NEHRU COLLEGE OF ENGINEERING AND RESEARCH CENTRE
(NAAC Accredited)
(Approved by AICTE, Affiliated to APJ Abdul Kalam Technological University, Kerala)

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

COURSE MATERIAL

EE205 : DC MACHINES AND TRANSFORMERS

VISION OF THE INSTITUTION
To mould true citizens who are millennium leaders and catalysts of change through excellence in education.
MISSION OF THE INSTITUTION
NCERC is committed to transform itself into a center of excellence in Learning and Research in Engineering and Frontier Technology and to impart quality education to mould technically competent citizens with moral integrity, social commitment and ethical values. We intend to facilitate our students to assimilate the latest technological know-how and to imbibe discipline, culture and spiritually, and to mould them in to technological giants, dedicated research scientists and intellectual leaders of the country who can spread the beams of light and happiness among the poor and the underprivileged.

ABOUT DEPARTMENT

- Established in: 2006
- Course offered: B.Tech Electrical and Electronics Engineering
- Approved by AICTE New Delhi and Accredited by NAAC
- Affiliated to the University of Dr. A P J Abdul Kalam Technological University.

DEPARTMENT VISION

To excel in technical education and research in the field of Electrical & Electronics Engineering by imparting innovative engineering theories, concepts and practices to improve the production and utilization of power and energy for the betterment of the Nation.

DEPARTMENT MISSION

1. To offer quality education in Electrical and Electronics Engineering and prepare the students for professional career and higher studies.
2. To create research collaboration with industries for gaining knowledge about real-time problems.
3. To prepare students with sound technical knowledge.
4. To make students socially responsible.

PROGRAM OUTCOME (PO'S)

Engineering Graduates will be able to:

PO 1. Engineering knowledge: Apply the knowledge of mathematics, science, engineering fundamentals, and an engineering specialization to the solution of complex engineering problems.

PO 2. Problem analysis: Identify, formulate, review research literature, and analyze complex engineering problems reaching substantiated conclusions using first principles of mathematics, natural sciences, and engineering sciences.

PO 3. Design/development of solutions: Design solutions for complex engineering problems and design system components or processes that meet the specified needs with appropriate consideration for the public health and safety, and the cultural, societal, and environmental considerations.

PO 4. Conduct investigations of complex problems: Use research-based knowledge and research methods including design of experiments, analysis and interpretation of data, and synthesis of the information to provide valid conclusions.

PO 5. Modern tool usage: Create, select, and apply appropriate techniques, resources, and modern engineering and IT tools including prediction and modeling to complex engineering activities with an understanding of the limitations.

PO 6. The engineer and society: Apply reasoning informed by the contextual knowledge to assess societal, health, safety, legal and cultural issues and the consequent responsibilities relevant to the professional engineering practice.

PO 7. Environment and sustainability: Understand the impact of the professional engineering solutions in societal and environmental contexts, and demonstrate the knowledge of, and need for sustainable development.

PO 8. Ethics: Apply ethical principles and commit to professional ethics and responsibilities and norms of the engineering practice.

PO 9. Individual and team work: Function effectively as an individual, and as a member or leader in diverse teams, and in multidisciplinary settings.

PO 10. Communication: Communicate effectively on complex engineering activities with the engineering community and with society at large, such as, being able to comprehend and write effective reports and design documentation, make effective presentations, and give and receive clear instructions.

PO 11. Project management and finance: Demonstrate knowledge and understanding of the engineering and management principles and apply these to one's own work, as a member and leader in a team, to manage projects and in multidisciplinary environments.

PO 12. Life-long learning: Recognize the need for, and have the preparation and ability to engage in independent and life-long learning in the broadest context of technological change.

PROGRAM SPECIFIC OUTCOME(PSO'S)

1. Apply Science, Engineering, Mathematics through differential and Integral Calculus, Complex Variables to solve Electrical Engineering Problems.
2. Demonstrate proficiency in the use of software and hardware to be required to practice electrical engineering profession.
3. Apply the knowledge of Ethical and Management principles required to work in a team as well as to lead a team.

COURSE OUTCOME

After the completion of the course the student will be able

CO 1	To understand the concepts of direct current machines construction details and winding design
CO 2	To understand the concepts of DC generator's principle of operation and performance analysis.
CO 3	To understand the concepts of DC Motor's principle of operation and performance analysis.
CO 4	To understand the concepts of single phase transformer's principle of operation, construction and equivalent circuit diagram.
CO 5	To understand the concepts of transformer's and autotransformer principle of operation and performance analysis.
CO 6	To understand the concepts of three phase transformer's principle of operation and performance analysis.

CO VS PO'S AND PSO'S MAPPING

CO	PO1	PO2	PO3	PO4	PO5	PO6	PO7	PO8	PO9	PO10	PO11	PO12	PSO 1	PSO 2	PSO 3
CO 1	3	3	2	2	-	-	-	-	-	-	-	2	2	2	2
CO 2	3	3	2	2	-	-	-	-	-	-	-	2	2	2	2
CO 3	3	3	2	2	-	-	-	-	-	-	-	2	2	2	2
CO 4	3	3	2	2	-	-	-	-	-	-	-	2	2	2	2
CO 5	3	3	2	2	-	-	-	-	-	-	-	2	2	2	2
CO 6	3	3	2	2	-	-	-	-	-	-	-	2	2	2	2

Note: H-Highly correlated=3, M-Medium correlated=2, L-Less correlated=1

SYLLABUS

Module	Contents	Hours	Semester Exam Marks
I	Electromagnetic principles for Machines Electro dynamical equations and their solution – rotational motion system – mutually coupled coils – construction of DC machines – energy conversion in rotating electrical machines – eddy currents and eddy current losses – flux distribution curve in the airgap – armature windings – lap and wave windings – selection criteria – equalizer rings – dummy coils.	9 hours	15%
II	DC generators – EMF equation – methods of excitation – separately and self excited – shunt, series, compound – armature reaction – effects of armature reaction – demagnetizing & cross magnetizing ampere-turns – compensating windings – interpoles – commutation – methods to improve commutation – voltage build-up – no load	9 hours	15%
III	DC motor – principle of operation – back emf – classification – torque equation – losses and efficiency – power flow diagram – performance characteristics of shunt, series and compound motors – starting of dc motors – necessity and types of starters – speed control – methods of speed control – testing – Swinburne's test – Hopkinson's test – separation of losses – retardation test – applications of dc motors.	9 hours	15%
IV	Transformers – principle of operation – types and construction, core type and shell type construction, dry type transformers, cooling of transformers – ideal transformer – transformation ratio – dot convention – polarity test – practical transformer – kVA rating – equivalent circuit – phasor diagram.	9 hours	15%
V	Transformer losses and efficiency – voltage regulation – OC & SC test – Sumpner's test – all day efficiency Autotransformer – saving of copper – current rating and kVA rating of autotransformers, parallel operation of single phase transformers, necessary and desirable conditions of parallel operation, on load and off load tap changers.	9 hours	20%
VI	3-phase transformer – 3-phase transformer connections – Δ-Δ, Y-Y , Δ-Y , Y-Δ, V-V – vector groupings Yy0, Dd0, Yd1, Yd11, Dy1, Dy11 – Scott connection – three winding transformer – tertiary winding – percentage and per unit impedance – parallel operation of three phase transformers.	9 hours	20%

QUESTION BANK

MODULE 1

1. Explain the flux distribution over the air gap of a dc machine.
2. What is eddy current loss? List out its impacts in a DC machine.
3. Derive the electro dynamical equation for an electro mechanical conversion system.
4. What is the need of equalizer rings and dummy coils?
5. Discuss the operating principle of mutually coupled coils.
6. Compare Lap and Wave windings used for DC machine.
7. State the principle behind the energy conversion in electrical machines.
8. With neat sketch explain the construction of a DC Machine.
9. Explain in detail about the Lap and Wave windings.
10. What is Magnetization and B–H curve?
11. Discuss the doubly excited rotating actuator and also calculate the torque equation.
12. Discuss the singly excited rotating actuator and also calculate the torque equation.
13. Discuss the singly excited linear actuator and also calculate the torque equation.
14. Design a lap winding for 8 slots and 2 coilsides per slot having 4 Poles.
15. Design a wave winding for 15 slots and 2 coilsides per slot having 4 Poles.

MODULE 2

1. Define the terms critical resistance and critical speed.
2. Derive the EMF equation of a DC Generator.
3. Explain the different methods of excitation of DC generators with suitable diagrams.
4. A DC shunt generator has a terminal voltage of 220 V, field current of 0.5A and load current of 12A. Find the induced voltage if the armature resistance is 0.2 Ω.
5. Define armature reaction. Explain it in detail with necessary diagrams.
6. Define Commutation. Mention the function of Commutator.
7. Define Commutation. Explain it in detail with necessary diagrams and how to improve it.
8. Write note on characteristics of a DC generator.
9. Write note on load characteristics of a DC shunt generator.
10. What are the types of losses in DC machine?
11. Compare the load characteristics of Series, Shunt and Compound DC generator.
12. Write note on magnetization characteristics of a DC generator.
13. Explain the parallel of operation of a DC generator with neat sketches. List its advantages.

MODULE 3

1. Explain the working principle of a DC motor.
2. How back EMF is generated in a DC motor? Explain its significance.

3. Justify the DC motor whether it is self-regulating motor or not.
4. Derive the voltage and power equation of a DC motor. Also find the condition for maximum power developed.
5. Derive the Torque equation of a DC motor.
6. With suitable diagrams describe the types of DC motor.
7. Draw and explain the electrical and mechanical characteristics of DC shunt motor.
8. Compare the performance characteristics of Series, Shunt and Compound DC motor.
9. Why starter is necessary for a motor? Explain the working of a 3-point starter with neat sketch.
10. Discuss the speed control of DC motor and various methods for speed control.
11. Explain the testing of a DC machine and various method of testing.
12. With neat sketch explain the Swinburne's test of a DC motor and also list the advantages and disadvantages.
13. With neat sketch explain theHopkinson's test of a DC motor.
14. With neat sketch explain theRetardation test of a DC motor.
15. A 4 pole, 240 V, wave connected shunt motor gives 11.19 kW when running at 1000 rpm and drawing armature and field currents of 50 A and 1 A respectively. It has 540 conductors. Its resistance is 0.1 Ω,assuming a drop of 1 V per brush, find a) Total torque b) Useful torque c) Useful flux per pole d) rotational losses e) Efficiency.

MODULE 4

1. Explain the principle of operation of a transformer and its construction.
2. Derive the EMF equation of a single phase transformer and also discuss the transformation ratio.
3. Give a brief note on working, types, advantages, disadvantages and applications of a Dry type transformer.
4. What is cooling of transformer? Discuss the types of cooling employed for transformer.
5. Discuss the working of an Ideal transformer and also draw the phasor diagramon load at a) lagging p.f. b) leading p.f. c) unity p.f.
6. With necessary steps deduce the equivalent circuit of a practical transformer referred to primary side.
7. Discuss the dot convention process used in mutually coupled coil of transformer.
8. Explain the polarity test of transformer.
9. Discuss the working of apractical transformer and also draw the phasor diagram on load at a) lagging p.f. b) leading p.f. c) unity p.f.
10. With necessary steps deduce the equivalent circuit of a practical transformer referred to secondary side.

11. Give a brief note on kVA rating of transformer. Also explain why transformer rating is always expressed in kVA?

MODULE 5

1. Enumerate the losses in a loaded transformer. Derive the condition for maximum efficiency in a transformer.
2. What are the necessary and desirable conditions for parallel operation of single phase transformers?
3. With a neat sketch describe the sumpner's method of testing transformers. How can the voltage regulation be predetermined using this test?
4. Dicuss various types of power losses occur in a transformer. Also explain why iron losses called constant loss.
5. Define efficiency and voltage regulation of transformer. Find condition for maximum efficiency of transformer.
6. Explain the OC and SC test performance on a single phase transformer.
7. What do you mean by All-Day efficiency of transformer?
8. Discuss the concept of autotransformer. Also list the advantage and applications of autotransformer.
9. Find the expression of power transfer in autotransformer.
10. Explain the saving of copper in autotransformer compare to two winding transformer. Also find the expression.
11. Discuss the current rating and kVA rating of autotransformer.
12. Differentiate between autotransformer and two winding transformer.
13. What is tap changing transformer? Also explain its types.
14. A two similar 200kVA single phase transformer gave the following results when tested by sumpners test. Mains wattmeter W1=4kW, series wattmeter W2=6kW at full load current. Find out individual transformer efficiencies at
    a. Full load at UPF
    b. Half load at 0.8 PF lead.

MODULE 6

1. What do you understand by three phase transformer? Also discuss their connection configuration.
2. Discuss the various three phase transformer connections.
3. What is vector grouping of three phase transformer, explain. Also discuss various vector group connection given below

a. Yy0, Dd0
b. Yy6, Dd6
c. Yd1, Dy1
d. Yd11, Dy11

4. Explain the three winding transformer. What is tertiary winding and list its advantages of using.
5. Explain the concept of per unit and percentage value. Also find the per unit and percentage impedance of transformer.
6. What are the necessary and desirable conditions for parallel operation of three phase transformers?
7. A step down transformer is connected to three phase 6kV supply. The supply current is 12A. The ratio of turns per phase is 10. Determine the secondary line voltage, line current and the output for the following connection.
   a. Delta - Delta
   b. Star – Star
   c. Star – Delta
   d. Delta - Star
8. With a neat sketch describe the scott connection transformers.
9. With a neat sketch describe the open delta connection transformers.

4

Module-1

Electro-Magnetic Induction:

* It is the production of an electromotive force or voltage across an electrical conductor due to its dynamic interaction with a magnetic field.

* Induced EMF in Electromechanical Systems given by,

$$e = lvB \quad — (1)$$

where,

l - Length of a conductor
v - speed at conductor moves
B - Flux density

* Force and Torque on a current carrying conductor is given by,

$$F = q(v * B) \quad — (2)$$

for homogeneous conductor,

$$F = I(l * B) \quad — (3)$$

In a rotating system,

$$T = r * F \quad — (4)$$

* Laws of EMI:

1) Biot-Savart Law:

Magnetic Field B at any point due to a steady current in an infinitely long straight wire is directly proportional to the current and inversely proportional to perpendicular to distance of the point from wire.

$$B = \frac{\mu_0 I}{2\pi r}$$

2) Ampere's Circuital Law:

It states that line integral of the vector $\bar{H}$ along any arbitrary closed path is equal to the current enclosed by the path.

$$\oint \bar{H}.\bar{dl} = I$$

3) Faraday's Law of EMI:

I Law:

It states that whenever a conductor cuts the magnetic flux, an emf is induced in that conductor.

II Law:

It states that, the magnetic of induced emf is directly proportional to the rate of change of flux.

$$e \propto \frac{d\phi}{dt}$$

$$e = N \frac{d\phi}{dt}$$

4) Lenz's Law:

It states that, when an emf is generated by a change in magnetic flux, the polarity of the induced emf is such, that it produces an current that opposes the cause.

$$e = - N \frac{d\phi}{dt}$$

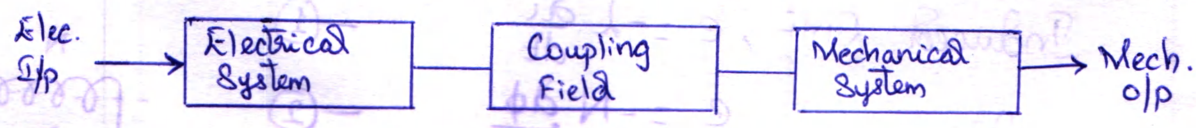
Electro-Mechanical Energy Conversion (EMEC):

* The conversion of electrical energy into mechanical energy or vice versa is known as EMEC.

* EMEC involves the interchange of energy between an electrical system and a mechanical system through the medium of a coupling electric field or magnetic field.

* Therefore, EMEC has three essential parts.

1) Electrical System
2) Coupling Field
3) Mechanical System.



* Coupling Field can be either electric field or magnetic field. But EMEC can be more effective when magnetic field is used as the medium.

* From this EMEC, the energy balance equation can be written as,

$$W_{elec} = W_{fld} + W_{mech} \quad \text{[Motor action]}$$

$$W_{mech} = W_{fld} + W_{elec} \quad \text{[Generator action]}$$

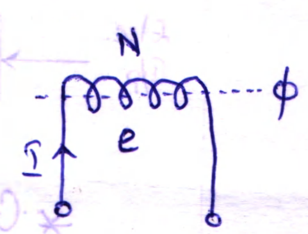
Mutually Coupled Coils:

* Magnetically coupled circuits are used to transfer energy from one circuit to another. When a circuit has two or more coils, flux produced by one coil links the other coil.
* If the current in the coil varies, flux also varies, thus an emf is induced in the conductor (self inductance) and in any nearby conductor (mutual inductance).
* Self Inductance (L):

It is defined as the property of the coil due to which it opposes the change of current flowing through it.

Induced EMF, $e = -L \frac{di}{dt}$ — (1)

Also, $e = -N \frac{d\phi}{dt}$ — (2)



$\therefore L \frac{di}{dt} = N \frac{d\phi}{dt}$

$L\, di = N\, d\phi$

$\therefore L = N \frac{d\phi}{di}$

$L = \frac{N\phi}{I}$ — (3)

In terms of reluctance,

$S = \frac{NI}{\phi}$

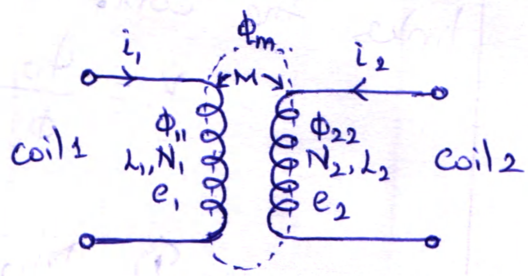
$\frac{\phi}{I} = \frac{N}{S}$ — (4)

sub, (4) in (3), $L = \frac{N^2}{S}$ — (5)

*Mutual Inductance (M):

It is defined as the property of the coil due to which it opposes the change of current in the other coil.

Let two coils carry current i_1 and i_2 which produces the fluxes ϕ_{11} and ϕ_{22} respectively.



$$\phi_m = \phi_{12} = \phi_{21}$$

$$M = M_{12} = M_{21}$$

Mutually induced emf is the emf induced in one coil due to change in other coil. Considering coil 2,

$$e_2 = -N_2 \frac{d\phi_m}{dt} \quad \text{— (1)}$$

$$e_2 = -M \frac{di_1}{dt} \quad \text{— (2)}$$

$$\therefore \; N_2 \frac{d\phi_m}{dt} = M \frac{di_1}{dt}$$

$$N_2 \, d\phi_m = M \, di_1$$

$$M = N_2 \frac{d\phi_m}{di_1}$$

$$\therefore M = \frac{N_2 \phi_m}{I_1} \quad \text{— (3)}$$

$$M_{12} = \frac{N_2 \phi_{12}}{I_1} \; \& \; M_{21} = \frac{N_1 \phi_{21}}{I_2} \quad \text{— (4)}$$

In terms of reluctance,

$$M = \frac{N_1 N_2}{S} \quad \text{— (5)}$$

* Coefficient of Coupling (K):

It is defined as the fraction of total flux that links the coil. The maximum value of K is unity.

$$K = \frac{\phi_{12}}{\phi_1} = \frac{\phi_{21}}{\phi_2} \quad \text{—(1)}$$

If $M_{12} = M_{21} = M$, then

$$M^2 = M_{12} * M_{21} \quad \text{—(2)}$$

$$= \frac{N_2 \phi_{12}}{i_1} * \frac{N_1 \phi_{21}}{i_2}$$

$$= N_1 N_2 \frac{\phi_{21}}{\phi_2} * \frac{\phi_2}{i_2} * \frac{\phi_{12}}{\phi_1} * \frac{\phi_1}{i_1}$$ [Multiply & Divide by ϕ_1 & ϕ_2]

$$= N_1 N_2 . K * \frac{\phi_2}{i_2} * K * \frac{\phi_1}{i_1}$$

$$= K^2 \frac{N_1 \phi_1}{i_1} * \frac{N_2 \phi_2}{i_2}$$

$$M^2 = K^2 L_1 L_2$$

Rearranging, $$K^2 = \frac{M^2}{L_1 L_2}$$

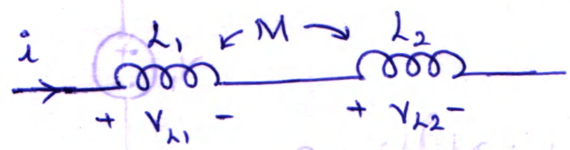
$$\therefore K = \frac{M}{\sqrt{L_1 L_2}} \quad \text{—(3)}$$

when, $K = 1 \rightarrow$ Magnetically tightly coupled.

$K = 0 \rightarrow$ Magnetically isolated.

Series connection of coupled coils:

* Consider two coils connected in series.



* In this case, the flux developed in both the coils adds each other and is called additive polarity.

$$V_{L1} = L_1 \frac{di}{dt} + M \frac{di}{dt} = (L_1 + M) \frac{di}{dt}$$

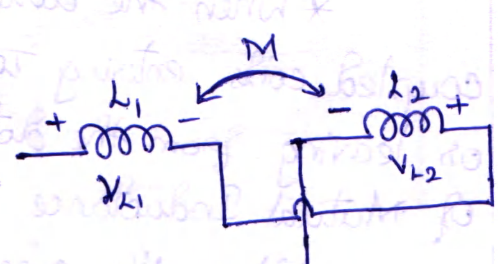
$$V_{L2} = L_2 \frac{di}{dt} + M \frac{di}{dt} = (L_2 + M) \frac{di}{dt}$$

$\therefore$ Total Voltage, $V_L = V_{L1} + V_{L2}$

$$L \frac{di}{dt} = (L_1 + M) \frac{di}{dt} + (L_2 + M) \frac{di_2}{dt}$$

$$\therefore L = L_1 + L_2 + 2M$$

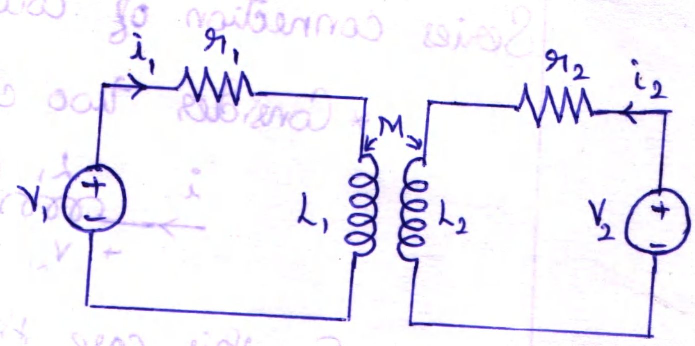
* Suppose the two coils are connected in such a pattern, then



$$\therefore L = L_1 + L_2 - 2M.$$

Here the fluxes of both the coils mutually oppose each other.

Modelling of Coupled Coils:



* Applying KVL for the circuit,

$$V_1 - i_1 r_1 - L_1 \frac{di_1}{dt} \pm M \frac{di_2}{dt} = 0$$

$$\therefore V_1 = i_1 r_1 + L_1 \frac{di_1}{dt} \pm M \frac{di_2}{dt} \quad \text{--- (1)}$$

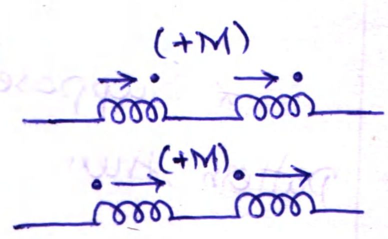
Similarly,

$$V_2 - i_2 r_2 - L_2 \frac{di_2}{dt} \pm M \frac{di_1}{dt} = 0$$

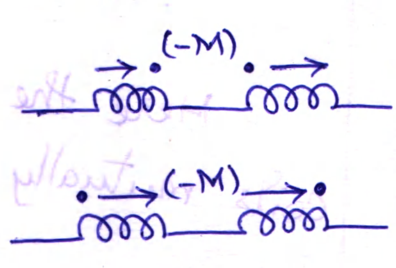
$$V_2 = i_2 r_2 + L_2 \frac{di_2}{dt} \pm M \frac{di_1}{dt} \quad \text{--- (2)}$$

Dot Convention in Coupled Coils:

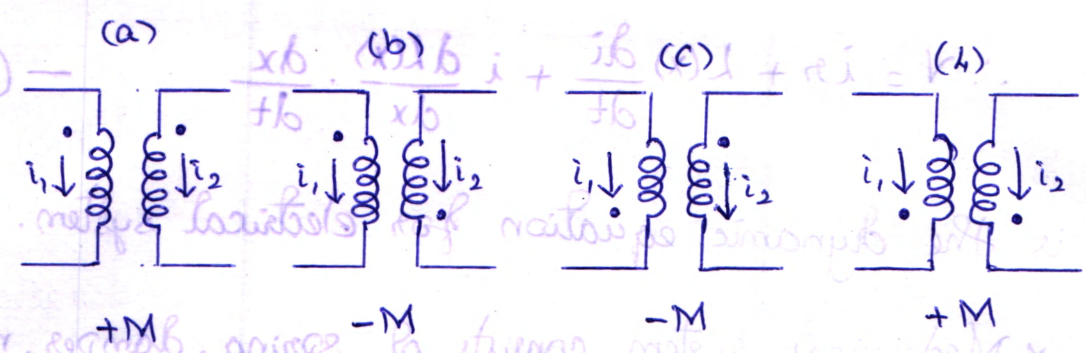
* It is used to find polarity of the induced voltage by a dot symbol.



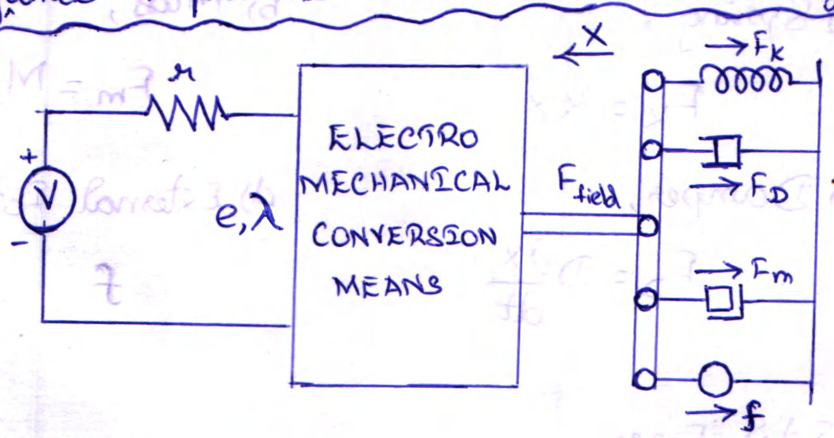
* When the current in two mutually coupled coils entering towards the dot or leaving from the dot, then the value of Mutual Inductance is positive.



* When the current through the one coil is leaving the dot and for other coil is entering the dot, then the value of Mutual Inductance is negative.



Dyamic Equations for Electro-Mechanical System



* EMEC devices operate with electrical system on one side and mechanical system on other side.
* Consider a movement x, then

$L(x) \rightarrow$ Self inductance of electromechanical conversion means

$\lambda \rightarrow$ Flux linkage of the device.

Applying KVL for electrical system,

$$v - ir - \frac{d\lambda}{dt} = 0$$

$$v - ir - \frac{d}{dt}[L(x)\, i] = 0$$

$$v = ir + \frac{d}{dt}[L(x)\, i]$$

$$\therefore V = ir + L(x)\frac{di}{dt} + i\frac{dL(x)}{dx}\cdot\frac{dx}{dt} \quad -(1)$$

This is the dynamic equation for electrical system.

* Mechanical system consists of spring, damper, mass and external force.

a) Spring,

$$F_k = kx.$$

b) Mass,

$$F_m = M\frac{d^2x}{dt^2}$$

c) Damper,

$$F_D = D\frac{dx}{dt}$$

d) External Force,

$$f$$

$\therefore$ Total Force,

$$F = F_m + F_D + F_k + f$$

$$F = M\frac{d^2x}{dt^2} + D\frac{dx}{dt} + kx + f \quad -(2)$$

This is the dynamic equation for mechanical system.

* Equation (1) & (2) are the dynamic equation for ElectroMechanical System.

Energy Conversion principle in rotating electrical machines:

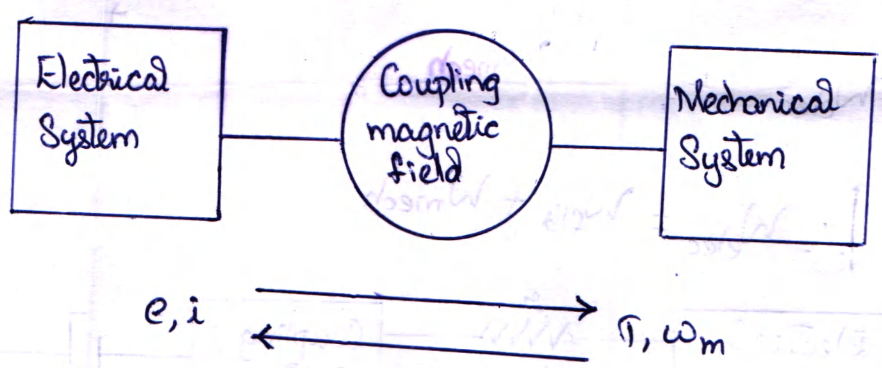
* In an energy conversion device out of the total input energy, some energy is converted into required form, some is dissipated and the rest is dissipated in the form of heat.

* Considering rotating electrical machines continuously convert energy into mechanical energy vice versa. This interchange of energy between an electrical system and a mechanical system takes place through the medium of coupling magnetic field.

* When the conversion takes place from

Electrical to Mechanical → Motor

Mechanical to Electrical → Generator



* The energy balanced equation must include these four energy terms and for a motor,

$$\left.\begin{matrix}\text{Total Electrical}\\ \text{Energy Input}\end{matrix}\right\} = \left\{\begin{matrix}\text{Mechanical}\\ \text{energy output}\end{matrix}\right\} + \left\{\begin{matrix}\text{Total Energy}\\ \text{stored}\end{matrix}\right\} + \left\{\begin{matrix}\text{Total energy}\\ \text{dissipated}\end{matrix}\right\}$$

$$W_{ei} = W_{mo} + W_{st} + W_{dis}$$

* Total energy stored in any device = Energy stored in magnetic field + Energy stored in mechanical system

$$W_{st} = W_{es} + W_{ms}$$

* Total energy dissipated = energy dissipated in electric circuit as ohmic losses + energy dissipated as friction & windage losses + energy dissipated as magnetic core losses

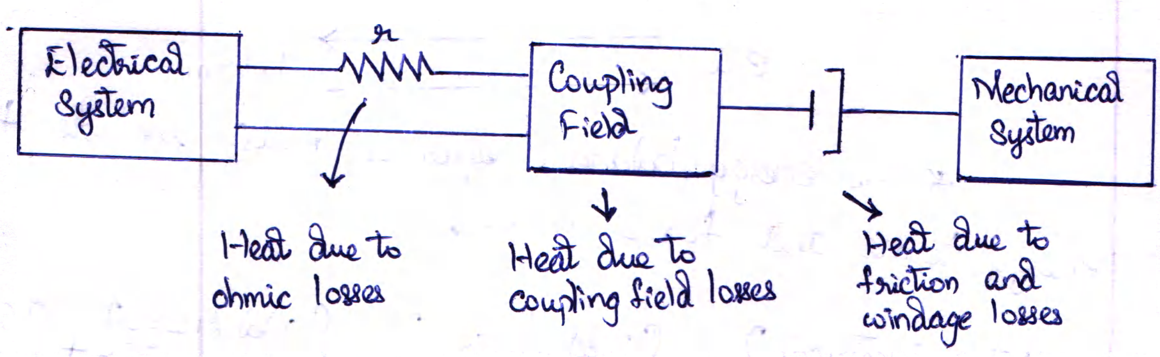
Therefore,

$$W_{ei} = W_{mo} + (W_{es} + W_{ms}) + (\text{ohmic losses} + \text{mechanical losses} + \text{coupling field losses})$$

$$(W_{ei} - \text{ohmic losses}) = (W_{mo} + W_{ms} + \text{mechanical losses}) + (W_{es} + \text{Coupling field losses})$$

$$W_{elec} = W_{mech} + W_{fld}$$

$$\therefore W_{elec} = W_{fld} + W_{mech}$$



Energy and Co-energy:

* Flux linkage is given by, $\lambda = N\phi$ — (1)
* Induced emf, $e = N\frac{d\phi}{dt} = \frac{d}{dt}(N\phi) = \frac{d\lambda}{dt}$ — (2)
* Electrical energy, $dW_{elec} = e\,i\,dt$

$$= \frac{d\lambda}{dt} i\,dt$$

$$= i\,d\lambda \quad — (3)$$

If no mechanical work is done, then energy balance equation will becomes,

$$dW_{elec} = dW_{fld} + dW_m \quad [\because dW_m = 0]$$

$$= dW_{fld} \quad — (4)$$

From (3) & (4), $dW_{fld} = i\,d\lambda$

$$= i\,d(N\phi)$$

$$= N i\,d\phi \quad — (5)$$

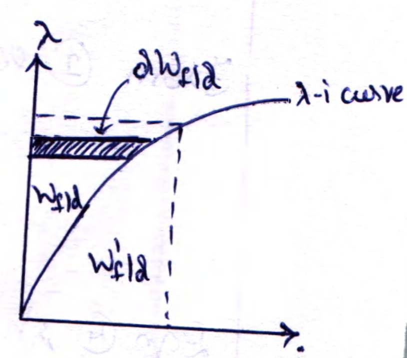
$$\therefore W_{fld} = N\int_0^{\phi} i\,d\phi = \int_0^{\lambda} i\,d\lambda \quad — (6)$$

In terms of B & H,

$$W_{fld} = N\int_0^{\phi} i\,d\phi = \int_0^{\phi} Ni\,d\phi = \int_0^{B} Hl\,A\,dB$$

$$\therefore W_{fld} = Al\int_0^{B} H\,dB \quad — (7)$$

$W_{fld} \rightarrow$ Energy ; $W'_{fld} \rightarrow$ Co-energy $= \int_0^{i} \lambda\,di$



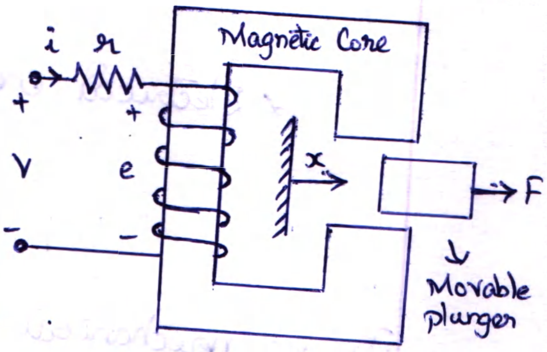
W_{fld} – determine force in terms of current

W'_{fld} – determine force in terms of flux linkage.

