LECTURE NOTES
On
Electrical Machine 1

Name of the Department- Electrical Engineering

SUBJECT CODE-1302

NAME OF THE SUBJECT- ELECTRICAL MACHINE1 (PART 2)

SEMESTER- 3RD

BRANCH- EE&EEE

PART2- MODULE3+ MODULE4

DETAIL SYLLABUS

Veer Surendra Sai University of Technology, Orissa, Burla, India
Department of Electrical Engineering,
Syllabus of Bachelor of Technology in Electrical & Electronics Engineering, 2010

(3RD SEMESTER)

ELECTRICAL MACHINES-I (3-1-0)

MODULE-I (10 HOURS)

Electromechanical Energy conversion, forces and torque in magnetic field systems – energy balance, energy and force in a singly excited magnetic field system, determination of magnetic force , coenergy, multi excited magnetic field systems.

DC Generators – Principle of operation, Action of commutator, constructional features, armature windings, lap and wave windings, simplex and multiplex windings, use of laminated armature, E. M.F. Equation,

Methods of Excitation: separately excited and self excited generators, build up of E.M.F., critical field resistance and critical speed , causes for failure to self excite and remedial measures, Armature reaction: Cross magnetizing and demagnetizing AT/pole, compensating winding, commutation, reactance voltage, methods of improving commutation

Load characteristics of shunt, series and compound generators, parallel operation of DC generators, use of equalizer bar and cross connection of field windings, load sharing.

MODULE-II (10 HOURS)

Transformers: Single phase transformer, Constructional details, Core, windings, Insulation, principle of operation, emf equation, magnetising current and core losses, no load and on load operation, Phasor diagram, equivalent circuit, losses and efficiency, condition for maximum efficiency, voltage regulation, approximate expression for voltage regulation, open circuit and short circuit tests, Sumpner’s test, Inrush of switching currents, harmonics in single phase transformers, magnetizing current wave form, Parallel operation of transformers.

MODULE-III (10 HOURS)

DC Motors: Principle of operation, Back E.M.F., Torque equation, characteristics and application of shunt, series and compound motors, Armature reaction and commutation, Starting of DC motor, Principle of operation of 3 point and 4 point starters, drum controller, Constant & Variable losses, calculation of efficiency, condition for maximum efficiency.

Speed control of DC Motors: Armature voltage and field flux control methods, Ward Leonard method.
Methods of Testing: direct, indirect and regenerative testing, brake test, Swinburne’s test, Load test, Hopkinson’s test, Field’s test, Retardation test, separation of stray losses in a DC motor test.

MODULE-IV (10 HOURS)

Three phase Transformer: Constructional features of three phase transformers – three phase connection of transformers (Dd0, Dd6, Yy0, Yy6, Dy1, Dy11, Yd1, Yd11, zigzag), Scott connection, open delta connection, three phase to six phase connection, oscillating neutral, tertiary winding, three winding transformer, equal and unequal turns ratio, parallel operation, load sharing.Distribution transformers, all day efficiency, Autotransformers, saving of copper, applications, tap- changing transformers, cooling of transformers.

Disclaimer

MODULE-III

DC MOTOR

TOPICS

DC Motors: Principle of operation, Back E.M.F., Torque equation, characteristics and application of shunt, series and compound motors, Armature reaction and commutation, Starting of DC motor, Principle of operation of 3 point and 4 point starters, drum controller, Constant & Variable losses, calculation of efficiency, condition for maximum efficiency.

Speed control of DC Motors: Armature voltage and field flux control methods, Ward Leonard method.

Methods of Testing: direct, indirect and regenerative testing, brake test, Swinburne's test, Load test, Hopkinson's test, Field's test, Retardation test, separation of stray losses in a DC motor test.

[Topics are arranged as per above sequence]

3.1 Principle of Operation

DC motor operates on the principle that when a current carrying conductor is placed in a magnetic field, it experiences a mechanical force given by F = BIL newton. Where 'B' = flux density in wb, 'I' is the current and 'L' is the length of the conductor. The direction of force can be found by Fleming's left hand rule. From the point of construction, there is no difference between a DC generator and DC motor. Figure 3.1 shows a multipolar DC motor. Armature conductors are carrying current downwards under North Pole and upwards under South Pole. When the field coils are excited, with current carrying armature conductors, a force is experienced by each armature conductor whose direction can be found by Fleming's left hand rule. This is shown by arrows on top of the conductors. The collective force produces a driving torque which sets the armature into rotation. The function of a commutator in DC motor is to provide a continuous and unidirectional torque.

In DC generator the work done in overcoming the magnetic drag is converted into electrical energy. Conversion of energy from electrical form to mechanical form by a DC motor takes place by the work done in overcoming the opposition which is called the 'back emf'.

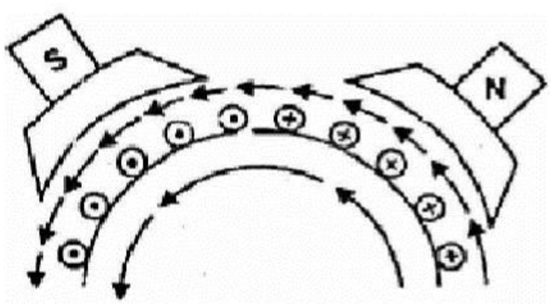


Fig. 3.1 Generation of force in DC motor

3.2 Back EMF

It is the dynamically induced emf in the armature conductors when the armature rotates following principle of DC motor. The direction of this induced emf can be determined using Fleming's right hand rule. This emf act in opposition to the supply voltage of the armature. It opposes the supply voltage that is why it is called back emf. The value of this induced emf is same as the value of the emf induced in dc generator. The work done in overcoming this opposition is converted into mechanical energy.

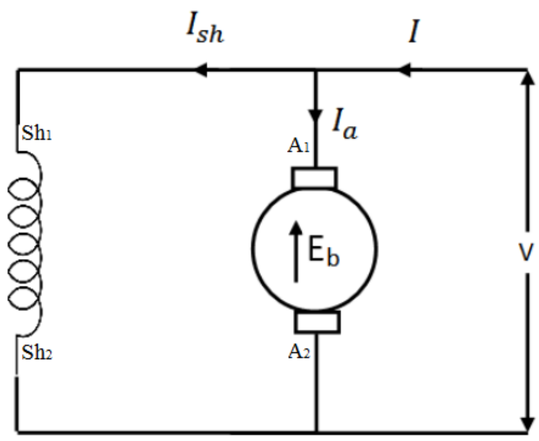


Fig. 3.2 Schematic diagram of DC shunt motor

Fig shown 3.2 a DC shunt motor the rotating armature generating the back emf E_b. The armature current can be written as

$$I_a = \frac{V_T - E_b}{r_a}$$

Where r_a is armature resistance,

$$\boxed{E_b = \frac{P\phi ZN}{60A}}$$

Armature current is proportional to back emf. So back emf is a controlling factor of armature current.

3.3Torque Equation

Let T_a = armature torque in N –m developed by the armature of a motor running at N.rps.

Therefore P = T_a X $\frac{2\pi N}{60}$ Watts

Electrical equivalent of mechanical power developed $P_m = E_b I_a$

$$P_m = E_b I_a = P = T_a \times \frac{2\pi N}{60}$$

$T_a = \frac{E_b I_a}{2\pi N} \times 60$ Also, on substituting for Eb i.e., $E_b = \frac{P\phi ZN}{60A}$

Therefore,

$$T_a = \frac{I_a \times 60}{2\pi N} \times \frac{P\phi ZN}{60A}$$

$$T_a = \frac{I_a}{2\pi} \times \frac{P\phi Z}{A}$$

$$\boxed{T_a = \frac{P\phi Z I_a}{2\pi A}} \text{N-m}$$

From the above equation for torque, it is seen that

(i) $T_a = k\phi I_a$

(ii) $T_a \propto I_a^2$ - For series motor (because $\phi \propto I_a$) before saturation. After saturation $T_a \propto I_a$

(iii) $T_a \propto I_a$ - For shunt motor. (because ϕ is constant in a shunt motor)

3.4 Characteristics of DC Motors

There are three important characteristics-

1. Armature torque vs armature current T_a vs I_a *(Electrical characteristics)*
2. Speed vs armature current characteristic N vs I_a
3. Speed vs torque N vs T_a (Mechanical characteristics)

3.4.1 Characteristics of DC shunt motor

3.4.1.1 Armature torque vs armature current T_a vs I_a characteristics

For a shunt motor flux can be assumed practically constant (at heavy loads, decreases, due to increased armature reaction)

$T_a = k\phi I_a$

ϕ is constant, $T_a \propto I_a$

Therefore electrical characteristic of a shunt motor is a straight line through origin shown by dotted line in figure 3.3. Armature reaction weakens the flux hence T_a vs I_a characteristic bends as shown by dark line in figure 3.3, Shunt motors should never be started on heavy loads, since it draws heavy current under such condition.

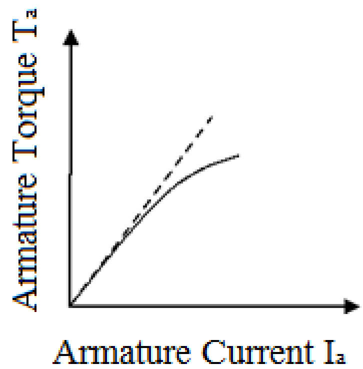


Fig. 3.3 Torque Current Characteristic of DC shunt motor

3.4.1.2 Speed vs armature current N_a vs I_a characteristics

$$N \propto \frac{E_b}{\phi}$$

$$N=\frac{V-I_a r_a}{k\phi}$$

$$N=\frac{V}{k\phi}-\frac{I_a r_a}{k\phi}$$

V is constant and in dc shunt motor ϕ is also constant. Thus with armature current speed drops and the speed current characteristics is drooping in nature is shown in figure 3.4.

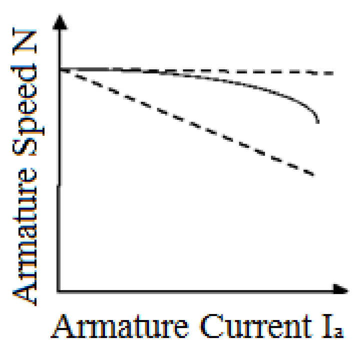


Fig. 3.4 Speed vs armature current characteristics of DC shunt motor

3.4.1.3 Speed vs armature torque N_a vs T_a characteristics

$$N=\frac{V}{k\phi}-\frac{I_a r_a}{k\phi}$$

$$I_a=\frac{T_a}{k\phi}$$

$$N=\frac{V}{k\phi}-\frac{r_a}{k\phi^2}T_a$$

Thus with increase with torque the speed of DC shunt motor decreases. The nature of the characteristics is drooping in nature shown in figure 3.5.

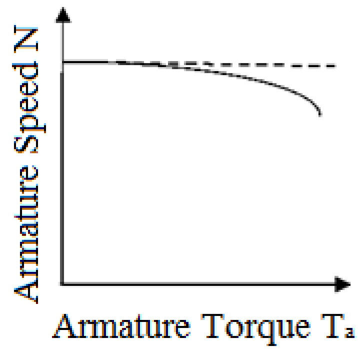


Fig. 3.5 Speed vs armature torque characteristics of DC shunt motor

3.4.2 Characteristics of DC series motor

3.4.2.1 Armature torque vs armature current T_a vs I_a characteristics

$T_a = k\phi I_a$

$T_a \propto I_a^2$ - For series motor (because $\phi \propto I_a$) before saturation

After saturation ϕ becomes constant thus $T_a \propto I_a$

At light loads, I_a and hence ϕ is small. But as I_a increases T_a increases as the square of the current up-to saturation. After saturation ϕ becomes constant, the characteristic becomes a straight line as shown in Figure 3.6. Therefore a series motor develops a torque proportional to the square of the armature current. This characteristic is suited where huge starting torque is required for accelerating heavy masses.

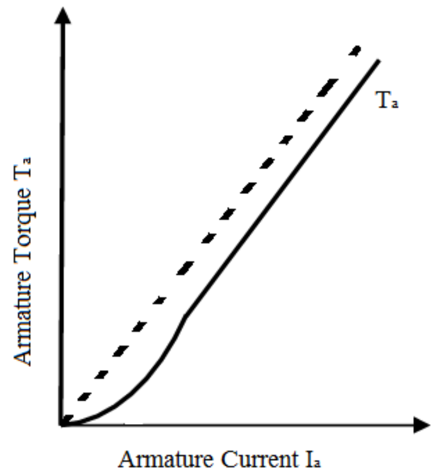


Fig. 3.6 Torque Current Characteristic of DC series motor

3.4.2.2 Speed vs armature current $N_a$vs I_a characteristics

$$N \propto \frac{E_b}{\phi}$$

$$N = \frac{V - I_a r_a}{k\phi}$$

$$N = \frac{V}{k\phi} - \frac{I_a r_a}{k\phi}$$

$$I_a \propto \phi$$

$$N = \frac{V}{k k_1 I_a} - \frac{k_1 r_a}{k}$$

$$N \propto \frac{1}{I_a}$$

If I_a increases, speed decreases. This characteristic is shown in figure 3.7. Therefore the speed is inversely proportional to armature current I_a. When load is heavy I_a ia heavy thus speed is low. When load is low I_a is low thus speed becomes dangerously high. Hence series motor should never started without load on it.

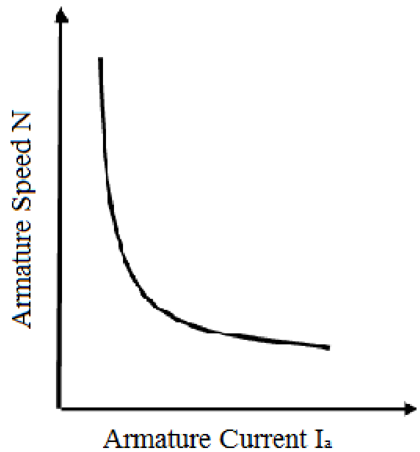


Fig. 3.7 Speed vs armature current characteristics of DC series motor

3.4.2.2 Speed vs armature torque N_a vs T_a characteristics

$$N=\frac{V}{k\phi}-\frac{I_a r_a}{k\phi} \text{ and } \phi = k_1 I_a$$

$$\therefore N=\frac{V}{kk_1 I_a}-\frac{I_a r_a}{kk_1 I_a}$$

$$\Rightarrow N=\frac{V}{kk_1 I_a}-\frac{r_a}{kk_1}$$

$$\text{Now, } T_a = kI_a^2 \quad \therefore I_a = \sqrt{\frac{T_a}{k}}$$

Substituting I_a

$$N=\frac{V\sqrt{k}}{kk_1\sqrt{T_a}}-\frac{r_a}{kk_1}$$

$$\Rightarrow N=\frac{\text{Const.}}{\sqrt{T_a}}-\text{Const.}$$

Thus Speed is inversely proportional to torque. The characteristics is shown in figure 3.8.

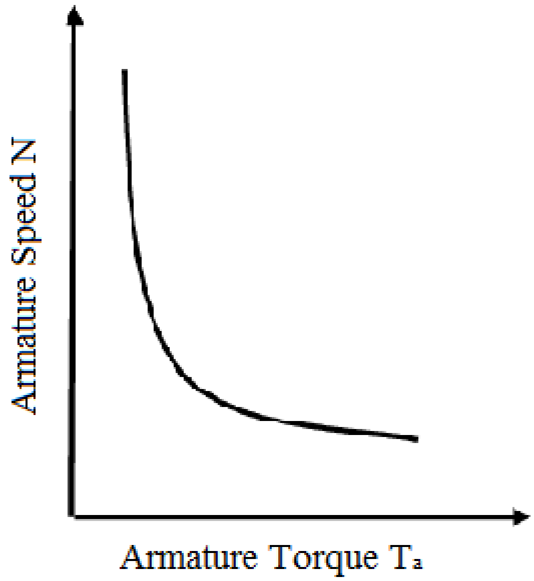


Fig. 3.8 Speed vs armature torque characteristics of DC series motor

3.4.3 Characteristics of DC compound motor

There are two different types of compound motors in common use, they are the cumulative compound motor and the differential compound motor. In the cumulative compound motor, the field produced by the series winding aids the field produced by the shunt winding. The speed of this motor falls more rapidly with increasing current than does that of the shunt motor because the field increases. In the differential compound motor, the flux from the series winding opposes the flux from the shunt winding. The field flux, therefore, decreases with increasing load current. Because the flux decreases, the speed may increases with increasing load. Depending on the ratio of the series-to-shunt field ampere-turns, the motor speed may increases very rapidly.

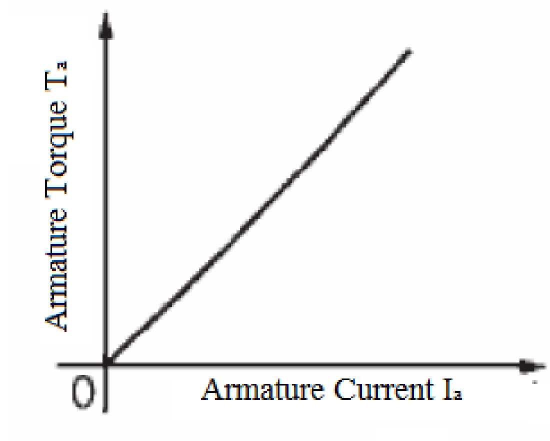


Fig. 3.9 Armature torque vs armature current characteristics of DC compound motor

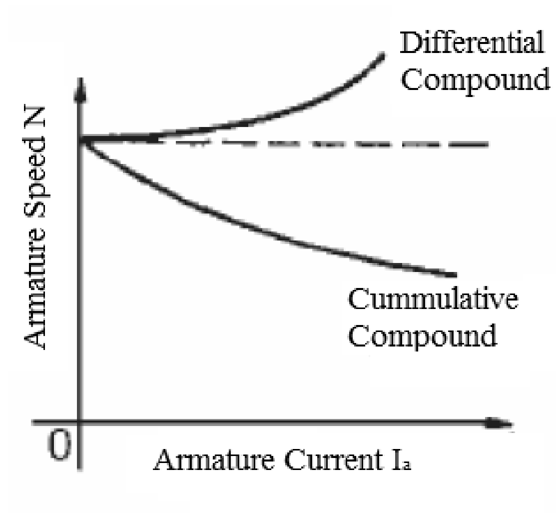


Fig. 3.10 Speed vs armature current characteristics of DC compound motors

3.4.3.1The torque-speed (c/s) of a cumulatively compound D.C motor

In the cumulative compounded D.C. motor, there is a component of flux which is constant and another component which is proportional to its armature current (and thus to its load). Therefore, the cumulatively compounded motor has a higher starting torque than a shunt motor (whose flux is constant) but a lower starting torque than a series motor (whose entire flux is proportional to armature current). At light loads, the series field has a very small effect, so the motor behaves approximately as a shunt D.C. motor. As the load gets very large, the series flux becomes quite important and the torque-speed curve begins to look like a series motor's (c/s). A comparison of the torque-speed (c/s) of each of these type of machines is shown in figure 3.11.

