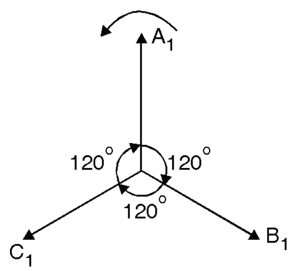


Fig. 2.2.1 : Positive Phase Sequence

- Positive phase sequence components are marked by subscript 1.
- The three phasors of this sequence are of equal magnitude and spaced 120° apart. These phasors are represented as, A_1

$$B_1 = A_1 \angle -120° = A_1 \cdot e^{-j\frac{2\pi}{3}} = \alpha^2 \cdot A_1.$$

$$C_1 = A_1 \angle 120° = A_1 \cdot e^{j\frac{2\pi}{3}} = \alpha\, A_1.$$

α is the complex number operator and defined as, $\alpha = e^{j\frac{2\pi}{3}}$.

Negative Phase Sequence

- In this system the phasors rotates in anticlockwise but attains maximum in reverse order i.e. A-C-B. This sequence arises under unbalanced condition when an unsymmetrical fault occurs.
- Negative phase sequence components are marked by subscript 2.

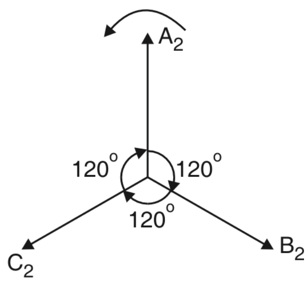


Fig. 2.2.2 : Negative Phase Sequence

- The three phasors of negative phase sequence are of equal magnitude and 120° apart. It is represented as, A_2

$$B_2 = A_2 \angle 120° = A_2 \cdot e^{j\frac{2\pi}{3}} = \alpha A_2.$$

$$C_2 = A_2 \angle -120° = A_2 \cdot e^{-j\frac{2\pi}{3}} = \alpha^2 A_2.$$

Zero Phase Sequence

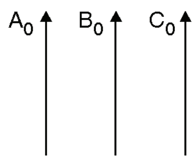


Fig. 2.2.3 : Zero Phase Sequence

- A phasor system combining three equal phasors in phase as shown in Fig. 2.2.3.
- These represents the residual current or voltages present under fault condition on three phase system with earth return present.
- It represents fault condition to ground. It's presence arises only when fault to earth current can return to system via star point of that system.
- In an earth fault positive and negative sequence components are also present. Zero sequence components are marked by subscript 0 and represented as,

$$A_0 = B_0 = C_0.$$

- Frequency of zero sequence phasors is equal to Triplen harmonics which don't rotate at all because they are in phase with each other.

2.3 Operators

- The complex number operator α is defined as, $\alpha = e^{j\,120°}$
- Multiplication of phasor by α or $e^{j\,120°}$ turns it through 120° in counter clockwise direction. Multiplying a phasor by α^2 or $e^{-j\,120°}$ turns it through 240° in counter clockwise direction.

Operator α has following properties,

$$\alpha = e^{j\frac{2\pi}{3}} = -0.5 + j\,0.866$$

$$\alpha^2 = e^{-j\frac{2\pi}{3}} = -0.5 - j\,0.866$$

$$\alpha^3 = e^{j0} = 1 + j0.$$

$$\alpha + \alpha^2 + 1 = 0$$

Syllabus Topic : Symmetrical Component Transformation

2.4 Symmetrical Components of Unsymmetrical Phasors

- V_a, V_b and V_c is a set of three balanced voltages. It is characterized by equal magnitude and phase difference of 120°.
- The set is said to have positive phase sequence if V_b lags V_a by 120° and V_c lags V_b by 120°.
- The three phasors can be expressed in terms of reference phasor V_a as,

$$V_a = V_a$$

$$V_b = \alpha^2 V_a$$

$$V_c = \alpha V_a$$

For the negative phase sequence

$$V_a = V_a$$

$$V_b = \alpha V_a$$

$$V_c = \alpha^2 V_a$$

- Positive phase sequence is marked by subscript 1. Hence a set of balanced positive sequence phasors is,

$$V_{a1},\ V_{b1} = \alpha^2 V_{a1},\ V_{c1} = \alpha V_{a1} \qquad ..(2.4.1)$$

- Similarly negative phase sequence is marked by subscript 2 and zero phase sequence by subscript 0. Hence the set of balanced negative and zero sequence phasors are,

$$V_{a2}, V_{b2} = \alpha V_{a2}, V_{c2} = \alpha^2 V_{a2} \qquad ...(2.4.2)$$

$$V_{a0}, V_{b0} = V_{a0}, V_{c0} = V_{a0} \qquad ...(2.4.3)$$

- Consider a set of three unbalanced voltages V_a, V_b, V_c. According to Fortescue's theorem the three phasors can be expressed as sum of positive, negative and zero sequence phasors.

$$V_a = V_{a1} + V_{a2} + V_{a0} \qquad ...(2.4.4)$$

$$V_b = V_{b1} + V_{b2} + V_{b0} \qquad ...(2.4.5)$$

$$V_c = V_{c1} + V_{c2} + V_{c0} \qquad ...(2.4.6)$$

Equations (2.4.4), (2.4.5) and (2.4.6) are called as symmetrical equations. These are used to obtain original phasors from symmetrical components. The addition of symmetrical components to generate V_a, V_b and V_c is indicated by the phasor diagram as shown in Fig. 2.4.1.

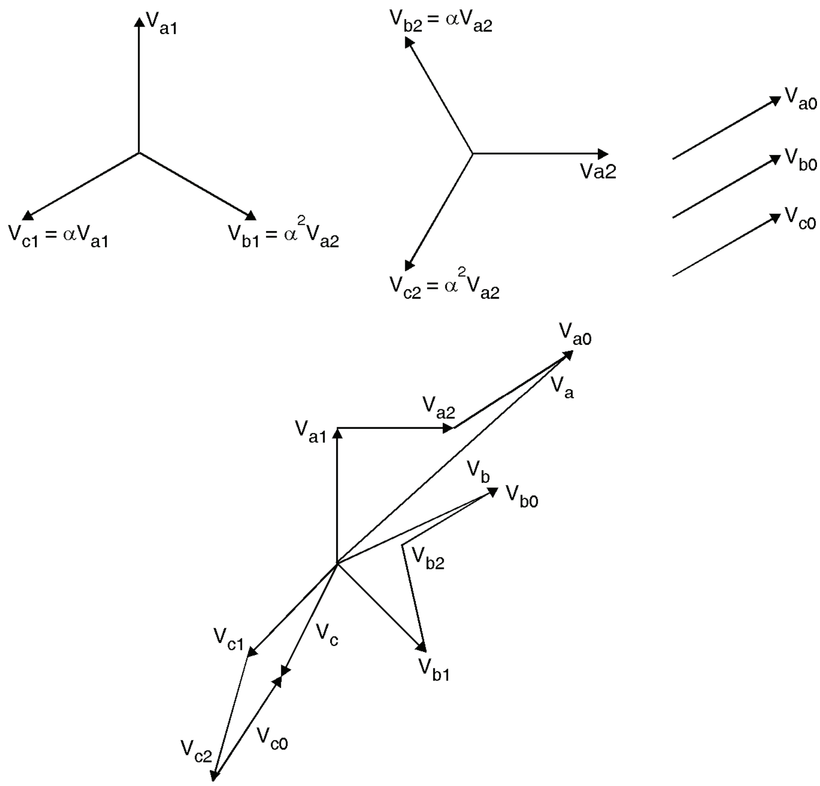


Fig. 2.4.1 : Phasor addition of symmetrical components to obtain set of original phasors

$$V_a = V_{a1} + V_{a2} + V_{a0} \qquad ...(2.4.7)$$

$$V_b = \alpha^2 V_{a1} + \alpha V_{a2} + V_{a0} \qquad ...(2.4.8)$$

$$V_c = \alpha V_{a1} + \alpha^2 V_{a2} + V_{a0} \qquad ...(2.4.9)$$

– These equations can be expressed in matrix form,

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ \alpha^2 & \alpha & 1 \\ \alpha & \alpha^2 & 1 \end{bmatrix} \begin{bmatrix} V_{a1} \\ V_{a2} \\ V_{a0} \end{bmatrix} \qquad ...(2.4.10)$$

or $$[\,V\,]_p = [\,A\,]\;[\,V\,]_s \qquad ...(2.4.11)$$

Where $[\,V\,]_p$ is vector of original phasors.

$[\,V\,]_s$ is vector of symmetrical components

$[\,A\,]$ is transformation matrix.

– We can write equation for $[\,V\,]_s$ from Equation (2.4.11),

$$[\,V\,]_s = [\,A\,]^{-1}\;[\,V\,]_p \qquad ...(2.4.12)$$

Computing $[\,A\,]^{-1}$, $$[\,A\,]^{-1} = \frac{1}{3}\begin{bmatrix} 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \\ 1 & 1 & 1 \end{bmatrix} \qquad ...(2.4.13)$$

– Replacing $[\,A\,]^{-1}$ with Equation (2.4.13) in Equation (2.4.12) we get,

$$\begin{bmatrix} V_{a1} \\ V_{a2} \\ V_{a0} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

$$\therefore V_{a1} = \frac{1}{3}\,(V_a + \alpha V_b + \alpha^2 V_c) \qquad ...(2.4.14)$$

$$V_{a2} = \frac{1}{3}\,(V_a + \alpha^2 V_b + \alpha V_c) \qquad ...(2.4.15)$$

$$V_{a0} = \frac{1}{3}\,(V_a + V_b + V_c) \qquad ...(2.4.16)$$

– Equation (2.4.7) to Equation (2.4.9) gives the relationship for obtaining original phasors from the symmetrical components and Equation (2.4.14) to Equation (2.4.16) gives the relationship for obtaining symmetrical components from original phasors.

– The above transformation is applicable for any set of phasors. Hence it can be apply to a set of currents.

$$[\,I\,]_p = [\,A\,]\,[\,I\,]_s \qquad ...(2.4.17)$$

and $$[\,I\,]_s = [\,A\,]^{-1}\,[\,I\,]_s \qquad ...(2.4.18)$$

From Equation (2.4.17) we can write,

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ \alpha^2 & \alpha & 1 \\ \alpha & \alpha^2 & 1 \end{bmatrix} \begin{bmatrix} I_{a1} \\ I_{a2} \\ I_{a0} \end{bmatrix} \qquad ...(2.4.19)$$

Hence,

$$I_a = I_{a1} + I_{a2} + I_{a0} \qquad ...(2.4.20)$$

$$I_b = \alpha^2 I_{a1} + \alpha I_{a2} + I_{a0} \qquad ...(2.4.21)$$

$$I_c = \alpha I_{a1} + \alpha^2 I_{a2} + I_{a0} \qquad ...(2.4.22)$$

Also from Equation (2.4.18) we can write,

$$\begin{bmatrix} I_{a1} \\ I_{a2} \\ I_{a0} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \qquad ...(2.4.23)$$

$$I_{a1} = \frac{1}{3} (I_a + \alpha I_b + \alpha^2 I_c) \qquad ...(2.4.24)$$

$$I_{a2} = \frac{1}{3} (I_a + \alpha^2 I_b + \alpha I_c) \qquad ...(2.4.25)$$

$$I_{a0} = \frac{1}{3} (I_a + I_b + I_c) \qquad ...(2.4.26)$$

Syllabus Topic : Phase Shift in Star-Delta Transformers

2.5 Phase Shift of Symmetrical Components in Star Delta Transformer Bank

- A phase shift occurs in positive sequence and negative sequence voltages and current while passing through a star delta transformer. This phase shift depends upon labelling of terminals.
- Fig. 2.5.1 shows a single phase transformer along with polarity marked. The transformer ends marked with dot have same polarity.
- Hence, voltage $V_{11'}$ is in phase with voltage $V_{22'}$.
- If we neglect the small amount of magnetizing current, the primary current I_1 entering the dotted end cancels the demagnetizing ampere turns of secondary current I_2.
- Hence I_1 and I_2 with the directions indicated in diagram are in phase. If direction of I_2 is reversed. I_1 and I_2 will be in phase opposition.
- Consider a star delta transformer as shown in Fig. 2.5.2(a). Assume that the transformer is excited with positive sequence voltages and carries positive sequence currents.

– For the shown polarities in Fig. 2.5.2(a) the phasor diagram is as shown in Fig. 2.5.3. We will get the following relationship between the voltages on the two sides of transformer.

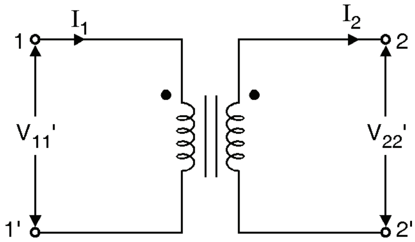


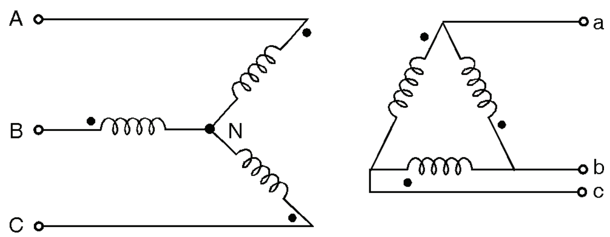
Fig. 2.5.1 : A single phase transformer with polarity markings

$$V_{AB1} = x\, V_{ab1} \angle 30^\circ. \qquad ...(2.5.1)$$

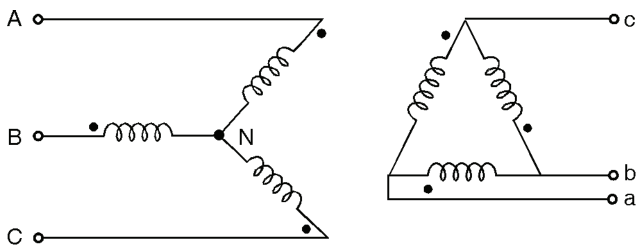
– Here x is the phase transformation ratio.

– Equation (2.5.1) indicates that the positive sequence line voltages on star side lead the corresponding voltage on delta side by 30°. The same is applicable to line to neutral voltages on the two sides and for line currents.

– The phase shift reverses if the delta side of transformer is connected as shown Fig. 2.5.2(b). In such connections the delta side quantities lead the star side quantities by 30°.



(a) Star side quantities lead delta side quantities by 30°



(b) Delta side quantities lead star side quantities by 30°
Fig. 2.5.2 : Star Delta transformer labelling

- If the transformer shown in Fig. 2.5.1 is excited by negative sequence voltages and currents then the phase shift gets reversed in comparison to the phase shift of positive phase sequence.
- The star side quantities lag the delta side quantities by 30° as shown in Fig. 2.5.4. If the delta side is connected as shown in Fig. 2.5.2(b) the delta side quantities lag the star side quantities by 30°.

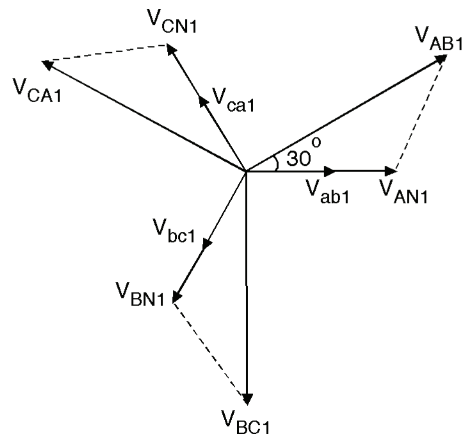


Fig. 2.5.3 : Phasor diagram representing positive sequence voltages of star delta transformer

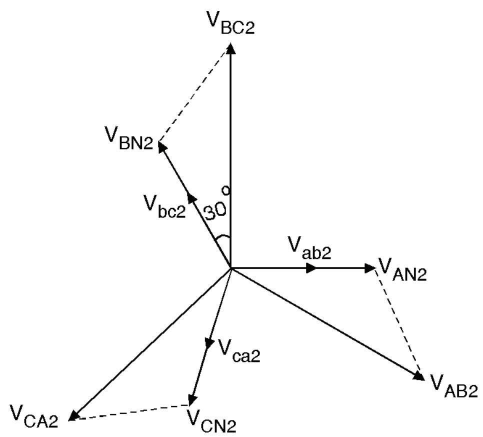


Fig. 2.5.4 : Phasor diagram representing negative sequence voltages of star delta transformer

Syllabus Topic : Power Invariance

2.6 Power in Terms of Symmetrical Components (Power Invariance)

→ (MU - Dec. 16)

Q. 2.6.1 What is power invariance in unsymmetrical fault analysis ? *(Refer section 2.6)*	**Dec. 16, 5 Marks**

- The power consumption of a three phase circuit can be determined directly from the symmetrical components. Total complex power in a three phase circuit is,

$$S = P + j\,Q = V_P^T \cdot I_P^* \qquad ...(2.6.1)$$

$$S = V_a\, I_a^* + V_b \cdot I_b^* + V_c\, I_c^* \qquad ...(2.6.2)$$

- Where V_a, V_b, V_c are voltages to neutral and I_a, I_b, I_c are currents flowing into the circuit in the three lines assuming star connected system.

$$S = [\, AV_s\,]^T \cdot [\, A \cdot I_s]^*$$

$$[\, V_P\,]^T = [\, A\, V_s\,]^T = A^T \cdot V_s^T$$

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}^T = \begin{bmatrix} 1 & 1 & 1 \\ \alpha^2 & \alpha & 1 \\ \alpha & \alpha^2 & 1 \end{bmatrix}^T \begin{bmatrix} V_{a1} \\ V_{a2} \\ V_{a0} \end{bmatrix}^T$$

$$= \begin{bmatrix} 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \\ 1 & 1 & 1 \end{bmatrix} [\, V_{a1}, V_{a2}, V_{a0}] \qquad ...(2.6.3)$$

$$[\, I_p\,]^* = [\, A\, I_s]^* = A^* \cdot I_s^*$$

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}^* = \begin{bmatrix} 1 & 1 & 1 \\ \alpha^2 & \alpha & 1 \\ \alpha & \alpha^2 & 1 \end{bmatrix}^* \begin{bmatrix} I_{a1} \\ I_{a2} \\ I_{a0} \end{bmatrix}^*$$

$$= \begin{bmatrix} 1 & 1 & 1 \\ \alpha & \alpha^2 & 1 \\ \alpha^2 & \alpha & 1 \end{bmatrix} \begin{bmatrix} I_{a1} \\ I_{a2} \\ I_{a0} \end{bmatrix}^* \qquad ...(2.6.4)$$

- Replacing V_p^T and I_p^* in Equation (2.6.1) with Equations (2.6.3) and (2.6.4)

$$S = [\, V_{a1}\, V_{a2}\, V_{a0}\,] \begin{bmatrix} 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} 1 & 1 & 1 \\ \alpha & \alpha^2 & 1 \\ \alpha^2 & \alpha & 1 \end{bmatrix} \begin{bmatrix} I_{a1} \\ I_{a2} \\ I_{a0} \end{bmatrix}^*$$

$$S = [\, V_{a1}\, V_{a2}\, V_{a0}] \begin{bmatrix} 3 & 0 & 0 \\ 0 & 3 & 0 \\ 0 & 0 & 3 \end{bmatrix} \begin{bmatrix} I_{a1} \\ I_{a2} \\ I_{a0} \end{bmatrix}^*$$

$$S = 3\, V_{a1}\, I_{a1}^* + 3\, V_{a2}\, I_{a2}^* + 3\, V_{a0}\, I_{a0}^* \qquad ...(2.6.5)$$

$$S = \text{Sum of the powers of symmetrical components.}$$

- This indicates that the symmetrical component transformation is power invariant i.e. the sum of powers of the three symmetrical components equals the three phase power.

2.7 Sequence Impedances and Sequence Networks

→ (MU – Dec. 15)

Q. 2.7.1 Discuss the sequence network of transformer.
(Refer section 2.7) **Dec. 15, 10 Marks**

- Power system elements transmission line, transformer and synchronous machines have three phase symmetry. Hence when currents of particular sequence are passed through these elements would produce a voltage drop of the some sequence.
- Thus the element possesses only self impedance to sequence currents.
- Therefore each element can be represented by three single phase sequence networks.
- These sequence networks are positive sequence network, negative sequence network and zero sequence network.
- These sequence networks are then interconnected in different ways to represent different unbalanced fault conditions. From this the sequence currents and voltages are calculated which are then converted into actual fault currents and voltages.

Syllabus Topic : Synchronous machine

2.7.1 Sequence Network of Unloaded Generators (Synchronous Machine)

- Unloaded three phase synchronous machine grounded through reactor is shown in Fig. 2.7.1. The three phase induced emfs are E_a, E_b and E_c.
- When a fault takes place at machine terminals current I_a, I_b, and I_c flows in lines. If the fault involves ground then current $I_n = I_a + I_b + I_c$ flows to neutral from ground through Z_n.
- These unbalanced line currents can be resolved into their symmetrical components. I_{a1}, I_{a2} and I_{a0}.
- Before the analysis of unsymmetrical fault, we must know the equivalent sequence network of machine to the flow of positive sequence, negative sequence and zero sequence currents.
- Due to winding symmetry currents of a particular sequence produces voltage drop of that sequence only. Hence there is no coupling between the sequence networks.

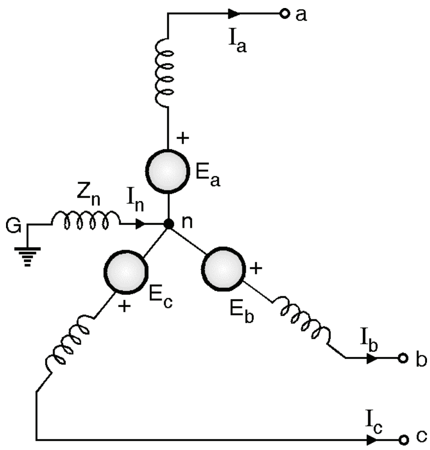


Fig. 2.7.1 : 3 phase synchronous generator with grounded neutral

2.7.2 Positive Sequence Impedance and Network

➔ (MU - May 15)

Q. 2.7.2	Discuss the positive, negative and zero sequence network of a synchronous machine. *(Refer sections 2.7.2, 2.7.3 and 2.7.4)* **May 15, 10 Marks**

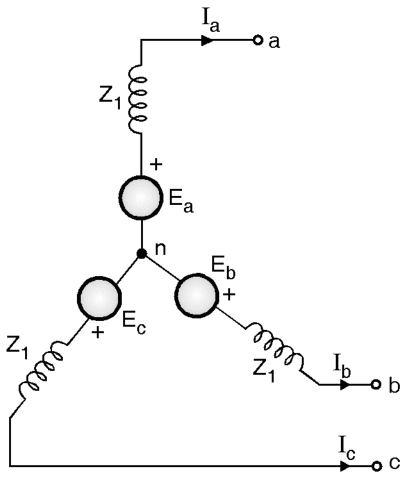
- Synchronous machine is designed with symmetrical windings, it induces emfs of positive sequence only. No negative and zero sequence voltages are induced in it.
- The flow of positive sequence currents produces a armature reaction field. It rotates at synchronous speed in the same direction as rotor.
- So with respect to field excitation it is stationary. The machine offers direct axis reactance.
- It's value reduces from sub transient reactance X_d'' to transient reactance (X_d') and finally to steady state reactance (X_d).
- The positive sequence impedance of the machine neglecting armature resistance is,

$$Z_1 = j X_d'' \text{ (for 1}^{st}\text{ cycle of transient)}$$

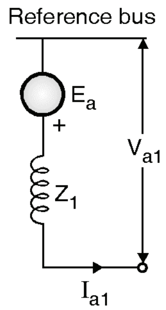
$$Z_1 = j X_d' \text{ (for 3-4 cycle of transient)}$$

$$Z_1 = j X_d \text{ (for steady state value)}$$

- During the short circuit if machine is unloaded the terminal voltage constitute positive sequence voltage. For loaded condition the voltage behind appropriate reactance constitutes the positive sequence voltage.
- Fig. 2.7.2(a) shows three phase model of positive sequence network of synchronous machine. As $I_n = 0$, Z_n does not appear for positive sequence currents.



(a) 3 phase model of positive sequence of synchronous machine



(b) 1 Phase model

Fig. 2.7.2

- As it is balanced network it can be represented by single phase network model as shown in Fig. 2.7.2(b). The reference bus for positive sequence network is at neutral potential.
- The neutral is at ground potential as no current is flowing from ground to neutral.
- The positive sequence voltage of terminal a with respect to reference bus is,

$$V_{a1} = E_a - Z_1 I_{a1}$$

2.7.3 Negative Sequence Impedance and Network

→ (MU - May 15)

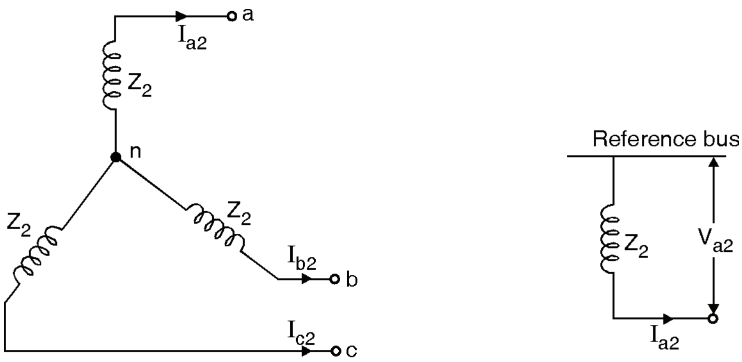
Q. 2.7.3	Discuss the positive, negative and zero sequence network of a synchronous machine. *(Refer sections 2.7.2, 2.7.3 and 2.7.4)* **May 15, 10 Marks**

- Synchronous machine has zero negative sequence induced voltage. The flow of negative sequence currents in the stator produces armature reaction field.
- It rotates in opposite direction to that of the positive sequence field. With respect to rotor it is at double the synchronous speed.
- Hence currents at double the stator frequency are induced in rotor field and damper winding.
- The negative sequence mmf is alternately present with reluctances of direct and quadrature axis which are sweeping over the rotor surface.
- The negative sequence impedance of the machine is,

$$Z_2 = j\frac{X_d'' + X_q''}{2} \; ; |Z_2| < |Z_1|$$

- Three Phase negative sequence model and 1 phase model of synchronous machine are shown in Fig. 2.7.3(a) and 2.7.3(b) respectively. The reference bus is at ground potential.
- The negative sequence voltage of terminal a with respect to reference bus is,

$$V_{a2} = -I_{a2} Z_2 \qquad \text{...(2.7.1)}$$



(a) 3 phase model **(b) 1 phase model**

Fig. 2.7.3 : Negative sequence network of synchronous machine

2.7.4 Zero Sequence Impedance and Network

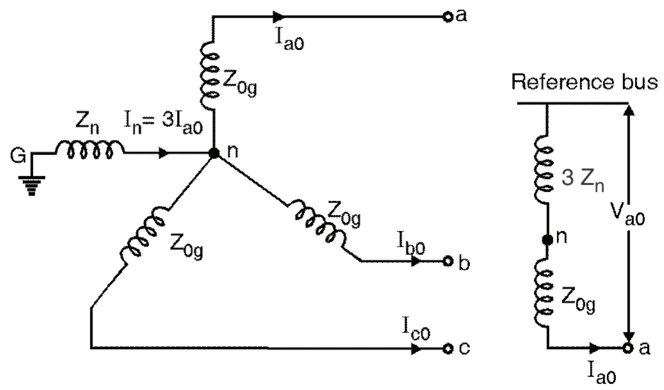
→ (MU - May 15)

Q. 2.7.4	Discuss the positive, negative and zero sequence network of a synchronous machine. *(Refer sections 2.7.2, 2.7.3 and 2.7.4)* **May 15, 10 Marks**

- No zero sequence voltages are induced in synchronous machine.
- The flow of zero sequence currents creates three mmfs which are in time phase but are distributed in space by 120°. Hence the resultant air gap flux is zero.
- Hence the rotor winding presents zero sequence impedance only to zero sequence currents.
- Fig. 2.7.4(a) and 2.7.4(b) shows zero sequence network models on three phase and single phase basis. The current flowing in Z_n is $I_n = 3\,I_{a0}$. Therefore the zero sequence voltage of terminal a with respect to reference bus is,

$$V_{a0} = -3\,Z_n I_{a0} - Z_{0g} I_{a0}$$

$$\therefore \quad V_{a0} = -(3\,Z_n + Z_{0g})\,I_{a0} \qquad \text{...(2.7.2)}$$



(a) 3 phase model **(b) 1 phase model**

Fig. 2.7.4 : Zero sequence networks of synchronous machines

- Z_{0g} is the per phase zero sequence impedance of the machine. The total zero sequence impedance is,

$$Z_0 = 3\ Z_n + Z_{0g}$$

- Hence, the zero sequence voltage of point a with respect to reference bus is,

$$V_{a0} = -Z_0\ I_{a0} \qquad \ldots(2.7.3)$$

2.8 Sequence Impedances of Circuit Elements

- The power system elements are synchronous machine, transformer and transmission line. We have studied the sequence impedances and networks of synchronous machine in previous section.
- Let's study the sequence impedances and networks for transformer and transmission lines.

Syllabus Topic : Sequence Impedance of Transmission Line

2.8.1 Sequence Impedance of Transmission Line

→ (MU - Dec. 16)

Q. 2.8.1 Discuss the sequence network for transmission lines.
(Refer section 2.8.1) **Dec. 16, 10 Marks**

- A three phase transmission line is completely symmetrical as it is fully transposed. Hence the per phase impedance offered by it is independent of the phase sequence of a balanced set of currents.

- The impedance offered by it for positive and negative sequence currents are identical.
- When only zero sequence currents flows in a transmission line, the current in each phase are identical in both magnitude and phase angle. Part of these currents return via ground while the rest return through the overhead ground wires.
- The ground wires are grounded at several towers. The return currents in the ground wires are not necessarily uniform along the entire length.
- The flow of zero sequence currents through the transmission lines, ground wires and ground create a magnetic field pattern.
- This magnetic field is different from that produced by the flow of positive and negative sequence currents.
- The zero sequence impedance of transmission line also accounts for the ground impedance,

$$Z_0 = Z_{l0} + 3\,Z_{g0}$$

- The zero sequence impedance of transmission line usually ranges from 2 to 3.5 times positive sequence impedance.
- Fig. 2.8.1 shows the circuit of fully transposed transmission line carrying unbalanced currents. The return path for I_n is sufficiently away from line. Hence the mutual effect is ignored.

Let X_s = self reactance of each line.

X_m = mutual reactance of any pair of line.

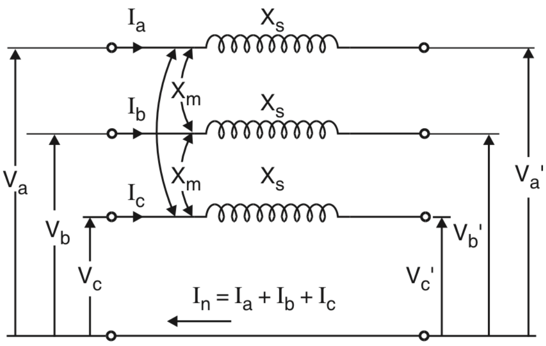


Fig. 2.8.1 : Circuit of fully transposed transmission line

Applying KVL to the circuit shown in Fig. 2.8.1 the following equations can be obtained,

$$V_a - V_a' = j X_s I_a + j X_m I_b + j X_m I_c$$

$$V_b - V_b' = j X_m I_a + j X_s I_b + j X_m I_c$$

$$V_c - V_c' = j X_m I_a + j X_m I_b + j X_s I_c \qquad ...(2.8.1)$$

In matrix form,

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} - \begin{bmatrix} V_a' \\ V_b' \\ V_c' \end{bmatrix} = j \begin{bmatrix} X_s & X_m & X_m \\ X_m & X_s & X_m \\ X_m & X_m & X_s \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \qquad ...(2.8.2)$$

$$V_p - V_p' = X I_p \qquad ...(2.8.3)$$

$$A (V_s - V_s') = A X I_s \qquad ...(2.8.4)$$

$$V_s - V_s' = A^{-1} X A I_s$$

Now,

$$A^{-1} X A = \frac{1}{3} \begin{bmatrix} 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} j X_s & j X_m & j X_m \\ j X_m & j X_s & j X_m \\ j X_m & j X_m & j X_s \end{bmatrix} \begin{bmatrix} 1 & 1 & 1 \\ \alpha^2 & \alpha & 1 \\ \alpha & \alpha^2 & 1 \end{bmatrix} \qquad ...(2.8.5)$$

$$= j \begin{bmatrix} X_s - X_m & 0 & 0 \\ 0 & X_s - X_m & 0 \\ 0 & 0 & X_s + 2X_m \end{bmatrix}$$

Thus Equation (2.8.4) can be written as,

$$\begin{bmatrix} V_1 \\ V_2 \\ V_0 \end{bmatrix} - \begin{bmatrix} V_1' \\ V_2' \\ V_0' \end{bmatrix} = j \begin{bmatrix} X_s - X_m & 0 & 0 \\ 0 & X_s - X_m & 0 \\ 0 & 0 & X_s + 2X_m \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_0 \end{bmatrix} \qquad ...(2.8.6)$$

$$= \begin{bmatrix} Z_1 & 0 & 0 \\ 0 & Z_2 & 0 \\ 0 & 0 & Z_0 \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_0 \end{bmatrix} \qquad ...(2.8.7)$$

Where, $Z_1 = j (X_s - X_m)$ = Positive sequence impedance

$Z_2 = j (X_s - X_m)$ = Negative sequence impedance

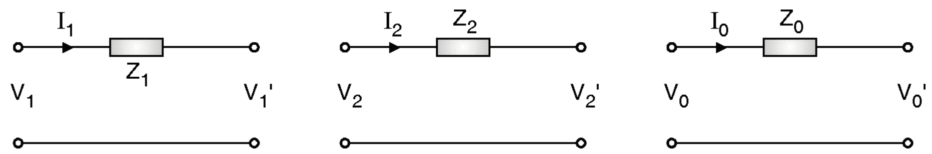
$Z_0 = j (X_s + 2X_m)$ = Zero sequence impedance

- Thus Equation (2.8.7) indicates that a fully transposed transmission line has,

  (i) Equal positive and negative sequence impedances.

(ii) Zero sequence impedance is larger than the positive or negative sequence impedance.

(iii) There is no mutual coupling between the sequence networks. The sequence networks are represented as,



(a) Positive sequence network **(b) Negative sequence network** **(c) Zero sequence network**

Fig. 2.8.2

Syllabus Topic : Sequence Impedances and Sequence Network of Transmission Line, Transformer

2.8.2 Sequence Impedances and Networks of Transformer

- Transformer is a static device. It's leakage impedance does not change with alteration of phase sequence of balanced applied voltage.
- The positive sequence series impedance of transformer is equal to its leakage impedance. The negative sequence impedance is also equal to its leakage impedance.

$$Z_1 = Z_2 = Z \text{ leakage}$$

- The zero sequence impedance of transformer is slightly different than positive and negative sequence impedances.

2.8.3 Zero Sequence Network of Transformer

- Transformers are having different types of connections. The zero sequence networks are different for different types of connections.
- The following observations are made before considering zero sequence networks of various types of transformers.
  (i) When magnetizing current is neglected transformer primary would carry current only if there is current flow on the secondary side.
  (ii) Zero sequence currents can flow in the legs of a star connection only if the star point is grounded. Grounded star point provides the necessary return path for zero sequence currents.
  (iii) No zero sequence current can flow in the lines connected to a delta connection as no current path is available for these currents. However, zero sequence currents can flow in the legs of delta. Such currents are produced due to the presence of zero sequence voltages in delta connection.

Let's now consider various types of transformer connections and their equivalent zero sequence networks.

(i) Y - Y transformer with any one neutral grounded

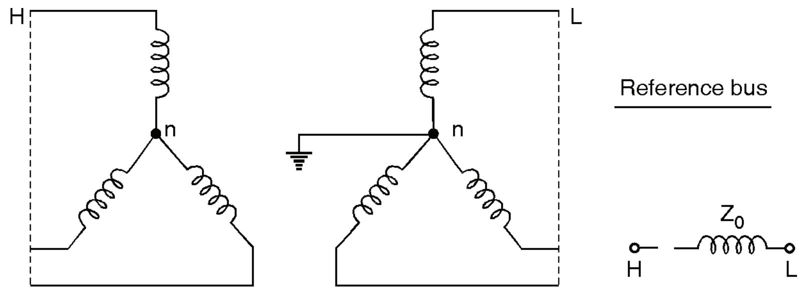


Fig. 2.8.3 : Y-Y transformer with one neutral grounded and its zero sequence network.

- If any one of the two neutrals of Y-Y transformer is ungrounded, zero sequence currents cannot flow in ungrounded star.
- Hence these currents cannot flow in grounded star. Thus open circuit exists in the zero sequence network between H and L.

(ii) Y-Y transformer with both neutral grounded

- When neutrals of both the windings are grounded, a path for the flow of zero sequence currents in the both windings exist via two grounded neutrals.
- Hence in the zero sequence network H and L is connected by zero sequence impedance of transformer.

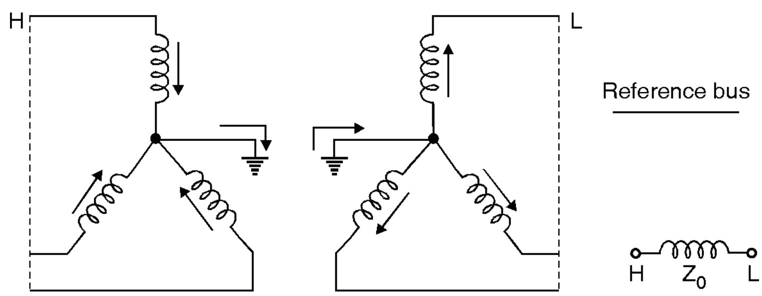


Fig. 2.8.4 : Y-Y transformer with both neutrals grounded and it's zero sequence network

(iii) Y - Δ transformer with grounded Y neutral

- The neutral of star side is grounded. Hence the zero sequence currents can flow in star because a path is available to ground.
- Balancing zero sequence current can flow in delta but no currents can flow through the lines connected to delta.
- Therefore the zero sequence network have a path from the line H on star side through zero sequence impedance of transformer to reference bus but an open circuit exists on the line L on delta side.
- If star neutral grounded through Z_n an impedance $3Z_n$ appears in series with Z_0 in zero sequence network.

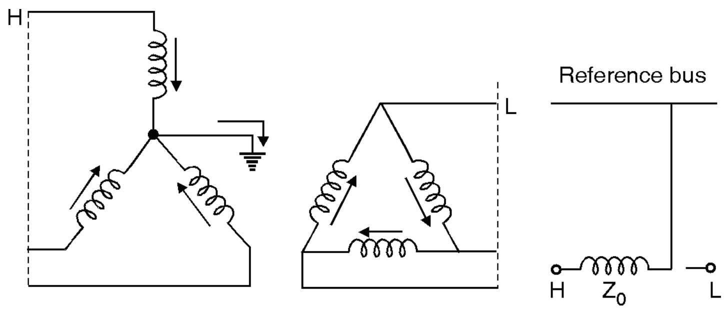


Fig. 2.8.5 : Y - Δ transformer with grounded star and it's zero sequence network

(iv) Y- Δ transformer with ungrounded star

- This is a special case of case (iii). The neutral of Y connected winding is ungrounded i.e. $Z_n = \infty$.
- Therefore no zero sequence current can flow in the transformer windings. The zero sequence network is as shown in Fig. 2.8.6.

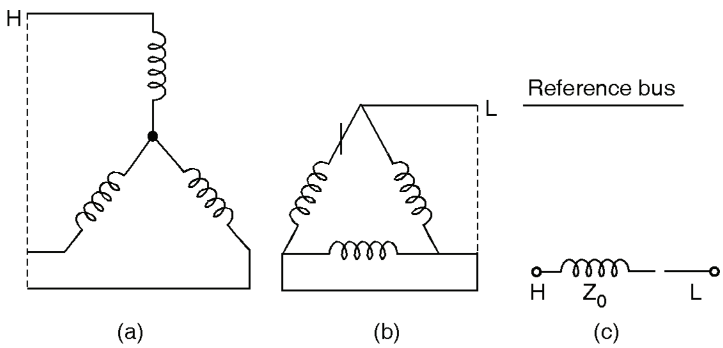


Fig. 2.8.6 : Y - Δ transformer with ungrounded neutral and it's zero sequence network

(v) Δ - Δ transformer

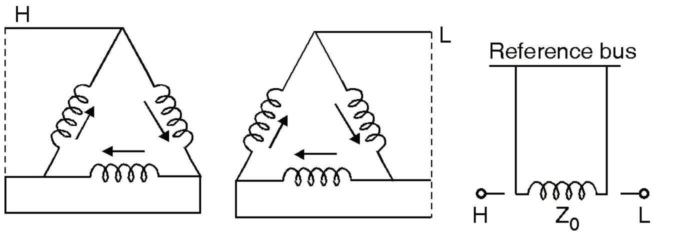


Fig. 2.8.7 : Δ - Δ transformer and it's zero sequence network

- Delta connected windings provides no return path. Hence zero sequence currents cannot flow in or out of Δ - Δ transformer.
- But these currents can circulate in the delta windings. Such circulating currents would exist only if the zero sequence voltages are somehow induced in either delta winding.
- Hence Z_0 is connected to reference bus on both ends to account for circulating zero sequence currents in two deltas and open circuit exists between H and L.

Syllabus Topic : Construction of Sequence Network Power System

2.9 Construction of Sequence Network Power System

This part is covered in (section 3.5).

2.10 Problems on Symmetrical Components

Ex. 2.10.1

A delta connected balanced resistive load is connected across an unbalanced three phase supply. The current in line A and B are 10 ∠ 30° and 15 ∠ – 60° respectively. Find current in line C. Find Symmetrical components of phase currents flowing in individual resistances of the delta connected load.

Soln. :

For a balanced systems,

$$I_a + I_b + I_c = 0$$

$$\therefore \quad I_c = -I_a - I_b$$

$$\therefore \quad I_c = -10 \angle 30° - 15 \angle -60°$$

$$\therefore \quad I_c = -16.16 + j\,7.99$$

$$= 18.02 \angle -26.3° \text{ A}$$

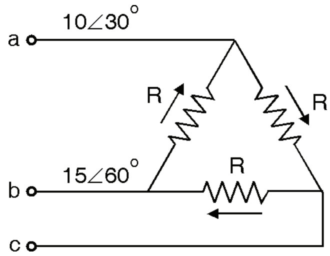


Fig. P. 2.10.1

Phase currents are obtained as,

$$I_{ab} = \frac{1}{3}(I_a - I_b) = \frac{1}{3}(10 \angle 30° - 15 \angle -60°)$$

$$= \frac{1}{3}(1.16 - j\,2.01)$$

$$= 0.77 \angle 60°1° \text{ A}$$

$$I_{bc} = \frac{1}{3}(I_b - I_c) = \frac{1}{3}(15 \angle -60° - 18.02 \angle -26.3°)$$

$$= \frac{1}{3}(-8.66 - j\,5.01)$$

$$= 3.33 \angle 30° \text{ A}$$

$$I_{ca} = \frac{1}{3}(I_c - I_a) = \frac{1}{3}(18.02 \angle -26° - 10 \angle 30°)$$

$$= \frac{1}{3}(7.53 - j\,2.88)$$

$$= 2.69 \angle -20.9° \text{ A}$$

= The symmetrical component of phase currents can be obtained as,

$$\begin{bmatrix} I_{ab0} \\ I_{ab1} \\ I_{ab2} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix}\begin{bmatrix} I_{ab} \\ I_{bc} \\ I_{ca} \end{bmatrix}$$

$$I_{ab0} = \frac{1}{3}[0.77 \angle 60 + 3.33 \angle 30 + 2.69 \angle -20.9]$$

$$= \frac{1}{3}[5.775 + j\,0.876]$$

$$= 1.95 \angle 8.62° \text{ A}$$

$$I_{ab1} = \frac{1}{3}[0.77 \angle 60 + 3.33 \angle 30 \times 1 \angle 120 + 2.69 \angle -20.9 \times 1 \angle -120]$$

$$= \frac{1}{3}[0.77 \angle 60 + 3.33 \angle 150 + 2.69 \angle -140.9]$$

$$= \frac{1}{3}[-4.575 - j\,0.691]$$

$$= 1.54 \angle 8.59° \text{ A}$$

$$I_{ab2} = \frac{1}{3}[0.77 \angle 60 + 3.33 \angle 30 \times 1 \angle -120° + 2.69 \angle -20.9 \times 1 \angle 120]$$

$$= \frac{1}{3}[0.77 \angle 60 + 3.33 \angle -90° + 2.69 \angle 99.1°]$$

$$= \frac{1}{3}[-0.04 - j\,5.32]$$

$$= 1.77 \angle 89.56° \text{ A}$$

$$I_{ab0} = I_{bc0} = I_{ca0} = 1.95 \angle 8.62° \text{ A}$$

Considering I_{ab1} as reference,

$$I_{bc1} = \alpha^2 I_{ab1}$$
$$= 1 \angle -120 \times 1.54 \angle 8.59°$$
$$= 1.54 \angle -111.4° \text{ A}$$
$$I_{ca1} = \alpha I_{ab1}$$
$$= 1 \angle 120° \times 1.54 \angle 8.59$$
$$= 1.54 \angle 128.59° \text{ A}$$

Considering I_{ab2} as reference,

$$I_{bc2} = \alpha I_{ab2}$$
$$= 1 \angle 120 \times 1.77 \angle 89.56°$$
$$= 1.77 \angle 209.56° \text{ A}$$
$$I_{ca2} = \alpha^2 I_{ab2}$$
$$= 1 \angle -120° \times 1.77 \angle 89.56°$$
$$= 1.77 \angle -30.44° \text{ A}$$

Ex. 2.10.2

One conductor of a three phase line is open. The current flowing to the Δ connected load through line "a" is 10 A. With the current in line "a" as reference and assuming that line "c" is open, find the symmetrical components of the line currents.

Soln. :

$$I_a = 10 \text{ A.}$$

as line c is open,

$$I_c = 0$$
$$I_a + I_b + I_c = 0$$
$$\therefore \quad I_b = -10 \text{ A.}$$

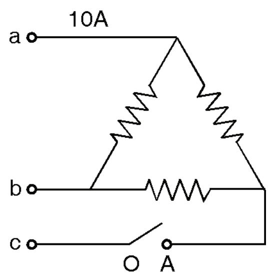


Fig. P. 2.10.2

The symmetrical components of these line currents are,

$$\begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

$$\begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 \angle 120 & 1 \angle -120° \\ 1 & 1 \angle -120° & 1 \angle 120° \end{bmatrix} \begin{bmatrix} 10 \\ -10 \\ 0 \end{bmatrix}$$

$$\therefore \quad I_{a0} = \frac{1}{3}\ [\ 10 - 10\ ] = 0$$

$$\therefore \quad I_{a1} = \frac{1}{3}\ [\ 10 - 10 \times\ 1\ \angle 120°] = \frac{1}{3}\ [\ 10 - (-\ 5 + j\ 8.66)\ ]$$

$$= \frac{1}{3}\ (\ 15 - j\ 8.66) = 5.67\ \angle -30°\ \text{A.}$$

$$I_{a2} = \frac{1}{3}\ [\ 10 - 10 \times 1\ \angle 120°\ ]$$

$$= \frac{1}{3}\ [\ 10 - 10\ \angle -120°\ ]$$

$$= \frac{1}{3}\ [\ 10 - (\ -5 - j\ 8.66)\ ]$$

$$= \frac{1}{3}\ [\ 15 + j\ 8.66] = 5.67\ \angle\ 30°\ \text{A.}$$

Ex. 2.10.3

The Voltage across a 3-phase unbalanced load are $V_a = 200\angle 40°$, $V_b = 320\ \angle\ 90°$, $V_c = 480\angle\ 340°$. Determine the symmetrical components of voltage. Phase sequence is abc.

Soln. :

Symmetrical components of voltages are,

$$\begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

$$\begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\ \angle\ 120 & 1\ \angle -120° \\ 1 & 1\ \angle -120° & 1\ \angle\ 120° \end{bmatrix} \begin{bmatrix} 200\ \angle\ 40° \\ 320\ \angle\ 90° \\ 480\ \angle\ 340° \end{bmatrix}$$

$$\therefore \quad V_{a0} = \frac{1}{3}\ [\ 200\ \angle\ 40° + 320\ \angle\ 90° + 480\ \angle\ 340°]$$

$$= \frac{1}{3}\ [\ 604.2 + j\ 284.4]$$

$$= 222.6\ \angle\ 25.2°\ \text{volts}$$

$$\therefore \quad V_{a1} = \frac{1}{3}\ [\ 200\ \angle\ 40° + 320\ \angle\ 210° + 480\ \angle\ 220°]$$

$$= \frac{1}{3}\ [-491.6 - j\ 339.9]$$

$$= 199.2\ \angle -145.3°\ \text{volts}$$

$$\therefore \quad V_{a2} = \frac{1}{3}\,[\,200\angle 40° + 320\angle -30° + 480\angle 100°]$$

$$= \frac{1}{3}\,[\,346.98 - j\,441.3]$$

$$= 187.12\angle\ 51.82° \text{ volts}$$

Ex. 2.10.4

The currents in three phase unbalanced system are I_R = (12 + j6) A. I_Y = (12 – j12) A, I_B = (–15 + j10) A. The phase sequence is RYB. Calculate positive, negative and zero sequence component of current.