Force calculation for Singly excited linear actuator: (SELA)

* In this, force is calculated from energy and co-energy for a singly excited linear actuator.

* Consider a SELA having a winding resistance, terminal voltage, winding current, movable plunger and force acting on plunger.



* After a time interval dt, the plunger has moved for a distance dx under the action of force F.

* Mechanical energy is given by,

$$dW_m = F dx \quad —①$$

* The amount of electrical energy that has been transferred into the magnetic field and converted into the mechanical work is given by,

$$dW_e = dW_f + dW_m \quad —②$$

* Electrical energy is given by,

$$dW_e = e i dt = \frac{d\lambda}{dt} i dt = i d\lambda \quad —③$$

From ② eqn,

$$dW_f = dW_e - dW_m$$

$$= i d\lambda - F dx \quad —④$$

Eqn ④ shows, energy stored in the magnetic field is a function of the flux linkage and position of the plunger.

Mathematically we can also write magnetic field energy as,

$$\partial W_f(\lambda, x) = \frac{\partial W_f(\lambda,x)}{\partial \lambda} d\lambda + \frac{\partial W_f(\lambda,x)}{\partial x} dx \quad — (5)$$

From (4) & (5),

$$i = \frac{\partial W_f(\lambda,x)}{\partial \lambda} \quad \text{and} \quad F = -\frac{\partial W_f(\lambda,x)}{\partial x} \quad — (6)$$

Energy stored in magnetic field is given by,

$$W_f(\lambda,x) = \int_0^\lambda i(\lambda,x)\, d\lambda$$

$$= \int_0^\lambda \frac{\lambda}{L(x)} d\lambda$$

$$= \frac{1}{L(x)} \int_0^\lambda \lambda\, d\lambda$$

$$W_f(\lambda,x) = \frac{\lambda^2}{2L(x)} \quad — (7)$$

Co-energy is given by,

$$W_f'(i,x) = \frac{1}{2} \cdot \frac{\lambda^2}{L(x)} = \frac{1}{2} \frac{[L(x)\, i]^2}{L(x)}$$

$$\therefore W_f'(i,x) = \frac{1}{2} i^2 L(x) \quad — (8)$$

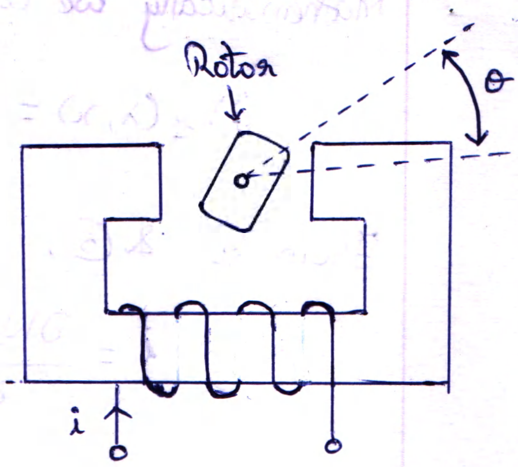
Force acting on the plunger,

wrt energy, $F = -\frac{\partial W_f(\lambda,x)}{\partial x} = \frac{1}{2}\left[\frac{\lambda}{L(x)}\right]^2 \frac{dL(x)}{dx} = \frac{1}{2} i^2 \frac{dL(x)}{dx}$ — (9)

wrt co-energy, $F = \frac{\partial W_f'(i,x)}{\partial x} = \frac{1}{2} i^2 \frac{dL(x)}{dx}$ — (10)

Singly Excited Rotating Actuator (SERA):

* Singly excited linear actuator becomes a singly excited rotating actuator if the linearly movable plunger is replaced by a rotor.



* Here, the change in the derivation is replace F by T and x by θ.

where,

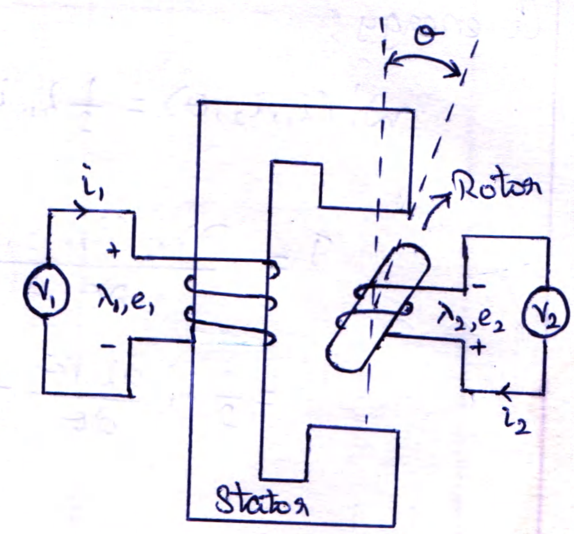
T - Torque

θ - angular displacement.

Energy	Co-energy
$dW_f = i\,d\lambda - T\,d\theta$	$dW_f' = i\,d\lambda + T\,d\theta$
$W_f(\lambda,\theta) = \int_0^{\lambda} i(\lambda,\theta)\,d\lambda$	$W_f'(i,\theta) = \int_0^{i} \lambda(i,\theta)\,d\theta$
$i = \frac{\partial W_f(\lambda,\theta)}{\partial \lambda}$	$\lambda = \frac{\partial W_f'(i,\theta)}{\partial i}$
$T = -\frac{\partial W_f(\lambda,\theta)}{\partial \theta}$	$T = \frac{\partial W_f'(i,\theta)}{\partial \theta}$
$W_f(\lambda,\theta) = \frac{1}{2}\frac{\lambda^2}{L(\theta)}$	$W_f'(i,\theta) = \frac{1}{2} i^2 L(\theta)$
$T = \frac{1}{2}\left[\frac{\lambda}{L(\theta)}\right]^2 \frac{dL(\theta)}{d\theta} = \frac{1}{2} i^2 \frac{dL(\theta)}{d\theta}$	$T = \frac{1}{2} i^2 \frac{dL(\theta)}{d\theta}$

Doubly Excited Rotating Actuator:

* Torque calculation discussed in SERA is equally applicable to doubly excited system.



* Since we have two excitation, Energy for electrical system is given by,

$$\partial W_e = e_1 i_1 dt + e_2 i_2 dt$$

$$= i_1 \partial\lambda_1 + i_2 \partial\lambda_2 \quad — (1)$$

and, $\partial W_m = T\partial\theta. \quad — (2)$

hence,

$$\partial W_f(\lambda_1, \lambda_2, \theta) = i_1 \partial\lambda_1 + i_2 \partial\lambda_2 - T\partial\theta$$

can also be written as,

$$\partial W_f(\lambda_1, \lambda_2, \theta) = \frac{\partial W_f(\lambda_1, \lambda_2, \theta)}{\partial\lambda_1} d\lambda_1 + \frac{\partial W_f(\lambda_1, \lambda_2, \theta)}{\partial\lambda_2} d\lambda_2 + \frac{\partial W_f(\lambda_1, \lambda_2, \theta)}{\partial\theta} d\theta$$

Energy,

$$W_f(\lambda_1, \lambda_2, \theta) = \frac{1}{2} \Gamma_{11} \lambda_1^2 + \frac{1}{2} \Gamma_{22} \lambda_2^2 + \Gamma_{12} \lambda_1 \lambda_2$$

Torque.

$$T = \frac{1}{2} i_1^2 \frac{dL_{11}(\theta)}{d\theta} + \frac{1}{2} i_2^2 \frac{dL_{22}(\theta)}{d\theta} + i_1 i_2 \frac{dL_{12}(\theta)}{d\theta}$$

where, $L_{12} = L_{21}$, $\Gamma_{11} = L_{22}/\Delta$, $\Gamma_{22} = L_{11}/\Delta$, $\Delta = L_{11} L_{12} - L_{12}^2$ and

$\Gamma_{12} = \Gamma_{21} = -L_{12}/\Delta$.

Co-energy,

$$W_f'(i_1, i_2, \theta) = \frac{1}{2} L_{11} i_1^2 + \frac{1}{2} L_{22} i_2^2 + L_{12} i_1 i_2$$

$$T = \frac{\partial W_f'(i_1, i_2, \theta)}{\partial \theta}$$

$$= \frac{1}{2} i_1^2 \frac{dL_{11}(\theta)}{d\theta} + \frac{1}{2} i_2^2 \frac{dL_{22}(\theta)}{d\theta} + i_1 i_2 \frac{dL_{12}(\theta)}{d\theta}$$

Construction of DC machine:

* DC generator and DC motor have the same general construction. All DC machines have main components. They are,

1) Field system
   a) Main Pole
      → Pole Core
      → Pole Shoe
      → Field winding
   b) Interpole
      → Interpole winding and core.
   c) Yoke

2) Armature System
   a) Armature Core
   b) Armature winding
   c) Brushes and Bearings
   d) Commutator

Yoke:

* The outer frame of a DC machine.
* It is made up of cast iron or steel (Small & large m/c)
* It provides mechanical strength for the whole assembly.
* It carries magnetic flux produced by the field winding/poles.

Main Pole:

Pole Core:

* It is composed of stacked laminations bolted inside the yoke.

Pole Shoe:

* It provide support to field winding.
* It reduce air gap between main pole and armature, in order to reduce reluctance.

Field Winding:

* It is mounted on poles (Pole core + Pole shoe) to electromagnetize it and produce necessary flux.

Interpole:

* It is also called commutating pole.
* It is placed between the main poles.
* It provides sparkless commutation.

Armature:

Armature Core:

* It consists of slotted soft-iron laminations that are stacked to form a cylindrical core.
* It is keyed to the shaft and rotates between the field poles.
* Core is laminated to reduce eddy current loss.
* Laminations are slotted to accomodate and provide mechanical security to armature winding.

Armature Winding:

* It is usually a former wound copper coil which rests in armature slots.
* Armature conductors are connected in series or parallel so as to increase voltage or current respectively.
* It is a closed-circuit winding.
* Winding can be wound by either lap or wave winding.

Brushes and Bearings:

* Brushes made of carbon and is in shape of rectangular block.
* Purpose of brushes is to ensure electrical connections between the rotating commutator and stationary external load circuit.
* Function of bearings is to reduce friction between the rotating and stationary parts of the machine.
* Ball or Roller bearings are fitted in the end housings.

Commutator:

* To convert internally developed alternating emf to unidirec-
-tional emf. (AC to DC)
* To facilitate the collection of current from armature conductors.
* To produce unidirectional torque in case of motors.
* It is cylindrical in shape and is made of wedge shaped segments of hard drawn high conductivity copper.

Winding Terminology:

Conductor:

An individual piece of wire placed in the slot.

Turn:

Two conductors connected in series and seperated by each other by a pole pitch.

Coil:

When one or more turns are connected in series.

Winding:

Number of coils arranged in coil group.

Pole Pitch:

Number of armature slots per pole.

Coil Pitch:

Distance between the two sides of a coil measured in terms of armature slots.

Full-Pitch winding:

If Coil pitch is equal to pole pitch.

Short Pitch winding:

If Coil pitch less than pole pitch.

Over pitched winding:

If Coil pitch greater than pole pitch.

Front Pitch(Y_F):

Distance between second conductor of one coil to first conductor of next coil attached to one commutator segment.

Back Pitch (Y_B):

Distance between first and second conductor of the same coil.

Resultant Pitch(Y_R):

Distance between first conductor of one coil and first conductor of next coil.

Commutator Pitch:

It is the number of commutator segments spanned by each coil of armature winding.

Types of Armature Winding:

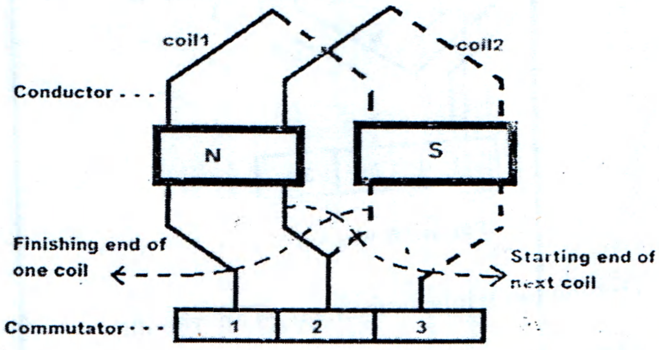
Types of Armature windings

Armature windings are mainly of two types

1. lap winding
2. wave winding

Lap Winding Simplex and Duplex Lap Winding

Lap winding is the winding in which successive coils overlap each other. It is named "Lap" winding because it doubles or laps back with its succeeding coils.



LAP winding

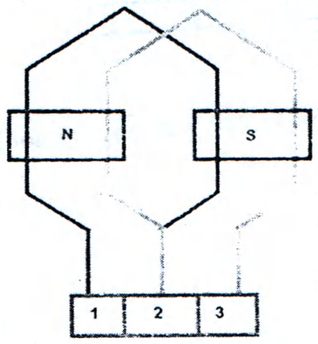
In this winding the finishing end of one coil is connected to one commutator segment and the starting end of the next coil is connected with same commutator segment. Here we can see in picture, the finishing end of coil - 1 and starting end of coil - 2 are both connected to the commutator segment – 2.

Lap winding are of two types –

1. Simplex Lap Winding
2. Duplex Lap Winding

Simplex Lap Winding

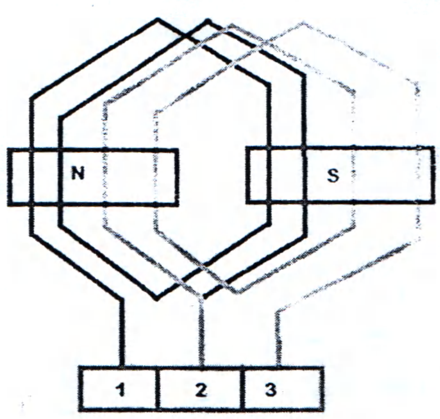
A winding in which the number of parallel path between the brushes is equal to the number of poles is called simplex lap winding.



Simplex lap winding

Duplex Lap Winding

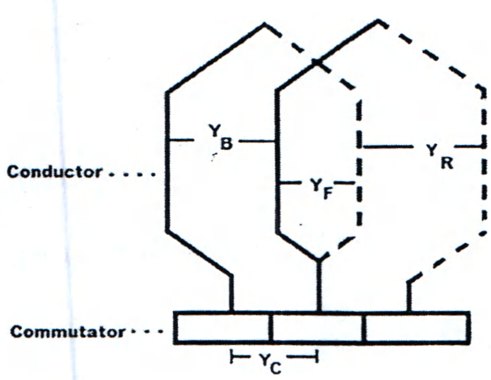
A winding in which the number of parallel path between the brushes is twice the number of poles is called duplex lap winding.



Duplex lap winding

Some important points to remember while designing the Lap winding:

If, Z = the number conductors
P = number of poles
Y_B = Back pitch
Y_F = Front pitch
Y_C = Commutator pitch
Y_A = Average pole pitch
Y_P = Pole pitch
Y_R = Resultant pitch



Then, the back and front pitches are of opposite sign and they cannot be equal.

$Y_B = Y_F \pm 2m$
m = multiplicity of the winding.
m = 1 for Simplex Lap winding
m = 2 for Duplex Lap winding
When,

$Y_B > Y_F$, i.e., $Y_B = Y_F + 2m$, it is called progressive winding.
$Y_B < Y_F$, i.e., $Y_B = Y_F - 2m$, it is called retrogressive winding.

Back pitch and front pitch must be odd integer.

Resultant pitch (Y_R) = Y_B - Y_F = 2m

Y_R is even because it is the difference between two odd numbers.

$$Average\ pitch\ (Y_A) = \frac{Y_B + Y_F}{2} = pole\ pitch\ (Y_P) = \frac{Z}{P}$$

$$Y_B = \frac{Z}{P} + 1$$

$$Y_F = \frac{Z}{P} - 1$$

Commutator pitch (Y_C) = ±m

Number of parallel path in the Lap winding = mP

Advantages of Lap Winding

- This winding is necessarily required for large current application because it has more parallel paths.
- It is suitable for low voltage and high current generators.

Disadvantages of Lap Winding

- It gives less emf compared to wave winding. This winding requires more no. of conductors for giving the same emf, it results high winding cost.
- It has less efficient utilization of space in the armature slots.

Equalizer Rings

In lap winding all the conductors in any parallel path lie under one pair of poles. If flux from all the poles is exactly the same, the induced emf in each path hence current carried by each path will be equal.

But in spite of best effort this condition is not practicable either due to variation in gap length or due to different magnetic properties of steel. The currents flowing in various paths may also differ due to difference in their resistances. Hence there is always slight difference in the generated voltage in the various parallel paths, and as a result, large circulating currents flow in the armature winding. These circulating currents not only tend to heat the armature above the temperature cause an undue amount of sparking at the brushes and commutator. Sparking should, of course be avoided, because it causes undue burning and wear of the commutator and brushes and, if carried too far, may result in flash-over from + ve to – ve brushes, a condition representing a short-circuit across the supply lines.

To overcome the detrimental effects resulting from the circulating currents, it is customary to employ equalizer connections in all lap wound armatures. These are low resistance copper wires that connect together points in the armature winding which should, under ideal conditions, be at exactly the same potential at all time but which, because of mechanical and electrical differences, they are not. Thus, the equalizer rings relieve the brushes to the circulating current load by causing the latter to be bypassed.

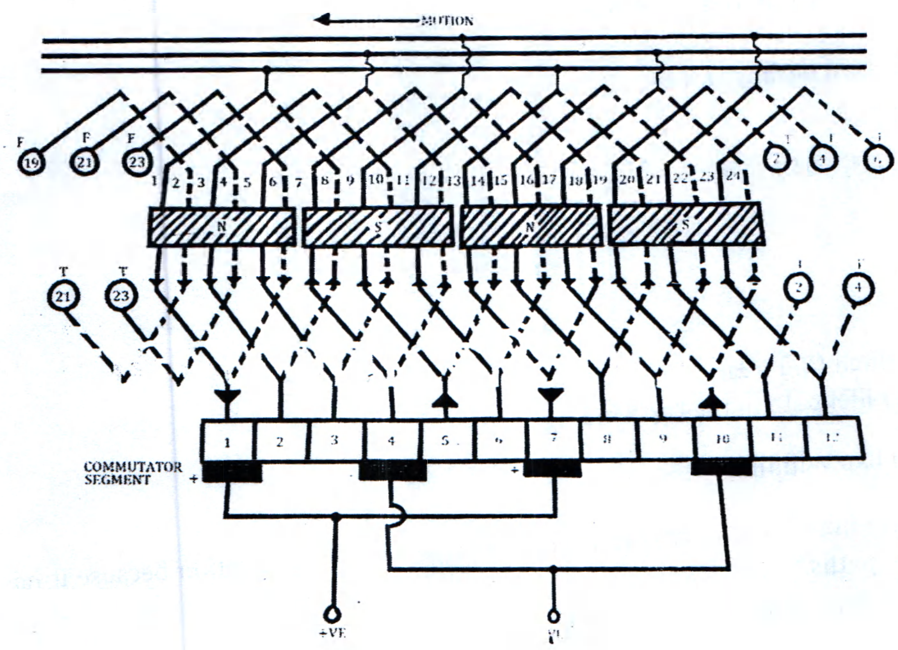


Figure 1: Simplex Lap Winding with Equalizer Connections

To make these equalizer connections, the number of coils should be multiples of the number of poles and the number of coils per pole should be divisible by a small number 2 or 3.

As an example assume a 4-pole generator having 24 coil sides. The number of coil sides per pole will be 6. The winding with equalizer connections is shown in Fig. 1. Note that every 3rd coil is connected to an equalizer. The coils that are connected to the same equalizer occupy the same position relative to the poles. This is necessary as such coils, at any instant, should be generating the same emf.

Note in Fig. 1. that

(i) one equalizer ring is connections to coil side two pole pitch apart,
(ii) number of connections to one equalizing ring is equal to the pair of poles
(iii) number of rings is equal to the number of coils under one pair of poles i.e. equal to {Number of coils / Number of pairs of poles} in case every coil is connected to an equation.

Theoretically, every coil should be connected to an equalizer but as this would require an undue number of equalizers, it is sufficient, practically, to connect every third or fourth coil. This is the reason why the number of coils per pole should be divisible by a small number as 2, 3 or 4. In Fig. 1 alternate coil has been connected to the equalizer ring and in such a case the winding is side to be 50% equalized. If all the coils were connected to the equalizer rings then the winding would have been 100% equalized.

Problem:

1. Design a 4 pole simplex lap wound armature containing 8 slots and 2 coil sides per slot.

$$\text{Pole pitch} = \frac{Z}{P} = \frac{8*2}{4} = 4$$

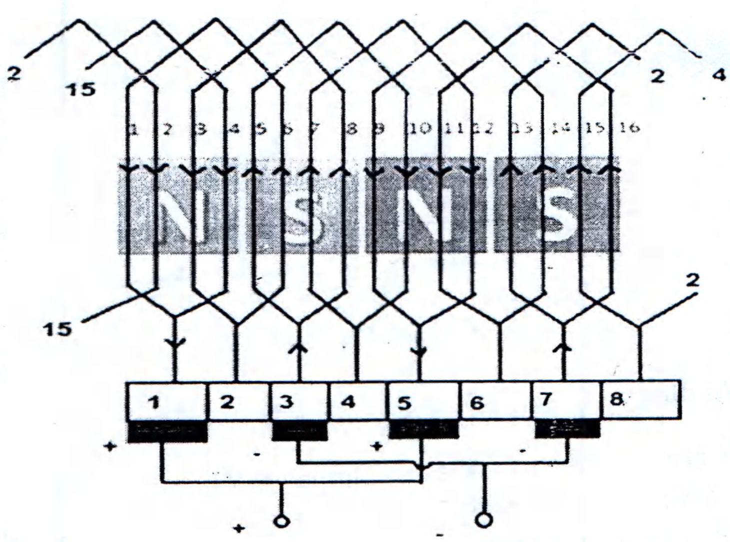
$$Y_B = \frac{Z}{P} + 1 = 4 + 1 = 5$$

$$Y_F = \frac{Z}{P} - 1 = 4 - 1 = 3$$

Number of conductors = 8*2 = 16

Let us start from 1st conductor,

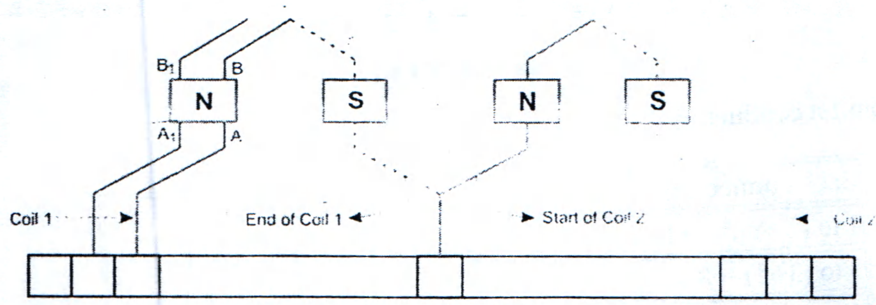
Back connections	Front connections
1 to (1+Y_B) = (1+5) = 6	6 to (6-Y_F) = (6 - 3) = 3
3 to (3+5) = 8	8 to (8-3) = 5
5 to (5+5) = 10	10 to (10-3) = 7
7 to (7+5) = 12	12 to (12-3) = 9
9 to (9+5) = 14	14 to (14-3) = 11
11 to (11+5) = 16	16 to (16-3) =13
13 to (13+5) = 18 = (18-16) = 2	2 to (18-3) = 15
15 to (15+5) = 20 = (20-16) = 4	4 to (20-3) = 17 = (17-16) = 1



Wave winding

Wave winding is one type of armature winding. In this winding, we connect the end of one coil to the starting of another coil of the same polarity as that of the first coil. In this type of winding the coil side (A - B) progresses forward around the armature to another coil side and goes on successively passing through N and S pole till it returns to a conductor (A1-B1) lying under the starting pole.

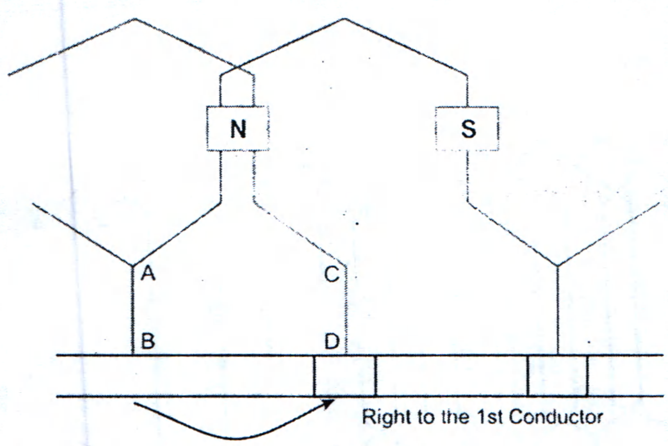
This winding forms a wave with its coil, that's why we call it as wave winding. Since we connect the coils in series here, we also call it series winding.



Wave Winding

Progressive Wave Winding

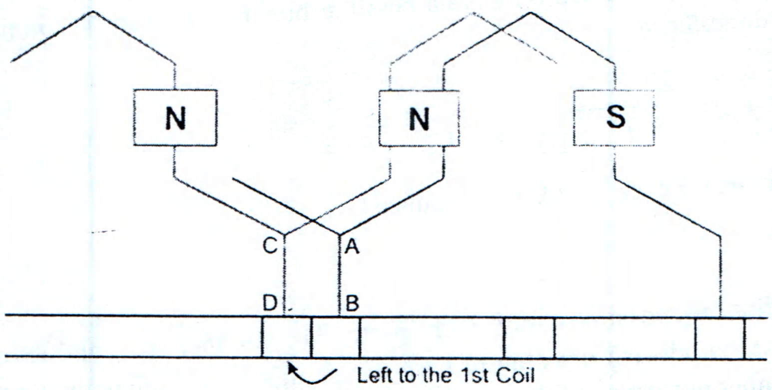
If after one round of the armature the coil falls in a slot right to its starting slot the winging is called Progressive wave winding. progressive wave winding



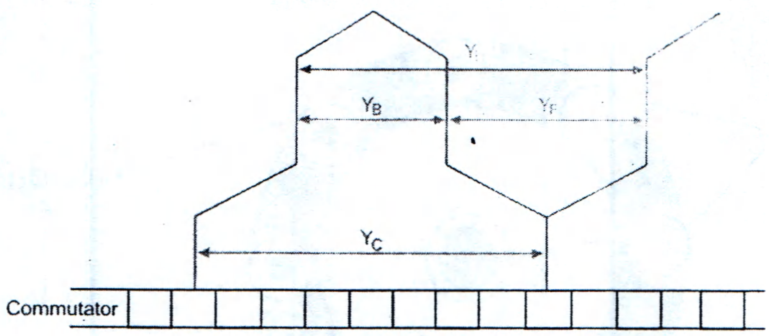
Progressive Wave Winding

Retrogressive Wave Winding

If after one round of the armature the coil falls in a slot left to its starting slot the winging is called Retrogressive wave winding. wave winding Here in the picture above we can see that 2nd conductor CD is in the left of the 1st conductor.



Important Points about Wave Winding



Wave Winding

In simplex wave winding Back pitch (YB) and front pitch (YF) are both odd and are of same sign. Back-pitch and front-pitch are nearly equal to the pole pitch and may be equal or differ by ±2.

+ for progressive winding, - for retrogressive winding.

$$Resultant\ pitch\ Y_R = Y_B \pm Y_F$$

$$Commutator\ pitch\ (Y_C) = average\ pitch\ (Y_A)$$

$$Average\ pitch\ Y_A = \frac{Y_B + Y_F}{2} = \frac{Z \pm 2}{P}$$

$$Therefore,\ Y_A = Y_B = Y_F$$

Here, Z is the no of conductors in the winding. P is the no of poles. Average pitch (YA) must be an integer number, because it may close itself. We take ± 2 (two) because after one round of the armature the winding falls sort of two conductors. If we take an average pitch Z/P then after one round the winding will close itself without including all coil sides. Since average pitch must be an integer, this winding is not possible with any no. of conductors. Let us take 8 conductors in a 4 pole machine.

$$Then.\ Y_A = \frac{Z \pm 2}{P} = \frac{8 \pm 2}{4} = \frac{10}{4} = 2\frac{1}{2}\ or\ 3\frac{1}{2}$$

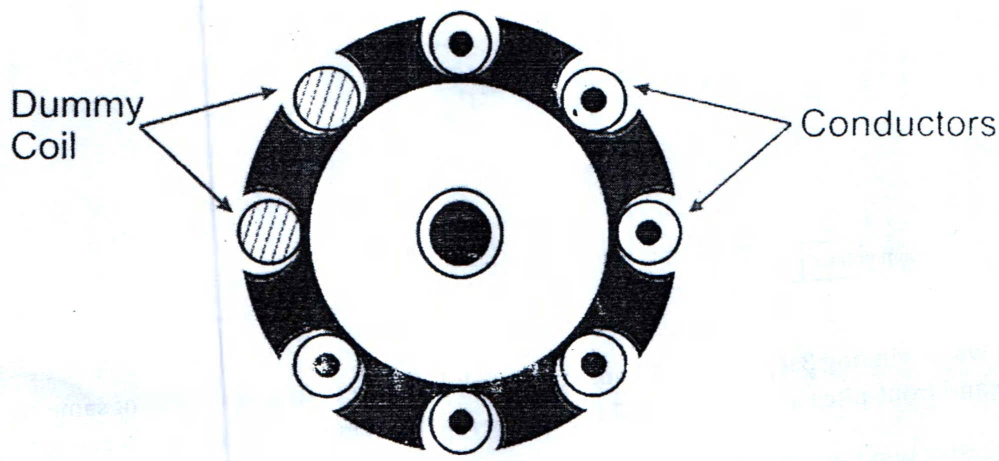
Being fractional no the wave winding is no possible but if there were 6 conductors then the winding can be done. Since,

$$Y_A = \frac{Z \pm 2}{P} = \frac{6 \pm 2}{4} = \frac{8}{4} = 2 \quad \textit{an integer}$$

For this problem the DUMMY COILS are introduced.

Dummy Coil

The wave winding is possible only with particular number of conductors and slots combinations. It is not always possible to have the standard stampings in the winding shop consist of the number of slots according to the design requirements. In such cases dummy coils are employed. These coils are placed in the slots to give the maçhine the mechanical balance but they are not electrically connected to the rest of the winding.



In multiplex wave winding

$$1.\ Y_B = Y_F \pm 2m$$

m is the multiplicity of the winding. m = 1 for simplex winding m = 2 for duplex winding.

2. The average pitch for multiplex wave winding is

$$(Y_A) = \frac{Z \pm 2m}{P}$$

and it must be an integer.

Advantage of Simplex Wave Winding

1. In this winding only two brushes are required but more parallel brushes can be added to make it equal to the number of poles. If one or more brushes set poor contacts with the commutator, satisfactory operation is still possible.
2. This winding gives sparkles commutation. The reason behind that it has two parallel paths irrespective of no of poles of the machine. The conductors in each of the two parallel path distributed around the armature in the entire circumference.
3. No. of conductors in each path = Z/2, Z is the total no. of conductors.

4. Generated emf = average emf induced in each path * Z/2
5. For a given no of poles and armature conductors it gives more emf than that of lap winding. Hence wave winding is used in high voltage and low current machines. This winding is suitable for small generators circuit with voltage rating 500-600V.
6. Current flowing through each conductor.

$$= \frac{current\ per\ path\ (I_a)}{2}$$

Ia is the armature current. Current per path for this kind of winding must not be exceeded 250A.

7. Resultant emf around the entire circuit is zero.

Disadvantage of simplex wave winding

Wave winding cannot be used in the machines having higher current rating because it has only two parallel paths.

Construction of Wave Winding

Let us develop a simplex and progressive wave winding diagram of a machine having 34 conductors in 17 slots and 4 poles.