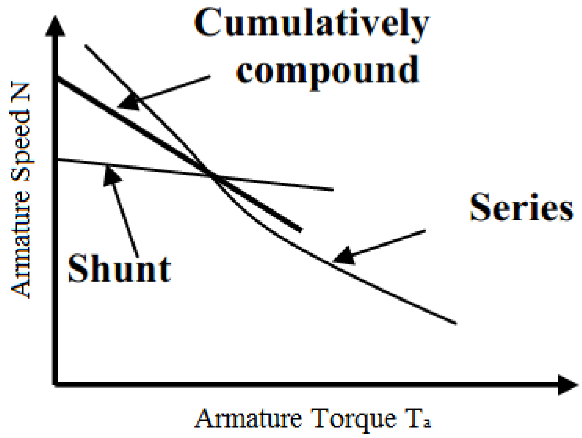


Fig. 3.11 Speed vs armature torque characteristics of DC motors

3.4.3.2 The torque-speed (c/s) of a differentially compound D.C motor

In a differentially compound D.C. motor, the shunt magneto motive force and series magneto motive force subtract from each other. This means that as the load on the motor increases, I_a increases and the flux in the motor decreases. But as the flux decreases, the speed of the motor increases. This speed increases causes anther increases in load, which further increases I_a, further decreasing the flux, and increasing the speed again. The result is that a differentially compounded motor is unstable and tends to run away. It is so bad that a differentially compounded motor is unsuitable for any application. The torque speed characteristics is shown in figure 3.12.

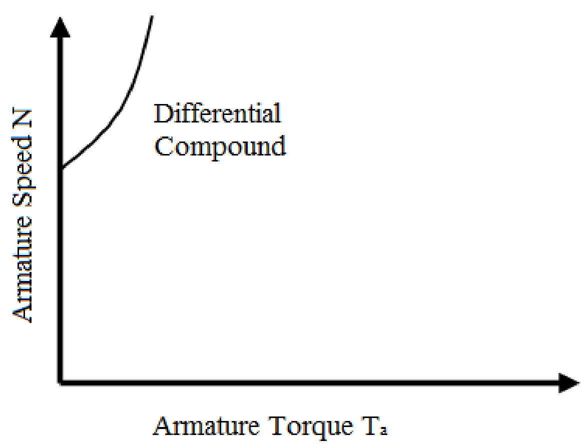


Fig. 3.12 Speed vs armature torque characteristics of DC differential compound motor

3.5 Application of DC motors

3.5.1 Application of DC shunt motor

The characteristics of a DC shunt motor give it a very good speed regulation, and it is classified as a constant speed motor, even though the speed does slightly decrease as load is increased. Shunt wound motors are used in industrial and automotive applications where precise control of speed and torque are required.

3.5.2 Application of DC series motor

For a given input current, the starting torque developed by a DC series motor is greater than that developed by a shunt motor. Hence series motors are used where huge starting torques are necessary. Ex. Cranes, hoists, electric traction etc. The DC series motor responds by decreasing its speed for the increased in load. The current drawn by the DC series motor for the given increase in load is lesser than DC shunt motor. The drop in speed with increased load is much more prominent in series motor than that in a shunt motor. Hence series motor is not suitable for applications requiring a constant speed.

3.5.3 Application of DC compound motor

Cumulative compound wound motors are virtually suitable for almost all applications like business machines, machine tools, agitators and mixers etc. Compound motors are used to drive loads such as shears, presses and reciprocating machines.

Differential compound motors are seldom used in practice (because of rising speed characteristics).

3.6 Armature Reaction

The action of magnetic field set up by armature current on the distribution of flux under main poles of a DC machine is called armature reaction.

When the armature of a DC machines carries current, the distributed armature winding produces its own mmf. The machine air gap is now acted upon by the resultant mmf distribution caused by the interaction of field ampere turns (AT_f) and armature ampere turns (AT_a). As a result the air gap flux density gets distorted.

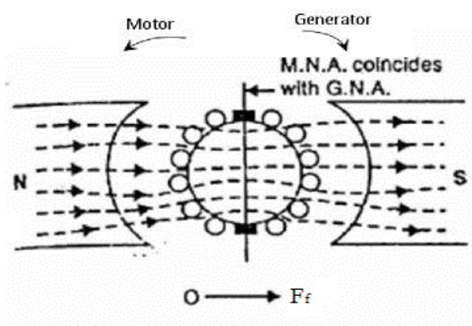


Fig. a

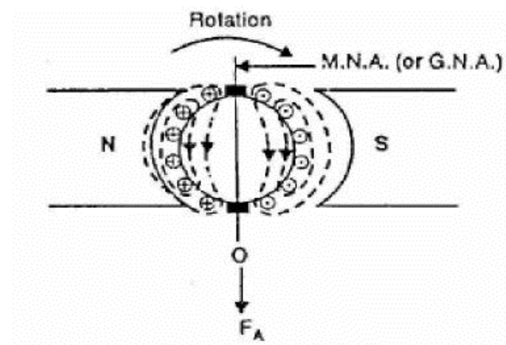


Fig. b

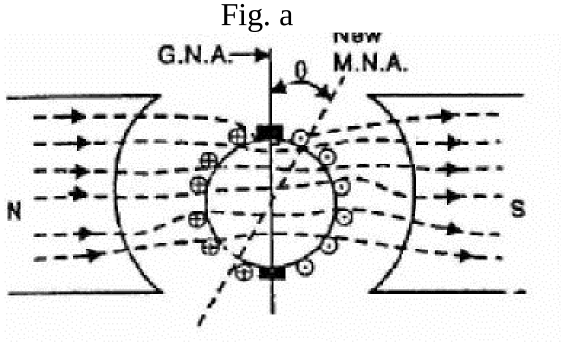


Fig. c

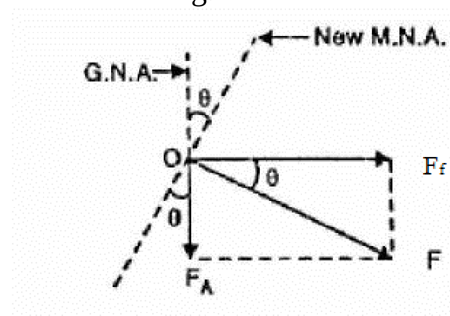


Fig. d

Figure a shows a two pole machine with single equivalent conductor in each slot and the main field mmf (F_f) acting alone. The axis of the main poles is called the direct axis (d-axis) and the interpolar axis is called quadrature axis (q-axis). It can be seen from the Figure b that armature mmf (F_a) is along the interpolar axis. F_a which is at 90^0 to the main field axis is known as cross magnetizing mmf.

Figure c shows the practical condition in which a DC machine operates when both the Field flux and armature flux are existing. Because of both fluxes are acting simultaneously, there is a shift in brush axis and crowding of flux lines at the trailing pole tip and flux lines are weakened or thinned at the leading pole tip. (The pole tip which is first met in the direction of rotation by the armature conductor is leading pole tip and the other is trailing pole tip).

If the iron in the magnetic circuit is assumed unsaturated, the net flux/pole remains unaffected by the armature reaction though the air gap flux density distribution gets distorted. If the main pole excitation is such that the iron is in the saturated region of magnetization (practical case) the increase in flux density at one end of the poles caused by armature reaction is less than the decrease at the other end, so that there is a net reduction in the flux/pole. This is called the demagnetizing effect.

Thus it can be summarized that the nature of armature reaction in a DC machine is

1. Cross magnetizing with its axis along the q-axis.
2. It causes no change in flux/pole if the iron is unsaturated but causes reduction in flux/pole in the presence of iron saturation. This is termed as demagnetizing effect. The resultant mmf ‘F’ is shown in figure d.

3.7 Commutation

The process of reversal of current in the short circuited armature coil is called ‘Commutation’. This process of reversal takes place when coil is passing through the interpolar axis (q-axis), the coil is short circuited through commutator segments and brush.

The process of commutation of coil ‘CD’ is shown Fig. 3.13. In sub figure ‘c’ coil ‘CD’ carries 20A current from left to right and is about to be short circuited in figure ‘d’ brush has moved by a small width and the brush current supplied by the coil are as shown. In figure ‘e’ coil ‘CD’ carries no current as the brush is at the middle of the short circuit period and the brush current in supplied by coil ‘AB’ and coil ‘EF’. In sub figure ‘f’ the coil ‘CD’ which was carrying current from left to right carries current from right to left. In sub fig ‘g’ spark is shown which is due to the reactance voltage. As the coil is embedded in the armature slots, which has high permeability, the coil possess appreciable amount of self inductance. The current is changed from +20 to –20. So due to self inductance and variation in the current from +20 to –20, a voltage is induced in the coil which is given by L dI/dt. This emf opposes the change in current in coil ‘CD’ thus sparking occurs.

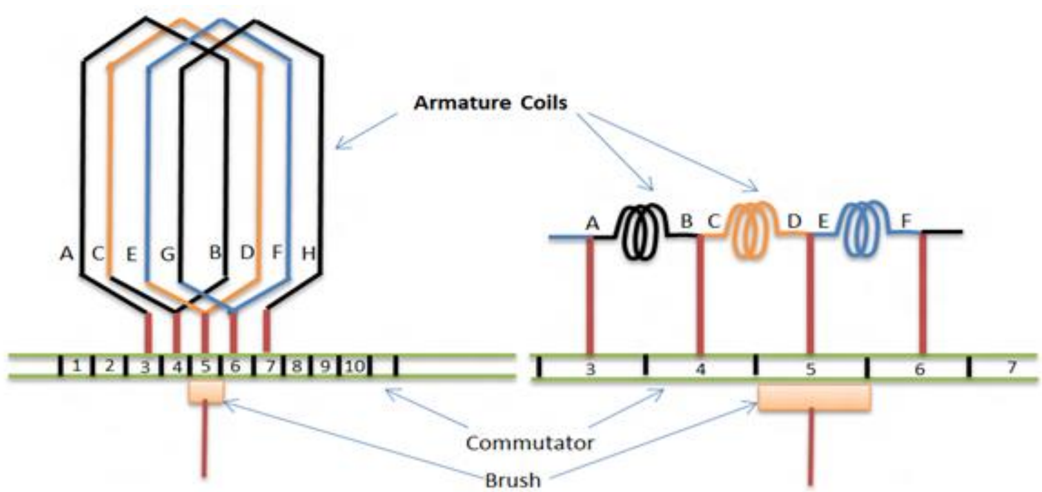


Fig a

Fig b

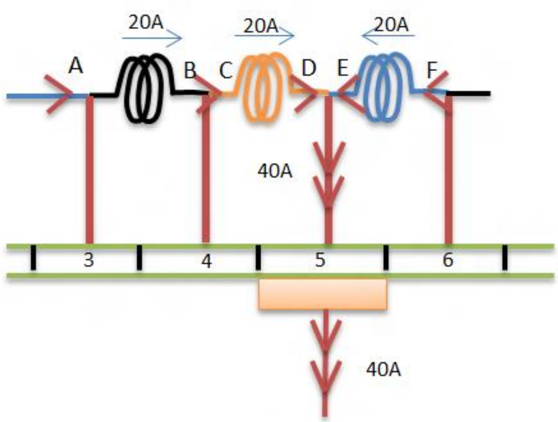


Fig.c

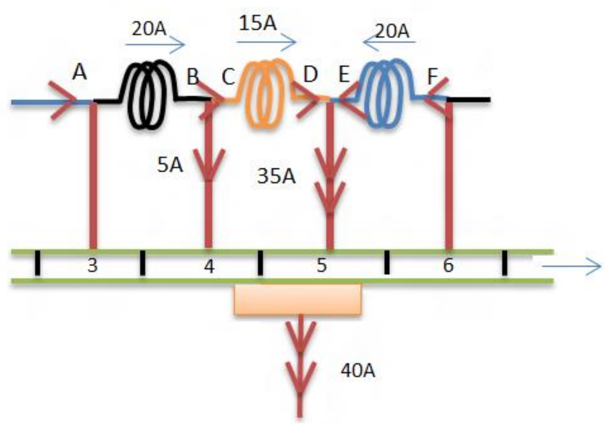


Fig.d

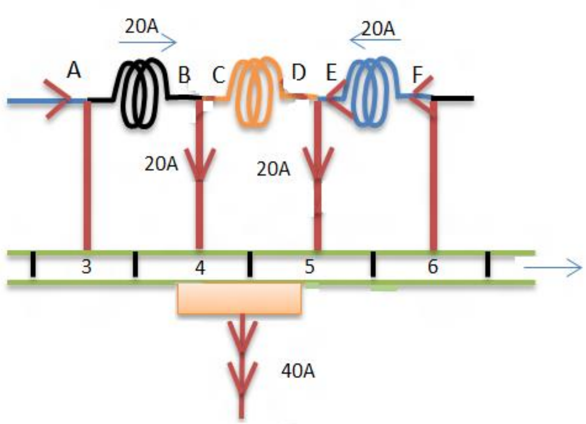


Fig.e

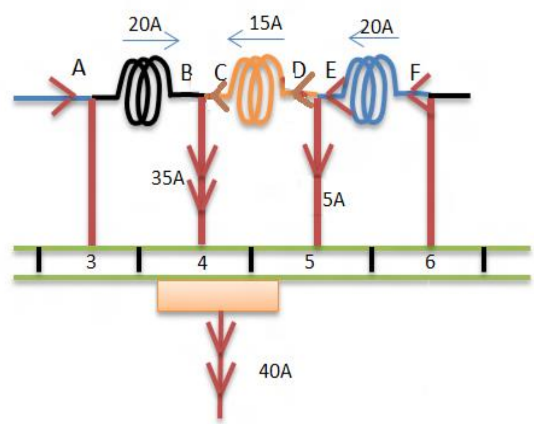


Fig.f

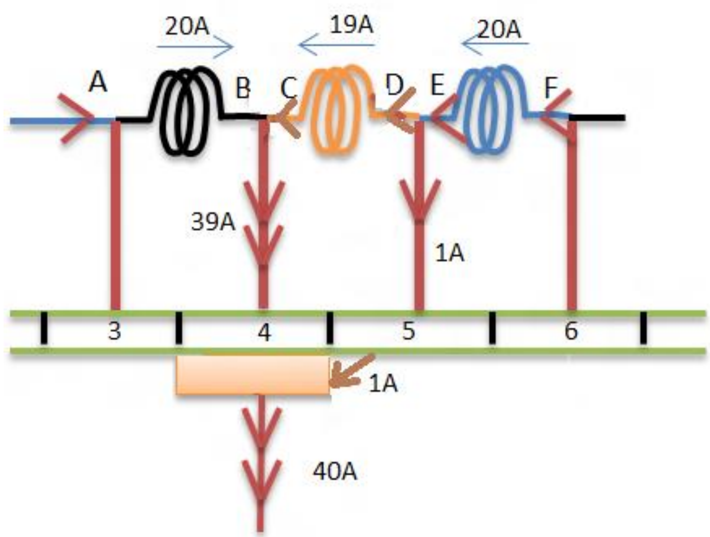


Fig.g

Fig. 3.13 a-g shows the process of commutation

3.8 Starting of DC Motor

Necessity of starter:

The current drawn by the armature is given by

$$I_a = \frac{V_T - E_b}{r_a}$$

At starting, as N=0 so Eb = 0 thus

$$I_a = \frac{V_T}{r_a}$$

Armature resistance will be very low. Therefore, the current drawn by the motor will be very high. In order to limit this high current, a starting resistance is connected in series with the armature. The starting resistance will be excluded from the circuit after the motor attains its rated speed. From there on back emf limits the current drawn by the motor.

3.8.1 Three Point Starter

The arrangement is shown in the figure 3.14 shows a three point starter for shunt motor.

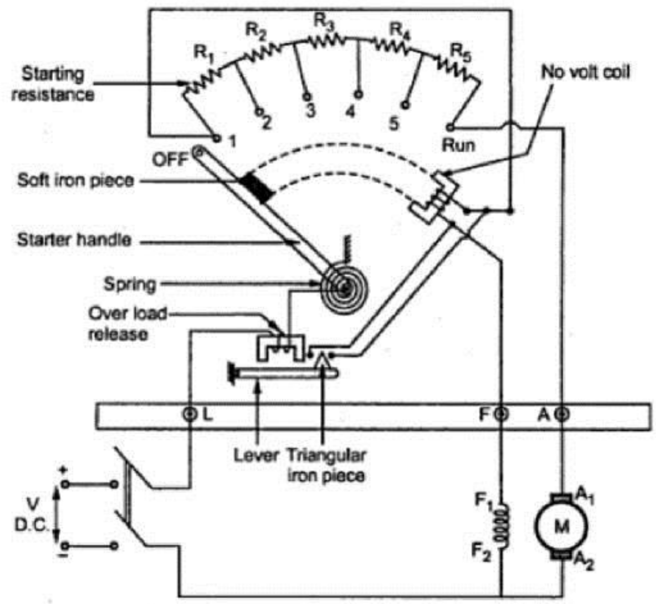


Fig. 3.14 Internal view of three point starter

It consists of resistances arranged in steps, R_1 to R_5 connected in series with the armature of the shunt motor. Field winding is connected across the supply through a protective device called 'NO – Volt Coil'. Another protection given to the motor in this starter is 'over load release coil'. To start the motor the starter handle is moved from OFF position to Run position gradually against the tension of a hinged spring. An iron piece is attached to the starter handle which is kept hold by the No-volt coil at Run position. The function of No volt coil is to get de-energized and release the handle when there is failure or disconnection or a break in the field circuit so that on restoration of supply, armature of the motor will not be connected across the lines without starter resistance. If the motor is over loaded beyond a certain predetermined value, then the electromagnet of overload release will exert a force enough to attract the lever which short circuits the electromagnet of No volt coil. Short circuiting of No volt coil results in de-energisation of it and hence the starter handle will be released and return to its off position due to the tension of the spring.

3.8.2 Four Point Starter

One important change is the No Volt Coil has been taken out of the shunt field and has been connected directly across the line through a Protecting resistance 'R'. When the arm touches stud one. The current divides into three paths, 1. Through the starter resistance and the armature, 2. Through shunt field and the field rheostat and 3.Through No-volt Coil and the protecting resistance 'R'. With this arrangement, any change of current in shunt field circuit does not affect the current passing though the NO-volt coil because, the two circuits are independent of each other. Thus the starter handle will not be released to its off position due to changes in the field current which may happen when the field resistance is varied. Fig 3.15 shows internal view of 4-point starter.