Soln. :

Sequence component of current are,

$$\begin{bmatrix} I_{R0} \\ I_{R1} \\ I_{R2} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix}\begin{bmatrix} I_R \\ I_Y \\ I_B \end{bmatrix}$$

$$I_R = 12 + j\,6 = 13.42\angle 26.6° \text{ A.}$$

$$I_Y = 12 - j\,12 = 17\angle -45° \text{ A.}$$

$$I_R = -15 + j\,10 = 18\angle -33.69° \text{ A.}$$

$$\begin{bmatrix} I_{R0} \\ I_{R1} \\ I_{R2} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\angle 120° & 1\angle -120° \\ 1 & 1\angle -120° & 1\angle 120° \end{bmatrix}\begin{bmatrix} 13.42\angle 26.6° \\ 17\angle -45° \\ 18\angle -33.69° \end{bmatrix}$$

$$I_{R0} = \frac{1}{3}[\,13.42\angle 26.6° + 17\angle -45° + 18\angle -33.69°\,]$$

$$= \frac{1}{3}\,[\,9 + j4\,]\ =\ 3.28\angle 24° \text{ A.}$$

$$\therefore \quad I_{R1} = \frac{1}{3}\,[\,13.42\angle 26.6° + 17\angle 75° + 18\angle -153.69°]$$

$$= \frac{1}{3}\,[\,0.4 - j\,14.43] = 4.81\angle -88.41° \text{ A.}$$

$$\therefore \quad I_{R2} = \frac{1}{3}\,[\,13.42\angle 26.6° + 17\angle -165° + 18\angle 86.31°]$$

$$= \frac{1}{3}\,[\,-3.26 + j\,19.6\,]$$

$$= 6.62\angle -81° \text{ A.}$$

$$\therefore \quad I_{R0} = I_{Y0} = I_{B0} = 3.28\angle 24°$$

I_{R1} is considered as reference

$$\therefore \quad I_{Y1} = \alpha^2 I_{R1}$$

$$= 1 \angle 120° \times 4.81 \angle -88.41° = 4.81 \angle -208.41° \text{ A.}$$

$$\therefore \quad I_{B1} = \alpha I_{R1} = 1 \angle 120° \times 4.81 \angle -88.41°$$

$$= 4.81 \angle 31.59° \text{ A.}$$

Considering I_{R2} as reference,

$$\therefore \quad I_{Y2} = \alpha I_{R2} = 1 \angle -120° \times 6.62 \angle -81° = 6.62 \angle 39° \text{ A.}$$

and

$$\therefore \quad I_{B2} = \alpha^2 I_{R2}$$

$$= 1 \angle -120° \times 6.62 \angle -81° = 6.62 \angle -201° \text{ A.}$$

Ex. 2.10.5 **May 16, 10 Marks**

Fig. P. 2.10.5 shows power system network. Draw zero sequence networks for this system. The system data is

Generator (G_1) : 50 MVA, 11 kV, $X_0 = 0.08$ p.u.

Transformer (T_1) : 50 MVA, 11/220 kV, $X_0 = 0.1$ p.u.

Generator (G_2) : 30 MVA, 11 kV, $X_0 = 0.07$ p.u.

Transformer (T_2) : 30 MVA, 220/11 kV, $X_0 = 0.09$ p.u.

Zero sequence reactance of line is 555.6 Ω.

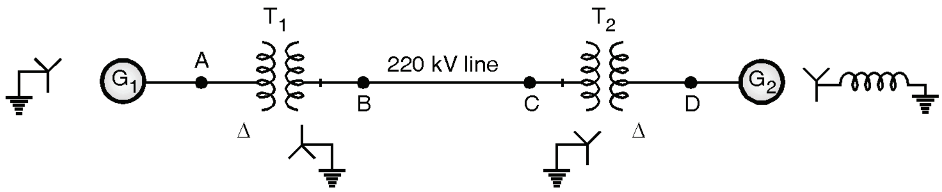


Fig. P. 2.10.5

Soln. :

Base MVA = 50 MVA

Base kV = 11 kV

(i) X_0 for G_1 = 0.08 p.u.

(ii) $$X_0 \text{ for } T_1 = 0.1 \times \frac{50}{50} \times \frac{11^2}{11^2} = 0.1 \text{ p.u.}$$

(iii) $$X_0 \text{ for } G_2 = 0.07 \times \frac{50}{30} \times \frac{11^2}{11^2} = 0.117 \text{ p.u.}$$

(iv) X_0 for $T_2 = 0.09 \times \dfrac{50}{30} \times \dfrac{11^2}{11^2} = 0.15$ p.u.

(v) For transmission line $= \dfrac{555.6 \times 50}{220^2} = 0.574$ p.u.

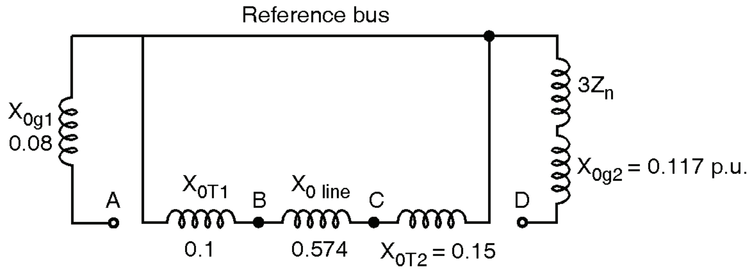


Fig. P. 2.10.5(a)

Ex. 2.10.6

Fig. P. 2.10.6 shows a power system network. Draw positive, negative and zero sequence networks. The system data is as follow :

Equipment	MVA Rating	Voltage Rating	X_1	X_2	X_0
Generator G_1	100	11 kV	0.25 p.u.	0.25 p.u.	0.05 p.u.
Generator G_2	100	11 kV	0.2 p.u.	0.2 p.u.	0.05 p.u.
Transformer T_1	100	11/220 kV	0.06 p.u.	0.06 p.u.	0.06 p.u.
Transformer T_2	100	11/220 kV	0.07 p.u.	0.07 p.u.	0.07 p.u.
Line 1	100	220 kV	48.4 Ω	48.4 Ω	145.2 Ω
Line 2	100	220 kV	48.4 Ω	48.4 Ω	145.2 Ω

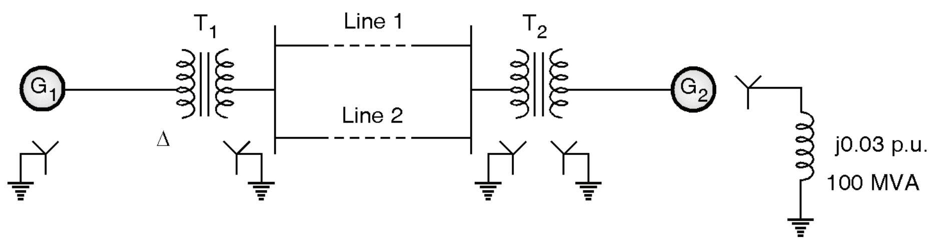


Fig. P. 2.10.6

Soln. :

The positive, negative and zero sequence reactances of all components are specified for their ratings except lines. Keeping it as it is and considering 100 MVA as base and 220 as base for line we can find X_1, X_2 and X_0 for lines.

$$\therefore \quad X_1, \text{line 1} = \frac{48.4 \times 100}{220^2} = 0.1$$

$$X_2, \text{line 1} = 0.1$$

$$X_1, \text{line 2} = 0.1$$

$$X_2, \text{line 2} = 0.1$$

$$X_0, \text{line 1} = \frac{145.2 \times 100}{220^2} = 0.3 = X_0, \text{line 2}$$

Positive sequence network

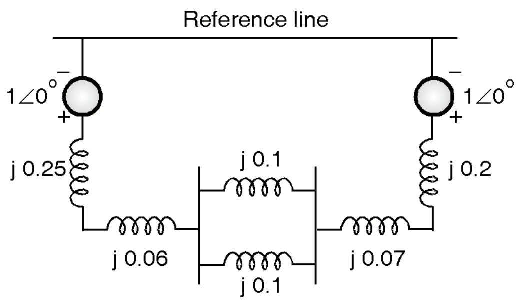


Fig. P. 2.10.6(a)

Negative sequence network

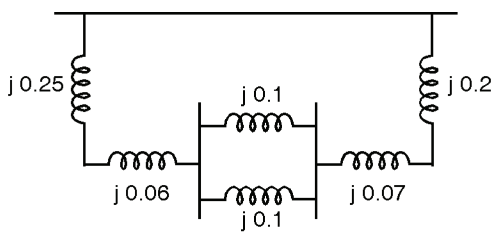


Fig. P. 2.10.6(b)

Zero sequence network

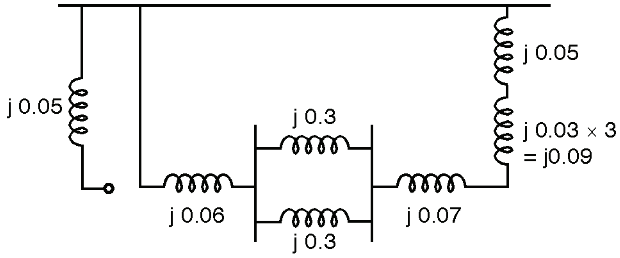


Fig. P.2.10.6(c)

Ex. 2.10.7 MU - May 15, 10 Marks

The line current in amperes in phases a, b, c respectively are (500 + j150), (100 – j600) and (–300 + j600). Determine the symmetrical components of current.

Soln. :

Symmetrical component of line currents are,

$$\begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix}\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

$$I_a = 500 + j150 = 522 \angle 16.7°A$$

$$I_b = 100 - j600 = 608.27 \angle -80.54°A$$

$$I_c = -300 + j600 = 670.8 \angle 111.56°A$$

$$\begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 \angle 120° & 1 \angle -120° \\ 1 & 1 \angle -120° & 1 \angle 120° \end{bmatrix}\begin{bmatrix} 522 \angle 16.7° \\ 608.27 \angle -80.54° \\ 670.8 \angle 116.56° \end{bmatrix}$$

$$I_{a0} = \frac{1}{3}[\,522 \angle 16.7 + 608.27 \angle -80.54 + 670.8 \angle 116.56^\circ\,]$$

$$= \frac{1}{3}[\,300 + j150\,] = 111.8 \angle 26.56° \text{ Amp.}$$

$$I_{a1} = \frac{1}{3}[\,522 \angle 16.7 + 608.27 \angle 39.46 + 670.8 \angle -3.44^\circ\,]$$

$$= \frac{1}{3}[\,1661.19 + j13.03\,] = 553.73 \angle 4.34° \text{ Amp.}$$

$$I_{a2} = \frac{1}{3}[\,522 \angle 16.7 + 608.27 \angle -200.54 + 670.8 \angle 236.56^\circ\,]$$

$$= \frac{1}{3}[\,-438.81 - j195.69\,]$$

$$= -160.15 \angle -155.96° \text{ Amp.}$$

Ex. 2.10.8 **MU - May 17, 10 Marks**

Determine the symmetrical component of currents in a 3 phase system, the original phasor of which are $I_R = 12 + j6$, $I_Y = 12 - j12$, $I_B = -15 + j10$.

Soln. :

Sequence component of current are,

$$\begin{bmatrix} I_{R0} \\ I_{R1} \\ I_{R2} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix}\begin{bmatrix} I_R \\ I_Y \\ I_B \end{bmatrix}$$

$$I_R = 12 + j\,6 = 13.42 \angle 26.6° \text{ A.}$$

$$I_Y = 12 - j\,12 = 17 \angle -45° \text{ A.}$$

$$I_B = -15 + j\,10 = 18 \angle -33.69° \text{ A.}$$

$$\begin{bmatrix} I_{R0} \\ I_{R1} \\ I_{R2} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\angle 120° & 1\angle -120° \\ 1 & 1\angle -120° & 1\angle 120° \end{bmatrix}\begin{bmatrix} 13.42 \angle 26.6° \\ 17 \angle -45° \\ 18 \angle -33.69° \end{bmatrix}$$

$$I_{R0} = \frac{1}{3}[\,13.42 \angle 26.6° + 17 \angle -45° + 18 \angle -33.69°\,]$$

$$= \frac{1}{3}[\,9 + j4\,] = 3.28 \angle 24° \text{ A.}$$

$$\therefore \quad I_{R1} = \frac{1}{3}[\,13.42 \angle 26.6° + 17 \angle 75° + 18 \angle -153.69°]$$

$$= \frac{1}{3}[\,0.4 - j\,14.43] = 4.81 \angle -88.41° \text{ A.}$$

$$\therefore \quad I_{R2} = \frac{1}{3}[\,13.42 \angle 26.6° + 17 \angle -165° + 18 \angle 86.31°]$$

$$= \frac{1}{3}[\,-3.26 + j\,19.6\,] = 6.62 \angle -81° \text{ A.}$$

$$\therefore \quad I_{R0} = I_{Y0} = I_{B0} = 3.28 \angle 24°$$

I_{R1} is considered as reference

$$\therefore \quad I_{Y1} = \alpha^2 I_{R1} = 1 \angle 120° \times 4.81 \angle -88.41°$$

$$= 4.81 \angle -208.41° \text{ A.}$$

$$\therefore \quad I_{B1} = \alpha I_{R1}$$

$$= 1 \angle 120° \times 4.81 \angle -88.41°$$

$$= 4.81 \angle 31.59° \text{ A.}$$

Considering I_{R2} as reference,

$$\therefore \quad I_{Y2} = \alpha I_{R2}$$

$$= 1 \angle -120° \times 6.62\angle -81°$$

$$= 6.62 \angle 39° \text{ A.}$$

and $\therefore \quad I_{B2} = \alpha^2 I_{R2}$

$$= 1 \angle -120° \times 6.62\angle -81°$$

$$= 6.62 \angle -201° \text{ A.}$$

2.10.1 Various Factors to be Considered While Constructing the Sequence Networks

The following factors should be considered while constructing the sequence networks.

(i) In a three phase unfaulted system with all loads balanced and in which the generator produces positive sequence voltages, only positive sequence currents flows. It results in balanced voltage drops of the same sequence. There are no negative sequence or zero sequence voltage drops.

(ii) In symmetrical systems, the currents and voltages of different sequences do not affect each other i.e. positive sequence currents produce only positive sequence voltage drops. By the same analogy, the negative sequence currents produces only negative sequence drops and zero sequence currents produce only zero sequence drops.

(iii) Negative and zero sequence currents are set up in circuits with unbalanced impedances only positive sequence currents flowing in an unbalanced system produce positive, negative and zero sequence voltage drops. The negative sequence currents flowing in an unbalanced system produce voltage drops of all three sequences. Same is true about zero sequence currents.

(iv) In a 3-phase 3 wire system, no zero sequence currents appear in the line conductor as there is no path for the zero sequence currents to flow.

In a 3 ph 4 wire system with neutral return, the neutral must carry unbalanced current. Therefore, it follows that $I_n = 3I_0$. At the grounded neutral of 3 phase wire system, positive and negative sequence voltages are zero. The neutral voltage is equal to the zero sequence voltage or $3I_0 Z_n$.

(v) In relation with point 4 above, phase conductors coming from undergrounded wire or delta connected transformer windings cannot have zero sequence current. In a delta winding, zero sequence currents if present produces circulating currents in the delta winding itself, as delta winding forms a closed path of low impedance for the zero sequence currents.

2.11 Difference between Symmetrical and Unsymmetrical Fault

→ **(MU - May 16)**

Q. 2.11.1 What is the difference between symmetrical and unsymmetrical fault. (Refer section 2.11) **May 16, 5 Marks**

Sr. No.	Symmetrical faults	Unsymmetrical faults
1.	In such faults all the phases are short circuited to each other and often to earth.	These faults involves only one or two phases. In such faults the three phase lines becomes unbalanced.
2.	Such types of faults are known as balanced faults as the system remain symmetrical	Such types of faults occurs between line to ground or between lines.
3.	These are the most severe type of fault as it involves largest current. But these types of faults occur rarely. Hence balanced short circuit calculation is performed to determine these fault currents.	These faults are : Single line to ground faults (LG); Line to line faults (LL); Double line to ground fault (LLG). As the system becomes unbalanced after occurrence of these faults, a symmetrical component method is used to determine fault current.

Exercise

Q. 1 Write a brief note on phase shift of symmetrical component in Y-Δ transformer banks. **(Section 2.5)** **(8 Marks)**

Q. 2 Write a note on zero sequence networks in brief. **(Sections 2.2, 2.7.4 and 2.8.3)** **(8 Marks)**

Q. 3 Describe how one can obtain symmetrical components of a given set of unbalanced three phasors of a three phase system. State in which direction the set of negative phasor rotate at time increases. State the frequency of zero sequence phasors. Describe the application of symmetrical components. **(Section 2.4)** **(10 Marks)**

Q. 4 Explain the zero sequence impedance of transformer for various connections. **(Section 2.8.3)** **(10 Marks)**

Q. 5 Obtain the expression for zero, positive and negative sequence reactances for fully transposed transmission lines with self impedance z_s and mutual impedance z_m.

(Section 2.7) **(10 Marks)**

Q. 6 Obtain the expression for 3 phase power in terms of sequence components.

(Section 2.6) **(10 Marks)**

2.12 University Questions and Answers

➔ May 2015

Q. 2(b) The line current in amperes in phases a, b, c respectively are (500 + j150), (100 – j600) and (–300 + j600). Determine the symmetrical components of current.

(Ans. : Refer Example 2.10.7) **(10 Marks)**

Q. 5(b) Discuss the positive, negative and zero sequence network of a synchronous machine

(Ans. : Refer sections 2.7.2, 2.7.3 and 2.7.4) **(10 Marks)**

➔ Dec. 2015

Q. 3(b) Discuss the sequence network of transformer.

(Ans. : Refer sections 2.7 and 2.7.1) **(10 Marks)**

➔ May 2016

Q. 1(a) What is the difference between symmetrical and unsymmetrical fault ?

(Ans. : Refer section 2.11) **(5 Marks)**

Q. 3(b) For a Fig. 1-Q. 3(b) draw the zero sequence network. The data for the system is

Generator G_1- 50 MVA, 11 KV, X_o = 0.08 pu

Transformer T_1 50 MVA ,11/220 KV, X_o = 0.1 pu

Generator G_2- 30 MVA, 11KV, X_o = 0.07 pu

Transformer T_2 30 MVA ,11/220 KV, X_o = 0.09 pu **(10 Marks)**

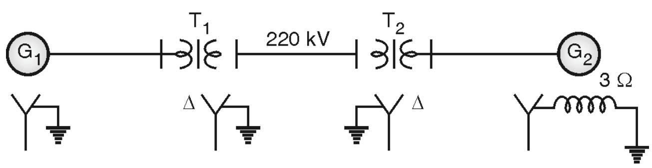


Fig. 1-Q. 3(b)

(Ans. : Refer Example 2.10.5)

➔ Dec. 2016

Q. 1(a) What is power invariance in unsymmetrical fault analysis. **(5 Marks)**

(Ans. : Refer section 2.6)

Q. 3(b) Discuss the sequence network for transmission lines.

(Ans. : Refer section 2.8.1) **(10 Marks)**

Q. 6(b) Discuss the various factors to be considered while constructing the sequence network of power system. **(10 Marks)**

(Ans. : Refer section 2.10.1)

➔ May 2017

Q. 3(b) Determine the symmetrical component of currents in a 3 phase system, the original phasor of which are $I_R = 12 + j6$, $I_Y = 12 - j12$, $I_B = -15 + j10$. **(10 Marks)**

(Ans. : Refer Example 2.10.8)

Chapter Ends...

❑❑❑

CHAPTER

3

Unsymmetrical Fault Analysis

Syllabus :

Types of unsymmetrical faults, Analysis of shunt type unsymmetrical faults : single line to ground (SLG) fault, line to line (L-L) fault, double line to ground (LLG) fault, bus impedance matrix method for analysis of shunt type unsymmetrical faults. Analysis of series type unsymmetrical faults : one open conductor faults, two open conductor fault.

Syllabus Topic : Types of Unsymmetrical Faults

3.1 Introduction of Unsymmetrical Faults (Types)

- In the previous section 2.1 we have studied symmetrical component method used for analysis of unsymmetrical faults.
- Also we have studied sequence components and sequence networks for power system elements. In this chapter we shall study unsymmetrical faults.
- The various types of unsymmetrical faults occurring in power system are,

  Shunt faults : (i) Single Line to Ground fault (LG)

  (ii) Line to Line fault (LL)

  (iii) Double Line to Ground fault (LLG)

  Series faults : (i) Open conductor fault (one or two conductor open)
- Three phase short circuit fault is rare but severe fault.
- These faults are analyzed to find rupturing capacity of circuit breakers.
- The unsymmetrical faults listed above occurs frequently in power system. In some situations the fault current of LG fault is more than three phase fault. These faults are analyzed for deciding relay setting and study of system stability.
- The method of symmetrical component is used to analyze unsymmetrical faults. In this chapter we will study how this tool is used for unsymmetrical faults analysis.

Syllabus Topic : Analysis of Shunt Type Unsymmetrical Faults : Single Line to Ground (SLG) Fault

3.2 Single Line to Ground (SLG) Fault on Unloaded Generator

→ (MU - May 16)

Q. 3.2.1 Derive the equation for fault current for LG fault.
(Refer section 3.2) **May 16, 10 Marks**

– Fig. 3.2.1 shows a solidly grounded unloaded generator. Let the fault takes place on phase a. At the fault point F, the current out of the power system and line to ground voltages are :

$$V_a = 0$$
$$I_b = 0$$
$$I_c = 0$$

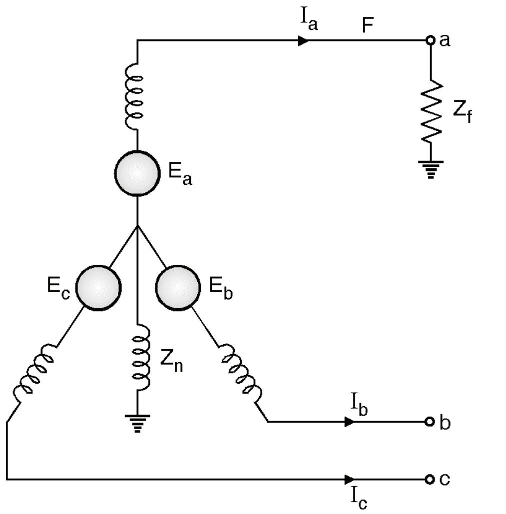


Fig. 3.2.1 : Unloaded generator : LG fault on phase a

– The symmetrical components of fault current are,

$$\begin{bmatrix} I_{a1} \\ I_{a2} \\ I_{a0} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \\ 1 & 1 & 1 \end{bmatrix}\begin{bmatrix} I_a \\ 0 \\ 0 \end{bmatrix}$$

$$I_{a1} = I_{a2} = I_{a0} = \frac{1}{3} I_a \quad \text{...(3.2.1)}$$

– The sequence network equations are,

$$V_{a0} = -I_{a0}(Z_0 + 3Z_n) \quad \text{...(3.2.2)}$$
$$V_{a1} = E_a - I_{a1}Z_1 \quad \text{...(3.2.3)}$$
$$V_{a2} = -I_{a2}Z_2 \quad \text{...(3.2.4)}$$

– Faulty phase voltage V_a can be written in terms of symmetrical components as,

$$V_a = I_a Z_f$$
$$V_{a1} + V_{a2} + V_{a0} = 3 I_{a1} Z_f \quad \text{...(3.2.5)}$$

– Substituting values of V_{a0}, V_{a1} and V_{a2} from Equations (3.2.2) and (3.2.3)

$$E_a - I_{a1} Z_1 - I_{a2} Z_2 - I_{a0} (Z_0 + 3 Z_n) = 3 I_{a1} Z_f$$

$$\therefore \quad I_{a1} = \frac{E}{Z_1 + Z_2 + (Z_0 + 3Z_n) + 3 Z_f} \qquad \text{...(3.2.6)}$$

- Equations (3.2.6) and (3.2.1) indicates that for the analysis of line to ground fault all the three sequence networks are required.
- All the sequence currents are equal in magnitude and phase angle, the three sequence networks must be connected in series. The interconnection of the sequence network is shown in Fig. 3.2.2.
- We have calculated $I_{a1} = I_{a2} = I_{a0}$. To calculate remaining three unknown V_{a0}, V_{a1}, V_{a2}, sequence network equations are used, we know that

$$\begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{bmatrix} = \begin{bmatrix} 0 \\ E_a \\ 0 \end{bmatrix} - \begin{bmatrix} Z_0 & 0 & 0 \\ 0 & Z_1 & 0 \\ 0 & 0 & Z_2 \end{bmatrix} \begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{bmatrix} \qquad \text{...(3.2.7)}$$

Substituting Equation (3.2.1) in Equation (3.2.7)

$$\begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{bmatrix} = \begin{bmatrix} 0 \\ E_a \\ 0 \end{bmatrix} - \begin{bmatrix} Z_0 & 0 & 0 \\ 0 & Z_1 & 0 \\ 0 & 0 & Z_2 \end{bmatrix} \begin{bmatrix} I_{a1} \\ I_{a1} \\ I_{a1} \end{bmatrix}$$

$$= \begin{bmatrix} 0 \\ E_a \\ 0 \end{bmatrix} - \begin{bmatrix} I_{a1} & Z_0 \\ I_{a1} & Z_1 \\ I_a & Z_2 \end{bmatrix}$$

$$\begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{bmatrix} = \begin{bmatrix} - I_{a1}Z_0 \\ E_a - I_{a1} Z_1 \\ - I_{a1} Z_2 \end{bmatrix}$$

$$\therefore \quad V_{a0} + V_{a1} + V_{a2} = 0 = -I_{a1} Z_0 + E_a - I_{a1}Z_1 - I_{a1}Z_1$$

$$\therefore \quad I_{a1} = \frac{E_a}{Z_1 + Z_2 + Z_0 + 3Z_n + 3 Z_f} \quad (\because \; Z_0 = (Z_0 + 3Z_n) + 3Z_f)$$

$$\text{...(3.2.8)}$$

- In Line to Ground (LG) fault the neutral current,

$$I_n = I_a = I_{a1} + I_{a2} + I_{a0}$$

$$I_n = 3 I_{a0} \qquad (\because \; I_{a0} = I_{a2} = I_{a0})$$

- If neutral is not grounded the zero sequence impedance Z_o becomes infinite and fault impedance Z_f is zero.

$$I_{a1} = \frac{E_a}{Z_1 + Z_2 + \infty} = 0 \qquad ...(3.2.9)$$

- The same result can be obtained if the system has isolated neutral. There is no return path for the current. Hence $I_{a1} = I_{a2} = I_{a0} = 0$.
- It indicates that for this system the fault current $I_a = 0$.

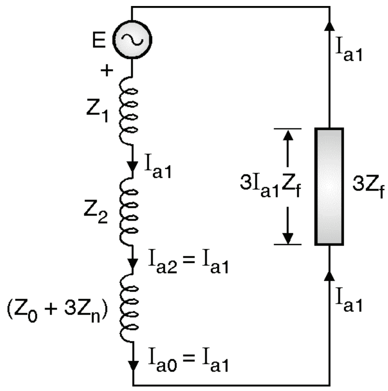


Fig. 3.2.2 : Interconnection of sequence networks for LG fault

Syllabus Topic : Analysis of Shunt Type Unsymmetrical Faults : Line to Line (L-L) Fault

3.3 Line to Line Fault on Unloaded Alternator (LL)

➔ (MU - Dec. 16, May 17)

Q. 3.3.1	Derive the equation for fault current for LL fault. *(Refer section 3.3)*	**Dec. 16, 10 Marks**
Q. 3.3.2	Discuss L-L fault in detail. *(Refer section 3.3)*	**May 17, 10 Marks**

- Consider a unloaded generator as shown in Fig. 3.3.1. Let's consider that a line to line fault occurs between terminals b and c through fault impedance Z_f. The current and voltages after occurrence of fault are,

$$I_a = 0$$
$$I_b, I_c = -I_b$$
$$V_b - V_c = I_b Z_f \qquad ...(3.3.1)$$

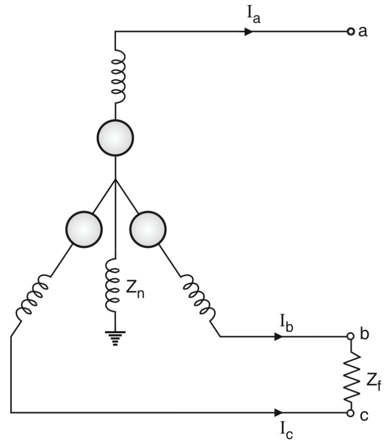


Fig. 3.3.1 : Unloaded generator LL fault

– The symmetrical components of fault current are,

$$\begin{bmatrix} I_{a1} \\ I_{a2} \\ I_{a0} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \\ 1 & 1 & 1 \end{bmatrix}\begin{bmatrix} 0 \\ I_b \\ -I_b \end{bmatrix}$$

$$I_{a1} = \frac{1}{3}(\alpha I_b - \alpha^2 I_b)$$

$$I_{a2} = \frac{1}{3}(\alpha^2 I_b - \alpha I_b) = -I_{a1} \quad \text{...(3.3.2)}$$

$$I_{a0} = 0 \quad \text{...(3.3.3)}$$

– The symmetrical component of voltages at fault F are,

$$\begin{bmatrix} V_{a1} \\ V_{a2} \\ V_{a0} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \\ 1 & 1 & 1 \end{bmatrix}\begin{bmatrix} V_a \\ V_b \\ V_b - I_b Z_f \end{bmatrix}$$

$$3 V_{a1} = V_a + \alpha V_b + \alpha^2 V_b - \alpha^2 I_b Z_f \quad \text{...(3.3.4)}$$

$$3 V_{a2} = V_a + \alpha^2 V_b + \alpha V_b - \alpha I_b Z_f \quad \text{...(3.3.5)}$$

From this we can write,

$$3(V_{a1} - V_{a2}) = (\alpha - \alpha^2) Z_f I_b = j\sqrt{3} Z_f I_b \quad \text{...(3.3.6)}$$

– The phase current can be expressed in symmetrical current as,

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ \alpha^2 & \alpha & 1 \\ \alpha & \alpha^2 & 1 \end{bmatrix}\begin{bmatrix} I_{a1} \\ I_{a2} \\ I_{a0} \end{bmatrix}$$

For the LL fault,

$$\begin{bmatrix} 0 \\ I_b \\ -I_b \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ \alpha^2 & \alpha & 1 \\ \alpha & \alpha^2 & 1 \end{bmatrix}\begin{bmatrix} I_{a1} \\ -I_{a1} \\ 0 \end{bmatrix}$$

$$\therefore \quad I_b = \alpha^2 I_{a1} - \alpha I_{a1} = (\alpha^2 - \alpha) I_{a1} = -j\sqrt{3} I_{a1} \quad \text{...(3.3.7)}$$

– Substituting Equation (3.3.7) in Equation (3.3.6) we get,

$$3(V_{a1} - V_{a2}) = j\sqrt{3} Z_f \cdot (-j\sqrt{3} I_{a1})$$

$$3(V_{a1} - V_{a2}) = 3 Z_f I_{a1}$$

$$\therefore \quad V_{a1} - V_{a2} = 3 Z_f I_{a1} \qquad \text{...(3.3.8)}$$

- Equations (3.3.2) and (3.3.8) suggests that the positive and negative sequence networks should be connected in parallel through series impedance Z_f. This is shown in Fig. 3.3.2.
- As $I_{a0} = 0$, the zero sequence network is unconnected.

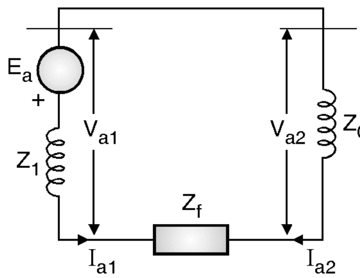


Fig. 3.3.2 : Interconnection of sequence network for LL fault.

- Now substituting V_{a1} and V_{a2} from the sequence network equations in Equation (3.3.1),

$$E_a - I_{a1} Z_1 = -I_{a2} Z_2 + I_{a1} Z_f$$

$$E_a - I_{a1} Z_1 = I_{a1}(Z_2 + Z_f) \qquad (\because I_{a2} = -I_{a1})$$

$$\therefore \quad I_{a1} = \frac{E_a}{Z_1 + Z_2 + Z_f} \qquad \text{...(3.3.9)}$$

Knowing I_{a1}, V_{a1} and V_{a2} can be calculated. From this voltage at fault can be calculated.

Syllabus Topic : Analysis of Shunt Type Unsymmetrical Faults : Double Line to Ground (LLG) Fault

3.4 Double Line to Ground (LLG) Fault on Unloaded Alternator

➔ (MU - May 15, Dec. 15)

Q. 3.4.1 Derive the equation for fault current and develop the sequence network for LLG fault on an unloaded synchronous generator.
(Refer section 3.4) **May 15, 10 Marks**

Q. 3.4.2 Derive the equation for fault current for LLG fault.
(Refer section 3.4) **Dec. 15, 10 Marks**

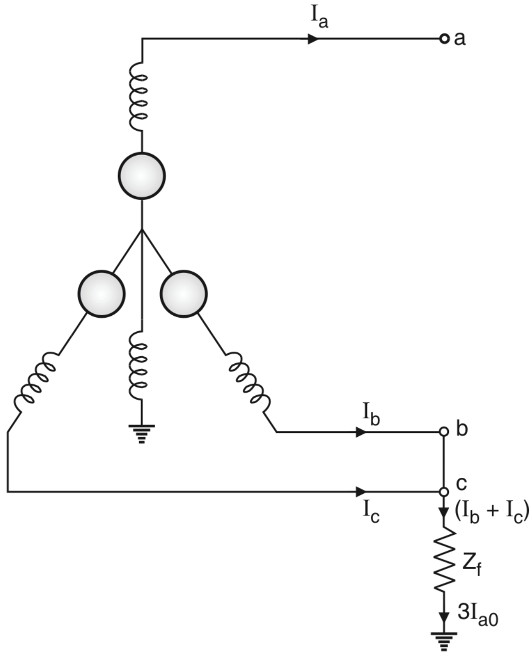


Fig. 3.4.1 : Unloaded generator : LLG fault

– Fig. 3.4.1 shows a unloaded generator. A double line to ground fault occurs between line b, c and ground. The current and voltages at fault point F are,

$$I_a = 0$$

$$I_{a1} + I_{a2} + I_{a0} = 0 \qquad \text{...(3.4.1)}$$

$$V_b = V_c = Z_f (I_b + I_c) \qquad \text{...(3.4.2)}$$

– The symmetrical components of voltage at point F are,

$$\begin{bmatrix} V_{a1} \\ V_{a2} \\ V_{a0} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_b \end{bmatrix}$$

$$V_{a1} = \frac{1}{3} [V_a + \alpha V_b + \alpha^2 V_b]$$

$$V_{a2} = \frac{1}{3} [V_a + \alpha^2 V_b + \alpha V_b]$$

$$\therefore \quad V_{a1} = V_{a2} = \frac{1}{3} [V_a + (\alpha + \alpha^2) V_b] \qquad \text{...(3.4.3)}$$

$$V_{a0} = \frac{1}{3} (V_a + 2 V_b) \qquad \text{...(3.4.4)}$$

– Subtracting Equation (3.4.3) from Equation (3.4.4),

$$V_{a0} - V_{a1} = \frac{1}{3}(2 - \alpha - \alpha^2)\, V_b = V_b = 3\, Z_f\, I_{a0}$$

$$\therefore \quad V_{a0} = V_{a1} + 3\, Z_f\, I_{a0} \qquad \ldots(3.4.5)$$

– From Equations (3.4.1), (3.4.3) and (3.4.5) the connections between sequence network can be drawn as shown in Fig. 3.4.2.

– From Fig. 3.4.2, we can write equation for current I_{a1} in terms of Thevenin's equivalent,

$$I_{a1} = \frac{E_a}{Z_1 + Z_2\,(Z_0 + 3\, Z_f) \,/\, Z_2 + Z_0 + 3\, Z_f}$$

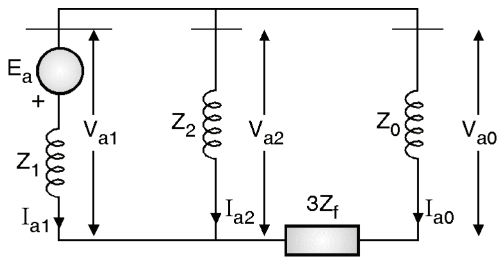


Fig. 3.4.2 : Interconnection of sequence networks for double line to ground (LLG) fault

3.5 Unsymmetrical Faults on Power System

➔ (MU - Dec. 16)

Q. 3.5.1 What is power invariance in unsymmetrical fault analysis ? *(Refer section 3.5)*	**Dec. 16, 5 Marks**

– As discussed earlier, various types of faults are occurring in power system. These faults are,

– Shunt type of faults :

(i) Single Line to Ground fault (LG)

(ii) Line to Line fault (LL)

(iii) Double Line to Ground fault (LLG)

– Series type of faults :

(i) Open conductor fault (one or two conductors open).

- These faults are easily analyzed by using Thevenin's theorem. This theorem is used to determine the changes in currents and voltages of linear network due to addition of impedance between two nodes.
- Consider the power system shown in Fig. 3.5.1 and Fig. 3.5.2 shows the illustration of the application of Thevenin's theorem for determination of equivalent positive, negative and zero sequence networks.
- Thevenin's equivalent of positive sequence network is obtained from the positive sequence network of power system.
- The Thevenin's voltage source is the prefault voltage at fault point and the equivalent impedance Z_{1eg} is the impedance seen from fault point.
- The positive sequence impedance of the alternator or synchronous machine depends upon the state of machine i.e. subtransient, transient or steady state.
- Thevenin's equivalent of negative and zero sequence networks are obtained from negative and zero sequence networks of power system.
- As the system is balanced, no negative and zero sequence currents are flowing through it before occurrence of fault.
- Hence per fault negative and zero sequence voltages at the fault point are zero and no emf occurs in the equivalent circuits.
- The impedances Z_{1eg}. and Z_{0eg}. are the Thevenin's equivalent impedance of negative and zero sequence network seen from fault point.
- In positive sequence network, the currents throughout the system due to the fault can be added to load currents before the fault to obtain total positive sequence currents during the fault.
- Hence the net fault current is the fault current considering the system under no load condition plus the load current superimposed over the faults currents.

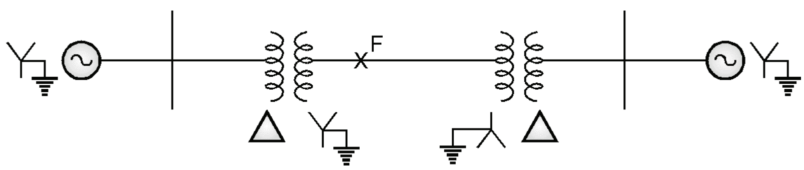


Fig. 3.5.1 : Single line diagram of 3 phase balanced system

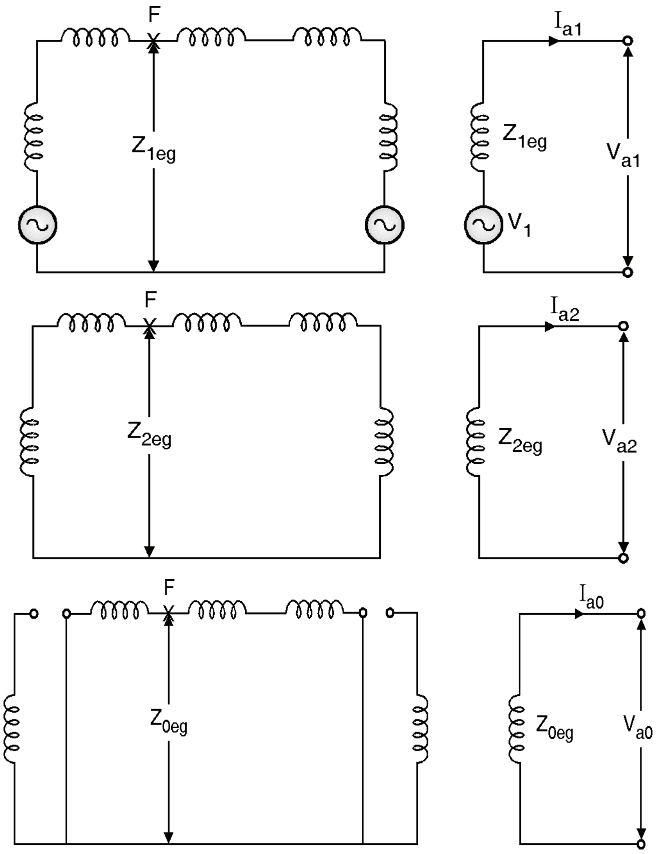


Fig. 3.5.2 : Thevenin′s equivalent networks of (a) Positive (b) Negative (c) Zero sequence networks

3.6 Single Line to Ground Fault on Power System

- Consider a power system as shown in Fig. 3.6.1. A line to ground fault occurs at point F in a power system through fault impedance Z_f.
- The currents and voltages at fault point are,

$$I_b = 0 \quad \ldots(3.6.1)$$

$$I_c = 0 \quad \ldots(3.6.2)$$

$$V_a = Z_f \cdot I_a \quad \ldots(3.6.3)$$

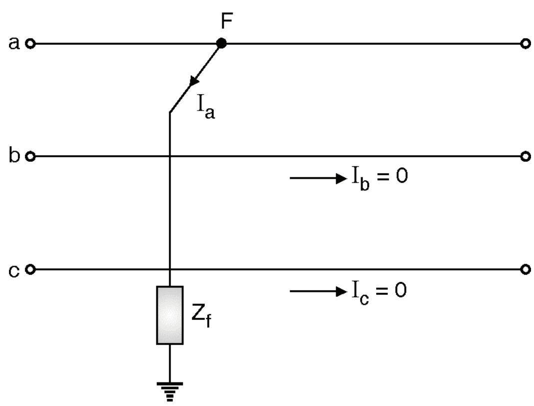


Fig. 3.6.1 : Single Line to Ground fault (LG) on power system

– The symmetrical components of fault current are,

$$\begin{bmatrix} I_{a1} \\ I_{a2} \\ I_{a0} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \\ 1 & 1 & 1 \end{bmatrix}\begin{bmatrix} I_a \\ 0 \\ 0 \end{bmatrix}$$

$$\therefore \quad I_{a1} = I_{a2} = I_{a0} = \frac{1}{3} I_a \quad \text{...(3.6.4)}$$

– Equation (3.6.3) can be expressed in symmetrical components as,

$$V_{a1} + V_{a2} + V_{a0} = Z_f I_a = 3 Z_f I_{a1} \quad \text{...(3.6.5)}$$

– Equations (3.6.4) and (3.6.5) indicate that all sequence current are equal and sum of sequence voltages equals $3 Z_f I_{a1}$.

– These equations suggest that all the sequence networks should be connected in series through an impedance $3 Z_f$. This is shown in Figs. 3.6.2 (a) and (b).

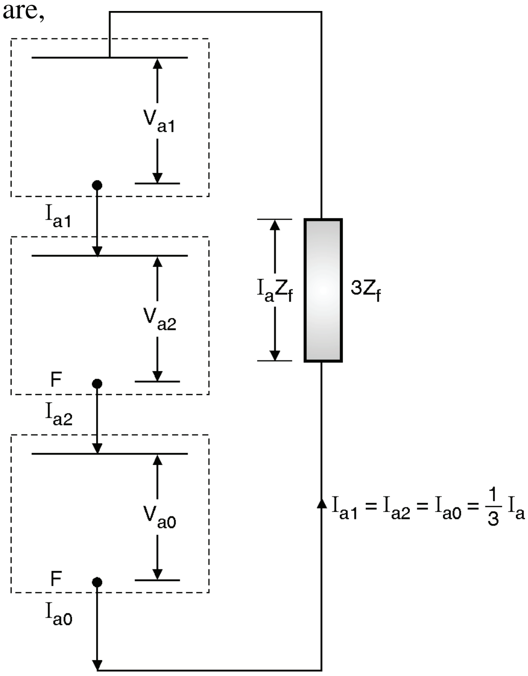


Fig. 3.6.2(a) : Sequence network connections for single line to ground fault (LG)

From this circuit the fault current is,

$$I_{a1} = \frac{E_a}{Z_1 + Z_2 + Z_0 + 3 Z_f} \quad \text{...(3.6.6)}$$

Fault current I_a is given as,

$$I_a = 3 I_{a1} = \frac{E_a}{Z_1 + Z_2 + Z_0 + 3 Z_f} \quad \text{...(3.6.7)}$$

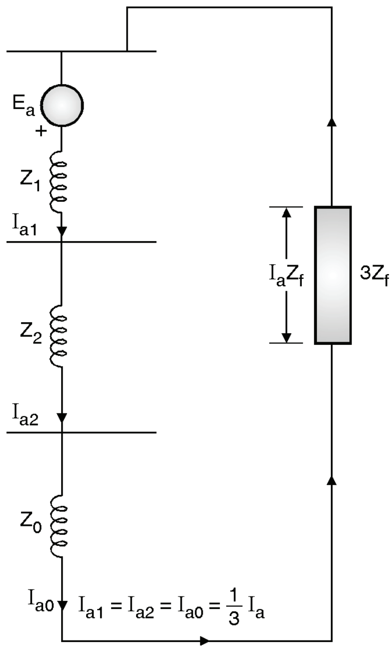


Fig. 3.6.2(b) : Shows Thevenin's equivalent circuit for LG fault

The voltage of line b under fault condition is,

$$V_b = \alpha^2 V_{a1} + \alpha V_{a2} + V_{a0}.$$

$$= \alpha^2 \left(E_a - \frac{I_a Z_1}{3}\right) + \alpha\left(-\frac{I_a Z_2}{3}\right) + \left(-\frac{I_a Z_0}{3}\right)$$

Substituting values of I_a,

$$V_b = E_a \frac{3\,\alpha^2 Z_f + Z_2\,(\alpha^2 - \alpha) + Z_0\,(\alpha^2 - 1)}{(Z_1 + Z_2 + Z_0) + 3\,Z_f} \qquad \ldots(3.6.8)$$

Similarly we can obtain expression for V_c.

3.7 Line to Line Fault on Power System

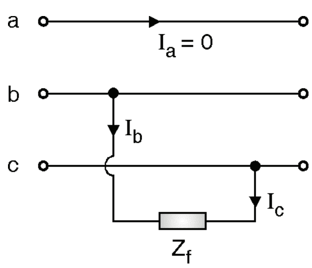


Fig. 3.7.1 : Line to line (LL) fault on power system

– Fig. 3.7.1 shows a line to line fault occurring in power system between line b and c through fault impedance Z_f.

– The current and voltages at fault are,

$$\left.\begin{aligned} I_a &= 0 \\ I_b,\quad I_c &= -I_b \\ V_b - V_c &= I_b Z_f \end{aligned}\right\} \qquad \ldots(3.7.1)$$

– Symmetrical components of fault currents are,

$$\begin{bmatrix} I_{a1} \\ I_{a2} \\ I_{a0} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \\ 1 & 1 & 1 \end{bmatrix}\begin{bmatrix} 0 \\ I_b \\ -I_b \end{bmatrix}$$

$$\therefore \quad I_{a1} = \frac{1}{3} I_b\,(\alpha - \alpha^2) \quad , \quad I_{a2} = \frac{1}{3} I_b\,(\alpha^2 - \alpha)$$

$$\therefore \quad I_{a2} = -I_{a1} \qquad \ldots(3.7.2)$$

$$I_{a0} = 0 \qquad \ldots(3.7.3)$$

– The symmetrical component of voltages are,

$$\begin{bmatrix} V_{a1} \\ V_{a2} \\ V_{a0} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \\ 1 & 1 & 1 \end{bmatrix}\begin{bmatrix} V_a \\ V_b \\ V_b - Z_f I_b \end{bmatrix}$$

$$V_{a1} = \frac{1}{3}[\, V_a + (\alpha + \alpha^2)\, V_b - \alpha^2 Z_f I_b \,] \qquad \ldots(3.7.4)$$

$$V_{a2} = \frac{1}{3}[\, V_a + (\alpha + \alpha^2)\, V_b - \alpha\, Z_f I_b \,] \qquad \ldots(3.7.5)$$

– Subtracting Equation (3.7.5) from Equation (3.7.4).

$$V_{a1} - V_{a2} = \frac{1}{3}[(\alpha - \alpha^2)\, Z_f I_b\,]$$

$$\therefore \quad 3\,(V_{a1} - V_{a2}) = j\sqrt{3}\, Z_f I_b \qquad \ldots(3.7.6)$$

– Similarly we can get I_b in terms of its symmetrical components as,

$$\begin{bmatrix} 0 \\ I_b \\ -I_b \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ \alpha^2 & \alpha & 1 \\ \alpha & \alpha^2 & 1 \end{bmatrix}\begin{bmatrix} I_{a1} \\ I_{a2} \\ I_{a0} \end{bmatrix}$$

$$\therefore \quad I_b = \alpha^2 I_{a1} + \alpha\, I_{a2} + I_{a0}$$

$$\therefore \quad I_b = I_{a1}\,(\alpha^2 - \alpha) \qquad \ldots(\because \; I_{a2} = -I_{a1},\, I_{a0} = 0)$$

$$\therefore \quad I_b = -j\sqrt{3}\, I_{a1} \qquad \ldots(3.7.7)$$

– Replacing I_b in Equation (3.7.6) with Equation (3.7.7).

$$3\,(V_{a1} - V_{a2}) = 3\, Z_f I_{a1}$$

$$\therefore \quad V_{a1} - V_{a2} = Zf\, I_{a1} \qquad \ldots(3.7.8)$$

– Equations (3.7.2) and (3.7.8) suggests that a positive sequence network is connected is parallel with negative sequence network through fault impedance Z_f. As I_{a0} is zero so zero sequence network is unconnected.

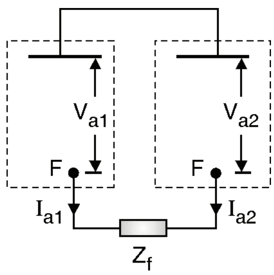


Fig. 3.7.2(a) : Sequence network Connection for line to line (LL) fault

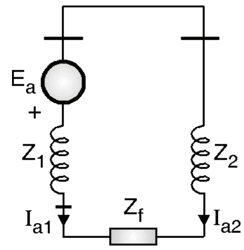


Fig. 3.7.2(b)

- Fig. 3.7.2(b) shows Thevenin's equivalent circuit for line to line fault.

  From this circuit,

$$I_{a1} = \frac{E_a}{Z_1 + Z_2 + Z_f} \quad \ldots(3.7.9)$$

- From Equation (3.7.7),

$$I_b = -I_c = \frac{-j\sqrt{3}\,E_a}{Z_1 + Z_2 + Z_f} \quad \ldots(3.7.10)$$

- From I_{a1}, V_{a1} and V_{a2} can be calculated. From this voltages at fault point can be calculated.

3.8 Double Line to Ground Fault on Power System

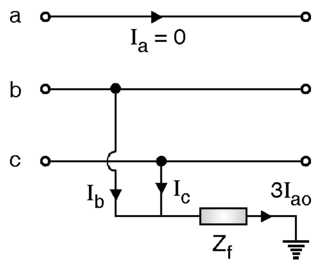


Fig. 3.8.1 : Double line to ground fault (LLG) on power system.

- Fig. 3.8.1 shows a double Line to Ground (LLG) fault on power system. The fault occurs on line b and c through fault impedance Z_f.
- The current and voltage at fault point are,

$$\left.\begin{aligned} I_a &= 0 \\ I_{a1} + I_{a2} + I_{a0} &= 0 \end{aligned}\right\} \quad \ldots(3.8.1)$$

$$V_b = V_c = Z_f (I_b + I_c) = 3\,Z_f\,I_{a0} \quad \ldots(3.8.2)$$

- The symmetrical component of voltages are,

$$\begin{bmatrix} V_{a1} \\ V_{a2} \\ V_{a0} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \\ 1 & 1 & 1 \end{bmatrix}\begin{bmatrix} V_a \\ V_b \\ V_b \end{bmatrix}$$

$$V_{a1} = \frac{1}{3}[V_a + (\alpha + \alpha^2) V_b]$$

$$V_{a2} = \frac{1}{3}[V_a + (\alpha + \alpha^2) V_b]$$

$$\therefore \quad V_{a1} = V_{a2} = \frac{1}{3}[V_a + (\alpha + \alpha^2) V_b] \quad \ldots(3.8.3)$$

$$V_{a0} = \frac{1}{3}(V_a + 2 V_b) \quad \ldots(3.8.4)$$

– Subtracting Equation (3.8.3) from Equation (3.8.4)

$$V_{a0} - V_{a1} = \frac{1}{3}(2 - \alpha - \alpha^2) V_b = 3 Z_f I_{a0}$$

$$V_{a0} = V_{a1} + 3 Z_f I_{ao} \quad \ldots(3.8.5)$$

– Equations (3.8.1), (3.8.3) and (3.8.5) indicates that the positive sequence and negative sequence network are connected in parallel and this parallel combination is connected to zero sequence network through fault impedance Z_f. This is shown in Figs. 3.8.2 (a) and (b).