Average pitch:

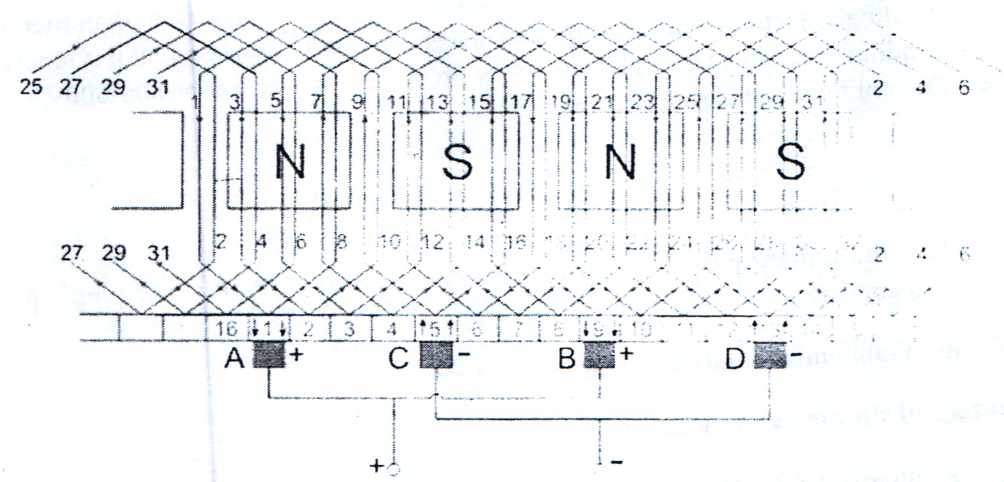
$$Y_A = \frac{Y_B + Y_F}{2} = \frac{Z + 2}{P} = \frac{34 + 2}{4} = 9$$

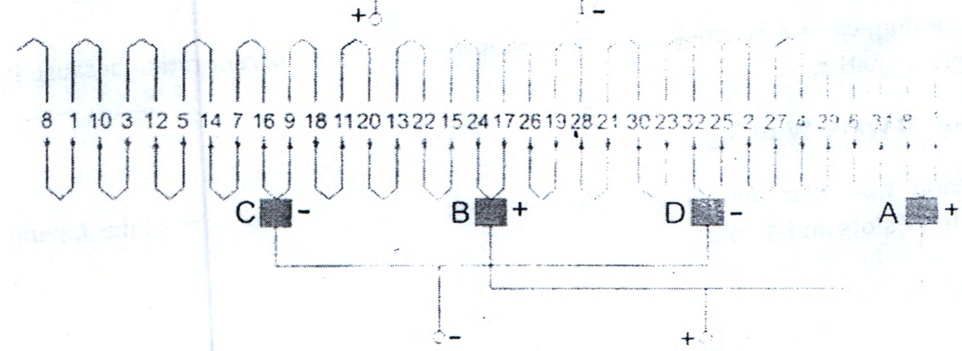
$$Therefore.\ Y_A = Y_B = Y_F = 9$$

Now we have to construct a table for the connection diagram:

Back Connections	Front Connections
1 to $(1+Y_B) = (1 + 9) = 10$	10 to $(10+Y_F) = (10 + 9) = 19$
19 to (19+9)=28	28 to (28+9)=37=(37-34)=3
3 to (3+9)=12	12 to (12+9)=21
21 to (21+9))=30	30 to (30+9)=39=(39-34)=5
5 to (5+9)=14	14 to(14+9)=23
23 to (23+9)=32	32 to (32+9)=41=(41-34)=7
7 to (7+9)=16	16 to (16+9)=25
25 to (25+9)=34	34 to (34+9)=43=(43-34)=9
9 to(9+9)=18	18 to (18+9)=27
27 to (27+9)=26=(36-34)=2	2 to (36+9)=45=(45-34)=11
11 to(11+9)=20	20 to (20+9)=29
29 to (29+9)=38=(38-34)=4	4 to (38+9)=47=(47-34)=13
13 to (13+9)=22	22 to (22+9)=31
31 to (31+9)=40=(40-34)=6	6 to (40+9)=49=(49-34)=15
15 to (15+9)=24	24 to(24+9)=33
33 to (33+9)=42=(42-34)=8	8 to (42+9)=51=(51-34)=17
17 to (17+9)=16	26 to (26+9)=35=(35-34)=1

Winding Diagram





General Rules for DC armature winding design

- Back pitch as well as front pitch should be nearly equal to pole pitch.
- Both back pitch and front pitch value should be an odd number
- Number of commutator segment should be equal to number of slots or coils.
- The armature winding should be an closed circuit.

Selection criteria for lap winding

- It is used when parallel connection of winding is needed.
- It is generally used for machine of rating above 500kW.
- It is used for low voltage and high current machines.
- It requires equalizer rings for obtaining better accommodation.

Selection criteria for wave winding

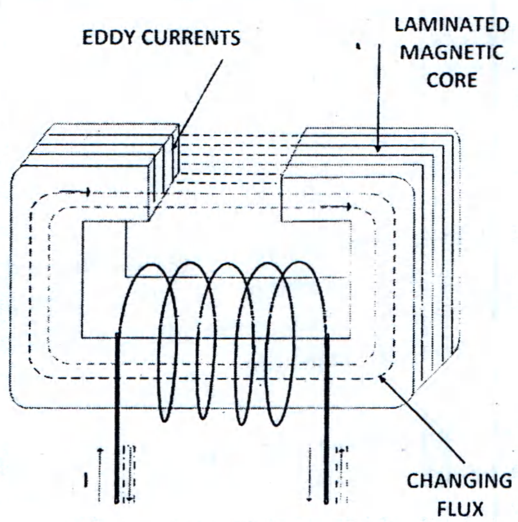
- It is used when series connection of winding is needed.
- It is generally used for machine of rating below 500kW.
- It is used for high voltage and low current machines.
- It requires dummy coils in order to provide mechanical balance for armature.

Eddy Current Loss

When an alternating magnetic field is applied to a magnetic material an emf is induced in the material itself according to Faraday's Law of Electromagnetic induction. Since the magnetic material is a conducting material, these EMFs circulate currents within the body of the material. These circulating currents are called Eddy Currents. They will occur when the conductor experiences a changing magnetic field.

In addition to voltage induced in armature conductor there is some voltage induced in the armature core. This voltage circulates currents within the armature called Eddy Currents.

As these currents are not responsible for doing any useful work, and it produces a loss (I^2R loss) in the magnetic material known as an Eddy Current Loss. Similar to hysteresis loss, eddy current loss also increases the temperature of the magnetic material. The hysteresis and the eddy current losses in a magnetic material are also known by the name iron losses or core losses or magnetic losses.



A sectional view of the magnetic core is shown in the figure above. When the changing flux links with the core itself, it induces emf in the core which in turns sets up the circulating current called Eddy Current and these current in return produces a loss called eddy current loss or (I^2R) loss, where I is the value of the current and R is the resistance of the eddy current path.

If the core is made up of solid iron of larger cross-sectional area, the magnitude of I will be very large and hence losses will be high. To reduce the eddy current loss mainly there are two methods.

- By reducing the magnitude of the eddy current.

  The magnitude of the current can be reduced by splitting the solid core into thin sheets called laminations, in the plane parallel to the magnetic field. Each lamination is insulated from each other by a thin layer of coating of varnish or oxide film. By laminating the core, the area of each section is reduced and hence the induced emf also reduces. As the area through which the current is passed is smaller, the resistance of eddy current path increases.

- The eddy current loss is also reduced by using a magnetic material having the higher value of resistivity like silicon steel.

Mathematical Expression for Eddy Current Loss

It is difficult to determine the eddy current loss from the resistance and current values, but by the experiments, the eddy current power loss in a magnetic material is given by the equation shown below

$$P_e = K_e B_m^2 t^2 f^2 \cdot V \qquad \text{watts}$$

where,
K_e – co-efficient of eddy current. Its value depends upon the nature of magnetic material
B_m – maximum value of flux density in wb/m²
T – thickness of lamination in meters
F – frequency of reversal of magnetic field in Hz
V – volume of magnetic material im m³

Applications of Eddy Currents

As you know that by the effect of Eddy Current the heat which is produced is not utilized for any useful work as they are a major source of energy loss in AC machines like transformer, generators, and motors and, therefore, it is known as an Eddy Current Loss. However, there are some uses of this eddy current like in Induction heating.

- In the case of **induction heating**, an iron shaft is placed as a core of an induction coil. A large amount of heat is produced at the outermost part of the shaft by the eddy current when the high-frequency current is passed through the coil. At the centre of the shaft, the amount of the heat reduces. This is because the outermost periphery of the shaft offers a low resistance path for the eddy currents.This process is used in automobiles for surface hardening of heavy shafts.
- The effect of eddy current is also used in electrical instruments like in induction type energy meters for providing braking torque
- For providing damping torque in permanent magnet moving coil instruments.
- Eddy current instruments are used for detecting cracks in metal parts.
- Used in trains having eddy currents brakes.

The above equation leads to the electro-mechanical energy conversion model shown in the below image.

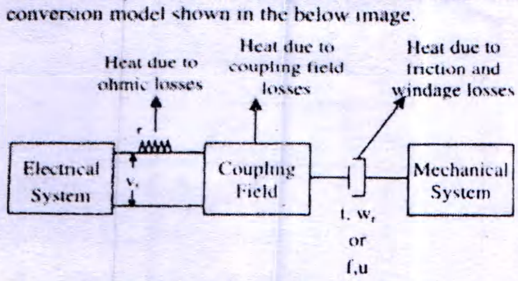


Figure 1.7: General representation of Electro-Mechanical Energy Conversion Device

W_{elec} is the net electrical input to the coupling field. W_{mech} is the total energy converted to mechanical form and it is equal to the sum of useful mechanical energy W_{mo}, mechanical energy stored W_{ms} and mechanical energy losses. W_{fld} is the total energy absorbed by the coupling field and it is equal to the sum of both stored field energy W_{es} and the coupling field energy losses.

Ques 7) Write detailed notes on eddy current and eddy current loss in magnetic circuit and also state how to reduce the eddy current loss considerably?

Ans: Eddy Current

Eddy current occurs when a coil is wrapped around a core and alternating AC supply is applied to it due to this the flux produced in the coil is also alternating. By Faraday's law of electromagnetic induction, the change in flux through the core causes emf induction inside the core. Due to induction of emf eddy current starts to flow in the core.

Eddy Current Loss

Due to this eddy current loss the energy is lost in the form of heat energy. Due to these eddy currents, some energy will be dissipated in the form of heat. It can be given by formulae:

$W_e = K_e (B_{max})^2 f^2 t^2 v$ watts or joules per second

Where, K_e = Eddy Current Constant
v = Volume of the Core in m^3
f = supply frequency in Hz
t = Thickness of lamination in metres

Eddy current losses can be reduced by laminations in the core. Thin sheet steels must be used which are insulated from each other. Due to insulated sheets the amount of current which flows get reduced and hence the eddy current losses.

How to Minimize Eddy Current Losses

1) In order to reduce the eddy current loss, the resistance of the core should be increased. In other words, low reluctance should be retained.
2) In devices like transformers, the core is made up of laminations of iron, i.e., the core is made up of thin sheets of steel, each lamination being insulated from others.
3) ferrite cores or iron dust cores are used.

Ques 8) What is magnetisation and B-H curves?

Or

Draw an explain B-H curve. What is meant by saturation, coercive force, residual magnetism? Show them in the diagram?

Ans: Magnetization

The process in which magnetic materials attains magnetism is called Magnetisation. Magnetism occurs when bringing the magnetic materials near the magnet.

B-H Curves

If an alternating magnetic field is applied to a soft magnetic material, the magnetic induction (B) changes with the magnetic field (H) as shown **figure 1.4.** The hysteresis loop, describing the relation between H and B, is called the magnetisation curve.

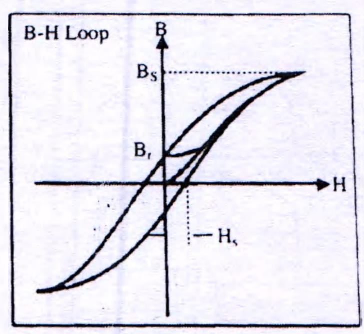


Figure 1.8

Initial Permeability

$$\mu_i = \frac{1}{\mu_o} \cdot \frac{\Delta B}{\Delta H}$$ Where μ_o – permeability of vacuum

The initial permeability μ_i defines the relative permeability at low excitation level.

Saturation Magnetisation, B_s

At high field strength, the induction flattens out at a value, called the saturation flux density, Bs.

Residual Flux Density, B_r

Residual flux density B_r, is a magnetic flux density remaining in material when the magnetic field strength is decreased to zero after being magnetised to its saturation point.

Coercive Field Strength, H_c

The residual flux reduces to zero at a certain reverse field strength which is referred to a coercively H_c.

Ques 9) Draw and explain the flux distribution curve in the air gap for various electrical machines?

Ans: Flux Density Distribution Curve in the Air Gap for Salient Pole Machine

Ideally beyond the pole surface the air gap is supposed to be infinite and hence there should be no flux density beyond the pole surface as it is shown in **figure 1.9.**

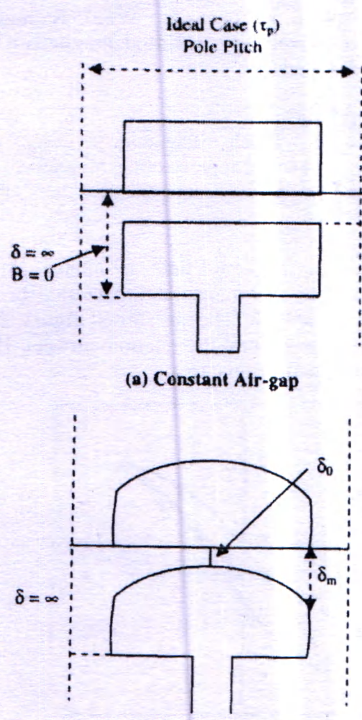


Figure 1.9: Flux Density Distribution Curve (Ideal Case)

$$\text{flux } \phi = \frac{\text{MMF}}{\text{Reluctance}}$$

$$= \frac{\text{MMF}}{1/\mu_0 A}$$

$$= \frac{\text{MMF} \cdot \mu_0 A}{l}$$

$$\text{flux density } B = \frac{\phi}{A} = \frac{\text{MMF} \cdot \mu_0}{l}$$

$$B = \frac{\mu_0 \cdot \text{MMF}}{\text{length of air gap}}$$

When permeability of iron is supposed to be infinite, no mmf will be required for iron portion whole of mmf is required for air gap of the machine.

It can be observed from that when length of air gap is constant, the flux density is constant. When air gap length varies sinusoidally then as the air gap decreases, the flux density increases and as the air gap increases flux density decreases as shown in **figure 1.12** for different type of machines.

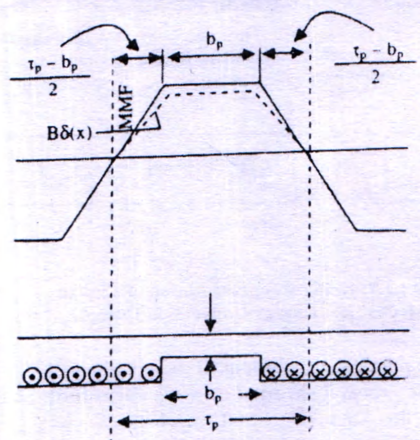


Figure 1.10: MMF and field Distribution Curve of a cylindrical rotor machine

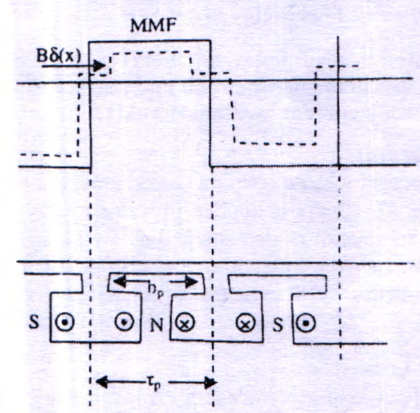


Figure 1.11: MMF and field Distribution curve in the case of salient pole synch, machine having cont. air gap

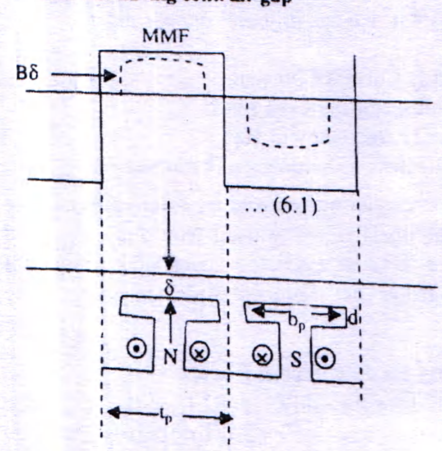


Figure 1.12: MMF and field Distribution curve in salient pole synch, machine having Sinusoidal air gap

Methods to find η:

1) Assuming that both m/c's have same η.
2) Assuming iron, friction and windage losses are same in both the m/c's.

Case (i):

$$\eta_m = \frac{\text{o/p of motor}}{\text{i/p of motor}}$$

$$\text{motor o/p} = \eta_m * \text{motor i/p}$$

$$= \eta_m * V(I_1 + I_2) = \text{generator i/p}$$

$$\eta_g = \frac{\text{generator o/p}}{\text{generator i/p}}$$

$$\text{generator o/p} = \eta_g * \text{generator i/p}$$

$$= \eta_g * \eta_m * V(I_1 + I_2)$$

as per case, $\eta = \eta_m = \eta_g$

$$\therefore \text{Generator output} = \eta^2 * V(I_1 + I_2)$$

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

$$\eta^2 = \frac{VI}{V(I_1 + I_2)}$$

$$\eta = \sqrt{\frac{I}{I_1 + I_2}}$$

Case (ii)

Armature Copper loss in generator $= (I_1 + I_3)^2 R_a$

Armature Copper loss in motor $= (I_1 + I_2 - I_4)^2 R_a$

Shunt copper loss in generator $= VI_3$

Shunt copper loss in motor $= VI_4$

Power drawn from DC supply $= VI_2$ = total losses in motor & generator

$$VI_2 = \text{total Copper loss} + \text{total Iron loss} + \text{total Mechanical loss}$$

$$VI_2 - \text{Copper loss} = \underbrace{\text{Iron loss} + \text{Mechanical loss}}$$

$$VI_2 - \text{Cu. loss} = W$$

$$\therefore W = VI_2 - \left[(I_1 + I_3)^2 R_a + (I_1 + I_2 - I_4)^2 R_a + VI_3 + VI_4\right]$$

where, $\frac{W}{2} \Rightarrow$ (Mech. losses + Iron losses) of each machine

For generator,

Gen. Output $= VI_1$

Total loss $= \frac{W}{2} + (I_1 + I_3)^2 R_a + VI_3$

$$\eta_G = \frac{o/p}{i/p} = \frac{o/p}{i/p + \text{loss}} = \frac{VI_1}{VI_1 + \frac{W}{2} + (I_1 + I_3)^2 R_a + VI_3}$$

For Motor,

Motor input $= V(I_1 + I_2)$

Total loss $= \frac{W}{2} + (I_1 + I_2 - I_4)^2 R_a + VI_4$

$$\eta_m = \frac{o/p}{i/p} = \frac{i/p - \text{losses}}{i/p} = \frac{V(I_1 + I_2) - \left[\frac{W}{2} + (I_1 + I_2 - I_4)^2 R_a + VI_4\right]}{V(I_1 + I_2)}$$

MODULE - 1

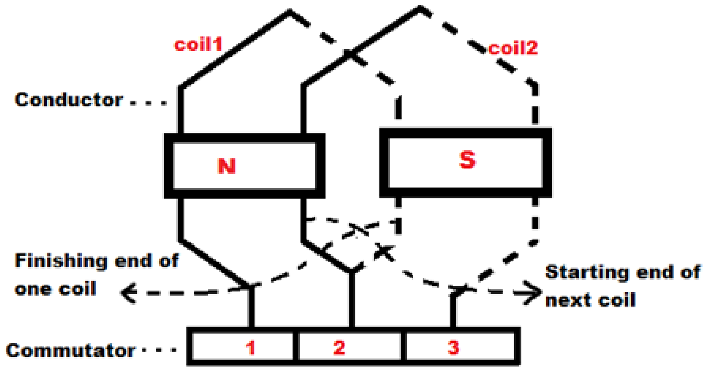
Types of Armature windings

Armature windings are mainly of two types

1. lap winding
2. wave winding

Lap Winding Simplex and Duplex Lap Winding

Lap winding is the winding in which successive coils overlap each other. It is named "Lap" winding because it doubles or laps back with its succeeding coils.



LAP winding

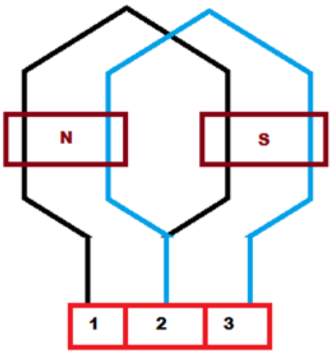
In this winding the finishing end of one coil is connected to one commutator segment and the starting end of the next coil is connected with same commutator segment. Here we can see in picture, the finishing end of coil - 1 and starting end of coil - 2 are both connected to the commutator segment – 2.

Lap winding are of two types –

1. Simplex Lap Winding
2. Duplex Lap Winding

Simplex Lap Winding

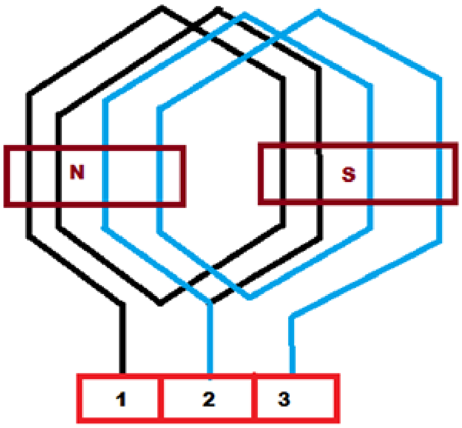
A winding in which the number of parallel path between the brushes is equal to the number of poles is called simplex lap winding.



Simplex lap winding

Duplex Lap Winding

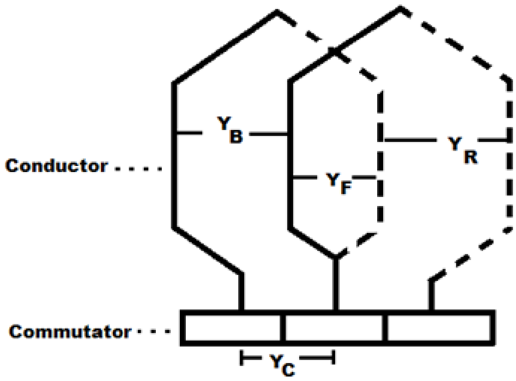
A winding in which the number of parallel path between the brushes is twice the number of poles is called duplex lap winding.



Duplex lap winding

Some important points to remember while designing the Lap winding:

If, Z = the number conductors
P = number of poles
Y_B = Back pitch
Y_F = Front pitch
Y_C = Commutator pitch
Y_A = Average pole pitch
Y_P = Pole pitch
Y_R = Resultant pitch



Then, the back and front pitches are of opposite sign and they cannot be equal.

$Y_B = Y_F \pm 2m$
m = multiplicity of the winding.
m = 1 for Simplex Lap winding
m = 2 for Duplex Lap winding
When,

$Y_B > Y_F$, i.e., $Y_B = Y_F + 2m$, it is called progressive winding.
$Y_B < Y_F$, i.e., $Y_B = Y_F - 2m$, it is called retrogressive winding.
Back pitch and front pitch must be odd integer.

Resultant pitch (Y_R) = $Y_B - Y_F = 2m$

Y_R is even because it is the difference between two odd numbers.

$$Average\ pitch\ (Y_A) = \frac{Y_B + Y_F}{2} = polepitch\ (Y_P) = \frac{Z}{P}$$

$$Y_B = \frac{Z}{P} + 1$$

$$Y_F = \frac{Z}{P} - 1$$

Commutator pitch (Y_C) = ±m
Number of parallel path in the Lap winding = mP

Advantages of Lap Winding

- This winding is necessarily required for large current application because it has more parallel paths.
- It is suitable for low voltage and high current generators.

Disadvantages of Lap Winding

- It gives less emf compared to wave winding. This winding requires more no. of conductors for giving the same emf, it results high winding cost.
- It has less efficient utilization of space in the armature slots.

Equalizer Rings

In lap winding all the conductors in any parallel path lie under one pair of poles. If flux from all the poles is exactly the same, the induced emf in each path hence current carried by each path will be equal.

But in spite of best effort this condition is not practicable either due to variation in gap length or due to different magnetic properties of steel. The currents flowing in various paths may also differ due to difference in their resistances. Hence there is always slight difference in the generated voltage in the various parallel paths, and as a result, large circulating currents flow in the armature winding. These circulating currents not only tend to heat the armature above the temperature cause an undue amount of sparking at the brushes and commutator. Sparking should, of course be avoided, because it causes undue burning and wear of the commutator and brushes and, if carried too far, may result in flash-over from + ve to – ve brushes, a condition representing a short-circuit across the supply lines.

To overcome the detrimental effects resulting from the circulating currents, it is customary to employ equalizer connections in all lap wound armatures. These are low resistance copper wires that connect together points in the armature winding which should, under ideal conditions, be at exactly the same potential at all time but which, because of mechanical and electrical differences, they are not. Thus, the equalizer rings relieve the brushes to the circulating current load by causing the latter to be bypassed.

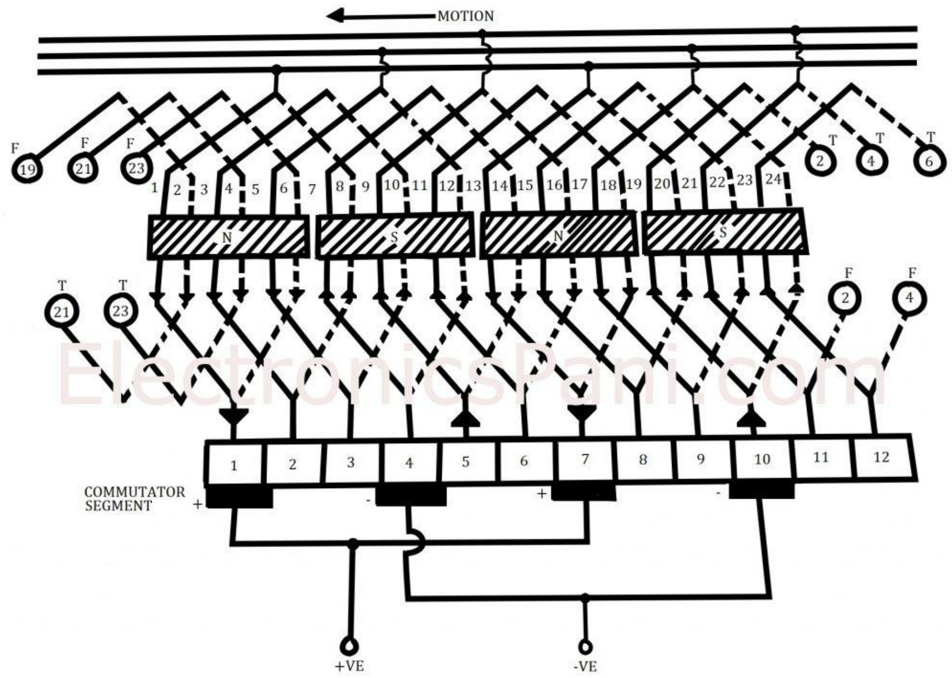


Figure 1: Simplex Lap Winding with Equalizer Connections

To make these equalizer connections, the number of coils should be multiples of the number of poles and the number of coils per pole should be divisible by a small number 2 or 3.

As an example assume a 4-pole generator having 24 coil sides. The number of coil sides per pole will be 6. The winding with equalizer connections is shown in Fig. 1. Note that every 3rd coil is connected to an equalizer. The coils that are connected to the same equalizer occupy the same position relative to the poles. This is necessary as such coils, at any instant, should be generating the same emf.

Note in Fig. 1. that

(i) one equalizer ring is connections to coil side two pole pitch apart,
(ii) number of connections to one equalizing ring is equal to the pair of poles
(iii) number of rings is equal to the number of coils under one pair of poles i.e. equal to {Number of coils / Number of pairs of poles} in case every coil is connected to an equation.

Theoretically, every coil should be connected to an equalizer but as this would require an undue number of equalizers, it is sufficient, practically, to connect every third or fourth coil. This is the reason why the number of coils per pole should be divisible by a small number as 2, 3 or 4. In Fig. 1 alternate coil has been connected to the equalizer ring and in such a case the winding is side to be 50% equalized. If all the coils were connected to the equalizer rings then the winding would have been 100% equalized.

Problem:

- Design a 4 pole simplex lap wound armature containing 8 slots and 2 coil sides per slot.

$$\text{Pole pitch} = \frac{Z}{P} = \frac{8*2}{4} = 4$$

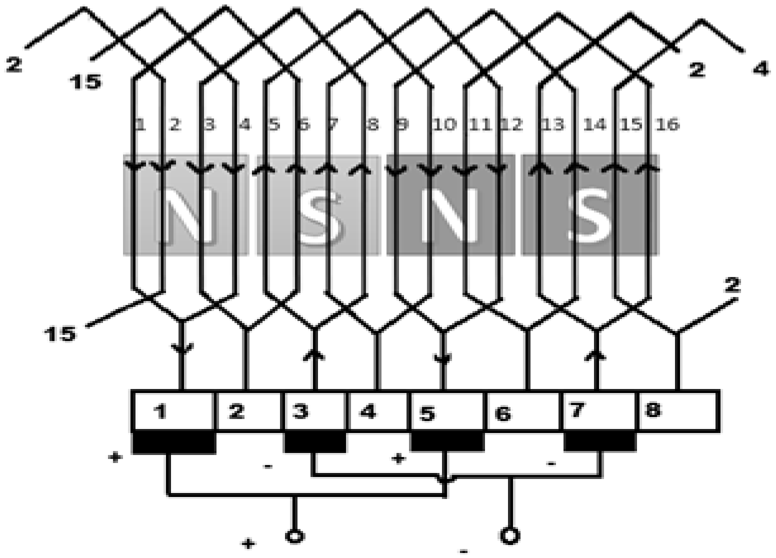
$$Y_B = \frac{Z}{P} + 1 = 4 + 1 = 5$$

$$Y_F = \frac{Z}{P} - 1 = 4 - 1 = 3$$

Number of conductors = 8*2 = 16

Let us start from 1st conductor,

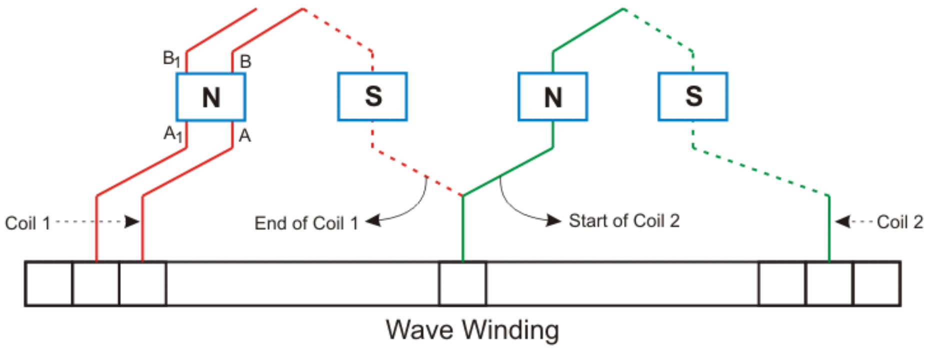
Back connections	Front connections
1 to (1+Y_B) = (1+5) = 6	6 to (6-Y_F) = (6 - 3) = 3
3 to (3+5) = 8	8 to (8-3) = 5
5 to (5+5) = 10	10 to (10-3) = 7
7 to (7+5) = 12	12 to (12-3) = 9
9 to (9+5) = 14	14 to (14-3) = 11
11 to (11+5) = 16	16 to (16-3) =13
13 to (13+5) = 18 = (18-16) = 2	2 to (18-3) = 15
15 to (15+5) = 20 = (20-16) = 4	4 to (20-3) = 17 = (17-16) = 1



Wave winding

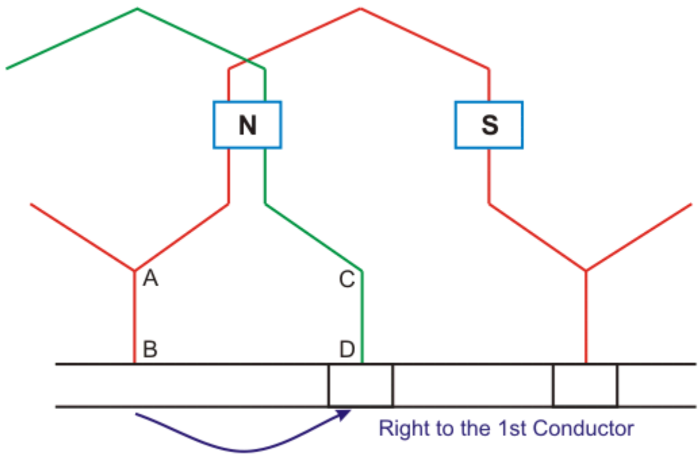
Wave winding is one type of armature winding. In this winding, we connect the end of one coil to the starting of another coil of the same polarity as that of the first coil. In this type of winding the coil side (A - B) progresses forward around the armature to another coil side and goes on successively passing through N and S pole till it returns to a conductor (A1-B1) lying under the starting pole.

This winding forms a wave with its coil, that's why we call it as wave winding. Since we connect the coils in series here, we also call it series winding.