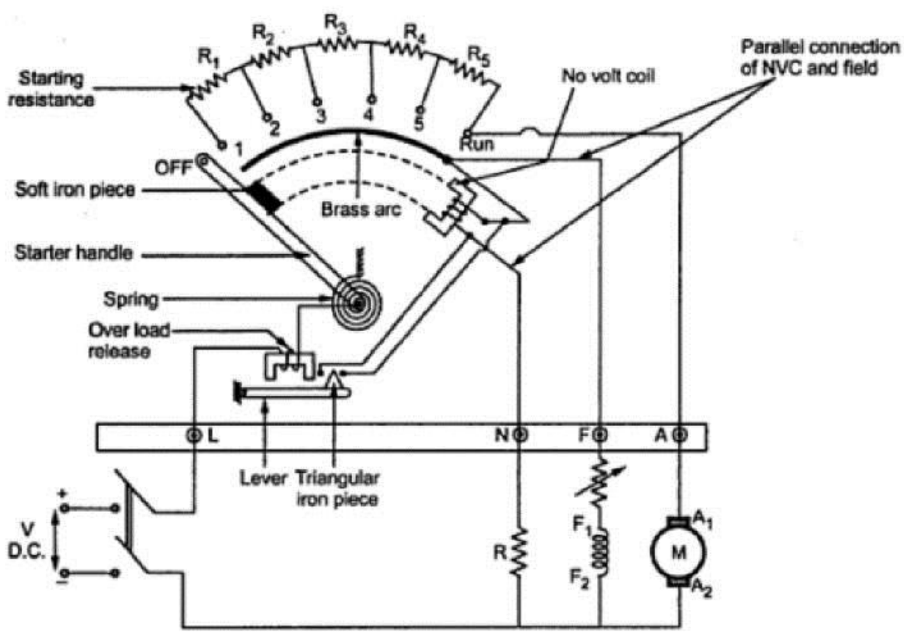


Fig. 3.15 Internal view of three point starter

3.9 DRUM CONTROLLERS

Drum controllers are used when an operator is controlling the motor directly. The drum controller is used to start, stop, reverse, and vary the speed of a motor. This type of controller is used on crane motors, elevators, machine tools, and other applications in heavy industry. As a result, the drum controller must be more rugged than the starting rheostat.

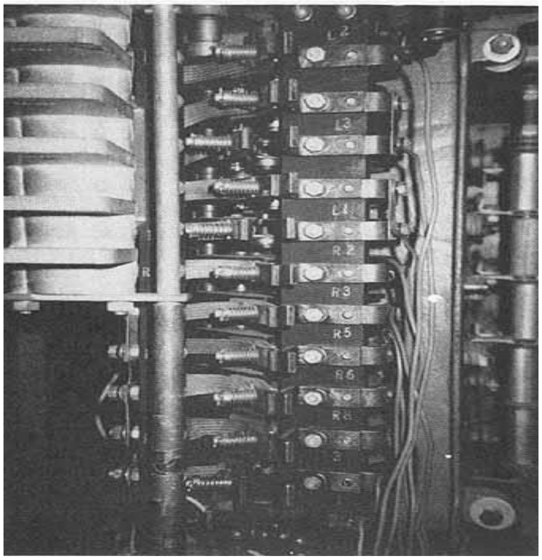


Fig. 3.16 Drum type controller shows contact fingers.

A drum controller with its cover removed is illustrated in 3.16. The switch consists of a series of contacts mounted on a movable cylinder. The contacts, which are insulated from the cylinder and from one another, are called movable contacts. There is another set of contacts, called stationary contacts, located inside the controller. These stationary contacts are arranged to touch the movable contacts as the cylinder is rotated. A handle, keyed to the shaft for the movable cylinder and contacts, is located on top of the drum controller. This handle can be moved either clockwise or counterclockwise to give a range of speed control in either direction of rotation. The handle can remain stationary in either the forward or reverse direction due to a roller and a notched wheel. A spring forces the roller into one of the notches at each successive position of the controller handle to keep the cylinder and movable contacts stationary until the handle is moved by the operator.

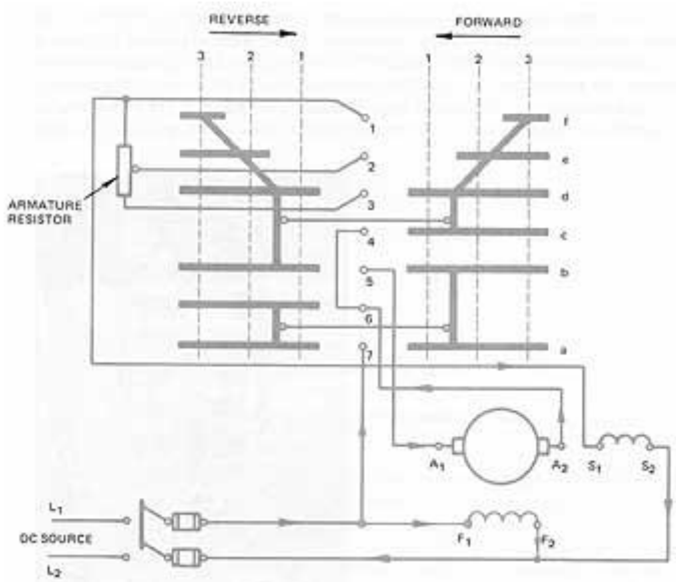


Fig. 3.17 Schematic diagram of a drum controller connected to a compound-wound motor

A drum controller with two steps of resistance is illustrated in 3.17. The contacts are represented in a flat position in this schematic diagram to make it easier to trace the circuit connections. To operate the motor in the forward direction, the set of contacts on the right must make contact with the center stationary contacts. Operation in the reverse direction requires that the set of movable contacts on the left makes contact with the center stationary contacts.

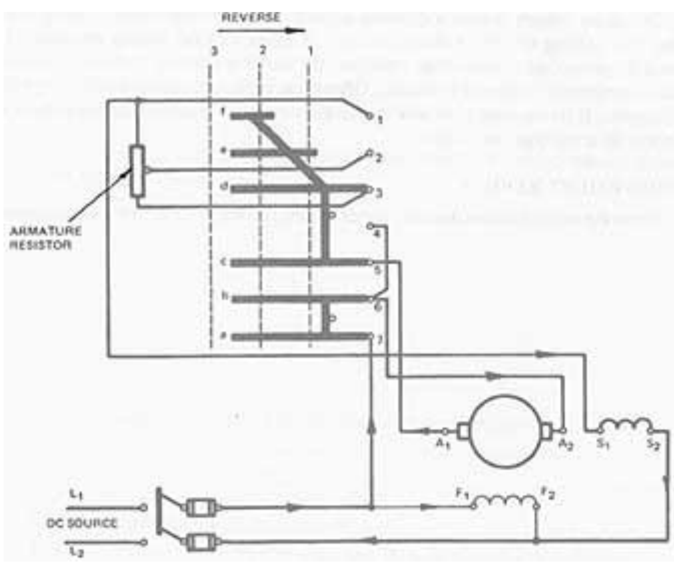


Fig. 3.18 First position of controller for reverse direction

Note in figure 3.17 that there are three forward positions and three reverse positions to which the controller handle can be set. In the first forward position, all of the resistance is in series with the armature. The circuit path for the first forward position is as follows:

1. Movable fingers a, b, c, and d contact the stationary contacts 7, 5, 4, and 3.

2. The current path is from the positive side of the line to contact 7, from 7 to a, from a to b, from b to 5, and then to armature terminal A1.

3. After passing through the armature winding to terminal A the current path is to stationary contact 6, and then to stationary contact 4.

4. From contact 4 the current path is to contact c, to d, and then to contact 3.

5. The current path then goes through the armature resistor, to the series field, and then back to the negative side of the line.

The shunt field of the compound motor is connected across the source voltage. On the second forward position of the controller handle, part of the resistance is cut out. The third forward position cuts out all of the resistance and puts the armature circuit directly across the source voltage.
In the first reverse position, all of the resistance is inserted in series with the armature. Fig. 3.18 shows the first position of the controller in the reverse direction. The current in the armature circuit's reversed. However, the current direction in the shunt and series fields is the same as the direction for the forward positions. A change in current direction in the armature only resulted in a change in the direction of rotation.

The second reverse position cuts out part of the resistance circuit. The third reverse position cuts out all of the resistance and puts the armature circuit directly across the source. Drum controllers with more positions for a greater control of speed can be obtained. However, these controllers all use the same type of circuit arrangement shown in this unit.

DC series motors require a different starting controller than shunt or compound motor. The holding circuit for the controller is in series with the starting resistance. If there is a low-voltage or no-voltage condition, the starter is returned to the off position. Drum controllers are still used frequently. Often drum controllers are used with ac as well as dc motors. It is important to be able to read the connection diagrams and the sequence diagrams on drum-type controllers.

3.10 Losses and efficiency of DC Machines

It is convenient to determine the efficiency of a rotating machine by determining the losses than by direct loading. Further it is not possible to arrange actual load for large and medium sized machines. By knowing the losses, the machine efficiency can be found by

$$\eta = \frac{\text{Output}}{\text{Output+Losses}} \text{(for Generator)}$$

$$\eta = \frac{\text{Input-Losses}}{\text{Input}} \text{(for Motor)}$$

In the process of energy conversion in rotating machines-current, flux and rotation are involved which cause losses in conductors, ferromagnetic materials and mechanical losses respectively.

Various losses occurring in a DC machine are listed below-

Total losses can be broadly divided into two types.

1) Constant losses

2) Variable losses

These losses can be further divided as

1) Constant losses –

i) Core loss or iron loss

a) Hysteresis loss

b) Eddy current loss

ii) Mechanical loss

a) Windage loss

b) Friction loss – brush friction loss and Bearing friction loss.

2) Variable losses –

i) copper loss ($I^2 r$)

a) Armature copper loss
b) Field copper loss
c) Brush contact loss

ii) Stray load loss

a) Copper stray load loss
b) Core stray load loss

Core loss or iron loss occurs in the armature core is due to the rotation of armature core in the magnetic flux produced by the field system. Iron loss consists of a) Hysteresis loss and b) Eddy current loss.

Hysteresis loss: This loss is due to the reversal of magnetization of armature core as the core passes under north and south poles alternatively. This loss depends on the volume and grade of iron, maximum value of flux density and frequency. Hysteresis loss is given by Steinmetz formula.

$W_h = K_h B_m^{1.6} f \ V$ Joule/sec or watt

Where K_h = Constant of proportionality- depends on core material.

B_m = Maximum flux density in Wb/m^2

f = Frequency in Hz

V = Volume of the armature core in m^3

Eddy Current Loss: Eddy currents are the currents set up by the induced emf in the armature core when the core cuts the magnetic flux. The loss occurring due to the flow of eddy current is known as eddy current loss. To reduce this loss the core is laminated, stacked and riveted. These laminations are insulated from each other by a thin coating of varnish. The effect of lamination is to reduce the current path because of increased resistance due to reduced cross section area of laminated core. Thus the magnitude of eddy current is reduced resulting in the reduction of eddy current loss.

Eddy Current loss is given by

$W_e = K_e B_m^2 f^2 t^2$V Watt

Where K_e = Constant of proportionality

B_m = Maximum flux density in Wb/m^2

f = Frequency in Hz

V = Volume of the armature core in m^3

t = Thickness of the lamination in meters

ii) Mechanical loss: these losses include losses due to windage, brush friction and bearing friction losses.

2) **Variable losses**: Variable losses consist of

(i) Copper loss:

a) Armature copper loss: This loss occurs in the armature windings because of the resistance of armature windings, when the current flows through them. The loss occurring is termed as copper loss or r loss. This loss varies with the varying load.

b) Field copper loss: This is the loss due to current flowing in the field windings of the machine. c) Brush contact drop: This is due the contact resistance between the brush and the commutator. This loss remains constant with load.

(ii) Stray load loss: The additional losses which vary with the load but cannot be related to current in a simple manner are called stray load loss. Stray load losses are.

Copper stray load loss: the loss occurring in the conductor due to skin effect and loss due to the eddy currents in the conductor set up by the flux passing through them are called copper stray load loss.

Core stray load loss: When the load current flows through the armature conductors, the flux density distribution gets distorted in the teeth and core. The flux density decreases at one end of the flux density wave and increases at the other. Since the core loss is proportional to the square of the flux density, the decrease in flux density will be less than the increase due to the increase in flux density, resulting in a net increase in the core loss predominantly in the teeth, is known as stray load loss in the core.

Further under highly saturated conditions of teeth, flux leaks through the frame and end shields causing eddy current loss in them. This loss is a component of stray load loss. Stray load loss is difficult to calculate accurately and therefore it is taken as 1 % of the output of a DC machine.

3.11EFFICIENCY OF A DC GENERATOR:

Power flow in a DC generator is shown in figure 3.19.

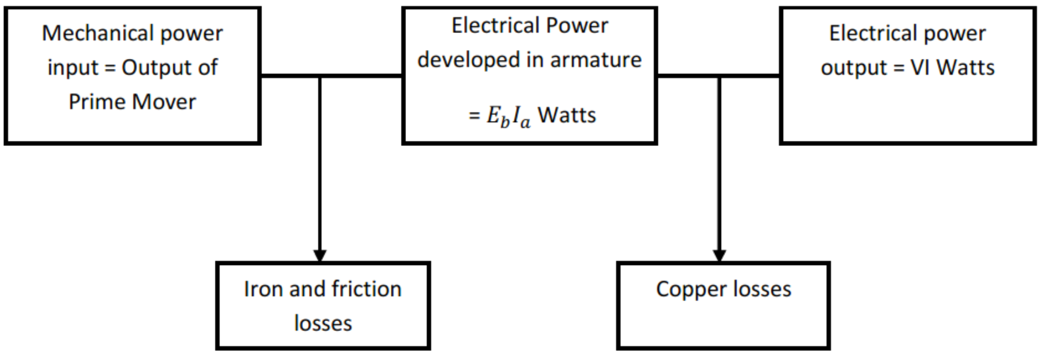


Fig. 3.19 Power flow in a DC generator

3.12 CONDITION FOR MAXIMUM EFFICIENCY

Generator output = VI;

Generator input = VI + losses.

Input $= VI + I_a^2 r_a + w_c$

If the shunt field current is negligible, then $I_a = I$

For maximum efficiency $\frac{d}{dI}(\eta) = 0$

$I_a^2 r_a = w_c$

Hence efficiency is maximum when variable loss = constant loss.

The load current corresponding to maximum efficiency is $I = \sqrt{\frac{w_c}{r_a}}$

EFFICIENCY OF DC MOTOR:

The power flow in a DC motor is shown in figure 3.20.

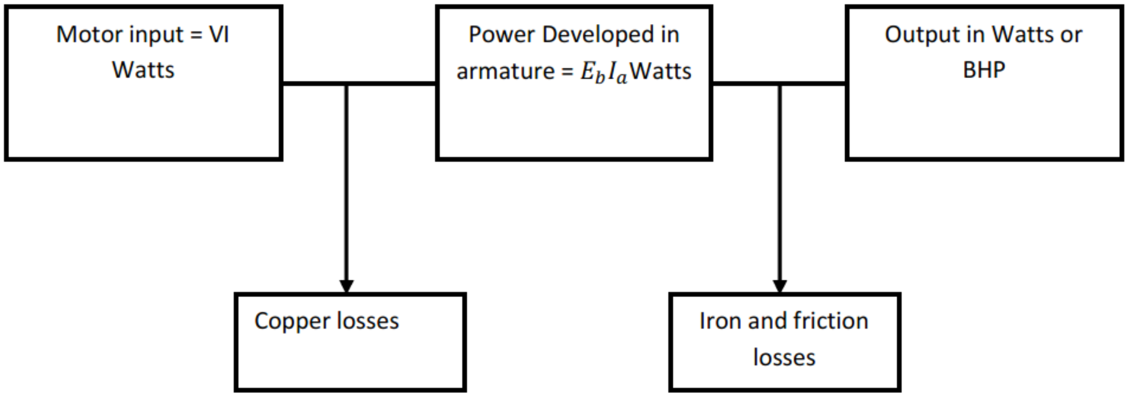


Fig. 3.20 Power flow in a DC generator

Efficiency $\eta = \dfrac{\text{Input-Losses}}{\text{Input}}$ (for Motor)

$$\eta = \frac{VI - I_a{}^2 r_a - w_c}{VI}$$

Efficiency is maximum when variable loss = constant loss.

3.12 Speed Control of DC Motor

DC motors are in general much more adaptable speed drives than AC motors. Speed of a DC motor can be controlled in a wide range.

$$\mathrm{N} = \frac{\mathrm{E_b}}{\mathrm{K}\phi} = \frac{\mathrm{V - I_a r_a}}{\mathrm{K}\phi}$$

The speed equation shows that speed can be controlled by-

1. Variation of field current which varies the flux/pole (ϕ) and is known as field control.
2. Variation of armature resistance known as armature voltage control.
3. Variation of terminal voltage 'V' known as Ward Leonard method.

3.12.1 Field Control

For a fixed terminal voltage, $\dfrac{\mathrm{N_2}}{\mathrm{N_1}} = \dfrac{\phi_2}{\phi_1} = \dfrac{If_2}{If_1}$

Limitations of speed control by field control:

1. 'N' below rated speed is not possible. Because ϕ can be decreased and cannot increase.
2. $N \propto \frac{1}{\phi}$ & $T \propto \phi$ for a given armature current, this method suits for constant kW drives only where 'T' decreases if speed decreases.
3. Not suited for speed reversal.

3.12.1.1 DC Shunt Motor

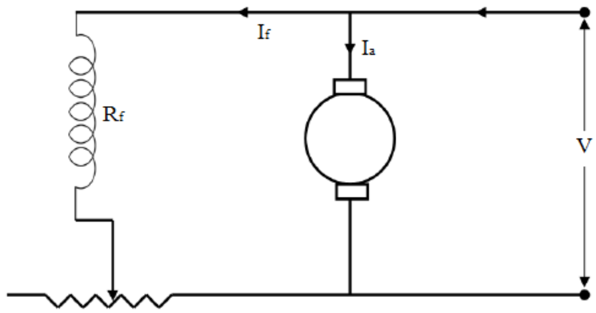


Fig. 3.21 Circuit diagram for speed control using field control method

Speed control is achieved by means of a rheostat in the field circuit as shown in the figure 3.21. The working range of the speed torque characteristics reduces with increasing speed in order for the armature current not to exceed the full load value with a weakening field.

3.12.1.2 DC Series Motor

Speed control is achieved by adjusting the field ampere turns. There are three ways for varying the field ampere turns.

A. Diverter field control

Diverter resistance R_d is connected across the field winding as shown in figure 3.22. By varying R_d the field current and hence the field ampere turns can be reduced.