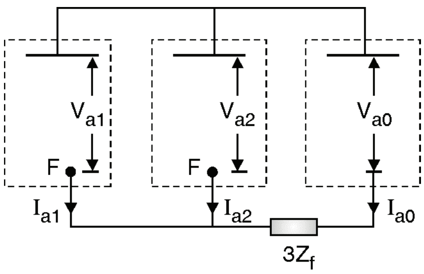


Fig. 3.8.2(a) : Sequence network connection for double line to ground (LLG) fault.

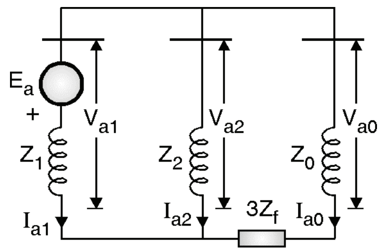


Fig. 3.8.2(b)

– Fig. 3.8.2(b) shows Thevenin's equivalent circuit for double line to ground fault.

The fault current is,

$$I_{a1} = \frac{E_a}{Z_1 + Z_2 \parallel (Z_0 + 3 Z_f)}$$

$$\therefore \quad I_{a1} = \frac{E_a}{Z_1 + Z_2 (Z_0 + 3 Z_f) / Z_2 + Z_0 + 3 Z_f} \quad \ldots(3.8.6)$$

Syllabus Topic : Bus Impedance Matrix Method for Analysis of Shunt Type Unsymmetrical Faults

3.9 Analysis of Unsymmetrical Faults using Bus Impedance Matrix

- Consider that there are 'n' number of buses in a system and a LG fault occurs i^{th} bus of this system.
- The connection of sequence network is as shown in Fig. 3.9.1. The positive sequence network is replaced by its Thevenin's equivalent i.e. the prefault voltage. V^0_{1-i} of bus i in series with the passive positive sequence network.
- As there is no prefault negative and zero sequence voltages, both are passive networks only.

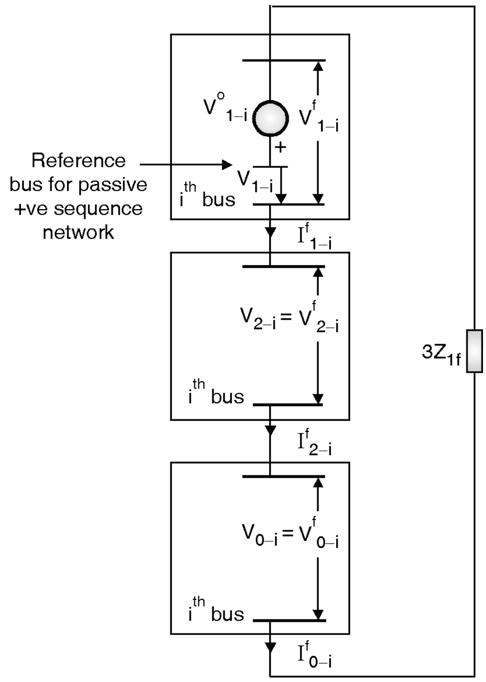


Fig. 3.9.1 : Connection of sequence network for LG fault on i^{th} bus

For passive positive sequence network,

$$V_{1-BUS} = Z_{1-BUS} \cdot I_{1-BUS} \qquad \ldots(3.9.1)$$

Where,

$$V_{1-BUS} = \begin{bmatrix} V_{1-1} \\ V_{1-2} \\ \vdots \\ V_{1-n} \end{bmatrix} = \text{positive sequence bus voltage vector} \qquad \ldots(3.9.2)$$

$$Z_{1-BUS} = \begin{bmatrix} Z_{1-11} & \cdots\cdots & Z_{1-1n} \\ : & & : \\ : & & : \\ Z_{1-nl} & \cdots\cdots & Z_{1-nn} \end{bmatrix} = \text{Positive sequence bus impedance matrix} \quad \ldots(3.9.3)$$

$$I_{1-BUS} = \begin{bmatrix} I_{1-1} \\ I_{1-2} \\ : \\ I_{1-n} \end{bmatrix} = \text{Positive sequence bus current injection vector.} \quad \ldots(3.9.4)$$

According to sequence network connection, current $-I^{f}_{1-i}$ is injected only at the faulted i^{th} bus of the positive sequence network. Hence,

$$I_{1-BUS} = \begin{bmatrix} 0 \\ 0 \\ : \\ -I^{f}_{1-i} \\ : \\ 0 \end{bmatrix} \quad \ldots(3.9.5)$$

– Hence the positive sequence voltage at the i^{th} bus of the passive positive sequence network is,

$$V_{1-i} = -Z_{1-ii} \cdot I^{f}_{1-i} \quad \ldots(3.9.6)$$

– Thus, the passive positive sequence network presents an impedance Z_{1-ii} to the positive sequence current I^{f}_{1-i} for negative sequence network.

$$V_{2-BUS} = Z_{2-BUS} \cdot I_{2-BUS} \quad \ldots(3.9.7)$$

– The negative sequence network is injected with current I^{f}_{1-i} at the i^{th} bus only. Hence,

$$I_{2-BUS} = \begin{bmatrix} 0 \\ 0 \\ : \\ -I^{f}_{2-i} \\ : \\ 0 \end{bmatrix} \quad \ldots(3.9.8)$$

The negative sequence voltage at i^{th} bus is,

$$V_{2-i} = -Z_{2-ii} \cdot I^{f}_{2-i} \quad \ldots(3.9.9)$$

– Thus negative sequence network offers an impedance Z_{2-ii} to the negative sequence current I^f_{2-i}, for zero sequence network,

$$V_{0-BUS} = Z_{0-BUS} \cdot I_{0-BUS}$$

$$I_{0-BUS} = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ -I^f_{0-i} \\ \vdots \\ 0 \end{bmatrix} \quad \ldots(3.9.10)$$

$$\therefore \quad V_{0-i} = -Z_{0-ii} \cdot I^f_{2-i} \quad \ldots(3.9.11)$$

– Thus zero sequence network offers an impedance Z_{0-ii} to the zero sequence current I^f_{0-i}

From sequence network connection, we can write,

$$I^f_{1-i} = I^f_{2-i} = I^f_{0-i}$$

$$= \frac{V^0_{1-i}}{Z_{1-ii} + Z_{2-ii} + Z_{0-ii} + 3Z_f} \quad \ldots(3.9.12)$$

– Similarly we can compute sequence currents for LL and LLG fault.

– We can now compute the postfault voltages at any bus.

– For passive positive sequence network, the voltage developed at bus k due to injection of current $-I^f_{1-i}$ at bus i is,

$$V_{1-k} = -Z_{1-ik} \cdot I^f_{1-i} \quad \ldots(3.9.13)$$

– Hence the postfault positive sequence voltage at bus k is,

$$V^f_{1-k} = V^0_{1-k} - Z_{1-ik} \cdot I^f_{1-i} \text{ ; } k = 1, 2\ldots.. n \quad \ldots(3.9.14)$$

Where, V^0_{1-k} = prefault positive sequence voltage at bus k.

Z_{1-ik} = ik th component of Z_{1-BUS}.

– As the prefault negative sequence bus voltage is zero, the postfault negative sequence bus voltage is,

$$V^f_{2-k} = 0 + V_{2-k}$$

$$V^f_{2-k} = -Z_{2-ik} \cdot I^f_{2-i} \quad \ldots(3.9.15)$$

where, Z_{2-ik} = ik th component of Z_{2-BUS}.

– The postfault zero sequence bus voltage is given as,

$$V^{f}_{0-k} = -Z_{0-ik} \cdot I^{f}_{0-i} \text{ ; } i = 1, 2,\ldots\ldots n. \qquad \ldots(3.9.16)$$

where, $Z_{0-ik} = ik^{th}$ component of Z_{0-BUS}.

- After computing postfault sequence voltages, the sequence currents in the lines can be computed as, for line pg. having sequence admittances Y_{1-pg} , Y_{2-pg} and Y_{0-pg}

$$\left.\begin{aligned} I^{f}_{1-pg} &= Y_{1-pg}\left(V^{f}_{1-p} - V^{f}_{1-g}\right) \\ I^{f}_{2-pg} &= Y_{2-pg}\left(V^{f}_{2-p} - V^{f}_{2-g}\right) \\ I^{f}_{0-pg} &= Y_{0-pg}\left(V^{f}_{2-p} - V^{f}_{2-g}\right) \end{aligned}\right\} \qquad \ldots(3.9.17)$$

- After computing sequence voltages and current, phase voltages and currents can be easily computed as,

$$V_{p} = A_{VS} \qquad I_{p} = A_{IS}.$$

- As this method requires computation of bus impedance matrices of all the three sequence networks, it seems to be more tedious and time consuming.
- But once the bus impedance matrices have been formed, fault analysis can be easily carried out for all the buses which is the aim of fault analysis.
- Also for any changes in power network bus impedance matrix can be easily modified.

3.10 Computer Calculation of Fault Current

- The current and voltage that activate the relays are the currents and voltages which flow or appear immediately after the occurrence of the fault.
- The fault current is very high. This current is to be interrupted by the circuit breaker. Both fault current and voltages are to be calculated.
- The voltages and currents during the faults are used to set the relays so that they can detect the faulted condition as fast as possible.
- The initial fault current is used to determine the required momentary duty of the breaker.
- The current and voltage a short while later are used to calculate the required interrupting capacity of breaker. The voltages and current are also used to calculate the short circuit capacity.
- The basic aim of fault study is to determine the impedance matrix of the system.

- The elements of impedance matrix along with the conditions of faults are used to calculate fault current and postfault voltages.
- Flow chart for short circuit studies:

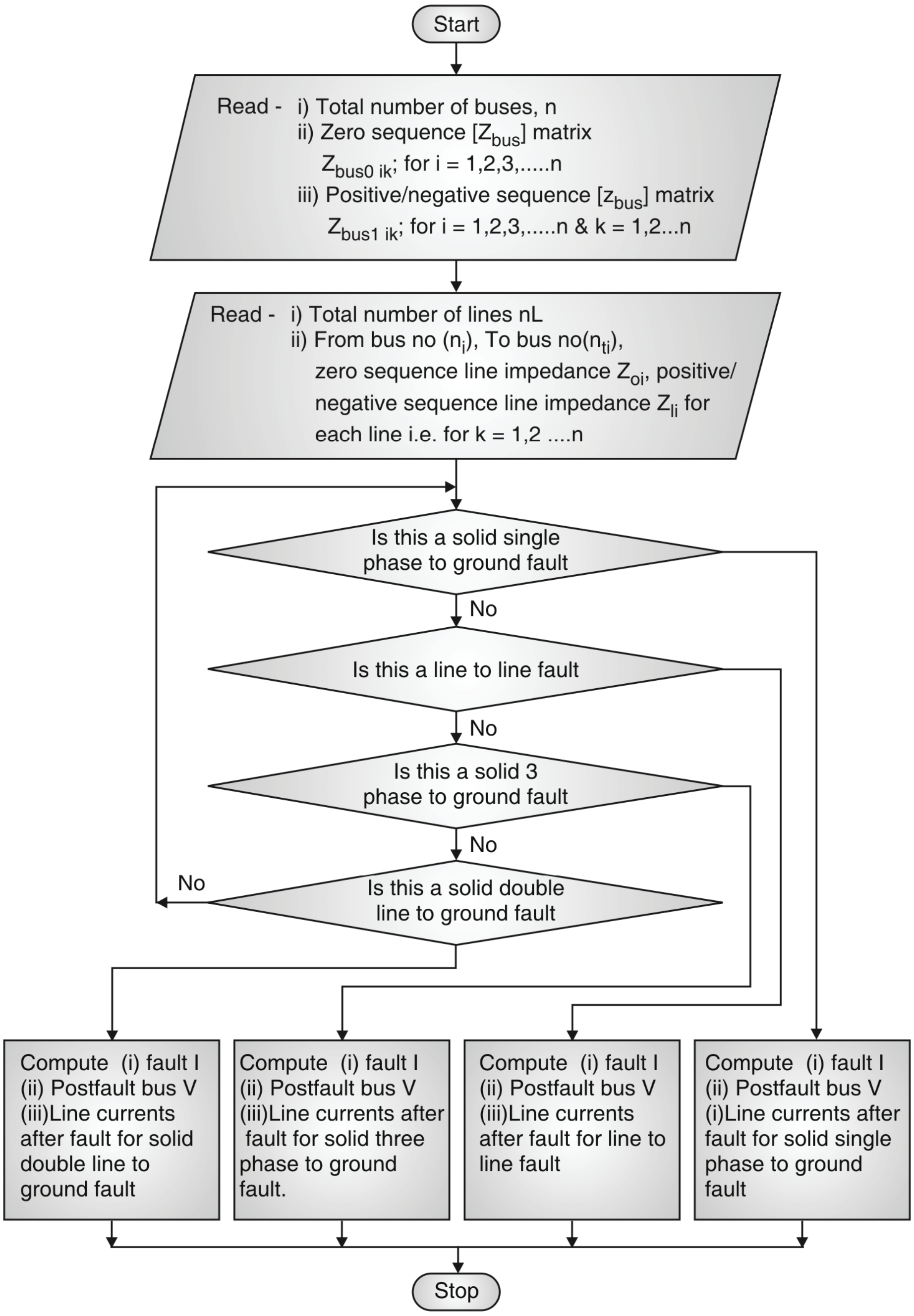


Fig. 3.10.1

Problems

Ex. 3.10.1

Two 25 MVA, 11 kV generators are connected to a common busbar which supplies a feeder. The star point of one of generators is grounded through a resistance of 1Ω, while that of other generator is isolated. A line-to-ground fault occurs at the far end of the feeder. Determine :

(i) The fault current and

(ii) The voltage to ground of healthy phase of the feeder at the fault point.

The sequence impedances of each generator and feeder are give below :

	Each generator (p.u.)	Feeder (Ω/ph)
X_1	j 0.2	j 0.4
X_2	j 0.15	j 0.4
X_0	j 0.08	j 0.8

Assume fault impedance to be zero.

Soln. :

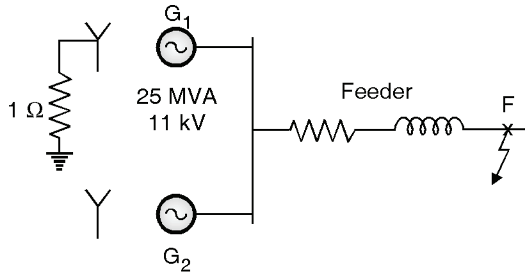


Fig. P. 3.10.1

(i) The two identical generators operate in parallel

$$X_{g1\ eg} = \frac{j\,0.2}{2} = j\,0.1 \text{ p.u.}$$

$$X_{g2\ eg} = \frac{j\,0.15}{2} = j\,0.075 \text{ p.u.}$$

The star point of second generator is isolated. Hence it's zero sequence reactance does not come into picture.

$$\text{Base MVA} = 25 \text{ MVA.}$$

$$\text{Base kV} = 11 \text{ kV.}$$

$$Z_{g0\ eg} = j\,0.08 + 3\,R_n$$

$$= j\,0.08 + 3\left(\frac{1 \times 25}{11^2}\right) = 0.619 + j\,0.08 \text{ p.u.}$$

Feeder's sequence impedance are specified in Ω. Let us convert it into p.u. considering 25 MVA as base MVA and 11 kV as base kV.

$$\therefore \quad X_{1f} = \frac{j\,0.4 \times 25}{11^2} = j\,0.083 \text{ p.u.}$$

$$X_{2f} = \frac{j\,0.4 \times 25}{11^2} = j\,0.083 \text{ p.u.}$$

$$X_{0f} = \frac{j\,0.8 \times 25}{11^2} = j\,0.165 \text{ p.u.}$$

Total positive, negative and zero sequence impedances up to fault point are,

$$X_{1T} = X_{1g\,eg} + X_{1f} = j\,0.1 + j\,0.083 = j\,0.183 \text{ p.u.}$$

$$X_{2T} = X_{2g\,eg} + X_{2f} = j\,0.075 + j\,0.083 = j\,0.158 \text{ p.u.}$$

$$X_{0T} = X_{0g\,eg} + X_{0f} = j\,0.619 + j\,0.08 + j\,0.165$$

$$= 0.619 + j\,0.245 \text{ p.u.} = 0.665 \angle 21.59\,.$$

For line to ground fault,

Fault current,

$$I_f = I_a = 3\,I_{a1} = \frac{3\,E_a}{X_{1T} + X_{2T} + X_{0T}}$$

$$\therefore \quad I_f = \frac{3 \times 1}{j\,0.183 + j\,0.158 + 0.619 + j\,0.245} = \frac{3}{0.619 + j\,0.586}$$

$$= \frac{3}{0.852 \angle 43.43} = 3.5 \angle -43.43 \text{ p.u.}$$

$$\text{Actual fault current} = 3.5 \times \frac{25}{\sqrt{3} \times 11} = 4.6 \text{ kA.}$$

(ii) Voltage of healthy phase at fault point

$$V_b = \alpha^2 \left(E_a - X_{1T} \frac{I_a}{3} \right) + \alpha \left(-X_{2T} \frac{I_a}{3} \right) + \left(-X_{0T} \frac{I_a}{3} \right)$$

$$= 1 \angle -120^\circ \left(1 - \frac{j\,0.183 \times 3.5 \angle -43.43}{3} \right) + 1 \angle 120$$

$$\left(-\frac{j\,0.158 \times 3.5 \angle -43.43}{3} \right) + \left(-\frac{0.665 \angle 21.59 \times 3.5 \angle -43.43}{3} \right)$$

$$= 0.867 \angle -109.7^\circ + (-0.184 \angle 166.57) + (-0.776 \angle -21.84)$$

$$\therefore \quad V_b = -0.8333 - j\,0.5697. = 1.009 \angle 34.36^\circ \text{ p.u.}$$

$$\text{Actual voltage} = 11.09 \text{ kV}$$

Ex. 3.10.2

A 25 MVA, 11 kV generator has $X_d = 0.2$ p.u., $X_2 = 0.3$ p.u. and $X_0 = 0.1$ p.u. The neutral of generator is solidly grounded. Determine the subtransient current in the generator and the line to line voltages for subtransient condition when a Y - B - G fault occurs at the generator terminals. Assume prefault currents and fault resistance to be zero.

Soln. : For double line to ground fault (Y - B - G fault)

$$I_{a1} = \frac{E_a}{Z_1 + \dfrac{Z_0 Z_2}{Z_0 + Z_2}}$$

Assuming prefault voltage $1\angle 0°$ p.u.

$$I_{a1} = \frac{1\angle 0}{X_d'' + \dfrac{X_2 \cdot X_0}{X_2 + X_0}} = \frac{1\angle 0°}{j\,0.2 + \dfrac{j\,0.3 \times j\,0.1}{j\,0.3 + j\,0.1}}$$

$$I_{a1} = \frac{1\angle 0°}{j\,0.275} = -j\,3.636$$

For LLG fault, $V_{a1} = V_{a2} = V_{a0}$

$$V_{a1} = E_a - I_{a1} X_d'' = 1 + j\,0.0 - (-j\,3.636)(j\,0.2)$$

$$= 1 - 0.7272 = 0.2727$$

$$V_{a2} = V_{a0} = 0.2727$$

$$I_{a2} = -\frac{V_{a2}}{X_2} = \frac{-0.2727}{j\,0.3} = j\,0.909$$

$$I_{a0} = -\frac{V_{a0}}{X_0} = \frac{-0.2727}{j\,0.1} = j\,2.727$$

$$I_{a2} + I_{a0} = j\,0.909 + j\,2.727 = j\,3.636 = -I_{a1}$$

$$\text{Fault current} = I_b + I_c = 3\,I_{a0}$$

$$= 3 \times j\,2.727 = j\,8.181 \text{ p.u.}$$

$$\text{Actual fault current} = \frac{8.181 \times 25 \times 10^6}{\sqrt{3} \times 11 \times 10^3} = 10.734 \text{ kA.}$$

Now, $V_a = V_{a1} + V_{a2} + V_{a0} = 3\,V_{a1} = 3 \times 0.2727 = 0.8181$ p.u.

$$V_b = V_c = 0$$

The line to line fault voltage are,

$$V_{ab} = V_a = 0.8181 \times \frac{11}{\sqrt{3}} = 5.196 \text{ kV}$$

$$V_{ac} = V_a = 0.8181 \times \frac{11}{\sqrt{3}} = 5.196 \text{ kV}$$

$$V_{bc} = 0.0 \text{ kV}$$

Ex. 3.10.3

A salient pole generator without dampers is rated 20 MVA, 13.8 kV and has a direct axis subtransient reactance of 0.25 p.u. The negative and zero sequence reactance are 0.35 p.u. and 0.1 p.u. respectively. The neutral of generator is solidly grounded. Determine the subtransient currents and the line to line voltages at the fault under subtransient conditions when a line to line fault occurs at b and c terminals of the generator.Assume that the generator is unloaded and operating at rated terminal voltage when the fault occurs. Neglect resistance.

Soln. :

The sequence network for LL fault is shown in Fig. P. 3.10.3 the zero sequence network is absent. The pre-fault voltage is assumed to be $1 \angle 0°$ p.u.

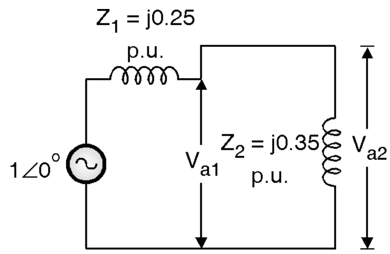


Fig. P. 3.10.3 : Sequence network for LL fault

(i) For LL fault

$$I_{a_1} = \frac{E_a}{Z_1 + Z_2} = \frac{1 \angle 0°}{j\,0.25 + j\,0.35}$$

$$= -j\,1.667 \text{ p.u.}$$

$$I_{a1} = -I_{a2} = -j\,1.667 \text{ p.u.}$$

$$I_{a2} = j\,1.667 \text{ p. u.}$$

$$I_{a0} = 0$$

To find out the fault current, $I_b = -I_c$.

$$\therefore \quad I_b = I_{b1} + I_{b2} + I_{b0} = I_{b1} + I_{b2} = \alpha^2 I_{a1} + \alpha I_{a2}$$

$$\therefore \quad I_b = 1 \angle -120° (-j\,1.667) + 1 \angle 120° (j\,1.667)$$

$$\therefore \quad I_b = -2.8872 + j\,0 = -2.8872 \text{ p.u.}$$

$$\text{Base current} = \frac{MVA_B}{\sqrt{3} \times kV_B} = \frac{20 \times 10^3}{\sqrt{3} \times 13.8} = 836.74 \text{ A.}$$

$$\therefore \quad \text{Fault current} = 2.8872 \times 836.72 = 2415.83 \text{ A.}$$

(ii) To find out line to line voltages

$$`V_{a1} = E_a - I_{a1} Z_1 = 1 + j\,0 - (-j\,1.667)(j\,0.25)$$

$$V_{a1} = 1 - 0.4167 = 0.5833 \text{ p.u.}$$

$$V_{a2} = -I_{a2} Z_2 = -(j\,1.667)(j\,0.35) = 0.5834 \text{ p.u.}$$

$$V_{a1} = V_{a2} = 0.5833 \text{ p.u.}$$

$$\therefore \quad V_a = V_{a1} + V_{a2} + V_{a0} = V_{a1} + V_{a2} = 0.5833 + 0.5833 = 1.1666 \text{ p.u.}$$

$$V_b = \alpha^2 V_{a1} + \alpha V_{a2}$$

$$V_b = 1 \angle -120° (0.5833) + 1 \angle 120° (0.5833) = -0.5833 \text{ p.u.}$$

$$V_b = V_c = -0.5833$$

$$\text{Line voltage,}\quad V_{ab} = V_a - V_b = 1.666 - (-0.5833) = 1.7499 \text{ p.u.}$$

$$V_{ac} = V_a - V_c = 1.7499 \text{ p.u.}$$

$$V_{bc} = V_b - V_c = 0 \text{ p.u.}$$

$$\text{The line to line voltage,} V_{ab} = 1.7499 \times \frac{13.8}{\sqrt{3}} = 13.94 \text{ kV}$$

$$V_{ac} = 13.94 \text{ kV} \quad , \quad V_{bc} = 0 \text{ kV}$$

Ex. 3.10.4

An unloaded star connected solidly grounded 10 MVA, 11 kV generator has positive, negative and zero sequence impedances are j 1.3 Ω, j 0.8 Ω and j 0.4 Ω respectively. A single line to ground fault occurs at the terminals of the generator.

(i) Calculate the fault current.

(ii) Determine the value of the inductive reactance that must be inserted at the generator neutral to limit the fault current to 50% of the value obtained in (i).

Soln. :

$$\text{Base MVA} = 10 \text{ MVA.}$$

$$\text{Base kV} = 11 \text{ kV.}$$

Considering these base values the positive, negative and zero sequence reactance of alternator can be expressed in p.u. as,

$$X_1 = \frac{j\,1.3 \times 10}{11^2} = j\,0.107 \text{ p.u.}$$

$$X_2 = \frac{j\,0.8 \times 10}{11^2} = j\,0.066 \text{ p.u.}$$

$$X_0 = \frac{j\,0.4 \times 10}{11^2} = j\,0.033 \text{ p.u.}$$

(i) For LG fault

Fault current

$$I_f = I_a = 3\,I_{a1} = \frac{3\,E_a}{X_1 + X_2 + X_0} = \frac{3 \times 1}{j\,0.107 + j\,0.066 + j\,0.033} = -j\,14.56$$

$$\text{Actual fault current} = \frac{14.56 \times 10 \times 10^6}{\sqrt{3} \times 11 \times 10^3} = 7642 \text{ A.}$$

(ii) To find the value of the inductive reactance that must be inserted to control fault up to 50%.

$$I_f = -j\,7.28 \text{ p. u.} = \frac{E_a}{X_1 + X_2 + X_0 + 3X_n}$$

$$X_1 + X_2 + X_0 + 3\,X_n = \frac{3\,E_a}{I_f} = \frac{3}{-j\,7.\,28} = j\,0.412$$

$$j\,0.107 + j\,0.066 + j\,0.033 + 3\,X_n = j\,0.412$$

$$3\,X_n = j\,0.206$$

$$\therefore \quad X_n = j\,0.0687 \text{ p.u.}$$

$$\text{Actual reactance to be added} = j\,0.0687 \times \frac{11^2}{10} = 0.831\ \Omega.$$

Ex. 3.10.5

A 25 MVA, 13.2 kV alternator with solidly grounded neutral has a subtransient reactance of 0.25 p.u. The negative and zero sequence reactances are 0.35 and 0.1 p.u. respectively. Find the fault current when,

(i) A single line to ground fault occurs at the terminals of an unloaded alternator and

(ii) A LL fault occurs.

Soln. :

(i) For single line to ground fault

Fault current,

$$I_f = I_a = 3\,I_{a1} = \frac{3\,E_a}{X_1 + X_2 + X_0} = \frac{3 \times 1}{j\,0.25 + j\,0.35 + j\,0.1} = -j\,4.28 \text{ p.u.}$$

$$\text{Actual fault current} = 4.28 \times \frac{25 \times 10^6}{\sqrt{3} \times 13.2 \times 10^3} = 4680 \text{ A.}$$

(ii) For LL fault

$$\text{Fault current } I_f = \frac{\sqrt{3}\,E_a}{X_1 + X_2} = \frac{\sqrt{3} \times 1}{j\,0.25 + j\,0.35} = -j\,2.887 \text{ p.u.}$$

$$\text{Actual fault current} = \frac{2.887 \times 25 \times 10^6}{\sqrt{3} \times 11 \times 10^3} = 3788.2 \text{ A.}$$

Ex. 3.10.6

A 50 MVA, 11 kV, 3-phase alternator was subjected to different types of faults. The fault currents were : 3-ϕ fault, 1870 Amp, line to line fault 2590 A, single line to ground fault 4130 A. The alternator neutral is solidly grounded. Find p.u. values of sequence reactances of alternators.

Soln. :

(i) For 3 phase fault

$$\text{Fault current } I_f = \frac{\frac{E_a}{\sqrt{3}}}{X_1}$$

$$1870 = \frac{11 \times \frac{10^3}{\sqrt{3}}}{X_1} \qquad \therefore \quad X_1 = 3.39\Omega$$

(ii) For LL fault

$$\text{Fault current} \quad I_f = \frac{\sqrt{3}\,E_a}{X_1 + X_2}$$

$$X_1 + X_2 = \frac{\sqrt{3}\,E_a}{I_f}$$

$$X_1 + X_2 = \frac{\dfrac{\sqrt{3} \times 11 \times 10^3}{\sqrt{3}}}{2590} = 4.247$$

$$\therefore \quad X_2 = 0.851$$

(iii) For LG fault

$$\text{Fault current} \quad I_f = I_a = 3\,I_{a1} = \frac{3\,E_a/\sqrt{3}}{X_1 + X_2 + X_0}$$

$$\therefore \quad X_1 + X_2 + X_0 = \frac{\sqrt{3}\,E_a}{I_{al}}$$

$$\therefore \quad X_1 + X_2 + X_0 = \frac{\sqrt{3} \times 11 \times 10^3}{4130}$$

$$\therefore \quad X_1 + X_2 + X_0 = 4.613\ \Omega$$

$$\therefore \quad X_0 = 0.37\ \Omega$$

To find per unit reactance's.

$$\text{Base MVA} = 50\ , \qquad \text{Base kV} = 11$$

$$\therefore \quad \text{Base reactance} = \frac{11^2 \times 10^6}{50 \times 10^6}$$

$$X_B = 2.42$$

$$\therefore \quad X_1\,\text{p.u.} = \frac{3.396}{2.42} = 1.40\ \text{p.u.}$$

$$\therefore \quad X_2\,\text{p.u.} = \frac{0.851}{2.42} = 0.35\ \text{p.u.}$$

$$\therefore \quad X_0\,\text{p.u.} = \frac{0.37}{2.42} = 0.15\ \text{p.u.}$$

Ex. 3.10.7

A generator rated 100 MVA, 20 kV has $X_1 = X_2 = 20\%$ and $X_0 = 5\%$. Its neutral is grounded through reactor of 0.32 ohms. The generator is operating at rated voltage with load and is disconnected from the system when a single line to ground fault occurs at its terminals. Find the subtransient current in the faulted phase and line to line voltages.

Soln. :

Base MVA = 100 , Base kV = 20

$$\text{Base reactance} = \frac{(20\times10^3)^2}{100\times10^6} = 4\Omega$$

$$\text{P.U. Neutral reactance} = \frac{0.32}{4} = 0.08 \text{ p.u.}$$

For LG fault, fault current

$$I_f = I_a = 3\,I_{a1} = \frac{3\,E_a}{X_1 + X_2 + X_0 + 3\,X_f}$$

$$I_f = \frac{3\times1}{j0.2 + j0.2 + j0.05 + 3\times j0.08}$$

$$I_f = -j4\cdot347 \text{ p.u.}$$

$$I_{a1} = I_{a2} = I_{a0} = -j1\cdot449 \text{ p.u.}$$

$$\text{Actual fault current} = \frac{4.347\times100\times10^6}{\sqrt{3}\times11\times10^3} = 22{,}820 \text{ A.} = 22.82 \text{ kA.}$$

Line voltages :

$$V_{a1} = 1\angle0 - I_{a1}X_1 = 1\angle0 - (-j1.449)\times(j0.2)$$

$$= 1 - 0.2898 = 0.7102 \text{ p.u.}$$

$$V_{a2} = -I_{a2}X_2 = -(-j1.449)\times(j0.2) = -0.2898 \text{ p.u.}$$

$$V_{a0} = -I_{a0}(X_0 + 3X_f)$$

$$= -(-j1.449)\times(j0.05 + 3\times j0.08) = 0.42021 \text{ p.u.}$$

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix}\begin{bmatrix} -0.4202 \\ 0.7102 \\ -0.2898 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\angle-120 & 1\angle120 \\ 1 & 1\angle120 & 1\angle-120 \end{bmatrix}\begin{bmatrix} -0.4202 \\ 0.7102 \\ -0.2898 \end{bmatrix}$$

$$= \begin{bmatrix} 0 \\ -0.402 + 1\times0.7102\angle-120^\circ - 0.2898\angle120^\circ \\ -0.402 + 0.7102\angle120^\circ - 0.2898\angle-120^\circ \end{bmatrix}$$

$$= \begin{bmatrix} 0 \\ -0.6122 - j\,0.865 \\ 0.192 + j\,0.865 \end{bmatrix} = \begin{bmatrix} 0 \\ 1.06\angle54.71^\circ \\ 0.88\angle77.5^\circ \end{bmatrix}$$

Syllabus Topic : Analysis of Series Type Unsymmetrical Faults : One Open Conductor Faults, Two Open Conductor Fault

3.11 Analysis of Series Type Unsymmetrical Faults / Open Conductor Faults

- Open conductor faults are the faults in series with the line.
- Open conductor faults are :

i) One conductor open
ii) Two conductor open

➜ **i) One conductor open fault**

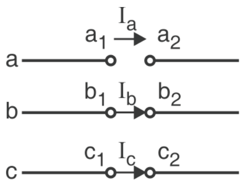


Fig. 3.11.1 : One conductor open fault

- Fig. 3.11.1 shows one conductor open fault.
- Assume that conductor a is open at $a_1 - a_2$ points.
- The current and voltage at fault point is given by,

$$I_a = 0$$

$$V_{b1\,b2} = V_{c1\,c2} = 0 \quad \ldots(3.11.1)$$

$$I_{a1} + I_{a2} + I_{a0} = 0 \text{ and } V_{(a1a2)\,1} = V_{(a1a2)2} = V_{(a1a2)\,0} = \frac{1}{3} V_{a1a2} \quad \ldots(3.11.2)$$

Where, $V_{(a1a2)\ 1}$, $V_{(a1a2)\ 1}$ and $V_{(a1a2)\ 0}$ are the positive, negative and zero sequence voltage of phase a.

The equations of sequence current and sequence voltage of phase a show a parallel connection of the sequence network as shown in Fig. 3.11.2.

Equation (3.11.2) indicates that the open conductor condition leads to equal series voltage drops in all the three sequence networks in the direction of current flow.

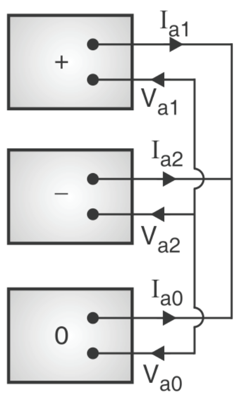


Fig. 3.11.2 : One conductor open equivalent sequence network

➜ ii) Two conductor open fault

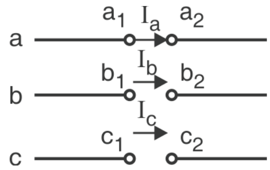


Fig. 3.11.3 : Two conductor open fault

- Fig. 3.11.3 shows two conductor open fault.
- The current and voltage at fault condition is given as,

$$\left.\begin{aligned} V_{a1\,a2} &= 0 \\ I_b = I_c &= 0 \end{aligned}\right\} \qquad \ldots(3.11.3)$$

The symmetrical currents and voltage equation for this faulty condition are given as,

$$V_{(a1a2)\,1} + V_{(a1a2)\,2} + V_{(a1a2)\,0} = 0$$

$$I_{a1} = I_{a2} = I_{a0} = \frac{1}{3} I_a \qquad \ldots(3.11.4)$$

Equation (3.11.4) indicates that the sequence networks for this fault are connected in series, as shown in Fig. 3.11.4.

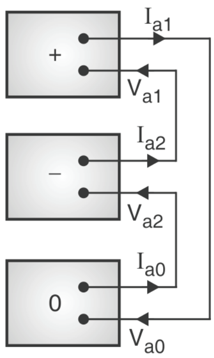


Fig. 3.11.4 : Two conductor open equivalent sequence network

Ex. 3.11.1

A 3 ph., 400 V Induction motor is operating on 3 ph., 400 V, 50 Hz balanced supply. The motor continues to run even when the fuse in phase A blows out causing open circuit in it. Determine the line currents and voltages $V_{a'a}$, V_{an} , V_{cn} and V_{Nn}. Assume positive and negative sequence impedance as (2.5 + j 0.5) and (0.6 + j1) ohms respectively and neglect source impedance.

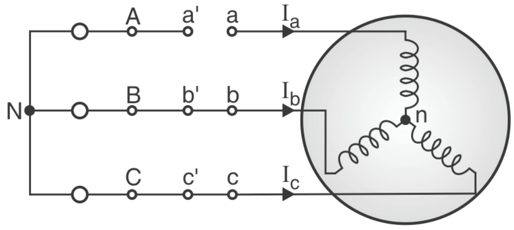


Fig. P. 3.11.1

Soln. :

Sequence network connections are as shown in Fig. P. 3.11.1(a). The zero sequence network is not connected because of absence of neutral wire.

$$I_{a2} = -I_{a1} \quad \ldots(1)$$

and $$V_{a'a1} = V_{a'a2} = V_{a'a0} \quad \ldots(2)$$

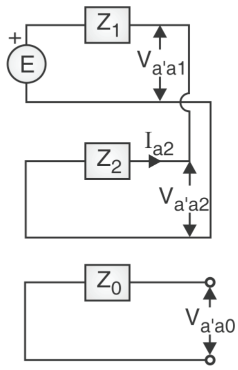


Fig. P. 3.11.1(a) : Sequence network

Applying Kirchhoff's second law to positive and negative sequence network.

$$V_{a'a1} = E - I_{a1} Z_1 \quad \ldots(3)$$

$$V_{a'a2} = -I_{a2} Z_2 \quad \ldots(4)$$

Substituting $I_{a2} = -I_{a1}$

and $V_{a'a1} = V_{a'a2}$ in Equation (4)

$$V_{a'a1} = I_a Z_2 \quad \ldots(5)$$

Substituting Equation (5) in Equation (3),

$$I_{a1} Z_2 = E - I_a Z_1$$

$$\therefore \quad I_{a1}(Z_1 + Z_2) = E$$

$$I_{a1} = \frac{E}{Z_1 + Z_2} = \frac{\frac{400\angle 0°}{\sqrt{3}}}{(2.5 + j0.5) + (0.6 + j1)}$$

$$I_{a1} = \frac{230.94 \angle 0°}{3.1 + j\,1.5} = 67.06 \angle -25.82° A$$

$$I_{a2} = -I_{a1} = -67.06 \angle -25.82° A$$

$$I_a = I_{a1} + I_{a2} = 0 \text{ A}$$

$$I_b = \alpha^2 I_{a1} + \alpha I_{a2} + I_{a0} \; \alpha^2 I_{a1} - \alpha I_{a1} + 0$$

$$= I_{a1}(\alpha^2 - \alpha) = 67.06 \angle -25.82° \times \sqrt{3} \angle -90°$$

$$= 116.15 \angle -115.82° \text{ Amp.}$$

$$I_c = -I_b = -116.15 \angle -115.82° \text{ Amp.}$$

$$V_{a'a2} = -I_{a2} \cdot Z_2 = 67.06 \angle -25.82° \times (0.6 + j1)$$

$$= 67.06 \angle -25.82° \times 1.17 \angle 59.04°$$

$$= 78.46 \angle 33.22° \text{ volts}$$

$$V_{a'a} = V_{a'a1} + V_{a'a2} + V_{a'a0} = 3\, V_{a'a2}$$

$$= 3 \times 78.46 \angle 33.22° = 235.38 \angle 33.22° \text{ Volts}$$

$$V_{an} = Z_1 I_{a1} + Z_2 I_{a2} = I_{a1}(Z_1 - Z_2)$$

$$= 67.06 \angle -25.82° \times (1.9 - j\,0.5)$$

$$= 67.06 \angle -25.82° \times (1.96 \angle 59.56°)$$

$$= 131.44 \angle 33.74° \text{ Volts}$$

$$V_{bn} = \alpha^2 Z_1 I_{a1} + \alpha Z_2 I_{a2} = (\alpha^2 Z_1 - \alpha Z_2) I_{a1}$$

$$= [(2.5 + j\,0.5)(-0.5 - 0.866) - (0.6 + j1)(-0.5 + j\,0.866)] I_{a1}$$

$$= 67.06 \angle -25.82° [(2.55 \angle 11.3°)(1 \angle 240°) - (1.17 \angle 59.04°)(1 \angle 120°)]$$

$$= 67.06 \angle -25.82° [(2.55 \angle 251.3° - 1.17 \angle 179.4°]$$

$$= 67.06 \angle -25.82° [-0.817 - 2.42 + 1.16 - 0.012]$$

$$= 67.06 \angle -25.82° [0.343 - 2.432]$$

$$= 67.06 \angle -25.82° \times 2.45 \angle -77.82°$$

$$= 164.3 \angle -103.6° \text{ Volts}$$

$$V_{cn} = \alpha Z_1 I_{a1} \times \alpha^2 Z_2 I_{a2} = I_{a1} (\alpha Z_1 - \alpha^2 Z_2)$$

$$= 67.06 \angle -25.82° \times [2.55 \angle 11.3 \times 1 \angle 120° - 1.17 \angle 59.04 \times 1 \angle 240°]$$

$$= 67.06 \angle -25.82° [2.55 \angle 131.3° - 1.17 \angle 299.04°]$$

$$= 67.06 \angle -25.82° [-1.68 + j\,1.91 - 0.56 + j1.02]$$

$$= 67.06 \angle -25.82° [2.24 + j\,2.93]$$

$$= 67.06 \angle -25.82° \times 3.69 \angle 52.6$$

$$= 247.45 \angle 26.78 \text{ Volts}$$

$$V_{Nn} = V_{a'a0} + V_{a'a2} = 78.46 \angle 33.22° \text{ Volts}$$

Exercise

Q. 1 Enlist the various un-symmetrical faults occurring in power system. **(Section 3.1)**

Q. 2 Draw the interconnection of sequence network for single line to ground fault and explain briefly. **(Sections 3.2)**

Q. 3 Draw the interconnection of sequence network for line to line fault on unloaded alternator. **(Section 3.3)**

Q. 4 Explain interconnection sequence network for double line to ground fault on unloaded alternator. **(Section 3.4)**

Q. 5 Explain line to line fault on power system and draw sequence network connection. **(Section 3.7)**

Q. 6 Draw a flow-chart for computer calculation of fault current. **(Section 3.10)**

Q. 7 Derive the expression for the fault current for a single line to ground fault as an unloaded generator. **(Section 3.2)**

Q. 8 Explain how fault current can be calculated when line to ground fault occur through a fault impedance Z_f. **(Section 3.8)**

Q. 9 Derive the double line to ground fault in a 3-phase alternator. **(Section 3.4)**

Q. 10 Draw and explain in brief a single line diagram of 3-phase balanced system. **(Section 3.5)**

3.12 University Questions and Answers

➔ May 2015

Q. 2(a) Derive the equation for fault current and develop the sequence network for LLG fault on an unloaded synchronous generator. *(Ans. : Refer section 3.4)* **(10 Marks)**

➔ Dec. 2015

Q. 3(a) Derive the equation for fault current for LLG fault. *(Ans. : Refer sections 3.4)* **(10 Marks)**

➔ May 2016

Q. 3(a) Derive the equation for fault current for LG fault. *(Ans. : Refer section 3.2)* **(10 Marks)**

➔ Dec.2016

Q. 3(a) Derive the equation for fault current for LL fault. *(Ans. : Refer section 3.3)* **(10 Marks)**

➔ May 2017

Q. 3(a) Discuss L-L fault in detail. *(Ans. : Refer section 3.3)* **(10 Marks)**

Chapter Ends...

❑❑❑

CHAPTER 4

Power System Transients

Syllabus :

Review of transients in simple circuits, recovery transient due to removal of short circuit, arcing grounds, capacitance switching, current chopping phenomenon.
Travelling waves on transmission lines, wave equation, reflection and refraction of waves, typical cases of line terminations, attenuation, Bewely lattice diagram.
Lightning phenomenon, mechanism of lightning stroke, shape of lightning voltage wave, over voltages due to lighting, lightning protection problem, significance of tower footing resistance in relation to lightning, insulator flashover and withstand voltages, protection against surges, surge arresters, surge capacitors, surge reactor and surge absorber, Lightning arresotrs and protective characteristics, dynamic voltage rise and arrester rating.

4.1 Introduction

– Power system operates in steady state. But the abnormal operations in system will make it unstable.

– The transients are produced in the system due to such abnormal operations.

– The various abnormal operating conditions of power system are,

  (i) Switching operation i.e. opening and closing a switch.

  (ii) Sudden change in the load

  (iii) Sudden short circuit (line to ground fault, line to line fault, 3 phase short circuit fault etc.)

  (iv) Lightning discharge

– These abnormal operations produce a current and voltage in a system which are higher in magnitude compared to that in steady state condition. Such current and voltages are known as transient current and transient voltages.

– It may damage the equipment in power system. Hence it is necessary to protect the system.

– In this unit we will study the transients produced in simple circuit, transients produced in alternator when a three phase short circuit occurs at its terminal, concept of restriking voltage produced after removal of short circuit, concept of travelling waves, it's attenuation, transients produced due to capacitance switching and over voltages due to arcing ground.

Syllabus Topic : Review of Transients Simple Circuit

4.2 Review of Transients Simple Circuit

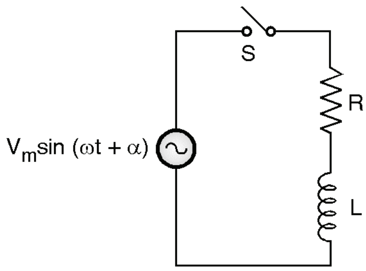


Fig. 4.2.1 : Series R-L circuit

– Fig. 4.2.1 shows a simple series R-L circuit fed from a sinusoidal AC source. When switch S is closed, the circuit equation is,

$$Ri + L\frac{di}{dt} = V_m \sin(\omega t + \alpha) \qquad \ldots(4.2.1)$$

– Where i is instantaneous value of current. The parameter α controls the instant on the voltage wave when switch is closed. Equation (4.2.1) can be solved to obtain current i as,

$$i = \frac{V_m}{\sqrt{R^2 + \omega^2 L^2}} \sin(\omega t + \alpha - \theta) \qquad \ldots(4.2.2)$$

$$i = \frac{V_m}{Z} \sin(\omega t + \alpha - \theta) \qquad \ldots(4.2.3)$$

Where, $Z = \sqrt{R^2 + \omega^2 L^2}$, $\theta = \tan^{-1}(\omega L/R)$

Initial condition is, $L\frac{di}{dt} + Ri = 0$

$$\therefore \quad i = A \cdot e^{-Rt/L} \qquad \ldots(4.2.4)$$

Hence complete solution of Equation (4.2.1) is,

$$i = \frac{V_m}{Z} \sin(\omega t + \alpha - \theta) + A \cdot e^{-Rt/L} \qquad \ldots(4.2.5)$$

Constant A can be found from initial condition that at t = 0, i = 0.

$$\frac{V_m}{Z} \sin(\omega t + \alpha - \theta) + A \cdot e^{-Rt/L} = 0$$

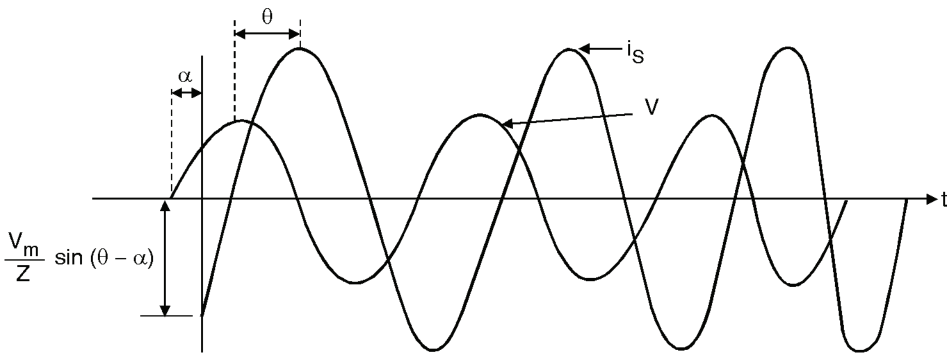
$$\therefore \quad A = -\frac{V_m}{Z} \sin(\alpha - \theta) \qquad \text{....(4.2.6)}$$

Hence the final solution is,

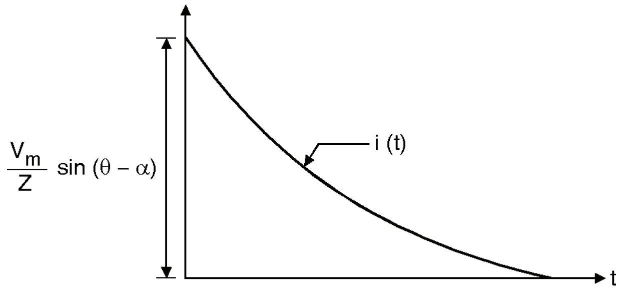
$$i = \frac{V_m}{Z} \sin(\omega t + \alpha - \theta) - \frac{V_m}{Z} \sin(\alpha - \theta) \cdot e^{-\frac{Rt}{L}}$$

$$i = \frac{V_m}{Z} \sin(\omega t + \alpha - \theta) + \frac{V_m}{Z} \sin(\theta - \alpha) \cdot e^{-\frac{Rt}{L}} \qquad \text{...(4.2.7)}$$

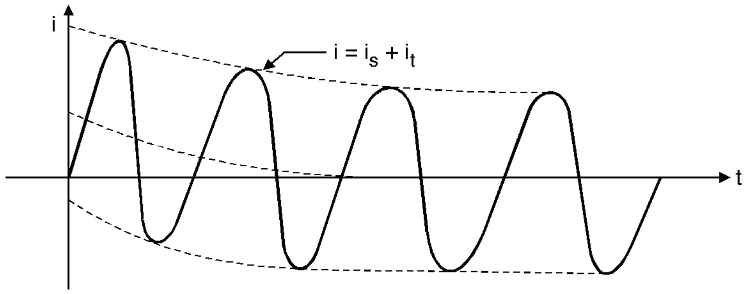
- In Equation (4.2.7) the current I has two components. The first component is steady state current or also called as ac sinusoidal component. It's amplitude is V_m/Z and is lagging the voltage phasor by an angle θ. The second component is a transient current or also known as DC offset current.
- It decays exponentially corresponding to time constant L/R. The waveform is shown in Fig. 4.2.2. D.C. offset current causes the total current to be unsymmetrical till the transient decay.
- If switching takes place at an instant when $\alpha = \theta$, the DC component will be zero and the current wave will be symmetrical.
- If switch is closed when $\alpha - \theta = \pm \frac{\pi}{2}$ the dc component will be maximum and the first peak of resultant current i becomes twice the peak value of the final steady state current. This is known as doubling effect.