Progressive Wave Winding

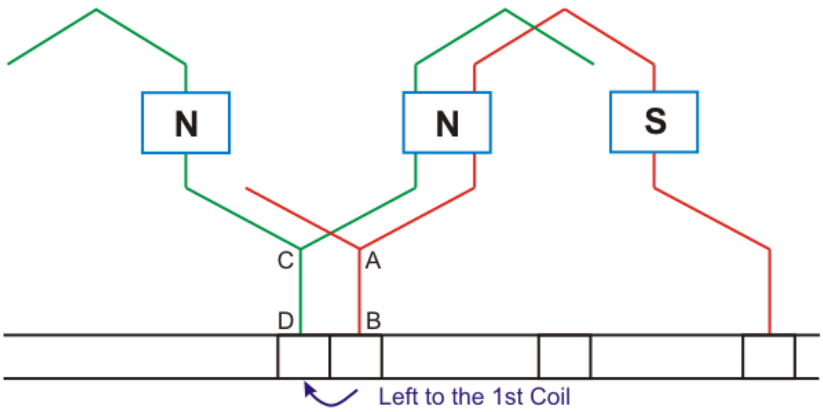
If after one round of the armature the coil falls in a slot right to its starting slot the winging is called Progressive wave winding. progressive wave winding



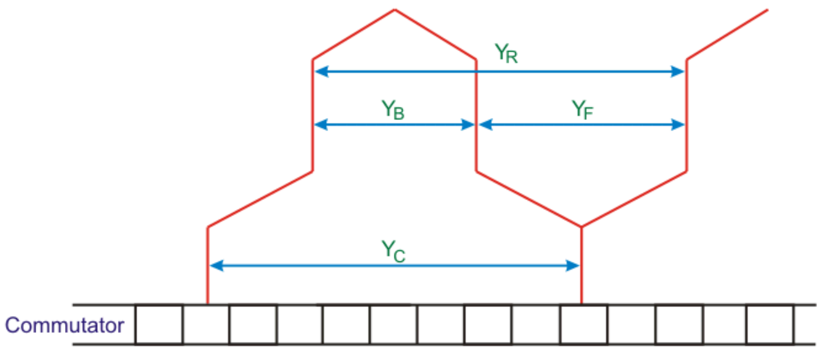
Progressive Wave Winding

Retrogressive Wave Winding

If after one round of the armature the coil falls in a slot left to its starting slot the winging is called Retrogressive wave winding. wave winding Here in the picture above we can see that 2nd conductor CD is in the left of the 1st conductor.



Important Points about Wave Winding



Wave Winding

In simplex wave winding Back pitch (YB) and front pitch (YF) are both odd and are of same sign. Back-pitch and front-pitch are nearly equal to the pole pitch and may be equal or differ by ±2.

+ for progressive winding, - for retrogressive winding.

$$Resultant\ pitch\ Y_R = Y_B + Y_F$$

$$Commutator\ pitch\ (Y_C) = average\ pitch\ (Y_A)$$

$$Average\ pitch\ Y_A = \frac{Y_B + Y_F}{2} = \frac{Z \pm 2}{P}$$

$$Therefore,\ Y_A = Y_B = Y_F$$

Here, Z is the no of conductors in the winding. P is the no of poles. Average pitch (YA) must be an integer number, because it may close itself. We take ± 2 (two) because after one round of the armature the winding falls sort of two conductors. If we take an average pitch Z/P then after one round the winding will close itself without including all coil sides. Since average pitch must be an integer, this winding is not possible with any no. of conductors. Let us take 8 conductors in a 4 pole machine.

$$Then,\ Y_A = \frac{Z \pm 2}{P} = \frac{8 \pm 2}{4} = \frac{10}{4} = 2\frac{1}{2}\ or\ 3\frac{1}{2}$$

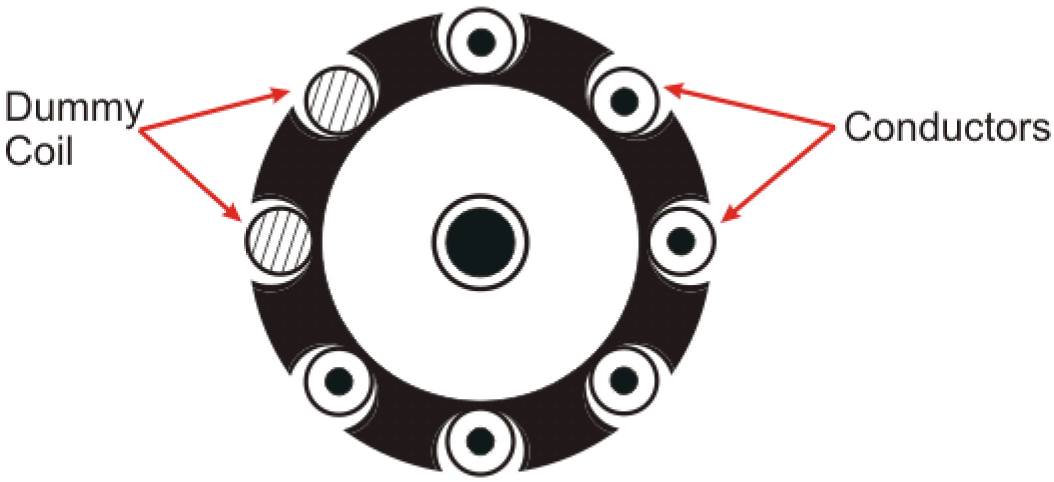
Being fractional no the wave winding is no possible but if there were 6 conductors then the winding can be done. Since,

$$Y_A = \frac{Z \pm 2}{P} = \frac{6 \pm 2}{4} = \frac{8}{4} = 2 = an\ integer.$$

For this problem the DUMMY COILS are introduced.

Dummy Coil

The wave winding is possible only with particular number of conductors and slots combinations. It is not always possible to have the standard stampings in the winding shop consist of the number of slots according to the design requirements. In such cases dummy coils are employed. These coils are placed in the slots to give the machine the mechanical balance but they are not electrically connected to the rest of the winding.



In multiplex wave winding

$$1.\ Y_B = Y_F \pm 2m$$

m is the multiplicity of the winding. m = 1 for simplex winding m = 2 for duplex winding.

$$2.\ The\ average\ pitch\ for\ multiplex\ wave\ winding\ is$$

$$(Y_A) = \frac{Z \pm 2m}{P}$$

$$and\ it\ must\ be\ an\ integer.$$

Advantage of Simplex Wave Winding

1. In this winding only two brushes are required but more parallel brushes can be added to make it equal to the number of poles. If one or more brushes set poor contacts with the commutator, satisfactory operation is still possible.
2. This winding gives sparkles commutation. The reason behind that it has two parallel paths irrespective of no of poles of the machine. The conductors in each of the two parallel path distributed around the armature in the entire circumference.
3. No. of conductors in each path = Z/2, Z is the total no. of conductors.
4. Generated emf = average emf induced in each path * Z/2
5. For a given no of poles and armature conductors it gives more emf than that of lap winding. Hence wave winding is used in high voltage and low current machines. This winding is suitable for small generators circuit with voltage rating 500-600V.
6. Current flowing through each conductor.

$$= \frac{current\ per\ path\ (I_a)}{2}$$

Ia is the armature current. Current per path for this kind of winding must not be exceeded 250A.

7. Resultant emf around the entire circuit is zero.

Disadvantage of simplex wave winding

Wave winding cannot be used in the machines having higher current rating because it has only two parallel paths.

Construction of Wave Winding

Let us develop a simplex and progressive wave winding diagram of a machine having 34 conductors in 17 slots and 4 poles.

Average pitch:

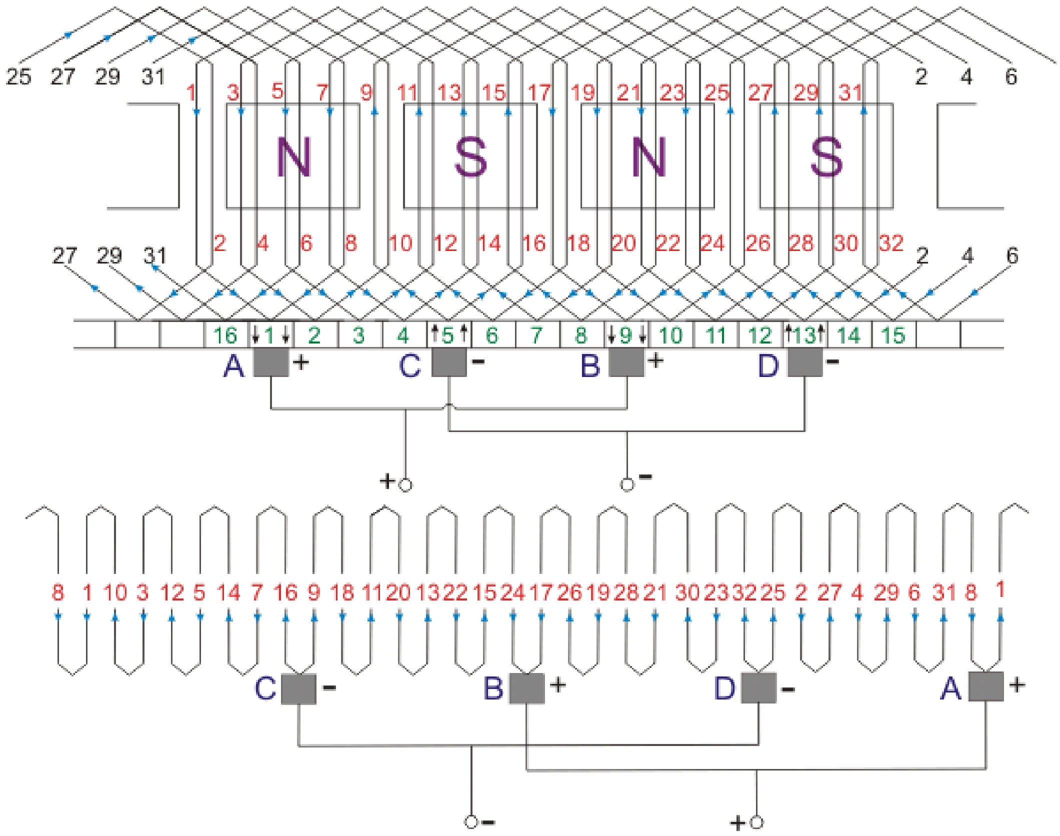
$$Y_A = \frac{Y_B + Y_F}{2} = \frac{Z+2}{P} = \frac{34 + 2}{4} = 9$$

$$Therefore,\ Y_A = Y_B = Y_F = 9$$

Now we have to construct a table for the connection diagram:

Back Connections	Front Connections
1 to (1+Y_B) $= (1 + 9) = 10$	10 to (10+Y_F) $= (10 + 9) = 19$
19 to (19+9)=28	28 to (28+9)=37=(37-34)=3
3 to (3+9)=12	12 to (12+9)=21
21 to (21+9))=30	30 to (30+9)=39=(39-34)=5
5 to (5+9)=14	14 to(14+9)=23
23 to (23+9)=32	32 to (32+9)=41=(41-34)=7
7 to (7+9)=16	16 to (16+9)=25
25 to (25+9)=34	34 to (34+9)=43=(43-34)=9
9 to(9+9)=18	18 to (18+9)=27
27 to (27+9)=26=(36-34)=2	2 to (36+9)=45=(45-34)=11
11 to(11+9)=20	20 to (20+9)=29
29 to (29+9)=38=(38-34)=4	4 to (38+9)=47=(47-34)=13
13 to (13+9)=22	22 to (22+9)=31
31 to (31+9)=40=(40-34)=6	6 to (40+9)=49=(49-34)=15
15 to (15+9)=24	24 to(24+9)=33
33 to (33+9)=42=(42-34)=8	8 to (42+9)=51=(51-34)=17
17 to (17+9)=16	26 to (26+9)=35=(35-34)=1

Winding Diagram



General Rules for DC armature winding design

- Back pitch as well as front pitch should be nearly equal to pole pitch.
- Both back pitch and front pitch value should be an odd number
- Number of commutator segment should be equal to number of slots or coils.
- The armature winding should be an closed circuit.

Selection criteria for lap winding

- It is used when parallel connection of winding is needed.
- It is generally used for machine of rating above 500kW.
- It is used for low voltage and high current machines.
- It requires equalizer rings for obtaining better accommodation.

Selection criteria for wave winding

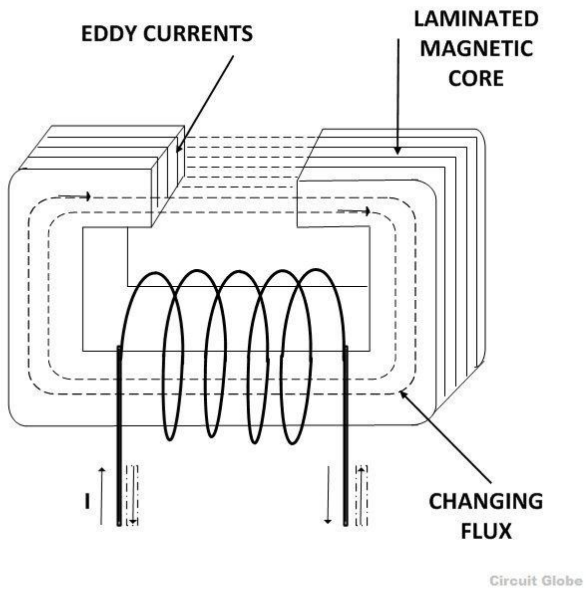
- It is used when series connection of winding is needed.
- It is generally used for machine of rating below 500kW.
- It is used for high voltage and low current machines.
- It requires dummy coils in order to provide mechanical balance for armature.

Eddy Current Loss

When an alternating magnetic field is applied to a magnetic material an emf is induced in the material itself according to Faraday's Law of Electromagnetic induction. Since the magnetic material is a conducting material, these EMFs circulate currents within the body of the material. These circulating currents are called Eddy Currents. They will occur when the conductor experiences a changing magnetic field.

In addition to voltage induced in armature conductor there is some voltage induced in the armature core. This voltage circulates currents within the armature called Eddy Currents.

As these currents are not responsible for doing any useful work, and it produces a loss (I^2R loss) in the magnetic material known as an Eddy Current Loss. Similar to hysteresis loss, eddy current loss also increases the temperature of the magnetic material. The hysteresis and the eddy current losses in a magnetic material are also known by the name iron losses or core losses or magnetic losses.



A sectional view of the magnetic core is shown in the figure above. When the changing flux links with the core itself, it induces emf in the core which in turns sets up the circulating current called Eddy Current and these current in return produces a loss called eddy current loss or (I^2R) loss, where I is the value of the current and R is the resistance of the eddy current path.

If the core is made up of solid iron of larger cross-sectional area, the magnitude of I will be very large and hence losses will be high. To reduce the eddy current loss mainly there are two methods.

- By reducing the magnitude of the eddy current.

  The magnitude of the current can be reduced by splitting the solid core into thin sheets called laminations, in the plane parallel to the magnetic field. Each lamination is insulated from each other by a thin layer of coating of varnish or oxide film. By laminating the core, the area of each section is reduced and hence the induced emf also reduces. As the area through which the current is passed is smaller, the resistance of eddy current path increases.

- The eddy current loss is also reduced by using a magnetic material having the higher value of resistivity like silicon steel.

Mathematical Expression for Eddy Current Loss

It is difficult to determine the eddy current loss from the resistance and current values, but by the experiments, the eddy current power loss in a magnetic material is given by the equation shown below

$$P_e = K_e B_m^2 t^2 f^2 V \qquad \text{watts}$$

where,
K_e – co-efficient of eddy current. Its value depends upon the nature of magnetic material
B_m – maximum value of flux density in wb/m^2

T – thickness of lamination in meters
F – frequency of reversal of magnetic field in Hz
V – volume of magnetic material im m^3

Applications of Eddy Currents

As you know that by the effect of Eddy Current the heat which is produced is not utilized for any useful work as they are a major source of energy loss in AC machines like transformer, generators, and motors and, therefore, it is known as an Eddy Current Loss. However, there are some uses of this eddy current like in Induction heating.

- In the case of **induction heating**, an iron shaft is placed as a core of an induction coil. A large amount of heat is produced at the outermost part of the shaft by the eddy current when the high-frequency current is passed through the coil. At the centre of the shaft, the amount of the heat reduces. This is because the outermost periphery of the shaft offers a low resistance path for the eddy currents.This process is used in automobiles for surface hardening of heavy shafts.
- The effect of eddy current is also used in electrical instruments like in induction type energy meters for providing braking torque
- For providing damping torque in permanent magnet moving coil instruments.
- Eddy current instruments are used for detecting cracks in metal parts.
- Used in trains having eddy currents brakes.

MODULE - 2

Types of DC Generators

The mmf necessary to establish flux in the magnetic circuit of a dc generator can be obtained by means of

- i. Permanent magnets
- ii. Field coils excited from some external source and
- iii. Field coils excited by the generator itself.

Generators are generally classified according to these methods of field excitation. On this basis, dc generators are divided into the following two classes:

1. Permanent magnet dc generators
2. Separately excited dc generators
3. Self excited dc generators

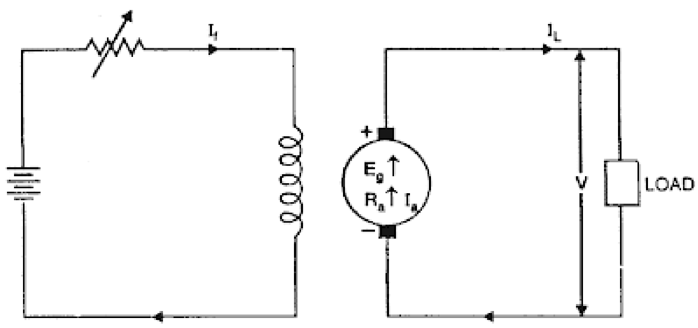
In permanent magnet dc machines, permanent magnet is used to establish flux in the magnetic circuit.

These generators are not found in industrial applications because of the low power generated from it. Such generators are employed only in small sizes like dynamos in motor cycles.
The behavior of a dc generator on load depends upon the method of field excitation adopted.

Separately Excited D.C. Generators

A dc generator whose field magnet winding is supplied from an independent external d.c. source (e.g., a battery etc.) is called a separately excited generator. Figure shows the connections of a separately excited generator. The voltage output depends upon the speed of rotation of armature and the field current ($E_g = \varphi ZNP/60A$). The greater the speed and field current, greater is the generated e.m.f.

It may be noted that separately excited d.c. generators are rarely used in practice. The d.c. generators are normally of self excited type.



Armature current, $I_a = I_L$
Terminal voltage, $V = E_g - I_aR_a$

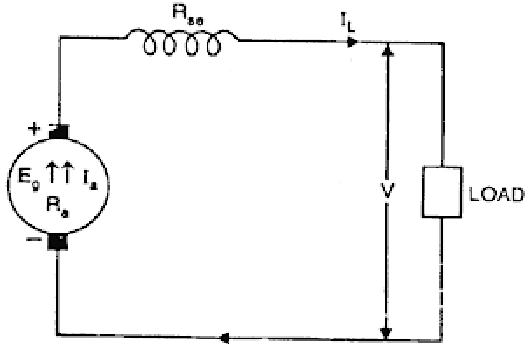
Electric power developed = E_gI_a
Power delivered to load = E_gI_a - I R = I E - I R = VI_a

Self-Excited D.C. Generators

A d.c. generator whose field magnet winding is supplied current from the output of the generator itself is called a self-excited generator. There are three types of self-excited generators depending upon the manner in which the field winding is connected to the armature, namely;

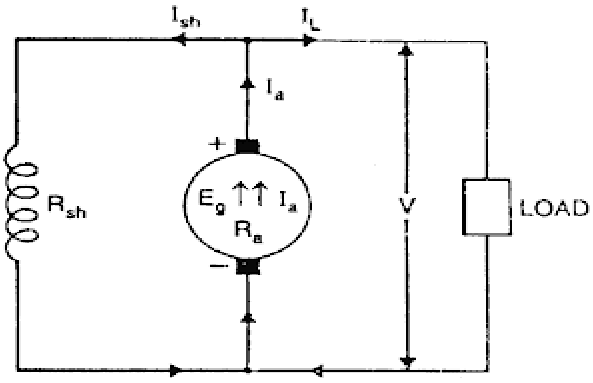
- i. Series generator
- ii. Shunt generator
- iii. Compound generator

Series generator
In a series wound generator, the field winding is connected in series with armature winding so that whole armature current flows through the field winding as well as the load. Figure shows the connections of a series wound generator. Since the field winding carries the whole of load current, it has a few turns of thick wire having low resistance. Series generators are rarely used except for special purposes e.g., as boosters.



Armature current, $I_a = I_{se} = I_L = I$ (say)
Terminal voltage, $V = E_G - I(R_a + R_{se})$
Power developed in armature = E_gI_a
Power delivered to load= VI_L

Shunt generator
In a shunt generator, the field winding is connected in parallel with the armature winding so that terminal voltage of the generator is applied across it. The shunt field winding has many turns of fine wire having high resistance. Therefore, only a part of armature current flows through shunt field winding and the rest flows through the load. Fig. (1.34) shows the connections of a shunt-wound generator.



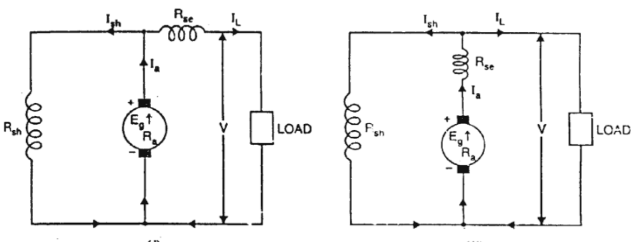
Shunt field current, $I_{sh} = V/R_{sh}$
Armature current, $I_a = I_L + I_{sh}$
Terminal voltage, $V = E_g - I_aR_a$
Power developed in armature = E_gI_a
Power delivered to load = VI_L

Compound generator

In a compound-wound generator, there are two sets of field windings on each pole - one is in series and the other in parallel with the armature. A compound wound generator may be:

• Short Shunt in which only shunt field winding is in parallel with the armature winding.

• Long Shunt in which shunt field winding is in parallel with both series field and armature winding.



Long shunt

Series field current, $I_{se} = I_a = I_L + I_{sh}$
Shunt field current, $I_{sh} = V/R_{sh}$
Terminal voltage, $V = E_g - I_a(R_a + R_{se})$
Power developed in armature = E_gI_a
Power delivered to load = VI_L

Short shunt

Series field current, $I_{se} = I_L$
Shunt field current,

Terminal voltage, $V = E_g - I_aR_a - I_{se}R_{se}$
Power developed in armature = E_gI_a
Power delivered to load = VI_L

In a compound generator the major portion of excitation is usually supplied by the shunt field. The shunt field is slightly weaker and the series field is considerably weaker than those of the corresponding machine in which the entire excitation is produced by a single shunt or a single series winding.

Compound wound generators are of two types, known as cumulative wound and differential wound generators. In cumulative wound generators the series field assists the shund field, whereas in differential wound generators, series field opposes the shunt field.

Armature Reaction in DC Generator

There are two windings in a dc generator and a dc motor:

- Field winding
- Armature winding.

The purpose of field winding is to produce magnetic field (called main flux) whereas the purpose of armature winding is to carry armature current.

Although the armature winding is not provided for the purpose of producing a magnetic field, still the current in the armature winding also produces a magnetic flux (called armature flux).

The armature flux distorts and weakens the main flux and create problems for the proper operation of the dc machines. The action of armature flux on the main flux is called **armature reaction in a dc generator**.

The phenomenon of **armature reaction in a dc generator** is shown in figure below. For the sake of clarity we are taking only one pole.

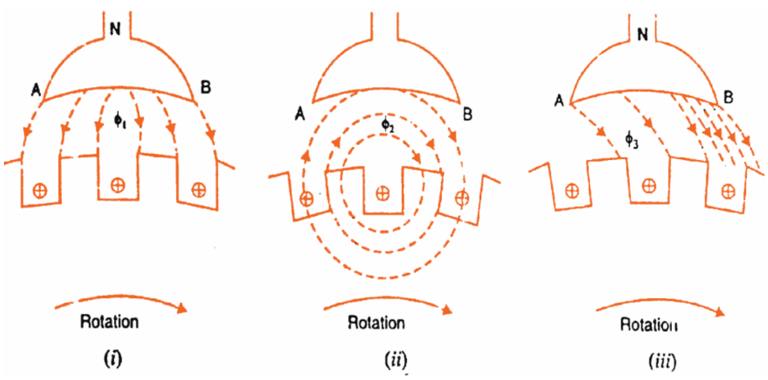


Figure (i)

When the generator is on no-load, a small current is flowing through the armature and therefore flux produced in the armature is very small and it does not affect the main flux φ_1 coming from the pole.

Figure (ii)

When the generator is loaded, high current start flowing through the armature conductors, thus a high flux φ_2 is set up as shown in fig (ii).

Figure (iii)

By superimposing the fluxes φ_1 and φ_2, we obtain the resulting flux φ_3 as shown in fig (iii). This is what happens to the flux under one pole under **armature reaction in a dc generator**. From fig (iii) it is clear that flux density at the trailing pole tip (point B) is increased while at the leading pole tip (point A) it is decreased.

This unequal field distribution due to **armature reaction in dc generator** produces the following two effects:

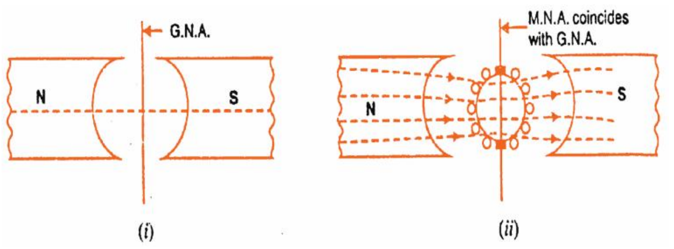
1. The main flux is distorted.
2. The main Flux is weakened.

The weakening of flux due to **armature reaction in a dc generator** also depends on the position of the brushes. For that we need to understand the geometrical and magnetic neutral axes.

Geometrical and Magnetic Neutral Axes

The geometrical neutral axis and magnetic neutral axis should be clearly understood in order to get a clear idea of **armature reaction in a dc generator**.

- The geometrical neutral axis (GNA.) is the axis that bisects the angle between the centre line of adjacent poles.
- The magnetic neutral axis (MNA.) is the axis drawn perpendicular to the mean direction of the flux passing through the centre of the armature. Noo e.m.f. is produced in the armature conductors along this axis because then they cut no flux. When no current is there in the armature conductors, the MNA coincides with GNA.



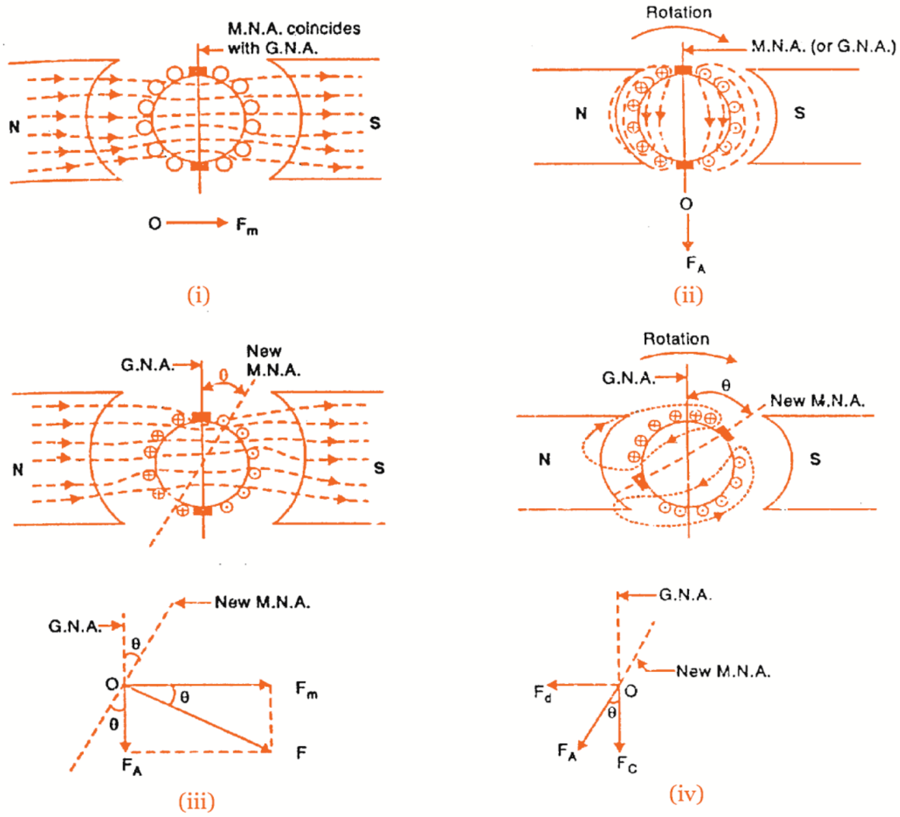
Explanation of Armature Reaction

The **armature reaction in a dc generator** is explained as below,

Consider no current in armature conductors, then MNA coincides with GNA. Now, when current start flowing through the armature conductors, due to the combined action of main flux and armature flux the MNA get shifted from GNA. In case of a generator, the M.N.A. is shifted in the direction of rotation of the machine. In order to achieve sparkless commutation, the brushes should be moved along the new MNA.
Under such a condition, the **armature reaction in a dc generator** produces the following two effects:

1. It demagnetizes or weakens the main flux.
2. It cross-magnetizes or distorts the main flux.

Let us discuss these effects of **armature reaction in a dc generator** by considering a 2-pole generator (though the following remarks also hold good for a multipolar generator).



1. Fig (i) shows the flux due to main poles (main flux) when the armature conductors carry no current. The flux across the air gap is uniform. The m.m.f. producing the main flux is represented in magnitude and direction by the vector OF_m in fig (i). Note that OF_m is perpendicular to GNA.

2. Fig (ii) shows the flux due to current flowing in armature conductors of dc generator alone (main poles unexcited). The armature conductors to the left of GNA. carry current "in" (×) and those to the right carry current "out" (•). The direction of magnetic lines of force can be found by cork screw rule. It is clear that armature flux is directed downward parallel to the brush axis. The m.m.f. producing the armature flux is represented in magnitude and direction by the vector OF_A in fig (ii).
3. Fig (iii) shows the flux due to the main poles and that due to current in armature conductors acting together. The resultant m.m.f. OF is the vector sum of OF_m and OF_A as shown in fig (iii). Since MNA. is always perpendicular to the resultant m.m.f., the MNA. is shifted through an angle θ. Note that MNA. is shifted in the direction of rotation of the generator.
4. In order to achieve sparkless commutation, the brushes must lie along the MNA. Consequently, the brushes are shifted through an angle θ so as to lie along the new MNA. as shown in Fig (iv). Due to brush shift, the m.m.f. FA of the armature is also rotated through the same angle θ. It is because some of the conductors which were earlier under N-pole now come under S-pole and vice-versa. The result is that armature m.m.f. F_A will no longer be vertically downward but will be rotated in the direction of rotation through an angle θ as shown in Fig (iv). Now F_A can be resolved into rectangular components F_c and F_d.

   - (a) The component F_d is in direct opposition to the m.m.f. OF_m due to main poles. It has a demagnetizing effect on the flux due to main poles. For this reason, it is called the demagnetizing or weakening component of **armature reaction in dc machines**.
   - (b) The component F_c is at right angles to the m.m.f. OF_m due to main poles. It distorts the main field. For this reason, it is called the cross magnetizing or distorting component of **armature reaction in dc machines**.

It may be noted that with the increase of armature current, both demagnetizing and distorting effects will increase.

How to Minimise Effect of Armature Reaction?

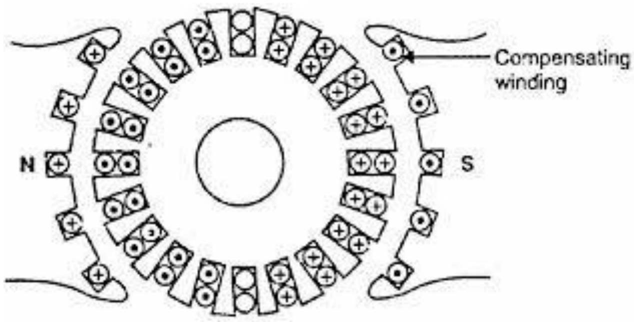
One easy and simplest way is to shift the brushes to the new position of magnetic neutral plane. Shifting the brushes to the advanced position (the new neutral plane) does not completely solve the problems of armature reaction. The effect of armature reaction varies with the load current. Therefore, each time the load current varies, the neutral plane shifts. This means the brush position must be changed each time the load current varies.

Where Compensating windings and Interpoles are Used?

In small generators, the effects of armature reaction are reduced by actually mechanically shifting the position of the brushes. The practice of shifting the brush position for each current variation is not practiced except in small generators. In larger generators, other means are taken to eliminate armature reaction. Compensating Windings or Interpoles are used for this purpose.

Compensating Windings

The cross-magnetizing effect of armature reaction may cause trouble in d.c. machines subjected to large fluctuations in load. In order to neutralize the cross magnetizing effect of armature reaction, a compensating winding is used.



The compensating windings consist of a series of coils embedded in slots in the pole faces. These coils are connected in series with the armature. The series-connected compensating windings produce a magnetic field, which varies directly with armature current. Because the compensating windings are wound to produce a field that opposes the magnetic field of the armature, they tend to cancel the cross magnetizing effect of the armature magnetic field.

The neutral plane will remain stationary and in its original position for all values of armature current. Because of this, once the brushes have been set correctly, they do not have to be moved again.

Interpoles

Another way to reduce the effects of armature reaction is to place small auxiliary poles called "interpoles" between the main field poles. The interpoles have a few turns of large wire and are connected in series with the armature.