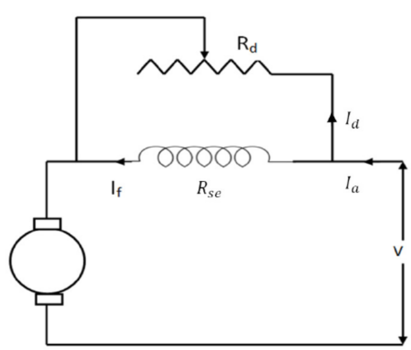


Fig. 3.22 Field diverter circuit

B. Tapped field control:

The field ampere turns are adjusted in steps by varying the number of turns included in the circuit as shown in figure 3.23. By changing number of field winding turns effective ampere turns of the field is changed thus field flux can be controlled.

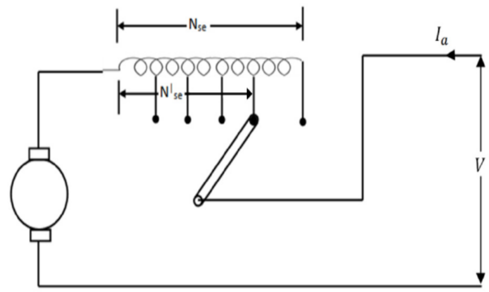


Fig. 3.23 Tapped field circuit

C. Series parallel control

In this method, the field windings are divided into two equal halves and then connected in series or parallel to control the field ampere turns as shown in figure 3.24 and 3.25respectively.

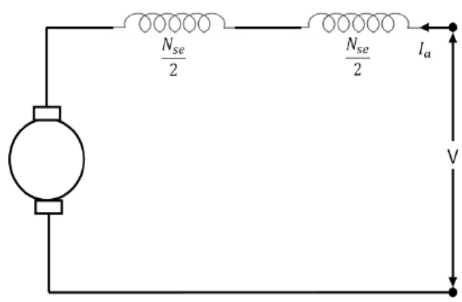


Fig. 3.24 Field circuit connected in series

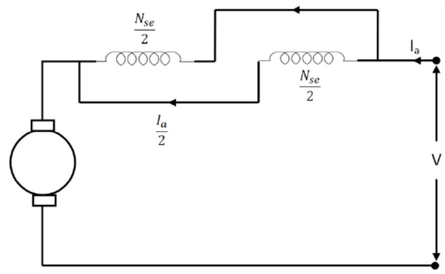


Fig. 3.25 Field circuit connected in parallel

3.12.2 Armature Voltage Control

In this method, applied voltage across the armature of the DC motor is varied. This method is superior to field control in the following aspects:

1. This method provides a constant torque drive.(if the ϕ and I_a are maximum, maximum torque can be obtained as $T \propto \phi I_a$)
2. Since main field ampere turns are maintained at large value, flux density distortion caused by armature reaction is limited.
3. Unlike field control scheme, speed reversal can be easily implemented.
4. This method requires a variable voltage supply which makes this method costlier.

3.12.2.1 DC Shunt Motor

Following are the armature control schemes for DC shunt motor.

1. Rheostatic control:

Here the applied armature voltage is varied by placing an adjustable resistance 'R' in series with the armature as shown in the figure 3.26. N vs T for varying 'R' is shown in figure 3.27.

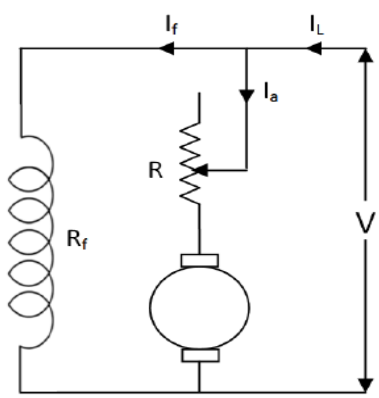


Fig. 3.27 Circuit diagram for armature resistance control

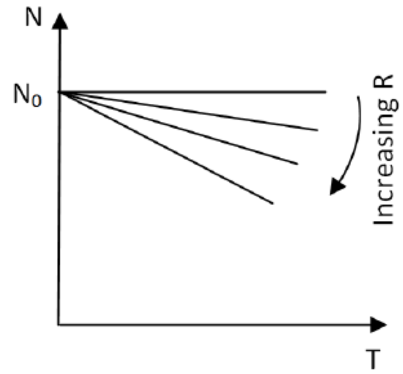


Fig. 3.28 Speed variation with torque for different resistance

Some of the limitations of the rheostatic method are:

Speeds only below rated speed

1. Range of speeds is limited because efficiency reduces drastically for large speed reductions
2. Speed regulation is poor. Because for a given resistance r_e, N varies directly with load.
3. Therefore this method is suitable for very small (fractional kW) or for short-time, intermittent slowdowns for medium sized motors.

2. Shunted armature control

In the armature rheostatic control method, the change in armature current due to change in load will affect the speed. Hence in this method the armature is shunted by an adjustable resistance as shown in figure 3.28.

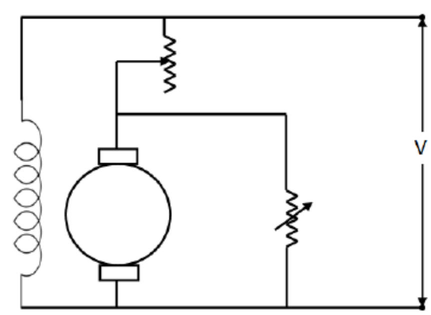


Fig. 3.28 Shunted armature control circuit

Advantages of this method are

1. Speed regulation will be better.

2. The changes in the armature current due to load will not be as effective as the armature is connected across a resistance.

3.12.3 Ward-Leonard Method

It is a combined armature and field control and is therefore operationally the most efficient method of speed control with a wide range. 'M_1' is the main motor whose speed control is required. The field of this motor is permanently connected across the DC supply lines. Its armature is supplied by a variable voltage derived by a Motor-Generator set. The motor M_2 act as prime mover for the generator can be AC motor or DC motor. The field of the DC generator is separately excited. The entire arrangement is shown in the figure 3.29. The reversible switch provided for the generator field makes it possible to easily reverse the generator excitation thereby reversing the voltage polarity for reversing the direction of rotation of motor. Though expensive, this arrangement can be easily adapted to feedback schemes for automatic control of speed. This method provides both constant torque and constant HP (or kW) drive.

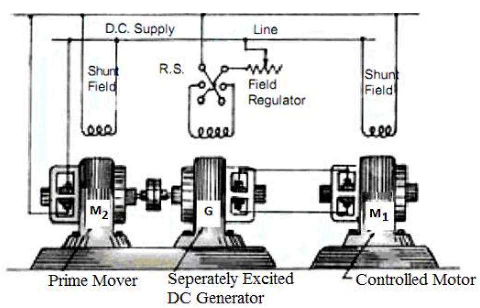


Fig. 3.29 Ward-Leonard speed control scheme

The armature and field winding of the motor are fed at maximum values at the base speed N_{base}. When armature voltage is reduced a constant torque speed control is obtained where the speed can be reduced below the base value, while the motor has full torque capability. When speed above N_{base} is required then the field is gradually weakened. The motor torque therefore reduces as its speed increases which corresponds to constant kW (or HP) drive. This is shown in the figure 3.30.

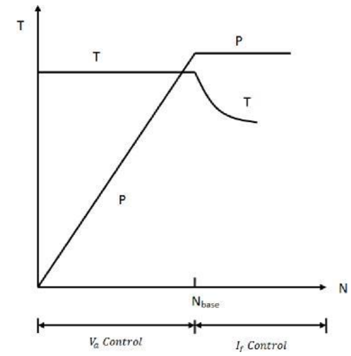


Fig. 3.30 Speed torque relation during Ward –Leonard speed control

Some of the features of the Ward Leonard system are given below:

1. As this method does not required any external resistance thus the efficiency is improved at all speeds and also when the generator emf becomes less than the back emf of the motor, the electrical power flows back from motor to generator, is converted to mechanical form and is returned to the mains via the driving AC motor.
2. Motor starts up smoothly therefore starting device is not required.
3. Reversal of speed is smoothly carried out.
4. Fine speed control from zero to rated value in both the directions are possible.

This method of speed control is used in

a. High speed elevators

b. Colliery winders

3.13 Testing of DC machines

Testing of DC machines can be broadly classified as

a) Direct method of Testing

b) Indirect method of testing

3.13.1 Direct method of testing

In this method, the DC machine is loaded directly by means of a brake applied to a water cooled pulley coupled to the shaft of the machine. The input and output are measured and efficiency is determined by $\eta = \dfrac{\text{Output}}{\text{Input}}$

It is not practically possible to arrange loads for machines of large capacity.

BRAKE TEST:
This is a direct method of testing. In this method of testing motor shaft is coupled to a Water cooled pulley which is loaded by means of weight as shown in figure 3.31.

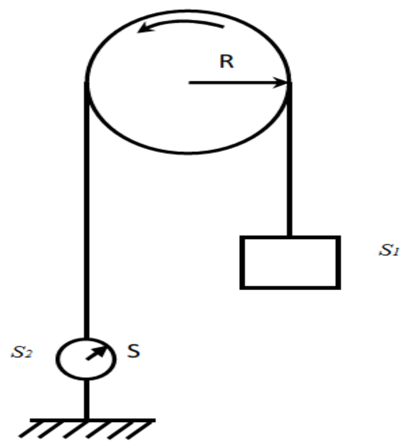


Fig. 3.31 Brake pulley arrangement for direct load test

S_1= suspended weight in kg

S_2= Reading in spring balance in kg

R = radius of pulley

n = speed in rps

V = Supply voltage

I = Full Load Current

Net pull due to friction = $(S_1 - S_2)$ kg

= 9.81 $(S_1 - S_2)$ Newton

Shaft torque = $(S_1 - S_2)$ R kg-mt

= 9.81 $(S_1 - S_2)$ R N-mt

Motor output power = T_{sh} X 2Πn Watt

= $(S_1 - S_2)$ R X 2Πn watts

Or 9.81 (S_1 — S_2)R X 2Πn watt.

Input power = VI watts

Therefore efficiency $= \eta = \frac{\text{Output}}{\text{Input}} = \frac{9.81\,(S_1 - S_2)R \times 2\Pi n}{VI}$

This method of testing can be used for small motors only because for a large motor it is difficult to arrange for dissipation of heat generated at the brake.

3.13.2 Indirect method of testing:

In this method, the machine is not actually loaded. The losses are determined. If the losses are known, then efficiency can be determined. Swinburne’s test and Hopkinson’s test are commonly used on shunt motors. But, as series motor cannot be started on No-load, these tests cannot be conducted on DC series motor.

3.13.2.1Swinburne’s Test

For a d.c shunt motor change of speed from no load to full load is quite small. Therefore, mechanical loss can be assumed to remain same from no load to full load. Also if field current is held constant during loading, the core loss too can be assumed to remain same.

In this test, the motor is run at rated speed under *no load* condition at rated voltage. The current drawn from the supply I_{L0} and the field current I_f are recorded. Now we note that:

Input power to the motor, $P_{in} = VI_{L0}$

Cu loss in the field circuit $P_{fl} = VI_f$

Power input to the armature, $= VI_{L0} - VI_f = V(I_{L0} - I_f) = VI_{a0}$

Cu loss in the armature circuit $= I^2_{a0}\, r_a$

Gross power developed by armature $= VI_{a0} - I^2_{a0}\, r_a = (V - I_{a0} r_a) I_{a0} = E_{b0} I_{a0}$

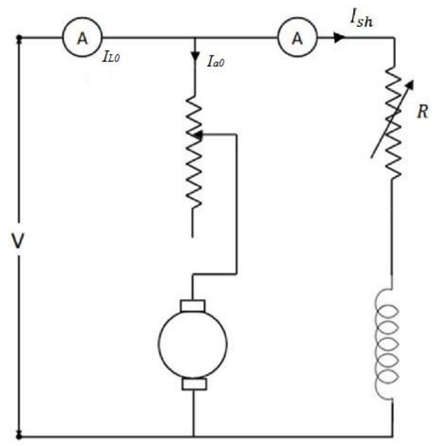


Fig. 3.32 Circuit diagram for Swinburne'*S* Test

Since the motor is operating under no load condition, net mechanical output power is zero. Hence the gross power developed by the armature must supply the core loss and friction & windage losses of the motor. Therefore,

$P_{core} + P_{friction} = (V - I_{a0} r_a) I_{a0} = E_{b0} I_{a0}$

Since, both P_{core} and $P_{friction}$ for a shunt motor remains practically constant from no load to full load, the sum of these losses is called constant rotational loss i.e.,

Constant rotational loss, $P_{rot} = P_{core} + P_{friction}$

In the Swinburne's test, the constant rotational loss comprising of core and friction loss is estimated from the above equation.

After knowing the value of P_{rot} from the Swinburne's test, we can fairly estimate the efficiency of the motor at any loading condition. Let the motor be loaded such that new current drawn from the supply is I_L and the new armature current is I_a. To estimate the efficiency of the loaded motor we proceed as follows:

Input power to the motor, $P_{in} = VI_L$

Cu loss in the field circuit $P_{fl} = VI_f$

Power input to the armature, $= VI_L - VI_f = V(I_L - I_f) = VI_a$

Cu loss in the armature circuit = $I^2_a r_a$

Gross power developed by armature = $VI_a - I^2_a r_a = (V - I_a r_a) I_a = E_b I_a$

Net mechanical output power, $P_{net\ mech} = E_b I_a - P_{rot}$

Efficiency of the loaded motor,

$$\eta = \frac{E_b I_a - P_{rot}}{VI_L} = \frac{P_{net\ mech}}{P_{in}}$$

The estimated value of P_{rot} obtained from Swinburne's test can also be used to estimate the efficiency of the shunt machine operating as a generator.

Output power of the generator, $P_{out} = VI_L$

Cu loss in the field circuit $P_{fl} = VI_f$

Output power of the armature, = $VI_L + VI_f = VI_a$

Mechanical input power, $P_{in\ mech} = VI_a + I^2_a r_a + P_{rot}$

Efficiency of the generator,

$$\eta = \frac{VI_L}{P_{in\ mech}} = \frac{VI_L}{VI_L + VI_f + I_a^2 r_a + P_{rot}}$$

As this test is done at no-load condition thus the power required is very less. From the test effect of armature reaction, temperature rise, commutation etc. cannot be predicted as the machine is not actually loaded.

3.13.2.2Load Test

To assess the rating of a machine a load test has to be conducted. When the machine is loaded, certain fraction of the input is lost inside the machine and appears as heat, increasing the temperature of the machine. If the temperature rise is excessive then it affects the insulations, ultimately leading to the breakdown of the insulation and the machine. The load test gives the information about the efficiency of a given machine at any load condition. Also, it gives the temperature rise of the machine. If the temperature rise is below the permissible value for the insulation then the machine can be safely operated at that load, else the load has to be reduced. The maximum continuous load that can be delivered by the machine without exceeding the temperature rise for the insulation used, is termed as the continuous rating of the machine. Thus the load test alone can give us the proper information of the rating and also can help in the direct measurement of the efficiency.

3.13.2.3 Hopkinson's Test

Here power drawn from the supply only corresponds to no load losses of the machines, the armature physically carries any amount of current (which can be controlled with ease). Two similar DC shunt motors are mechanically coupled. Electrically these two machines are eventually connected in parallel and controlled in such a way that one machine acts as a generator and the other as motor.

Two similar (same rating) machines are connected and coupled as shown in figure 3.33. With switch is open initially, the first machine is run as a shunt motor at rated speed. It may be noted that the second machine is operating as a separately excited generator because its field winding is excited and it is driven by the first machine. The value of the voltage across the switch is either close to twice supply voltage or small voltage. In fact the voltmeter practically reads the difference of the induced voltages in the armature of the machines. In case if the voltmeter reading is high, then the armature connection of the generator should be reversed and start afresh. Now if the voltmeter is found to read small voltage then any attempt to close the switch may result into large circulating current as the armature resistances are small. By adjusting the field current I_{fg} of the generator the voltmeter reading may be adjusted to zero ($E_g \approx E_b$) and switch is now closed. Both the machines are now connected in parallel as shown in figure 3.33.

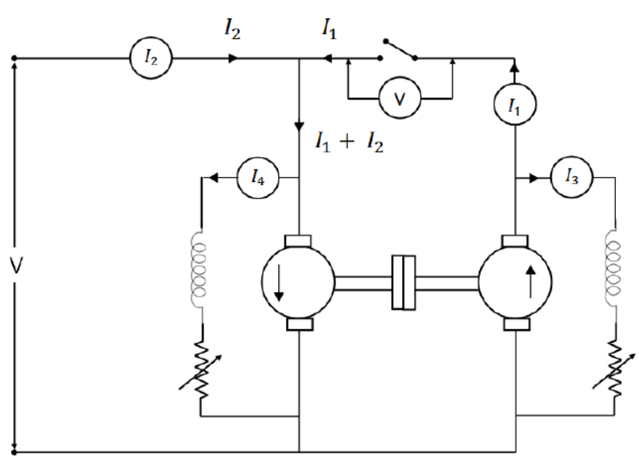


Fig. 3.33 Connection of Hopkinson's Test

After the machines are successfully connected in parallel, if the field current of generator is increased (by decreasing generator field resistance), then E_g becomes greater than E_b and both armature current of generator and motor increase, Thus by increasing field current of generator (alternatively decreasing field current of motor) one can make $E_g > E_b$ so as to make the second machine act as generator and first machine as motor. In practice, it is also required to control the field current of the motor to maintain speed constant at rated value. The interesting point to be noted here is that the armature current of generator and motor are not reflected in the supply side line. Thus current drawn from supply remains small (corresponding to losses of both the machines). The loading is sustained by the output power of the generator running the motor and vice versa. The machines can be loaded to full load current without the need of any loading arrangement.