(a) Symmetrical current
Fig. 4.2.2 (Cont…)



(b) DC offset current



(c) Resultant current

Fig. 4.2.2 : Current waveform in series R-L circuit

4.3 Sudden Short Circuit of an Alternator

- During abnormal operation, the alternator may be subjected to transient conditions.
- These short circuits may develop severe mechanical stresses on the armature coil.
- This develops large torque which may damage alternator or its prime mover. Hence it is necessary to protect alternator. The analysis of alternator under transient conditions is useful in predicting the possible condition that may result from abnormal operations.
- During short circuit analysis, armature and field winding of alternator is assumed to be purely inductive as they do not contain any capacitance and their resistances are almost negligible. Due to this the flux linkages in the armature or field circuit cannot be changed suddenly by application of short circuit to armature winding.
- The current flowing in the armature of alternator when it's terminals are short circuited is similar to that flowing in series R-L circuit. However in series R-L circuit reactance is constant quantity and in alternator it is a function of time.

- Let's assume that the alternator is operating at no load condition. Under normal operating there is no mmf due to armature reaction.
- When a three phase short circuit occurs at the terminals of alternator the current in armature increases to a large value.
- As the resistance of winding is negligible compared to its reactance, the current is highly lagging and power factor is approximately zero.
- This sudden increase in armature current produces armature reaction. Air gap flux cannot change instantaneously.
- The armature reaction opposes the main excitation.
- To counter this demagnetisation currents appear in the field winding and damper winding in a direction to help main flue.
- Thus in the initial part of the short circuit the equivalent circuit of alternator appears as shown in Fig. 4.3.1. Under steady state condition the armature reaction of alternator produces demagnetizing flux. This effects modelled as X_a.
- The short circuit current decay in accordance with winding time constants.
- The time constant of the damper winding is much less than the of field winding.
- Damper winding has low leakage inductance and field winding has high leakage inductance.
- In the initial part of short circuit the damper winding and field winding have transformer currents induced in them.
- Hence in the circuit model their reactance X_f and $X_{d\omega}$ appear in parallel with X_a. As damper winding currents are first to die out, $X_{d\omega}$ effectively becomes open circuited.
- At later stage X_f becomes open circuited. The machine reactance changes from the parallel combination of X_a, X_f and $X_{d\omega}$ during initial period of short circuit to X_a and X_f in parallel in the middle period of short circuit and finally to X_a in steady state. This is shown in Fig. 4.3.1.
- The reactance of machine in the initial period of short circuit is called as subtransient reactance of machine. It is expressed as X_d'' and given as,

$$X_d'' = X_f + \frac{1}{(1/X_a + 1/X_f + 1/X_{d\omega})} \qquad \ldots(4.3.1)$$

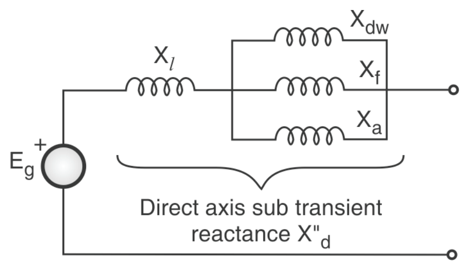
– The reactance effective after damper winding currents have died out is called as transient reactance. It is expressed as X_d' and given as,

$$X_d' \;=\; X_f + (X_a \parallel X_f) \qquad \text{...(4.3.2)}$$

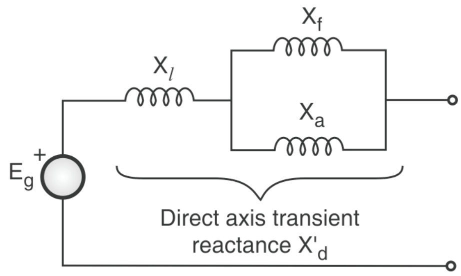
– The reactance under steady state condition is the synchronous reactance of the machine. Obviously,

$$X_d'' \;<\; X_d' < X_d \qquad \text{...(4.3.3)}$$

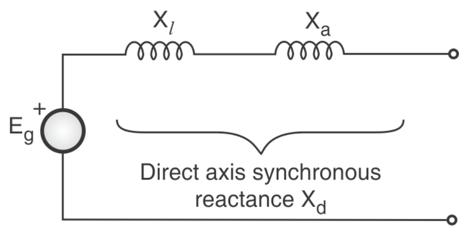
Thus machine offers a time varying reactance.



(a) Circuit model during sub-transient period of short circuit



(b) Circuit model during transient period of short circuit



(c) Steady state short circuit model

Fig. 4.3.1 : Equivalent circuits of alternator during sub transient, transient and steady state period of short circuit

4.3.1 Analysis of Short Circuit Current

– When short circuit occurs at the terminals of synchronous generator, the initial short circuit current is limited by the sub-transient reactance.

- The short circuit current consist of symmetrical component and dc component.
- As the voltage of three phases are 120° apart, the short circuit occurs at different points on the voltage of each phase.
- Hence the DC component will be different in each phase.
- If DC component is neglected, the oscillogram of the armature current is as shown in Fig. 4.3.2.
- Initially the current is limited by sub-transient reactance, for few cycle then controlled by transient reactance and finally it settles down to steady state value limited by synchronous reactance of machine.
- The total short circuit period can be divided into three periods.

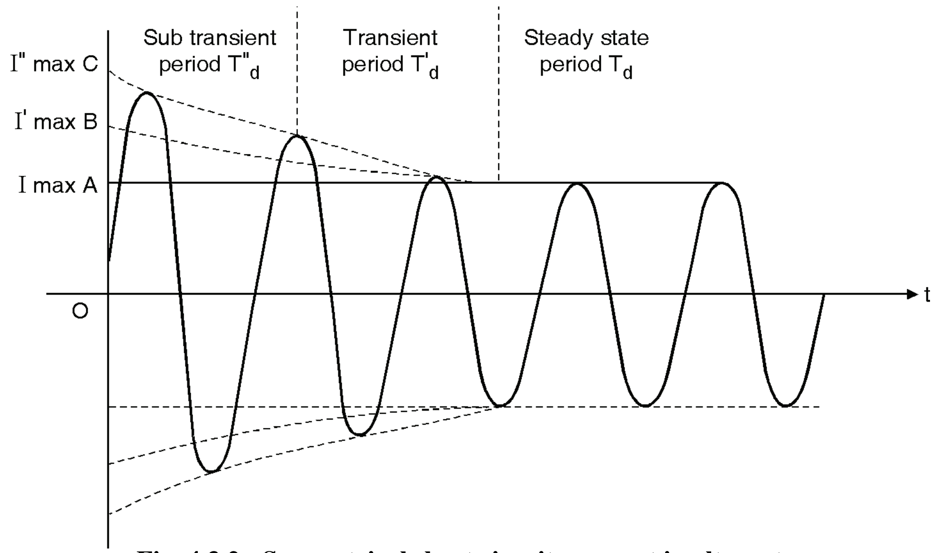


Fig. 4.3.2 : Symmetrical short circuits current in alternator

Subtransient period

- Lasting only for first few cycles during which the current decrement is rapid.
- Transient period covering relatively larger time during which current decrement is moderate and finally steady state period. Thus the corresponding current is,

$$|I| = \frac{OA}{\sqrt{2}} = \frac{|E|}{X_d}$$

$$|I'| = \frac{OB}{\sqrt{2}} = \frac{|E|}{X'_d}$$

$$|I''| = \frac{OC}{\sqrt{2}} = \frac{|E|}{X''_d}$$

Where, $|E|$ is rms value of phase voltage

$|I|$ is rms value of steady state short circuit current

$|I'|$ is rms value of transient current

$|I''|$ is rms value of subtransient current

X_d is direct axis synchronous reactance

X'_d is direct axis transient reactance

X''_d is direct axis subtransient reactance

Syllabus Topic : Recovery Transient due to Removal of Short Circuit

4.3.2 Restriking Voltage after Removal of Short Circuit

→ (MU - May 16)

Q. 4.3.1 Discuss the phenomenon of transient due to removal of short circuit.
(Refer section 4.3.2) **May 16, 10 Marks**

- When the circuit is opened under fault condition it produces a transient known as recovery voltage transient. This transient affect the behaviour of circuit interrupting and protective devices. Fig. 4.3.3 shows a simple circuit in which a load is fed through circuit breaker. Occurrence of fault suddenly isolates the load.
- During this time heavy fault current flows through the circuit which is limited by inductance. C is the natural capacitance of the circuit adjacent to the circuit breaker.
- Circuit breaker contacts are opened to clear the fault. This it self will not interrupt the current as the arc will be produced between the contacts. So current will continue to flow through the arc.
- Successful interruption of current depends upon controlling and final extinguishing of arc. Interruption is affected at the instant when current is zero. For the analysis of circuit, the time is measured from the instant of fault interruption.

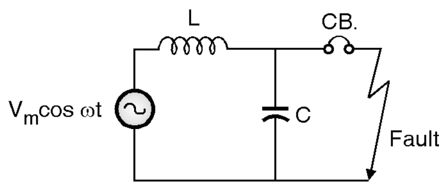


Fig. 4.3.3

The circuit equation is,

$$L\frac{di}{dt} + V_c = V_m \cos \omega t \qquad \ldots(4.3.4)$$

Where, i is current through circuit breaker.

V_c is voltage across circuit breaker

i and V_c are related as,

$$i = C\frac{dV_c}{dt} \qquad \ldots(4.3.5)$$

From Equations (4.3.4) and (4.3.5)

$$\frac{d^2V_c}{dt^2} + \frac{V_c}{LC} = \frac{V_m}{LC}\cos \omega t \qquad \ldots(4.3.6)$$

Taking Laplace transform of Equation (4.3.6) and substituting ω_0^2 for 1/LC,

$$P^2V_c(s) - s\,V_c(0) - V_c'(0) + \omega_0^2\,V_c(s) = \omega_0^2\,V_m + \frac{s}{s^2+\omega^2} \qquad \ldots(4.3.7)$$

Where, $V_c(s)$ is Laplace transform of V_c

$V_c\,(0)$ is the value of V_c at t = 0

$V_c'(0)$ is the value of $\frac{dV_c}{dt}$ at t = 0

Neglecting arc voltage $V_c(0)$ is zero from Equation (4.3.5),

$$V_c'(0) = \frac{i(0)}{C} = 0$$

Settling $V_c(0)$ and $V_c'(0)$ equal to zero. Equation (4.3.7) is,

$$V_c(s) = \omega_0^2 V_m \frac{s}{(s^2+\omega^2)(s^2+\omega_0^2)} = \frac{\omega_0^2 V_m}{\omega_0^2-\omega^2}\left[\frac{s}{s^2+\omega^2} - \frac{s}{s^2+\omega_0^2}\right] \qquad \ldots(4.3.8)$$

Taking inverse from of Equation (4.3.8),

$$V_c = \frac{\omega_0^2}{\omega_0^2-\omega^2}V_m(\cos \omega t - \cos \omega_0 t) \qquad \ldots(4.3.9)$$

Generally $\omega_0 >> \omega$, so that $\omega_0^2/\omega_0^2 - \omega^2 \simeq 1$.

$$\therefore \quad V_c = V_m(\cos \omega t - \cos \omega_0 t) \qquad \ldots(4.3.10)$$

– The natural frequency oscillation persist for small interval. During this interval the change in the power frequency is very small and neglected. Then.

$$V_c = V_m(1 - \cos \omega_0\, t) \qquad \ldots(4.3.11)$$

- Fig. 4.3.4 shows transient recovery voltage across the circuit breaker.
- After removal of fault, the source charges the capacitance. The inertia of circuit inductance causes an over swing of the voltage.
- The system losses damp the oscillations provided during this period.
- The voltage V_c is transient recovery voltage.
- If natural frequency ω_0 is high the voltage across circuit breaker contacts rise quickly to high magnitude.
- If this rate of rise of recovery voltage exceeds the rate of rise of build up of the electric strength of the space between the contacts, the arc will restrike.
- This will delay the circuit interruption for further half cycle.
- Due to possibility of restriking of the arc, the transient recovery voltage is also known as restriking voltage.

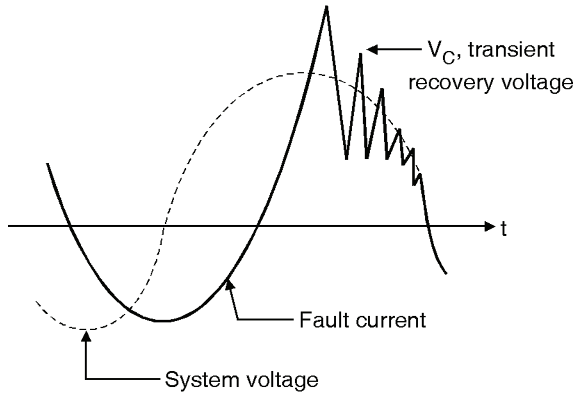


Fig. 4.3.4 : Transient recovery voltage across circuit breaker

Syllabus Topic : Arcing Grounds

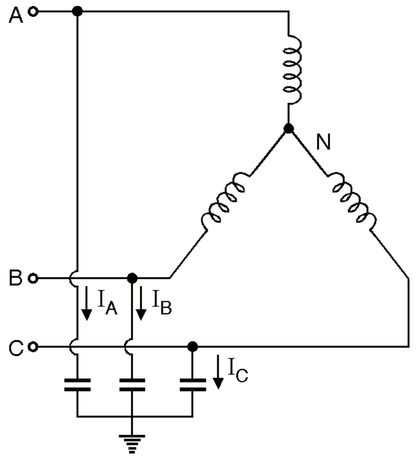
4.4 Arcing Grounds

➔ (MU - Dec. 15)

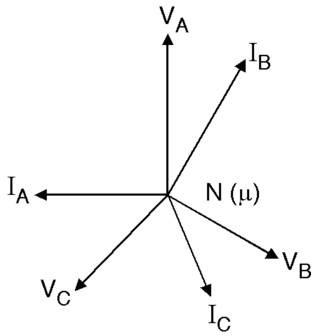
Q. 4.4.1 Discuss the phenomenon of arcing ground. *(Refer section 4.4)* **Dec. 15, 10 Marks**

- A Fault current which involves arc path may produce very high transient voltages. In an isolated neutral system during a single line to ground fault an intermittent arcing may take place.

- This phenomenon is called as arcing ground. A three phase isolated neutral system is shown in Fig. 4.4.1(a).
- Each line conductor has the same capacitance to ground as the lines are transposed.
- Under healthy operating conditions the three capacitance currents are equal and balanced as shown in Fig. 4.4.1(b).



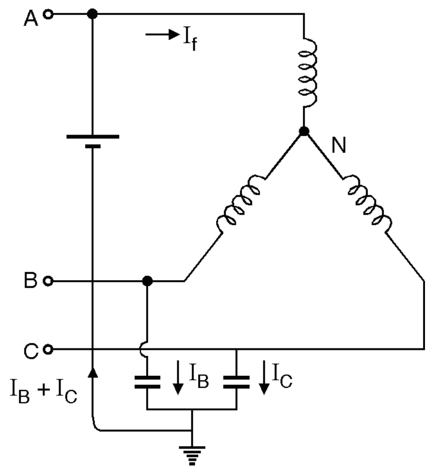
(a) 3 ph isolated neutral system under healthy operating condition



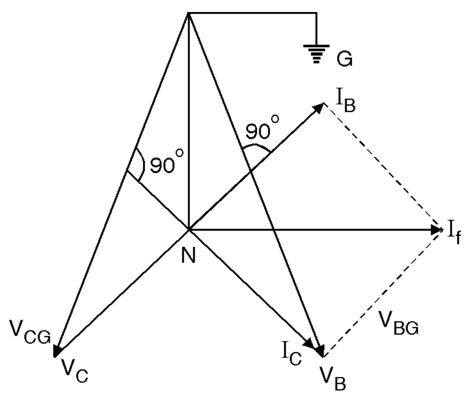
(b) Phasor diagram showing capacitance current
Fig. 4.4.1

- Consider that a single line to ground fault takes place on line A. This will short circuit the capacitance of line A and voltage of that phase becomes zero.
- The potential of healthy phase increases to a value equal to line to line voltage. The currents flowing from these healthy phases to ground is equal to $\sqrt{3}$ times the previous current.

- These currents have a different phase relationship as shown in Fig. 4.4.1(b). These currents returns through fault and sufficient to support an arc. In this way the arcing ground is established. It may flashover the insulators. It is a trouble if the arc appears across circuit breakers.
- The system will try to come to its balanced condition if the arc is momentarily interrupted at a current zero. At the moment of Arc extinction C_A is discharged but C_B and C_C have considerable voltage across them. The charges of these capacitors remain trapped.
- This voltage will superimpose the power frequency voltage variations. As the circuit has inherent inductance, the changes in voltage across the capacitance are of oscillatory nature.
- This will cause the arc to restrike and cause further transient disturbance.
- Due to trouble of arcing grounds power systems are rarely operated with insulated neutral.
- To overcome such troubles the neutral is grounded solidly or through resistance or reactance.



(a) Circuit showing single line to ground fault on phase A of isolated neutral system



(b) Phasor diagram
Fig. 4.4.2

Syllabus Topic : Capacitance Switching

4.5 Capacitance Switching

→ **(MU - Dec. 16)**

Q. 4.5.1	Discuss the phenomenon of capacitance switching. *(Refer section 4.5)* **Dec. 16, 10 Marks**

- A hazardous condition occurs in power system when a capacitor bank connected to long transmission line is disconnected.
- Consider a power system shown in Fig. 4.5.1(a). L is a source inductance and C is the capacitor bank connected to a system through switch S.
- Let us consider that the switch S interrupts the capacitance current at instant A. At this instant the capacitor is charged to its maximum value E_m. As the capacitor is isolated from the source, it retains this charge.
- At instant B (half cycle later) the voltage across switch reaches a peak value of 2 E_m. This voltage reignite the arc and cause oscillatory transient.
- After resignation the current in the circuit is given as,

$$i_{(E)} = \frac{-2\,E_m}{\sqrt{L/C}} \sin\left(\frac{t}{\sqrt{LC}}\right) \qquad \text{...(4.5.1)}$$

The transient voltage across capacitor is,

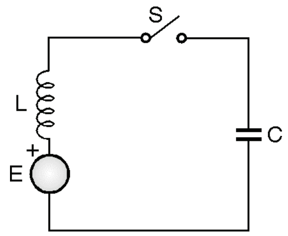
$$= -2E_m\,(1 - \cos t/\sqrt{LC}\,) \qquad \text{...(4.5.2)}$$

It is high frequency transient voltage.

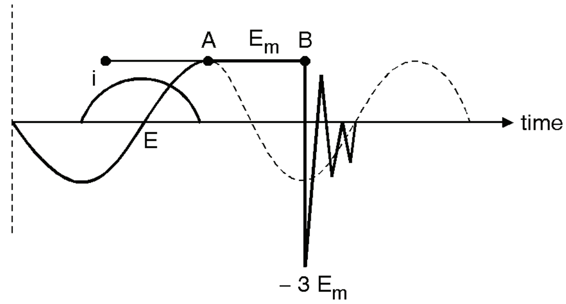
The voltage across the capacitor = Initial voltage across capacitor + High frequency transient voltage

$$= E_m - 2E_m\,(1 - \cos\,(\,t\,/\,\sqrt{LC}\,) \qquad \text{...(4.5.3)}$$

- This can increase upto a maximum value of – 3 E_m as shown in Fig. 4.5.1(b). Interruption of circuit or a second restrike can cause still higher voltage.



(a) Circuit of switching off a capacitor bank connected to line



(b) Voltage build up

Fig. 4.5.1

Syllabus Topic : Current Chopping Phenomenon

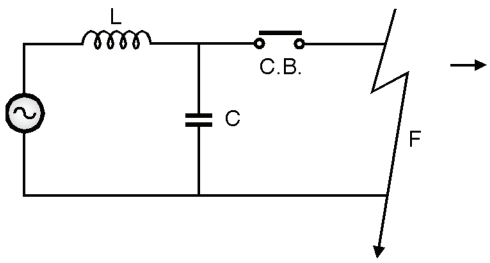
4.6 Current Chopping

- It is the phenomena of current interruption before natural current zero is reached. This occurs mainly in air blast circuit breaker because they retain same extinguishing power irrespective of the magnitude of current to be interrupted.
- When interrupting low inductive current e.g. magnetizing current of transformer, a rapid deionising effect causes current, to fall to its zero value before natural current zero this is called currents chopping.
- Consider the Fig. 4.6.1(a) and (b) shown i arc is current at point 'a' when chopping is done i.e. it is made zero. So energy stored in the inductance i.e. it is made zero. So energy stored in the inductance i.e. $\frac{1}{2}$ Li^2 is transferred to the capacitor which charges it latter to a voltage.

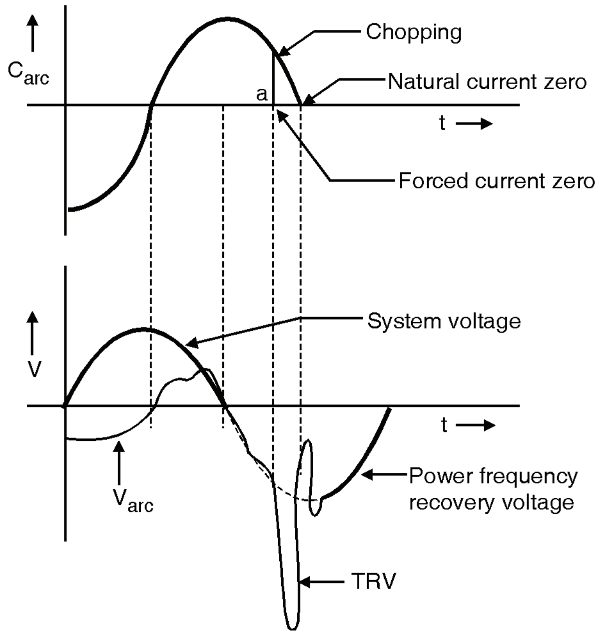
$$v = i\sqrt{\frac{L}{C}}$$

$$\frac{1}{2}Li^2 = \frac{1}{2}CV^2 \text{ J} \qquad \text{and} \qquad f_n = \frac{1}{2\pi\sqrt{LC}}$$

$$v = i\sqrt{\frac{L}{C}}$$



(a) Circuit



(b) Waves current chopping

Fig. 4.6.1

- This voltage is very high, such a transient voltage. This high voltage causes restriking of arc before the voltage reaches its maximum value.
- Restriking of arc draws energy from capacitor and so voltage across capacitor decreases.
- The point to which this restriking voltage will rise will depend on RRRV. If it is less then time taken to reach maximum value is more and deionising effect will be more predominant.
- Deionising effect which is still in action will produce second current Chop. This value of current is smaller than previous one.
- Again restriking voltage builds up having high RRRV appears across the contacts, unless the arc continues.
- If arc restrikes further several chops may occur before the final interruption of current and circuit breaker may fail to clear the fault. If restriking does not occur, a very high voltage appears across the contacts.

Syllabus Topic : Travelling Wave on Transmission Lines

4.7 Travelling Wave on Transmission Lines

➔ (MU - Dec. 16)

Q. 4.7.1 Discuss the phenomenon of traveling wave on case of termination of line as open circuit. *(Refer section 4.7)* **Dec. 16, 10 Marks**

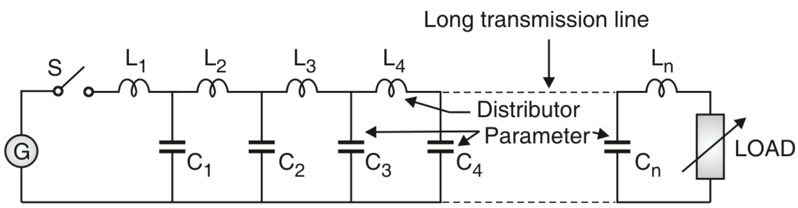


Fig. 4.7.1

- We can represent a long transmission line by π circuit of distributed L and C parameters as shown in the following Fig. 4.7.1.
- This circuit has the ability to support of travelling waves voltages and current. It has a finite velocity of **electromagnetic field propagation.**
- In such a circuit the changes in the current and voltages owing to lightening and switching do not appear simultaneously in all the parts of the circuit but spread out in the form of travelling waves or surges.
- Takes the instant of switch 'S' made 'ON'. At this instant complete line is not energised instantly but takes finite time to reach voltage / current at far end.
- At this instant inductance 'L' acts as an open circuit and C as short circuit instantly. But next sections are uncharged as voltage across C_1, is zero. In fraction of time, C_1 is charged to some value, the chain starts charging C_2 ... C_3, and gradually the line gets charged.
- This gradual build-up of voltage over a transmission line conductors can be regarded a voltage wave travelling one to other end. The gradual charging of capacitances is due to associated current wave.
- A current wave which is accompanied by a voltage wave sets up a magnetic field in the surrounding space. Reflections and refractions of these surges are produced at junctions and terminations in the line.

Syllabus Topic : Wave Equation

4.7.1 Wave Equation

Let us derive the following relations from the basic terms.

(i) Surge Impedance (Z_s) or Natural Impedance (Z_n)

$$Z_s \text{ or } Z_n = \sqrt{\frac{L}{C}}$$

(ii) Velocity of propagation (υ)

$$\upsilon = 3 \times 10^8 \text{ m/sec}$$

Let,

L : Inductance (in Heneries) per m length of line

C : Capacitance of line per unit length of line

E : Voltage along the length (volts)

I : Current in line

υ = Velocity of propagation m/sec.

$\in_o$ = Permittivity of air = $\boxed{\frac{1}{36\pi} \times 10^{-9}}$

$\in_r$ = 1 relative permittivity

Let us represent the line and a switch to energize the line when made 'ON'.

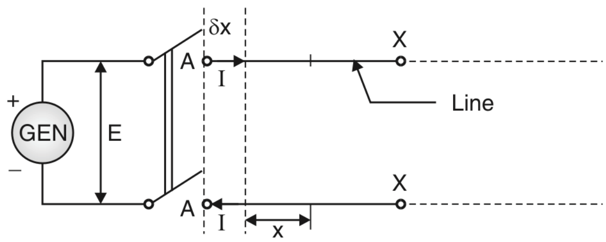


Fig. 4.7.2

– Take a small length of line δx and small time interval δt current I and voltage E along the length is produced.

– Current produces magnetic flux back, EMF is generated, it balances E in this length of line.

$\therefore$ Inductance in length $\delta x = L \times \delta x$

$\therefore$ flux built up $= I \times (L \times dx)$

Using relation as, $$L = \frac{N\phi}{I}$$

$$N = \text{Unity}$$

$$\therefore \quad \phi = I \times L$$

$\therefore$ Rate of built of flux gives rise to back EMF.

With this base, Let us prove that

(i) $Z_s = \sqrt{\frac{L}{C}}$ (ii) $\upsilon = 3 \times 10^8$ m/sec

So we have $E = IL \frac{\delta x}{\delta t} = IL\,\upsilon$ …(i)

Where υ is the velocity propagation of wave.

- The current I carries a charge I δt in the time δt, and this charge remains on the line to charge it upto the potential of E.
- Since the capacitance of length δx of the line is C δx (C is the capacitance of the line per unit length), It's charge is E C δx, so we have

$$I\,\delta t = EC\,\delta x$$

$$\text{Or} \quad I = E\,C \frac{\delta x}{\delta t} = E\,C\,\upsilon \qquad \text{…(ii)}$$

Thus switching on, an EMF on to the line. We got the relation of υ and also of I.

See Equations (i) and (ii).

- Dividing Equation (i) by Equation (ii) we get,

$$\frac{E}{I} = \frac{I\,L\,\upsilon}{E\,C\,\upsilon} = \frac{I}{E} \cdot \frac{L}{C}$$

$$\text{Or} \quad \frac{E^2}{I^2} = \frac{L}{C}$$

$$\text{Or} \quad \frac{E}{I} = \sqrt{\frac{L}{C}} = Z_n \text{ (Say)} \qquad \text{…(iii)}$$

- This is the ratio of voltage to current giving rise to impedance. This impedance Z_n is called as natural impedance or surge impedance Z_s. Whose value depend only on. Line constant, Value of surge impedance -

$$\boxed{\begin{aligned} Z_s &= 400\ \Omega \text{ to } 600\ \Omega \text{ for overhead line} \\ Z_s &= 40\ \Omega \text{ to } 60\ \Omega \text{ for cables.} \end{aligned}}$$

Now, To derive the relation of velocity of propagation (υ)

Take the multiplication of the derived Equation (i) of E and Equation (ii) of current (I).

$$EI = IL\upsilon \times EC\upsilon = E\,I\,L\,C\,\upsilon^2$$

$$\text{Or} \quad \upsilon^2 = \frac{1}{LC}$$

$$\text{Or} \quad \upsilon = \sqrt{\frac{1}{LC}} \qquad \ldots\text{(iv)}$$

Substituting the values of L and C for overhead lines in above expression, we have

$$\upsilon = \frac{1}{2 \times 10^{-7} \log_e \frac{d}{r} \times \frac{2\pi\varepsilon_0 \varepsilon_r}{\log_e \frac{d}{r}}}$$

For an overhead line $L = 2 \times 10^{-7} \log_e \frac{d}{r}$ H/m and $C = \frac{2\pi\varepsilon_0 \varepsilon_r}{\log_e \frac{d}{r}}$ F/m

$$= \frac{1}{\sqrt{4\pi\varepsilon_0 \times 10^{-7}}} = \frac{1}{\sqrt{4\pi \cdot \frac{1}{36\pi} \times 10^{-9} \times 10^{-7}}}$$

$$= 3 \times 10^8 \text{ m/s}$$

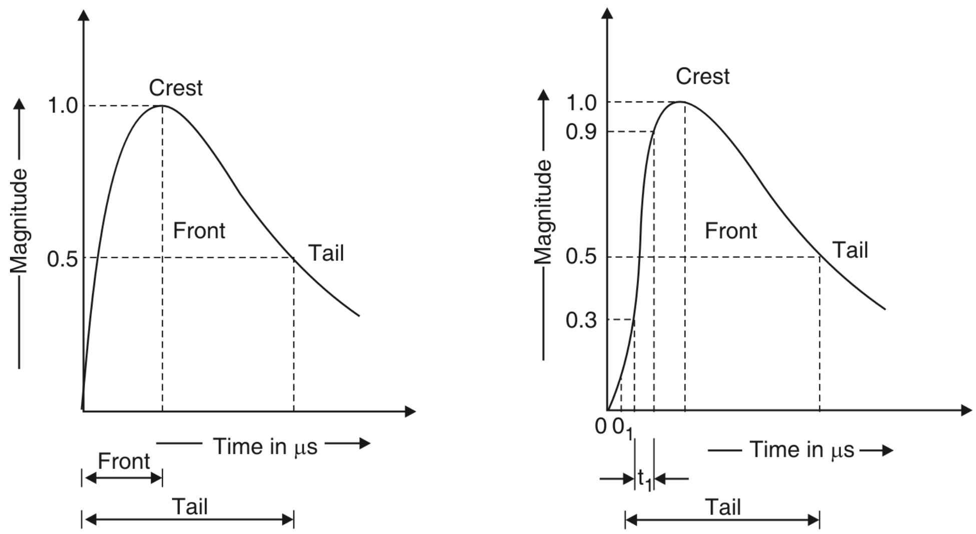
$\therefore$ Velocity of propagation $\upsilon = 3 \times 10^8$ m/s ...(v)

- This is same for all overhead lines as L and C is same for all lines.
- This value of υ is same as υ of **'light'.**
- This derived value is for the resistance less line.
- In actual case when resistance is also considered along with L and C the υ is lesser by 5 to 10 % than the derived value of υ. υ = 285 m/µsec.
- In comparison with overhead line, in case of cable, υ is much less because for air $\in_r = 1$ and for soil $\in_r > 1$ i.e. dielectric constant.

$\in_r$ is in between 2.5 to 4. For cables

$$\boxed{\upsilon \text{ for cable} = \frac{3 \times 10^8}{\sqrt{\in_r}}} \qquad \ldots\text{(vi)}$$

4.7.1.1 Shape and Specifications of Travelling Wave



(a) High initial rate of rise **(b) Slow initial rate of rise 0_1**

Fig. 4.7.3 : Travelling wave

Fig. 4.7.3(a) shown the wave form of high initial rate of rise.

Fig. 4.7.3(b) shown the wave form of slow initial rate of rise of a long toe.

Let us describe the wave shape for the specifications like crest, front, tail etc.

(1) Crest : It is expressed in kV or kA. Crest is the maximum amplitude of the wave (See Fig. 4.7.3)

(2) Front : It is expressed in ms or μs. The front of the wave is the portion of the wave before the crest. Time is measured from the beginning, up to crest. (See Fig. 4.7.3)

In Fig. 4.7.3(b) of slow initial rate, virtual front is considered which is determined by straight lines between 30% and 90% points (see Fig. 4.7.3(b)).

The virtual front is $1.667 \times t_1$. The extension of this straight line to X-axis gives 0_1 i.e. virtual zero.

(3) Tail : It is expressed in μsec.

This is the portion of the wave beyond crest. The time is measured from the beginning of wave upto the wave reduction to 50% of its values at crest. (see Fig. 4.7.3)

See Fig. 4.7.3(b) of slow initial rate of long toe type, its tail time is measured from 0_1 to 50% values on tail.

(4) Polarity : It is the polarity of crest voltage or current.

The way in which it is expressed as + 500 / 1.0 / 25.0

In this expression the first Fig. 4.7.3(a) is 500 kV crest second Fig. 4.7.3(b) is 1 μsec front and the 3rd stands for tail of 25 μsec.

Step wave is represented as shown Fig. 4.7.4 :

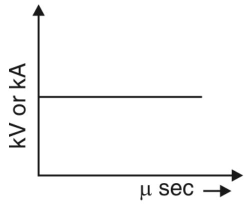


Fig. 4.7.4

Such wave jumps suddenly from zero to full value and is maintained at that value thereafter.

Syllabus Topic : Reflection and Refraction of Waves

4.7.2 Reflection and Refraction of Waves

→ (MU- May 17)

Q. 4.7.2 Discuss the reflection and refraction of voltage and current wave on an short circuit transmission line. *(Refer section 4.7.2)* **May 17, 10 Marks**

- As discussed in sections 4.7 reflections and refractions of the surges / waves are produced at the junctions and terminations in the line. Impedance suddenly changes at these points and even at loading points, line cable junctions and even faults constitute such discontinuities.
- Independent waves meeting along a line will combine in accordance with their polarity to provide different voltage and current levels at the meeting point.
- Standard sign conversions are adopted :
  - o Forward waves of current and voltages are given **same polarities.**
  - o If the wave is being reflected the corresponding current and voltage waves are given **opposite polarity.**
  - o **Illustration :** Wave of current and voltage being transmitted along line of characteristic impedance Z_C, terminated by an impedance Z.

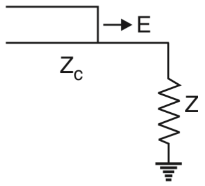


Fig. 4.7.5 : Line terminated impedance Z

Let us see the various relations of voltage currents, impedances and co-efficients.

Let, E and I represent incident waves

E_T and I_T represent transmitted waves

(Transmitted waves are also called as refracted waves)

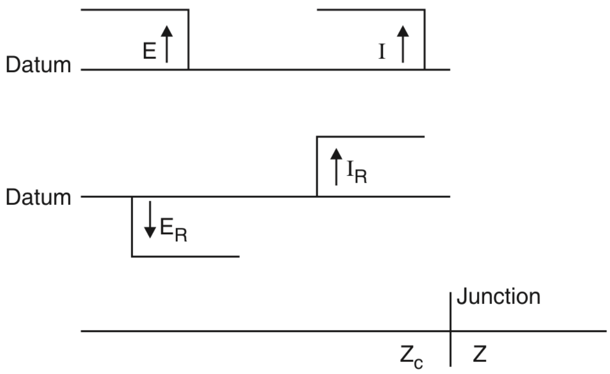


Fig. 4.7.6 : Transmission and Reflection at discontinuities

- E_R and I_R represent reflected waves see these illustrations in the above Fig. 4.7.6.
- Incident, transmitted (refracted), and reflected voltage and currents can be written by the following relations.

$$E = I \cdot Z_C \qquad \text{...(vii)}$$

$$E_T = I_T \cdot Z \qquad \text{...(viii)}$$

$$E_R = -I_R \cdot Z_C \qquad \text{...(ix)}$$

Note : Negative sign because E_R and I_R are travelling in negative direction of X i.e. backwards on the same line.

- The transmitted terms will be algebraic sum of incident and reflected terms.

  Hence,

$$E_T = E + E_R \qquad \text{...(x)}$$

$$I_T = I + I_R \qquad \text{...(xi)}$$

– From Equations (vii), (viii) and (ix)

$$I = \frac{E}{Z_C}; \qquad I_T = \frac{E_T}{Z}; \qquad \text{and} \quad I_R = -\frac{E_R}{Z_C}$$

Putting these values in Equation (xi) we get,

$$\frac{E_T}{Z} = \frac{E}{Z_C} - \frac{E_R}{Z_C} \qquad \text{...(xii)}$$

– From Equations (x) and (xii) we get,

$$\frac{E_T}{Z} = \frac{E}{Z_C} - \frac{E_T - E}{Z_C}$$

$$\text{Or} \quad E_T \times \frac{Z_C}{Z} + E_T = 2E$$

$$\text{Or} \quad E_T \left(1 + \frac{Z_C}{Z}\right) = 2\,E$$

$$\text{Or} \quad E_T = E\,\frac{2Z}{Z + Z_C} \qquad \text{...(xiii)}$$

$$I_T = \frac{E_T}{Z} = \frac{2E}{Z + Z_C} = \frac{2Z_C\,I}{Z + Z_C} \qquad \text{...(xiv)}$$

$$E_R = ET - E = \frac{2ZE}{Z + Z_C} - E = E\,\frac{Z - Z_C}{Z + Z_C} \qquad \text{...(xv)}$$

$$\text{and} \quad I_R = \frac{-E_R}{Z_C} = \frac{-E}{Z_C} \times \frac{Z - Z_C}{Z + Z_C} = I\,\frac{Z_C - Z}{Z_C + Z} \qquad \text{...(xvi)}$$

The coefficients $\frac{2Z}{Z + Z_C}$ and $\frac{Z - Z_C}{Z_C + Z}$ are called coefficient of refraction and reflection respectively.

From these derived terms following things to be noted.

– Transmitted (refracted) current and voltages always have **positive polarity.**

– Polarity of reflected wave depends on magnitudes relationship between Z_C and Z.

So if (i) $Z_C > Z$ ….then voltage wave negative and current wave is positive.

If (ii) $Z > Z_C$ ….then voltage wave positive and current wave is negative.

Solved Problem

Ex. 4.7.1 **May 16, 10 Marks**

A voltage having a crest value of 3000 KV is travelling on the line of 750 K.V. The surge impedance of line is 300 ohm.

Calculate :

(1) Current line current before reaching the arrestor

(2) Current through arrestor

(3) Value of arrestor resistance for this condition

(4) Reflected voltage

(5) Verify the reflection and refraction coefficient

Soln. :

Let surge impedance noted by Z_S

Crest value voltage by e_f

Line voltage $e_A =$ 1700 kV

$Z_S = 300$, $e_f = 3000$ kV, $e_A = 1700$ kV

1. $i_f = e_f / Z_S = 3000 \times 10^3/300 = 10^4$ A or 10 kA

2. The voltage equation is

$$2e_f = Z_S\, I_A + e_A$$

$$2 \times 3000 \times 10^3 = 300\, I_A + 1700 \times 10^3$$

$$I_A = 1433 \text{ A or } 14.333 \text{ kA}$$

3. $$R = \text{Resistance of arrester} = \frac{e_A}{I_A}$$

$$= \frac{1700 \times 10^3}{14.333 \times 10^3} = 118.61 \text{ ohm}$$

4. $$1700 = 3000 + e_r$$

$$e_r = 1300 \text{ kV}$$

$$\text{Reflection coefficient} = \frac{-1300}{3000} = -0.433$$

$$\text{Refraction coefficient} = \frac{1700}{3000} = 0.567$$

5. $$\text{Reflection coefficient} = \frac{R - Z_c}{R + Z_c} = \frac{118.61 - 300}{118.61 + 300} = -0.433$$

$$\text{Refraction coefficient} = \frac{2R}{R + Z_c} = \frac{2 \times 118.61}{118.61 + 300} = 0.567$$

Syllabus Topic : Typical Cases of Line Terminations

4.8 Typical Cases of Line Terminations

In this section we are going to study relations of waves of different terminations like,

(i) Open circuited line
(ii) Short circuited line
(iii) Line terminated by an Impedance = Z_C
(iv) Line connected to a cable.

(i) Open circuited line

See the reflection of wave in open circuited line.

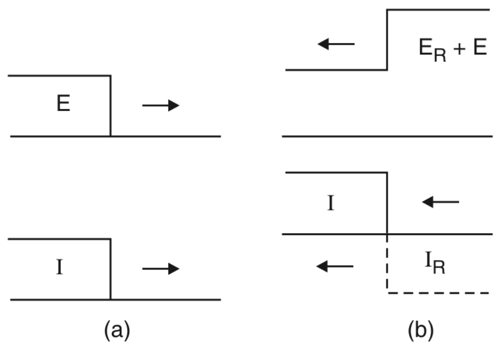


Fig. 4.8.1 : Reflection of waves at open circuit

The line is open at receiving end so the impedance Z = ∞.

– The transmitted wave :

$$E_T = 2E \text{ (doubling effect)} \quad \ldots(i)(a)$$

$$I_T = \text{Zero} \quad \ldots(i)(b)$$

$$E_R = E \quad \ldots(i)(c)$$

$$I_R = -I \quad \ldots(i)(d)$$

To satisfy the boundary conditions on open circuit when incident current wave I arrives at the open circuit then naturally reflected wave is at once initialed = – I. (See the Fig. 4.8.1).

(ii) Short circuited line

See the transmitted and reflected waves shown in the Fig. 4.8.2.

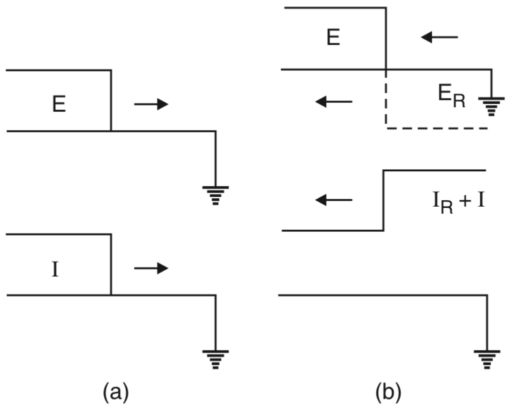


Fig. 4.8.2 : Reflection of waves at short-circuit

- Line is short circuited at the receiving end and hence Z = 0.

  The transmitted and reflected waves are given as

$$E_T = 0 \quad \text{...(ii)(a)}$$

$$I_T = 2I \quad \text{...(ii)(b)}$$

$$E_R = -E \quad \text{...(ii)(c)}$$

$$I_R = I \quad \text{...(ii)(d)}$$

- At short circuit the voltage across it = Zero.
- To satisfy this, the incident voltage E arriving at short circuit so reflected wave must be equal to – E. Shown in Equation (ii)(c).

(iii) Line terminated by an impedance equal to surge Impedance

So, if $Z = Z_C$ then waves are….

$$E_T = E \quad \text{...(iii)(a)}$$

$$I_T = I \quad \text{...(iii)(b)}$$

$$E_R = 0 \quad \text{...(iii)(c)}$$

$$I_R = 0 \quad \text{...(iii)(d)}$$

- This shows that line is correctly terminated.
- There will be no reflection.
- Hence E_T equals E and I_T equal I.

(iv) Line connected to a cable

- It is advantageous to connect a cable to the terminating overhead line near to a station.
- This is because, due to the capacitance of the cable the advantages is that the voltage entering at the cable from O.H. line is only 20% of the incident voltage.
- Besides this reduction, one more advantage is that it reduces the steepness of the wave
- Steepness reductions helps in reducing voltage distribution along the equipment windings.

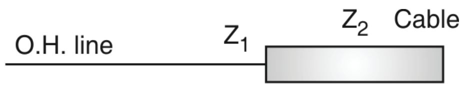


Fig. 4.8.3 : line connected to cable.

Z_1 and Z_2 are different values.

So it suffers reflection and refraction at the cable junction.

- The transmitted (i.e. refracted) voltages can be written as

$$E_T = \frac{2 Z_2 \cdot E}{Z_1 + Z_2} \quad \ldots(iv)$$

- Surge impedance = 500 Ω of O.H. line and only 50 Ω of cable approximately.
- So voltage entering the cable will be

$$E_T = E \times \frac{2 \times 50}{50 + 500} = \frac{2}{11} \simeq 20\% \text{ of incident voltage.}$$

- Here, care is taken to select the length of cable.
- Cable length should not be shorter than the expected length of the wave.
- If it is shorter then successive reflections at the junction are caused and pilling up of voltage may attain the level of incident voltage.

☞ Numerical on travelling wave

Ex. 4.8.1

An O.H. line of characteristic impedance Z_1 = 500 Ω is connected at the station to a single phase cable of characteristic impedance Z_2 = 60 Ω. A travelling wave of vertical front and infinite tail of 100 kV magnitude originates in the overhead line and travels towards the junction with the cable.

Find :
- (i) Transmitted voltage (E_T)
- (ii) Transmitted (refracted) current (I_T)
- (iii) Energy transmitted cable in 2 μsec.
- (iv) Reflected voltages (E_R)

Soln. :

Incident voltage E = 100 kV ; $Z_1 = 500\ \Omega$, $Z_2 = 60\ \Omega$ using equation (xiv).

(i) Transmitting voltage $E_T = \dfrac{2 Z_2 \cdot E}{Z_1 + Z_L}$

$$\therefore \quad E_T = \frac{2 \times 60 \times 100}{500 + 60} = \mathbf{21.428\ kV}$$

(ii) For finding transmitting (refracting) current I_T

$$I_T = \frac{\text{Voltage}}{\text{Impedance}} = \frac{E_T}{Z_2} = \frac{21.428 \times 10^3}{60} = \mathbf{375.14\ Amp.}$$

(iii) Energy transmitted into cable during 2 μsec.

$$\text{Energy} = \text{voltage} \times I_T \times t = E_T \times I_T \times t$$

$$= 21.428 \times 10^3 \times 375.14 \times 2 \times 10^{-6} = \mathbf{16.077\ Joules}$$

(iv) Reflected voltage (E_R)

$$E_R = E \times \frac{Z_2 - Z_1}{Z_2 + Z_1} = 100 \times \frac{500 - 60}{500 + 60} = -78.57\ \text{kV}$$

(Reflected voltage has minus sign.)

Check as per relation equation IV.

$$E_T = E + E_R = 100 - 78.57$$

$$= \mathbf{21.43 \simeq 21.428}$$

Syllabus Topic : Attenuation

4.9 Attenuation of Travelling Waves

- In analysis of power system it is assumed that the lines are lossless and there is no distortion or attenuation of waves.
- But in power system there are always losses. Consideration of these losses makes analysis difficult. But these losses are desirable as waves energy is dissipated through these losses.
- Losses occurs in system due to line resistance, leakage conductance and corona. The losses due to line resistance are important. The losses due to corona at high voltages are greater than due to line resistance.
- While travelling along the line the waves undergoes three changes :
  (i) The crest of the wave is attenuated or decreased in magnitude.
  (ii) The wave gets elongated, its irregularities are smoothened and steepness is reduced.

(iii) Voltage and current waves cease to be similar.

These changes occurs simultaneously. Second and third change is known as distortion.

- At high voltages the electric field gradient in air increases to a critical value. Due to this air gets ionized and loses its insulating properties. If the potential of line is increased beyond this then corona discharge occurs. It produces a ozone gas in the air surrounding the conductor.
- Due to this a violet glow occurs around the conductor. It is also associated with hissing sound. The energy required to ionize air is supplied by waves.
- The surges are unaffected till the threshold voltage is reached (corona threshold). Above this voltage the effect is pronounced. This initial peak is removed by the time the eave travelled to 2 to 3 kms. After this attenuation continuous at slightly reduced rate. The centre and tail of the wave are built at the expense of front.
- Wave attenuation due to corona is more pronounced for positive wave than negative waves, it is because of greater corona loss for positive waves.
- Attenuation is calculated by using foust and Manger empirical formula,

$$e = \frac{E}{1 + KE_x} \qquad \ldots(4.9.1)$$

Where, e = surge voltage at distance x from origin, kV

E = surge voltage at origin, kV

K = Attenuation constant $\simeq$ 0.00019 for short waves (5 μsec.)

$\simeq$ 0.0001 for long waves (20 μsec)

x = Distance travelled in km

- Decrease in the amplitude of waveform.
- A voltage wave incident on the transmission line at an initial pt, x = 0 will travel at a velocity v such that at a later time 't' at an initial point x = vt from the point of incident shown in the following Fig. 4.9.1.

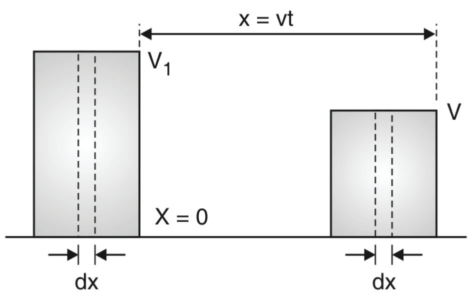


Fig. 4.9.1 : Attenuation of voltages on transmission line

- In doing so, if crest value of voltage is higher than the corona disruptive voltage for the conductor, it loses energy while it travels.
- Its amplitude decreases corresponding to the lower energy content. Also in addition to attenuation or decrease in amplitude wave shape shows distortion.
- Energy distortion is electromagnetic and also electrostatic form.
- Time rate of loss of stored energy = power loss due to corona. See the Fig. 4.9.1.
- Total energy in the differential length dx of the wave is given as...

$$dw = \frac{1}{2}(C \cdot dx)\, V^2 + \frac{1}{2}(L \cdot dx)\, I^2$$

Where C and L are per unit length.