Interpoles are wound and placed so that each interpole has the same magnetic polarity as the main pole ahead of it, in the direction of rotation. The field generated by the interpoles produces the same effect as the compensating winding.

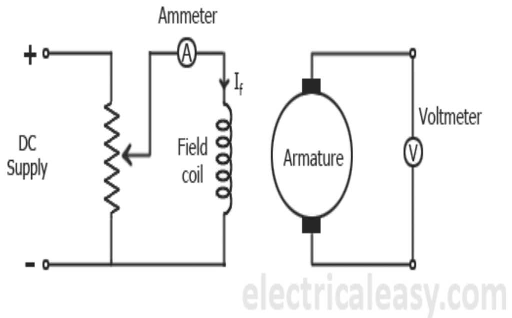
This field, in effect, cancels the armature reaction for all values of load current by causing a shift in the neutral plane opposite to the shift caused by armature reaction. The amount of shift caused by the interpoles will equal the shift caused by armature reaction since both shifts are a result of armature current.

Characteristics of DC Generators

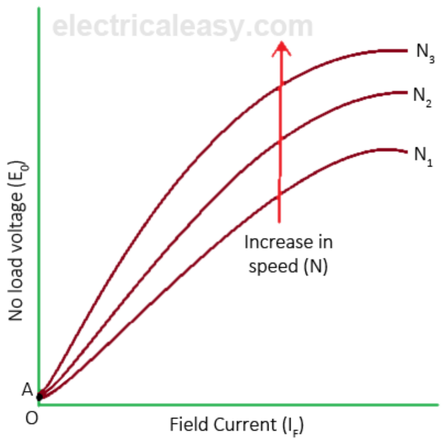
Generally, following three characteristics of DC generators are taken into considerations: (i) Open Circuit Characteristic (O.C.C.), (ii) Internal or Total Characteristic and (iii) External Characteristic. These **characteristics of DC generators** are explained below.

1. Open Circuit Characteristic (O.C.C.) (E_0/I_f)

Open circuit characteristic is also known as **magnetic characteristic** or **no-load saturation characteristic**. This characteristic shows the relation between generated emf at no load (E_0) and the field current (I_f) at a given fixed speed. The O.C.C. curve is just the magnetization curve and it is practically similar for all type of generators. The data for O.C.C. curve is obtained by operating the generator at no load and keeping a constant speed. Field current is gradually increased and the corresponding terminal voltage is recorded. The connection arrangement to obtain O.C.C. curve is as shown in the figure below. For shunt or series excited generators, the field winding is disconnected from the machine and connected across an external supply.



Now, from the emf equation of dc generator, we know that $E_g = k\phi$. Hence, the generated emf should be directly proportional to field flux (and hence, also directly proportional to the field current). However, even when the field current is zero, some amount of emf is generated (represented by OA in the figure below). This initially induced emf is due to the fact that there exists some residual magnetism in the field poles. Due to the residual magnetism, a small initial emf is induced in the armature. This initially induced emf aids the existing residual flux, and hence, increasing the overall field flux. This consequently increases the induced emf. Thus, O.C.C. follows a straight line. However, as the flux density increases, the poles get saturated and the ϕ becomes practically constant. Thus, even we increase the I_f further, ϕ remains constant and hence, E_g also remains constant. Hence, the O.C.C. curve looks like the B-H characteristic.



Open Circuit Characteristic (O.C.C.)

The above figure shows a typical no-load saturation curve or open circuit characteristics for all types of DC generators.

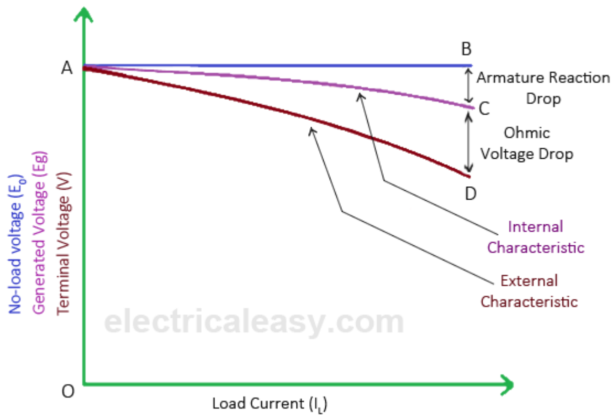
2. Internal or Total Characteristic (E/I_a)

An internal characteristic curve shows the relation between the on-load generated emf (E_g) and the armature current (I_a). The on-load generated emf E_g is always less than E_0 due to the armature reaction. E_g can be determined by subtracting the drop due to demagnetizing effect of armature reaction from no-load voltage E_0. Therefore, internal characteristic curve lies below the O.C.C. curve.

3. External Characteristic (V/I_L)

An external characteristic curve shows the relation between terminal voltage (V) and the load current (I_L). Terminal voltage V is less than the generated emf E_g due to voltage drop in the armature circuit. Therefore, external characteristic curve lies below the internal characteristic curve. External characteristics are very important to determine the suitability of a generator for a given purpose. Therefore, this type of characteristic is sometimes also called as **performance characteristic** or **load characteristic**.

Characteristics of separately excited DC Generator

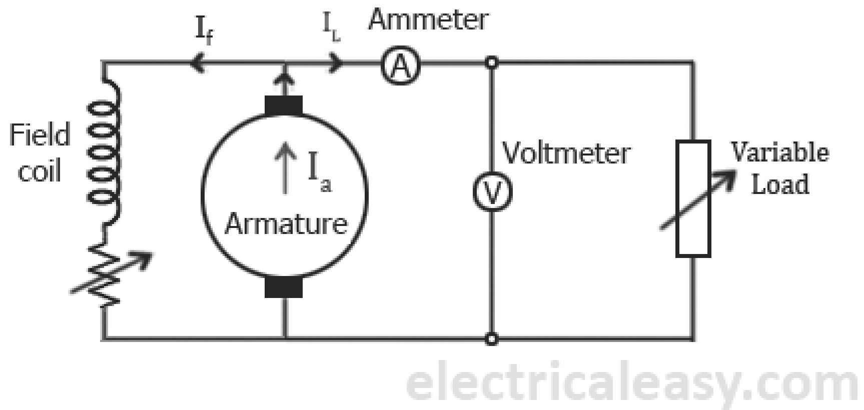


Characteristics of separately excited DC generator

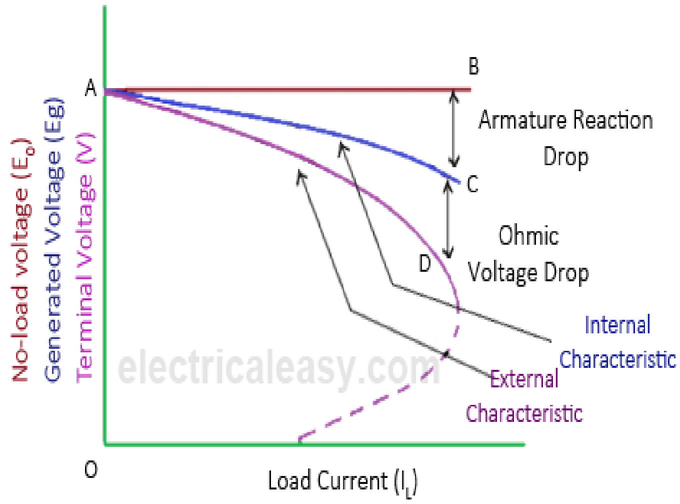
If there is no armature reaction and armature voltage drop, the voltage will remain constant for any load current. Thus, the straight lines AB in above figure represents the no-load voltage vs load current I_L. Due to the demagnetizing effect of armature reaction, the on-load generated emf is less than the no-load voltage. The curve AC represents the on-load generated emf E_g vs load current I_L i.e. internal characteristic (as $I_a = I_L$ for a separately excited dc generator). Also, the terminal voltage is lesser due to ohmic drop occurring in the armature and brushes. The curve AD represents the terminal voltage vs. load current i.e. external characteristic.

Characteristics of DC Shunt Generator

To determine the internal and external load characteristics of a DC shunt generator the machine is allowed to build up its voltage before applying any external load. To build up voltage of a shunt generator, the generator is driven at the rated speed by a prime mover. Initial voltage is induced due to residual magnetism in the field poles. The generator builds up its voltage as explained by the O.C.C. curve. When the generator has built up the voltage, it is gradually loaded with resistive load and readings are taken at suitable intervals. Connection arrangement is as shown in the figure below.



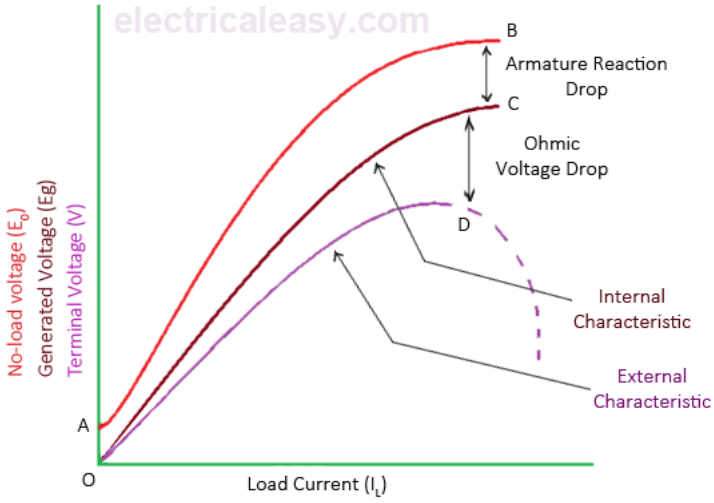
Unlike, separately excited DC generator, here, $I_L \neq I_a$. For a shunt generator, $I_a = I_L + I_f$. Hence, the internal characteristic can be easily transmitted to Eg vs. I_L by subtracting the correct value of I_f from I_a.



Characteristics of DC shunt generator

During a normal running condition, when load resistance is decreased, the load current increases. But, as we go on decreasing the load resistance, terminal voltage also falls. So, load resistance can be decreased up to a certain limit, after which the terminal voltage drastically decreases due to excessive armature reaction at very high armature current and increased I^2R losses. Hence, beyond this limit any further decrease in load resistance results in decreasing load current. Consequently, the external characteristic curve turns back as shown by dotted line in the above figure.

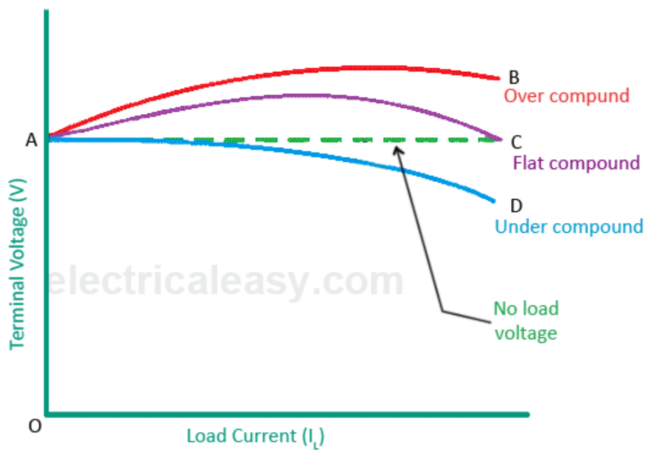
Characteristics of DC Series Generator



Characteristics of DC series generator

The curve AB in above figure identical to open circuit characteristic (O.C.C.) curve. This is because in DC series generators field winding is connected in series with armature and load. Hence, here load current is similar to field current (i.e. $I_L = I_f$). The curve OC and OD represent internal and external characteristic respectively. In a DC series generator, terminal voltage increases with the load current. This is because, as the load current increases, field current also increases. However, beyond a certain limit, terminal voltage starts decreasing with increase in load. This is due to excessive demagnetizing effects of the armature reaction.

Characteristics of DC Compound Generator



External characteristic of DC compound generator

The above figure shows the external characteristics of DC compound generators. If series winding amp-turns are adjusted so that, increase in load current causes increase in terminal voltage then the generator is called to be over compounded. The external characteristic for over compounded generator is shown by the curve AB in above figure. If series winding amp-turns are adjusted so that, the terminal voltage remains constant even the load current is increased, then the generator is called to be flat compounded. The external characteristic for a flat compounded generator is shown by the curve AC. If the series winding has lesser number of turns than that would be required to be flat compounded, then the generator is called to be under compounded. The external characteristics for an under compounded generator are shown by the curve AD.

Losses in DC Machine

As we know "Energy neither can be created nor it can be destroyed, it can only be transferred from one form to another". In DC machine, mechanical energy is converted into the electrical energy. During this process, the total input power is not transformed into output power. Some part of input power gets wasted in various forms. The form of this loss may vary from one machine to another. These losses give in rise in temperature of machine and reduce the efficiency of the machine. In DC Machine, there are broadly four main categories of energy loss.

Copper Losses or Electrical Losses in DC Machine or Winding Loss

The copper losses are the winding losses taking place during the current flowing through the winding. These losses occur due to the resistance in the winding. In DC machine, there are only two winding, armature and field winding.

Thus copper losses categories in three parts; armature loss, field winding loss, and brush contact resistance loss. The copper losses are proportional to square of the current flowing through the winding.

Armature Copper Loss in DC Machine

Armature copper loss = $I_a^2R_a$

Where, I_a is armature current and R^a is armature resistance.

These losses are about 30% of the total full load losses.

Field Winding Copper Loss in DC Machine

Field winding copper loss = $I_f^2R_f$

Where, I_f is field current and R_f is field resistance.

These losses are about 25% theoretically, but practically it is constant.

Brush Contact Resistance Loss in DC Machine

Brush contact loss attributes to resistance between the surface of brush and commutator. It is not a loss which could be calculated separately as it is a part of variable losses. Generally, it contributes in both the types of copper losses. So, they are factor in the calculation of above losses.

Core Losses or Iron Losses in DC Machine or Magnetic Losses

As iron core of the armature is rotating in magnetic field, some losses occurs in the core which is called core losses. Normally, machines are operated with constant speed, so these losses are almost constant. These losses are categorized in two form; Hysteresis loss and Eddy current loss.

Hysteresis Loss in DC Machine

Hysteresis losses occur in the armature winding due to reversal of magnetization of the core. When the core of the armature exposed to magnetic field, it undergoes one complete rotation of magnetic reversal. The portion of armature which is under S-pole, after completing half electrical revolution, the same piece will be under the N-pole, and the magnetic lines are reversed in order to overturn the magnetism within the core. The constant process of magnetic reversal in the armature, consume some amount of energy which is called hysteresis loss. The percentage of loss depends upon the quality and volume of the iron.

The Frequency of Magnetic Reversal

$$f = \frac{PN}{120}$$

Where,

P = Number of poles

N = Speed in rpm

Steinmetz Formula

The Steinmetz formula is for the calculation of hysteresis loss.

$$Hysteresis\ loss\ P_h = \eta B_{max}^{1.6} f V \ \ watts$$

Where,

η = Steinmetz hysteresis co-efficient

B_{max} = Maximum flux Density in armature winding

F = Frequency of magnetic reversals

V = Volume of armature in m^3.

Eddy Current Loss in DC Machine

According to Faraday’s law of electromagnetic induction, when an iron core rotates in the magnetic field, an emf is also induced in the core. Similarly, when armature rotates in magnetic field, small amount of emf induced in the core which allows flow of charge in the body due to conductivity of the core. This current is useless for the machine. This loss of current is called eddy current. This loss is almost constant for the DC machines. It could be minimized by selecting the laminated core.

Mechanical Losses in DC Machine

The losses associated with mechanical friction of the machine are called mechanical losses. These losses occur due to friction in the moving parts of the machine like bearing, brushes etc, and windage losses occurs due to the air inside the rotating coil of the machine. These losses are usually very small about 15% of full load loss.

Stray Load Losses in DC Machine

There are some more losses other than the losses which have been discussed above. These losses are called stray-load losses. These miscellaneous losses are due to the short-circuit current in the coil undergoing commutation, distortion of flux due to armature and many more losses which are difficult to find. These losses are difficult to determine. However, they are taken as 1% of the whole load power output.

Parallel Operation of D.C. Generators:

Here this explains you the **parallel operation of dc generators** and load sharing among them for the continuous power supply.In a d.c power plant, power is usually supplied from several generators of small ratings connected in parallel instead of from one large **generator**. This is due to the following reasons:

(i) Continuity of service:

If a single large generator is used in the power plant, then in case of its breakdown, the whole plant will be shut down. However, if power is supplied from a number of small units **operating in parallel**, then in case of failure of one unit, the continuity of supply can be maintained by other healthy units.

(ii) Efficiency:

Generators run most efficiently when loaded to their rated capacity.Electric power costs less per kWh when the generator producing it is efficiently loaded.Therefore, when load demand on power plant decreases, one or more generators can be shut down and the remaining units can be efficiently loaded.

(iii) Maintenance and repair:

Generators generally require routine-maintenance and repair. Therefore, if **generators are operated in parallel**, the routine or emergency operations can be performed by isolating the affected generator while the load is being supplied by other units. This leads to both safety and economy.

(iv) Increasing plant capacity:

In the modern world of increasing population, the use of electricity is continuously increasing. When added capacity is required, the new unit can be simply paralleled with the old units.In many situations, a single unit of desired large capacity may not be available.In that case, a number of smaller units can be operated in parallel to meet the load requirement. Generally, a single large unit is more expensive.

(v) Non-availability of single large unit:
In many situations, a single unit of desired large capacity may not be available. In that case, a number of smaller units can be **operated in parallel** to meet the load requirement. Generally, a single large unit is more expensive.

Connecting Shunt Generators in Parallel:
The generators in a power plant are **connected in parallel through bus-bars**. The bus-bars are heavy thick copper bars and they act as +ve and -ve terminals.The positive terminals of the **generators** are connected to the +ve side of bus-bars and negative terminals to the negative side of bus-bars.

Fig. (3.15) shows shunt generator 1 connected to the bus-bars and supplying load. When the load on the power plant increases beyond the capacity of this **generator**, the second shunt generator 2 is connected in parallel with the first to meet the increased load demand. The procedure for **paralleling generator** 2 with generator 1 is as under:

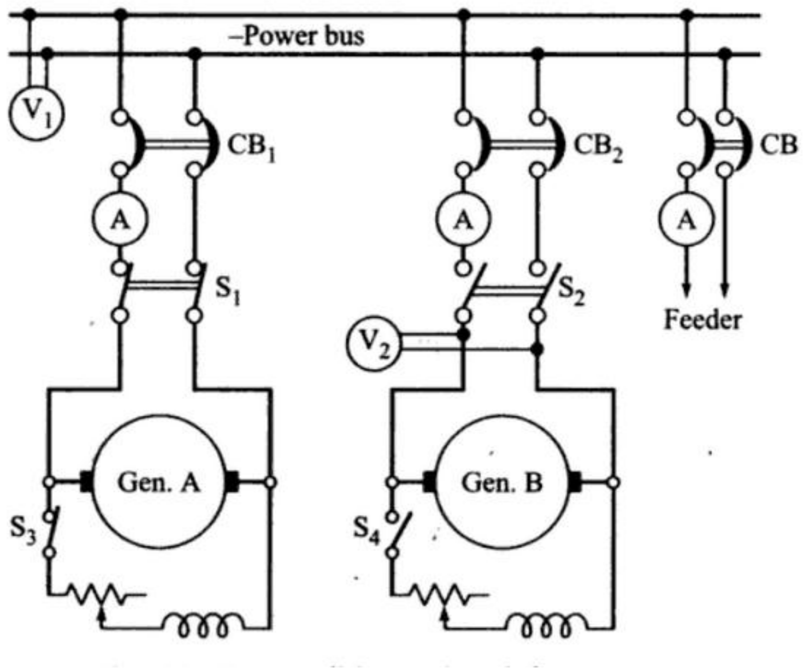
(i) The prime mover of generator 2 is brought up to the rated speed. Now switch S4 in the field circuit of the generator 2 is closed.

(ii) Next circuit breaker CB-2 is closed and the excitation of **generator** 2 is adjusted till it is generates a voltage equal to the bus-bars voltage. This is
indicated by voltmeter V2.

(iii) Now the generator 2 is ready to be **paralleled with generator** 1. The main switch S3 is closed, thus putting generator 2 in **parallel with generator** 1. Note that generator 2 is not supplying any load because it's generated e.m.f. is equal to bus-bars voltage. The generator is said to be “floating” (i.e., not supplying any load) on the bus-bars.

(iv) If **generator** 2 is to deliver any current, then it's generated voltage E should be greater than the bus-bars voltage V. In that case, the current supplied by it is $I = (E - V)/R_a$ where Ra is the resistance of the armature circuit. By increasing the field current (and hence induced e.m.f. E), the generator 2 can be made to supply the proper amount of load.

(v) The load may be shifted from one shunt generator to another merely by adjusting the field excitation. Thus if **generator** 1 is to be shut down, the whole load can be shifted onto generator 2 provided it has the capacity to supply that load. In that case, reduce the current supplied by generator 1 to zero (This will be indicated by ammeter A1) open C.B.-1 and then open the main switch S1.



Load Sharing of two generators:

The **load sharing between shunt generators** in parallel can be easily regulated because of their drooping characteristics. The load may be shifted from one generator to another merely by adjusting the field excitation. Let us discuss the load sharing of two **generators** which have unequal no-load voltages.

Let $E1, E2$ = no-load voltages of the two generators

$R1, R2$ = their armature resistances

V = common terminal voltage (Bus-bars voltage)

then $I1 = (E1 - V)/R1$ and $I2 = (E2 - V)/R2$

Thus the current output of the **generators** depends upon the values of E1 and E3.These values may be changed by field rheostats. The common terminal voltage (or bus-bars voltage) will depend upon

(i) the e.m.f.s of individual generators and

(ii) the total load current supplied.

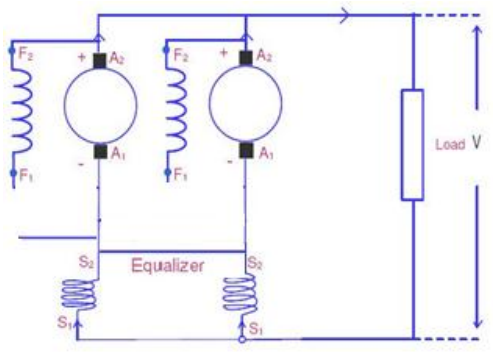
It is generally desired to keep the bus bars voltage constant. This can be achieved by adjusting the field excitations of the **generators operating in parallel**.

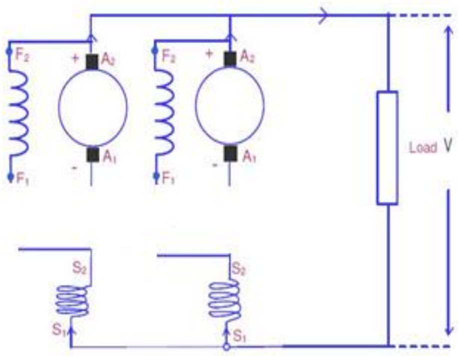
Compound Generators in Parallel:

Under-compounded generators also operate satisfactorily in parallel but over compounded generators will not operate satisfactorily unless their series fields are paralleled. This is achieved by connecting two negative brushes together as shown in Fig. (3.16) (i). The conductor used to connect these brushes is generally called equaliser bar. Suppose that an attempt is made to operate the two **generators** in Fig. (3.16) (ii) in parallel without an equaliser bar. If, for any reason, the current supplied by generator 1 increase slightly, the current in its series field will increase and raise the generated voltage.

This will cause generator 1 to take more load. Since total load supplied to the system is constant, the current in generator 2 must decrease and as a result, its series field is weakened. Since this effect is cumulative, the generator 1 will take the entire load and drive **generator** 2 as a motor. Under such conditions, the current in the two machines will be in the direction shown in Fig. (3.16) (ii). After machine 2 changes from a generator to a motor, the current in the shunt field will remain in the same direction, but the current in the armature and series field will reverse.

Thus the magnetising action, of the series field opposes that of the shunt field. As the current taken by the machine 2 increases, the demagnetizing action of series field becomes greater and the resultant field becomes weaker. The resultant field will finally become zero and at that time machine 2 will short circuit machine 1, opening the breaker of either or both machines.





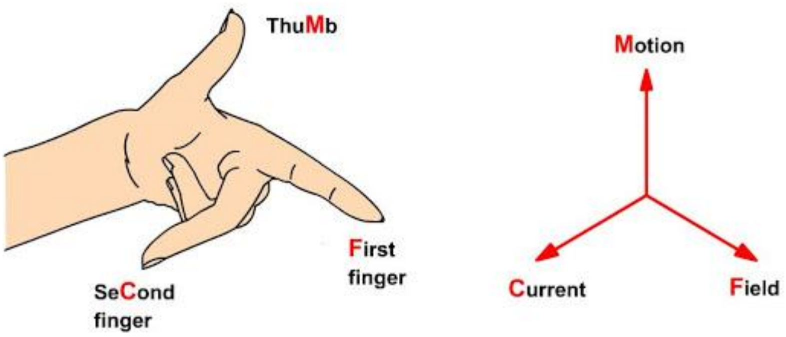
When the equaliser bar is used, a stabilising action exists and neither machine tends to take the entire load. To consider this, suppose that current delivered by generator 1 increase. The increased current will not only pass through the series field of **generator** 1 but also through the equaliser bar and series field of generator 2.Therefore, the voltage of both the machines increases and the generator 2 will take a part of the load.

MODULE 3

Working Principle of a DC Motor

A motor is an electrical machine which converts electrical energy into mechanical energy. The principle of working of a DC motor is that "whenever a current carrying conductor is placed in a magnetic field, it experiences a mechanical force". The direction of this force is given by Fleming's left hand rule and it's magnitude is given by F = BIL. Where, B = magnetic flux density, I = current and L = length of the conductor within the magnetic field.

Fleming's left hand rule: If we stretch the first finger, second finger and thumb of our left hand to be perpendicular to each other and direction of magnetic field is represented by the first finger, direction of the current is represented by second finger then the thumb represents the direction of the force experienced by the current carrying conductor.



The formula calculates the magnitude of the force,

$$F = BIl \quad \text{newton}$$

Before understanding the working of DC motor, first, we have to know about its construction. The armature and stator are the two main parts of the DC motor. The armature is the rotating part, and the stator is their stationary part. The armature coil is connected to the DC supply.

The armature coil consists the commutators and brushes. The commutators convert the AC induced in the armature into DC and the brushes transfer the current from rotating part of the motor to the stationary external load. The armature is placed between the north and south pole of the permanent or electromagnet.

For simplicity, consider that the armature has only one coil which is placed between the magnetic field shown below in the figure A. When the DC supply is given to the armature coil the current starts flowing through it. This current develops its own field around the coil.

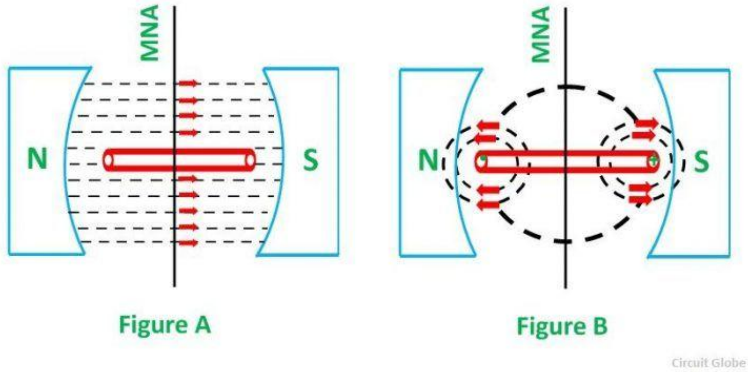


Figure A Figure B

By the interaction of the fields (produced by the coil and the magnet), the resultant field develops across the conductor. The resultant field tends to regain its original position, i.e. in the axis of the main field. The field exerts the force at the ends of the conductor, and thus the coil starts rotating.

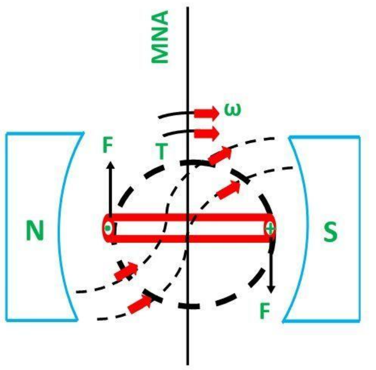
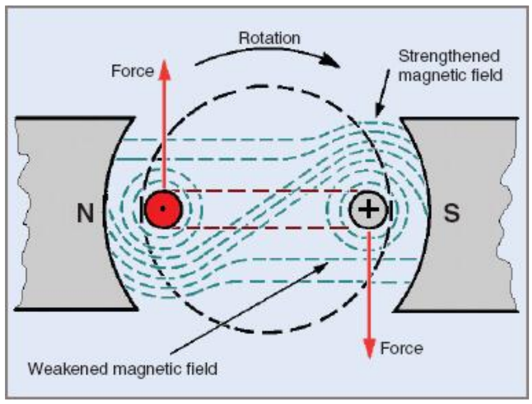
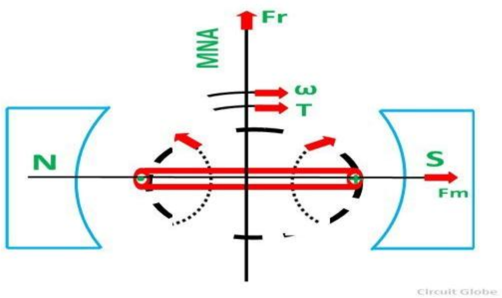


Figure C



Let the field produced by the main field be Fm, and this field rotates in the clockwise direction. When the current flows in the coil, they produce their own magnetic field say, Fr. The field Fr tries to come in the direction of the main field. Thereby, the torque act on the armature coil.

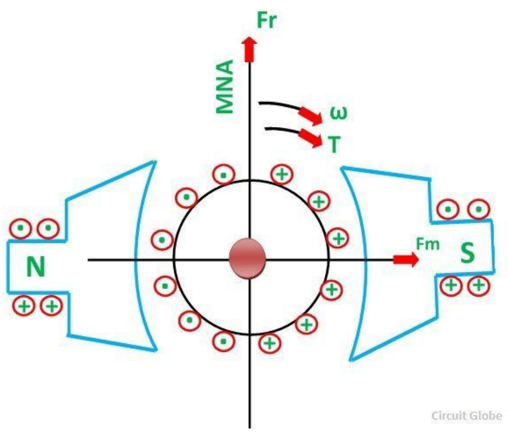


The actual DC motor consists of a large number of armature coils. The speed of the motor is directly proportional to the number of coils used in the motor. These coils are kept under the impact of the magnetic field.

The one end of the conductors is kept under the influence of the north pole, and the other end is kept under the influence of the south pole. The current enters into the armature coil through the north pole and move outwards through the south pole.

When the coil moves from one brush to another, at the same time the polarity of the coil also changes. Thus, the direction of the force or torque acting on the coil remains the same.

The torque induces in the coil become zero when the armature coil is perpendicular to the main field. The zero torque means the motor stops rotating. For solving this problem, the number of armature coil is used in the rotor. So, if one of their coils is perpendicular to the field, then the other coils induce the torque. And the rotor moves continuously.



Also, for obtaining the continuous torque, the arrangement is kept in such a way that whenever the coils cut the magnetic neutral axis of the magnet the direction of current in the coils become reversed. This can be done with the help of the commutator.

Back EMF

According to fundamental laws of nature, no energy conversion is possible until there is something to oppose the conversion. In case of generators this opposition is provided by magnetic drag, but in case of dc motors there is back emf. When the armature of the motor is rotating, the conductors are also cutting the magnetic flux lines and hence according to the Faraday's law of electromagnetic induction, an emf induces in the armature conductors. The direction of this induced emf is such that it opposes the armature current (I_a). The circuit diagram below illustrates the direction of the back emf and armature current. Magnitude of Back emf can be given by the emf equation of DC generator.

Significance of Back Emf:

Magnitude of back emf is directly proportional to speed of the motor. Consider the load on a dc motor is suddenly reduced. In this case, required torque will be small as compared to the current torque. Speed of the motor will start increasing due to the excess torque. Hence, being proportional to the speed, magnitude of the back emf will also increase. With increasing back emf armature current will start decreasing. Torque being proportional to the armature current, it will also decrease until it becomes sufficient for the load. Thus, speed of the motor will regulate.

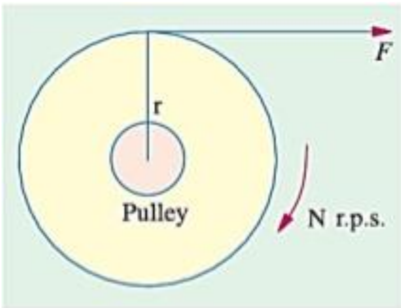
On the other hand, if a dc motor is suddenly loaded, the load will cause decrease in the speed. Due to decrease in speed, back emf will also decrease allowing more armature current. Increased armature current will increase the torque to satisfy the load requirement. Hence, presence of the back emf makes a dc motor 'self-regulating'.

Torque equation of DC Motor

Torque acting on a body is quantitatively defined as the product of force acting on the body and perpendicular distance of the line of action of force from the axis of rotation.

i.e $T = F \times r \sin\theta$

Qualitatively , torque is the tendency of a force to cause a rotational motion, or to bring about a change in rotational motion .



Each conductor experiences a force and the conductors lie near the surface of the rotor at a common radius from its center. Hence torque is produced at the circumference of the rotor and rotor starts rotating.