Calculation

V= supply voltage

Motor input = $V(I_1+I_2)$

Generator output = VI_1

If it is assumed both machines have the same efficiency 'η', then,

Output of motor = η x input = η x $V(I_1+I_2)$ = input to generator

Output of generator = η x input = η x $\eta V(I_1+I_2) = \eta^2 V(I_1+I_2)$

$VI_1 = \eta^2 V(I_1+I_2)$

Therefore, $\eta = \sqrt{\dfrac{I_1}{I_1+I_2}}$

Armature copper loss in motor = $(I_1 + I_2 - I_4)^2 r_a$

Shunt field copper loss in motor = VI_4

Armature copper loss in generator = $(I_1 + I_3)^2 r_a$

Shunt field copper loss in generator = VI_3

Power drawn from supply = VI_2

Therefore stray losses = $VI_2 - [(I_1 + I_2 - I_4)^2 r_a + VI_4 + (I_1 + I_3)^2 r_a + VI_3]$= W (say)

Stray losses/motor = $\frac{W}{2}$

Therefore for generator

Total losses= $(I_1+I_2)^2 r_a + VI_3 + \frac{W}{2} = W_g$

Output = VI_1, therefore

$$\eta_{generator} = \frac{VI_1}{VI_1+W_g} = \frac{output}{output+losses}$$

For motor,

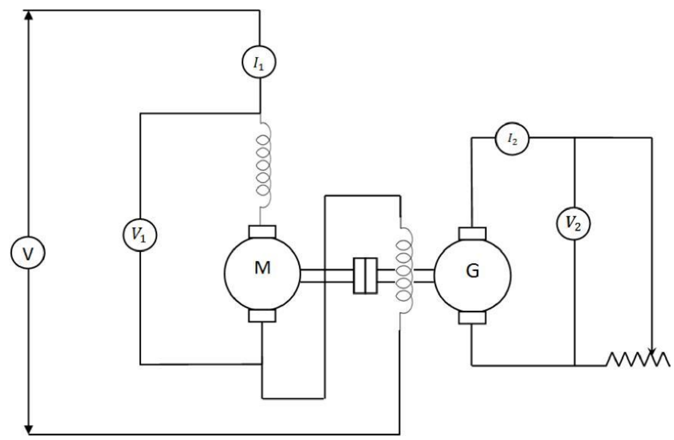
Total losses = $(I_1+I_2-I_4)^2 r_a + VI_4 + \frac{W}{2} = W_m$

Input to motor = $V(I_1+I_2)$

Therefore $\eta_{motor} = \frac{V(I_1+I_2)-W_m}{V(I_1+I_2)}$

3.13.2.4Field's Test

Figure 3.34 shows the circuit for fields test. This test is applicable to two similar series motor. One of the machine runs as a motor and drives a generator whose output is wasted in a variable load 'R'. Both machine field coils are in series and both run at same speed so that iron and friction losses are made equal.



3.34 Circuit diagram for Field's test on DC series motor

Load resistance 'R' is varied till the motor current reaches its full load value.

V = Supply voltage

I_1 = Motor current

V_2 = Generator terminal voltage

I_2 = Load current

Input = VI_1 and output = V_2I_2

R_a and R_{se} = hot resistances.

Total losses in the set $W_t = VI_1 – V_2I_2$

Armature and Field copper losses $W_c = (R_a + 2\ r_{se})\ I_1^2 + I_a^2R_a$

Stray losses for the set = $W_t – W_c$

Stray losses per machine $W_s = \frac{W_t - W_c}{2}$

Motor efficiency :

Input=V_1I_1

Losses=$\left(R_a + R_{se}\right) I_1^2 + W_s = W_m\,(\text{say})$

$$\eta_{motor} = \frac{VI_1 + W_m}{VI_1}$$

Generator efficiency: η of generator is of little use, because its field winding is separately excited

Generator output = VI_2

Field copper loss = $I_1^2 r_{se}$

Armature copper loss = $I_1^2 r_a$

Total losses = $I_1^2 r_{se} + I_1^2 r_a + W_s = W_g\,(\text{say})$

$$\eta_{generator} = \frac{VI_2}{V_2 + W_g}$$

3.12.2.5Reatardation Test

This method is applicable to shunt motors and generators and is used for finding the stray losses. If armature and shunt copper losses are known for a given load, efficiency can be calculated. The circuit is shown in figure 3.35.

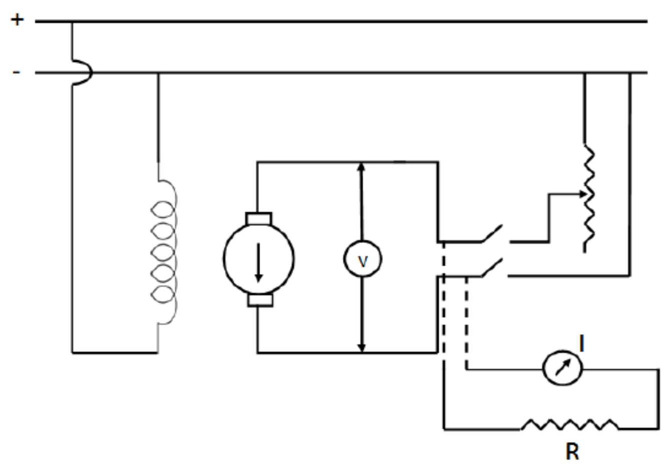


Fig. 3.35 Circuit diagram for Retardation test on DC motor

Machine is speeded up slightly beyond its rated speed and then supply is cut off from the armature while keeping the field excited. Armature will slow down and its kinetic energy is needed to meet rotational losses. i.e., friction and windage losses.

Kinetic energy of the armature = $\frac{1}{2}I\omega^2$

I = Moment of inertia of the armature

ω = Angular velocity.

Rotational losses;

N = Rate of loss of K.E.

Rate of loss of Kinetic energy $W = \frac{d}{dt}\left[\frac{1}{2}I\omega^2\right] = I\omega\frac{d\omega}{dt}$

Two quantities need to be known

(i) Moment of Inertia ‘I

(ii) $\frac{d\omega}{dt}$ or $\frac{dN}{dt}$ (because $\omega \propto N$)

(i) Finding $\frac{d\omega}{dt}$:

The voltmeter "V" in the circuit shown in Fig. 3.35 is used as per speed indicator by suitably grading it because $E \propto N$. Then the supply is cut off, the armature speed and hence voltmeter reading falls. Voltage and time at different interval are noted and a curve is drawn between time and speed as shown in fig. 3.36.

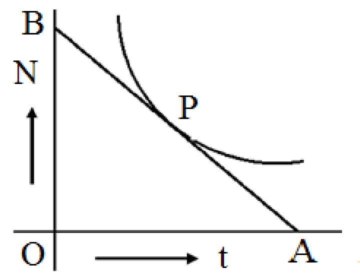


Fig. 3.36 Change of speed with time

In the fig. 3.36 AB- tangent drawn at P

Therefore $\frac{dN}{dt} = \frac{OB(rpm)}{OA(sec)}$

$$W=I\times\omega\times\frac{d\omega}{dt}$$

$$\omega=\frac{2\pi N}{60}$$

$$W=I\left(\frac{2\pi N}{60}\right)\frac{d}{dt}\left(\frac{2\pi N}{60}\right)$$

$$W=\left(\frac{2\pi}{60}\right)^2.I.N.\frac{dN}{dt}$$

(ii) Finding Moment of Inertia "I":

There are two methods of finding the moment of inertia 'I'

(a) I is calculated:

(i) Slowing down curve with armature alone is calculated.

(ii) A fly wheel is keyed to the shaft and the curve is drawn again

For any given speed, $\frac{dN}{dt}$ and $\frac{dN}{dt_1}$ are determined as before.

Therefore $W=\left(\frac{2\pi}{60}\right)^2 .I.N.\frac{dN}{dt_1}$ 1st case

$W=\left(\frac{2\pi}{60}\right)^2 \left(I+I_1\right)N.\frac{dN}{dt_2}$ 2nd Case

The two cases are equal because losses in two cases will be almost same.

$$I\frac{dN}{dt}=\left(I+I_1\right)\frac{dN}{dt}.\frac{I+I1}{I}\left(\frac{dN}{dt_2}\right)=\frac{dN}{dt_1}$$

$$\frac{I+I1}{I}=\frac{dN}{dt_2}$$

$$I=I_1\times\frac{t_2}{t_1-t_2}$$

(b) I is eliminated:

In this method, time taken to slow down is noted with armature alone and then a retarding torque is applied electrically i.e., a non-inductive resistance is connected to the armature.

The additional loss is $I_a^2\left(R_a+R\right) or VI_a$

Let W^1 be the power then

$$W=\left(\frac{2\pi}{60}\right)^2 IN.\frac{dN}{dt_1}$$

$$W+W^1=\left(\frac{2\pi}{60}\right)^2 IN.\frac{dN}{dt_2}$$

$\frac{dN}{dt_1}$ = rate of change of speed without electrical load

$\frac{dN}{dt_2}$ = rate of change of speed with electrical load

$$\frac{W+W^1}{W}=\frac{\frac{dN}{dt_2}}{\frac{dN}{dt_1}}$$

or, $W=W^1\times\frac{dt_2}{dt_1-dt_2}$

or $W=W^1\times\frac{t_2}{t_1-t_2}$

Module IV

[THREE PHASE TRANSFORMER]

TOPICS

Three Phase Transformers: Constructional features of three phase transformers – three phase connection of transformers (Dd0, Dd6, Yy0, Yy6, Dy1, Dy11, Yd1, Yd11, zigzag), Scott connection, open delta connection, three phase to six phase connection, oscillating neutral, tertiary winding, three winding transformer, equal and unequal turns ratio, parallel operation, load sharing. Distribution transformers, all day efficiency, Autotransformers, saving of copper, applications, tap- changing transformers, cooling of transformers.

[Topics are arranged as per above sequence]

Three Phase Transformers

4.1 Introduction

Electric power is generated in generating stations, using three phase alternators at 11 KV. This voltage is further stepped up to 66 KV, 110 KV, 230 KV or 400 KV using 3 phase power transformers and power is transmitted at this high voltage through transmission lines. At the receiving substations, these high voltages are stepped down by 3 phase transformers to 11 KV. This is further stepped down to 400 volts at load centers by means of distribution transformers. For generation, transmission and distribution, 3 phase system is economical. Therefore 3 phase transformers are very essential for the above purpose. The sectional view of a 3 phase power transformer is shown in Fig.4.1.

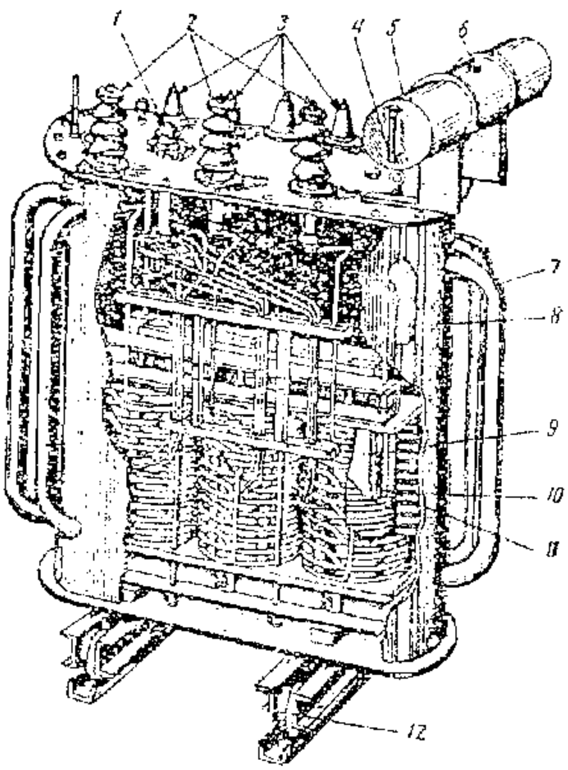


Fig. 4.1 100 KVA oil immersed power transformer

1. Tap-changer switch handle
2. Porcelain-bushing insulator (For high voltage)
3. Bushing insulators (For low voltages)
4. Oil gauge

5. Oil tank
6. Breather plug
7. Cooling pipes
8. Tank front wall
9. Core,
10. High voltage winding
11. Low voltage winding
12. Wheels or rollers.

4.2 Construction of Three phase Transformer

Three phase transformers comprise of three primary and three secondary windings. They are wound over the laminated core as we have seen in single phase transformers. Three phase transformers are also of core type or shell type as in single phase transformers. The basic principle of a three phase transformer is illustrated in fig 4.2 in which the primary windings and secondary windings of three phases are shown. The primary windings can be inter connected in star or delta and put across three phase supply.

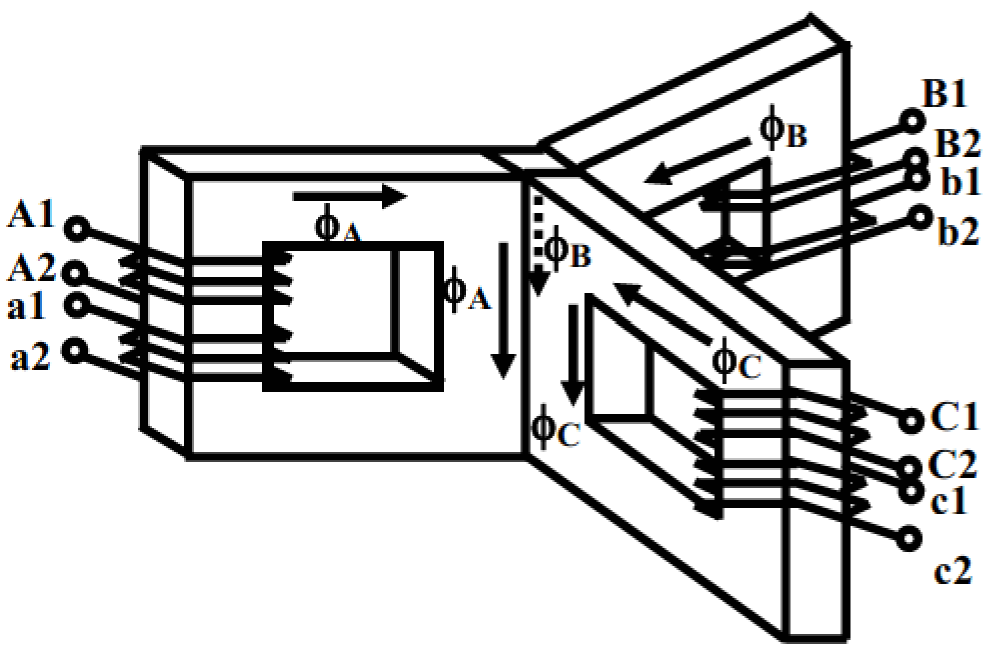


Fig. 4.2 3-phase core-type Transformer

The three cores are 120° apart and their unwound limbs are shown in contact with each other. The center core formed by these three limbs, carries the flux produced by the three phase currents I_R, I_Y and I_B. As at any instant $I_R+I_y+I_B=0$, the sum of three fluxes (flux in the center limb) is also zero.

Therefore it will make no difference if the common limb is removed. All the three limbs are placed in one plane in case of a practical transformer as shown in fig 4.3.

The core type transformers are usually wound with circular cylindrical coils. The construction and assembly of laminations and yoke of a three phase core type transformer is shown in fig 4.4 one method of arrangement of windings in a three phase transformer is shown.

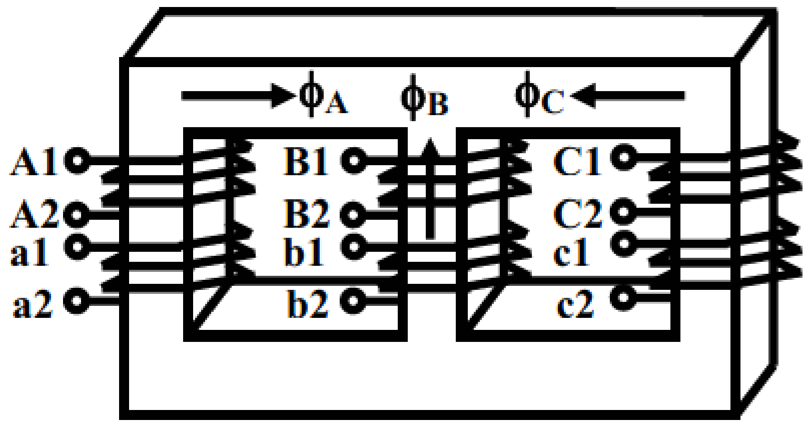


Fig. 4.3 A practical core type three phase transformer

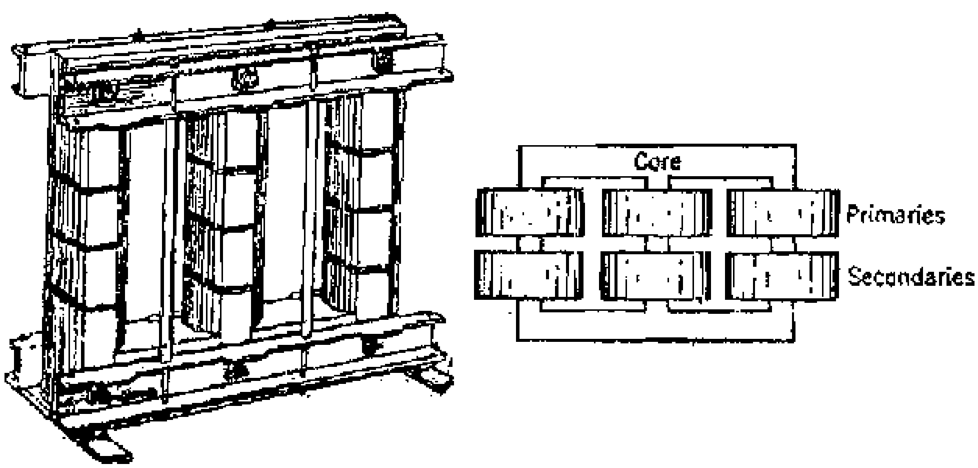


Fig. 4.4 Core type transformer windings and construction

In the other method the primary and secondary windings are wound one over the other in each limb. The low-tension windings are wound directly over the core but are, of course, insulated for it. The high tension windings are wound over the low— tension windings and adequate insulation is provided between the two windings.

The primary and secondary windings of the three phase transformer can also be interconnected as star or delta.

4.3 Three Phase Transformer connections:-

The identical single phase transformers can be suitably inter-connected and used instead of a single unit 3—phase transformer. The single unit 3 phase transformer is housed in a single tank. But the transformer bank is made up of three separate single phase transformers each with its own, tanks and bushings. This method is preferred in mines and high altitude power stations because transportation becomes easier. Bank method is adopted also when the voltage involved is high because it is easier to provide proper insulation in each single phase transformer.

As compared to a bank of single phase transformers, the main advantages of a single unit 3-phase transformer are that it occupies less floor space for equal rating, less weight costs about 20% less and further that only one unit is to be handled and connected.

There are various methods available for transforming 3 phase voltages to higher or lower 3 phase voltages. The most common connections are (i) star — star (ii) Delta—Delta (iii) Star —Delta (iv) Delta — Star.

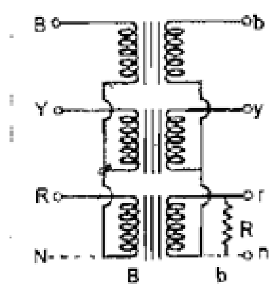


Fig 4.5 Star-star connection

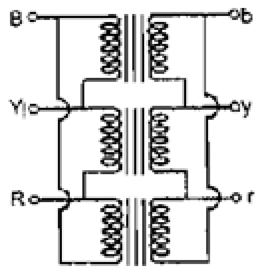


Fig. 4.6 Delta-delta connection

The star-star connection is most economical for small, high voltage transformers because the number of turns per phase and the amount of insulation required is minimum (as phase voltage is only 1/3 of line voltage. In fig. 4.5 a bank of three transformers connected in star on both the primary and the secondary sides is shown. The ratio of line voltages on the primary to the secondary sides is the same as a transformation ratio of single phase transformer.