We have seen in case of surge travelling wave relations of V, I, Z, L and C.

$$\text{Surge impedance } Z = \sqrt{\frac{L}{C}}$$

$$\text{Wave velocity of propagation } \upsilon = \frac{1}{\sqrt{\frac{L}{C}}}$$

$$I^2 = \frac{V^2}{Z^2} = V^2\, C/L$$

$$\therefore \quad dw = C \cdot dx \cdot V^2$$

- Considering capacitance does not charge then rate of dissipation of Energy

$$= \frac{dw}{dt} = d\,(CV^2 \cdot dx)\,/dt$$

$$= 2\,C \cdot V \cdot dx \cdot \frac{dv}{dt}$$

$\therefore$ Power loss over the differential length dx is given by,

$$P_C = f\,(v) \cdot dx \quad \text{So that } 2\,CV \cdot \frac{dv}{dt},$$

$$= -P_C = -f\,(V)$$

☞ **Linear relationship**

Let, $f(v) = k_s\,(V - V_0)$ then with V_i = initial voltages,

$$2\,CV\frac{dv}{dt} = k_s\,(V - V_0),$$

by separating the variables and using initial condition

$$V = V_i \text{ at } t = 0 \text{ yields}$$

$$(V - V_0)\, e^{V/V_0} = (V_i - V_0) \cdot e^{(V_i \propto t)/V_0}$$

Where $\alpha = \frac{k_s}{2C}$ and V_0 = corona inception voltage.

Similarity voltages in excess of corona inception at any time t or dis x = υt will be

$$\frac{(V - V_0)}{(V_i - V_0)} = e^{(V_i - V - \propto t)/ V_0}$$

Syllabus Topic : Bewley Lattice Diagram

4.10 Bewley Lattice Diagram

- This diagram is useful to know at a glance the position and direction of all successive reflections.
- This diagram is also called as Zig-Zag diagram.
- In the previous sections we studied the travelling wave when reaches terminal point, it is transmitted (refracted) and reflected as well.
- When such reflected wave reaches the initiation point it is again reflected (re-reflected) from here and such reflections continued.
- There may appear loss (attenuation) of both voltage and current waves.
- To keep track of such repeated refection is difficult.
- In such difficulties the use of Bewely Lattice diagram plays an important part.
- Instead of explaining this diagram theoretically it will be simple for understanding taking the numerical values in a problem and solving step by step ...

Problem

Ex. 4.10.1

Take following problem. A lossless line talking E_g the voltage from generator and its length is x meters. Load across line = $\frac{1}{4}$ of the surge impedance. And generator surge impedance = $\frac{1}{2}$ of the surge impedance. Draw Bewley's Lattice Diagram.

Soln. :

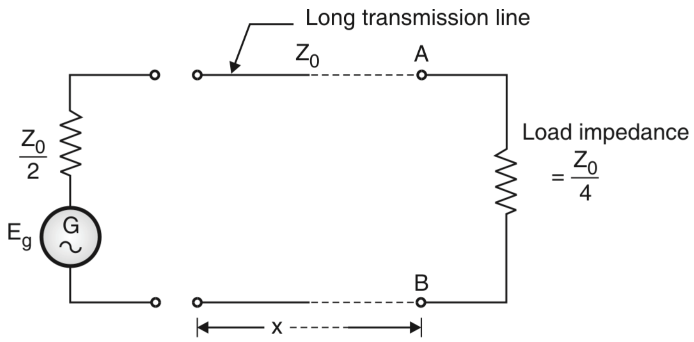


Fig. P. 4.10.1

Solution step by step.

Step 1 : To find sending end current I_S and sending end.

Voltage E_S

$$\therefore \quad \text{Sending end current } I_S = \frac{E_0}{\text{Impedance}} = \frac{E_0}{\frac{Z_0}{Z} + Z_0 + \frac{Z_0}{4}} = \frac{4}{7} \cdot \frac{E_0}{Z_0}$$

Sending end voltage

$$E_S = E_0 - \left(\frac{4}{7} \cdot \frac{E_0}{Z_0}\right) \cdot \frac{Z_0}{Z}$$

Step 2 : To find reflection co-efficient K_L at load end.

$$\therefore \quad K_L = \frac{Z_l - Z_0}{Z_L + Z_0} = \frac{\frac{Z_0}{4} - Z_0}{\frac{Z_0}{4} + Z_0} = -\frac{3}{5}$$

Step 3 : To find reflection co-efficient at generating end.

$$K_g = \frac{\frac{Z_0}{2} - Z_0}{\frac{Z_0}{2} + Z_0} = -\frac{1}{3}$$

Step 4 :

To determine the time taken for the wave to reach at the end of the line.

Now knowing the reflection co-efficient at both the generating end and at the load end, Bewely's lattice diagrams can be drawn which are as matter of fact the traces of the wave front of various reflections. Fig. P. 4.10.2(a) represents the bewley's lattice diagram for the current wave while Fig. P. 4.10.2(b) illustrates the lattice diagram for voltage wave.

The time taken for the surge to travel distance x $= \frac{x}{\upsilon}$ = t seconds (say)

Where υ is the velocity of the surge equal to 3×10^8 m / sec

Considering first the current wave

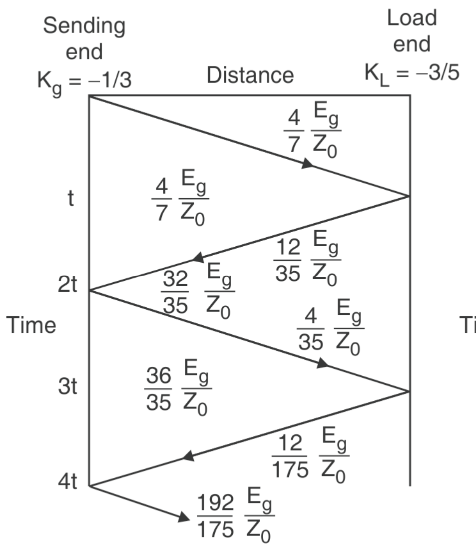
The initial surge of current at end A is $\frac{4}{7}\frac{E_v}{Z_0}$ Which reaches end B in t second and is reflected there which can be obtained in view of equation.

$$i_r = -\frac{e_r}{Z_0} = -K_l \frac{e_f}{Z_0}$$

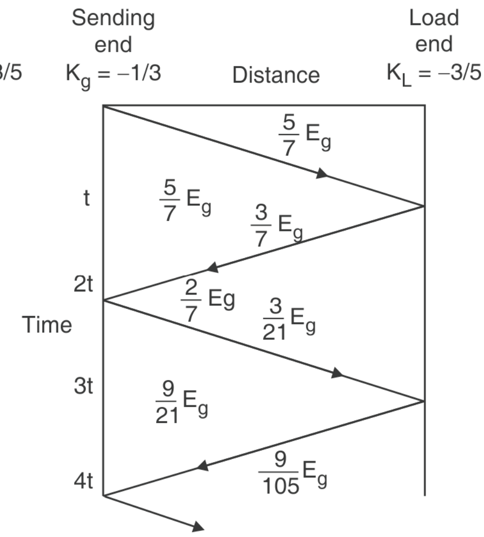
$$\text{Thus reflected current} = -K_L\, i_r = -\frac{4}{7}\frac{E_a}{Z_0} \times \left(-\frac{3}{5}\right) = \frac{12}{35} - \frac{E_a}{Z_0}$$

After a lapse of total 2t seconds the current wave is aging reflected and is given as,

$$= -\left(-\frac{3}{5}\right)\frac{12}{35}\frac{E_a}{Z_0} = \frac{4}{35} - \frac{E_a}{Z_0}$$



(a) Current lattice diagram



(b) Voltage Lattice diagram

Fig. P. 4.10.2

Fig. P. 4.10.2(a) represents the different reflections, the time is represented along the vertical axis and distance along the horizontal axis while magnitude of the wave front is represented within the zigzag line. The numbers within the zigzag lines represents the sum of individual waves.

Voltage wave

The first reflection after t seconds (from load end) in view of equation. ($e_r = K_L \cdot e_f$)

$$= K_L\, e_f = \left(-\frac{3}{5}\right)\frac{5}{7}E_g = -\frac{3}{7}E_g$$

The second reflection from sending end

$$= \left(-\frac{1}{3}\right)\left(-\frac{3}{7}\right)E_g = \frac{3}{21}\; E_g$$

Similarly other reflections can be obtained which are represented in Fig. 4.10.2(b).

4.11 Over Voltage (Introduction)

- Overvoltage (or surge voltages) on the electric power systems are due to various reasons.
- If the system is working on the normal voltage satisfactory then it will not stress the insulation severely due to normal working temperature cause of normal currents.
- But the voltage stresses due to over voltages can be so high that they may prove dangerous to the line, equipment and accessories. The system may be damaged.
- In order to avoid such happenings the equipments and lines are to be provided with protective device and schemes to work effectively under abnormal conditions and disconnect them for safety or divert the surge energy to the earth or absorb the surge energy in some absorbers.

4.11.1 The Voltage Surge Nature

- Sudden rise in the voltage for a very small duration on the power system is called as voltage surge or transient voltage, as shown in the Fig. 4.11.1.
- These surges are generally produced due to switching ON or OFF or lightning or fault occurrence due to some reasons.
- A steep front wave in a short time t, when voltage reaches maximum value E_m and time t_1 is very short 1 to 5 μsec.
- Time t_2 is the decay of wave to its half the maximum value $\frac{E_m}{2}$. The wave is specified in the time t_1 and t_2, for example, if t_1 = 1 μsec. and t_2 = 60 μsec. then surge is specified as 1/60 μsec. surge.

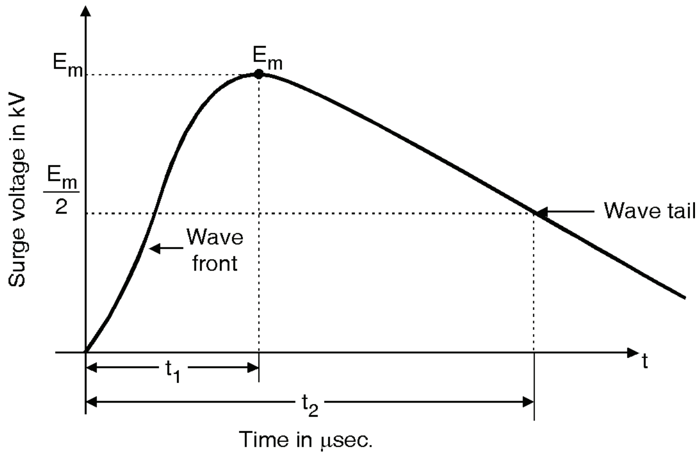


Fig. 4.11.1 : Voltage surge

4.11.2 Causes of Overvoltages

These are broadly divided into two categories :

1. External causes of overvoltages.
2. Internal causes of overvoltages.

4.11.2.1 External Causes

These are the severe causes and induce a very steep and high amplitude surge wave and dangerous to the power supply lines and equipments.

These causes may be due to the following :

(i) Direct lightning strokes.

(ii) Electro-magnetically induced due to lightning discharge taking place near the line.

(iii) Voltage induced due to change in atmospheric conditions along the line - length.

(iv) Electrostatically induced voltages due to presence of charged clouds nearby.

(v) Electrostatically induced voltages due to the frictional effects of small particles such as dirt, dust, snow.

4.11.2.2 Internal Causes

The surge produced due to internal cause are not to steep and do not have much more amplitude as compared with surge due to lightning.

The system voltage hardly increases to twice the normal voltage of the power lines. Internal causes may be :

(i) Switching surge	(ii) Insulation failure
(iii) Arcing grounds	(iv) Resonance.

(i) Switching surge

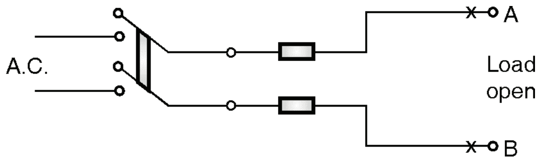


Fig. 4.11.2 : Switching surge

(a) The circuit opened and closed causes the over voltage and produce a voltage surge of the nature oscillatory and take the form of damped sinusoidal. When unloaded line is connected to the voltage source a voltage wave is set up which travels along the line.

On reaching the terminal point 'A' it is bounced back to the supply end without change in sign. On the system therefore double voltage is developed $\left(2 \times \sqrt{2}\, E_{rms}\right)$. This is of temporary nature and line stabilizes with its normal voltage. The same effect is produced when unloaded line is switched off.

(b) In case of loaded line also a high voltage is developed on the line. This voltage will be 2 × instantaneous current × impedance of the line i.e. = $2\ i\ Z_n$. Where line impedance (called as natural impedance) $Z_n = \sqrt{\frac{L}{C}}$ where, L and C are line constants.

Taking a simple case,

$$Z_n = 1000,\ I_{rms} = 100 \text{ Amp.}$$

$$\therefore \quad \text{Voltage} = 2\ i\ Z_n$$

$$= 2 \times \sqrt{2} \times 100 \times 1000 \text{ volts}$$

$$= \frac{2 \times \sqrt{2} \times 100 \times 1000}{1000} \text{ kV} = 282.8 \text{ kV}$$

Maximum voltage on the line is therefore,

$$= V_m + 282.8 \text{ kV where } V_m \text{ is maximum of line voltage.}$$

(c) Current chopping : Refer (Section 4.6)

(ii) Insulation failure

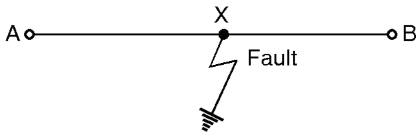


Fig. 4.11.3 : Insulation failure

If the insulation of the line fails due to conductor grounding i.e. conductor touches to ground a voltage of the system increases. This fault is shown in the above Fig. 4.11.3. Take the case of line is earthed at point X and the line has a potential of E volts. Then two equal voltages are caused i.e. – E volts travelling along point B in the section XB, and along XA and these sections contain currents equal to $\frac{-E}{Z_n}$ and $\frac{+E}{Z_n}$ respectively. Both these currents pass through fault point X to the earth = $\frac{2E}{Z_n}$.

(iii) Arcing grounds

The phenomenon of intermittent arc taking place in line to ground fault of a 3-phase system with consequent production of transients is known as arcing grounds. These are cumulative and cause damage to the equipment in the power system by causing breakdown of insulation. This can be prevented by neutral earthling.

(iv) Resonance

We know that resonance is the condition of the circuit when inductive reactance X_L and capacitive reactance X_C of the line becomes equal and net reactance becomes zero. Impedance becomes minimum and power factor of the circuit becomes unity. In resonance voltage magnification takes place and voltage in the line increases. In transmission lines as X_L is small the resonance condition is rare but it may be in case of cables buried underground.

Syllabus Topic : Lightning Phenomenon (Mechanism of Lightening Stroke)

4.12 Lightning Phenomenon (Mechanism of Lightening Stroke)

→ (MU - May 16)

Q. 4.12.1 Discuss the phenomenon lightning.
(Refer sections 4.12, 4.12.1 and 4.12.2) **May 16, 10 Marks**

- The discharge of the charged cloud to the ground is called as Lightning Phenomenon.
- Lightning is a huge spark and it takes place when the clouds are charged to such a high potential positive or negative w.r.t. the earth or a neighboring cloud and if this happens then there is possibility of insulation of air breaks down (destroyed).
- An electric discharge between cloud and earth, between clouds or between the charge centers of the same cloud is known as **lightning**.
- Lightning is a huge spark and takes place when clouds are charged to such a high potential (positive or negative) with respect to earth or a neighboring cloud that the dielectric strength of neighboring medium (air) is destroyed.
- During the uprush of warm moist air from earth, the friction between the air and the tiny particles of water causes the building up of charges.
- When drops of water are formed, the larger drops become positively charged and the smaller drops become negatively charged. When the drops of water accumulate they form clouds.
- The charge on a cloud may become so great that it may discharge to another cloud or to earth and we call this discharge as lightning.
- The thunder which accompanies lightning is due to the fact that lightning suddenly heats up the air, thereby causing it to expand.
- The surrounding air pushes the expanded air back and forth causing the wave motion of air which we recognize as thunder.

4.12.1 How the Lightning Discharge is Produced ?

→ (MU - May 16)

> **Q. 4.12.2** Discuss the phenomenon lightning.
> *(Refer sections 4.12, 4.12.1 and 4.12.2)* **(May 16, 10 Marks)**

- The charged clouds pass over the earth and hence as per the theory of induction of the earth acquires the equal and opposite charge.
- Taking the case that a positive charged cloud passes over the portion of the earth naturally earth portion will have negative charge on it.

– There exists a potential difference between the charged cloud and the earth. As the charge on the cloud increase the potential gradient will also increase a stage may come that when potential gradient is <5 kV/cm> 10 kV/cm then insulation of air breaks down and lightning stroke starts from cloud to earth. Let us study the mechanism of the lightning stroke in three stages.

Stage 1

After the break in the air, leader streamer/pilot streamer carries charge from the cloud towards the earth. This process continues as long as the cloud feeds enough charge to the streamer to maintain the voltage gradient on the tip of the leader streamer above the breaking strength of the air but if the gradient is not maintained the process stops and the leader streamer is unable to carry the charge to the earth. So no lightning stroke on the earth as shown in the Fig. 4.12.1. In this situation the current in the streamer is less than 100 Amp. and its velocity of propagation is about 0.05% of the velocity of light and its luminosity is very weak and lightning is not seen by the eyes.

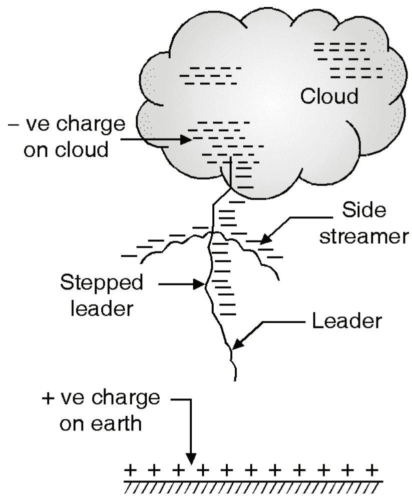


Fig. 4.12.1 : Leader stream does not reach the earth

Stage 2

If the leader streamer moves towards the earth it makes contact with some object on the earth, it is accompanied by points of luminescence travelling like jumping. This gives rises to stepped leaders as shown in the Fig. 4.12.2.

In such situation the velocity of stepped leaders may exceed one sixth of that of the velocity of light and distance travelled in one step may be 50 meters. The step leaders are producing sufficient luminosity and give rise to first visual phenomenon of lightning discharge.

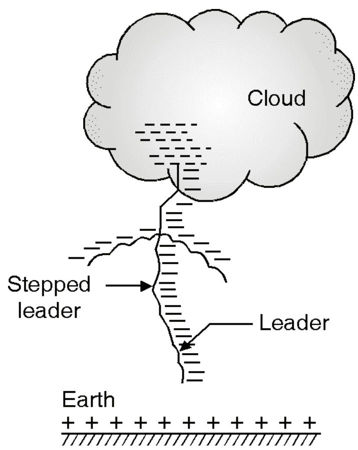


Fig. 4.12.2 : First visual lightning discharge

Stage 3

The path of leader streamer is a path of ionization and therefore of complete breakdown of insulation.

As the leader streamer reaches near the earth, a return streamer shoots up from the earth Fig. 4.12.3 to the cloud, following the same path as the main channel of the downward leader. The action can be compared with the closing of a switch between the positive and negative terminal; the downward leader having negative charge and return streamer the positive charge. This phenomenon causes a sudden spark which we call "lightning". The negative charge and positive charge come together and get neutralized at lightning stroke. The further lightning stroke may be initiated from the other portion of the cloud.

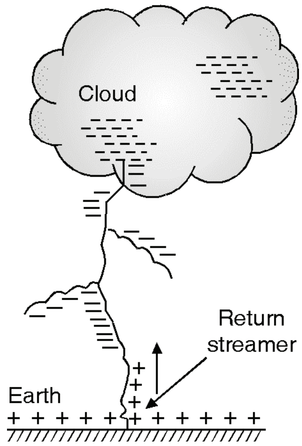


Fig. 4.12.3 : Lightning

4.12.2 Lightning

➔ (MU- May 16)

Q. 4.12.3 Discuss the phenomenon lightning.
(Refer sections 4.12, 4.12.1 and 4.12.2) **May 16, 10 Marks**

1. The lightning which is seen by our eyes appears to be a single flash but in fact it is made up of number of separate strokes.
2. Strokes are one after the other from 0.0005 sec. to 0.5 seconds and hence will see a combined flash to these.
3. Negatively charged clouds are about 87% in comparison with positively charged cloud which are only 13%.
4. Information collected from all over the world speaks that there are about 100 lightning strokes produced per second.
5. Currents in the lightning strokes are in the range of 10 kA to 90 kA.

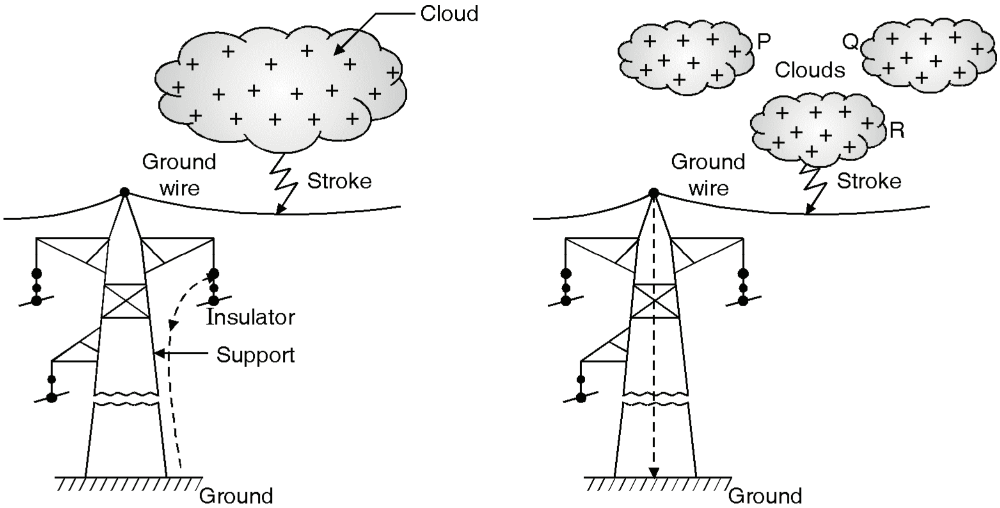
4.12.3 Lightning Strokes

We have seen how the lightning stroke is produced. This stroke may strick the electrical system (1) Directly or (2) Indirectly.

1. Direct Stroke	2. Indirect Stroke

4.12.3.1 Direct Stroke

- The lightning stroke discharges directly from the cloud to the subject equipment like over head lines (transmission or distribution lines). And the path of the current due to this stroke is from the cloud, to the line the insulators then via poles (supports, towers) to the ground.
- The over voltages set up may so huge to flash over this path directly to the ground. This stroke again may be type (A) and (B) shown in the Fig. 4.12.4 (a) and (b).



(a) Direct stroke type (A) **(b) Direct stroke type (B)**

Fig. 4.12.4

- In stroke a, the lightning discharge is from the cloud to the subject equipment i.e. an overhead line in this case as shown in Fig. 4.12.4(a). The cloud will induce a charge of opposite sign on the tall object (overhead line).
- When the potential between the cloud and line exceeds the breakdown value of air, the lightning discharge occurs between the cloud and the line.

4.12.3.2 Indirect Stroke

- Indirect strokes result from the electro-statically induced charges on the conductors due to the presence of charge clouds.
- This is illustrated in Fig. 4.12.5. A positively charged cloud is above the line and induces a negative charge on the line by electrostatic induction.

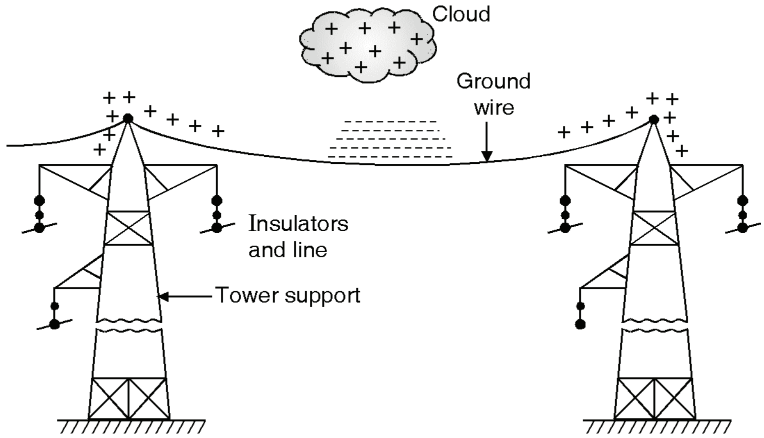


Fig. 4.12.5 : Indirect stroke

- This negative charge, however, will be only on that portion of the line right under the cloud and the portions of the line away from it will be positively charged as shown in Fig. 4.12.5.
- The induced positive charge leaks slowly to earth via the insulator. When the cloud discharges to earth or to another cloud, the negative charge on the wire is isolated it cannot flow quickly to earth over the insulators.
- The result is that negative charge rushes along the line in both directions in the form of travelling waves.

Syllabus Topic : Over Voltage due to Lightening

4.13 Over Voltage due to Lightening and Protection from Direct Strokes

- The surges on the power system may originate from switching and from other causes but the most important and dangerous surges are those caused by lightning.
- The lightning surges may cause serious damage to the expensive equipment in the power system (e.g. generators, transformers etc.) either by direct strokes on the equipment or by strokes on the transmission lines that reach the equipment as travelling wave.
- It is necessary to provide protection against both kinds of surges. Following devices are commonly used for protection against lightning surges.

1. Earthing screen.
2. Overhead ground wires.
3. Lightning arrestors or surge diverters.

- Earthing screen provides protection to power stations and sub-stations against direct stroke whereas overhead ground wires protect the transmission lines against direct lightning strokes.
- However, lightning arrestors or surge diverters protect the station apparatus against both direct strokes and the strokes that come into the apparatus as travelling waves.

4.13.1 Earthing Screen

- The power stations and sub-stations generally house expensive equipment. For their protection earthing screen is provided. It consists of a network of copper conductors (generally called shield or screen) mounted all over the electrical equipment in the sub-station or power station.
- The shield is properly connected to earth on at least two points through a low impedance. On the occurrence of direct stroke on the station, screen provides a low resistance path by which lightning surges are conducted to ground.
- In this way station equipment is protected against damage. The limitation of this method is that it does not provide protection against the travelling waves which may reach the equipment in the station.

4.13.2 Overhead Ground (Earth) Wires

The most effective method of providing protection to transmission lines against direct lightning strokes is by the use of overhead ground wires as shown in Fig. 4.13.1. The ground wires are placed above the line conductors at such positions that practically all lightning strokes are intercepted by them. The ground wires are grounded at each tower or pole through as low resistance as possible. Due to their proper location, the ground wires will take up all the lightning strokes instead of allowing them to line conductors.

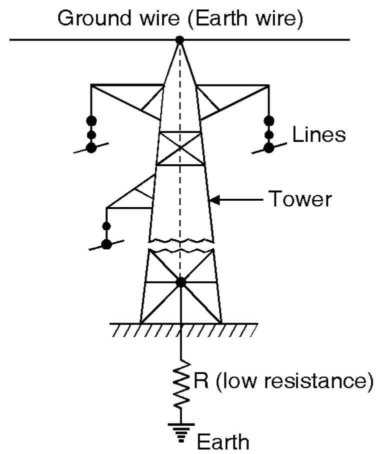


Fig. 4.13.1

Footing resistance of the tower must be kept as low as possible so that surge current immediately passes to the ground without any chance of insulator flash-over.

Advantages of such ground wire system are

(i) Good protection of line from lightning strokes.

(ii) It reduces voltage induced in the line conductors due to discharge of neighboring cloud.

(iii) Due to its action of short circuiting secondary ground wire provides damping effect on any disturbance travelling along the line.

Disadvantages

(i) Additional cost of ground conductor.

(ii) Possibility of breaking of ground conductor and falling on line to create short circuit fault.

Syllabus Topic : Lightening Protection Problem

4.14 General Principle of the Lightening Protection Problem

This is based on the statical procedures which is out-lined in steps.

Step 1

Knowledge of number of strokes contacting 100 km of line per year this needs.

- Field observations at the line route
- Tower height (h_t)
- Ground wire height (h_g)
- Separation between ground wires (S_g).

Step 2 : A stroke contacting a tower.

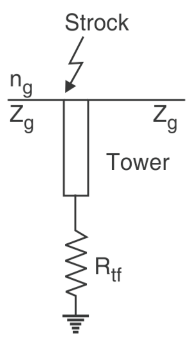


Fig. 4.14.1 : Impedance presented to lightening stroke at tower

Let, R_{tf} : Tower footing resistance

Z_g : Surge impedance of ground wire

k_f : Coupling to line conductors

Z_s : Surge impedance of lightening strokes $\simeq 400\ \Omega$

N_g : number of ground wires.

Refer Fig. the stroke will see an impedance to ground governed by

(i) Tower footing resistance : R_{tf}

(ii) Surge impedance of ground wire : Z_g

(iii) Coupling to line conductors : k_f : coupling factor

(iv) Surge impedance Z_s of lightening stroke channel itself. Which is $\simeq 400\ \Omega$

Neglecting up and down reflections of tower and if n_s = number of wires, then approximate tower top potential V_t is given by the following.

$$V_t = \frac{I_S}{\left(\frac{1}{R_{if}} + \frac{2n_g}{Z_g} + \frac{1}{Z_s}\right)} \qquad \text{...(i)}$$

Where I_S = Stroke current and denominator is the total admittance.

Ex. 4.14.1

A tower having two ground wires of 500 Ω surge impedance each and footing resistance 40 Ω. The lightening stroke surge impedance is 400Ω. If stroke current is 40 kA crest value, calculate the tower top potential.

Soln. :

Given data : $Z_g = 500\ \Omega$, $n_g = 2$, $I_s = 40$ kA crest, $R_{tf} = 40\ \Omega$

$Z_S = 400\ \Omega$, tower top potential $V_t = ?$

$$V_t = \frac{I_S}{\left(\frac{1}{R_{if}} + \frac{2n_g}{Z_g} + \frac{1}{Z_s}\right)} = \frac{40 \times 10^3}{\frac{1}{40} + \frac{2 \times 2}{500} + \frac{1}{400}}$$

$$= \frac{40 \times 10^3}{0.025 + 0.008 + 0.002} = 1126760.563 \text{ volt}$$

$$= 1126.76 \text{ kV crest}$$

Step 3

The knowledge of tower footing resistance (R_{tf}) is essential. Different methods are used to calculate this for various footing arrangements.

Step 4

Let, V_i = max. voltage experienced by insulators supporting conductors.

E_m = crest value of line to ground power frequency voltage

K_f = Coupling factors between ground wire (s) and phase current $\simeq 0.2$ to 0.3

If tower top voltage is V_t as expressed in Equation (i).

Then, $V_i = V_t (1 - K_f) + E_m$

Ex. 4.14.2

A 735 kV line has coupling co-efficient = 0.25 tower top potential = 2000 kV, find voltage experienced by insulator string.

Soln. :

The crest value $E_m = \dfrac{735 \times \sqrt{2}}{3} = 600$ kV

Using relation,

$$V_i = V_t (1 - k_f) + E_m$$

$$\therefore \quad V_i = 2000 (1 - 0.25) + 600$$

$$= 1500 + 600 = 2100 \text{ kV}$$

Definition of coupling factor (k_f)

It is the ratio $k_f = \dfrac{\log_e\left(\dfrac{h}{h_1}\right)}{\log_e\left(\dfrac{2H}{r}\right)} \simeq 0.2$ to 0.3

Where, h = distance between conductor and ground wire

h_1 = distance between image and ground

H = height of ground wire above the ground

r = radius of ground wire

Step 5

V_i across insulator is now estimated as in 4th step we enquire in the laboratory whether this exceeds the flash-over voltage of the string. For no flashover V_i must equal the withstand voltage of string.

This needs that flash-over and withstand voltage of insulator string when subjected to lightening impulses must be available from the laboratory studies (statistical data) under every type of atmospherical conditions.

Step 6

Voltage experienced by the insulator is the function of the crest value of lightening stroke current feeding into the zero resistance ground. Statically data in this connection is collected in the laboratory records. $p_i = 1.175 - 0.015\ I_C$, this expression is valid where p_i = probability (fraction) of strokes having a current of crest value I_C kAmp.

Step 7

Now, we are in a position to calculate the number of time in a year per 100 km of line. Which gives the voltage in excess of flashover voltage of the insulator.

This relation is derived as :

Let, p_i = probability that crest value of lightening stroke current yielding the flash-over voltage of insulator will be found.

N_S = number of strokes contacting the line per year per 100 km length

p_t = The fraction of strokes N_s which will contact the tower

N_t = Probable number of trip outs for those strokes contesting the towers.

To this must be added the number of strokes among N_S that causes mid-span flashover.

The derived relation is given below :

$$N_i = p_i \cdot p_t \cdot N_S$$

Syllabus Topic : Significance of Tower Footing Resistance in Relation to Lighting

4.15 Tower Footing Resistance (R_{tf})

➔ **(MU - Dec. 15, May 17)**

Q. 4.15.1 What the role of tower footing resistance ?
(Refer section 4.15) **Dec. 15, May 17, 5 Marks**

- The tower footing resistance must be as minimum as possible.
- Tower footing resistance depends on various factors like
  (i) Soil resistivity
  (ii) Type of electrode configuration employed
  (iii) Area exposed between electrode and soil for current spreading over it.
- Different types of electrode configuration :
  (i) Hemispherical

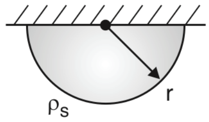
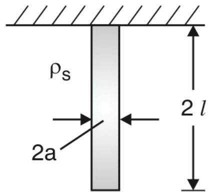


Fig. 4.15.1

(ii) Vertical driven-rod



Radius of rod = a

Length of rod = $2l$

Fig. 4.15.2

This is long spender rod about 2 to 5 cm in diameter and 10 to 15 meters in length vertically down into the soil and connected to tower legs.

(iii) Horizontal wire buried in ground

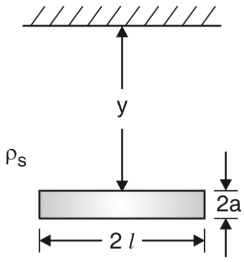


Fig. 4.15.3

- This wire is called as **'counterpoise'.**
- It is used where vertical rod cannot be driven in soil.
- Its length is about 50 to 150 meters

Soil resistivities (ρ_s) in ohm-meter

(i) Sea water = 10^0

(ii) Moist soil = 10^1

(iii) Loose soil/clay = 10^2

(iv) Rock = 10^3

- The resistance can be calculated for different electrode configuration as detailed in the Table 4.15.1.

Table 4.15.1

Sr. No.	Electrode shape	(Resistance formula) ρ_s = resistivity
1.	Hemispherical radius R	$= \rho_s \cdot l / \; 2\pi R$
2.	Vertical driven Rod Radius = a Length = $2l$	$= \frac{\rho_s}{2\pi l} (2l/a)$ or $\frac{\rho_s}{2\pi l}\left(ln \frac{4l}{a} - 1\right)$
3.	Horizontal wire (depth y) Radius = a Length = $2l$	$= \frac{\rho_s}{2\pi l}\; ln \left(\frac{2l}{a}\right)\left[1 + \frac{ln\,(l/y)}{ln\,(2l/a)}\right]$ OR $= \left(\frac{\rho_s}{2\pi l}\right) ln\;(2l^2/ay)$

Syllabus Topic : Insulator Flashover and Withstand Voltages

4.16 Insulation Flashovers and Withstand Voltages

- An insulator disc is generally a standard dimension like (14.6 cm × 25.4 cm) (old unit in inches $5\frac{3''}{4} \times 10''$).
- During positive polarity lightening impulses such discs generally show a better linear characteristic between spark-over voltage and number of discs.

  See the Table 4.16.1 for dry atmosphere.

Table 4.16.1

Time in micro-seconds to break down	Crest value in kV/disc
0.5 μsec	188 kV
1 μsec	150 kV
2 μsec	125 kV
3 μsec	110 kV

Time in micro-seconds to break down	Crest value in kV/disc
4 μsec	105 kV
6 μsec	97.5 kV
8 μsec	92.5 kV

(i) Power frequency

Flash over voltage = 75 kV/disc, crest value

or Flash over voltage = 53 kV/disc, r.m.s. value

The standard disc has the following values –

- Leakage distance over its surface = 31.8 cm
- Creeping strength used in 1 kV/cm of leakage distance r.m.s. value

(These are in fair/dry weather)

(ii) Conductor to conductor flash-over

Flash over voltage V_{cc} = 590 kV/meter, crest.

This imperial relation is derived (under positive lightening wave) on experimental work.

(iii) Strings in parallel

- Many insulators are stressed in parallel when lightening strokes hit the line
- Single string values for voltage can be used for flash-over and withstand strength.

Syllabus Topic : Protection Against Surges, Surge Arrestors

4.17 Protection against Surges (Lightning Arrestors or Surge Arrestors)

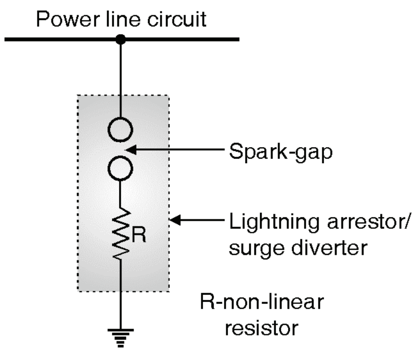
Earthing screens and ground wires are suggested for protection against direct lightning strokes but they are unable to protect the equipment against travelling waves. The lightning arrestors or surge diverters take care of the terminal equipments against such surges.

4.17.1 Function of Arrestors

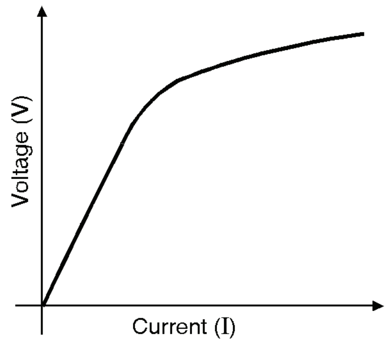
The function of the lightning arrestor or surge diverter is to conduct the high voltage, surges on the power system to the ground, thus discharging the impulse surge to earth and to dissipate energy in the form of heat.

4.17.2 Schematic Representation and Functioning of Arrestor

Basically, the arrestor has a spark-gap and to its series a non-linear resistor. (Property of non-linear resistance is that its resistance decreases as the voltage or current increase and vice-versa). One end of arrestor is connected to the equipment terminal and the other is perfectly earthed.



(a) Lightning arrestor location



(b) V/I characteristic of non-linear resistor

Fig. 4.17.1 : Lightning arrestor

The spark gap can be set as per the system voltage. Its length is so selected that arc is not produced due to normal system voltage but due to an abnormal high voltage produces a spark (arc) in the spark-gap. The arc is formed due to breaking of insulation of air across the gap due high surge voltage.

4.17.3 Working of Arrestor/Surge Diverter

Step 1 : No current jumps in the spark-gap when system voltage is having its normal value and equipment is working.

Step 2 : When the line voltage increases due to surges, this high voltage breaks the gap and an arc is produced (current jumps though the gap and passes through resistance R to ground). The arc finds the low resistance path to ground and the surge is not sent back to the line.

Step 3 : As the gap sparks over due to over-voltage. Since, the property of non-linear resistance is to offer high resistance to high voltage it prevents the effect of short circuit.

Step 4 : After the surge is over, the resistor offers high resistance to make the gap non-conducting.

4.17.4 Design of Lightning Arrestor

The design should be such that :

1. When the surge is over, the arc should go out immediately otherwise the current through gap and resistant will be maintained to flow destroying gap and resistor.
2. During the surge current the voltage drop i.e. Surge current (I) × Resistance should not exceed the breakdown strength of insulation of the equipment to be protected against such surges.

4.18 Types of Lightning Arrestors

In all types of arrestors the mechanism is to provide a low resistance path for the surge currents to the ground so that the high voltage produced will not affect the equipment and its insulation remain in tack.

There are so many types depending upon :

(i) Equipment to be protected.
(ii) Type of gap produced.
(iii) Chemicals used.
(iv) Discs used.

The main types to be studied under this topic are :

1. Rod-gap arrestor.
2. Horn-gap arrestor
3. Multi-gap arrestor
4. Expulsion type arrestor
5. Thyrite disc-valve type arrestor.

Let us study the brief descriptions of these types.

4.18.1 Rod-Gap Arrestor

This is generally located across the bushings of transformer and generally used as back up protection in case of main arrestors.

☞ **Construction**

As shown in Fig. 4.18.1 the arrestor is in the form of bend-rods having spark-gap between the two. The upper rod is connected to the line electrically and the lower one is connected to earth to carry away surge current.

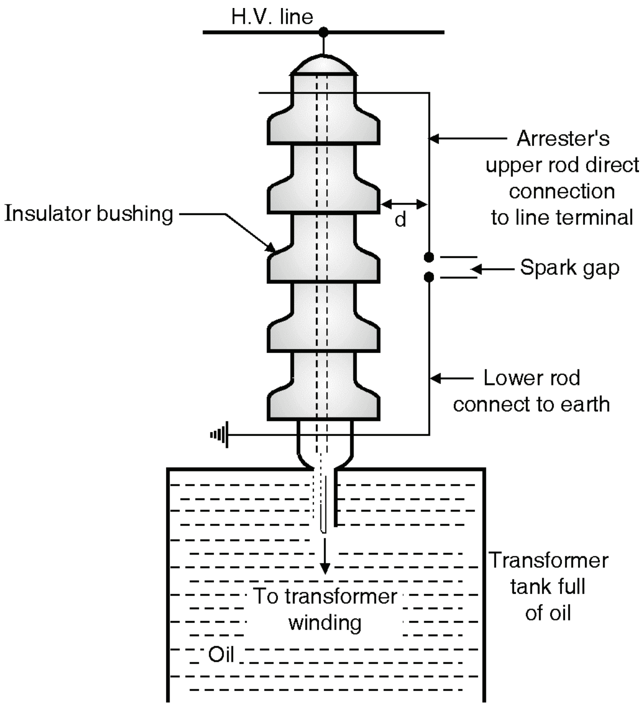


Fig. 4.18.1 : Rod-gap arrestor

Dimensions

- 1.5 cm rods bend at 90° as shown, distance 'd' between gap and bushing outside face > $\frac{1}{3}$ gap length to avoid reaching of arc to the bushing body.
- The gap length is so adjusted that breakdown should occur at 0.8 of spark over voltage.

Working

- Under normal voltage conditions the gap acts as a air insulation and non-conducting and the line voltage is ineffective to make the gap conducting.
- Now when the voltage increases so suddenly due to surge on the line, this surge voltage breaks the gap between the rods and spark over (arc) is produced.
- Surge current passes from the line to spark-gap to second rod and finally to the earth within a very short time and the equipment is protected. After the surge the gap as a insulator under normal voltage of the line.

☞ Drawbacks and Limitations

1. It is expected that after the surge is over arc shall blow off but there is a chance of remaining it in the gap due to the normal voltage also. This is due to absence of non-linear resistance in its circuit. This may lead to short circuit.
2. If not properly designed the rods may bend, melt damage due to overheating caused by the arc.
3. Rain water, humidity, temperatures may affect the gap and arrestor may not give good service.
4. The polarity of the surge may also affect the performance of the arrestor.

So its uses are limited.

☞ Applications

(i) Transformer protection.

(ii) Backup protection with main arrestors.

4.18.2 Horn Gap Arrestors

This type arrestor also used at the limited places due to it unreliability i.e. it is used as backup protection with main arrestor.

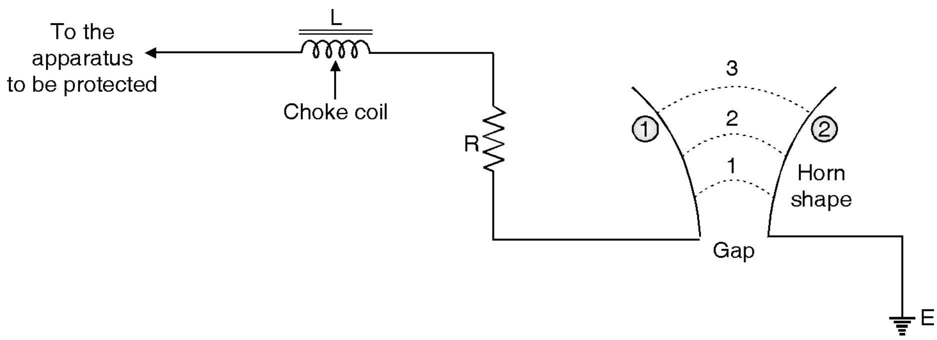


Fig. 4.18.2 : Horn gap arrestor

☞ Construction

- (1) and (2) are the rods bent to give horn like construction with the air gap in between the shape of horns widening on the top portion and narrow at the bottom portion. The horns are supported on the insulating base of porcelain.
- As shown in Fig. 4.18.2, one horn connecting goes to the apparatus to be protected through a resistance ‘R’ and a choking coil ‘L’.

- The second horn connection goes to the ground for earth connection. The resistance 'R' plays an important part in the circuit. It helps in limiting the follow current to a small value.
- Inductance of chock coil 'L' also helps and protects the equipment by providing high reactance ($X_L = 2\pi f_t L$) where f_t is the transient frequency which is very high.
- At normal frequency the reactance $X_L = 2\pi fL$ is small as f is only 50 Hz. Hence, chock coil does not allow the transients to enter the apparatus to be protected.

Working

- The gap between the horns is so adjusted that normal voltage and frequency does not produce arc between the horns. The gap acts as an insulating media.
- But when overvoltage occurs due to surges or transients, the voltage is sufficient to break the insulation of the air-gap and spark (arc) is produced. The air in the gap is heated up and hence goes up and speeded up due to magnetic effect as shown in the Fig. 4.18.2 the arc moves in stage 1, stage 2 and 3.
- At position 3, the distance is much more and the surge voltage cannot maintain the arc and it vanishes and normal condition is brought into the circuit.
- This way the equipment is protected from a voltage surge. The excess charge is conducted through portion 2 of the horn and goes to earth.

Advantages

1. This is superior than rod-type because arc is self clearing and no chance of short circuit.
2. R and L limits the current to small values.

Drawbacks/Limitations

1. Time of operation is about 2 to 3 seconds, hence not reliable.
2. Some materials or birds my fall in the horn gap creating troubles.
3. Due to long use, corrosion and pitting takes place hence setting between the horns for proper air-gap is disturbed and hence performance is affected.

Uses

As said earlier its uses are limited due to unreliability and used for backup protection with main arrestors.

4.18.3 Multi-gap Arrestor

This type is used for power lines voltage not exceeding 33 kV.

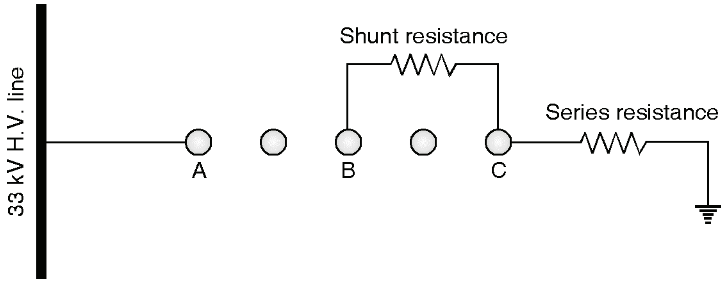


Fig. 4.18.3 : Multi-gap arrestor

☞ **Construction**

– This arrestor is superior than the rod-gap and horn-type arrestor. There are arc (air) gaps between A, B and C. And shunt resistance is connected between B and C whereas, from the last C connection goes to earth via series resistance.

– The cylinders A, B, C etc. are made of zinc alloys and the separated by gaps and insulated from one another. Cylinder ‘A’ is connected electrically to the H.V. line as shown 33 kV. The last ‘C’ cylinder connection goes to earth via series resistance.

– By introducing series resistance the degree of protection against travelling waves is reduced but this is compensated by connecting shunt resistance between B and C.

☞ **Working**

– Under normal working voltage (say 33 kV) ‘B’ is at the ground potential, hence series gaps are open and no arcing between the gaps is possible. If now overvoltage such as transients or surges are developed this very high voltage is sufficient to produce arc between gap A and B.

– This surge heavy current will follow the straight through path to earth via shunted gap B and C instead of alternative path through shunt resistance.

– When surge is over the arc B to C go out and at all if any current persists it is limited by these two resistances which form a series circuit.

– This current is too small to maintain the arc between A and B. In this way the normal conditions are re-stored and system functions on normal working voltage. The equipment is thus protected from over voltage.

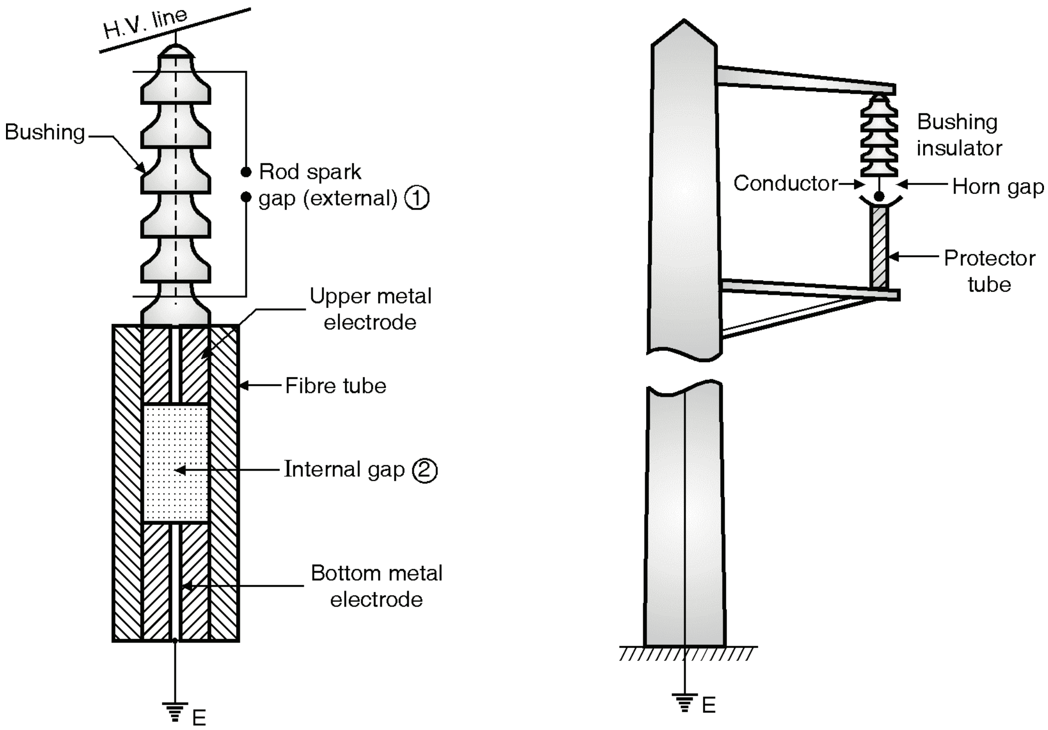
Use : These are suitable for the power line equipment upto 33 kV.