Since all conductors experience equal force and are equidistant from center , therefore
Total torque = torque on one conductor × total number of conductors
Let

r=average armature radius
L=effective length of each conductor
Z=total number of armature conductors
A=number of parallel paths
I_a =armature current
I=current through each conductor= I_a / A
B=average flux density
Φ=flux per pole
P=number of poles
a=cross-sectional area of flux path per pole at radius r = (2πrL / P)

Force on each conductor = BIL
Torque due to one conductor = F * 2πr
Mechanical Power Developed = workdone / time

As,

$$I=\frac{I_a}{A} \quad \text{and} \quad B = \frac{\Phi}{a} = \frac{\Phi}{\left(\frac{2\pi r L}{P}\right)}$$

∴ Total armature torque, T_a = (Torque due to one conductor) × (total number of armature conductors)

$$= BILr \times Z$$

$$= \frac{\Phi}{\left(\frac{2\pi r L}{P}\right)}\left(\frac{I_a}{A}\right) Lr\,Z$$

$$= \frac{P\Phi I_a Z}{2\pi A}$$

or

$$T_a = 0.159\Phi I_a Z\left(\frac{P}{A}\right)$$

Note. From the above equation for the torque, we find that $T_a \propto \Phi I_a$.

(*a*) In the case of a series motor, Φ is directly proportional to I_a (before saturation) because field windings carry full armature current $\therefore\ T_a \propto I_a^2$

(*b*) For shunt motors, Φ is practically constant, hence $T_a \propto I_a$.

As seen from (*iii*) above

$$T_a = \frac{E_b\, I_a}{2\pi\, N} \text{ N - m - N in r.p.s.}$$

If N is in r.p.m., then

$$T_a = \frac{E_b\, I_a}{2\pi\, N/60} = 60\,\frac{E_b\, I_a}{2\pi N} = \frac{60}{2\pi}\,\frac{E_b\, I_a}{N} = 9.55\,\frac{E_b I_a}{N} \text{ N-m}$$

29.8. Shaft Torque (T_{sh})

The whole of the armature torque, as calculated above, is not available for doing useful work, because a certain percentage of it is required for supplying iron and friction losses in the motor.

The torque which is available for doing useful work is known as shaft torque T_{sh}. It is so called because it is available at the shaft. The motor output is given by

Output = $T_{sh} \times 2\pi N$ Watt provided T_{sh} is in N-m and N in r.p.s.

$$\therefore \quad T_{sh} = \frac{\text{Output in watts}}{2\pi N} \text{ N- m} - N \text{ in r.p.s}$$

$$= \frac{\text{Output in watts}}{2\pi N/60} \text{ N-m} - N \text{ in r.p.m.}$$

$$= \frac{60}{2\pi}\,\frac{\text{output}}{N} = 9.55\,\frac{\text{Output}}{N} \text{ N-m.}$$

The difference $(T_a - T_{sh})$ is known as lost torque and is due to iron and friction losses of the motor.

Characteristics of DC Motors

Generally, three characteristic curves are considered important for DC motors which are, (i) Torque vs. armature current, (ii) Speed vs. armature current and (iii) Speed vs. torque. These are explained below for each type of DC motor. These characteristics are determined by keeping the following two relations in mind.

$$\mathbf{T_a \propto \phi . I_a} \text{ and } \mathbf{N \propto E_b/\phi}$$

These above equations can be studied at - emf and torque equation of dc machine. For a DC motor, magnitude of the back emf is given by the same emf equation of a dc generator i.e. $E_b = P\phi NZ / 60A$. For a machine, P, Z and A are constant, therefore, $N \propto E_b/\phi$

Characteristics Of DC Series Motors

Torque Vs. Armature Current (T_a-I_a)

This characteristic is also known as **electrical characteristic**. We know that torque is directly proportional to the product of armature current and field flux, $T_a \propto \phi . I_a$. In DC series motors, field winding is connected in series with the armature, i.e. $I_a = I_f$. Therefore, before magnetic saturation of the field, flux ϕ is directly proportional to Ia. Hence, before magnetic saturation $T_a \alpha I_a^2$. Therefore, the T_a-I_a curve is parabola for smaller values of I_a.

After magnetic saturation of the field poles, flux ϕ is independent of armature current Ia. Therefore, the torque varies proportionally to I_a only, $T \propto I_a$. Therefore, after magnetic saturation, T_a-I_a curve becomes a straight line.

The shaft torque (T_{sh}) is less than armature torque (T_a) due to stray losses. Hence, the curve T_{sh} vs I_a lies slightly lower.

In DC series motors, (prior to magnetic saturation) torque increases as the square of armature current, these motors are used where high starting torque is required.

Speed Vs. Armature Current (N-I_a)

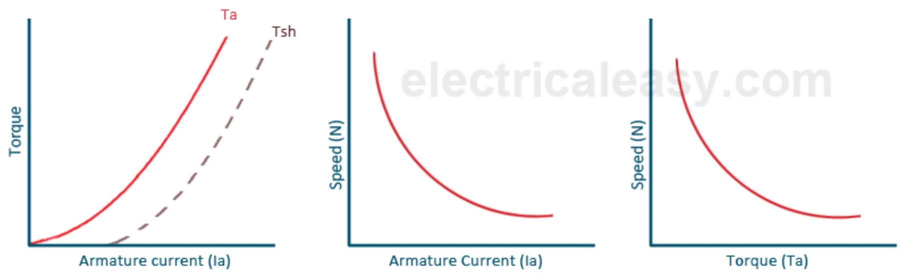
We know the relation, $N \propto E_b/\phi$

For small load current (and hence for small armature current) change in back emf Eb is small and it may be neglected. Hence, for small currents speed is inversely proportional to ϕ. As we know, flux is directly proportional to I_a, speed is inversely proportional to I_a. Therefore, when armature current is very small the speed becomes dangerously high. That is **why a series motor should never be started without some mechanical load**.

But, at heavy loads, armature current I_a is large. And hence, speed is low which results in decreased back emf E_b. Due to decreased E_b, more armature current is allowed.

Speed Vs. Torque (N-T_a)

This characteristic is also called as **mechanical characteristic**. From the above two **characteristics of DC series motor**, it can be found that when speed is high, torque is low and vice versa.



Characteristics of DC series motor

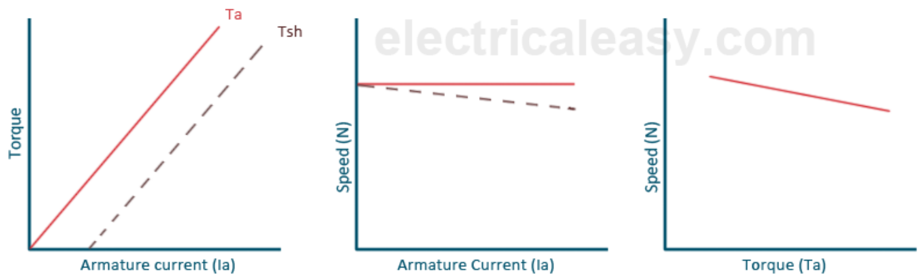
Characteristics Of DC Shunt Motors

Torque Vs. Armature Current (T_a-I_a)

In case of DC shunt motors, we can assume the field flux ϕ to be constant. Though at heavy loads, ϕ decreases in a small amount due to increased armature reaction. As we are neglecting the change in the flux ϕ, we can say that torque is proportional to armature current. Hence, the Ta-Ia characteristic for a dc shunt motor will be a straight line through the origin. Since heavy starting load needs heavy starting current, **shunt motor should never be started on a heavy load**.

Speed Vs. Armature Current (N-Ia)

As flux ϕ is assumed to be constant, we can say $N \propto E_b$. But, as back emf is also almost constant, the speed should remain constant. But practically, ϕ as well as E_b decreases with increase in load. Back emf E_b decreases slightly more than ϕ, therefore, the speed decreases slightly. Generally, the speed decreases only by 5 to 15% of full load speed. Therefore, **a shunt motor can be assumed as a constant speed motor**. In speed vs. armature current characteristic in the following figure, the straight horizontal line represents the ideal characteristic and the actual characteristic is shown by the dotted line.



Characteristics of DC shunt motor

Characteristics of DC Compound Motor

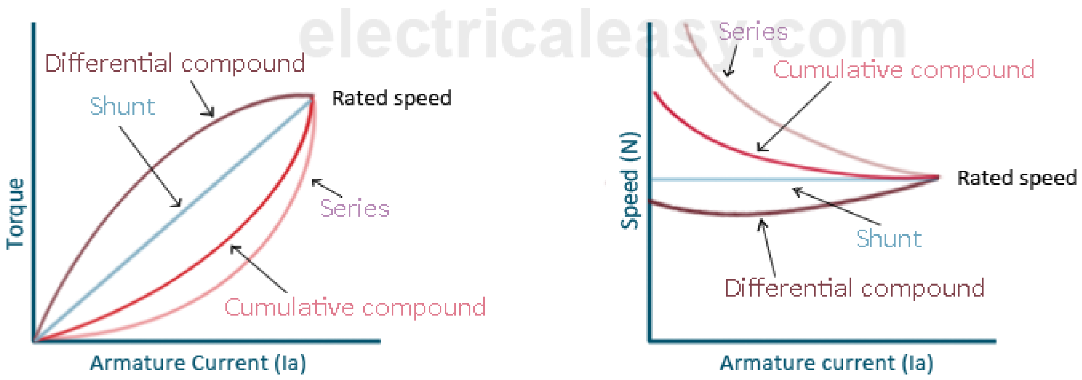
DC compound motors have both series as well as shunt winding. In a compound motor, if series and shunt windings are connected such that series flux is in direction as that of the shunt flux then the motor is said to be cumulatively compounded. And if the series flux is opposite to the direction of the shunt flux, then the motor is said to be differentially compounded. Characteristics of both these compound motors are explained below.

(a) Cumulative compound motor

Cumulative compound motors are used where series characteristics are required but the load is likely to be removed completely. Series winding takes care of the heavy load, whereas the shunt winding prevents the motor from running at dangerously high speed when the load is suddenly removed. These motors have generally employed a flywheel, where sudden and temporary loads are applied like in rolling mills.

(b) Differential compound motor

Since in differential field motors, series flux opposes shunt flux, the total flux decreases with increase in load. Due to this, the speed remains almost constant or even it may increase slightly with increase in load ($N \propto E_b/\phi$). Differential compound motors are not commonly used, but they find limited applications in experimental and research work.



Characteristics of DC compound motor

Need for Starter

A starter in simple words is a device that helps in the starting and running of a DC motor. Now the question is why these DC motors require the assistance of the starter in the first case. The only explanation to that is given by the presence of back emf E_b, which plays a critical role in governing the operation of the motor. The back emf, develops as the motor armature starts to rotate in presence of the magnetic field, by generating action and counters the supply voltage. This also essentially means that the back emf at the starting is zero, and develops gradually as the motor gathers speed.

The general motor emf equation

$$V = E_b + I_a R_a$$

at starting is modified to $V = I_a.R_a$ as at starting $E_b = 0$.

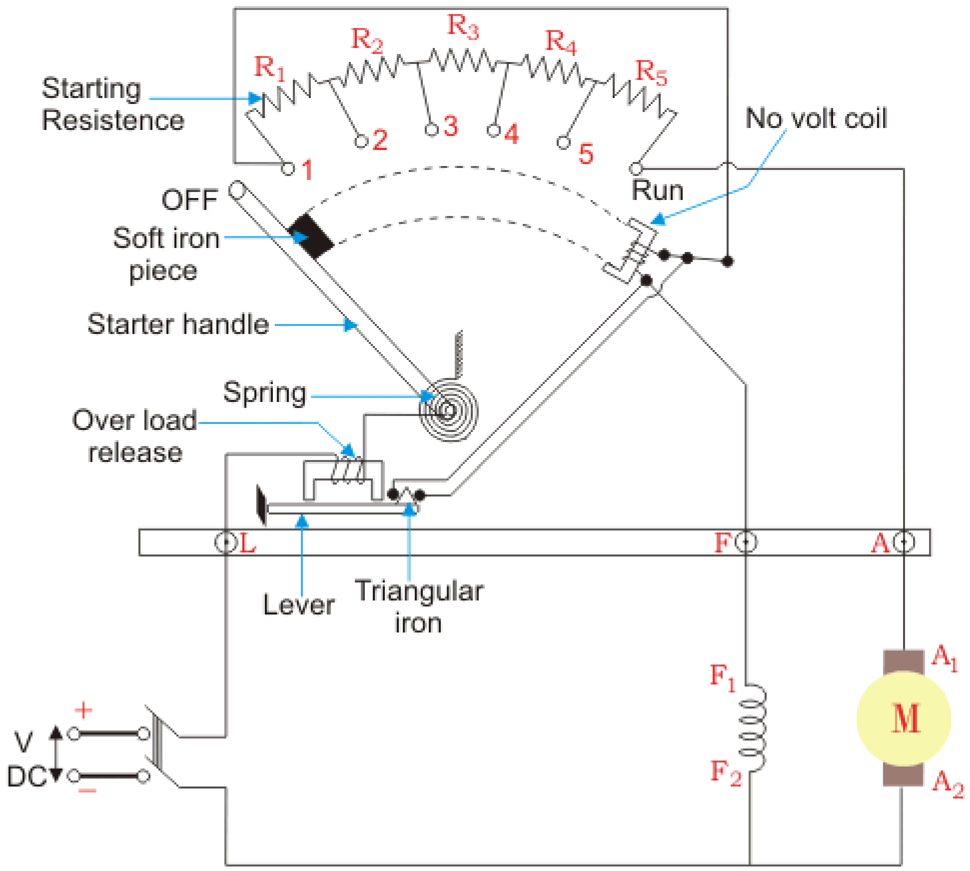
$$Ia = \frac{V}{Ra}$$

Thus we can well understand from the above equation that the current will be dangerously high at starting (as armature resistance Ra is small) and hence its important that we make use of a device like the 3 point starter to limit the starting current to an allowable lower value.

Three Point Starter

Construction

A starter is a variable resistance, integrated into the number of sections as shown in the figure.



Three Point Starter

The contact points of these sections are called studs and are shown separately as OFF, 1, 2, 3, 4, 5, RUN. Other than that there are three main points, referred to as

- 'L' Line terminal. (Connected to positive of supply.)
- 'A' Armature terminal. (Connected to the armature winding.)
- 'F' Field terminal. (Connected to the field winding.)

And from there it gets the name 3 point starter. Now studying the construction of 3 point starter in further details reveals that the point 'L' is connected to an electromagnet called overload release (OLR) as shown in the figure. The other end of OLR is connected to the lower end of conducting lever of starter handle where spring is also attached with it, and the starter handle also contains a soft iron piece housed on it. This handle is free to move to the other side RUN against the force of the spring. This spring brings back the handle to its original OFF position under the influence of its own force. Another parallel path is derived from the stud '1', given to another electromagnet called No Volt Coil (NVC) which is further connected to terminal 'F.' The starting resistance at starting is entirely in series with the armature. The OLR and NVC act as the two protecting devices of the starter.

Working of Three Point Starter

To start with the handle is in the OFF position when the supply to the DC motor is switched on. Then handle is slowly moved against the spring force to make contact with stud No. 1. At this point, field winding of the shunt or the compound motor gets supply through the parallel path provided to starting the resistance, through No Voltage Coil. While entire starting resistance comes in series with the armature. The high starting armature current thus gets limited as the current equation at this stage becomes

$$Ia = \frac{V}{Ra + Rst}$$

As the handle is moved further, it goes on making contact with studs 2, 3, 4, etc., thus gradually cutting off the series resistance from the armature circuit as the motor gathers speed. Finally, when the starter handle is in 'RUN' position, the entire starting resistance is eliminated, and the motor runs with normal speed.

This is because back emf is developed consequently with speed to counter the supply voltage and reduce the armature current.

So the external electrical resistance is not required anymore and is removed for optimum operation. The handle is moved manually from OFF to the RUN position with the development of speed. Now the obvious question is once the handle is taken to the RUN position how it is supposed to stay there, as long as the motor is running.

To find the answer to this question let us look into the working of No Voltage Coil.

Working of No Voltage Coil of 3 Point Starter

The supply to the field winding is derived through no voltage coil. So when field current flows, the NVC is magnetized. Now when the handle is in the 'RUN' position, a soft iron piece is connected to the handle and gets attracted by the magnetic force produced by NVC, because of flow of current through it. The NVC is designed in such a way that it holds the handle in 'RUN' position against the force of the spring as long as supply is given to the motor. Thus NVC holds the handle in the 'RUN' position and hence also called hold on coil.

Now when there is any kind of supply failure, the current flow through NVC is affected and it immediately loses its magnetic property and is unable to keep the soft iron piece on the handle, attracted. At this point under the action of the spring force, the handle comes back to OFF position, opening the circuit and thus switching off the motor. So due to the combination of NVC and the spring, the starter handle always comes back to OFF position whenever there is any supply problem. Thus it also acts as a protective device safeguarding the motor from any kind of abnormality.

Drawbacks of a Three Point Starter

The 3 point starter suffers from a serious drawback for motors with a large variation of speed by adjustment of the field rheostat. To increase the speed of the motor field resistance can be increased. Therefore current through the shunt field is reduced. Field current becomes very low which results in holding electromagnet too weak to overcome the force exerted by the spring. The holding magnet may release the arm of the starter during the normal operation of the motor and thus disconnect the motor from the line. This is not desirable. A four point starter is thus used.

Four Point Starter

Working Principle of Four Point Starter

The 4 point starter like in the case of a 3 point starter also acts as a protective device that helps in safeguarding the armature of the shunt or compound excited DC motor against the high starting current produced in the absence of back emf at starting.
The 4 point starter has a lot of constructional and functional similarity to a three point starter, but this special device has an additional point and a coil in its construction. This naturally brings about some difference in its functionality, though the basic operational characteristic remains the same. The basic difference in circuit of 4 point starter as compared to 3 point starter is that the holding coil is removed from the shunt field current and is connected directly across the line with current limiting resistance in series.

Now to go into the details of operation of 4 point starter, let's have a look at its constructional diagram, and figure out its point of difference with a 3 point starter.

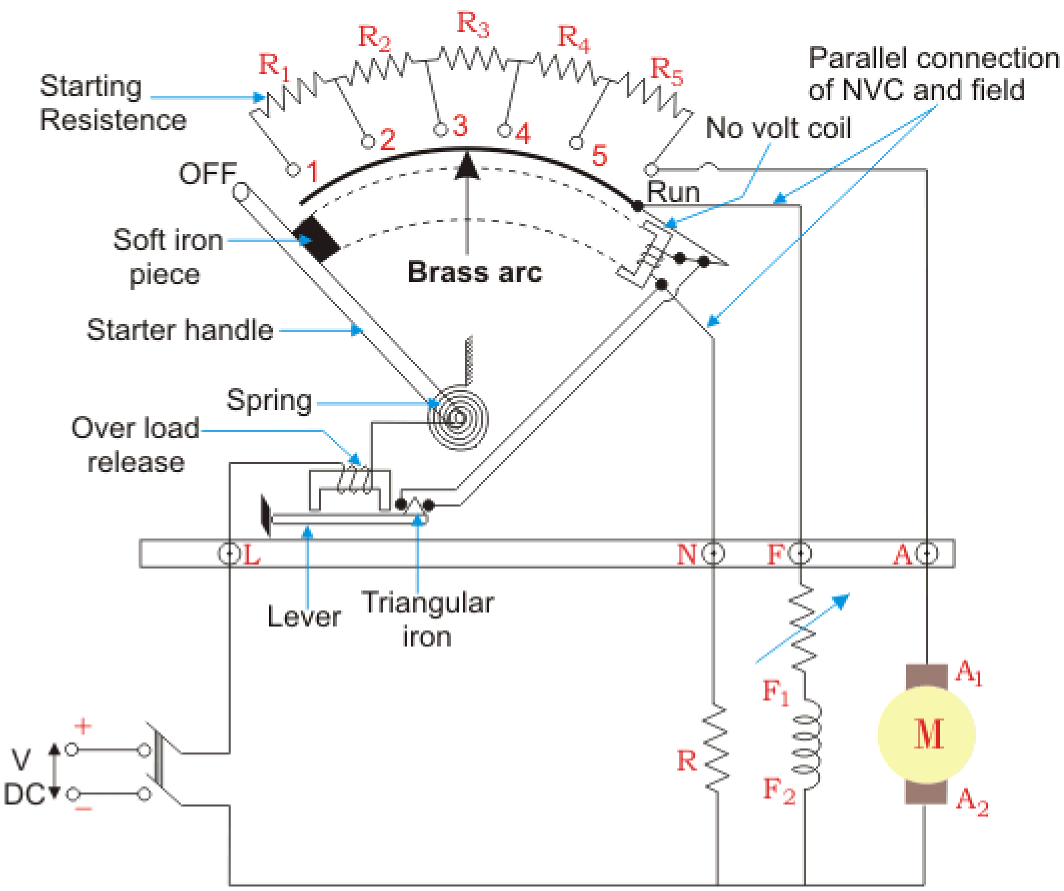
Construction and Operation of Four Point Starter

A 4 point starter as the name suggests has 4 main operational points, namely

- 'L' Line terminal. (Connected to positive of supply.)
- 'A' Armature terminal. (Connected to the armature winding.)
- 'F' Field terminal. (Connected to the field winding.)
- Like in the case of the 3 point starter, and in addition to it there is, A 4th point N. (Connected to the No Voltage Coil NVC)

The remarkable difference in case of a 4 point starter is that the No Voltage Coil is connected independently across the supply through the fourth terminal called 'N' in addition to the 'L', 'F' and 'A'. As a direct consequence of that, any change in the field supply current does not bring about any difference in the performance of the NVC. Thus it must be ensured that no voltage coil always produce a force which is strong enough to hold the handle in its 'RUN' position, against force of the spring, under all the operational conditions. Such a current is adjusted through No Voltage Coil with the help of fixed resistance R connected in series with the NVC using fourth point 'N' as shown in the figure.

Apart from this above mentioned fact, the 4 point and 3 point starters are similar in all other ways like possessing is a variable resistance, integrated into number of sections as shown in the figure above. The contact points of these sections are called studs and are shown separately as OFF, 1, 2, 3, 4, 5, RUN, over which the handle is free to be maneuvered manually to regulate the starting current with gathering speed.



Four Point Starter

Now to understand its way of operating let's have a closer look at the diagram given above. Considering that supply is given and the handle is taken stud No.1, then the circuit is complete and line current that starts flowing through the starter. In this situation we can see that the current will be divided into 3 parts, flowing through 3 different points.

- 1 part flows through the starting resistance (R_1+ R_2 + R_3.....) and then to the armature.
- A 2nd part flowing through the field winding F.
- And a 3rd part flowing through the no voltage coil in series with the protective resistance R.

So the point to be noted here is that with this particular arrangement any change in the shunt field circuit does not bring about any change in the no voltage coil as the two circuits are independent of each other. This essentially means that the electromagnet pull subjected upon the soft iron bar of the handle by the no voltage coil at all points of time should be high enough to keep the handle at its RUN position, or rather prevent the spring force from restoring the handle at its original OFF position, irrespective of how the field rheostat is adjusted.

This marks the operational difference between a 4 point starter and a 3 point starter. As otherwise both are almost similar and are used for limiting the starting current to a shunt wound DC motor or compound wound DC motor, and thus act as a protective device.

Testing of DC Machines

There are several tests that are conducted for testing a dc machine (generator or motor) to judge its performance. The most important performance tests to be conducted on dc machine are:

1. The magnetization or open-circuit test.
2. The load characteristic.
3. The determination of efficiency curve.
4. The temperature rise test.

Here we mainly deals with the determination of efficiency curve. The efficiency of a d.c. machine depends upon its losses. The smaller the loss, the greater is the efficiency of the machine and vice-versa.

The consideration of losses in a dc machine is important for two principal reasons.

- First, losses determine the efficiency of the machine and appreciably influence its operating cost.
- Secondly, losses determine the heating of the machine and hence the power output that may be obtained without undue deterioration of the insulation.

In this we shall focus on the various methods for the determination of the efficiency of a d.c. machine.

Efficiency of a D.C. Machine

The determination of efficiency of DC machine is important for the testing of DC machines. The power that a dc machine receives is called the input and the power it gives out is called the output. Therefore, the efficiency of a d.c. machine, like that of any energy-transferring device, is given by;

Efficiency = Output / Input -------------------------------①

Output = Input - Losses and Input = Output + Losses

Therefore, the efficiency of a d.c. machine can also be expressed in the following forms:

Efficiency = (Input - Losses) / Input -----------------------②

Efficiency = Output / (Output + Losses) --------------------③

The most obvious method of determining the efficiency of a d.c. machine is to directly load it and measure the input power and output power. Then we can use Eq ① to determine the efficiency of the machine. This method suffers from three main drawbacks.

- First, this method requires the application of load on the machine.
- Secondly, for machines of large rating, the loads of the required sizes may not be available.
- Thirdly, even if it is possible to provide such loads, large power will be dissipated, making it an expensive method.

The most common method of measuring the efficiency of a d.c. machine is to determine its losses (instead of measuring the input and output on load). We can then use Eq ② or Eq ③ to determine the efficiency of the machine. This method has the obvious advantage of convenience and economy.

Methods for determining Efficiency of DC Machines

There are three different methods of determining the efficiency of a dc machine, namely,

1. Direct method,
2. Indirect method
3. Regenerative method.

Direct Method for Determining Efficiency

By this method the efficiency and losses of only small machines can be determined. In this method full load is applied to the machine and output is directly measured.

Though this method is very simple in looking but involves complication in the measurement of mechanical power input in the case of generator, and output in the case of a motor.

In the case of a generator, the input mechanical power is measured by connecting some form of dynamo-meter to the prime mover and water resistance load is applied.

This method is wasteful, since all the input is to be wasted and can only be used in case of small machines due to the-difficulty of having enough power and suitable brake arrangements in case of larger machines.

Indirect Method

By Indirect method of testing of dc machines, efficiency of shunt and compound dc machines can be determined.

This method enables the determination of losses without actually loading the machine. The power is required to supply the losses only, so there is no difficulty in applying this method even to very large machines.

Although the efficiency can be calculated with fair accuracy from the results obtained with this method, the disadvantage of this method is that the machine is run light during the test which gives no indication as to the temperature rise on load or to the commutating qualities of the machines.

Regenerative Method

Regenerative method requires two identical machines; one of them operates as a motor and drives the other, which is mechanically coupled to it.

The other machine operates as a generator and feedback power into the supply. Thus the total power drawn from the supply is only for supplying the internal losses of the two machines.

Thus very large machines may be tested as the power required is small.

Important Tests of DC Machines

The important Tests of DC machines are classified as under

1. Efficiency By Direct Loading
2. Brake test
3. Using calibrated generator
4. Swinburne's Method (Indirect Method)
5. Regenerative or Hopkinson's-Test (Regenerative Method)
6. Retardation or Running down Test

Swinburne's test

Swinburne's test is the simplest indirect method of **testing dc machines**. In this method, the dc machine (generator or motor) is run as a motor at no-load and losses of the machine are determined. Once the losses of the machine are known, its efficiency at any desired load can be determined in advance.

It may be noted that this method is applicable to those machines in which flux is practically constant at all loads e.g., shunt and compound machines.

Steps to find the Efficiency

Let us see how the efficiency of a dc shunt machine (generator or motor) is determined by this method. The test insists of two steps:

1. Determination of hot resistances of windings
2. Determination of constant losses

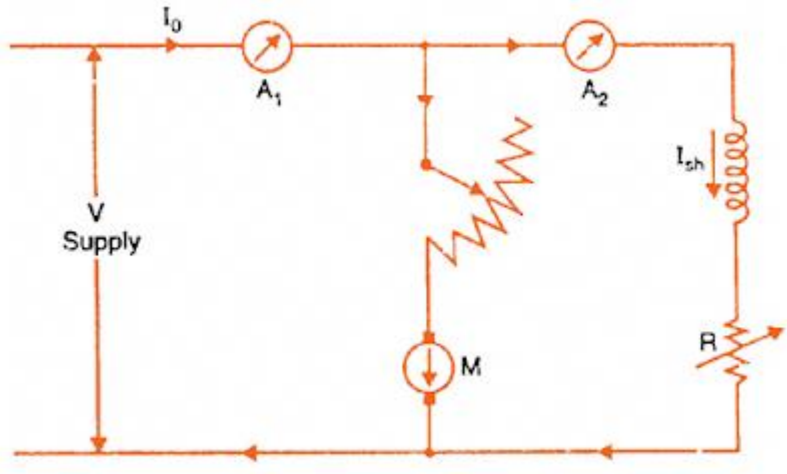
Determination of hot resistances of windings

The armature resistance and shunt field resistance are measured at room temperature (say, at 15°C) using voltmeter ammeter method (battery, voltmeter and ammeter). Since these resistances are measured when the machine is cold, they must be converted to values corresponding to the temperature at which the machine would work on full-load.

Generally, these values are measured for a temperature rise of 40°C above the room temperature. From the data so obtained, different losses are computed and efficiency is determined.

Determination of constant losses

The machine is run as a motor on no-load with supply voltage adjusted to the rated voltage



i.e. voltage stamped on the nameplate. The speed of the motor is adjusted to the rated speed with the help of field regulator R as shown in figure (for more details please visit speed control of dc shunt motor).

Let V = Supply voltage
I_o = No-load current read by ammeter A_1
I_{sh} = Shunt-field current read by ammeter A_2.

$$\therefore \text{No-load armature current, } I_{a0} = I_o - I_{sh}$$
$$\text{No-load input power to motor} = V\, I_o$$
$$\text{No-load power input to armature} = V\, I_{ao} = V\,(I_o - I_{sh})$$

Since the output of the motor is zero, the no-load input power to the armature supplies
(a) iron losses in the core (b) friction loss
(c) windage loss (d) armature Cu loss [$I_{ao}^2R_a$ or $(I_o - I_{sh})^2R_a$.

$$\text{Constant losses, } W_c = \text{Input to motor} - \text{Armature Cu loss}$$

$$W_c = V\, I_o - (I_o - I_{sh})^2R_a$$

Since constant losses are known, the efficiency of the machine at any other load can be determined. Suppose it is desired to determine the efficiency of the machine at load current I. Then,

Armature current, $Ia = I - I_{sh}$ ... if the machine is motoring
$= I + I_{sh}$ ... if the machine is generating

Efficiency when running as a motor

Input power to motor = VI
Armature Cu loss = $I_a^2R_a = (I - I_{sh})^2R_a$
Constant losses = W_c found above
Total losses = $(I - I_{sh})^2R_a + W_c$
∴ Motor efficiency, η_m = (Input - Losses)/Input = $[VI - (I - I_{sh})^2R_a + W_c]/VI$

Efficiency when running as a generator

Output of generator= VI
Armature Cu loss = $I_a^2R_a$ = $(I + I_{sh})^2R_a$
Constant losses = W_c found above
Total losses = $(I + I_{sh})^2R_a + W_c$
∴ Generator efficiency, η_G = Output/(Output+Losses) = $VI/[VI + (I + I_{sh})^2R_a + W_c]$

Advantages of Swinburne's test

The following are the advantages of swinburne's test

- The power required to carry out the test is small because it is a no-load test. Therefore, this method is quite economical.
- The efficiency can be determined at any load because constant losses are known.
- This test is very convenient.

Disadvantages of Swinburne's test

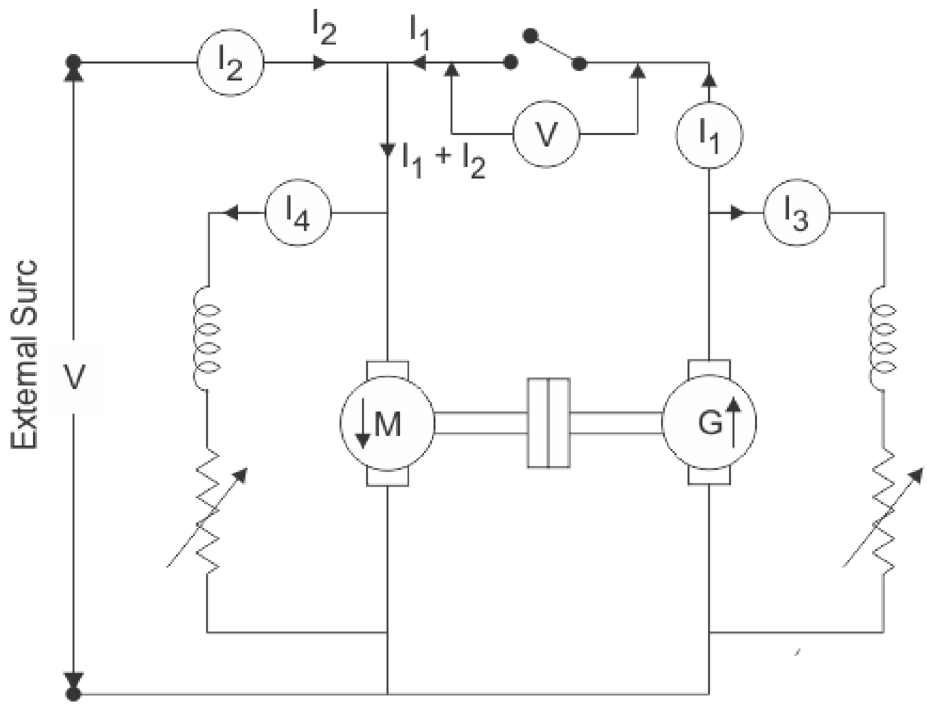
The disadvantages of swinburne's test are given below

- It does not take into account the stray load losses that occur when the machine is loaded.
- This test does not enable us to check the performance of the machine on full-load. For example, it does not indicate whether commutation on full load is satisfactory and whether the temperature rise is within the specified limits.
-
- This test does not give quite accurate efficiency of the machine. It is because iron losses under actual load are greater than those measured. This is mainly due to armature reaction distorting the field.