The delta— delta connection is economical for large capacity, low voltage transformers in which insulation problem is not a serious one. The transformer connection are as shown in fig. 4.6.

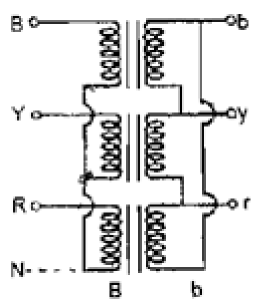


Fig. 4.7 Star-delta connection

The main use of star-delta connection is at the substation end of the transmission line where the voltage is to be stepped down. The primary winding is star connected with grounded neutral as shown in Fig. 4.7. The ratio between the secondary and primary line voltage is 1/3 times the transformation ratio of each single phase transformer. There is a 30° shift between the primary and secondary line voltages which means that a star-delta transformer bank cannot be paralleled with either a star-star or a delta-delta bank.

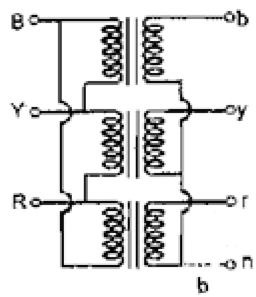


Fig. 4.8 Delta-star connection

Delta-Star connection is generally employed where it is necessary to step up the voltage. The connection is shown in fig. 4.8. The neutral of the secondary is grounded for providing 3-phase, 4-wire service. The connection is very popular because it can be used to serve both the 3-phase power equipment and single phase lighting circuits.

4.4Vector Group of 3-phase transformer

The secondary voltages of a 3-phase transformer may undergo a *phase shift* of either +30° leading or -30° lagging or 0° i.e, no phase shift or 180° reversal with respective line or phase to neutral voltages. On the name plate of a three phase transformer, the vector group is mentioned. Typical representation of the vector group could be Ydl or Dy 11 etc. The first capital latter Y indicates that the primary is connected in star and the second lower case latter d indicates delta connection of the secondary side. The third numerical figure conveys the angle of phase shift based on *clock convention.* The minute hand is used to represent the primary phase to neutral voltage and always shown to occupy the position 12. The hour hand represents the secondary phase to neutral voltage and may, depending upon phase shift, occupy position other than 12 as shown in the figure 4.9. The angle between two consecutive numbers on the clock is 30°.

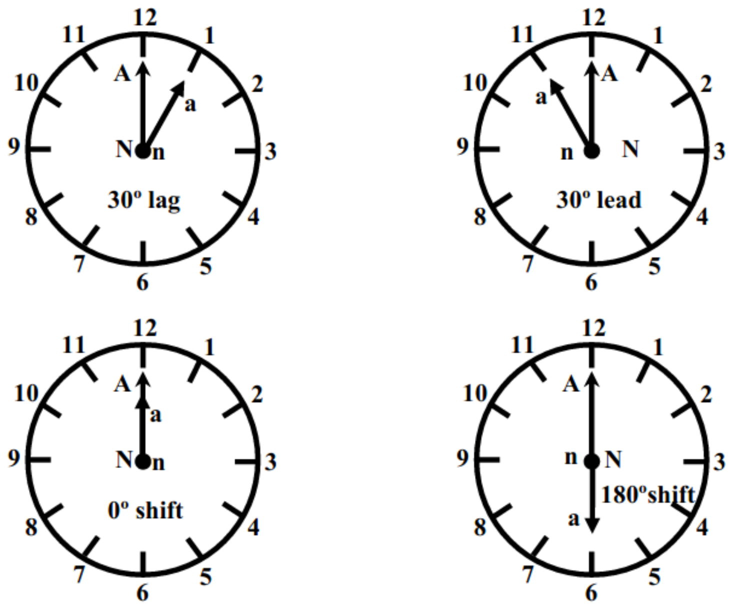


Fig. 4.9 Clock convention representing vector groups

4.4.1 Delta/delta (Dd0, Dd6) connection

The connection of Dd0 is shown in fig. 4.10 and the voltages on primary and secondary sides is also shown on the phasor diagram. The phase angle difference between the phase voltage of high voltage side and low voltage side is zero degree (0°).

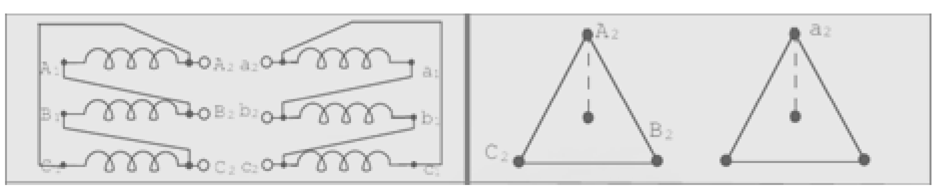


Fig 4.10 Dd0 connection and phasor diagram

The connection of Dd6 is shown in fig. 4.11 and the voltages on primary and secondary sides is also shown on the phasor diagram. The phase angle difference between the phase voltage of high voltage side and low voltage side is 180°.

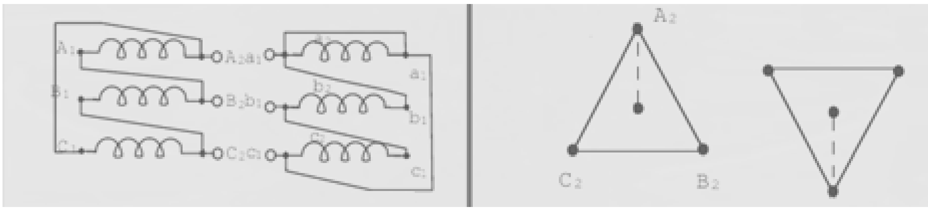


Fig 4.11 Dd6 connection and phasor diagram

This connection proves to be economical for large low voltage transformers as it increases number of turns per phase. Primary side line voltage is equal to secondary side line voltage. Primary side phase voltage is equal to secondary side phase voltage. There is no phase shift between primary and secondary voltages for Dd0 connection. There is 180° phase shift between primary and secondary voltages for Dd6 connection.

Advantages

- **Sinusoidal Voltage at Secondary:** In order to get secondary voltage as sinusoidal, the magnetizing current of transformer must contain a third harmonic component. The delta connection provides a closed path for circulation of third harmonic component of current. The flux remains sinusoidal which results in sinusoidal voltages.

- **Suitable for Unbalanced Load:** Even if the load is unbalanced the three phase voltages remains constant. Thus it suitable for unbalanced loading also.

- **Carry 58% Load if One Transfer is Faulty in Transformer Bank**: If there is bank of single phase transformers connected in delta-delta fashion and if one of the transformers is disabled then the supply can be continued with remaining tow transformers of course with reduced efficiency.

- **No Distortion in Secondary Voltage**: there is no any phase displacement between primary and secondary voltages. There is no distortion of flux as the third harmonic component of magnetizing current can flow in the delta connected primary windings without flowing in the line wires .there is no distortion in the secondary voltages.

- **Economical for Low Voltage:** Due to delta connection, phase voltage is same as line voltage hence winding have more number of turns. But phase current is (1/√3) times the line current. Hence the cross-section of the windings is very less. This makes the connection economical for low voltages transformers.

- **Reduce Cross section of Conductor:** The conductor is required of smaller Cross section as the phase current is 1/√3 times of the line current. It increases number of turns per phase and reduces the necessary cross sectional area of conductors thus insulation problem is not present.

- **Absent of Third Harmonic Voltage:** Due to closed delta, third harmonic voltages are absent.

- The absence of star or neutral point proves to be advantageous in some cases.

Disadvantages

- Due to the absence of neutral point it is not suitable for three phase four wire system.

- More insulation is required and the voltage appearing between windings and core will be equal to full line voltage in case of earth fault on one phase.

Application

- Suitable for large, low voltage transformers.

- This Type of Connection is normally uncommon but used in some industrial facilities to reduce impact of SLG faults on the primary system

- It is generally used in systems where it need to be carry large currents on low voltages and especially when continuity of service is to be maintained even though one of the phases develops fault.

4.4.2 Star/star (YyO, Yy6) connection

This is the most economical one for small high voltage transformers. Insulation cost is highly reduced. Neutral wire can permit mixed loading. Triplen harmonics are absent in the lines. These triplen harmonic currents cannot flow, unless there is a neutral wire. This connection produces oscillating neutral. Three phase shell type units have large triplen harmonic phase voltage. However three phase core type transformers work satisfactorily. A tertiary mesh connected winding may be required to stabilize the oscillating neutral due to third harmonics in three phase banks.

The connection of Yy0 is shown in fig. 4.12 and the voltages on primary and secondary sides is also shown on the phasor diagram. The phase angle difference between the phase voltage of high voltage side and low voltage side is zero degree (0°).

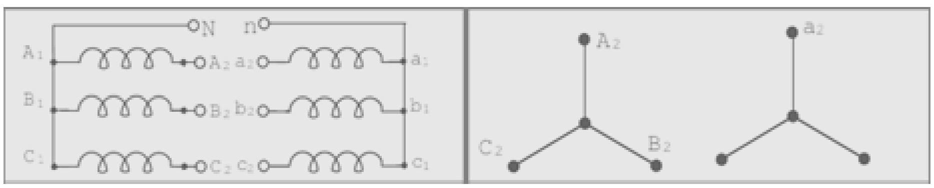


Fig .4.12 Yy0 connection and phasor diagram

The connection of Yy6 is shown in fig. 4.13 and the voltages on primary and secondary sides is also shown on the phasor diagram. The phase angle difference between the phase voltage of high voltage side and low voltage side is 180°.

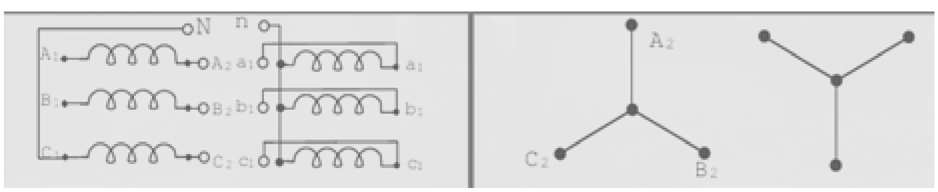


Fig 4.13. Yy6 connection and phasor diagram

- In Primary Winding Each Phase is120°electrical degrees out of phase with the other two phases.
- In Secondary Winding Each Phase is120°electrical degrees out of phase with the other two phases.

- Each primary winding is magnetically linked to one secondary winding through a common core leg. Sets of windings that are magnetically linked are drawn parallel to each other in the vector diagram. In the Y-Y connection, each primary and secondary winding is connected to a neutral point.
- The neutral point may or may not be brought out to an external physical connection and the neutral may or may not be grounded.

Advantages of Y-y connection

- **No Phase Displacement:** The primary and secondary circuits are in phase; i.e., there are no phase angle displacements introduced by the Y-Y connection. This is an important advantage when transformers are used to interconnect systems of different voltages in a cascading manner. For example, suppose there are four systems operating at 800, 440, 220, and 66 kV that need to be interconnected. Substations can be constructed using Y-Y transformer connections to interconnect any two of these voltages. The 800 kV systems can be tied with the 66 kV systems through a single 800 to 66 kV transformation or through a series of cascading transformations at 440,220 and 66 kV.
- **Required Few Turns for winding:** Due to star connection, phase voltages is (1/√3) times the line voltage. Hence less number of turns is required. Also the stress on insulation is less. This makes the connection economical for small high voltage purposes.
- **Required Less Insulation Level:** If the neutral end of a Y-connected winding is grounded, then there is an opportunity to use reduced levels of insulation at the neutral end of the winding. A winding that is connected across the phases requires full insulation throughout the winding.
- **Handle Heavy Load:** Due to star connection, phase current is same as line current. Hence windings have to carry high currents. This makes cross section of the windings high. Thus the windings are mechanically strong and windings can bear heavy loads and short circuit current.
- **Use for Three phases Four Wires System:** As neutral is available, suitable for three phases four wire

system.

- **Eliminate Distortion in Secondary Phase Voltage:** The connection of primary neutral to the neutral of generator eliminates distortion in the secondary phase voltages by giving path to triple frequency currents toward to generator.
- **Sinusoidal voltage on secondary side:** Neutral give path to flow Triple frequency current to flow Generator side thus sinusoidal voltage on primary will give sinusoidal voltage on secondary side.
- **Used as Auto Transformer:** A Y-Y transformer may be constructed as an autotransformer, with the possibility of great cost savings compared to the two-winding transformer construction.
- **Better Protective Relaying:** The protective relay settings will be protecting better on the line to ground faults when the Y-Y transformer connections with solidly grounded neutrals are applied.

Disadvantages

- **The Third harmonic issue:** The voltages in any phase of a Y-Y transformer are 1200 apart from the voltages in any other phase. However, the third-harmonic components of each phase will be in phase with each other. Nonlinearities in the transformer core always lead to generation of third harmonic. These components will add up resulting in large (can be even larger than the fundamental component) third harmonic component.
- **Overvoltage at Lighting Load:** The presence of third (and other zero-sequence) harmonics at an ungrounded neutral can cause overvoltage conditions at light load. When constructing a Y-Y transformer using single-phase transformers connected in a bank, the measured line-to-neutral voltages are not 57.7% of the system phase-to-phase voltage at no load but are about 68% and diminish very rapidly as the bank is loaded. The effective values of voltages at different frequencies combine by taking the square root of the sum of the voltages squared. With sinusoidal phase-to-phase voltage, the third-harmonic component of the phase-to-neutral

voltage is about 60%.

- **Voltage drop at Unbalance Load:** There can be a large voltage drop for unbalanced phase-to-neutral loads. This is caused by the fact that phase-to-phase loads cause a voltage drop through the leakage reactance of the transformer whereas phase-to-neutral loads cause a voltage drop through the magnetizing reactance, which is 100 to 1000 times larger than the leakage reactance.
- **Overheated Transformer Tank:** Under certain circumstances, a Y-Y connected three-phase trans-can produce severe tank overheating that can quickly destroy the transformer. This usually occurs with an open phase on the primary circuit and load on the secondary.
- **Over Excitation of Core in Fault Condition:** If a phase-to-ground fault occurs on the primary circuit with the primary neutral grounded, then the phase-to-neutral voltage on the un faulted phases increases to 173% of the normal voltage. This would almost certainly result in over excitation of the core, with greatly increased magnetizing currents and core losses
- If the neutrals of the primary and secondary are both brought out, then a phase-to-ground fault on the secondary circuit causes neutral fault current to flow in the primary circuit. Ground protection re- laying in the neutral of the primary circuit may then operate for faults on the secondary circuit
- **Neutral Shifting:** If the load on the secondary side unbalanced then the performance of this connection is not satisfactory then the shifting of neutral point is possible. To prevent this, star point of the primary is required to be connected to the star point of the generator.
- **Distortion of Secondary voltage:** Even though the star or neutral point of the primary is earthed, the third harmonic present in the alternator voltage may appear on the secondary side. This causes distortion in the secondary phase voltages.
- **Over Voltage at Light Load:** The presence of third (and other zero-sequence) harmonics at an ungrounded neutral can cause overvoltage conditions at light load.

- **Difficulty in coordination of Ground Protection:** In Y-Y Transformer, a low-side ground fault causes primary ground fault current, making coordination more difficult.

- **Increase Healthy Phase Voltage under Phase to ground Fault:** If a phase-to-ground fault occurs on the primary circuit with the primary neutral grounded, then the phase-to-neutral voltage on the UN faulted phase's increases to 173% of the normal voltage. If the neutrals of the primary and secondary are both brought out, then a phase-to-ground fault on the secondary circuit causes neutral fault current to flow in the primary circuit.

- **Trip the T/C in Line-Ground Fault:** All harmonics will propagate through the transformer, zero-sequence current path is continuous through the transformer, one line-to-ground fault will trip the transformer.

- **Suitable for Core Type Transformer:** The third harmonic voltage and current is absent in such type of connection with three phase wire system or shell type of three phase units, the third harmonic phase voltage may be high. This type of connection is more suitable for core type transformers.

Application

- This Type of Transformer is rarely used due to problems with unbalanced loads.

- It is economical for small high voltage transformers as the number of turns per phase and the amount of insulation required is less.

4.4.3 Star/Delta connection(Yd1/Yd11)

There is a +30 Degree or -30 Degree Phase Shift between Secondary Phase Voltage to Primary Phase Voltage. The connection of Yd1 is shown in fig. 4.14 and the voltages on primary and secondary sides is also shown on the phasor diagram. The phase angle difference between the phase voltage of high voltage side and low voltage side is -30°.

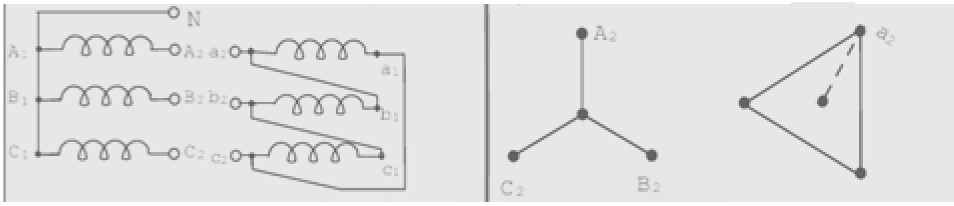


Fig 4.14. Yd1 connection and phasor diagram

The connection of Yd11 is shown in fig. 4.15 and the voltages on primary and secondary sides is also shown on the phasor diagram. The phase angle difference between the phase voltage of high voltage side and low voltage side is 30°.

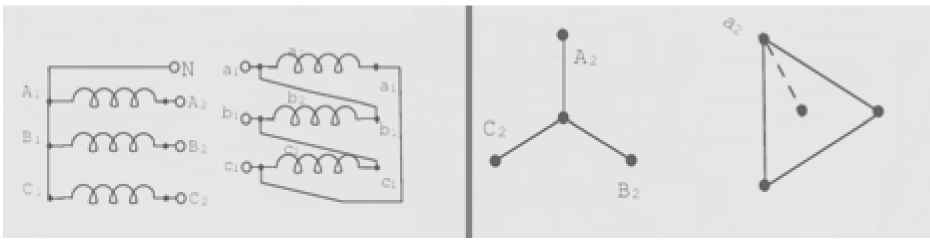


Fig 4.15. Yd11 connection and phasor diagram

Advantages

- The primary side is star connected. Hence fewer numbers of turns are required. This makes the connection economical for large high voltage step down power transformers.
- The neutral available on the primary can be earthed to avoid distortion.
- The neutral point allows both types of loads (single phase or three phases) to be met.
- Large unbalanced loads can be handled satisfactory.
- The Y-D connection has no problem with third harmonic components due to circulating currents inD. It is also more stable to unbalanced loads since the D partially redistributes any imbalance that occurs.
- The delta connected winding carries third harmonic current due to which potential of neutral point is stabilized. Some saving in cost of insulation is achieved if HV side is star connected. But in practice the HV side is normally connected in delta so that the three phase loads like motors and single phase loads like lighting loads can be supplied by LV side using three phase

four wire system.