4.18.4 Expulsion Type Arrestor

The other name of the arrestor is "Protector Tube". This arrestor is used on the power lines upto 33 kV. As the name suggests the gases formed during its operation are expelled from the tube through a vent.

☞ **Construction**

– There are two gaps provided one is 'rod gap' and the other gap is in the fibre tube. The first gap is external gap and second is the internal gap. Both these gaps are in series. The external gap is similar to the rod gap arrestor connected to the conductor.



(a) Construction **(b) Schematic representation**

Fig. 4.18.4 : Expulsion type arrestor

– The lower connection goes to the upper metal electrode of the tube and from the lower electrode the connection goes to the ground (earth).

- The fibre tube encloses these two metal electrodes in which second gap is present. For 3-phase lines such three units are required connection of one unit is shown in the Fig. 4.18.4.

Working

- Under the normal working conditions both gaps appear and act as insulators and no arc if production in normal conditions. But on the voltage surge a tremendous voltage is produced an arc is struck in the upper gap between the rods.
- The arc is also produced between the electrodes inside the fibre tube (i.e. in second gap). A lot of heat is produced due to high surge current. This heat vaporises some of the fibre material of the tube and a neutral gas is produced.
- This gas is an un-ionized mixture of water vapour and decomposition product of fibre. A very high pressure is built up in the tube gap due to this gas formation in a very short time. This is expelled through the lower hollow electrode.
- As the gas leaves the tube violently, it carries away the ionized air around the arc. The effect is so strong, the arc is extinguished at current zero state and does not restrict.

This arrestor is superior than the previous types.

Advantages

1. Cost is cheap.
2. Installation is very easy.
3. The restriking possibility of the arc is nil.

Drawbacks/Limitations

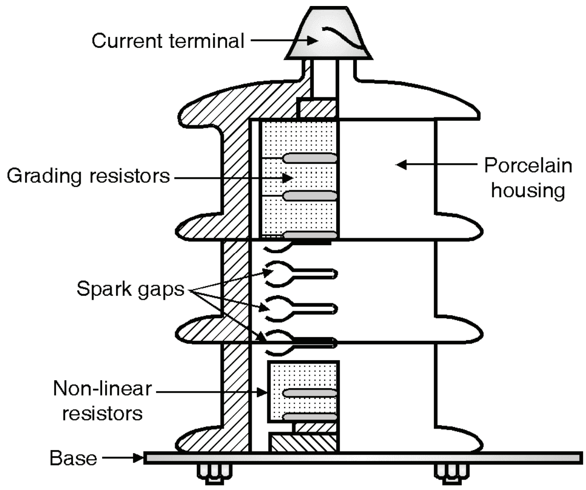
1. Volt/Ampere characteristic of this arrestor is poor and hence not used for costly equipments.
2. Life is short due to consumption of fibre of the tube if the strokes are repeated.
3. This arrestor cannot be mounted in an enclosed equipment due to gas discharges during operations.

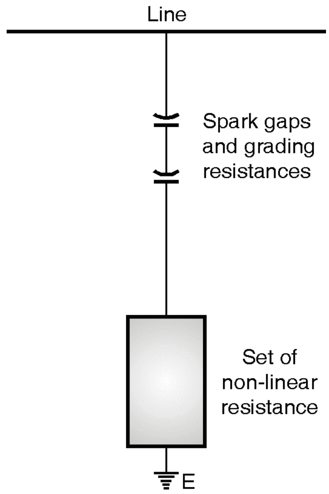
Use

1. This is suitable for power lines and equipment rated upto 33 kV.
2. These are used to prevent flash-over of line insulators, isolators and bus-insulators.

4.18.5 Thyrite Disc-Valve Type Arrestor

These are suitable on high voltage power lines. This is non-linear diverter.





(a) Construction **(b) Schematic diagram of connection**

Fig. 4.18.5 : Valve type arrestor (Half Sectional View)

☞ Construction

- The unit consists of spark gaps in series and also the assembly of non-linear resistance discs of thyrite.
- The spark gap assembly consists of a series of electrodes, some of which the flat and the others are a specially shaped designs with pressed out projections.
- The resistance elements are generally made up in the form of blocks compose of small crystals, silicon carbide bound together by means of an inorganic binder, the assembly being heat treated in an oven.
- Both assemblies i.e. of spark-gap and resistors are accommodated in series within a completely tight porcelain housing. The housing is perfectly sealed so that moisture, humidity not to enter inside. These arrestors are classified as (i) Station type (ii) Line type (iii) Distribution type.
- The voltage distribution across the gaps is linearised by means of additional resistances elements called as grading resistors.

- The assembly of grading resistances, spark gaps and non-linear resistances which are housed in the air tight porcelain are shown in the Fig. 4.18.5(a) whereas, connection of line, arrestor and earth is shown in the Fig. 4.18.5(b).
- The speciality of non-linear resistance is such that they offer a high resistance to the current when normal system voltage is applied but very low resistance to the high value surge currents so that surge current is quickly passes through these resistances to the ground.

☞ **Working**

Under the normal conditions the normal line voltage is insufficient to break the air gaps and no arc is produce and equipments work safely. On the occurrence of very high voltage due to transients or surges breakdown of series gaps takes place.

The non-linear resistance offer a low resistance path to the surge current and it passes to the earth within a very short time. The arc vanishes does not restrike back over the line. When the surge is over, the resistance offer a very high insulation (resistance) to the normal supply voltage of the system and stop the flow of current.

☞ **Advantages**

1. Provide very reliable and effective protection to the equipment like cables, transformers and other equipments.
2. The impulse ratio $= \dfrac{\text{Breakdown voltage under surge condition}}{\text{Breakdown voltage under low frequency condition}}$ is practically unity.
3. Speed of operation is very high (operation completes in less than one second).
4. It sparks over at a predetermined voltage.
5. They dissipate surge energy.
6. They discharge high frequency surges without any change in spark-over characteristic.

☞ **Drawbacks/Limitations**

1. They may fail to check the surges of very steep wave front from reaching the terminal apparatus.
2. If moisture enters, they lose their performance.

Uses

To protect important equipment in power stations operation on voltage upto 22 kV and higher. Used in station handling voltages upto 66 kV.

4.19 Metal Oxide Lightning Arrestor

4.19.1 Construction

A stack of zenox disc is mounted in a sealed porcelain housing.

- Each such disc is wedged in place with silicone rubber.
- This silicone rubber offers heat transfer and it also protects from physical damages.
- A conducting surface is applied on the end faces of each dices. This ensures proper contact and uniform current distribution.

4.19.2 Material Used

The zenox value elements are made of a compound of zinc oxide and other metal oxides in small amount. All these are thoroughly mixed and made powder formed and pressed to form disc.

- These disc are well fired at high temperature and it results the disc in dense form of poly crystalline ceramic.
- Under the electric stress the inner layers conduct resulting in highly non-linear characteristics.
- Under normal condition current does not exceed 1 milliampere. But when the surge reaches the arrester then it conducts current which is necessary to restrict the over voltages.

4.19.3 Comparison of Metal Oxide Lighting Arrester with Thyrite Disc Arrester

Sr. No.	Thyrite Disc Arrester	Metal Oxide Lightning Arrester
1.	Average.	Superior than thyrite type.
2.	Construction bulky.	Construction simple.
3.	Average energy absorption capacity.	Superior energy absorption capacity.
4.	Surge production is better.	Surge protection is best.
5.	Protective characteristic are normal.	Better protective characteristics.
6.	Used on medium EHV lines.	Used on high EHV lines upto 240 kV.

4.19.4 Locations of Lightning Arrestors

(i) It is located near the apparatus to be protected.

(ii) On overhead lines, the first equipment is the L.A. from line to substation.

(iii) Installed near transformer terminals.

(iv) Installed at definite height so that its characteristic should not affect.

4.19.5 Selection of Lightning (Surge) Arresters

Following are the requirements of the protective devices hence proper care is taken for selection.

(1) The voltage across the arrester during discharge (Residual voltage) should not be too low nor too high.

(2) It should have adequate energy absorption capacity so that it is not damaged.

(3) During normal frequency condition it should not take any current.

(4) Its breakdown capacity should be more than normal power frequency voltages and the permissible over voltages.

(5) It divert immediately the transient voltages to earth which are more than insulation withstand level.

Syllabus Topic : Surge Absorbers, Shape of Lightening Voltage Wave

4.20 Surge Absorbers

– Sudden rise in the voltage for a very short period on the power system is known as a voltage surge or transient voltage.

– When lightning struck a line; the surge rushes along the line just as flood of water along a narrow valley.

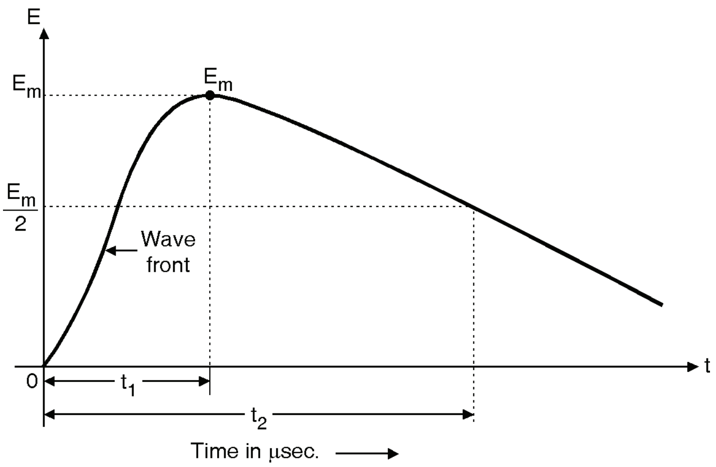


Fig. 4.20.1 : Voltage surge wave

- Typical nature of lightening voltage surge, Refer Fig. 4.20.1. The description of this wave is as below.
- The lightning introduces a steep fronted wave. Steeper the wavefront, more rapid is the build-up of voltage at any point in the network. The voltage surge is generally specified in terms of rise time t_1 to react and the time t_2 to decay to half of the peak value $\left(\frac{E_m}{2}\right)$.
- If the t_1 = 1 μsec. and t_2 = 50 μsec. The surge is specified 1/50 μsec. the travelling wave damages the terminal apparatus.
- The damage depends upon the amplitude of the surge (i.e. E_m) and also upon the steepness of the wavefront (i.e. if t_1 is very small).
- The purpose of installing a "surge absorber" is to reduce the steepness of the wavefront of the surge wave.
- Surge absorber is therefore a protective device which reduces the steepness of wavefront of a surge by absorbing surge energy.

Table 4.20.1

Sr. No.	Surge Absorber	Surge Diverter/Lightning Arrestor
1.	Absorbs the surge energy to eliminate the surge and to protect the equipment.	Diverts the surge to the earth and eliminate the surge to protect the equipment.
2.	Construction very simple and less costly.	Construction not so simple but somewhat costly.

Let us study some of the surge absorbers :

4.20.1 Types of Surge Absorbers

1. Condenser surge absorber.
2. Choke and resistance surge absorber.
3. Ferranti surge absorber.

Syllabus Topic : Surge Capacitor

4.20.1.1 Surge Capacitor / Condenser Surge Absorber

→ (MU - May 15, May 16)

Q. 4.20.1 Discuss the role of surge capacitor, surge reactor and surge absorber.

(Refer sections 4.20.1.1, 4.20.1.2 and 4.20.1.3) **May 15, May 16, 10 Marks**

- Capacitive reactance $X_C = \frac{1}{2\pi fC}$ i.e. it is inversely proportional to frequency. At power frequency (50 Hz), X_C is large and hence no current flows from line to earth at normal voltage and normal frequency of the line.
- But when overvoltage appears due to transients or surges due to the high frequency of the surge voltage X_C becomes very small and shorted and thus immediately the current (energy) passes to the ground.
- Hence, capacitor absorbs surge energy and allows it to dissipate in the ground and the equipment like transformer windings are protected from surges.

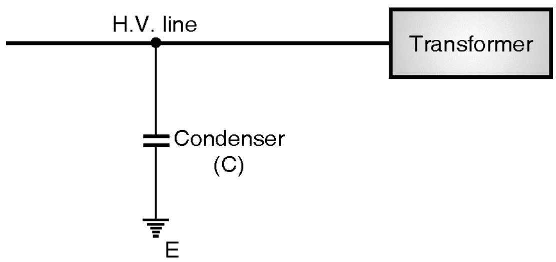


Fig. 4.20.2 : Condenser surge absorber

Syllabus Topic : Surge Reactor

4.20.1.2 Choke and Resistance (Reactor) Surge Absorber

→ (MU - May 15, May 16)

Q. 4.20.2 Discuss the role of surge capacitor, surge reactor and surge absorber.

(Refer sections 4.20.1.1, 4.20.1.2 and 4.20.1.3) **May 15, May 16, 10 Marks**

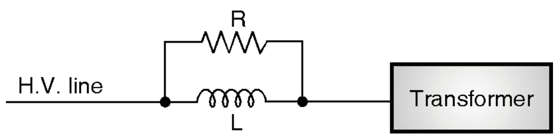


Fig. 4.20.3 : Choke and resistance surge arrester

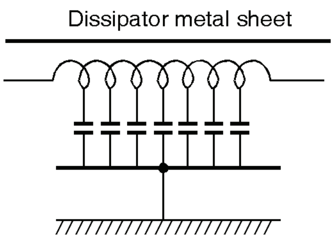
- In this type of absorber, a resistance and inductor coil connected in parallel forming a series circuit of line, R and L and the equipment (transformer).
- At the normal conditions and power frequency $X_L = 2\pi fL$ is small. But in case of surge voltage developed in the line X_L becomes very large and the current passes through the resistance where the energy is absorbed (I^2Rt). Thus, the surge energy is dissipated in 'R' to produce heat.

4.20.1.3 Ferranti Surge Absorber

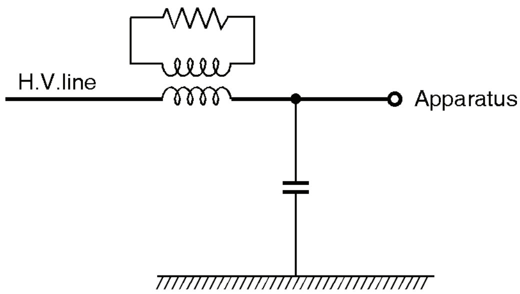
→ (MU - May 15, May 16)

Q. 4.20.3 Discuss the role of surge capacitor, surge reactor and surge absorber.
(Refer sections 4.20.1.1, 4.20.1.2 and 4.20.1.3) **May 15, May 16, 10 Marks**

- This is the most modern type of absorber. It consists of an air-cored inductor connected in series with each line and surrounded by a grounded metallic sheet. This surrounding metal is insulated from inductor and connected to the ground (earth).
- This sheet is called as dissipated. The sheet is thus magnetically coupled to inductor but electrically isolated from it by air.
- This arrangement acts as a air-cored transformer whose primary is an inductor coil and metallic dissipated is a short circuited secondary of a single turn. Wherever, the travelling wave is incident on the surge absorber, the energy contained in the wave is dissipated in the form of heat generated in the dissipated sheet (i) due to current set up in it by ordinary transformer action and (ii) by eddy currents.
- The steepness of the wave front is also reduced because of the series inductance of the inductor coil.



(a) 66 kV ferranti, surge absorber represented schematically



(b) Equivalent circuit

Fig. 4.20.4 : Surge absorber

Syllabus Topic : Lightning Arrestors and their Protective Characteristics

4.21 Lightning Arrestors and their Protective Characteristics

→ (MU - May 15, Dec. 16, May 17)

Q. 4.21.1 Explain the terms protective characteristics, dynamic voltage rise and rating in case of lightning arrestor.
(Refer sections 4.21 and 4.22) **May 15, May 17, 10 Marks**

Q. 4.21.2 Discuss the terms protective characteristics, Dynamic voltage rise, Arrestor rating.
(Refer sections 4.21 and 4.22) **Dec. 16, 10 Marks**

- Different types of Lighting arresters their locations and construction working etc has already been studied so far.
- Lighting arrestors also called as surge absorbers because they are also meant for switching surge protection, protect primarily major equipments like transformer, rotating machines, shunt reactors and even the entire sub-stations.

4.21.1 Protective Characteristic

Protective Characteristic of L.A. or Surge Absorber for their selections are :

(i) Protective ratio (N_p) (ii) Discharge current (iii) Protective level

Let us describe these important protective characteristic of LA/SA for proper selection.

4.21.1.1 Protective ratio (N_P)

This is the most important property.

Protective ratio is defined as the ratio :

$$N_p = \frac{\text{Peak impulse Insulation Level of protected Equipment}}{\text{Rated Arrester power frequecny voltage RMS value}}$$

The other important ratio is Earthing co-efficient EC

$$EC = \frac{\text{RMS value of healthy phase voltage at arrester location}}{\text{Line to Line votlage at the arrester location}}$$

- Earth fault EFF = $\sqrt{3} \cdot EC$
- EC and EFF are the selection governing factors of arresters voltage ratings.
- As per ISS, on 400 kV line with a maximum operating voltage of 420 kV, an 80 % arrester has a rating of 336 kV r.m.s. with EC = 0.8 and EFF = $0.8\sqrt{3}$

Table 4.21.1 : Protective characteristic of L.A.

Sr. No.	Country	Maximum services Voltage V_m, kV, r.m.s.	Arrester Rating V_a Ph. Gr. kV. R.m.s.	Earthing Coefficient* $C_E = V_a / V_m$	Impulse Protective Level, V_p kV, peak	Protective Level Ratio $N_p = V_p/V_p/V_a$	Station equipment impulse withstand level, V_s, kV, peak	Protective ratio** $C_p = V_S/V_p$	Impulse withstand ratio $C_i = V_s/V_m$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
1.	U.S.A	360	258	0.72	750	2.91	1050	1.4	2.92
2.	India	420	336	0.8	1100	3.27	1550	1.41	3.7
3.	France	420	375	0.89	1200	3.2	1450	1.21	3.45
4.	Germany	420	390	0.93	1156	2.97	1450	1.25	3.45
5.	Switzerland	420	345	0.82	1100	3.19	1550	1.41	3.7
6.	Canada	525	440-480	0.84 –0.91	1260	2.85	1675	1.33	3.19
			480	0.91	1350		(1800)		(3.43)

- Under the fault (single line to ground) voltage of faulted phase is zero but voltage of two other healthy phase will rise above the normal working voltage.
- In such situation the L.A. should be capable to sustain this rise without spark-over of series gaps.

4.21.1.2 Discharge Current

- This is the second important protective property needed for LA selection. The lightening type impulse current arrester material has to discharge without damage to itself.
- Following table shows standard surge current 8/20 μs taken from I.S. standards

Table 4.21.2

Crest 8/20 μs current (Amp.)	5000	10000	15000	20000
System voltage (kV)	Upto 230 kV	345 to 400	900	750 kV

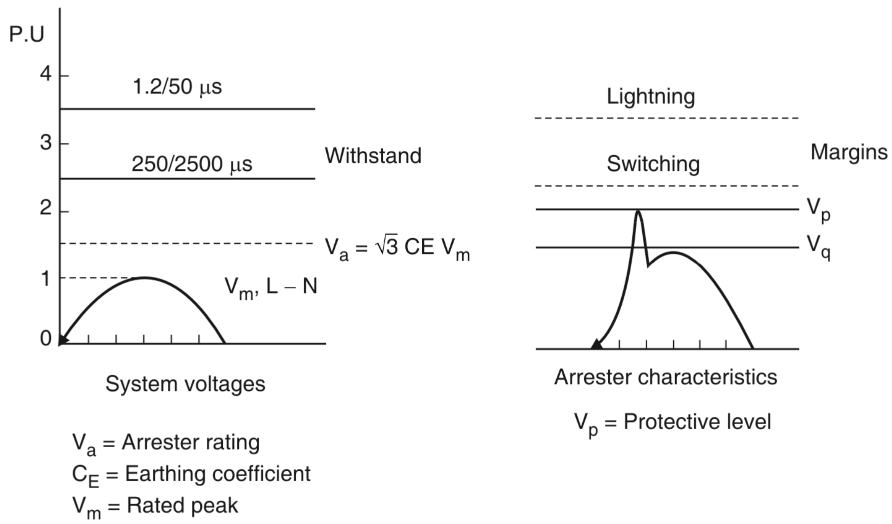
4.21.1.3 Protective Level

This is the third important protective property of LA for selection. This is the protective level offered by it to the connected equipment.

Table 4.21.3: L.A. Protective Level and Equipment Insulation (for transformers)

Nominal System kV, RMS	Highest Equipment Voltage, kV RMS	Rated Switching Impulse withstand (Phase Neutral) kV crest	Rated lightning Impulse Withstand Voltage, kV crest	L.A. Protective Level kV, crest
275	300	750 850	850 and 950 950 and 1050	
345	362	850 950	950 and 1050 1050 and 1175	625 – 770
400	420	950 1050	1050 and1175 1050 and 1175	
500	525	1050 1175	1175, 1300 and 1425, 1175, 1300 and 1425	
750	765	1425 1550	1425 and 1550 1550 and 1800 1800 and 1950	895 – 1010 1010 1300 - 1465

The above discussed characteristics are represents below :



(a) System voltage **(b) Arrester characteristics**

Fig. 4.21.1 : Arrester voltage rating CE overvoltage, switching impulse protective level of arrester and margins

V_a = Arrester Rating

V_p = Protective Level

C_C = Earthing Coefficient

V_m = Rated Peak

Syllabus Topic : Dynamic Voltage-rise and Arrester-rating

4.22 Dynamic Voltage-rise and Arrester-rating

→ (MU - May 15, Dec. 16, May 17)

Q.4.22.1 Explain the terms protective characteristics, dynamic voltage rise and rating in case of lightning arrestor.

(Ans. : Refer sections 4.21 and 4.22) **May 15, May 17, 10 Marks**

Q. 4.22.2 Discuss the terms protective characteristics, Dynamic voltage rise, Arrestor rating.

(Ans. : Refer sections 4.21 and 4.22) **Dec. 16, 10 Marks**

- Arrester voltage rating selection depends on the voltage rise of the healthy phases at the arrester location. When a single line to ground fault takes place.
- Let us take three different cases of the faults occurring at different places as describes below. Let us see the illustration of dynamic voltage rise under single phase to ground fault.

First case

Isolated neutral system with bus-fault on phase C. As shown in Fig. 4.22.1, the fault is in phase 'C'. The voltage of the healthy two phases to ground will rise to line-to-line voltage.

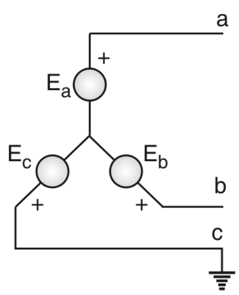


Fig. 4.22.1

Earthing co-efficient E_C

$$= \frac{\text{Healthy phase voltage}}{\text{Line to line voltage}} = 1$$

And corresponding Earth Factor (EFF)

$$= \sqrt{3}$$

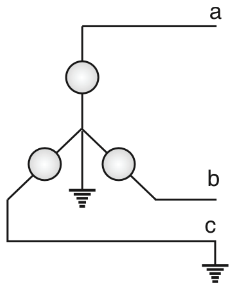


Fig. 4.22.2

Second case : (See Fig. 4.22.2)

Solidly grounded neutral system with a bus-fault.

See the Fig. 4.22.2 in which fault is shown. Note that the healthy phases do not experience any rise in voltage from the normal; operating condition.

Hence in this case Earthing coefficient EC and Earth Fault factors are given as :

$$EC = 1/\sqrt{3} \quad \text{and} \quad EFF = 1$$

Third case

A general system with a fault beyond connected equipment. This fault location is shown in this Fig. 4.22.3. Here Earthing co-efficient EC is between $\frac{1}{\sqrt{3}}$ to 1.

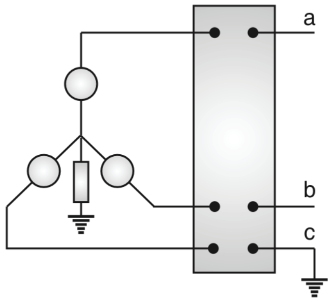


Fig. 4.22.3

The value is derived in terms of ratio.

$$\frac{Z_0}{Z_1} \text{ i.e. ratio } \frac{\text{Zero sequence impedance}}{\text{positive sequence impedance upto the fault}}$$

When single line to ground fault occurs, according to symmetrical component theory, the three sequence networks are connected in series as shown in Fig. 4.22.4. Only the positive sequence network contains a driving voltage E. The current is

$$I = E \,|\, (Z_0 + Z_1 + Z_2)$$

The three sequence voltages at the fault are

$$V_0 = E_0 - IZ_0 = -E \,|\, (1 + Z_1 / Z_0 + Z_2 / Z_0)$$

$$V_1 = E_1 - IZ_1 = E - E \,|\, (1 + Z_0 / Z_1 + Z_2 / Z_1)$$

$$V_2 = E_2 - IZ_2 = -E \,|\, (1 + Z_0 / Z_2 + Z_1 / Z_2)$$

For static equipment such as lines and transformers,

$Z_1 = Z_2$. Let, up to the fault,

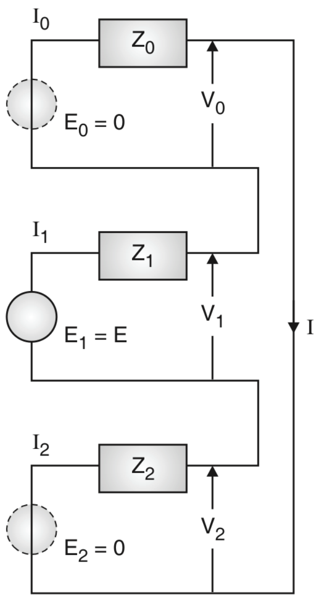


Fig. 4.22.4 : Connection of sequence networks and calculation of arrester rating under dynamic voltage rise.

$m = Z_0 / Z_1$ = zero sequence impedance /positive sequence impedance

Then, $V_0/E = -m/(m+2)$, $V_1/E = (m+1)/(m+2)$

and $V_2/E = -1/(m+2)$

The healthy phase voltage such as V_b is with $a = 1 \angle 120°$

$$\frac{V_b}{E} = \frac{V_0 + a^2 V_1 + aV}{E}$$

$$= \frac{-m + (-0.5 - j\,0.866)(m+1) - (-0.5 + j\,0.866)}{m+2}$$

and its p.u. value is

$$\left|\frac{V_b}{E}\right| = \sqrt{3}\left|\frac{\sqrt{m^2+m+1}}{m+2}\right| \text{ when m is real quantity}$$

This will apply when $R_0 \mid x_0 = R_1 / x$ where R and x are the resistance and reactance components of Z. The earthing coefficient is therefore

$$EC = \left|\frac{V_b}{\sqrt{3}\,E}\right| = \left|\frac{\sqrt{m^2+m+1}}{m+2}\right| ; \; m \neq 0,$$

When m various from 1 to ∞ the earthing coefficient (EC) and earth fault factors (EFF) have the following values

$m = Z_0 / Z_1$	1	2	2.5	3	3.5	4	5	7.5	10	∞
EC	0.578	0.66	0.7	0.721	0.744	0.764	0.795	0.849	0.88	1
EFF	1	1.14	1.20	1.25	1.29	1.323	1.38	1.47	1.52	$\sqrt{3}$

Exercise

Q. 1 Explain transient in simple R.L. circuit. **(Section 4.2)**

Q. 2 Write a note on sudden S.C. of an Alternator. **(Section 4.3)**

Q. 3 Given the analysis of S.C. current **(Section 4.3.1)**

Q. 4 Elaborate restricting voltage after removal of short circuit. **(Section 4.3.2)**

Q. 5 Explain over voltage due to arcing grounds. **(Section 4.4)**

Q. 6 What is capacitance switching ? Draw circuit diagram and voltage built up wave. **(Section 4.5)**

Q. 7 Write a note on current chopping. **(Section 4.6)**

Q. 8 Write a brief how travelling waves are produced on transmission line.**(Section 4.7)**

Q. 9 Derive the following relations of waves **(Section 4.7.1)**

(i) Surge impedance $Z_s = \sqrt{L/C}$ (ii) Velocity of propagation $\upsilon = 3 \times 10^8$ m/sec.

Q. 10 Describe clearly the shape travelling wave with specifications. **(Section 4.7.1.1)**

Q. 11 Write a detailed note with derivations about reflection and refraction waves. **(Section 4.7.2)**

Q. 12 Write the formula for

(i) Refraction co-efficient (ii) Reflection co-efficient **(Section 4.7.2 (last para))**

Q. 13 Which are the 4-typical cases of line terminations ? **(Section 4.8)**

Q. 14 In respect of terminal cases write the wave equations. **(Section 4.8)**

Q. 15 What are the advantages of line connected to cable at station? **(Section 4.8(iv))**

Q. 16 Characteristics impedances of O.H. line and connected cable at station are respectively 400 Ω and 50 Ω. Vertical front travelling wave has tail and magnitude 100 kV travelling from line toward cable junction.

Find : (i) E_T, (ii) I_T, (iii) Energy transmitted into cable in 2 μ sec time and (iv) E_R, (v) check that $E_T = E + E_R$.

Ans. :

(i) 22.22 kV (ii) 444.4 A (iii) 19.75 J (iv) – 77.78 kV

(v) $E + E_R = 100 - 77.78 = 22.22 = E$

Q. 17 Write a detailed note on Attenuation **(Section 4.9)**

Q. 18 State the advantages of Bewley's Lattic Diagram. **(Section 4.10)**

Q. 19 Explain step – by – step solution by Bewley's Lattic Diagram of positions and direction of all successive reflections of waves. **(Section 4.10.1)**

Q. 20 State the external and internal causes and over voltages. **(Sections 4.11.2.1 and 4.11.2.2)**

Q. 21 Explain the mechanism of Lightening phenomenon. **(Sections 4.12.1, 2 and 3)**

Q. 22 With relevant figures explain Direct and indirect lightening strokes. **(Sections 4.12.3.1 and 4.12.3.2)**

Q. 23 What are the different protection provided to transmission line sub-stations ? **(Section 4.13)**

Q. 24 Write brief notes on :

(1) Earthing screen for line protection **(Section 4.13.1)**

(2) Over-head ground wire continued for line protection **(Section 4.13.2)**

Q. 25 Write a detailed note on Tower Footing resistance. **(Section 4.15)**

Q. 26 Write a note on Insulation flashover and withstand voltage. **(Section 4.16)**

Q. 27 Write on the function of Arrester. **(Section 4.17.1)**

Q. 28 Explain the working of Arrester. **(Section 4.17.3)**

Q. 29 List the different types of lightening arresters used for protection.
(Sections 4.18.1, 2, 3, 4, 5 etc.)

Q. 30 Write a note on selection and locations of lightening arresters. **(Sections 4.19.4, 5)**

Q. 31 Write a note on surge Arrester. **(Section 4.20)**

Q. 32 Give the types of surge Arresters. **(Section 4.20.1)**

Q. 33 Write a note on Ferranti surge Absorber. **(Section 4.20.1.3)**

Q. 34 Write fully on L.A. and their protective characteristics. **(Section 4.21)**

Q. 35 Explain dynamic voltage rise and Arrester rating. **(Section 4.22)**

4.23 University Questions and Answers

➔ May 2015

Q. 3(a) Explain the terms protective characteristics, dynamic voltage rise and rating in case of lightning arrestor. *(Ans. : Refer sections 4.21 and 4.22)* **(10 Marks)**

Q. 6(a) Discuss the role of surge capacitor, surge reactor and surge absorber. *(Ans. : Refer sections 4.20.1.1 and 4.20.1.2)* **(10 Marks)**

➔ Dec. 2015

Q. 1(c) What the role of tower footing resistance ? *(Ans. : Refer section 4.15)* **(5 Marks)**

Q. 4(a) Discuss the phenomenon of arcing ground. *(Ans. : Refer section 4.4)* **(10 Marks)**

➔ May 2016

Q. 4(a) Discuss the phenomenon of transient due to removal of short circuit.

(Ans. : Refer section 4.3.2) **(10 Marks)**

Q. 4(b) A voltage having a crest value of 3000 KV is travelling on the line of 750 K.V. The surge impedance of line is 300 ohm.

Calculate :

(1) Current line current before reaching the arrestor

(2) Current through arrestor

(3) Value of arrestor resistance for this condition

(4) Reflected voltage

(5) Verify the reflection and refraction coefficient

(Ans. : Refer Example 4.7.1) **(10 Marks)**

Q. 5(a) Discuss the application of surge reactor, capacitor and surge arrestor.

(Ans. : Refer sections 4.20.1.1,4.20.1.2 and 4.20.1.3) **(10 Marks)**

Q. 6(a) Discuss the phenomenon lightning.

(Ans. : Refer sections 4.12,4.12.1 and 4.12.2) **(10 Marks)**

➔ Dec. 2016

Q. 4(a) Discuss the phenomenon of capacitance switching.

(Ans. : Refer section 4.5) **(10 Marks)**

Q. 4(b) Discuss the terms protective characteristics, Dynamic voltage rise, Arrestor rating.

(Ans. : Refer sections 4.21 and 4.22) **(10 Marks)**

Q. 5(a) Discuss the phenomenon of traveling wave on case of termination of line as open circuit. *(Ans. : Refer section 4.7)* **(10 Marks)**

➔ May 2017

Q. 1(c) What is the rate of tower footing resistance ? *(Ans. : Refer section 4.15)* **(5 Marks)**

Q. 4(a) Discuss the reflection and refraction of voltage and current wave on an short circuit transmission line. *(Ans. : Refer section 4.7.2)* **(10 Marks)**

Q. 4(b) Explain the terms Protective characteristics, Dynamic voltage rise and rating in case of lighting arrester. *(Ans. : Refer sections 4.21 and 4.22)* **(10 Marks)**

Chapter Ends...

❑❑❑

CHAPTER 5 Insulation Co-ordination

Syllabus :

Volt time curve, basic approach to insulation co-ordination in power system, over voltage protection, ground wires, insulation coordination based on lightning, surge protection of rotating machines and transformers.

Syllabus Topic : Basic Approach to Insulation Co-Ordination in Power System

5.1 Introduction (Meaning of Insulation Co-ordination, Basic Approach)

→ **(MU - Dec. 16)**

Q. 5.1.1 Discuss the importance of insulation coordination.
(Refer section 5.1) **Dec. 16, 5 Marks**

- Switchgear engineering section needs the knowledge of insulation co-ordination for determining the appropriate insulation of switchgear to select appropriate lightening arresters at various locations.
- For selection of insulation level the over voltages shall be considered. The insulation co-ordination consists of steps taken to prevent the probable damages due to over voltages caused by short circuits, lightning switching surges impulses.
- Insulation co-ordination may be regarded as :
- The co-relation of impulse withstands level of equipment with the protective characteristics of a lightening arrester such that insulation is protected from impulse over voltages.

5.1.1 Definition Related to Insulation Co-ordination

1. Normal voltage

Line to Line (RMS) voltage i.e. 11 kV, 33 kV, 132 kV, 220 kV etc. These may be the line to line voltage of lines.

2. The highest voltage

This is the highest line to line RMS voltage which the line can sustain under normal operating conditions at any time on the system that may just for

Normal	Highest
11 kV	12 kV
132 kV	125 kV
220 kV	245 kV

3. Insulation level

This is the capacity of the insulation of the apparatus withstanding dielectric stresses imposed by voltage levels of the system.

4. Highest voltage level of the equipment

It is the highest RMS line to line voltage for which the apparatus is designed (u_m).

5. Over voltage

It is the time dependent voltage between the phase and the earth of the value exceeding $\frac{\sqrt{2}}{\sqrt{3}} u_m$.

6. Phase to phase per unit voltage

$$\text{It is the ratio} = \frac{\text{Maximum peak to peak voltage}}{\text{Highest phase to phase equipment voltage}}$$

7. Protection level of a protective devise

- It is the highest peak voltage value which must not be exceeded at the terminals of the protective devices when switching waves/impulse waves are applied under the specified conditions.
- For each system voltage basic impulse insulation level has been fixed by most of the National and International Standards.

- The major substation equipment, viz., transformers, breakers, isolating switches, current transformers, potential transformers are manufactured for the same insulation level, except where transformers may be manufactured for a lower step of insulation level in consideration of the economy possible.
- Sometimes, when the lightning arrestors are installed right on the terminals of the transformers. Some of the substation equipment may fall outside the protective zone determined from the withstand level of the equipment, discharge voltage of the lightning arrestor and the distance between the equipment and the lightning arrestor and the equipment may be arranged with one step higher BIL.
- In general, four levels of insulation in a station are recognized; the bus insulation is highest, the post insulators, breakers, switches etc., next lower; the transmission former next lower; and the lightning arrestor is the lowest.
- The percentage of margins between these different levels are not uniform but can be attained on a reasonably constant basis by the use of commercially available components of equipment.
- With bus insulation, for example, it is a simple matter in high voltage station to add one or two insulator units in a strain bus without significant increase in cost. The insulation of the disconnecting switches is brought to a satisfactory level by usually using the next higher rated switch above the insulation class of the system.
- The transformers are insulated for the lowest level that can be protected with adequate margin of safety above the level of the arrestor which is required to withstand 50 cycle over-voltage of the system not only in normal service but also under fault conditions.
- The co-ordination of insulation as practiced by the AG and ESC in station equipment of various system voltages is shown in Table 5.1.1.

Table 5.1.1

Impulse kV				
Rated System Voltage kV	**Bus Installation**	**Switch and Post Insulation**	**Transformers**	**Circuit Breakers**
23	330	225	150	150
34.5	420	235	200	200

Impulse kV				
Rated System Voltage kV	**Bus Installation**	**Switch and Post Insulation**	**Transformers**	**Circuit Breakers**
69	565	440	350	350
115	865	590	550/450	650
138	1000	590	550/450	650
330	1665	1475	1175	1175

The values for transformers and circuit breakers are withstand values while those for bus and switch insulators are critical values.

Table 5.1.2 : Standard insulation levels as per practice of M.S.E.B. India

System Voltage kV rms	Impulse Strength of Transformer Winding 1/50 μS Full Wave kV peak	Dry Flash Over Voltage kV rms	Wet Flash Over Voltage kV rms
230	900	530	385
110	550	320	240
66	350	260	180
33	200	170	120

Syllabus Topic : Volt Time Curve

5.1.1.1 Volt Time Characteristic

– The volt time characteristics of various switchgears like circuit breakers, transformers etc are different and hence insulation of the protective devices should be properly coordinated.

– The basic concept of insulation co-ordination is as shown in Fig. 5.1.1. Curve A is the volt-time curve of the protective device and B the volt-time curve of the equipment to the protected.

A – Protecting device

B – Device to be protected

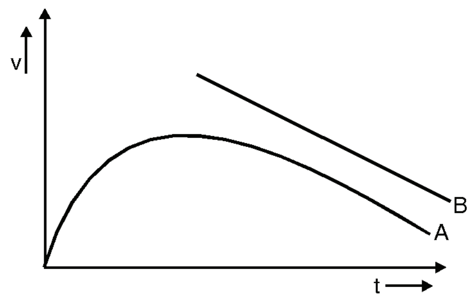


Fig. 5.1.1

- From above characteristics it can be concluded that - for any insulation having a withstand voltage strength in excess of the insulation strength of curve B is protected by the protective device of curve A.
- The coordination of insulation should cover both, guarding the equipment insulation and safety of protective equipment. Some guidelines have been mentioned for insulation co-ordination .These include following terms :

Syllabus Topic : Insulation Co-ordination Based on Lightning

5.1.1.2 Basic Impulse Insulation Level (BIL)

- Basic Impulse Insulation Level (BIL) are reference levels expressed in impulse crest voltage with a standard wave not longer than 1.2/50 μsec. wave.
- The insulation of apparatus should be tested and the level of insulation should be greater than or equal to the basic insulation level.
- The Basic Impulse Level (BIL) i.e. the lightning impulse withstands level is established for each system nominal voltage for different apparatus.
- The BIL of various apparatus should be above the system protective level, by suitable margin.
- The margin is quantified with respect to air insulation. The statistical methods are used for this purpose. The conventional methods are used in case of composite insulation apparatus e.g. Transformer.

Requirements of ideal protective device which is connected in parallel or in shunt are :

(a) Flashover should not take place for power frequency over voltages.

(b) The volt-time characteristics of the device must lie below the withstand voltage of the protected apparatus or insulation. However if there is marginal difference between the two that marginal difference should be sufficient to take accountability of different effects such as changes in the characteristic of the devices due to ageing, difference in distance, polarity, atmospheric variations etc.

(c) It should be capable of discharging high energies contained in surges i.e. energy should be rapidly dissipated and recover insulation strength quickly.

(d) It should not allow the power frequency-follow-on current to flow.

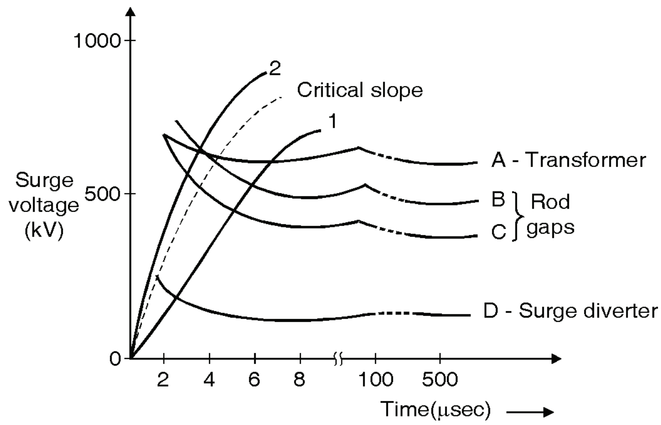


Fig. 5.1.2 : Volt-time characteristic of transformer, rod gaps and surge diverters

– The lightening arrester protects the transformer insulation for the entire time span. If rate of rise of surge is less than 1, the rod gaps protects transformer insulation and if the surge voltage rise follows curve 2, only surge diverter can protect the transformer insulation.

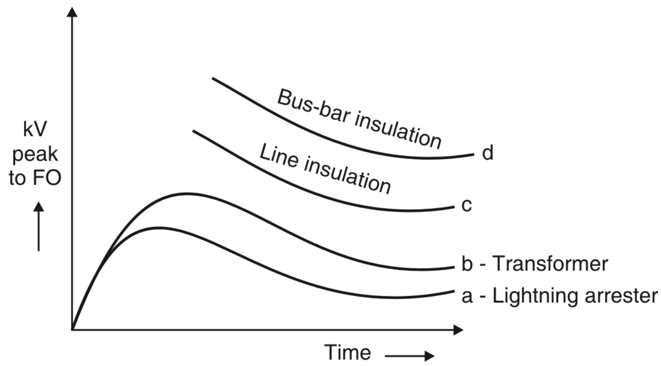


Fig. 5.1.3 : Volt-time-curve

– Fig. 5.1.3 gives relative position of volt-time curves of various equipment in a sub-station for proper co-ordination.

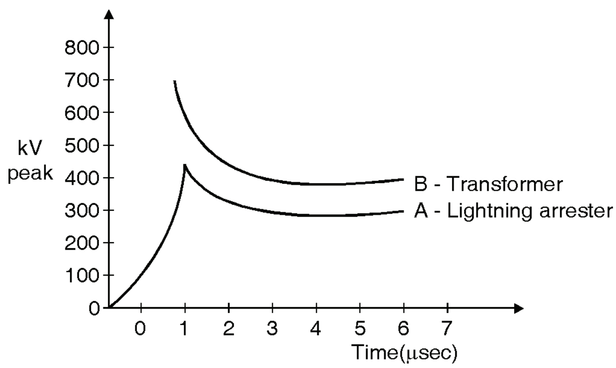


Fig. 5.1.4

Table 5.1.3 : Basic impulse insulation levels

Sr. No.	Reference class (kV)	Standard basic impulse level (kV)	Reduced insulation levels
1.	23	150	–
2.	34.5	200	–
3.	46	250	–
4.	69	350	–
5.	92	450	–
6.	115	550	450
7.	138	650	550
8.	161	750	650
9.	196	900	–
10.	230	1050	900
11.	287	1300	1050
12.	345	1550	1300

- The last column in Table 5.1.3 indicates reduced insulation levels. These levels are referred for selecting insulation levels for systems that operate above 345 kV (solidly grounded).In such systems the switching surges are more dominant than lightening surges.
- For e.g. A system operating at 345 kV, let the switching voltage is 2.85 pu then $345 \times 2.85 = 983.25$ kV which is lightning level voltage.
- Whereas at 500 kV, keeping the same switching voltage we get, $500 \times 2.85 = 1425$ kV switching voltage which is much greater than the lightning voltage level.
- The ratio of switching voltage to operating voltage can be reduced by switching resistances. A resistance of suitable value is connected across circuit breaker contacts. Because of these switching resistances this ratio is brought down to 2.0 pu for 500 kV and 1.7 for 765 kV.
- For switching voltages the reduced levels in the third column are referred i.e. for 345 kV the standard BIL is 1550 kV but if the equipment can withstand up to 1300 kV to 1425 kV the purpose is served.

- To illustrate the selection of BIL of a transformer to be operated on a 161kV system. Assume that transformer is of large capacity and its star point is solidly grounded.
- The grounding is such that the line to ground voltage of the healthy phase during a ground fault on one of the phases is say 74% of normal line to line voltage.
- Allowing for 5% overvoltage during operating conditions, the arrester r.m.s operating voltage will be $1.05 \times 0.74 \times 161 = 125.09$ kV.
- The nearest standard rating is 125 kV. The characteristics of such lightning arrester are shown in Fig. 5.1.4.
- From the fig the breakdown value of arrester is 500kV. Assume a 15% margin plus 35kV between the insulation levels of LA and the transformer, the insulation level of transformer should be at least equal to $500 + 0.15 \times 500 + 35 = 610$ kV, from Fig. 5.1.4 (or from table the reduced level of transformer for 161 kV is 650 kV) the insulation level of transformer is 650 kV, therefore a lightning arrester of 125 kV rating can be applied.

Syllabus Topic : Over – voltage Protection

5.2 Over – voltage Protection

☞ **Lightning Arrester/surge diverters**

- Earthing screens and ground wires are suggested for protection against direct lightning strokes but they are unable to protect the equipment against travelling waves.
- The lightning arresters or surge diverters take care of the terminal equipments against such surges.

5.2.1 Function of Lightning Arrester/ Surge Diverters

The function of the lightning arrester or surge diverter is to conduct the high voltage, surges on the power system to the ground, thus discharging the impulse surge to earth and to dissipate energy in the form of heat.

5.2.2 Schematic Representation and Functioning of Arrester

Students should refer chapter 3 for detailed study of Arresters/surge diverters etc.

Syllabus Topic : Ground Wires

5.3 Ground Wires

→ **(MU - May 15)**

Q. 5.3.1 Discuss the role of ground wire and tower footing resistance.
(Refer section 5.3) **May 15, 5 Marks**

As discussed in Ch. 4 Section 4.13 the different devices are used for protection again lightening surges. These devices are :

(i) Earthing screen

(ii) Over - head ground wires

(iii) Lightening arresters / surge diverters.

- Ground wire plays a very important part on the transmission lines to protect the equipments.
- The ground wire locations for different structures of HV tower lines are shown in the following sketches. Also refer the figure of such ground wire location explained in section 4.13.2.
- Ground wires have sufficient mechanical strength. Their location on the H.T. towers is such that they shield the line conductors from the direct strokes.
- The selection of such wires are more from mechanical point of view, rather than electrical point of view. Ground wire should be non-corrosive.

☞ **Clearance of conductors on tower**

- According to the dielectric strengths the sufficient clearances shall be maintained between conductors, tower structure, ground wires, earth etc.
- **Clearance of ground wire :** Sufficient clearances are to be provided between ground wires and line conductors.
- Care should be taken to maintain these clearances at the centre of the span so that there is no flash-over.
- Care is taken to have minimum tower footing resistance so that lightening discharge current passes to earth quickly and easily.

☞ Placement / locations of ground wires supports

The ground wires are placed high above the conductors and are so located, that they are well out on the towers.

- They are not exactly above the conductors.
- This avoids the possibility of short circuit occurring in the event of swinging of conductors under ice loading etc.
- **Angle of projection :** This is the angle between the vertical centre line from the ground wire and the line joining the supported centre points of outer conductor and wire It should be < 30° (This angle is shown in the figures)

  This avoids possibility of side stork to the conductor.

5.3.1 Location of ground wires on

(i) Single circuit and 2 ground wires on tower
(ii) Double circuit and two ground wires.
(iii) Single ground wire on zig-zag formation of 3 - phase conductors
(iv) 11 or 33 kV pole supports.

(i) Single circuit and 2 ground wires on tower

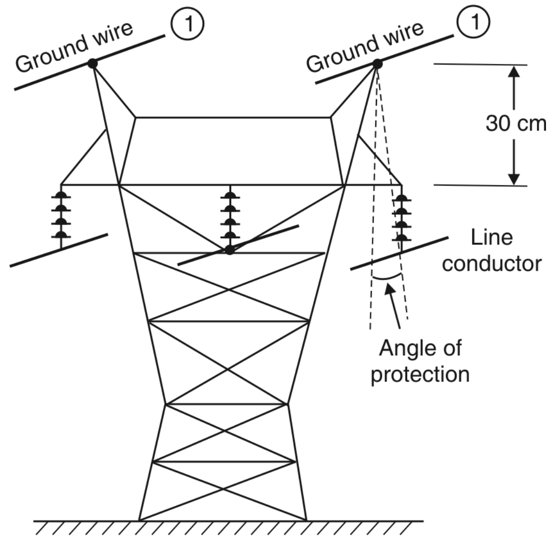


Fig. 5.3.1 : Single circuit over the tower with two ground wires

(ii) Double circuit and two ground wires

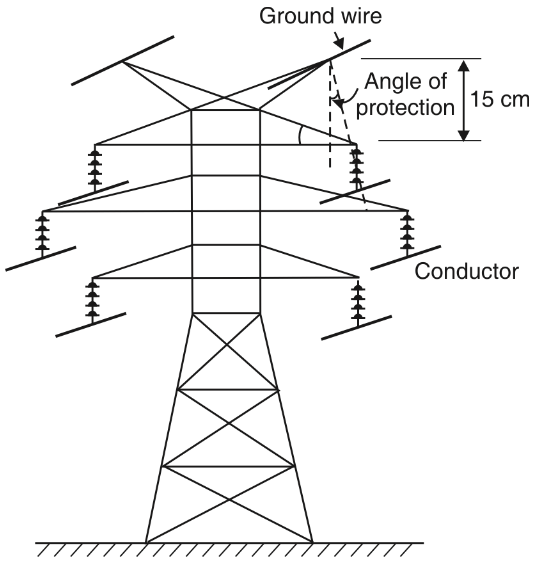


Fig. 5.3.2 : Double circuit over a tower with two ground wires

(iii) Single ground wire on zig-zag formation of 3 - phase conductors

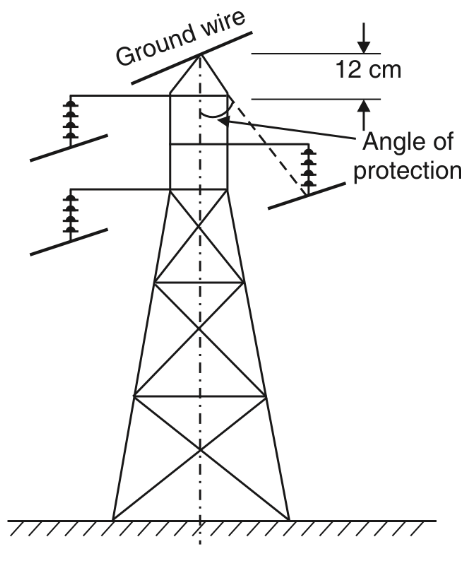


Fig. 5.3.3 : Single ground wires over the tower location of the ground wire on towers

(iv) 11 or 33 kV pole supports

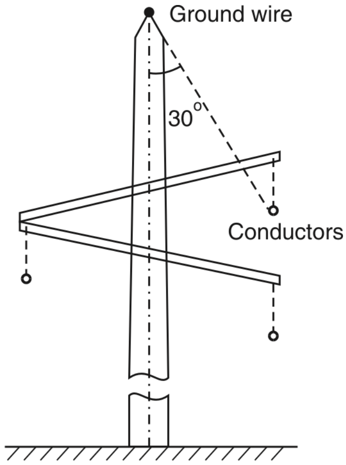


Fig. 5.3.4 : Location of the ground wire on 11 or 33 kV supports

☞ Coupling Factor

- Consider an arrangement of conductor and earth wire as illustrated in Fig. 5.3.5.
- Let, the ground wire is connected to earth through a high resistance R_E. Let, a lighting stroke occur at point P on the ground wire, it causes current I_1 and I_2 to flow in either direction from p.