Hopkinson's Test

Hopkinson's Test is another useful method of testing the efficiency of a DC machine. It is a full load test and it requires two identical machines which are coupled to each other. One of these two machines is operated as a generator to supply the mechanical power to the motor and the other is operated as a motor to drive the generator. For this process of back to back driving the motor and the generator, Hopkinson's test is also called back-to-back test or regenerative test. If there are no losses in the machine, then no external power supply would have needed. But due to the drop in the generator output voltage we need an extra voltage source to supply the proper input voltage to the motor. Hence, the power drawn from the external supply is therefore used to overcome the internal losses of the motor-generator set. **Hopkinson's test** is also called regenerative test or back to back test or heat run test.

Here is a circuit connection for the **Hopkinson's test** shown in figure below. A motor and a generator, both identical, are coupled together. When the machine is started it is started as motor. The shunt field resistance of the machine is adjusted so that the motor can run at its rated speed. The generator voltage is now made equal to the supply voltage by adjusting the shunt field resistance connected across the generator. This equality of these two voltages of generator and supply is indicated by the voltmeter as it gives a zero reading at this point connected across the switch. The machine can run at rated speed and at desired load by varying the field currents of the motor and the generator.



Hopkinson's Test of DC Machine

Methods to find η:

1) Assuming that both m/c's have same η.
2) Assuming iron, friction and windage losses are same in both the m/c's.

Case (i):

$$\eta_m = \frac{o/p \text{ of motor}}{i/p \text{ of motor}}$$

$$\text{motor } o/p = \eta_m * \text{motor } i/p$$

$$= \eta_m * V(I_1 + I_2) = \text{generator } i/p$$

$$\eta_g = \frac{\text{generator } o/p}{\text{generator } i/p}$$

$$\text{generator } o/p = \eta_g * \text{generator } i/p$$

$$= \eta_g * \eta_m * V(I_1 + I_2)$$

as per case, $\eta = \eta_m = \eta_g$

$$\therefore \text{Generator output} = \eta^2 * V(I_1 + I_2)$$

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

$$\eta^2 = \frac{VI}{V(I_1 + I_2)}$$

$$\eta = \sqrt{\frac{I}{I_1 + I_2}}$$

Case (ii)

Armature Copper loss in generator $= (I_1 + I_3)^2 R_a$

Armature Copper loss in motor $= (I_1 + I_2 - I_4)^2 R_a$

Shunt copper loss in generator $= VI_3$

Shunt copper loss in motor $= VI_4$

Power drawn from DC supply $= VI_2$ = total losses in motor & generator

$$VI_2 = \text{total Copper loss} + \text{total Iron loss} + \text{total Mechanical loss}$$

$$VI_2 - \text{Copper loss} = \underbrace{\text{Iron loss} + \text{Mechanical loss}}$$

$$VI_2 - \text{Cu. loss} = W$$

$$\therefore W = VI_2 - \left[(I_1+I_3)^2 R_a + (I_1+I_2-I_4)^2 R_a + VI_3 + VI_4\right]$$

where, $\frac{W}{2} \Rightarrow$ (Mech. losses + Iron losses) of each machine

For generator,

Gen. Output $= VI_1$

Total loss $= \frac{W}{2} + (I_1 + I_3)^2 R_a + VI_3$

$$\eta_G = \frac{o/p}{i/p} = \frac{o/p}{i/p + loss} = \frac{VI_1}{VI_1 + \frac{W}{2} + (I_1+I_3)^2 R_a + VI_3}$$

For Motor,

Motor input $= V(I_1 + I_2)$

Total loss $= \frac{W}{2} + (I_1 + I_2 - I_4)^2 R_a + VI_4$

$$\eta_M = \frac{o/p}{i/p} = \frac{i/p - losses}{i/p} = \frac{V(I_1+I_2) - \left[\frac{W}{2} + (I_1+I_2-I_4)^2 R_a + VI_4\right]}{V(I_1+I_2)}$$

Advantages of Hopkinson's Test

The merits of this test are…

1. This test requires very small power compared to full-load power of the motor-generator coupled system. That is why it is economical. Large machines can be tested at rated load without much power consumption.
2. Temperature rise and commutation can be observed and maintained in the limit because this test is done under full load condition.
3. Change in iron loss due to flux distortion can be taken into account due to the advantage of its full load condition.
4. Efficiency at different loads can be determined.

Disadvantages of Hopkinson's Test

The demerits of this test are

1. It is difficult to find two identical machines needed for **Hopkinson's test**.
2. Both machines cannot be loaded equally all the time.
3. It is not possible to get separate iron losses for the two machines though they are different because of their excitations.
4. It is difficult to operate the machines at rated speed because field currents vary widely.

Speed of a DC motor

We know, back emf E_b of a DC motor is the induced emf in the armature conductors due to the rotation of armature in magnetic field. Thus, magnitude of the E_b can be given by the EMF equation of a DC generator.

$$E_b = PØNZ/60A$$

(where, P = no. of poles, Ø = flux/pole, N = speed in rpm, Z = no. of armature conductors, A = parallel paths)

E_b can also be given as,

$$E_b = V - IaRa$$

thus, from the above equations

$$N = E_b\ 60A/PØZ$$

but, for a DC motor A, P and Z are constants

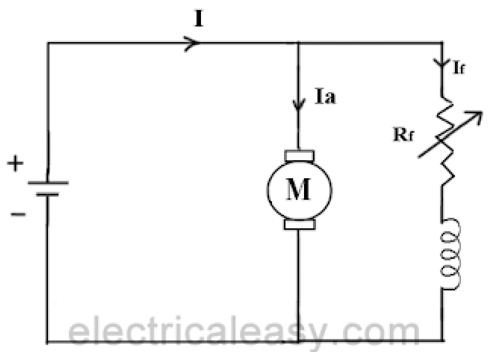
$$\text{Therefore, } N \propto K\ E_b/Ø \qquad \text{(where, K=constant)}$$

This shows the speed of a dc motor is directly proportional to the back emf and inversely proportional to the flux per pole.

Speed control methods of DC motor

Speed control of Shunt motor

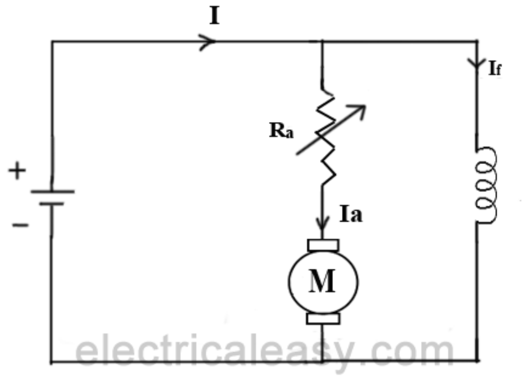
1. Flux control method



It is already explained above that the speed of a dc motor is inversely proportional to the flux per pole. Thus by decreasing the flux, speed can be increased and vice versa.

To control the flux, a rheostat is added in series with the field winding, as shown in the circuit diagram. Adding more resistance in series with the field winding will increase the speed as it decreases the flux. In shunt motors, as field current is relatively very small, Ish2R loss is small and, hence, this method is quite efficient. Though speed can be increased above the rated value by reducing flux with this method, it puts a limit to maximum speed as weakening of flux beyond the limit will adversely affect the commutation.

2. Armature control method



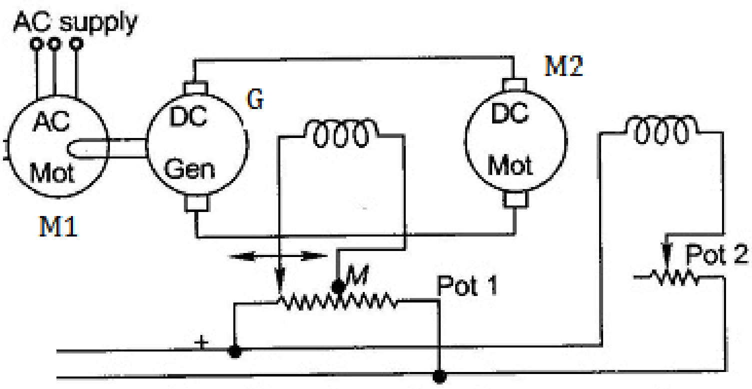
Speed of a dc motor is directly proportional to the back emf E_b and $E_b = V - I_aR_a$. That means, when the supply voltage V and the armature resistance Ra are kept constant, speed is directly proportional to the armature current Ia. Thus, if we add a resistance in series with the armature, I_a decreases and, hence, the speed also decreases. Greater the resistance in series with the armature, greater the decrease in speed.

3. Voltage Control Method

a) Multiple voltage control:

In this method, the shunt field is connected to a fixed exciting voltage and armature is supplied with different voltages. Voltage across armature is changed with the help of a suitable switchgear. The speed is approximately proportional to the voltage across the armature.

b) Ward-Leonard System:



(a) Ward-Leonard speed control system

This system is used where very sensitive speed control of motor is required (e.g electric excavators, elevators etc.). The arrangement of this system is as shown in the figure at right.

M2 is the motor whose speed control is required.

M1 may be any AC motor or DC motor with constant speed.

G is a generator directly coupled to M1.

In this method, the output from the generator G is fed to the armature of the motor M2 whose speed is to be controlled. The output voltage of the generator G can be varied from zero to its maximum value by means of its field regulator and, hence, the armature voltage of the motor M2 is varied very smoothly. Hence, very smooth speed control of the dc motor can be obtained by this method.

Speed control of series motor

1. Flux control method

Field divertor: A veritable resistance is connected parallel to the series field as shown in fig (a). This variable resistor is called as divertor, as the desired amount of current can be diverted through this resistor and hence current through field coil can be decreased. Hence, flux can be decreased to the desired amount and speed can be increased.

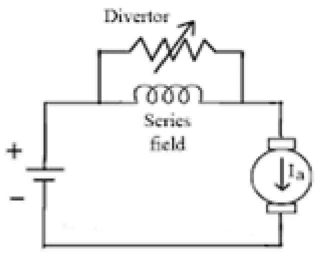


fig (a) Field Divertor

Armature divertor: Divertor is connected across the armature as in fig (b).

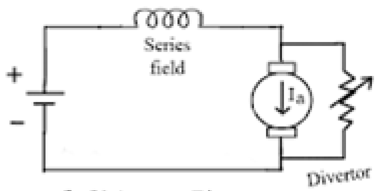


fig (b) Armature Divertor

For a given constant load torque, if armature current is reduced then flux must increase. As, $T_a \propto \text{Ø} I_a$. This will result in an increase in current taken from the supply and hence flux Ø will increase and subsequently speed of the motor will decrease.

Tapped field control: As shown in fig (c) field coil is tapped dividing number of turns. Thus we can select different value of Ø by selecting different number of turns.

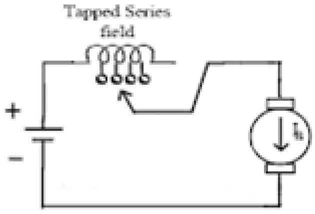


fig (c) Tapped field

Paralleling field coils: In this method, several speeds can be obtained by regrouping coils as shown in fig (d).

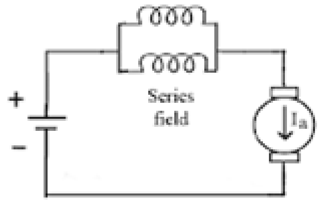


fig (d) Paralleling Field coils

2. Variable resistance in series with armature

By introducing a resistance in series with the armature, voltage across the armature can be reduced. And, hence, speed reduces in proportion with it.

3. Series-parallel control

This system is widely used in electric traction, where two or more mechanically coupled series motors are employed. For low speeds, the motors are connected in series, and for higher speeds the motors are connected in parallel.

When in series, the motors have the same current passing through them, although voltage across each motor is divided. When in parallel, the voltage across each motor is same although the current gets divided.

MODULE 4

Definition of Transformer

A transformer is a static machine used for transforming power from one circuit to another without changing frequency. This is a very basic definition of transformer. Since, there is no rotating or moving part, so a transformer is a static device. Transformer operates on an ac supply. A transformer works on the principle of mutual induction.

History of Transformer

If we want to know the history of transformer we have to go back long in the 1880s. Around 50 years before that in 1830 the property of induction was discovered, and this is the working principle of transformer. Later the transformer design was improved resulting in more efficiency and lesser size. Gradually the large capacity of transformers in the range of several KVA, MVA came into existence. In the year 1950, 400KV electrical power transformer was introduced in high voltage electrical power system. In the early 1970s, unit rating as large as 1100 MVA was produced. Various manufacturers manufactured 800KV and even higher KV class transformers in the year 1980.

Use of Power Transformer

Generation of electrical power in low voltage level is very much cost effective. Theoretically, this low voltage level power can be transmitted to the receiving end. This low voltage power if transmitted results in greater line current which indeed causes more line losses. But if the voltage level of a power is increased, the current of the power is reduced which causes reduction in ohmic or I^2R losses in the system, reduction in cross-sectional area of the conductor i.e. reduction in capital cost of the system and it also improves the voltage regulation of the system. Because of these, low level power must be stepped up for efficient electrical power transmission. This is done by step up transformer at the sending side of the power system network. As this high voltage power may not be distributed to the consumers directly, this must be stepped down to the desired level at the receiving end with the help of step down transformer. Electrical power transformer thus plays a vital role in power transmission.

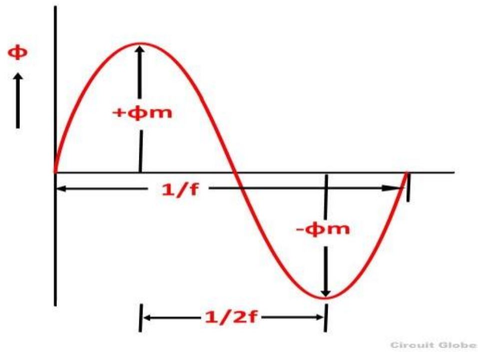
Two winding transformers are generally used where ratio of high voltage and low voltage is greater than 2. It is cost effective to use auto transformer where the ratio between high voltage and low voltage is less than 2. Again a single unit three phase transformer is more cost effective than a bank of three single phase transformers unit in a three phase system. But a single three phase transformer unit is a bit difficult to transport and have to be removed from service entirely if one of the phase winding breaks down.

EMF Equation of a Transformer

When a sinusoidal voltage is applied to the primary winding of a transformer, alternating flux ϕ_m sets up in the iron core of the transformer. This sinusoidal flux links with both primary and secondary winding. The function of flux is a sine function. The rate of change of flux with respect to time is derived mathematically.

The derivation of EMF Equation of the transformer is shown below. Let

- ϕ_m be the maximum value of flux in Weber
- f be the supply frequency in Hz
- N_1 is the number of turns in the primary winding
- N_2 is the number of turns in the secondary winding
- Φ is the flux per turn in Weber



As shown in the above figure that the flux changes from + ϕ_m to – ϕ_m in half a cycle of 1/2f seconds.

By Faraday's Law

Let E_1 is the emf induced in the primary winding

$$E_1 = -\frac{d\psi}{dt} \dots\dots\dots (1)$$

Where $\Psi = N_1\phi$

$$\text{Therefore, } E_1 = -N_1 \frac{d\varphi}{dt} \dots\dots\dots(2)$$

Since ϕ is due to AC supply $\phi = \phi_m$ Sinwt

$$E_1 = -N_1 \frac{d}{dt} (\varphi_m \text{ Sinwt})$$

$$E_1 = -N_1 \, w\varphi_m \text{ Coswt}$$

$$E_1 = N_1 w\varphi_m \text{ Sin}(wt - \pi/2) \dots\dots\dots . (3)$$

So the induced emf lags flux by 90 degrees.

Maximum valve of emf

$$E_1 \text{max} = N_1 w\varphi_m \dots\dots\dots . (4)$$

But $w = 2\pi f$

$$E_1 max = 2\pi f N_1 \varphi_m \dots\dots\dots (5)$$

Root mean square RMS value is

$$E_1 = \frac{E_{1max}}{\sqrt{2}} \dots\dots\dots (6)$$

Putting the value of E_1max in equation (6) we get

$$E_1 = \sqrt{2}\pi f N_1 \varphi_m \dots\dots (7)$$

Putting the value of $\pi = 3.14$ in the equation (7) we will get the value of E_1 as

$$E_1 = 4.44 f N_1 \varphi_m \dots\dots\dots (8)$$

Similarly

$$E_2 = \sqrt{2}\pi f N_2 \varphi_m$$

Or

$$E_2 = 4.44 f N_2 \varphi_m \dots\dots\dots (9)$$

Now, equating the equation (8) and (9) we get

$$\frac{E_2}{E_1} = \frac{4.44 f N_2 \varphi_m}{4.44 f N_1 \varphi_m}$$

Or

$$\frac{E_2}{E_1} = \frac{N_2}{N_1} = K$$

The above equation is called the turn ratio where K is known as transformation ratio. The equation (8) and (9) can also be written as shown below using the relation ($\phi m = B_m \times A_i$) where Ai is the iron area and Bm is the maximum value of flux density.

$$E_1 = 4.44 N_1 f B_m A_i \ \text{Volts} \quad \text{and} \quad E_2 = 4.44 N_2 f B_m A_i \ \text{Volts}$$

Types of Transformer

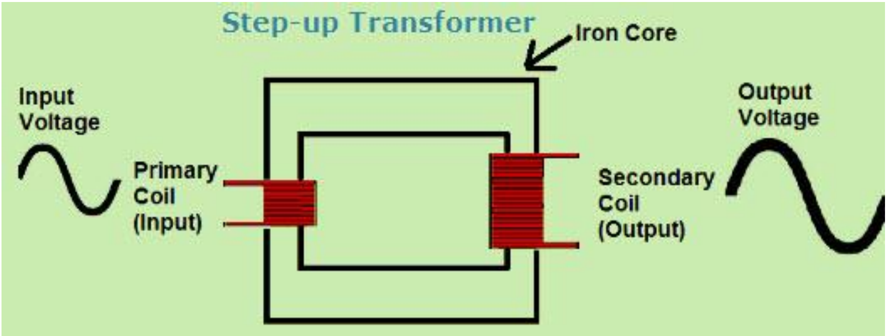
Transformers can be categorized in different ways, depending upon their purpose, use, construction etc. The types of transformer are as follows,

- **Based on Voltage Levels**

  These are the most commonly used transformer types for all the applications. Depends upon the voltage ratios from primary to secondary windings, the transformers are classified as step-up and step-down transformers.

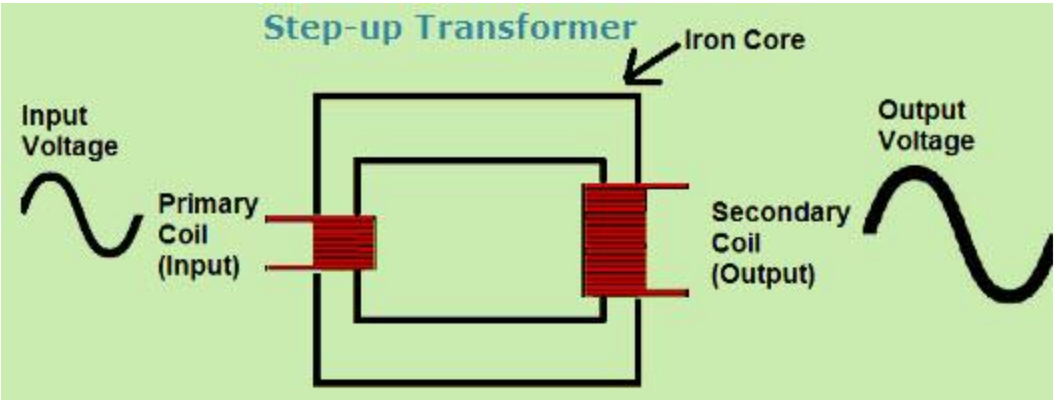
Step-Up Transformer

As the name states that, the secondary voltage is stepped up with a ratio compared to primary voltage. This can be achieved by increasing the number of windings in the secondary than the primary windings as shown in the figure. In power plant, this transformer is used as connecting transformer of the generator to the grid.



Step-Down Transformer

It used to step down the voltage level from lower to higher level at secondary side as shown below so that it is called as a step-down transformer. The winding turns more on the primary side than the secondary side.



In distribution networks, the step-down transformer is commonly used to convert the high grid voltage to low voltage that can be used for home appliances.

- **Based on Phase Levels**

Single Phase Transformer

A single phase Transformer is a static device, works on the principle of Faraday's law of mutual Induction. At a constant level of frequency and variation of voltage level, the transformer transfers AC power from one circuit to the other circuit. There are two types of windings in the transformer. The winding to which AC supply is given is termed as Primary winding and in the secondary winding, the load is connected.

Three Phase Transformer

If the three single phase transformer is taken and connected together with their all the three primary winding connected to each other as one and all the three secondary windings to each other, forming as one secondary winding, the transformer is said to behave as three phase transformer, that means a bank of three single phase transformer connected together which acts as a three-phase transformer.

Three phase supply is mainly used for electric power generation, transmission and distribution for industrial purpose. It is less costly to assemble three single phase transformer to form three-phase transformer than to purchase one single three-phase transformer. The three-phase transformer connection can be done by Star (Wye) and Delta (Mesh) type.

The connection of primary and secondary winding can be done by various combinations shown below

Primary Winding	Secondary Winding
Star (Wye)	Star
Delta (mesh)	Delta

Primary Winding	Secondary Winding
Star	Delta
Delta	Star

The combination of primary winding and the secondary winding is done as star-star, delta-delta, star-delta and delta-star.

- Electrical transformer

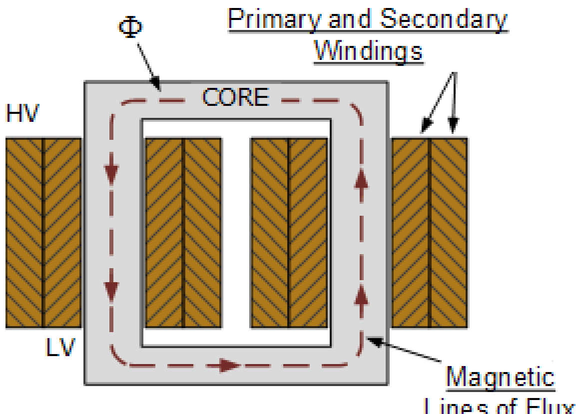
  Electrical Power Transformer, Distribution Transformer and Instrument Transformer - Power transformers are generally used in transmission network for stepping up or down the voltage level. It operates mainly during high or peak loads and has maximum efficiency at or near full load. Distribution transformer steps down the voltage for distribution purpose to domestic or commercial users. It has good voltage regulation and operates 24 hrs a day with maximum efficiency at 50% of full load. Instrument transformers include C.T and P.T which are used to reduce high voltages and current to lesser values which can be measured by conventional instruments.
- Two Winding Transformer and One winding Transformer
  1. The two-winding transformer is one in which two windings are linked by a common time-varying magnetic flux. One of these windings, known as the primary, receives power at a given voltage from a source and the other winding, known as the secondary, delivers power, usually at a value of voltage different from that of the source, to the load. The roles of the primary and secondary windings can be interchanged. However, in iron-core transformers a given winding must operate at a voltage that does not exceed its rated value at rated frequency - otherwise the exciting current becomes excessive.
  2. The One-winding transformer having only one winding. In this type, a part of winding acts as a primary and the other as a secondary.
- Oil Cooled and Dry Type Transformer

  In oil cooled transformer the cooling medium is transformer oil whereas the dry type transformer is air cooled.
- Core type, Shell type and Berry type transformer
  1. Core type transformer: It has two vertical legs or limbs with two horizontal sections named yoke. Core is rectangular in shape with a common magnetic circuit. Cylindrical coils (HV and LV) are placed on both the limbs.
  2. Shell type transformer: It has a central limb and two outer limbs. Both HV, LV coils are placed on the central limb. The double magnetic circuit is present.

3. Berry type transformer: The core looks like spokes of wheels. Tightly fitted metal sheet tanks are used for housing this type of transformer with transformer oil filled inside.

Core Type Transformer

In a simple core type construction of the transformer, rectangular frame laminations are formed to build the core of the transformer. The laminations are cut in the form of L-shape strips as shown in the figure below. In order to avoid high reluctance at the joints where laminations are butted against each other, the alternate layers are placed differently to eliminate the continuous joints.

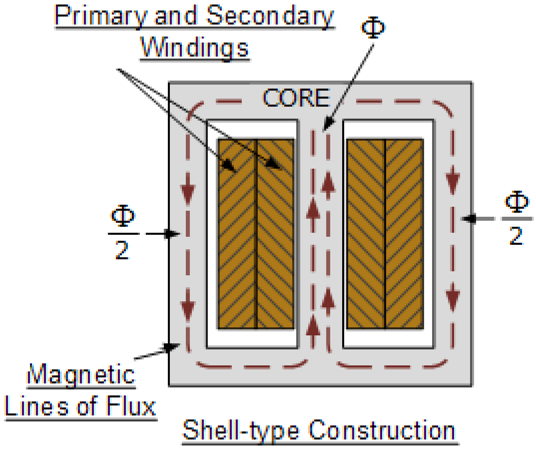


Core-type Construction

The primary and the secondary windings are interleaved to reduce the leakage flux. Half of the each winding are placed side by side or concentrically on either limb of the core. To reduce the insulation, the low voltage winding is always placed nearer to the core.

Shell Type Transformer

In shell type transformer the individual laminations are cut in the form of long strips of E and I shape as shown in the figure below. It has two magnetic circuits, and the core has three limbs. The central limb carries whole of the flux whereas the side limbs carry half of the flux. Therefore, the width of the central is double to that of the outer limbs.



The leakage flux is reduced by the subdivision of the windings which in return have lesser reactances. Both the primary and the secondary windings are placed on the central limb side by side. To reduce the cost of lamination between the core and the low voltage winding. The windings are formed and is wound to the cylindrical shape and then the core laminations are inserted later.

Dry Type Transformer

Dry type transformer never uses any insulating liquid where its winding with core be immerged. Rather windings with core are kept within a sealed tank that is pressurized with air.

Type of Dry Type Transformer

The dry type transformer is of two types. They are

1. Cast Resin Dry Type Transformer (CRT)
2. Vacuum pressure Impregnated Transformer (VPI)

Cast Resin Dry Type Transformer (CRT)

Cast resin dry type transformer (CRT) is used in the high moisture prone areas. It is because of its primary and secondary windings are encapsulated with epoxy resin. This encapsulation helps to prevent moisture to penetrate to affect the winding material. Complete protection is achieved by this cast resin encapsulation so that the transformer can work without disruption in highly moisture prone area. Thus this transformer is non hygroscopic. This type of transformer is available in ratings of 25 KVA to 12,500 KVA. with insulation class of F (90°C Temp. Rise).

This type of transformer has some featured advantages. They are-

- Better over load capacity.
- Low partial discharge along with low loss. Hence efficiency is very good.
- As it is with non inflammable winding insulation, it offers zero risk to fire hazard. So it is suitable for indoor installation.
- Can be fitted outdoor in IP 45 enclosure.

- And off course non hygroscopic.

Vacuum Pressure Impregnated Transformer (VPI)

This type of transformer is made with minimum flammable material as insulation of windings. The windings of this transformer are made in foil or strip in a continuous layer. But for higher voltages, the winding is made of disks that are connected in series or parallel as per power rating with respect to voltage level. The insulation of the winding is void free impregnation that is made with class H polyester resin. The primary and secondary winding with core are placed safely within a vacuum protective box. Moisture Ingress Protection is high and it never gets affected by moisture.

This type of transformer is available from 5KVA to 30MVA with insulation grade F (155°C) and H(180°C). It's with Protection up to IP56.

This type of transformer has several advantages. They are-

- High mechanical strength.
- Void free insulation.
- No temperature fluctuation.
- Easy maintenance.
- Less prone to fire hazard.

Advantages of Dry Type Transformer

The main advantages of dry type transformer are given below.

- Safety for people and property.
- Maintenance and pollution-free solution.
- Easy installation.
- Side clearance is less.
- Environmentally friendly.
- Excellent capacity to support overloads.
- Reduced cost on civil installation works and fire protection systems.
- Excellent performance in case of seismic events.
- No fire hazard.
- Excellent resistance to short circuit currents.
- Long lasting due to low thermal and dielectric heating.
- Suited for damp and contaminated areas.

Disadvantages of Dry Type Transformer

But there are some disadvantages of dry type transformer. They are-

- Dry type transformer is long lasting and with less chance of winding failure. But once it fails whole set up is to changed, i.e. complete change of high voltage and low voltage winding with limb.
- For same power and voltage rating, dry type transformer is costlier than oil cooled transformer.

Application of Dry Type Transformer

- Chemical, oil and gas industry
- Environmentally sensitive areas (e.g. water protection areas)
- Fire-risk areas (e.g. forests)
- Inner-city substations
- Indoor and underground substations
- Renewable generation (e.g. off-shore wind turbines)

Important Factors to Design a Dry Type Transformer

The important design parameters for a dry type transformer are given below.

- **Choice of Insulation Type**
  Generally F and H class of insulation of insulation is used to insulate the primary and secondary winding. It is because these classes have high temperature withstand property, i.e. 155oC for F and 180oC for H class of insulation. Generally varnish and polyester resin are used as insulation of the winding. Apart from the temperature withstand capability, mechanical strength; dielectric strength and resistance to thermal shock are the basic capabilities that have to be fulfilled by the insulation selected for the windings.
- **Selection of Winding Material**
  Generally copper and aluminum are used to make the winding or coil. Though copper is better conductor, aluminum conductor wound transformer possesses low cost and weight. For the same current rating, copper conductor with less cross section is used as the winding material in the transformer. Copper coil provides more mechanical strength than aluminum coil.
- **Selection of Core Material with Low Hysteresis Loss**
  Core material selection is very important in transformer design. Core material must possess high permeability and less hysteresis loss. But both cannot be achieved in any core material. Generally silicon steel, CRGO etc are used to allow minimum hysteresis loss with higher permeability.
- **Regulation**
  When transformer secondary voltage drops abruptly due to increase in load, this regulation is called poor regulation. Poor regulation is due to transformer higher internal leakage reactance. So, leakage reactance is kept within 2% during design.
- **Life Expectancy**
  Life of the transformer depends on the breakdown of winding insulation due to temperature rising effect in winding due to overloading. Normally class B, F and H insulation is preferred for dry type transformer to withstand higher temperature gradient including ambient temperature. So design of the transformer must be done with respect to the rise of the temperature of operating full load condition.
- **Losses**
  No load losses mean core loss and eddy current that is independent of loading condition. But in loading condition copper loss occurs that includes the iron loss to increase the value of voltage regulation, i.e. poor voltage regulation. Leakage

reactance and winding resistance must be within moderate value to minimize this loss and better voltage regulation, thus higher efficiency.

- **Overloading**

  Over loading condition is harmful for transformer for long time span. Overloading is the cause of overheating when transformer has to fulfill its connected load demand. Hence huge amount of current makes copper loss in the winding, and that causes transformer damage. To cool the winding, fan-cooling system is provided in dry type transformer.

- **K-factor**

  It is the ability of withstanding of heat generated by non sinusoidal current in the transformer winding. Pure sine wave is not obtained in voltage and current wave form. It is due to today's various electronic devices uses. Several harmonics are present in the voltage and current wave form. Robust design of a transformer off course bothers k-factor to provide transformer long lasting life.

- **Insulation Level**

  In transformer design, insulation level adjustment is an important factor. Generally insulation level is chosen as per basic impulse level and system over voltage. Strong insulation level increases the life of a transformer.

Cooling Methods of a Transformer

No transformer is truly an 'ideal transformer' and hence each will incur some losses, most of which get converted into heat. If this heat is not dissipated properly, the excess temperature in transformer may cause serious problems like insulation failure. It is obvious that transformer needs a cooling system. Transformers can be divided in two types as

(i) Dry type transformers and

(ii) Oil immersed transformers.

Different cooling methods of transformers are -

For dry type transformers

- Air Natural (AN)
- Air Blast

For oil immersed tranformers

- Oil Natural Air Natural (ONAN)
- Oil Natural Air Forced (ONAF)
- Oil Forced Air Forced (OFAF)
- Oil Forced Water Forced (OFWF)
- Oil Natural Water Forced (ONWF)

Cooling methods for Dry type Transformers

Air Natural or Self air cooled transformer

This method of transformer cooling is generally used in small transformers (upto 3 MVA). In this method the transformer is allowed to cool by natural air flow surrounding it.

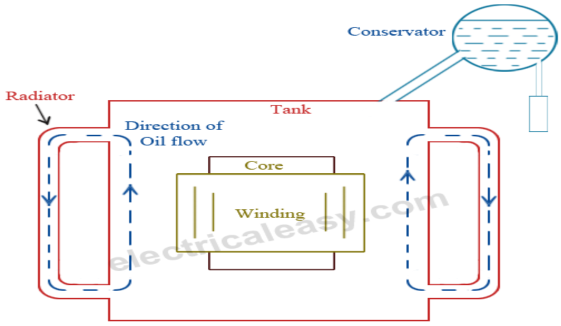
Air Blast

For transformers rated more than 3 MVA, cooling by natural air method is inadequate. In this method, air is forced on the core and windings with the help of fans or blowers. The air supply must be filtered to prevent the accumulation of dust particles in ventilation ducts. This method can be used for transformers upto 15 MVA.