- **As Grounding Transformer:** In Power System Mostly grounded Y- Δ transformer is used for no other purpose than to provide a good ground source in ungrounded Delta system.

Disadvantages

- In this type of connection, the secondary voltage is not in phase with the primary. Hence it is not possible to operate this connection in parallel with star-star or delta-delta connected transformer.
- One problem associated with this connection is that the secondary voltage is shifted by 30^0 with respect to the primary voltage. This can cause problems when paralleling 3-phase transformers since transformers secondary voltages must be in-phase to be paralleled. Therefore, we must pay attention to these shifts.
- If secondary of this transformer should be paralleled with secondary of another transformer without phase shift, there would be a problem

Application

- It is commonly employed for power supply transformers.
- This type of connection is commonly employed at the substation end of the transmission line. The main use with this connection is to step down the voltage. The neutral available on the primary side is grounded. It can be seen that there is phase difference of 30° between primary and secondary line voltages.
- Commonly used in a step-down transformer, Y connection on the HV side reduces insulation costs the neutral point on the HV side can be grounded, stable with respect to unbalanced loads. As for example, at the end of a transmission line. The neutral of the primary winding is earthed. In this system, line voltage ratio is 1/√3 Times of transformer turn-ratio and secondary voltage lags behind primary voltage by 30°. Also third harmonic currents flows in

to give a sinusoidal flux.

4.4.4 <u>Delta-star connection (Dy1/Dy11)</u>

In this type of connection, the primary connected in delta fashion while the secondary current is connected in star. There is s +30 Degree or -30 Degree Phase Shift between Secondary Phase Voltage to Primary Phase Voltage.

The connection of Dy1 is shown in fig. 4.16 and the voltages on primary and secondary sides is also shown on the phasor diagram. The phase angle difference between the phase voltage of high voltage side and low voltage side is -30°.

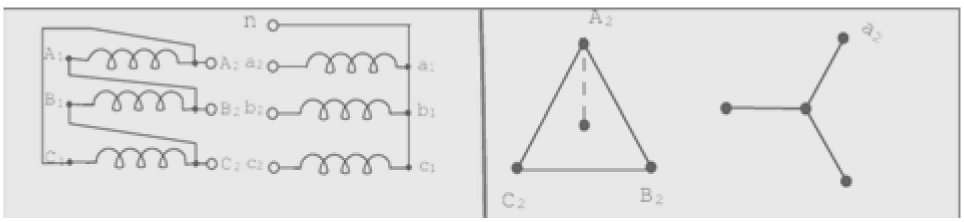


Fig 4.16. Dy1 connection and phasor diagram

The connection of Dy11 is shown in fig. 4.17 and the voltages on primary and secondary sides is also shown on the phasor diagram. The phase angle difference between the phase voltage of high voltage side and low voltage side is 30°.

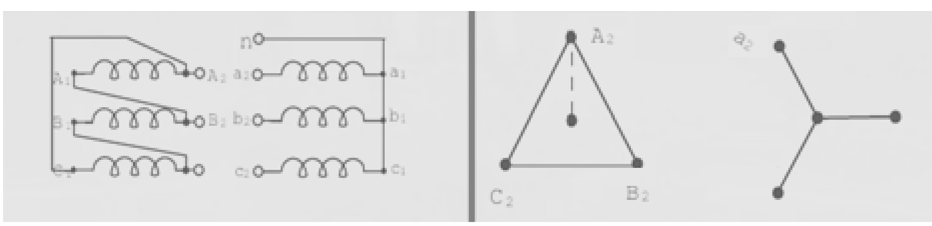


Fig 4.17. Dy11 connection and phasor diagram

Advantages

- **Cross section area of winding is less at Primary side**: On primary side due to delta connection winding cross-section required is less.

- **Used at Three phase four wire System:** On secondary side, neutral is available, due to which it can be used for 3-phase, 4 wire supply system.
- **No distortion of Secondary Voltage:** No distortion due to third harmonic components.
- **Handled large unbalanced Load:** Large unbalanced loads can be handled without any difficulty.
- **Grounding Isolation between Primary and Secondary:** Assuming that the neutral of the Y-connected secondary circuit is grounded, a load connected phase-to-neutral or a phase-to-ground fault produces two equal and opposite currents in two phases in the primary circuit without any neutral ground current in the primary circuit. Therefore, in contrast with the Y-Y connection, phase-to-ground faults or current unbalance in the secondary circuit will not affect ground protective relaying applied to the primary circuit. This feature enables proper coordination of protective devices and is a very important design consideration.
- The neutral of the Y grounded is sometimes referred to as a grounding bank, because it provides a local source of ground current at the secondary that is isolated from the primary circuit.
- **Harmonic Suppression:** The magnetizing current must contain odd harmonics for the induced voltages to be sinusoidal and the third harmonic is the dominant harmonic component. In a three-phase system the third harmonic currents of all three phases are in phase with each other because they are zero-sequence currents. In the Y-Y connection, the only path for third harmonic current is through the neutral. In the Δ -Y connection, however, the third harmonic currents, being equal in amplitude and in phase with each other, are able to circulate around the path formed by the Δ connected winding. The same thing is true for the other zero-sequence harmonics.
- **Grounding Bank:** It provides a local source of ground current at the secondary that is isolated from the primary circuit. For suppose an ungrounded generator supplies a simple radial system

through Δ-Y transformer with grounded Neutral at secondary as shown Figure. The generator can supply a single-phase-to-neutral load through the -grounded Y transformer.

Disadvantages

- In this type of connection, the secondary voltage is not in phase with the primary. Hence it is not possible to operate this connection in parallel with star-star or delta-delta connected transformer.

- One problem associated with this connection is that the secondary voltage is shifted by 30^0 with respect to the primary voltage. This can cause problems when paralleling 3-phase transformers since transformers secondary voltages must be in-phase to be paralleled. Therefore, we must pay attention to these shifts.

- If secondary of this transformer should be paralleled with secondary of another transformer without phase shift, there would be a problem.

Application

- **Commonly used in a step-up transformer:** As for example, at the beginning of a HT transmission line. In this case neutral point is stable and will not float in case of unbalanced loading. There is no distortion of flux because existence of a Δ -connection allows a path for the third-harmonic components. The line voltage ratio is √3 times of transformer turn-ratio and the secondary voltage leads the primary one by 30°. In recent years, this arrangement has become very popular for distribution system as it provides 3- Ø, 4-wire system.

- **Commonly used in commercial, industrial, and high-density residential locations**: To supply three-phase distribution systems. An example would be a distribution transformer with a delta primary, running on three 11kV phases with no neutral or earth required, and a star (or wye) secondary providing a 3-phase supply at 400 V, with the domestic voltage of 230 available between each phase and an earthed neutral point.

- **Used as Generator Transformer:** The Δ-Y transformer connection is used universally for connecting generators to transmission systems.

Delta-zigzag and Star zigzag connections (Dz0/Dz6 & Yz1/Yz6) –

The connection of Dz0 is shown in fig. 4.18 and the voltages on primary and secondary sides is also shown on the phasor diagram. The phase angle difference between the phase voltage of high voltage side and low voltage side is 0°.

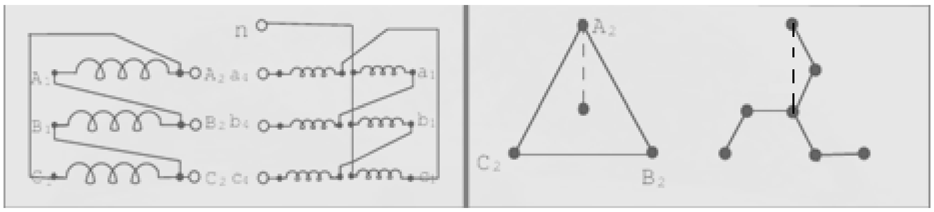


Fig 4.18. Dz0 connection and phasor diagram

The connection of Dz6 is shown in fig. 4.19 and the voltages on primary and secondary sides is also shown on the phasor diagram. The phase angle difference between the phase voltage of high voltage side and low voltage side is 180°.

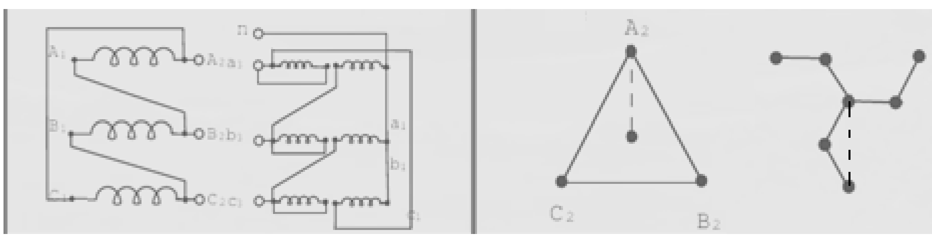


Fig 4.19. Dz6 connection and phasor diagram

The connection of Yz1 is shown in fig. 4.20 and the voltages on primary and secondary sides is also shown on the phasor diagram. The phase angle difference between the phase voltage of high voltage side and low voltage side is -30°.

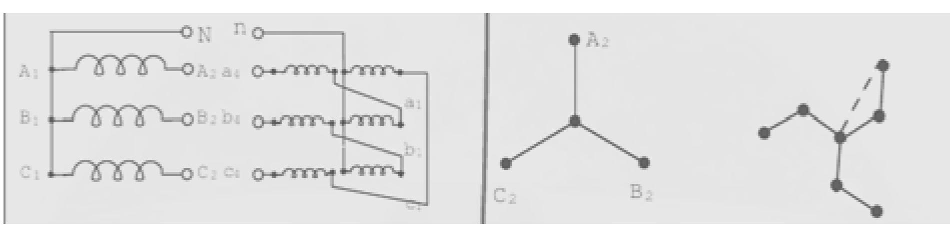


Fig 4.20. Yz1 connection and phasor diagram

The connection of Yz11 is shown in fig. 4.21 and the voltages on primary and secondary sides is also shown on the phasor diagram. The phase angle difference between the phase voltage of high voltage side and low voltage side is 30°.

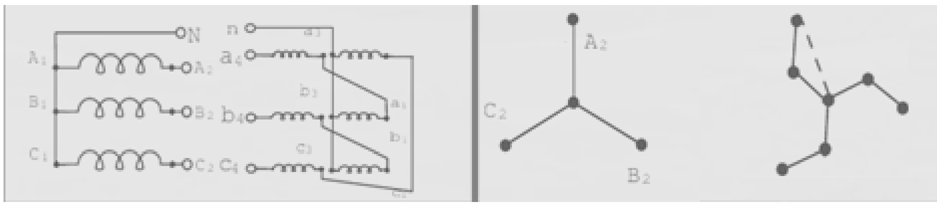


Fig 4.22 Yz11 connection and phasor diagram

- These connections are employed where delta connections are weak. Interconnection of phases in zigzag winding effects a reduction of third harmonic voltages and at the same time permits unbalanced loading.
- This connection may be used with either delta connected or star connected winding either for step-up or step-down transformers. In either case, the zigzag winding produces the same angular displacement as a delta winding, and at the same time provides a neutral for earthing purposes.
- The amount of copper required from a zigzag winding in 15% more than a corresponding star or delta winding. This is extensively used for earthing transformer.
- Due to **zigzag** connection (interconnection between phases), third harmonic voltages are reduced. It also allows unbalanced loading. The zigzag connection is employed for LV winding. For a given total voltage per phase, the zigzag side requires 15% more turns as compared to normal phase connection. In cases where delta connections are weak due to large number of turns and small cross sections, then zigzag star connection is preferred. It is also used in rectifiers.

<u>4.5 Scott connection</u>

There are two main reasons for the need to transform from three phases to two phases,

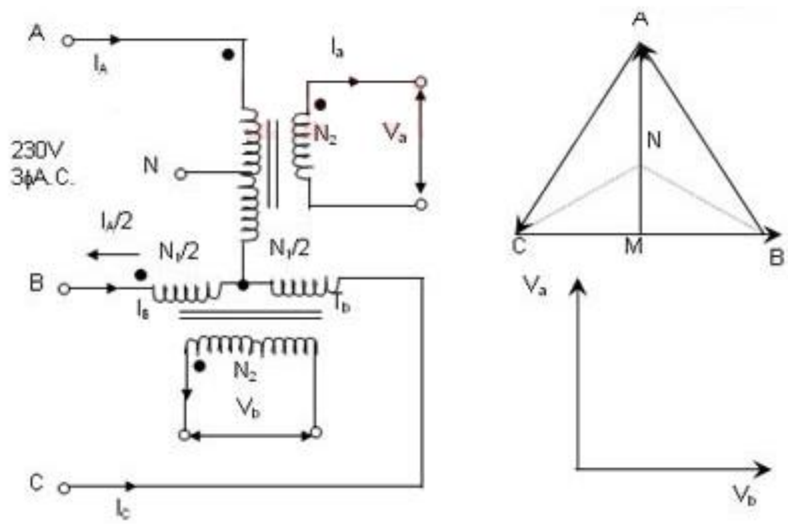
1. To give a supply to an existing two phase system from a three phase supply.

2. To supply two phase furnace transformers from a three phase source.

Two-phase systems can have 3-wire, 4-wire, or 5-wire circuits. It is needed to be considering that a two-phase system is not 2/3 of a three-phase system. Balanced three-wire, two-phase circuits have two phase wires, both carrying approximately the same amount of current, with a neutral wire carrying 1.414 times the currents in the phase wires. The phase-to-neutral voltages are 90° out of phase with each other.

Two phase 4-wire circuits are essentially just two ungrounded single-phase circuits that are electrically 90° out of phase with each other. Two phase 5-wire circuits have four phase wires plus a neutral; the four phase wires are 90° out of phase with each other.

A Scott-T transformer (also called a Scott connection) is a type of circuit used to derive two-phase power from a three-phase source or vice-versa. The Scott connection evenly distributes a balanced load between the phases of the source. Scott T Transformers require a three phase power input and provide two equal single phase outputs called Main and Teaser. The MAIN and Teaser outputs are 90 degrees out of phase. The MAIN and the Teaser outputs must not be connected in parallel or in series as it creates a vector current imbalance on the primary side. MAIN and Teaser outputs are on separate cores. An external jumper is also required to connect the primary side of the MAIN and Teaser sections. The schematic of a typical Scott T Transformer is shown below:



4.23 Connection diagram of Scott-connected transformer and vector relation of input and output

From the phasor diagram it is clear that the secondary voltages are of two phases with equal magnitude and 90° phase displacement.

Scott T Transformer is built with two single phase transformers of equal power rating. Assuming the desired voltage is the same on the two and three phase sides, the Scott-T transformer connection consists of a center-tapped 1:1 ratio main transformer, T1, and an 86.6% (0.5√3) ratio teaser transformer, T2. The center-tapped side of T1 is connected between two of the phases on the three-phase side. Its center tap then connects to one end of the lower turn count side of T2, the other end connects to the remaining phase. The other side of the transformers then connects directly to the two pairs of a two-phase four-wire system.

If the main transformer has a turn’s ratio of 1: 1, then the teaser transformer requires a turn’s ratio of 0.866: 1 for balanced operation. The principle of operation of the Scott connection can be most easily seen by first applying a current to the teaser secondary windings, and then applying a current to the main secondary winding, calculating the primary currents separately and superimposing the results.

The primary three-phase currents are balanced; i.e., the phase currents have the same magnitude and their phase angles are 120° apart. The apparent power supplied by the main transformer is greater than the apparent power supplied by the teaser transformer. This is easily verified by observing that the primary currents in both transformers have the same magnitude; however, the primary voltage of the teaser transformer is only 86.6% as great as the primary voltage of the main transformer. Therefore, the teaser transforms only 86.6% of the apparent power transformed by the main.

- The total real power delivered to the two phase load is equal to the total real power supplied from the three-phase system, the total apparent power transformed by both transformers is greater than the total apparent power delivered to the two-phase load.
- The apparent power transformed by the teaser is 0.866 X IH1= 1.0 and the apparent power transformed by the main is 1.0X IH2 =1.1547 for a total of 2.1547 of apparent power transformed.
- The additional 0.1547 per unit of apparent power is due to parasitic reactive power owing between the two halves of the primary winding in the main transformer.
- Single-phase transformers used in the Scott connection are specialty items that are virtually impossible to buy ‘‘off the shelf ’’ nowadays. In an emergency, standard distribution transformers can be used.

If desired, a three phase, two phase, or single phase load may be supplied simultaneously using scott-connection. The neutral points can be available for grounding or loading purposes. The Scott T connection in theory would be suitable for supplying a three, two and single phase load simultaneously, but such loads are not found together in modern practice.

The Scott T would not be recommended as a connection for 3 phase to 3 phase applications for the following reasons:

The loads of modern buildings and office buildings are inherently unbalanced and contain equipment that can be sensitive to potential voltage fluctuations that may be caused by the Scott T design.

A properly sized Scott T transformer will have to be a minimum of 7.75% larger than the equivalent Delta-Wye transformer. Properly sized, it would be a bulkier and heavier option and should not be considered a less expensive solution.

4.6 Open Delta or V-Connection

As seen previously in connection of three single phase transformers that if one of the transformers is unable to operate then the supply to the load can be continued with the remaining two transformers at the cost of reduced efficiency. The connection that obtained is called V-V connection or open delta connection.

Consider the Fig. 4.24 in which 3 phase supply is connected to the primaries. At the secondary side three equal three phase voltages will be available on no load.

The voltages are shown on phasor diagram. The connection is used when the three phase load is very very small to warrant the installation of full three phase transformer.

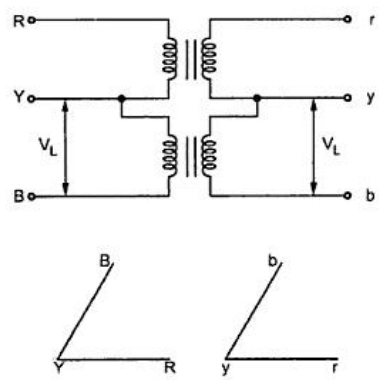


Fig. 4.24 Open delta connection of transformer at noload

If one of the transformers fails in Δ - Δ bank and if it is required to continue the supply even though at reduced capacity until the transformer which is removed from the bank is repaired or a new one is installed then this type of connection is most suitable.