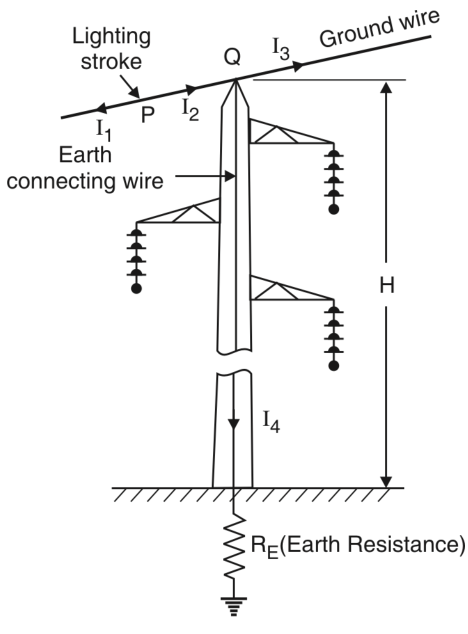


Fig. 5.3.5 : Arrangement of conductors and earth representing lightening current

- Again, at point Q the current sub-divides and let I_4 amperes flow to the ground. Since, the resistance R_E is high and when current I_4 flows through it causes a voltage drop across it.
- Thus, the ground wire does not remain at earth potential ; put is at higher potential ; let, this potential be V_g.

$$\text{i.e. } V_g = R_E I_4 \quad \ldots(1)$$

Let V_1 be the potential between the conductor and earth.

$$\text{Let, } K = \frac{V_1}{V_g}$$

K is coupling co-efficient

$$K = \frac{\log_e\left(\frac{h}{h_1}\right)}{\log_e\left(\frac{2H}{r}\right)}$$

Where h = distance between conductor and ground wire

h_1 = distance between image and ground

H = height of ground wire above ground

r = radius of ground wire

5.4 Insulation Levels of Equipments

Table 5.4.1

Impulse kV				
Rated System Voltage kV	**Bus Installation**	**Switch and Post Insulation**	**Transformers**	**Circuit Breakers**
23	330	225	150	150
34.5	420	235	200	200
69	565	440	350	350
115	865	590	550/450	650
138	1000	590	550/450	650
330	1665	1475	1175	1175

The values for transformers and circuit breakers are withstand values while those for bus and switch insulators are critical values.

Table 5.4.2 : Standard insulation levels as per practice of M.S.E.B. India

System Voltage kV rms	Impulse Strength of Transformer Winding 1/50 μS Full Wave kV peak	Dry Flash Over Voltage kV rms	Wet Flash Over Voltage kV rms
230	900	530	385
110	550	320	240
66	350	260	180
33	200	170	120

5.5 Basic Concept of Insulation Co-ordination

The following characteristics show the basic concept of co-ordination of insulations.

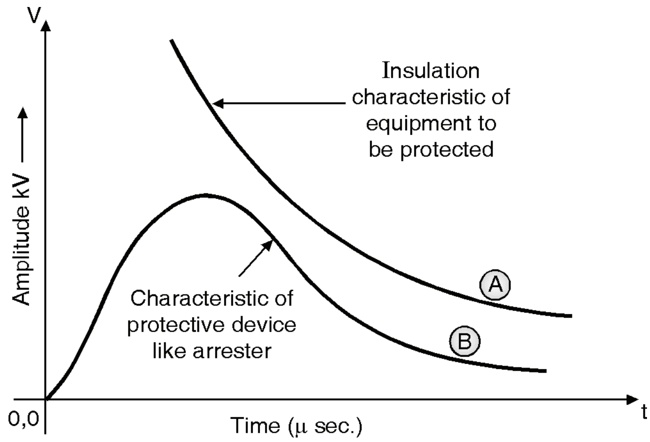


Fig. 5.5.1 : Co-ordination of insulation (characteristic)

5.6 Line Diagram of Power System Equipment

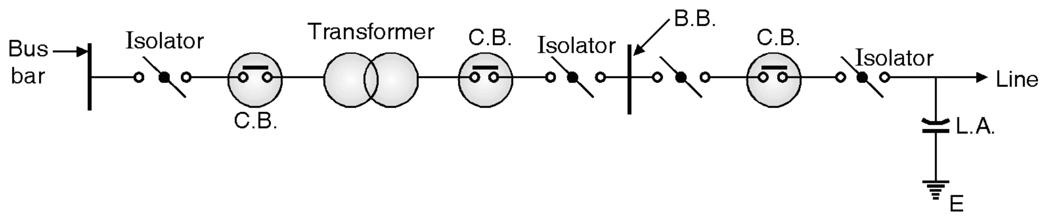


Fig. 5.6.1 : Power system equipment

5.7 Insulation Co-ordination of various Equipment

The lightning arrestor will spark-over at a voltage less than the insulation withstand voltage of the equipment i.e. to say the protective device must have a lower protective level (B) characteristic than that of the equipment characteristic (A) i.e. characteristic (B) is below (A).

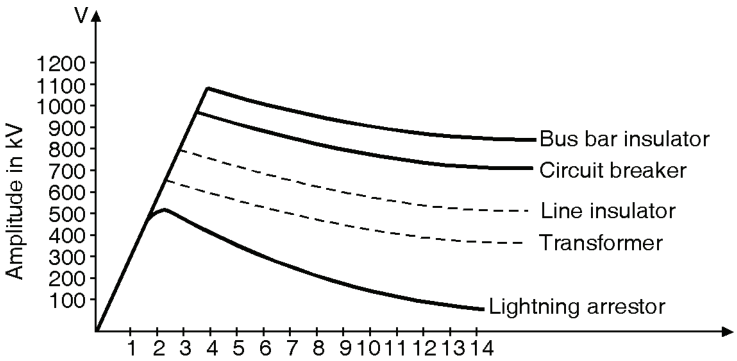


Fig. 5.7.1 : Insulation co-ordination of various equipment

Syllabus Topic : Surge Protection of Rotating Machines and Transformer

5.8 Surge Protection of Rotating Machines and Transformer

➔ (MU - Dec. 15, May 17)

Q. 5.8.1	Discuss the surge protection of rotating machines and transformer.
	(Refer section 5.8) **Dec. 15, May 17, 10 Marks**

Protection of rotating machines and transformer against over-voltage surges.

- Note that voltage with stand strength of as rotating machines, in comparison with static machine like transformer is much lesser.
- The rotating machine should be in a position to withstand voltage - surges of magnitudes and shapes up to the test voltage.
- To limit the surge level to the safe value flatten the wave front surge equipment is provided.

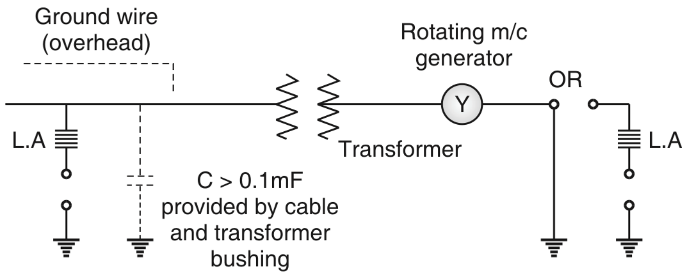


Fig. 5.8.1

- Overhead earth wire (ground wire) is used to shield the open line. This wire is also known as surge modifier.
- Between earth of each stator winding and line terminal a capacitance of minimum value of 0.1 μF is necessary.
- Alternatively a cable of same capacitances is connected between the machine and overhead line.
- Capacitance is provided by cable and transformer bushing shall be at least 0.1 μF.
- RC surge absorbers are connected in **shunt.**
- During overvoltage surges, the transformer insulation should withstand the stresses.
- Design of transformer insulation based on over voltage surges.
- Lightening arresters are provided at the terminals important transformers generators and motors.

5.9 Harmful Effects of Travelling Waves and Protection Against them

As seen in the previous articles, shielding the lines and stations by overhead ground wires provide adequate protection against direct lightning strokes and also reduces electrostatically/electromagnetically induced over voltages. But this type of protection cannot prevent travelling waves which may reach terminal equipments.

The travelling waves can cause the following damages :

1. Insulation of the windings may be damaged due to internal flash-over by the high peak (E_m) voltage of the voltage surge.
2. Inter-turn insulation of transformer may be damaged due to steep front of the surge wave causing internal flash over.

3. Insulators of the terminal equipment may be damaged due to external flash-over by the high peak (E_m) surge wave.
4. Resonance and high voltages resulting from the steep fronted wave may cause internal/external flash-over of an unpredicted nature causing building up of oscillations in the electrical equipments.

Hence, it is absolutely necessary to provide some protective device at the stations or substations for the protection of the equipment against the travelling waves caused by lightning. The protective devices used for this purpose are :

(i) Road gap lightning arrestors.

(ii) Arcing horns across string insulators.

(iii) Different types of lightning arrestors or surge diverters/absorbers.

(iv) Earthing screens.

(v) Overhead ground wires which have been studied in the previous articles.

5.10 Statistical Methods for Insulation Co-Ordination

- Both the over voltages due to lightning or switching and the breakdown strengths of insulating media are of statistical nature.
- Not all lightning or switching surges are dangerous to the insulation and particular specimens need not necessarily flashover or puncture at a particular voltage.
- Therefore it is important, to design the insulation of various equipment to be protected and the devices used for protection not for worst possible condition but for worst probable condition as **the cost of insulation** for system of the voltage more than 380 kV **are proportional to square of the voltage**.
- Therefore any small saving in insulation will result in large sums when considered for such large modern power systems.
- However, this would involve some level of risk of failure. Accept some level of risk of failure than to design a risk free but a very costly system.
- The statistical methods call for a, very rigorous experimentation and analysis work so as to find probability of occurrence of over voltages and probability of failure of insulation.
- In order to co-ordinate the electrical stresses due to overvoltage with the electrical strengths of dielectric medium, it has been found convenient to represent overvoltage

distribution in the form of probability density function and the insulation breakdown probability by cumulative distribution function as shown in Fig. 5.10.1.

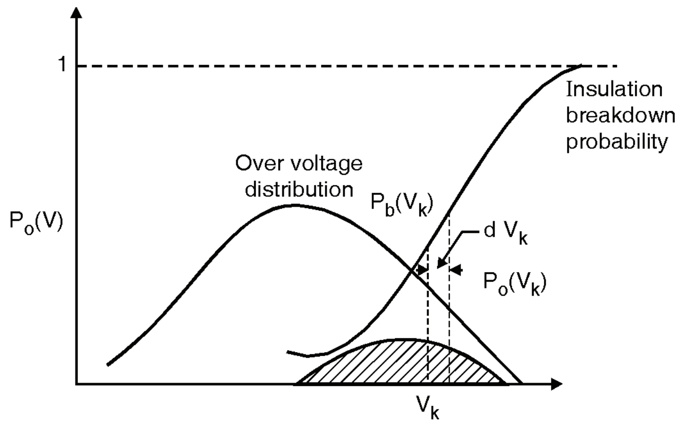


Fig. 5.10.1 : Overvoltage distribution and insulation breakdown probability

- Suppose P_o (V_k) is the probability density of an overvoltage V_k and P_o (V_k) dV_k the probability of occurrence of overvoltage having a peak value V_k.
- To obtain the probability of disruptive discharges due to these over voltages having a value between V_k and $V_k + dV_k$, their probability of occurrence P_o (V_k) dV_k, shall be multiplied by P_b (V_k) that an impulse of the given type and of value V_k will produce a discharge.
- The resultant probability or risk of failure for over voltages between V_k and $V_k + dV_k$ is thus,

$$\| \; dR = P_b (V_k) P_o (V_k) dV_k \; \|$$

- For the total voltage range we obtain the total probability of failure or risk of failure.

$$\left\| \; R = \int_0^\infty P_b (V_k) P_o (V_k) dV_k \; \right\|$$

- The risk of failure will thus be given by the shaded area under the curve.
- In actual practice, however it is uneconomical to use the complete distribution functions for the occurrence of over voltages and for the withstand of insulation and therefore a compromise solution is adapted as shown in Fig. 5.10.2(a) and (b).

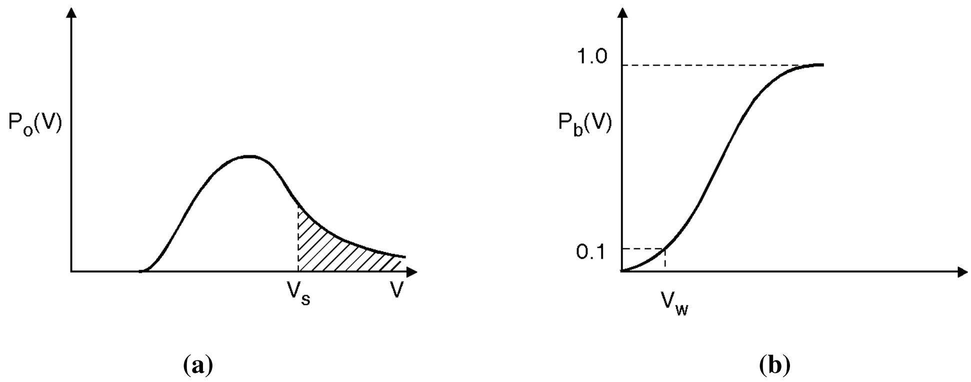


Fig. 5.10.2

- Fig. 5.10.2 shows probability of occurrence of overvoltage, which will result into breakdown, by the shaded area for voltage greater than $\mathbf{V_s}$ known as **statistical overvoltage**.
- In Fig. 5.10.2(b) $\mathbf{V_w}$ is the **withstand voltage** which results in flashover only in 10% of applications and for remaining 90% of applied impulse, no breakdown of insulation occurs. This voltage is known as **statistical withstand voltage $\mathbf{V_w}$**.

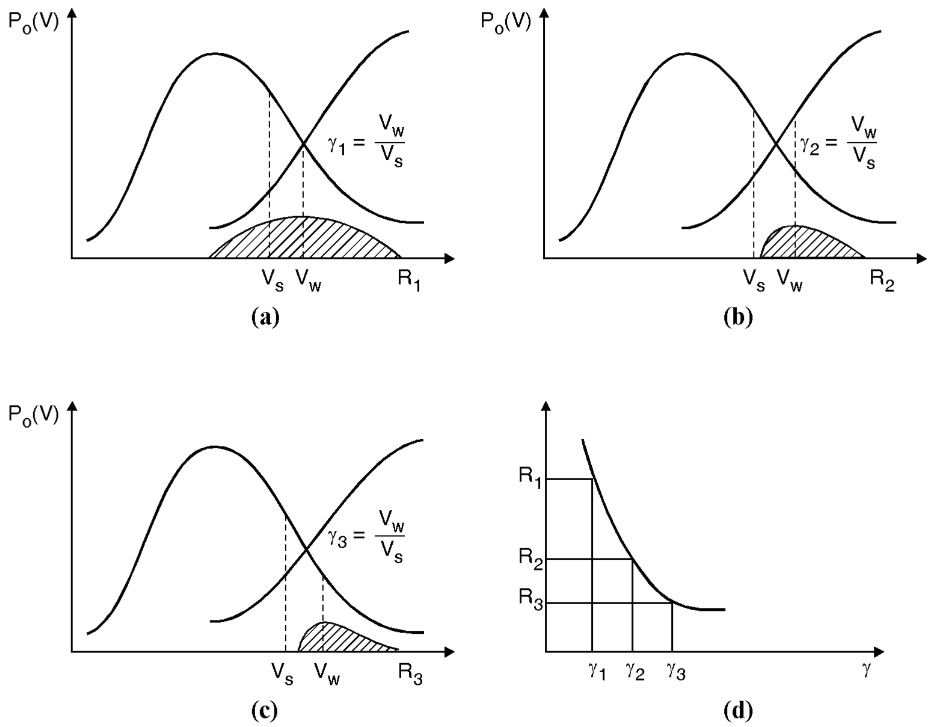


Fig. 5.10.3

- Fig. 5.10.3 risk of failure as a function of statistical safety factor. Fig. 5.10.3(a) to (c) shows the functions P_b (V) and P_o (V) plotted for 3 different cases of insulation strength, keeping the overvoltage distribution the same.
- The cumulative function which gives the undetermined withstand voltage is gradually shifted along the V-axis i.e. towards higher values of V and the density function $P_o(V_k)$ is the same in Fig. 5.10.3(a) to (c) .
- The shifting of the cumulative distribution curve to right is equivalent to increasing the insulation strength.
- Let the statistical factor of safety be defined as $\gamma = V_w/V_s$ and as the withstand characteristic is shifted towards right, the statistical factor of safety increases and hence risk of failure decreases as shown in Fig. 5.10.3(d). However, cost of insulation goes up as the factor of safety is increased.

The problem of insulation co-ordination can be studied under these steps :

1. Selection of a suitable insulation which is a function of reference class voltage (i.e. $1.05 \times$ operating voltage of system).
2. The design of various equipments such that the breakdown or flashover strength of all insulation in the station equals or exceeds the selected levels as mentioned in point 1.
3. Selection of protective devices that will give the apparatus as good protection as can be justified economically.

The above procedure requires that the apparatus to be protected shall have a withstand test value not less than the kV magnitude irrespective of the polarity of the wave positive or negative and irrespective of how the system was grounded.

5.11 Conditions for Perfect Co-ordination of Insulation

This will be perfect when following conditions are satisfied :

(i) In case of breakdown in insulation the vital parts of the equipment (or plant) shall be safe.

(ii) The insulation should withstand operating voltage and so also major over – voltages.

(iii) Only External over voltage should cause breakdown.

(iv) The discharge must flow very quickly to the earth (ground) whether it is internal or external.

5.12 Factors on which Basic Insulation Level Depend

(i) Lightening flash – over frequency and

(ii) Power frequency on these two the insulation of line is based upon.

- On the incoming line of sub-station there are many methods to co-ordinate insulation levels. The best method is to establish a definite basic level for all the insulations in the substations and to adjust that the insulation of the equipotent to bring to this basic level.
- The situation can be tackled if the above procedure is adopted by the following steps :
    1. For different voltages-selection of suitable insulation level.
    2. Selection of protective devices that will give the equipment a good protection that to economically.
    3. Selection of insulation levels for switch – gear and transformer used in conjunction with the transmission line.
    4. To co-relate the insulation levels of transformers, switchgears and other equipments along with the incoming line.
    5. To see that the flash – over strength of all the insulation in the sub-station will be equal or exceed the basic level.
    6. To decide minimum clearance needed between line conductor and earth so as to achieves proper insulation level.

Exercise

Q. 1 State the meaning of insulation co-ordination. **(Section 5.1)**

Q. 2 Define the following in relation with insulation co-ordination. **(Section 5.1.1)**

(i)	Normal voltage	(ii)	Highest voltage
(iii)	Insulation level	(iv)	Highest voltage level of equipment
(v)	Over-voltage	(vi)	Phase to phase per unit voltage
(vii)	Voltage time characteristic	(viii)	Basic impulse insulation level (BIL)

Q. 3 Draw the voltage - time characteristic of transformer, rod gaps and surge diverter. **(Section 5.1.1, Fig. 5.1.2)**

Q. 4 Draw the volt - time characteristic of transformer, lightening arrester, line insulation and bus-bar. **(Section 5.1.1, Fig. 5.1.3)**

Q. 5 Draw the volt - time curves giving relative positions of various equipments in sub-station for proper insulation co-ordination. **(Section 5.1.1, Fig. 5.1.4)**

Q. 6 Draw the characteristic which shows basic concept of co-ordination of insulations. **(Section 5.5, Fig. 5.5.1)**

Q. 7 Draw a one line diagram of power system equipment and show the insulation co-ordination of various equipments. **(Sections 5.6 and 5.7)**

Q. 8 Write a note on protection of rotating machines and transformer against over voltages. **(Section 5.8)**

Q. 9 Draw the different locations of ground wires on 220 kV tower line. **(Sections 5.3.1, 5.3.2 and 5.3.3)**

Q. 10 Show the angle of protection, drawing sketch of ground wires and conductors on a 132 kV tower line. **(Section 5.3.1(i))**

Q. 11 Write a note on Ground wire. **(Section 5.3)**

Q. 12 What are the harmful effects of travelling waves ? What protective devices are used for the same. **(Section 5.9)**

Q. 13 Write a full note on statistical methods for insulation co-ordination. **(Section 5.10)**

Q. 14 What conditions are to be fulfilled for perfect co-ordination of insulation. **(Section 5.11)**

Q. 15 What are the factors on which Basic insulation level depends ? **(Section 5.12)**

5.13 University Questions and Answers

➔ May 2015

Q. 1(d) Discuss the role of ground wire and tower footing resistance.
(Ans. : Refer section 5.3) **(5 Marks)**

➔ Dec. 2015

Q. 5(a) Discuss the surge protection of rotating machines and transformer.
(Ans. : Refer section 5.8) **(10 Marks)**

➔ Dec. 2016

Q. 1(b) Discuss the importance of insulation coordination. *(Ans. : Refer section 5.1)* **(5 Marks)**

➔ May 2017

Q. 5(b) Discuss the surge protection of transformer and rotating machine.
(Ans. : Refer section 5.8) **(10 Marks)**

Chapter Ends...

❑❑❑

CHAPTER

6

Corona

Syllabus :

Phenomenon of corona, Disruptive critical voltage, Visual critical voltage, corona loss, factors affecting corona loss, Radio interference due to corona, practical considerations of corona loss, corona in bundled conductor lines, corona ring, corona pulses- their generation and properties in EHV lines, charge voltage (q-V) diagram and corona loss.

Syllabus Topic : Phenomenon of Corona

6.1 What is Corona ? (Phenomenon of Corona)

- Overhead lines operate at high voltage, so electrostatic field is produced between the conductors.
- The conductors have air gap between them, so air acts as a dielectric medium. The dielectric strength of air at normal temperature and pressure is 30 kV/cm.
- If the voltage between conductors is so high that it causes potential gradient between the conductors exceeds this value, breakdown of air will take place i.e. air is ionized and current flows through it i.e. discharge takes place through air.
- The moment, the potential gradient value between conductors reaches 30 kV/cm air in the vicinity of conductor becomes conducting and a hissing sound is heard and some vibrations are produced in conductor.
- Then a dark violet glow occurs around the conductor along with a hissing noise.
- This noise is because of ozone gas is produced during this process.
- The entire process described in above paragraphs is known as ‘Corona’.

"In short, a phenomenon of corona is seen in the high voltage transmission lines in the form of luminous envelop surrounding the H.V. conductor accompanied by a hissing sound of ozone gas so produced at a higher voltage."

– The rate of ionization of corona discharge is not uniform, but has certain fluctuations and sudden changes which produce the similar other changes of the electric field.

– These changes can disturb "radio reception" and bring Radio Interference (R.I.).

6.1.1 Corona in Case of D.C. and A.C. Lines

– In case of D.C. High Voltage positive and negative conductor wires, the positive wire has a uniform glow about it but around the negative conductor it is more spotty and sometimes it is in the form of short streamers from the rough to sharp spots on the conductor wire.

– In case of A.C. High Voltage, the appearance of the two conductors is the same, this is because, and the conductors are alternately positive and negative due to frequency.

6.1.2 Effect of Voltage Level on Corona

– Corona envelope glow larger and larger as the voltage increases. Effective diameter of conductor increases.

– If the voltage is increased to a very high value the size of envelope becomes so large that finally there is a spark over between conductors. If the spacing between the conductors is less, than spark over may occur before corona is noticed.

6.1.3 Appearance of Corona (How Corona looks like)

– Conductor having smooth or polished surface, the dark violet glow during corona is uniform throughout the length of conductor. If surface of conductor is not uniform, the glow is brightest at sharp points. (Refer Fig. 6.1.1)

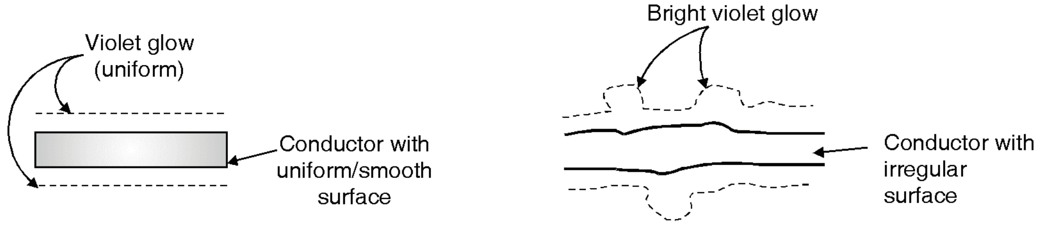


Fig 6.1.1 : Appearance of corona

Syllabus Topic : Disruptive Critical Voltage

6.2 Disruptive Critical Voltage (V_d)

➔ (MU - May 15, Dec. 16, May 17)

Q. 6.2.1 Explain the terms critical voltage, visual critical voltage and corona ring. *(Refer sections 6.2, 6.3 and 6.7.1)* **May 15, 10 Marks**

Q. 6.2.2 Explain the terms with reference to corona disruptive critical voltage, visual critical voltage, power loss. *(Refer sections 6.2, 6.3 and 6.4)* **Dec. 16, 10 Marks**

Q. 6.2.3 Explain the terms critical voltage, Visual critical voltage. *(Refer sections 6.2 and 6.3)* **May 17, 10 Marks**

"The potential difference between the conductors at which electric field intensity at the surface of conductor exceeds the critical value and corona is generated is known as disruptive voltage (V_d).

- Or the minimum voltage at which ionization just takes place is called as disruptive voltage (V_d).
- Corona begins when the peak value of critical field intensity at the surface of conductor just equals to 30 kV/cm [or 3×10^6 V/m].This is on the assumption of smooth conductor surface, large diameter of conductor, in the air at normal temperature and pressure.

6.2.1 To Prove the Relation of Critical Disruptive Voltage

The critical intensity is proportional to density of air hence proportional to barometric pressure (p) and inversely proportional to absolute temperature.

Taking relative density at θ_0^{o} C and 76 cm of Hg as 1

$\therefore$ Relative density (δ) at barometric pressure p and temperature θ°C is given by,

$$\delta = \frac{p}{76}\left(\frac{273+\theta_0}{273+\theta}\right)$$

Now taking $\theta_0 = 20°C$

$$\therefore \quad \delta = \frac{p}{76}\,\frac{(273+20)}{273+\theta}$$

$$\therefore \quad \text{Relative density} \quad \boxed{\delta = \frac{3.86\,p}{273+\theta}} \qquad \ldots(6.2.1)$$

Taking into account the surface factor m_0 which = 1 for smooth conductor and 0.93 to 0.98 for rough surface and surface is exposed to atmosphere.

$\therefore$ Critical intensity $\boxed{E_0 = \left(3 \times \frac{10^6}{\sqrt{2}}\right) \cdot \delta \cdot m_0 \text{ Volts/m}}$ …(6.2.2)

– Now for a single phase line each of radius = r, the voltage V between the two conductors is given by ,

$\boxed{V = \frac{q}{\pi \in_0} \, ln \, \frac{D}{r}}$ …. (Proved value). …(6.2.3)

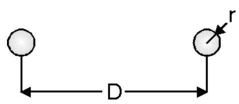


Fig. 6.2.1

Where, r = Radius of conductor

D = Distance between conductor

q = Charge in coulombs on each conductor per meter length

$\in_0$ = 8.854×10^{-12} permittivity of air.

– Also from the Gauss's theorem the electric field intensity (E_r) at any point is given by,

$\boxed{E_r = \frac{q}{2\pi \in_0 r} \text{ Volts/m.}}$ …(6.2.4)

– From these two relative Equations (6.2.3) and (6.2.4) combining we get,

$\boxed{V = 2r \cdot E_r \, ln \, \frac{D}{r}}$ …(6.2.5)

When E_r reaches E_0, the voltage between the conductors is the disruptive critical voltages V_d.

Substituting the value of E_0 from Equation (6.2.2) into Equation (6.2.5)

$\boxed{V_d = \frac{6 \times 10^6}{\sqrt{2}} \cdot r \cdot \delta \cdot m_0 \, ln \, \frac{D}{r} \text{ Volts.}}$ …(6.2.6)

This is for single phase.

The derived value of phase to neutral value and value of voltage V for a 3 phase line is given by,

$$\boxed{V = \frac{q}{2\pi \in_0} \ln \frac{D_{eq}}{r}} \quad \ldots(6.2.7)$$

…where D_{eq} is equivalent spacing of conductors.

– Thus from Equations (6.2.4) and (6.2.7)

We get, $$V = r \cdot E_r \cdot \ln \frac{D_{eq}}{r} \quad \ldots.(6.2.8)$$

Now when E_r becomes = E_0, the voltage V is the disruptive voltage V_d.

∴ For 3 phase lines.

$$\boxed{V_d = \frac{3 \times 10^6}{\sqrt{2}} \cdot r \cdot \delta \cdot m_0 \ \ln \frac{(D_{eq})}{r} \text{ volts.}} \quad \ldots(6.2.9)$$

Where, r = Radius of conductor

D = Relative density

m_0 = Surface factor

D_{eq} = Equivalent distance (spacing of conductors)

V_d = Critical disruptive voltage phase value.

Syllabus Topic : Visual Critical Voltage

6.3 Visual Critical Voltage

→ **(MU - May 15, Dec. 16, May 17)**

Q. 6.3.1 Explain the terms critical voltage, visual critical voltage and corona ring.
(Refer sections 6.2, 6.3 and 6.7.1) **May 15, 10 Marks**

Q. 6.3.2 Explain the terms with reference to corona disruptive critical voltage, visual critical voltage, power loss. *(Refer sections 6.2, 6.3 and 6.4)* **Dec. 16, 10 Marks**

Q. 6.3.3 Explain the terms critical voltage, visual critical voltage.
(Refer sections 6.2 and 6.3) **May 17, 10 Marks**

– When the potential gradient is raised to a critical value called as critical disruptive voltage (V_d), ionization of air in the immediate vicinity commerce up to this stage there is no visual corona.

– Visual glow occurs at a greater potential gradient.

– Visual glow does not occur when the electric intensity becomes equal to the value E_0 but starts at higher value of intensity E_v.

– This is because the dielectric break down of air requires a finite volume of overstressed air.

– Finite amount of dielectric energy is therefore necessary to cause 'Visual corona'.

– Following is the empirical formula for E_v.

$$\boxed{E_v = 3 \times \frac{10^6}{\sqrt{2}} \cdot \delta \cdot m_v \left(1 + \frac{0.03}{\sqrt{\delta_r}}\right) \text{ Volts /meter}} \quad \ldots(6.3.1)$$

Where, r = radius of conductor in meters

m_v = irregularity factor (surface)

= 1 for smooth surface.

= 0.93 to 0.98 for rough surface exposed.

m_v = to air, 0.72 for local corona in 'stranded' conductors.

= 0.82 for decided corona on stranded conductors.

Now, referring the various relations derived above….

Substitute E_v in place of E_r in Equations (6.2.5) and (6.2.8),

We get the visual critical voltages for

Single phase and 3-phase lines as :

(a) For single phase lines

$$\boxed{V_v = \frac{6 \times 10^6}{\sqrt{2}} \cdot \delta \cdot m_v \left(1 + \frac{0.03}{\sqrt{\delta_r}}\right) ln \frac{D}{r} \text{ Volts.}} \quad \ldots(6.3.2)$$

(b) For 3-phase lines

$$\boxed{V_v = \frac{3 \times 10^6}{\sqrt{2}} \cdot r \cdot \delta \cdot m_v \left(1 + \frac{0.03}{\sqrt{\delta r}}\right) ln \frac{D_{eq}}{r} \text{ Volts.}} \quad \ldots(6.3.3)$$

Note : In Equations (6.3.2) and (6.3.3) r and D, D_{eq}. are to be taken in meters.

Syllabus Topic : Corona Loss

6.4 Corona Loss and its Effect

→ (MU - Dec. 16)

> **Q. 6.4.1** Explain the terms with reference to corona disruptive critical voltage, visual critical voltage, power loss. *(Refer sections 6.2, 6.3 and 6.4)* **Dec. 16, 10 Marks**

When the surface voltages gradient at the line conductor reaches the critical breakdown stress (i.e. 30 kV/cm) corona appears. Due to heat and light produced in formation corona there is a loss of power and energy dissipation.

- This loss of power/energy is called as **'Corona-loss'**.
- Naturally due this loss of power, the efficiency of the transmission line is decreased.
- There is also a minor effect on the voltage regulation of the line. This is always neglected.
- Corona loss in Extra High Voltage (EHV) lines (AC) can vary between few kW/km length of conductor in normal and fair whether atmospheric conditions.
- Corona loss in very high i.e. hundreds of kW/km in bad weather conditions particularly during thunderstorm.

Following is the "Peek's formula" for determining corona loss in fair whether condition.

$$\text{Power loss in Corona } P_c = 243.5\ \frac{(f + 25)}{\delta} \cdot \sqrt{\frac{r}{D}} \cdot (V - V_d)^2 \times 10^5 \text{ kW/km/phase)} \qquad \ldots(6.4.1)$$

In this formula,

r = Radius of conductor in metres

D = Or D_r…. equivalent spacing between conductors in meters

f = Frequency of the system (generally f = 50 Hz)

V = Phase voltage in kV r.m.s.

V_d = Disruptive critical voltage in kV r.m.s.

δ = Relative density.

> **Note :** The above relation is for fair weather condition. In stormy weather condition the formula is modified by taking V_d = 0.8 of V_d under fair condition.

$\therefore$ P_c (in stormy condition)

$$= 243.5 \frac{(f+25)}{\delta} \cdot \sqrt{\frac{r}{D}} (V - 0.8 V_d)^2 \times 10^3 \text{ kW/km/phase} \quad \ldots(6.4.2)$$

The above formula as used when the ratio is upto and greater than 1.8 and corona losses are predominant.

i.e. $\frac{V}{V_d} \geq 1.8$

for the ratio $\frac{V}{V_d} < 1.8$ Peterson's formula is used.

– Peterson's formula for corona less (When $\frac{V}{V_d} < 1.8$)

$$P_c = \frac{21 \times 10^{-6} \cdot f \cdot V^2}{\left(\log_{10} \frac{D}{r}\right)^2} \times F \text{ kW/km/phase} \quad \ldots(6.4.3)$$

In the above relation F is a factor whose value depends on the ratio of $\left(\frac{V}{V_d}\right)$

'F' can be selected (if not given) form the following table.

Ratio $\left(\frac{V}{V_d}\right)$	**Value of factor 'F'**
0.6	0.012
0.8	0.018
1.0	0.05
1.2	0.08
1.4	0.30
1.6	1.00
1.8	3.5
2.0	6.0
2.2	8.8

Note : Results obtained from Peer's formula and Peterson's formula are different.

6.5 Numerical Examples

Ex. 6.5.1

A delta connected 3 phase 220 kV, 3 phase transmission line has equivalent spacing between conductors is 6 metres. The radius of the conductor wire is 11.1255 mm. The additional data given is as follows :

Temperature θ = 25°C

Rough surface m_0 = 0.84

Pressure = 73 cm of Hg.

Find the critical disruptive voltage (V_d)

Soln. :

To find : relative density δ.

$$\therefore \quad \delta = \frac{3.86\ p}{273+\theta} = \frac{3.86 \times 73}{273+25} = 0.94557$$

Using the relation (6.3.2) to find disruptive critical voltage (V_d),

$$\therefore \quad V_d = \frac{3 \times 10^6 p}{\sqrt{2}} \times r \cdot \delta \cdot m_0\ ln \frac{D_{eq}}{r} \text{ Volts}$$

$$= \frac{3 \times 10^6}{\sqrt{2}} \times 11.1255 \times 10^{-3} \times 0.94557 \times 0.84\ ln \left(\frac{6}{11.1255 \times 10^{-3}} \right)$$

$$= 118 \times 10^3 \text{ Volts}$$

$$\therefore \quad \boxed{\mathbf{V_d = 118\ kV}}$$

Ex. 6.5.2

The transmission line is Δ connected having the following data,

Voltage = 220 kV.

For local corona m_v = 0.72 i.e. irregularity factor,

Temperature and pressure θ = 25°C , p = 73 cm of Hg.

Diameter of conductor = 22.26 mm

Equivalent spacing D_{eq} = 6 meters

Find the visual critical voltage (V_v).

Soln. :

$$\text{Radius of the conductor } r = \frac{\text{diameter}}{2} = \frac{22.26}{2} = 11.13 \text{ mm} = 11.13 \times 10^{-3} \text{ m}$$

To find : Relative density 'δ'

$$\therefore \quad \delta = \frac{3.86\ p}{273+\theta} = \frac{3.86 \times 73}{273+25} = 0.94557$$

Using the derived relation (Equation 6.3.3)

To find : Visual critical voltage (V_v)

$$V_v = \frac{3 \times 10^6}{\sqrt{2}} \times r \cdot \delta \cdot m_v \cdot \left(\frac{1 + 0.03}{\sqrt{\delta_r}}\right) ln\left(\frac{D_{eq}}{r}\right) \text{volts.}$$

$$= \frac{3 \times 10^6}{\sqrt{2}} \times 11.13 \times 10^{-3} \times 0.94557 \times 0.72$$

$$\left(\frac{1 + 0.03}{\sqrt{0.94557 \times 11.13 \times 10^{-3}}}\right) ln\left(\frac{6}{11.13 \times 10^{-3}}\right) \text{volts.}$$

$$V_v = 130.7 \times 10^3 \text{ volts.}$$

$$= 130.7 \text{ kV}$$

$$\boxed{\mathbf{V_v = 130.7\ kV}}$$

Ex. 6.5.3

Refer Ex. 6.5.2 find the visual critical voltage (V_v) for general (decided) corona assuming the proper value of irregularity factor.

Soln. :

Let us assume irregularity factor as 0.82 for this case.

$$\therefore \quad m_v = 0.82$$

As calculated in the previous Ex. 6.5.2

$$\delta = 0.94557$$

Using the derived relation (Equation 6.3.3) to find V_v.

$$V_v = \frac{3 \times 10^6}{\sqrt{2}} \times r \cdot \delta \times m_v \left(\frac{1 + 0.03}{\sqrt{\delta_r}}\right) ln\left(\frac{D_{eq}}{r}\right) \text{volts}$$

$$V_v = \frac{3 \times 10^6}{\sqrt{2}} \times 11.13 \times 10^{-3} \times 0.94557 \times 0.82$$

$$\left(\frac{1 + 0.03}{\sqrt{0.94557 \times 11.13 \times 10^{-3}}}\right) ln\left(\frac{6}{11.13 \times 10^{-3}}\right) \text{volts.}$$

$$V_v = 148.7955 \times 10^3 \text{ volts.}$$

$$= 148.7955 \text{ kV}$$

$$\boxed{\mathbf{V_v = 148.7955\ kV}}$$

Ex. 6.5.4

A High voltage 132 kV 3-phase transmission line has equilateral spacing of D_{eq} = 3 metres. The conductor radius = 0.585×10^{-2} meters.

Following is the additional data.

Surface irregularity factor $m_0 = 0.96$

Temperature and pressure respectively 20°C and 72 cm of Hg.

Determine the critical disruptive voltage and also find the corona loss in foul whether condition in which case critical disruptive voltage drops down to 80% of the value in normal weather condition.

Soln. :

$$\text{Relative density} \quad \delta = \frac{3.86\,p}{273+\theta} = \frac{3.86 \times 72}{273+20} = 0.96$$

To find : Critical disruptive voltage (V_d)

$$V_d = \frac{3 \times 10^6}{\sqrt{2}} \times r \cdot \delta \cdot m_0 \cdot ln\left(\frac{D_{eq}}{r}\right) \text{volts.}$$

$$= \frac{3 \times 10^6}{\sqrt{2}} \times 0.585 \times 10^{-3} \times 0.96 \times 0.96 \times ln\left(\frac{3}{0.585 \times 10^{-3}}\right)$$

$$V_d = 71.22 \times 10^3 \text{ volts.}$$

$$= 71.22 \text{ kV}$$

For foul weather the critical disruptive voltage.

$$= 0.8 \times 71.22 = 56.976 \text{ kV}$$

Now to find corona loss in foul weather condition using the following peeks formula,

$$\text{Now,} \quad V = \frac{132}{\sqrt{3}} = 74.473 \text{ kV}$$

Power loss in corona,

$$P_c = 243.5\left(\frac{f+25}{\delta}\right)\sqrt{\frac{r}{D}} \cdot (V - V_d)^2 \times 10^{-5} \text{ kW/km/phase}$$

$$= 243.5\left(\frac{50+25}{0.96}\right)\sqrt{\frac{0.585 \times 10^{-2}}{3}}(74.473 - 56.976)^2 \times 10^{-5} \text{ kW/km/phase}$$

$$= 2.57 \text{ kW/km/phase}$$

$$\boxed{\mathbf{P_c = 2.57\ kW/km/ph}}$$

Ex. 6.5.5

A 250 km long 3-phase 220 kV - Δ formation transmission line has equilateral spacing D = 6 metres. The conductor radius r = 11.13 mm.

Temperature = 25°C and pressure p = 73 cm of Hg.

Surface factor $m_0 = 0.84$

Find, (i) relative density δ

(ii) critical disruptive voltage (V_d)

(iii) corona loss per phase in fair weather condition

(iv) total corona loss of line.

Soln. :

$$\delta = \frac{3.86\ p}{273+\theta} = \frac{3.86 \times 73}{273+25} = 0.94557$$

Critical disruptive voltage (V_d)

$$V_d = \frac{3 \times 10^6}{\sqrt{2}} \times r \cdot \delta \cdot m_0 \times ln\left(\frac{D_{eq}}{r}\right) \text{volts.}$$

$$= \frac{3 \times 10^6}{\sqrt{2}} \times 11.13 \times 10^{-3} \times 0.94557 \times 0.84\ ln\left(\frac{6}{11.13 \times 10^{-3}}\right)$$

$$= 118 \times 10^3 \text{ volts}$$

$$\boxed{V_d = 118 \text{ kV}}$$

Now phase voltage $= \frac{220}{\sqrt{3}} = 127$ kV

$\therefore$ Corona loss

$$P_c = 243.5\left(\frac{f+25}{\delta}\right)\sqrt{\frac{r}{D}} \cdot (V - V_d)^2 \times 10^{-5} \text{ kW/km/phase}$$

$$= 243.5\left(\frac{50+25}{0.94557}\right) \times \sqrt{\frac{11.13 \times 10^{-3}}{6}}(127-118)^2 \times 10^{-5} \text{ kW/km/phase}$$

$$= 0.6737 \text{ kW/km/phase}$$

The loss is for one km length.

for full length of line of 250 km the corona loss is,

Corona loss $= 0.6737 \times 250 = 168.425$ kW per phase.

Corona loss for all the 3 phases $= 168.425 \times 3$

$= \boxed{505.275 \text{ kW}}$

Ex. 6.5.6

Find in the above Ex. 6.5.4 total corona loss in the stormy bad weather.

Soln. :

$$P_c = 243.5\left(\frac{f+25}{\delta}\right)\sqrt{\frac{r}{D}} \cdot (V - 0.8\ V_d)^2 \times 10^5 \text{ kW/km/phase}$$

$$= 243.5\left(\frac{50+25}{0.94557}\right) \times \sqrt{\frac{11.13 \times 10^{-3}}{6}} \cdot [127 - 0.8\ (118)\ ]^2 \times 10^{-5} \text{ kW/km/phase}$$

$\therefore$ $\boxed{P_c = 8.841 \text{ kW/km/phase}}$ in bad weather condition

Total corona loss in bad weather for all the 3 phases, which are 250 km in length.

$$P_c = 8.841 \times 250 \times 3$$

$$P_c = 6630.75 \text{ kW}$$

$$\boxed{\mathbf{P_c = 6630.75 \text{ kW}}}$$

Ex. 6.5.7

Find the critical disruptive voltage and corona loss for a 3 phase line which is operating at 220 kV, 50 Hz frequency. The line has conductor of 1.5 cm diameter arranged in a 3 meter delta connection. Assume air density, of 1.05 and dielectric strength of air to be 21.1 kV/cm.

Soln. : $D_{eq} = 3$ meter

$$V_{phase} = \frac{V_L}{\sqrt{3}} = \frac{220}{\sqrt{3}} = 127 \text{ kV}$$

$$r = \frac{d}{2} = \frac{1.5}{2} = 0.75 \text{ cm} = 0.75 \times 10^{-2}$$

$$g_0 = \text{breakdown strength of air} = 21.1 \text{ kV/m}$$

$$\delta = \text{air density} = 1.05$$

Assume surface factor $m_0 = 0.84$ or $= 1$

$$\text{Disruptive voltage } (V_d) = \frac{3 \times 10^6}{\sqrt{2}} \cdot r \cdot \delta \cdot m_0 \; ln\left(\frac{D_{eq}}{r}\right) \text{volts}$$

$$= \frac{3 \times 10^6}{\sqrt{2}} \times 0.75 \times 10^{-2} \times 1.05 \times 1 \times ln\left(\frac{3}{0.75 \times 10^{-2}}\right)$$

$$= 10 \times 10^4 \text{ volts}$$

$$= \boxed{\mathbf{100 \text{ kV}}} \text{ phase value.}$$

$$\text{Corona loss } P_c = 243.5 \frac{(f + 25)}{\delta} \cdot \frac{\sqrt{r}}{D_{eq}} (V - V_d)^2 \times 10^{-5} \text{ kW/km/phase}$$

$$= 243.5 \left(\frac{50 + 25}{1.05}\right) \cdot \frac{\sqrt{0.75 \times 10^{-2}}}{3} (127 - 0.8 \times 100)^2 \times 10^{-5}$$

$$= 0.66 \text{ kW/km/phase}$$

Total loss for 3 phase = $0.66 \times 3 = \boxed{\mathbf{1.98 \text{ kW/km}}}$

Ex. 6.5.8

A 3 phase 220 kV, 50 Hz line is 250 km long consisting of 22.26 mm diameter conductor spaced in a 6 meter delta configuration.

The following data can be assumed. Temperature = 25°C, pressure = 73 cm of mercury, surface factor = 0.84, irregularity factor for local corona = 0.72. Irregularity factor for general corona = 0.82.

Find the total loss in the fair. Whether using Peek's formula.

Soln. :

$$r = \frac{22.6}{2} = 11.13 \text{ mm}, \quad 11.13 \times 10^{-3} \text{ m}$$

$$\delta = \frac{3.86 \times 73}{273 + 25} = 0.9456$$

$$m_0 = 0.84 \quad \text{and} \quad D = 6 \text{ m given values,}$$

$\therefore$ To find : V_d.

$$V_d = \frac{3 \times 10^6}{\sqrt{2}} \times r \times \delta \times m_0 \cdot ln\left(\frac{D_{eq}}{r}\right) \text{volts}$$

$$= \frac{3 \times 10^6}{\sqrt{2}} \times 11.13 \times 10^{-3} \times 0.9456 \times 0.84 \left(\frac{6}{11.13 \times 10^{-3}}\right)$$

$$= 118 \times 10^3 \text{ volts} = 118 \text{ kV.}$$

For fair weather condition to find corona loss (P_c)

$$V_{ph} = \frac{V_L}{\sqrt{3}} = \frac{220}{\sqrt{3}} = 127 \text{ kV and found value } V_d = 118 \text{ kV}$$

$$\therefore \quad P_c = 243.5 \frac{(f + 25)}{\delta} \cdot \frac{\sqrt{r}}{D_{eq}} (V - V_d)^2 \times 10^{-5} \text{ kW/km/phase}$$

$$= 243.5 \left(\frac{50 + 25}{0.9456}\right) \cdot \frac{\sqrt{11.13 \times 10^{-3}}}{6} (127 - 118)^2 \times 10^5 \text{ kW/km/phase}$$

$$= 0.6738 \text{ kW/km/phase}$$

Total power loss for 250 km for all 3 phase

$$= 0.6738 \times 250 \times 3$$

$$= \boxed{\mathbf{505.35 \text{ kW}}}$$

Ex. 6.5.9

Find the disruptive critical voltage for a 3-ph line consisting of 21 mm diameter conductors spaced in a 6 m delta configuration. Take temperature as 25°C, pressure as 73 cm of Hg and surface factor 0.85. What should be the voltage of transmission ?

Soln. :

Diameter = 21 mm $\therefore$ radius r = 10.5 mm, temp θ = 25°C, pressure of Hg = 73 cm,

surface factor $m_o = 0.85$

relative density $\delta = \frac{3.86\text{ p}}{273+\theta} = \frac{3.86 \times 73}{273+25} = 0.94557$

Critical disruptive voltage (V_d)

$$V_d = \frac{3 \times 10^6}{\sqrt{2}}\ r \cdot \delta \cdot m_0 \times ln\left(\frac{D_{eq}}{r}\right) \text{volts}$$

$$= \frac{3 \times 10^6}{\sqrt{2}} \times 10.5 \times 10^{-3} \times 0.94557 \times 0.85\ ln\left(\frac{6}{10.5 \times 10^{-3}}\right)$$

$$= \frac{3 \times 10^6}{\sqrt{2}} \times 8.4392 \times 10^{-3} \times ln\ (571.428)$$

$$= \frac{3 \times 10^6}{\sqrt{2}} \times 8.4392 \times 10^{-3} \times 6.3481$$

$$= 2.1213 \times 10^6 \times 10^{-3} \times 53.5728$$

$$= 113.64 \times 10^3 \text{ volts}$$

i.e. $V_d = 113.64$ kV

The nearing value of transmission voltage is more than V_d

$\therefore$ Phase voltage of line $= \frac{230}{\sqrt{3}} = \boxed{\mathbf{132.79\ kV}}$

Syllabus Topic : Factors Affecting Corona Loss

6.6 Factors Affecting Corona

→ **(MU - May 16)**

Q. 6.6.1 Explain the various factors affecting the corona.
(Refer section 6.6) **May 16, 10 Marks**

Following are the different factors affecting corona :

1. **Atmospheric conditions**

   The corona occurs because of ionization of air between the conductors. In stormy weather conditions, rainy condition number of irons in air between the conductors will be more hence chances of corona occurrence will increase.

2. **Physical conditions of conductor**

   These include :

   (i) **Line voltage :** If line voltage is more, electrostatic field between conductors is more and chances of occurrence of corona are more. Low voltage does not produce corona effect.

(ii) **Ratio $\frac{D}{r}$:** 'D' is the distance between the conductors and 'r' is the radius of conductor. If the distance between the conductors is made large compared to the radius (or diameter), possibility of corona occurrence is reduced. Because of large spacing, the strength of electrostatic field reduces.

(iii) **The nature of conductor surface**

The rough and irregular surface of conductor gives rise to more corona. Thus, stranded conductors' gives rise to more coronas compared to circular conductor.

(iv) **Roughness of conductor** surface causes field distortion and high voltage gradients are developed in local area of conductor. Thus, chances of occurrence of corona are more.

3. Effect of frequency (f)

Corona is directly proportional to system frequency. (see Equation 6.4.1)

4. Effect of density (δ) of air

Corona is inversely proportional to density of air. At high attitudes (Hills) density (δ) is lesser and hence in these regions corona is more than corona on the line passing on flat areas.

5. Effect of air conductivity

Higher conductivity leads to higher corona.

6. Effect of air conductors due to load current

If conductor is at low temperature then dew-drops may be accumulated on the surface or conductor in winter seasons.

So it causes larger corona. But due to higher load currents, the temperature of conductor increases and formation of dew is prevented and corona loss is reduced.

7. Bundling of conductors

Effective diameter of bundled conductor is much more than of equivalent single conductor. Corona loss reduces due to bundling of conductors.

Note : Observe the effect of line voltage on corona and effect of rate of rain on corona in the Fig. 6.6.1 and Fig. 6.6.2.

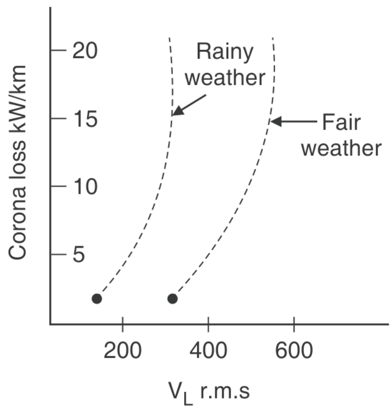


Fig. 6.6.1 : Role of line voltage on corona

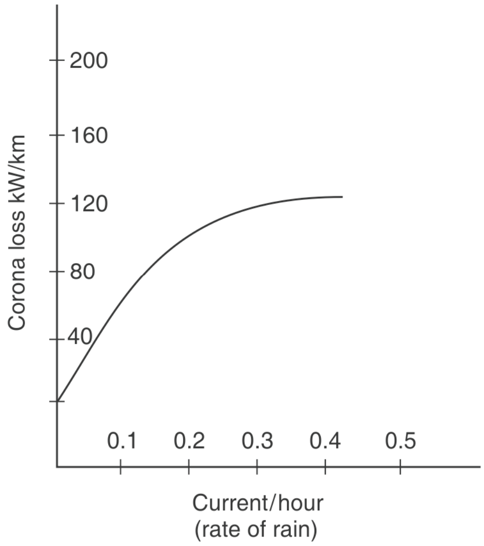


Fig. 6.6.2 : Effect of rate of rain on corona.

6.7 Methods of Reducing Corona Effect

(i) By increasing conductor diameter or by increasing spacing between the conductors, the corona effect can be reduced.

But the spacing between the conductors cannot be increased above a certain limit, hence conductor diameter is increased. Hollow conductors can be used. If ACSR is used, its diameter should be large.

(ii) The other hardware parts : clamps, support etc. on 11 kV line are designed with smooth surface.

(iii) Operating the line at lower voltage reduces corona effect.

(iv) Use of corona ring reduces corona losses.

(v) Using Bundled conductors.

Syllabus Topic : Corona Rings

6.7.1 Corona Rings

→ **(MU - May 15)**

Q. 6.7.1 Explain the terms critical voltage, visual critical voltage and corona ring.
(Refer sections 6.2, 6.3 and 6.7.1) **May 15, 10 Marks**

- Corona rings are also called as **anti-corona rings**. It is a torrid of conductive material, usually metal. These rings have smooth round surfaces which are designed to distribute charge across a wider area.
- Thus they reduce the electric field and the resulting corona discharges. Corona rings are installed on electric insulators, particle accelerators, lightning arresters, high voltage bushing terminals and other high voltage equipment.

6.7.2 Corona in Bundled Conductors

- In bundled conductors lines maximum surface electric field is less than for single conductor lines.
- It is therefore possible by replacing a single conductor by two or more conductors (called as bundling of conductors) with the same total cross-sectional area to obtain an increase in corona starting voltage.
- This helps in reduction of corona loss. This also helps in reducing radio interference.

6.8 Line Design Based on Corona

Severe corona effects are observed at working voltage 33kV or more than 33kV.

- Care is to be taken in designing the lines to avoid corona on the sub-stations and bus-bars rated 33 kV or more than 33 kV.
- If due care is not taken then highly ionised air may cause flash-over in the insulators or between the phases.
- The equipment may be damaged due to flash-over.
- The biggest disadvantage of corona is the power-loss. Corona loss reduces the transmission efficiency. If the design is well then this loss of efficiency is not that value of consideration.
- In bad weather (thunderstorms, fog, rains) corona loss increases. This point is also to be taken into account while designing transmission line.
- Due to non-sinusoidal corona currents, 3^{rd} harmonic current flow is noticed. Due to this corona loss is increased.
- These harmonics cause inductive interference on the parallel communicating circuits.

- The design engineer should take into account the critical voltage. At least critical voltage should be 10% more than the line operating voltage.
- This suggests that spacing between the conductors should be more. Radio - interference aspects of corona should to take care of.
- In a region where there is rare chance of bad weather (only few events) it might be better to allow considerable corona loss during these bad atmospheric periods so as to take the continuous benefit and enjoy of higher voltage without increasing cost of line construction appreciably. Concluding that the design engineer should find a good compromise in all these aspects.

6.8.1 For Transmission Line Design One of The Most Important Thing is Spacing between the Conductors i.e. D or D_{eg}.

Following are the design considerations :

(1) Temperature of line
(2) Wind pressure
(3) Ice deposition
(4) Tensile strength of the conductor
(5) Corona formation

If D >>> r electrostatic stresses are reduced and which avoids corona formation. But large D (spacing) means large size of cross-arms, big size and height of supporting pole/towers which proves to be very costly.

In case of string insulators support to the line, elliptical swing of conductors to be taken care of note than swing may be even 45°. Table 6.8.1 shows design criteria of spacing of conductors.

Table 6.8.1

Sr. No.	Operating voltage	Vertical spacing	Horizontal spacing	Distance between conductors and supports
1.	100/230 V, 45 m span	46 cm	38 cm	15 cm
2.	100/230 V, 60 m span	61 cm	46 cm	23 cm
3.	11 kV	76 cm	115 cm	31 cm
4.	22 kV	91 cm	137 cm	46 cm
5.	33 kV	122 cm	153 cm	61 cm
6.	66 kV	200 cm	325 cm	76 cm
7.	110 kV	315 cm	495 cm	110 cm
8.	132 kV	370 cm	590 cm	130 cm

6.9 Advantages and Disadvantages of Corona

6.9.1 Advantages of Corona

➔ (MU - May 15, Dec. 15)

Q. 6.9.1	What are the advantages of corona ? *(Refer section 6.9.1)*	**May 15, 5 Marks**
Q. 6.9.2	Discuss the advantages and disadvantages of corona. *(Refer sections 6.9.1 and 6.9.2)*	**Dec. 15, 10 Marks**

In the earlier days, corona was considered something to be avoided because of energy loss due to it. But now a day's corona is considered beneficial due to following advantages :

(i) Transient effects due to surges are reduced and equipments connected to line are protected. Charges induced on line by lightening or other causes are partly dissipated as corona loss.

Probability of flash-over is reduced. System performance is thus improved.

(ii) During corona, air surrounding conductor becomes conducting so virtual diameter of conductor increases which reduces electrostatic stress between the conductors. Which is advantageous.

6.9.2 Disadvantages of Corona

➔ (MU - Dec. 15, May 17)

Q. 6.9.3	Discuss the advantages and disadvantages of corona. *(Refer sections 6.9.1 and 6.9.2)*	**Dec. 15, 10 Marks**
Q. 6.9.4	Discuss the disadvantages of corona. *(Refer section 6.9.2)*	**May 17, 5 Marks**

(i) Corona causes power loss, so transmission line efficiency reduces.

(ii) Ozone gas produced during corona causes corrosion of conductor. In the presence of moisture nitrous acid is produced which attacks a conductor material.

(iii) Corona creates interference in radio communication. This is due to the production of 3^{rd} harmonics due to non-sinusoidal corona currents.

Syllabus Topic : Radio Interference due to Corona

6.10 Various Effects of Corona on Transmission Lines and Communication Lines

– An adverse effect is produced on the wireless signals for corona formed on transmission lines, this is due to current pulses generated by corona discharges.

- Amplitude broadcasting, power line carrier, aviation, marine ships calls (SOS) and other similar services are badly distributed due to corona interferences.
- Corona discharge effects are spread over kilometres of lines on its both sides. The increase in the radio interference field is gradual up to a voltage a little bit below the minimum voltage at which measurable corona loss occurs.
- Above this voltage the radio interference increases very rapidly. Conductor surface and conductor diameter decides the rate of increase of radio interference.
- This rate is higher for smooth surface and large diameter of conductor. The designer of the transmission line has to bear in mind that the voltage shall be below the datum at which radio interference starts rapidly in the fair weather conditions.
- When the line conductors are not smooth and clean, the radio interference occurs quickly.
- Sometimes air born materials (particles) on the conductor surface remain and a darkish coat appears on the conductor surface due to formation of **semicarboniferrous** material.
- This coating covers at the scratches and injuries of the conductor surface.
- In dealing with the radio interference problem, the design engineer has to take into consideration various factors like available signals intensities along the line, the satisfactory ratio : $\frac{\text{Signal}}{\text{Noise}}$, effects of surrounding climate (weather) on Radio Interference (RI) factors and also the importance of the communication services etc.
- Corona produces inductive interference between transmission lines and wireless (lines), signals. Amplitude modulated broadcasting, power line carrier, aviation, marine and other similar services are affected by due to this interference. Transmission line conductors are always clean so radio interference occurs.
- Radio interference field produces by transmission line is inversely proportional to radio frequencies.
- This shows that higher frequency band services like T.V., frequency modulated broadcasting, microwave relay and radars have less chance of affecting their services.
- Radio services are affected by production noise due to R.I.
- The R.I. due to corona is of the importance for lines above 200 kV.
- All the discussion shows that line design becomes complicated due to corona.
- In Extra High Voltage (EHV) lines the radio noise is a very important consideration is designing a line.
- This noise, as is associated with corona, is mainly dependent on the voltage gradients at the conductors.

- We know that corona is associated with air density 'δ' humidity, wind contaminants, imperfections and precipitation.
- By experiments it is found that radio-noise for 750 kV line in fair weather at the distance 15 metres from the line is in between 40 to 45 dB (decibels).
- This noise is lesser in bad weather.
- For frequency modulated radio receivers, T.V. receivers the noise so produced due to EHV lines is not that serious.
- During bad weather, however, the TV reception may be affected near the vicinity of EHV lines.

Syllabus Topic : Practical Considerations of Corona Loss

6.10.1 Practical Considerations of Corona Loss

- Corona has many disadvantages (See Section 6.9.2).
- Corona loss reduces transmission efficiency to a small extend.
- Loss is much more in bad weathers.
- The another disadvantage is that the leakage current due to corona takes place only during peak periods of voltage waves.
- Large third harmonics are produced which affects inductive interference with parallel communication circuits.
- Corona produces "Ozone" which cause deterioration is any organic material in the vicinity of the line.
- Corona can also act as safety valve, it causes attenuation of travelling waves due to lightening.
- The charges induced on the line by lightening are practically dissipated as corona loss – corona acts as safety value.
- The critical voltage of the line can be increased by providing more spacing between the lines. But it will increase tower cost; also inductive reactance drop will increase.
- Sometimes higher conductor size is desirable which increases critical voltage.
- But instead of large size conductor tolerate corona loss for economy.
- But don't neglect radio interference effect due to corona.

Syllabus Topic : Corona in Bundled Conductor Lines

6.11 Bundled Conductors

- Bundling of conductor means use of more than one conductor per phase. Particularly in extra H.V. line 2, 3 or 4 conductors are bundled.
- The spacing between the conductors of individual bundle is kept constant by the use of **'Spacers'**.
- Use of bundled conductors reduces corona loss and performance of the EHV line improves.
- Also visual corona voltages at which the corona becomes visible is raised by bundling the conductors.
- The voltage gradient is not uniform in case of bundled conductors but it is very much reduced (5 to 15%) this is the reason for less corona loss.
- Comparison of corona loss – (500 kV line)

  One conductor : 1.06 kW/ conductor / km.

  Two conductors : 0.778 kW/conductor / km.

  Three conductors : 0.558 kW/conductor / km.

  Four conductors : 0.417 kW/conductor / km.
- In EHV lines use of bundled conductors also help in reducing ratio interference.

6.12 Increase in Effective Radius of Conductor and Coupling Factors

The partial discharge of air around a line conductor is the process of charge particles and ions to move in the vicinity of conductor under applied voltage and field.

Taking first negative half cycle and then positive half cycle of the voltage :

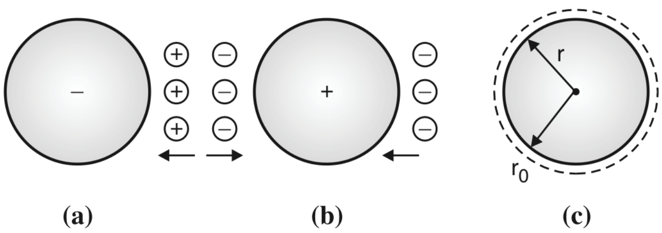


Fig. 6.12.1 : Space charge distribution in corona and increase in effective of conductor

See the Fig. 6.12.1 of part (a) :

- An electron avalanche is formed due to free electrons near negative conductor when repeated, acquiring sufficient energy.
- Positive ions are attracted towards negative conductor.
- Electrons drift into lower fields. They attach one-word to neutral atoms of 'Ni' or 'O' to form negative ions.
- Electric fields supply energy for initial ionization by collision.
- In positive half cycle negative ions are attracted towards conductor.
- Due to local conditions not all ions drift back to conductor.
- Space charge is left behind.
- Due to hysteresis effect there is an energy loss.
- Also, there an increase in effective capacitance.
- This is because of presence of charged particles; the effective charge of the conductor ground electrode system is increased.
- See Fig. 6.12.1(c) : We can say alternatively by assuming that the conductor diameter (radius r to r_0) is effectively increased by the conducting channel up to a certain extend where the electric field intensity decreases to a value equal to that required for further ionization, namely, the **"corona inception gradient".**

Syllabus Topic : Charge Voltage (q - V) Diagram

6.13 Charge / Voltage (i.e. q - V) Diagram

➔ **(MU - Dec. 15, May 17)**

Q. 6.13.1 Discuss the corona q-V diagram.
(Refer section 6.13) **Dec. 15, May 17, 10 Marks**

Let V_0 = the corona inception voltage

q_0 = the corresponding charge when voltage is V_0

V_m = Maximum voltage

q_m = corresponding charge at V_m.

For construction of q – V diagram taking the case of V_0 and V_m voltages….

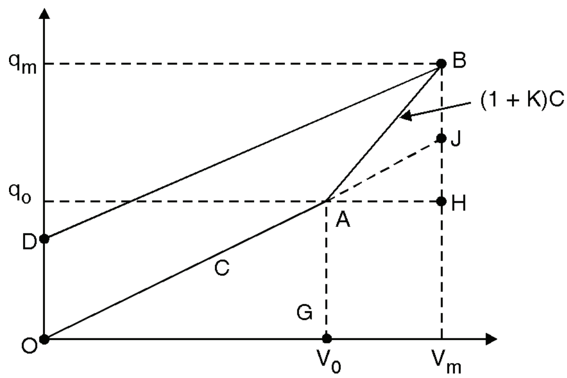


Fig. 6.13.1 : q–V diagram of corona

- Say corona is not present, then capacitance of conductor is dependent on the physical radium of the metallic conductor.
- Then, the charge-voltage relation is a straight line 'OA' where capacitance $C = \frac{q_0}{V_0}$ (Fig. 6.13.1).
- Beyond this voltage there is an increase in the charge (more rapid than given by the slope C of straight line q_0 / V_0 relation).
- This line is AB in the Fig. 6.13.1 (1 + K) C.
- Voltage is becoming maximum V_m.
- When voltage decreases from V_m, considering hysteresis effect then the charge – voltage relation line is 'BD'.
- See the Fig. 6.13.1 and note that slope of BD almost equals 'C'.
- This shows that space-charge cloud near the conductor has been absorbed into the conductor.
- And, the charges which are far away from the conductor are not entirely pulled back.
- The above diagram is helpful in working out the energy loss.
- Area OABD gives energy loss.
- To calculate this area :

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

$$= (\text{Area DOFB}) - \frac{1}{2} q_0 V_0 - q_0 (V_m - V_0) - \frac{1}{2} (q_m - V_0)(V_m - V_0)$$

$$= \text{(Area DOFB)} - \frac{1}{2} [q_0 V_m + q_m (V_m - V_0)]$$

Now, the lines are equal to

$$BH = q_m - q_0 = (1 + K) q_0 (V_m - V_0) / V_0$$

Here, k = experimental factor = 0.7

$$JH = q_0 (V_m - V_0) / V_0$$

$$BF = q_m = q_0 + (1 + K)_{q0} (V_m - V_0)_{V0}$$

$$D0 = BJ = BH - JH$$

$$= Kq_0 (V_m - V_0) / V_0$$

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

$$= Kq_0 (V_m - V_o) V_m/V_0 + \frac{1}{2} q_0 V_m^2 / V_0$$

$$\text{Area OAG} = \frac{1}{2} q_0 V_0$$

$$\text{Area AGFH} = q_0 (V_m - V_0)$$

$$\text{Area AHB} = \frac{1}{2} (q_m - q_0) (V_m - V_0)$$

$$= \frac{1}{2} q_0 \left(V_m^2 - V_0^2 \right) / V_0 + \frac{1}{2} Kq_0 (V_m - V_0)^2 / V_0$$

Adding area

$$OAG + AGFH + AHB = \frac{1}{2} (q_0 / V_0) \left[V_m^2 + K (V_m - V_o)^2 \right]$$

$\therefore$ **The area which give the losses ie. OABD for the unipolar wave form of voltages.**

$$\therefore \quad OABD = \frac{1}{2} K \cdot q_0 (V_m - V_0) (V_m - V_0) / V_0$$

$$= \frac{1}{2} KC \left(V_m^2 - V_0^2 \right)$$

- For an AC voltage for 1 cycle the energy loss will be twice the energy loss as derived above for the unipolar waveform of voltage.

Hence,

$$W_{ac} = 2 \times \left[\frac{1}{2} KC \left(V_m^2 - V_0^2 \right) \right]$$

$$= KC \left(V_m^2 - V_0^2 \right)$$

Corresponding power loss will be,

$$P_C = F \times W_{ac}$$
$$= F \cdot KC \left(V_m^2 - V_0^2 \right)$$

If the maximum voltage is very close to the corona inception voltage V_0, we can write,

$$V_m^2 - V_0^2 = (V_m + V_0)(V_m - V_0)$$
$$= 2 V_m (V_m - V_0)$$
$$\therefore \quad P_C = 2f\, KC\, V_m (V_m - V_0)$$

In these equations the voltages are of crest volume for effective values of V_m and V_0.

$$\therefore \quad P_C = 4\, fKC\, V (V - V_0)$$

Syllabus Topic : Corona Pulses : Their Generation and Properties In EHV Lines

6.14 Corona Pulses : Their Generation and Properties

Types of corona discharge from transmission line conductors

(1) Pulse-less or glow corona

(2) Pulse type or streamer corona

Pulse less (glow) corona gives rise to only energy loss. Pulse type (streamer) corona gives in addition to energy loss interference to radio broadcast in the range of frequency 0.5 MHz to to 1.6 MHz.

Disturbances due to the following :

(i) **From broken insulators and loose guy-wires :** spark discharges are produced.

These discharges interference in TV receptions in frequency range from 80 MHz to 200 MHz.

(ii) **From rain-drops and high humidity conditions :** Audible noise is produce which disturbs the systems.

(iii) **Corona on conductors :** causes interference to carrier communication and signalling in the frequency range of 30 kHz to 500 kHz.

How to face these problems

– **Radio and TV interference :** Locate receivers far enough from the line in a lateral direction such that noise generated by the line is low enough at the receiver location in order to yield satisfactory quality of reception.

– **Carrier interference :** In this case the problem is one of determining the transmitter and receiving powers to combat line-generated noise power.

6.15 Mechanism of Generation and Characteristics of Pulse Type Corona Affecting radio Reception

– In gas discharge phenomena under high impressed electric fields free electrons and ions are created in space which contains very few initial electrons.

– Current builds up in conductor from zero value to maximum caused by the **"avalanche"** mechanism and their motion towards the proper electrode.

– After the maximum value, there is fall in current. This is because lowering electric field due to relatively heavy immobile space charge-cloud which lowers the velocity of ions.

– Pulses are generated with short crease times and relatively longer fall time.

– See the single positive and negative pulse is shown below for D.C. excitation.

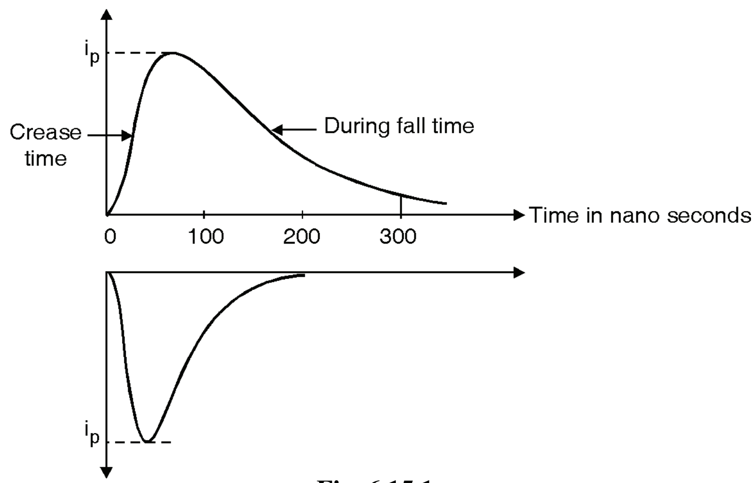


Fig. 6.15.1

Similar pulse occurs during the positive and negative half cycles under ac excitation.

– The positive corona have the equations :

$$i_{+ve} = k_+ i_p (e^{-\alpha t} - e^{-\beta t})$$

– The negative pulses can be described by

$$i_{-ve} = k_- i_p t^{-3/2} \cdot e^{-r/t - \delta t}$$

These equations are for formulating mathematical models of the radio noise problems.

6.16 Typical Average Values of Pulse Properties are as follows for Negative and Positive Pulse

Time in Nano-seconds :

Sr. No.	Type	Time to crease	Time to 50% on tail	Peak value of current	Repetition rate pulse / sec	
					AC	DC
1.	+ ve	50 ns	200 ns	100 mA	Power frequency	1,000
2.	– ve	20 ns	50 ns	10 mA	100 × P.F.	10,000

Note : Pulse are larger as diameter of conductor increases.

In very small wires positive pulse are absent and only glow corona can result. Negative pulses though present are named **'Trichel pulses'.**

Negative pulse effects are negligible as view point of ratio interference.

Positive polarity pulse are important.

Exercise

Q. 1 What is a corona ? How it is formed in H.V. transmission lines ? **(Section 6.1)** **(4 Marks)**

Q. 2 What are the advantages and disadvantages of corona ? **(Section 6.9)** **(4 Marks)**

Q. 3 What is disruptive critical voltage and visual critical voltage in corona ? **(Sections 6.2 and 6.3)** **(6 Marks)**

Q. 4 Write the formula for relative density (δ) of air. **(Section 6.2.1)** **(2 Marks)**

Q. 5 Write the relations to find disruptive critical voltage (V_d) and visual critical voltage (V_c). **(Sections 6.2.1 and 6.3)** **(4 Marks)**

Q. 6 What do you mean 'corona loss' ? **(Section 6.4)** **(2 Marks)**

Q. 7 Write the relation to find corona loss (P_c). **(Section 6.4, Equation 6.4.3)** **(2 Marks)**

Q. 8 Write the Peterson's formula for corona loss when $\frac{V}{V_d} < 1.8$. State the meaning of each term in it. **(Section 6.4, Equation 6.4.3)** **(4 Marks)**

Q. 9 3-phase transmission line is represented in the above sketch.

Find the visual critical corona voltage from the following data

The air temperature $\theta = 21°C$, pressure p = 73 cm of Hg.

Local corona irregularity factor m_v = 0.L84

[Ans. V_v = 78.7 kV] **(6 Marks)**

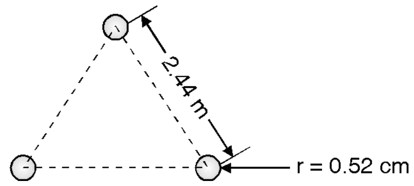


Fig. Q. 9

Q. 10 Elaborate the factors affecting corona. **(Section 6.6)** **(4 Marks)**

Q. 11 Explain the methods of reducing corona. **(Section 6.7)** **(6 Marks)**

Q. 12 Write a note on Line design based on corona. **(Section 6.8)** **(4 Marks)**

Q. 13 Elaborate the Radio interference due to corona. **(Section 6.10)** **(4 Marks)**

Q. 14 Write a note on bundled conductor. **(Section 6.11)** **(4 Marks)**

Q. 15 Draw the charge voltage (q – V) diagram related to corona and write the formula for loss of energy for (i) unipolar wave form of voltage (ii) A.C. voltage of one cycle. **(Section 6.13)** **(6 Marks)**

Q. 16 Prove that in corona the loss of energy = $\frac{1}{2}$ KC $\left(V_m^2 - V_0^2\right)$ using q – V diagram. **(Section 6.13)** **(6 Marks)**

Q. 17 Which are the two types of corona discharges from transmission line conductors what are their effects ? **(Section 6.14)** **(6 Marks)**

Q. 18 What are the discharges due to

(i) Broken insulators and loose guy wires.

(ii) Rain drop

(iii) Corona on conductors. **(Section 6.14)** **(6 Marks)**

Q. 19 How TV / Radio interference and carrier interference be minimized ? **(Section 6.14)** **(4 Marks)**

Q. 20 Draw the positive and negative pulses for D.C. excitation. **(Section 6.15)** **(4 Marks)**

Q. 21 Write the equation for

(i) Positive corona wave

(ii) Negative pulses **(Section 6.15)** **(6 Marks)**

Q. 22 What are the factors and conditions affecting corona loss? Explain them briefly. **(Section 6.4)** **(7 Marks)**

Q. 23 Find the disruptive critical voltage for a 3-ph line consisting of 21 mm diameter conductors spaced in a 6 m delta configuration. Take temperature as 25° C, pressure as 73 cm of Hg and surface factor 0.85. What should be the voltage of transmission? **(Ex. 6.5.9)** **(7 Marks)**

Q. 24 Find the critical disruptive voltage and corona loss for a 3 phase line which is operating at 220 kV, 50 Hz frequency. The line has conductor of 1.5 cm diameter arranged in a 3 meter delta connection. Assume air density factor of 1.05 and dielectric strength of air to be 21.1 kV/cm. **(Ex. 6.5.7)** **(7 Marks)**

Q. 25 Explain how corona affects the electrical design of transmission line. State the factors on which corona loss depends. **(Sections 6.10 and 6.4)** **(7 Marks)**

Q. 26 A 3 phase 220 kV, 50 Hz line is 250 km long consisting of 22.26 mm diameter conductor spaced 6 meter delta configuration.

The following data can be assumed Temperature = 25°C, pressure = 73 cm of mercury, surface factor = 0.84, irregularity factor for local corona = 0.72. Irregularity factor for general corona = 0.82.

Find the total loss in the fair whether using Peek's formula. **(Ex. 6.5.8)** **(7 Marks)**

Q. 27 The disruptive critical voltage is less than visual critical voltage.

(Equations 6.2.9 and 6.3.3) **(2 Marks)**

Q. 28 Find the disruptive critical voltage and visual corona voltage (local as well as general corona) for a 3-phase 220 kV line consisting of 22.26 mm diameter conductors spaced in a 6 m delta configuration. The following data can be assumed: Temperature 25° C, pressure 73 cm of mercury, surface factor 0.84, irregularity factor for local corona 0.72, and irregularity factor for general (decided) corona 0.82.

(Similar to Ex. 6.5.1) **(7 Marks)**

Q. 29 Write a short note on phenomena of corona. **(Section 6.1)** **(7 Marks)**

6.17 University Questions and Answers

➔ May 2015

Q. 1 What are the advantages of corona ? *(Ans. : Refer section 6.9.1)* **(5 Marks)**

Q. 2 Explain the terms critical voltage, visual critical voltage and corona ring. *(Ans. : Refer sections 6.2, 6.3 and 6.7.1)* **(10 Marks)**

➔ Dec. 2015

Q. 3 Discusses the corona q–V diagram. *(Ans. : Refer section 6.13)* **(5 Marks)**

Q. 4 Discuss the advantages and disadvantages of corona. *(Ans. : Refer sections 6.9.1 and 6.9.2)* **(10 Marks)**

➔ May 2016

Q. 5 Explain the various factors affecting the corona. *(Ans. : Refer section 6.6)* **(10 Marks)**

➔ Dec. 2016

Q. 6 Explain the terms with reference to corona disruptive critical voltage, visual critical voltage, power loss. *(Ans. : Refer sections 6.2, 6.3 and 6.4)* **(10 Marks)**

➔ May 2017

Q. 7 Discuss the disadvantages of corona. *(Ans. : Refer section 6.9.2)* **(5 Marks)**

Q. 8 Explain the terms critical voltage, Visual critical voltage.

(Ans. :Refer sections 6.2 and 6.3) **(10 Marks)**

Q. 9 Discuss the corona q-V diagram. *(Ans. : Refer section 6.13)* **(10 Marks)**

Chapter Ends...

❑❑❑

Appendix A

Solved University Question Paper of Dec. 2018

Power System - II

[3 Hours] **[80 Marks]**

Note :

1. Question No 1 is compulsory.
2. Solve any three out of the remaining.
3. Figures to right side indicates marks.
4. Assume the suitable data and and mention the same if required.

Q. 1 Answer the following **(20 Marks)**

(a) Why are the pre fault currents usually neglected in fault computation ? **(05 Marks)**

Ans. :

– A phase shift occurs in positive sequence and negative sequence voltages and current while passing through a star delta transformer. This phase shift depends upon labelling of terminals.

– Fig. 1-Q. 1(a) shows a single phase transformer along with polarity marked. The transformer ends marked with dot have same polarity.

– Hence, voltage $V_{11'}$ is in phase with voltage $V_{22'}$.

– If we neglect the small amount of magnetizing current, the primary current I_1 entering the dotted end cancels the demagnetizing ampere turns of secondary current I_2.

– Hence I_1 and I_2 with the directions indicated in diagram are in phase. If direction of I_2 is reversed. I_1 and I_2 will be in phase opposition.

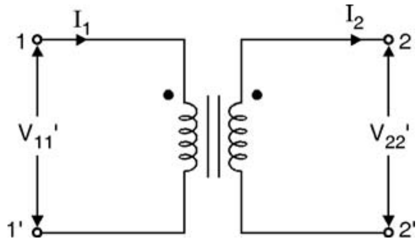


Fig. 1-Q. 1(a) : A single phase transformer with polarity markings

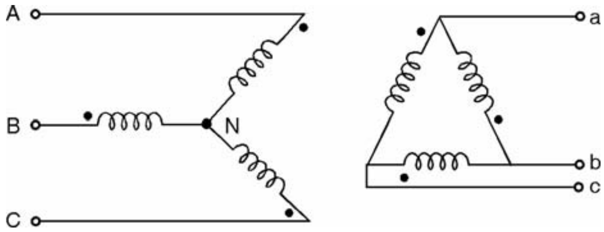
– Consider a star delta transformer as shown in Fig. 2-Q. 1(a)(i). Assume that the transformer is excited with positive sequence voltages and carries positive sequence currents. For the shown polarities in Fig. 2-Q. 1(a)(i) the phasor diagram is as shown in Fig. 3-Q. 1(a). We will get the following relationship between the voltages on the two sides of transformer.

$$V_{AB1} = x\, V_{ab1} \angle 30°. \qquad ...(1)$$

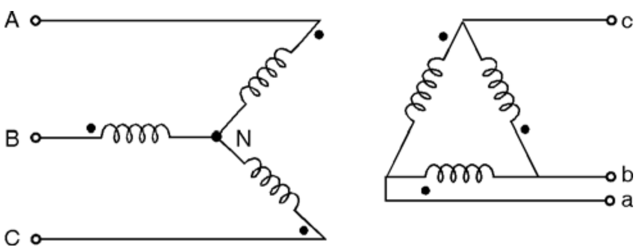
– Here x is the phase transformation ratio.

– Equation (1) indicates that the positive sequence line voltages on star side lead the corresponding voltage on delta side by 30°. The same is applicable to line to neutral voltages on the two sides and for line currents.

– The phase shift reverses if the delta side of transformer is connected as shown Fig. 2-Q. 1(a)(ii). In such connections the delta side quantities lead the star side quantities by 30°.



(i) Star side quantities lead delta side quantities by 30°



(ii) Delta side quantities lead star side quantities by 30°

Fig. 2-Q. 1(a) : Star Delta tansformer labelling

– If the transformer shown in Fig. 1-Q. 1(a) is excited by negative sequence voltages and currents then the phase shift gets reversed in comparison to the phase shift of positive phase sequence.

– The star side quantities lag the delta side quantities by 30° as shown in Fig. 4-Q. 1(a). If the delta side is connected as shown in Fig. 2-Q. 1(a)(ii) the delta side quantities lag the star side quantities by 30°.

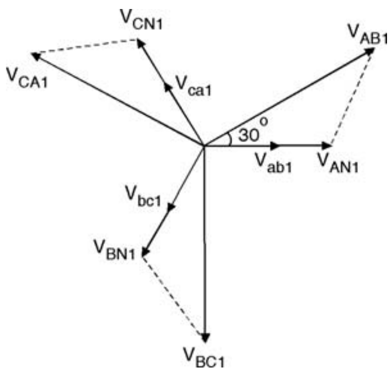


Fig. 3-Q. 1(a) : Phasor diagram representing positive sequence voltages of star delta transformer

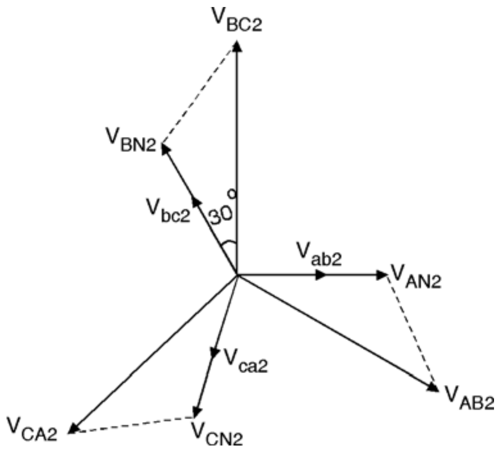


Fig. 4-Q. 1(a) : Phasor diagram representing negative sequence voltages of star delta transformer

(b) Why the HV lines provided with ground wire as a topmost conductor ?
(Refer section 5.3) **(05 Marks)**

(c) Which type of fault/faults occurs frequently? And why ?
(Refer section 3.1) **(05 Marks)**

(d) Why insulation coordination is required ? **(Refer section 5.1)** **(05 Marks)**

Q. 2 (a) Derive the Fortesque Theorem for symmetrical component analysis.
(Refer section 2.4) **(10 Marks)**

(b) A 25 MVA 13.2 KV alternator with solidly grounded neutral has sub transient reactance of 0.25 pu. The negative and zero sequence reluctances are 0.35 and 0.1 pu respectively. A single line to ground fault occurs at the terminals of an unloaded alternator, determine the fault current and line to line voltages. Neglect resistance. **(Refer Ex. 3.10.5)** **(10 Marks)**

Q. 3 (a) Derive the equation for fault current for a double line to ground fault. State the various assumptions**.** Draw the sequence network for same.
(Refer section 3.8) **(10 Marks)**

(b) In a Four Bus system (1,2,3,4) buses are connected to each other by 1Ω element as 1- 2; 2 - 4; 4- 3; 3 - 3 and 1- 4. Taking Bus 4 as reference Obtain [Z_{Bus}]. **(10 Marks)**

Soln.:

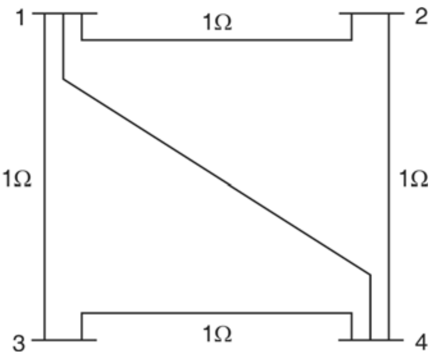


Fig.1-Q.3(b)

$$Z_{11} = Z_{12} + Z_{13} + Z_{14} = 3\ \Omega$$

$$Z_{22} = Z_{21} + Z_{24} = 2\ \Omega$$

$$Z_{33} = Z_{31} + Z_{34} = 2\ \Omega$$

$$Z_{44} = Z_{42} + Z_{41} + Z_{43} = 3\ \Omega$$

$$Z_{Bus} = \begin{bmatrix} 3 & -1 & -1 & -1 \\ -1 & 2 & 0 & -1 \\ -1 & 0 & 2 & -1 \\ -1 & -1 & -1 & 3 \end{bmatrix}$$

Q. 4 (a) Discuss the phenomenon of transient generation due to capacitance switching.
(Refer section 4.5) **(10 Marks)**

(b) Discuss the terms with respect to lightning phenomenon " Insulator Flashover, Withstand Voltage; Direct Stroke". **(Refer section 4.16 and 4.12.3.1)** **(10 Marks)**

Q. 5 (a) A Surge of 15 KV is traveling along the cable towards the junction with an overload line. The inductance and capacitance of cable and overhead line are respectively 0.3 mH. 0.4uF and 1.5mH. 0.012 uF per Km. Find the voltage rise at the junction due to surge.

(10 Marks)

Soln.:

The surge travels from the cable towards the overhead line. Hence there is positive voltage reflection at the junction.

$$\text{The Natural impedance of the cable} = \sqrt{\frac{0.3 \times 10^{-3}}{0.4 \times 10^{-6}}}$$

$$= 27.38\ \Omega$$

$$\text{The Natural impedance of the line} = \sqrt{\frac{1.5 \times 10^{-3}}{0.012 \times 10^{-6}}}$$

$$= 353\ \Omega$$

The voltage rise at the junction is the voltage transmitted into the overhead line as the voltage is zero before the surge reaches the junction.

$$E'' = \frac{2 \times 353 \times 15}{353 \times 27.38} = 27.87\text{ kV}$$

(b) Write an algorithm for short circuit studies.

(Refer Section 1.9) **(10 Marks)**

Q. 6 (a) Find critical disruptive voltage, and critical voltage for local and general corona on three phase over head transmission line consisting of three standard copper conductors spaced 2.5 m apart at the corners of an equilateral triangle. Air temperature and pressure are 21 degree centigrade and 73.6 cm of mercury respectively. The conductor diameter, surface irregularity factor and surface factors are 10.4 mm, 0.85, 0.7 and 0.8 respectively.

(10 Marks)

Soln.:

Critical Disruptive Voltage is,

$$V_d = 21.1\ m\ \delta r\ ln\frac{d}{r}$$

$$\delta = \frac{3.92\ b}{273 + t} = \frac{3.92 \times 73.6}{294} = 0.\ 9813$$

$$V_d = 21.1 \times 0.85 \times 0.9813 \times 0.52\ ln\frac{250}{0.52}$$

$$= 56.5\text{ Kv}$$

$$\text{Critical Disruptive line to line Voltage} = 56.5 \times \sqrt{3} = 97.89\text{ kV}$$

Visual Critical Voltage ,

$$V_v = 21.1\ m\ \delta r \left[1 + \frac{0.3}{\sqrt{r\delta}}\right] ln \frac{d}{r}$$

$$\sqrt{r\delta} = \sqrt{0.52 \times 0.9813} = 0.71433$$

$$V_v \text{ for local Corona} = 21.1 \times 0.7 \times 0.9813 \times 0.52\ [1 + 0.42]\ ln \frac{d}{r}$$

$$= 66.07 \text{ kV}$$

$$V_v \text{ line to line} = 66.07 \times \sqrt{3}$$

$$= 114.44 \text{ kV}$$

$$\text{Visual Critical Voltage for general Corona} = 114.44 \times \frac{0.8}{0.7} = 130.78 \text{ kV}$$

(b) Discuss the sequence network of Synchronous Machine.

(Refer section 2.7) **(10 Marks)**

❒❒❒

LIST OF BOOK SELLERS

Airoli

- **Sai Book Depot**
  (Ph. No. 9769760097)

Andheri (E)

- **Books Emporium,**
  (Ph. No. 28203894)
- **Andheri Book Depot**
  (9594503334, 02226830432)

Andheri (W)

- **Book Point,**
  (Ph. 9892106828, 8976521805)
- **City Book Centre,**
  (Ph. No. 65532739)
- **Bhawans Book Stall**
  (Ph. 022-26232839)

Badlapur

- **Gajanan Book depot.**
  (Ph. 9324706988)

Bandra (W)

- **National Book Stall**
  (Ph. No. 26049526)
- **Navjivan Book Centre,**
  (Ph. No. 26422157)

Bhandup

- **Raj Book Depot**
  (Ph. No. 25949511
  9920494643, 8169644301)

Bhayandar (E)

- **Ujwal Book Depot**
  (Ph. No. 28048406
  9322064884, 28148406)

Bhayandar (E)

- **Lalit Stores**
  (Ph. No. 7738550078)
- **Shree Laxmi Stores**
  (Ph. No. 28040894
  9819260262)

Boisar (W)

- **Gandhi Stationery**
  (Ph. No. 02525- 253935)

Borivali (W)

- **My Stores (jayant Book Depo)**
  (Ph. No. 9869000411)
- **Pustakkala**
  (Ph. No. 9619847487)
- **Shree Ganesh Book Centre**
  (Ph. No. 9820157587)
  022-28051251
- **Bhavesh Stores**
  (Ph. No. 9004046364)

CBD Belapur

- **Sai Book Centre,**
  (Ph. No. 9869028936)

Charni Road

- **Lakhani Book Depot**
  (Ph. No. 23854356) closed
- **Students' Book Depot**
  (Ph. No. 23853708)
- **Vidyarthi Book Depot**
  (Ph. No. 23858828)

Chembur (E)

- **Jayesh Book Centre**
  (Ph. No. 25285416)
- **Nandu Book House**
  (Ph. No. 25211441)
- **Balaji Book Centre**
  (Ph. No. 022-25202527)
- **Raj Book Tredars (9967145757)**
- **Ambika book centre**
  Ph. 9702498850, 8108388011
- **Ramchandra Book Depot**
  7208340059

Chowpatty

- **Winner Book Centre**
  (Ph. No. 23641307)

Colaba

- **Prabhat Stores**
  (Ph. No. 22189759)

Dadar (W)

- **Sandhya Book Stall**
  (Ph. No. 9930764748)
- **Jagdishwar Book depot**
  9967186017
- **Union Book Stall**
  (022-24223069, 02224330017
- **Jagdish Book Depo**
- **Mr. Ashish Desai** 9702721241
  9833286718 ,

Dahisar (E)

- **Selection Centre**
  (Ph. No. 28285002)
- **Arihant Book Depot**
  (Ph. No. 9004455564)

Dombivali (W)

- **Mahavir Book Depot**
  (Ph. No. 9004936870)

Fort

- **Aarti Book Co.**
  (Ph. No. 22047397)

Ghatkopar (W)

- **Shah Book Depot**
  (Ph. No. 25156319)
- **Rachana Book Cemtre**
  022-25163280, 9769454365

Girgaon

- **Bharat Sales.**
  (Ph. No. 66390580)
- **Joshi Book Depot**
  (Ph. No. 23819335)

Goregaon (E)

- **Arihant Book Agency**
  (Ph. No. 29270646)
- **Hem Book Store**
  (Ph. No. 9819834615)
- **Agrawal Book Depot**
  (Ph. 28722452 / 8898538617)

Goregaon (W)

- **Anjali trading Co.**
  022-28714025, 9819737977
- **Bhavesh Store**
  (Ph. No. 9969084078)
- **Santosh Book Depot**
  (Ph. No. 28766126)

Jogeshwari (E)

- **Ashtvinayk Book Centre**
  02228230035

Kalyan (W)

- **Bagade Stores**
  (Ph. No. 0251-2204280)
- **Kalyan Book Depot**
  8879274234 0251-2211733
- **New Alankar Book Depot**
  (Ph. No. 9920553161)

Kandivali (E)

- **Thakur College Book Centre**
  (Ph. No. 28851540)
- **Jay Bholenath**
  (Ph. No. 28856635)
- **Shweta Book Depot**
  (Ph. No. 9920998776)
- **Ambika Book and Xerox**
  (Ph. No. 9867541173)
- **Ambika Book Depot**
  (Ph. No. 9821263050)

Kandivali (W)

- **Parshva Book Centre**
  (Ph. No. 28076628)
- **Maru Book Centre**
  (Ph. 9930033087 / 28072124)

Khar Road (W)

- **Goklesh Book Centre**
  (Ph. No. 26498981)

Kharghar

- **Krisha Book Stores**
  (Ph. No. 27744962)
- **Krishna Book Centre**
  (Ph. No. 27749988)
- **College Book Store**
  9987644718

Kopar Khairane

- **Bhavesh Book Stall**
  (Ph. No. 27547616)

Kurla

- **Prabhat Stores**
  (Ph. No. 25227693)

Malad (E)

- **Champion Stores**
  (Ph. No. 28825444)

Malad (W)

- **My Book Store**
  (Ph. No. 28809098)
- **Balaji Emporium**
  (Ph. No. 8879296445)

Matunga(CR)

- **Madhu Book Depot**
  (Ph. No. 9324216999)
- **Shanti Book Store**
  (Ph. No. 02224010275)
- **Ashirwad Book Depot 9819690271**
- **Popular Book Depot**

Mazgaon

- **Mazgaon Book Depot**
  (Ph. No. 23722081)

Mira Road (E)

- **Jyoti** (Ph. No. 9821004164)

Mulund E

- **Samarth Book center**

Mulund (W)

- **Jagdish Book Dept**
  (Ph. No. 9820757241, 9987372415)
- **Pooja Book Depot**
  (Ph. No. 9870408310)

- **Sonal Book Depot**
  (Ph. No. 25642210),
  02225909532
- **Gurukrupa book store**

Nalla Sopara (E)

- **Students Book Centre**
  (Ph. No. 9975559343)

Nerul

- **Ganesh Book Depot**
  (Ph. No. 27700531)
- **New balaji books**
  9930199920

Palghar (W)

- **Navneet Book Stores**
  (Ph. 02525-252515)
- **Deepak Stationery**
  (Ph. 02525- 254038)

Panvel

- **Shree Narayan Stores**
  (Ph. No. 27454767)
- **Deepak Book Store 7666436858**

Rabale

Nilkanth Book House 9930924060

Shelu

- **Navneet Book Stall**
  9930764748

Sion (W)

- **S.K. Book Stall**
  (Ph. No. 24045605)

Thane(E)

- **Krishna Book Depot**
  (Ph. No. 9833610506)

Thane(w)

- **Jagdish Book Depot**
  (Ph. No. 9820841353, 9324557615
- **Laxmi Book Depot**
  (Ph. No. 25367371)
- **Saraswati Book Depot**
  (Ph. No. 25367777)
- **Gurukrupa Book store**

Ulhasnagar

- **Hira Book Sellers**
  (Ph. No. 0251-2569521),
  9834573334
- **Gyandhara Book Depo**
  9075647467, 9619472379,
  9702048450

Vasai Road (W)

- **Bhavik Book Centre**
  (Ph. 2334280 / 9960099927)

- **Ambika Book centre**
  (Ph. 0250-2331365 /
  9022336465, 9960099927)
- **Saif books corner**
  9270037671,

Gajanan Krupa Book Centre
(Ph. No. 0250-2333592)

Vashi

- **Student Book Store**
  (Ph. No. 27662724)
- **Milan Book Depot**
  (Ph. No. 27662002)

Vidya Vihar

- **Milan Book Centre**
  (Ph. No. 9833198030)
- **Varsha Book Centre**
  (Ph. No. 9022222036, 9987979762)

Vidya Vihar (E)

- **Social Book Centre**
  (Ph. No. 21027362) 8898553424

Vikhroli

- **Lata Book Depot**
  (Ph. No. 25749289)

Vile Parle (E)

- **Parle Book Depot**
  (Ph. No. 26145984)
- **The Book Shop**
  (Ph. No. 26182420)

Vile Parle (W)

- **Parle Book Centre**
  (Ph. No. 26188389)
- **Vijay Book Centre**
  (Ph. No. 9920906667)

Virar (W)

- **Bhavik Book Depot**
  (Ph. 9270902323 / 9320230990)
- **Siddhivinayak Book Centre**
  (Ph. 7875284237 / 9320230990)
- **Shah Book Center**
  (Ph. No. 9860044173)
- **Jagdish Book Depot**
  (Ph. No. 8268925491)
- **Swastik Book Centre**
  (Ph. 2502642,2508472)
- **Shivam Book & Stationery**
  Shop (Ph. 6095799)

WADALA

- **Vijay book depot 022-24150553**
- **Mital traders**
  982156920, 8879747908

Note

Note