When it is anticipated that in future the load increase, then it requires closing of open delta. In such cases open delta connection is preferred. It can be noted here that the removal of one of the transformers will not give the total load carried by V - V bank as two third of the capacity of Δ - Δ bank.

The load that can be carried by V - V bank is only 57.7% of it.

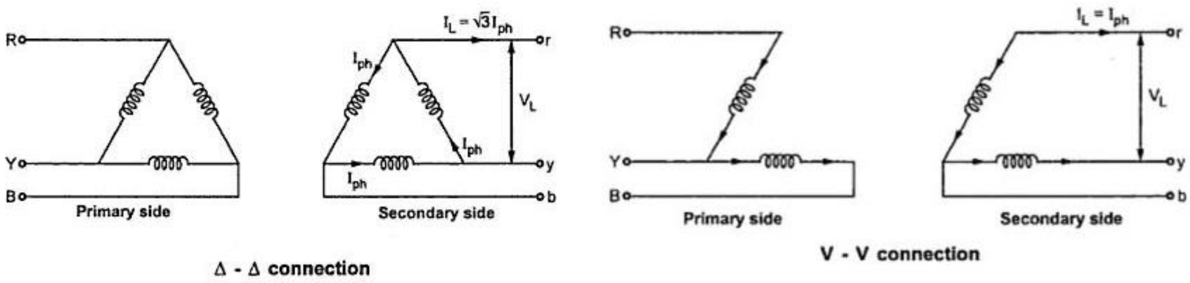


Fig. 4.25 Delta-delta and V-V connection

It can be seen from the Fig. 4.25 of delta delta connection that

$$\Delta - \Delta \text{ capacity} = \sqrt{3}\, V_L I_L = \sqrt{3}\, V_L (\sqrt{3}\, I_{ph})$$
$$\Delta - \Delta \text{ capacity} = 3\, V_L I_{ph}$$

It can also be noted from the Fig. 4.25 V-V connection that the secondary line current I_L is equal to the phase current I_{ph}.

$$\text{V- V capacity} = \sqrt{3}\, V_L I_L = \sqrt{3}\, V_L I_{ph}$$

$$\text{So, } \frac{\text{V-V capacity}}{\Delta - \Delta \text{ capacity}} = \frac{\sqrt{3} V_L I_{ph}}{3 V_L I_{ph}} = \frac{1}{\sqrt{3}} = 0.577 \simeq 58\%$$

Thus the three phase load that can be carried without exceeding the ratings of the transformers is 57.5 percent of the original load. Hence it is not 66.7 % which was expected otherwise.

The reduction in the rating can be calculated as {(66.67 - 57.735)/(57.735)}x 100 = 15.476

Suppose that we consider three transformers connected in Δ - Δ fashion and supplying their rated load. Now one transformer is removed then each of the remaining two transformers will be overloaded. The overload on each transformer will be given as,

$$\frac{\text{Total load in V-V}}{\text{VA rating of each transformer}} = \frac{\sqrt{3} V_L I_{ph}}{V_L I_{ph}} = \sqrt{3} = 1.732$$

This overload can be carried temporarily if provision is made to reduce the load otherwise overheating and breakdown of the remaining two transformers would take place.

- The limitation with V -V connection are given below :

The average p.f. at which V- V bank is operating is less than that with the load . This power p.f is 86.6 % of the balanced load p.f.

- The two transformers in V -V bank operate at different power factor except for balanced unity p.f .load.
- The terminals voltages available on the secondary side become unbalanced. This may happen even though load is perfectly balanced.
- Thus in summary we can say that if tow transformers are connected in V - V fashion and are loaded to rated capacity and one transformer is added to increase the total capacity by √3 or 173.2 %. Thus the increase in capacity is 73.2 % when converting from a V - V system to a Δ-Δ system.
- With a bank of tow single phase transformers connected in V-V fashion supplying a balanced 3 phase load with cosΦ asp.f., one of the transformer operate at a p.f. of cos (30-Φ) and other at cos (30+Φ). The powers of tow transformers are given by,

$$P_1 = KVA \cos(30-\Phi)$$

$$P_2 = KVA \cos(30+\Phi)$$

4.7Oscillating Neutral

In addition to the operation of transformers on the sinusoidal supplies, the harmonic behavior becomes important as the size and rating of the transformer increases. The effects of the harmonic currents are

1. Additional copper losses due to harmonic currents
2. Increased core losses
3. Increased electro-magnetic interference with communication circuits.

On the other hand the harmonic voltages of the transformer cause

1. Increased dielectric stress on insulation
2. Electro static interference with communication circuits.

3. Resonance between winding reactance and feeder capacitance.

In the present times a greater awareness is generated by the problems of harmonic voltages and currents produced by non-linear loads like the power electronic converters. These combine with non-linear nature of transformer core and produce severe distortions in voltages and currents and increase the power loss. Thus the study of harmonics is of great practical significance in the operation of transformers.

In the case of single phase transformers connected to form three phase bank, each transformer is magnetically decoupled from the other. The flow of harmonic currents are decided by the type of the electrical connection used on the primary and secondary sides. Also, there are three fundamental voltages in the present case each displaced from the other by 120 electrical degrees. Because of the symmetry of the a.c. wave about the time axis only odd harmonics need to be considered. The harmonics which are triplen (multiples of three) behave in a similar manner as they are co-phasal or in phase in the three phases. The non-triplen harmonics behave in a similar manner to the fundamental and have ±120° phase displacement between them.

When the connection of the transformer is Yy without neutral wires both primary and secondary connected in star no closed path exists. As the triplen harmonics are always in phase, by virtue of the Y connection they get canceled in the line voltages. Non-triplen harmonics like fundamental, become 0 times phase value and appear in the line voltages. Line currents remain sinusoidal except for non-triplen harmonic currents. Flux wave in each transformer will be flat topped and the phase voltages remain peaked. The potential of the neutral is no longer steady. The star point oscillates due to the third harmonic voltages. This is termed as "oscillating neutral".

4.8 Tertiary winding

Apart from the Primary & Secondary windings, there sometimes placed a third winding in power transformers called "Tertiary Winding". Its purpose is to provide a circulating path for the harmonics (especially third harmonics) produced in the transformers along with power frequency (50Hz. third harmonic means 150 Hz oscillations). In delta-delta, delta-star and star-delta transformers all voltages are balanced and there is no floating of neutral or oscillating neutral. The floating of neutral is developed in the case star-star connection only. The transformers are sometimes constructed with three windings. The main windings are connected to form star-star connection and the third winding known as tertiary winding is used to make a closed delta connection to stabilize the neutrals of both primary and secondary circuits. The tertiary winding carries the third-harmonic currents.

4.9 Three Winding Transformers

Thus far we have looked at transformers which have one single primary winding and one single secondary winding. But the beauty of transformers is that they allow us to have more than just one winding in either the primary or secondary side. Transformers which have three winding are known commonly as **Three Winding Transformers**.

The principal of operation of a *three winding transformer* is no different from that of an ordinary transformer. Primary and secondary voltages, currents and turns ratios are all calculated the same, the difference this time is that we need to pay special attention to the voltage polarities of each coil winding, the dot convention marking the positive (or negative) polarity of the winding, when we connect them together.

Three winding transformers, also known as a three-coil, or three-winding transformer, contain one primary and two secondary coils on a common laminated core. They can be either a single-phase transformer or a three-phase transformer, (three-winding, three-phase transformer) the operation is the same.

Three Winding Transformers can also be used to provide either a step-up, a step-down, or a combination of both between the various windings. In fact a three winding transformers have two secondary windings on the same core with each one providing a different voltage or current level output.

As transformers operate on the principal of mutual induction, each individual winding of a three winding transformer supports the same number of volts per turn, therefore the volt-ampere product in each winding is the same, that is $N_P/N_S = V_P/V_S$ with any turns ratio between the individual coil windings being relative to the primary supply.

In electronic circuits, one transformer is often used to supply a variety of lower voltage levels for different components in the electronic circuitry. A typical application of three winding transformers is in power supplies and Triac Switching Converters. So a transformer have two secondary windings, each of which is electrically isolated from the others, just as it is electrically isolated from the primary. Then each of the secondary coils will produce a voltage that is proportional to its number of coil turns.

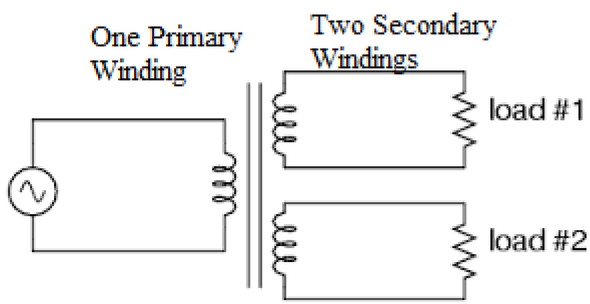


Fig. 4.27 A three winding transformer

The secondary windings can be connected together in various configurations producing a higher voltage or current supply. It must be noted that connecting together transformer windings is only possible if the two windings are electrically identical. That is their current and voltage ratings are the same.

4.10 Parallel operation of three phase transformer

4.10.1Advantages of using transformers in parallel

1. <u>To maximize electrical power system efficiency:</u> Generally electrical power transformer gives the maximum efficiency at full load. If we run numbers of transformers in parallel, we can switch on only those transformers which will give the total demand by running nearer to its full load rating for that time. When load increases, we can switch none by one other transformer connected in parallel to fulfill the total demand. In this way we can run the system

with maximum efficiency.

2. To maximize electrical power system availability: If numbers of transformers run in parallel, we can shut down any one of them for maintenance purpose. Other parallel transformers in system will serve the load without total interruption of power.

3. To maximize power system reliability: If any one of the transformers run in parallel, is tripped due to fault of other parallel transformers is the system will share the load, hence power supply may not be interrupted if the shared loads do not make other transformers over loaded.

4. To maximize electrical power system flexibility: There is always a chance of increasing or decreasing future demand of power system. If it is predicted that power demand will be increased in future, there must be a provision of connecting transformers in system in parallel to fulfill the extra demand because, it is not economical from business point of view to install a bigger rated single transformer by forecasting the increased future demand as it is unnecessary investment of money. Again if future demand is decreased, transformers running in parallel can be removed from system to balance the capital investment and its return.

4.10.2 Conditions for parallel operation

Certain conditions have to be met before two or more transformers are connected in parallel and share a common load satisfactorily. They are,

1. The voltage ratio must be the same.
2. The per unit impedance of each machine on its own base must be the same.
3. The polarity must be the same, so that there is no circulating current between the transformers.
4. The phase sequence must be the same and no phase difference must exist between the voltages of the two transformers.

- **Same voltage ratio :** Generally the turns ratio and voltage ratio are taken to be the same. If the ratio is large there can be considerable error in the voltages even if the turns ratios are the same. When the primaries are connected to same bus bars, if the secondaries do not show the same voltage, paralleling them would result in a circulating current between the secondaries. Reflected circulating current will be there on the primary side also. Thus even without connecting a load considerable current can be drawn by the transformers and they produce copper losses. In two identical transformers with percentage impedance of 5 percent, a no-load voltage difference of one percent will result in a circulating current of 10 percent of full load current. This circulating current gets added to the load current when the load is connected resulting in unequal sharing of the load. In such cases the combined full load of the two transformers can never be met without one transformer getting overloaded.

- **Per unit impedance:** Transformers of different ratings may be required to operate in parallel. If they have to share the total load in proportion to their ratings the larger machine has to draw more current. The voltage drop across each machine has to be the same by virtue of their connection at the input and the output ends. Thus the larger machines have smaller impedance and smaller machines must have larger ohmic impedance. Thus the impedances must be in the inverse ratios of the ratings. As the voltage drops must be the same the per unit impedance of each transformer on its own base, must be equal. In addition if active and reactive power are required to be shared in proportion to the ratings the impedance angles also must be the same. Thus we have the requirement that per unit resistance and per unit reactance of both the transformers must be the same for proper load sharing.
- **Polarity of connection:** The polarity of connection in the case of single phase transformers can be either same or opposite. Inside the loop formed by the two secondaries the resulting voltage must be zero. If wrong polarity is chosen the two voltages get added and short circuit results. In the case of polyphase banks it is possible to have permanent phase error between the phases with substantial circulating current. Such transformer banks must not be connected in parallel. The turns ratios in such groups can be adjusted to give very close voltage ratios but phase errors cannot be compensated. Phase error of 0.6 degree gives rise to one percent difference in voltage. Hence poly phase transformers belonging to the same vector group alone

must be taken for paralleling.

Transformers having —30° angle can be paralleled to that having +30° angle by reversing the phase sequence of both primary and secondary terminals of one of the transformers. This way one can overcome the problem of the phase angle error.

- **Phase sequence-** The phase sequence of operation becomes relevant only in the case of poly phase systems. The poly phase banks belonging to same vector group can be connected in parallel. A transformer with +30° phase angle however can be paralleled with the one with —30° phase angle, the phase sequence is reversed for one of them both at primary and secondary terminals. If the phase sequences are not the same then the two transformers cannot be connected in parallel even if they belong to same vector group. The phase sequence can be found out by the use of a phase sequence indicator.

4.11 Load Sharing

When the transformers have equal voltage ratios, the magnitudes of secondary no-load voltages are equal. Further if the primary leakage impedance drops due to exciting currents are also equal, then $\overline{E}_a = \overline{E}_b$ and the circulating current at no load is zero.

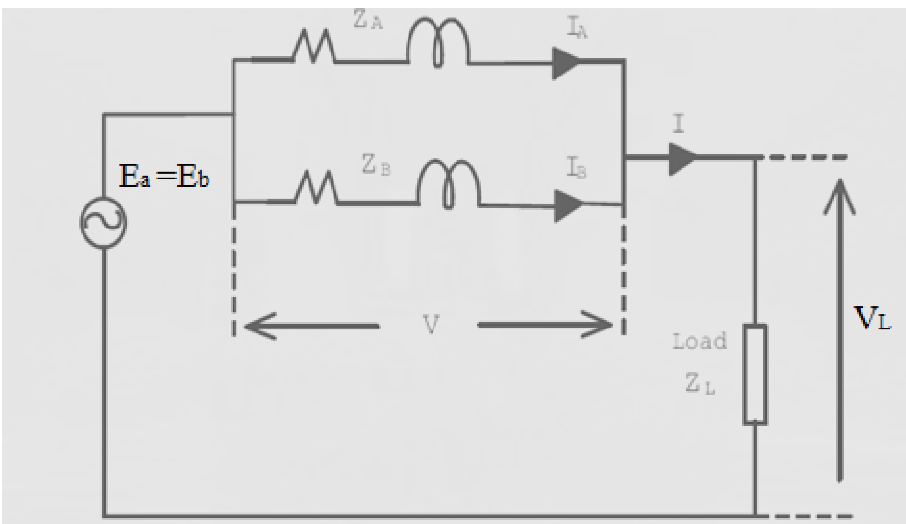


Fig. 4.28 Circuit modelling of two transformer in parallel

The equivalent circuit of two three phase transformer connected in parallel connected with a load of

Z_L impedance on per phase basis is drawn in fig 4.28. In this figure transformer A and B are operating in parallel. I_A and I_B are the load current of the two transformer.

The voltage equation of transformer A is

$$\bar{E}_a - \bar{I}_a \bar{Z}_a = \bar{V}_L = \bar{I}\bar{Z}_L$$

Since $\bar{E}_a = \bar{E}_b$; $\bar{E}_b - \bar{I}_a \bar{Z}_a = \bar{V}_L = \bar{I}\bar{Z}_L$

The voltage equation of transformer B is

$$\bar{E}_b - \bar{I}_b \bar{Z}_b = \bar{V}_L = \bar{I}\bar{Z}_L$$
$$\bar{E}_b - \bar{I}_a \bar{Z}_a = \bar{E}_b - \bar{I}_b \bar{Z}_b$$
$$\bar{I}_a \bar{Z}_a = \bar{I}_b \bar{Z}_b$$

According to the voltage drops across the two equivalent leakage impedance Za and Zb are equal.

According to KCL we can write

$$\bar{I} = \bar{I}_a + \bar{I}_b = \bar{I}_a + \frac{\bar{I}_a \bar{Z}_a}{\bar{Z}_b}$$

$$\bar{I}_a = \bar{I}\,\frac{\bar{Z}_b}{\bar{Z}_a + \bar{Z}_b}$$

$$\text{similarly, } \bar{I}_b = \bar{I}\,\frac{\bar{Z}_a}{\bar{Z}_a + \bar{Z}_b}$$

Multiplying both the current equations by terminal voltage we get,

$$\bar{S}_a = \bar{S}\,\frac{\bar{Z}_b}{\bar{Z}_a + \bar{Z}_b}$$

$$\text{similarly, } \bar{S}_b = \bar{S}\,\frac{\bar{Z}_a}{\bar{Z}_a + \bar{Z}_b}$$

Thus the power sharing in between two transformer is given in above equation in VA rating.

Acknowledgement

The committee members gratefully acknowledge google, scribd, NPTEL, openoffice, sumantra pdf, scilab for myriad suggestions and help for preparing this lecture note. The committee members also wants to express their gratitude to the persons out there who thinks knowledge should be free and be accessible and sharable without any restrictions so that every single person on this planet has the same opportunity to explore, expand and become enlightened by the collective gifts of mankind.

However apart from this lecture note students/readers are strongly recommended to follow the below mentioned books in the references and above all confer with the faculty for thorough knowledge of this authoritative subject of electrical engineering.

References

[1] P.S. Bimbhra, Electrical Machinery, Khanna Pub, 7th Ed.

[2] P.S. Bimbhra, Generalized Theory of Electrical Machine, Khanna Pub., 2nd Ed.

[3] M.G. Say, The Performance and Design of Alternating Current Machines, CBS Pub., 3rd Ed.

[4] A.E.Fitzgerald, S.D.Umans, C.Kingsley Jr., Electric Machinery, McGraw Hill Education(india) pvt. Ltd., 6th Ed.

[5] A.S. langsdorf, Theory of Alternating Current Machinery, McGraw Hill Education(india) pvt. Ltd., 2nd Ed.

[6]T.C. Lloyd, A.F. Puchstein and A.G. Conrad, Alternating-Current Machines, John Wiley& Sons pub., 3rd Ed.

[7] Irving Kosow, Electric Machinery and Transformers, Pearson India, 2nd Ed.

[8] C.L.Dawes, A course in Electrical Engineering, Vol-I, Vol-II, Mcgraw Hill Book Company Inc.

[9] P.K. Mukherjee & S. Chakravorty, Electrical Machines, Dhanpat Rai Publications, 2nd Ed.

[10] I.J Nagrath & D.P.Kothari, Electrical Machines, McGraw Hill Education(india) pvt. Ltd., 4th Ed.

[11] N.N.Parker Smith, Problems in Electrical Engineering, CBS Pub. 9th Ed.

Best of Luck to All the Students