Cooling methods for Oil Immersed Transformers

Oil Natural Air Natural (ONAN)

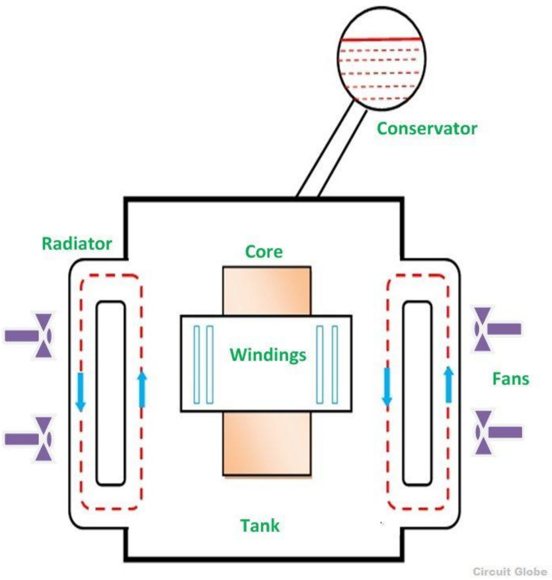
This method is used for oil immersed transformers. In this method, the heat generated in the core and winding is transferred to the oil. According to the principle of convection, the heated oil flows in the upward direction and then in the radiator. The vacant place is filled up by cooled oil from the radiator. The heat from the oil will dissipate in the atmosphere due to the natural air flow around the transformer. In this way, the oil in transformer keeps circulating due to natural convection and dissipating heat in atmosphere due to natural conduction. This method can be used for transformers upto about 30 MVA.



Oil Natural Air Natural (ONAN) - Cooling of Transformer

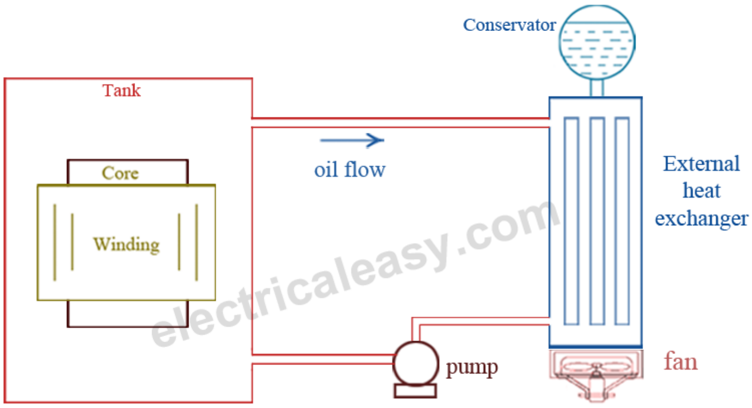
Oil Natural Air Forced (ONAF)

The heat dissipation can be improved further by applying forced air on the dissipating surface. Forced air provides faster heat dissipation than natural air flow. In this method, fans are mounted near the radiator and may be provided with an automatic starting arrangement, which turns on when temperature increases beyond certain value. This transformer cooling method is generally used for large transformers upto about 60 MVA.



Oil Forced Air Forced (OFAF)

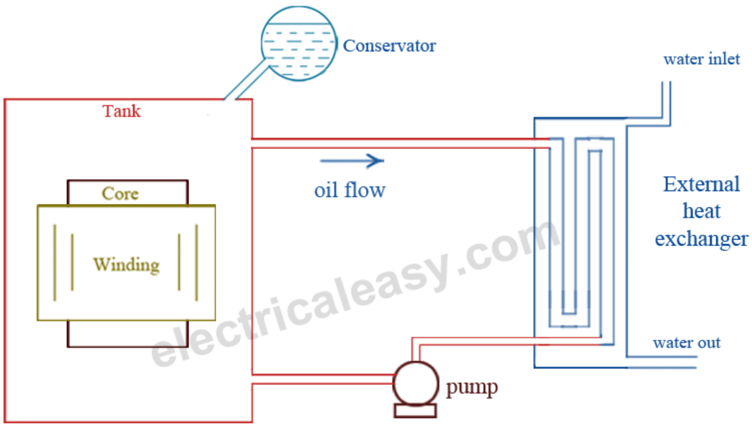
In this method, oil is circulated with the help of a pump. The oil circulation is forced through the heat exchangers. Then compressed air is forced to flow on the heat exchanger with the help of fans. The heat exchangers may be mounted separately from the transformer tank and connected through pipes at top and bottom as shown in the figure. This type of cooling is provided for higher rating transformers at substations or power stations.



Oil Forced Air Forced (OFAF) - Cooling of Transformer

Oil Forced Water Forced (OFWF)

This method is similar to OFAF method, but here forced water flow is used to dissipate hear from the heat exchangers. The oil is forced to flow through the heat exchanger with the help of a pump, where the heat is dissipated in the water which is also forced to flow. The heated water is taken away to cool in separate coolers. This type of cooling is used in very large transformers having rating of several hundreds MVA.



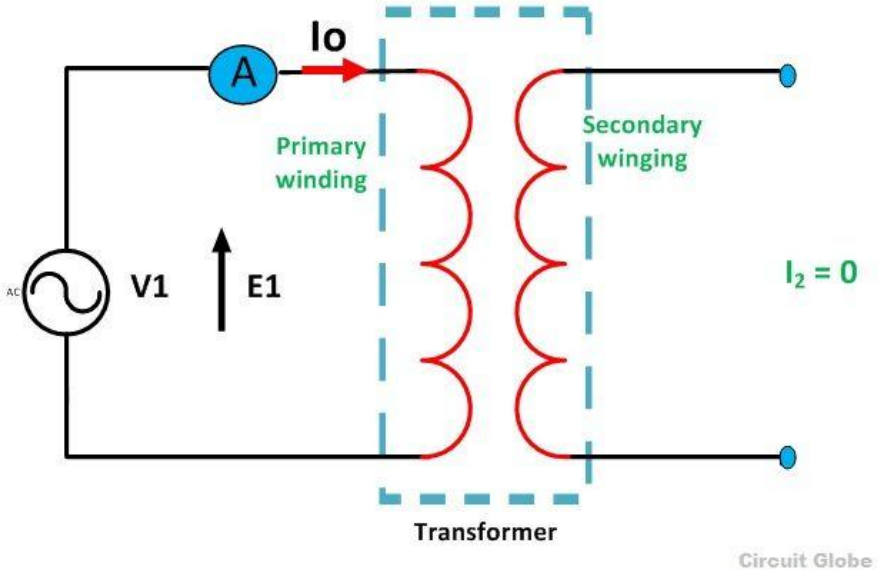
Oil Forced Water Forced (OFWF) - Cooling of Transformer

Oil Natural Water Forced (ONWF)

In Oil Natural Water Force cooling method the transformer core and the windings are immersed in the oil tank. A radiator is installed outside the tank aa the temperature rises and the oil heats up and moves upward the heat is dissipated by the natural process of convection and oil is passed through the radiator, but the water is pumped and passed through the heat exchanger for cooling of the oil.

Transformer on No Load Condition

When the transformer is operating at no load, the secondary winding is open circuited, which means there is no load on the secondary side of the transformer and, therefore, current in the secondary will be zero, while primary winding carries a small current I0 called no load current which is 2 to 10% of the rated current. This current is responsible for supplying the iron losses (hysteresis and eddy current losses) in the core and a very small amount of copper losses in the primary winding. The angle of lag depends upon the losses in the transformer. The power factor is very low and varies from 0.1 to 0.15.



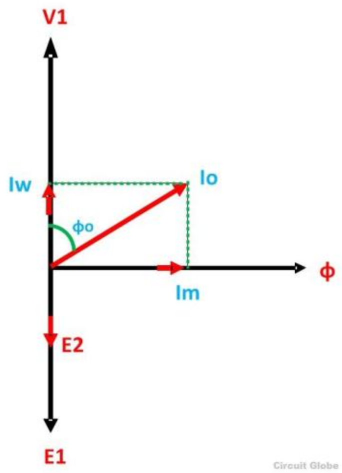
The no load current consists of two components

- Reactive or magnetizing component I_m. (It is in quadrature with the applied voltage V_1. It produces flux in the core and does not consume any power)

- Active or power component I_w, also known as working component. (It is in phase with the applied voltage V_1. It supplies the iron losses and a small amount of primary copper loss)

The following steps are given below to draw the phasor diagram

1. The function of the magnetizing component is to produce the magnetizing flux, and thus, it will be in phase with the flux.
2. Induced emf in the primary and the secondary winding lags the flux ϕ by 90 degrees.
3. The primary copper loss is neglected, and secondary current losses are zero as $I_2 = 0$. Therefore, the current I_0 lags behind the voltage vector V_1 by an angle ϕ_0 called no-load power factor angle shown in the phasor diagram above.
4. The applied voltage V_1 is drawn equal and opposite to the induced emf E_1 because the difference between the two, at no load, is negligible.
5. Active component I_w is drawn in phase with the applied voltage V_1.
6. The phasor sum of magnetizing current I_m and the working current I_w gives the no load current I_0.



From the phasor diagram drawn above, the following conclusions are made

Working component $I_w = I_0 \cos\varphi_0$

No load current $I_0 = \sqrt{I_w^2 + I_m^2}$

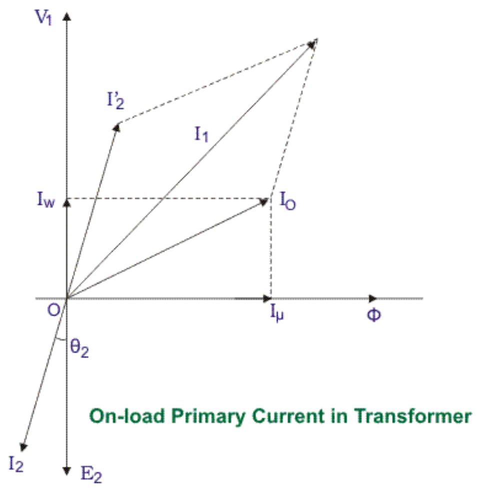
Magnetizing component $I_m = I_0 \sin\varphi_0$

Power factor $\cos\varphi_0 = \frac{I_w}{I_0}$

No load power input $P_0 = V_1 I_0 \cos\varphi_0$

Practical Transformer on Load having No Winding Resistance and Leakage Reactance

Now we will examine the behaviour of above said transformer on load that means load is connected to the secondary terminals. Consider, a transformer having core loss but no copper loss and leakage reactance. Whenever a load is connected to the secondary winding, load current will start to flow through the load as well as secondary winding. This load current solely depends upon the characteristics of the load and also upon the secondary voltage of the transformer. This current is called secondary current or load current, here it is denoted as I_2. As I_2 is flowing through the secondary, a self mmf in secondary winding will be produced. Here it is N_2I_2, where, N_2 is the number of turns of the secondary winding of transformer.



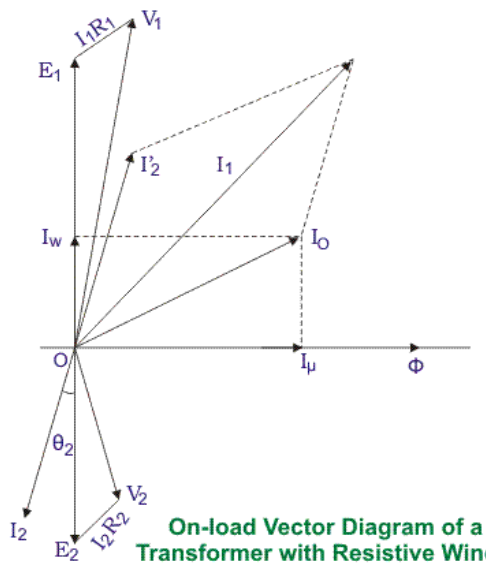
This mmf or magneto motive force in the secondary winding produces flux φ_2. This φ_2 will oppose the main magnetizing flux and momentarily weakens the main flux and tries to reduce primary self-induced emf E_1. If E_1 falls below the primary source voltage V_1, there will be an extra current flowing from source to primary winding. This extra primary current I_2' produces extra flux φ' in the core which will neutralize the secondary counter flux φ_2. Hence the main magnetizing flux of core, Φ remains unchanged irrespective of load. So total current, this transformer draws from source can be divided into two components. First one is utilized for magnetizing the core and compensating the core loss, i.e., I_o. It is the no-load component of the primary current. The second one is utilized for compensating the counter flux of the secondary winding. It is known as load component of the primary current. Hence total no load primary current I_1 of an electrical power transformer having no winding resistance and leakage reactance can be represented as follows

$$I_1 = I_0 + I_2'$$

where θ_2 is the angle between Secondary Voltage and Secondary Current of the transformer. Now we will precede one further step toward a more practical aspect of a transformer.

Practical Transformer on Load, with Resistive Winding, but No Leakage Reactance

Now, consider the winding resistance of transformer but no leakage reactance. So far we have discussed about the transformer which has ideal windings, means winding with no resistance and leakage reactance, but now we will consider one transformer which has internal resistance in the winding but no leakage reactance. As the windings are resistive, there would be a voltage drop in the windings.



On-load Vector Diagram of a Transformer with Resistive Winding

We have proved earlier that, total primary current from the source on load is I_1. The voltage drop in the primary winding with resistance, R_1 is I_1R_1. Obviously, induced emf across primary winding E_1, is not exactly equal to source voltage V1. E1 is less than V_1 by voltage drop I_1R_1.

$$V_1 = E_1 + I_1R_1$$

Again in the case of secondary, the voltage induced across the secondary winding, E_2 does not totally appear across the load since it also drops by an amount I_2R_2, where R_2 is the secondary winding resistance and I_2 is secondary current or load current. Similarly, voltage equation of the secondary side of the transformer will be

$$V_2 = E_2 - I_2R_2$$

Practical Transformer on Load, with Resistance as well as Leakage Reactance

Now we will consider the condition, when there is leakage reactance of transformer as well as winding resistance of transformer.

Let leakage reactance of primary and secondary windings of the transformer are X_1 and X_2 respectively. Hence total impedance of primary and secondary winding of transformer with resistance R_1 and R_2 respectively, can be represented as,

$$Z_1 = R_1 + jX_1\ (impedance\ of\ primary\ winding)$$

$$Z_2 = R_2 + jX_2\ (impedance\ of\ secondary\ winding)$$

We have already established the voltage equation of a transformer on load, with only resistances in the windings, where voltage drops in the windings occur only due to resistive voltage drop. But when we consider leakage reactance of transformer windings, voltage drop occurs in the winding not only because of resistance, it is because of impedance of transformer windings. Hence, actual voltage equation of a transformer can easily be determined by just replacing resistances R_1 & R_2 in the previously established voltage equations by Z_1 and Z_2. Therefore, the voltage equations are,

$$V_1 = E_1 + I_1Z_1 \ \& \ V_2 = E_2 - I_2Z_2$$

$$V_1 = E_1 + I_1(R_1 + jX_1)$$

$$\Rightarrow V_1 = E_1 + I_1R_1 + jI_1X_1$$

$$V_2 = E_2 - I_2(R_2 + jX_2)$$

$$\Rightarrow V_2 = E_2 - I_2R_2 - jI_2X_2$$

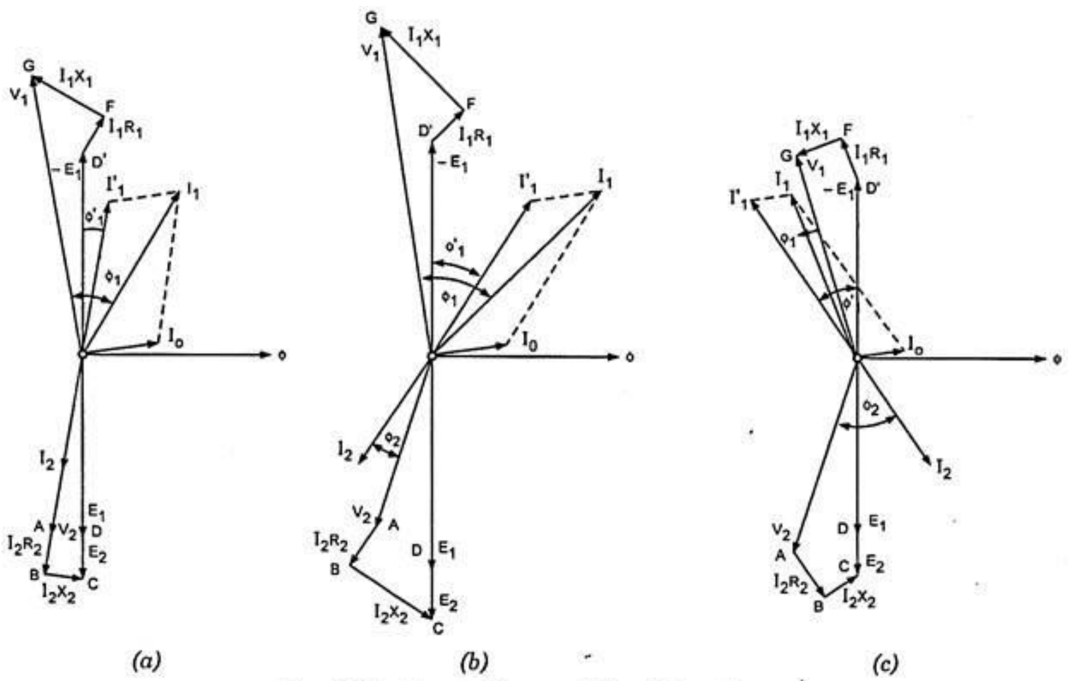


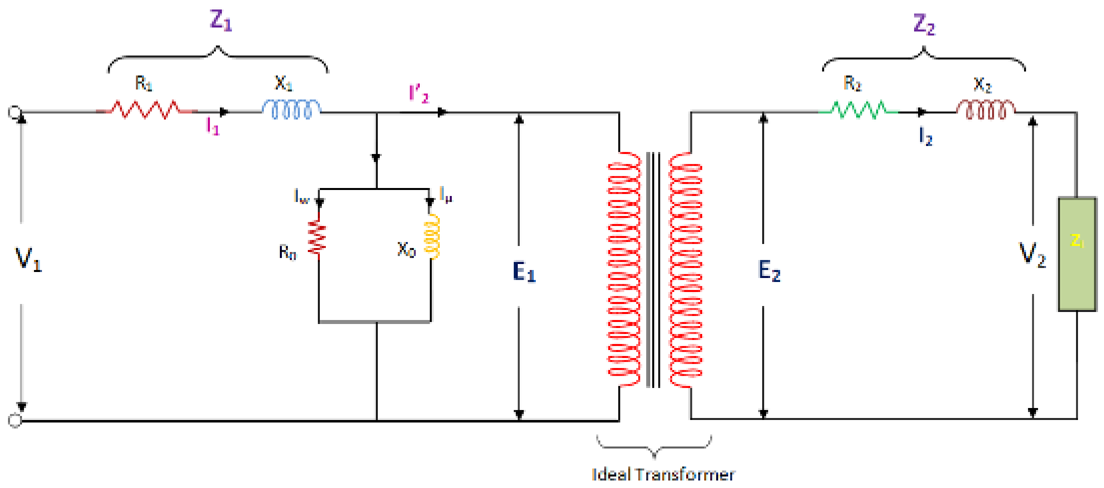
Fig. 10.14 *Phasor Diagram of Actual Transformer*

Resistance drops are in the direction of current vector but, reactive drop will be perpendicular to the current vector as shown in the above vector diagram of transformer.

Equivalent Circuit diagram of single phase Transformer

Equivalent circuit diagram of a transformer is basically a diagram which can be resolved into an equivalent circuit in which the resistance and leakage reactance of the transformer are imagined to be external to the winding.

The equivalent circuit diagram of transformer is given below:-



Equivalent Circuit diagram of Transformer

Where,

R_1 =Primary Winding Resistance.

R_2= Secondary winding Resistance.

I_0= No-load current.

$I_\mu = I_m$ = Magnetizing Component,

$I_w = I_c$ = Working Component,

This I_μ & I_w are connected in parallel across the primary circuit. The value of E_1 (Primary e.m.f) is obtained by subtracting vectorially I_1 Z_1 from V_1 . The value of $X_0 = E_1$ / I_0 and $R_0 = E_1 / I_w$. We know that the relation of E_1 and E_2 is $E_2 / E_1 = N_2 / N_1 = K$, (transformation Ratio)

From the equivalent circuit , we can easily calculate the total impedance of to transfer voltage, current, and impedance either to the primary or the secondary.

The secondary circuit is shown in fig-1. and its equivalent primary value is shown in fig-2,

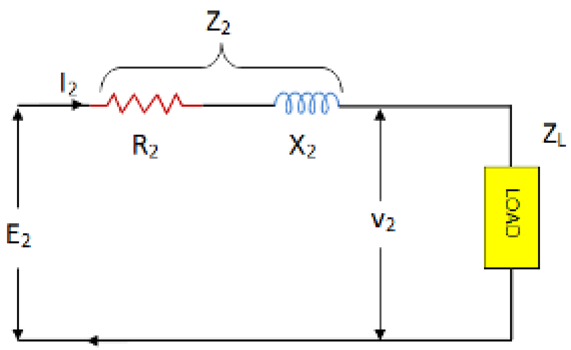


fig-1

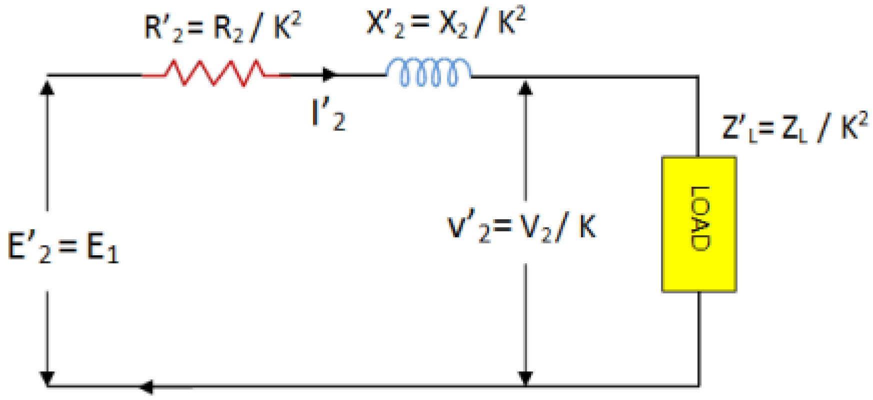


fig-2

The total equivalent circuit of the transformer is obtained by adding in the primary impedance as shown in – Fig-3 .

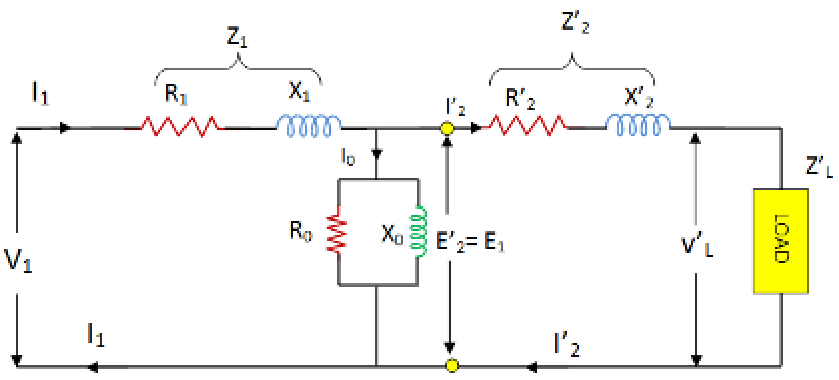


fig-3

And It can be simplified the terminals shown in fig – 4 & further simplify the equivalent circuit is shown in fig.- 5 ,

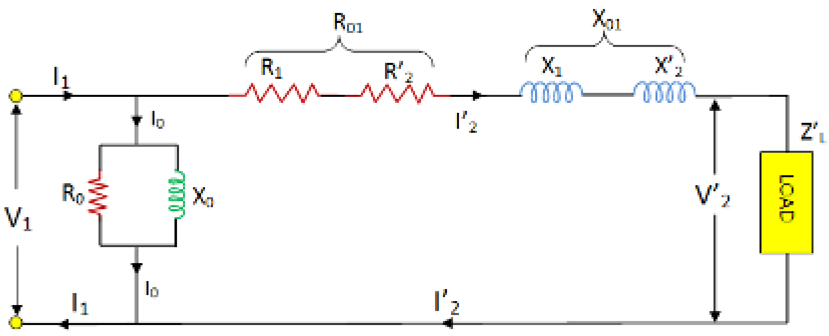


fig-4

At last, the circuit is simplified altogether as shown in fig- 5 .

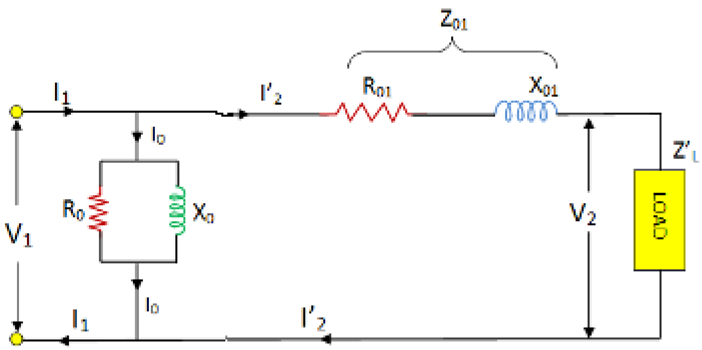


fig-5

The following are the values of resistance and reactance given below
Secondary resistance referred to primary side is given as

$$R'_2 = \frac{R_2}{K^2}$$

The equivalent resistance referred to primary side is given as

$$R_{ep} = R_1 + R'_2$$

Secondary reactance referred to primary side is given as

$$X'_2 = \frac{X_2}{K^2}$$

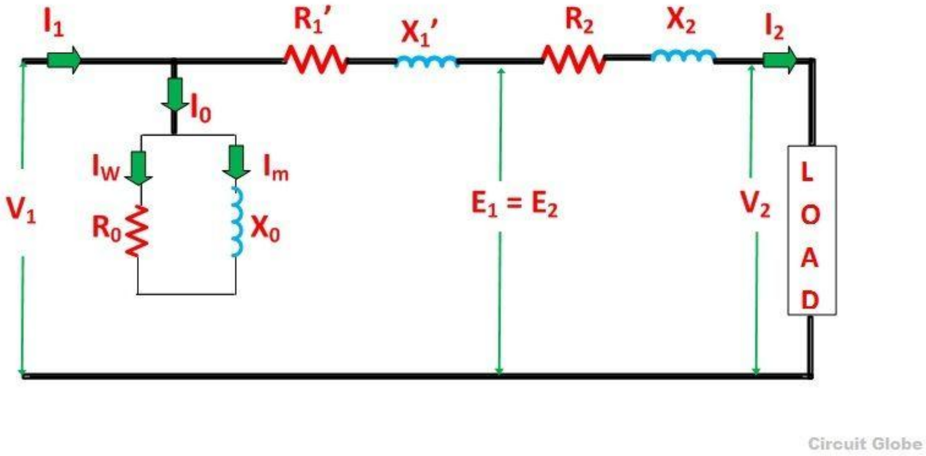
The equivalent reactance referred to primary side is given as

$$X_{ep} = X_1 + X'_2$$

The simplified circuit diagram of the transformer is shown below

Equivalent Circuit When all the Quantities are Referred to Secondary side

The equivalent circuit diagram of the transformer is shown below when all the quantities are referred to the secondary side.



The following are the values of resistance and reactance given below

Primary resistance referred to secondary side is given as

$$R_1' = K^2 R_1$$

The equivalent resistance referred to secondary side is given as

$$R_{es} = R_2 + R_1'$$

Primary reactance referred to secondary side is given as

$$X_1' = K^2 X_1$$

The equivalent reactance referred to secondary side is given as

$$X_{eq} = X_2 + X_I'$$

No load current I_0 is hardly 3 to 5% of full load rated current, the parallel branch consisting of resistance R_0 and reactance X_0 can be omitted without introducing any appreciable error in the behavior of the transformer under the loaded condition.

Further simplification of the equivalent circuit of the transformer can be done by neglecting the parallel branch consisting R_0 and X_0.

From the equivalent circuit which is shown in fig.-3 , the total impedance between the input terminal is ,

$$Z = Z_1 + Z_m \,||\, (Z_2' + Z_l') = \left(Z1 + \frac{Z_m\,(Z_m' + Z_L')}{Z_m + (Z_2' + Z_L')} \right)$$

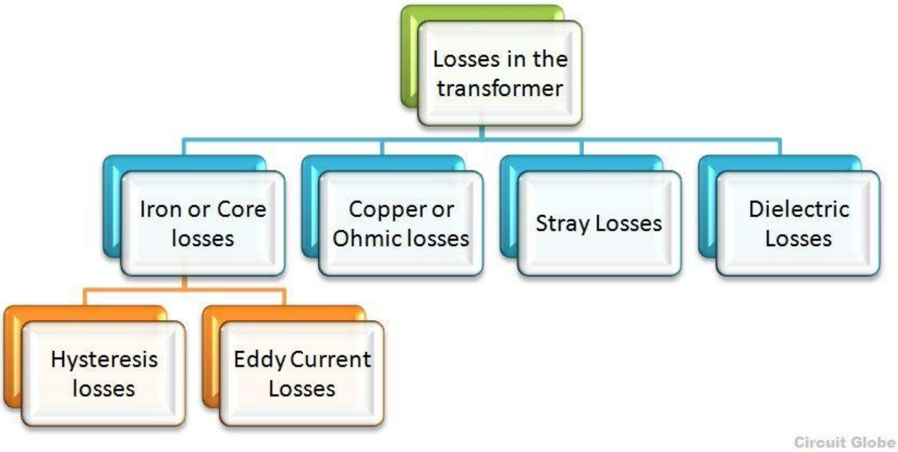
This is so because there are two parallel circuits, one having an impedance of Z_m and the other having Z'_2 and Z'_L in series with each other.

$$V_1 = I_1 \left[Z_1 + \frac{Z_m (Z'_m + Z'_L)}{Z_m + (Z'_2 + Z'_L)} \right]$$

MODULE 5

Types of Losses in a Transformer

There are various types of losses in the transformer such as iron losses, copper losses, hysteresis losses, eddy current losses, stray loss, and dielectric losses. The hysteresis losses occur because of the variation of the magnetisation in the core of the transformer and the copper loss occur because of the transformer winding resistance. The various types of losses are explained below in detail.



Iron Losses

Iron losses are caused by the alternating flux in the core of the transformer as this loss occurs in the core it is also known as Core loss. Iron loss is further divided into hysteresis and eddy current loss.

Hysteresis Loss

The core of the transformer is subjected to an alternating magnetising force, and for each cycle of emf, a hysteresis loop is traced out. Power is dissipated in the form of heat known as hysteresis loss and given by the equation shown below

$$P_h = K\eta B_{max}^{1.6} f V \quad \text{watts}$$

Where

- Kη is a proportionality constant which depends upon the volume and quality of the material of the core used in the transformer.
- f is the supply frequency
- Bmax is the maximum or peak value of the flux density

The iron or core losses can be minimised by using silicon steel material for the construction of the core of the transformer.

Eddy Current Loss

When the flux links with a closed circuit, an emf is induced in the circuit and the current flows, the value of the current depends upon the amount of emf around the circuit and the resistance of the circuit. Since the core is made of conducting material, these EMFs circulates currents within the body of the material. These circulating currents are called Eddy Currents. They will occur when the conductor experiences a changing magnetic field. As these currents are not responsible for doing any useful work, and it produces a loss (I2R loss) in the magnetic material known as an Eddy Current Loss.
The eddy current loss is minimised by making the core with thin laminations.

The equation of the eddy current loss is given as

$$P_e = K_e B_m^2 t^2 f^2 V \qquad \text{watts}$$

Where,

- Ke – co-efficient of eddy current. Its value depends upon the nature of magnetic material like volume and resistivity of core material, thickness of laminations
- Bm – maximum value of flux density in wb/m2
- T – thickness of lamination in meters
- F – frequency of reversal of magnetic field in Hz
- V – volume of magnetic material in m3

Copper Loss Or Ohmic Loss

These losses occur due to ohmic resistance of the transformer windings. If I_1 and I_2 are the primary and the secondary current. R_1 and R_2 are the resistance of primary and secondary winding then the copper losses occurring in the primary and secondary winding will be $I_1^2R_1$ and $I_2^2R_2$ respectively.

Therefore, the total copper losses will be

$$P_c = I_1^2 R_1 + I_2^2 R_2$$

These losses varied according to the load and known hence it is also known as variable losses. Copper losses vary as the square of the load current.

Stray Loss

The occurrence of these stray losses is due to the presence of leakage field. The percentage of these losses is very small as compared to the iron and copper losses so they can be neglected.

Dielectric Loss

Dielectric loss occurs in the insulating material of the transformer that is in the oil of the transformer, or in the solid insulations. When the oil gets deteriorated or the solid insulation get damaged, or its quality decreases, and because of this, the efficiency of transformer is effected.

Voltage Regulation of a Transformer

Definition: The voltage regulation is defined as the change in the magnitude of receiving and sending the voltage of the transformer. The voltage regulation determines the ability of the transformer to provide the constant voltage for variable loads.

When the transformer is loaded with continuous supply voltage, the terminal voltage of the transformer varies. The variation of voltage depends on the load and its power factor.

Mathematically, the voltage regulation is represented as

$$\text{Voltage Regulation} = \frac{E_2 - V_2}{E_2}$$

$$\%\ \text{Voltage Regulation} = \frac{E_2 - V_2}{E_2} \times 100$$

where,
E_2 – secondary terminal voltage at no load
V_2 – secondary terminal voltage at full load

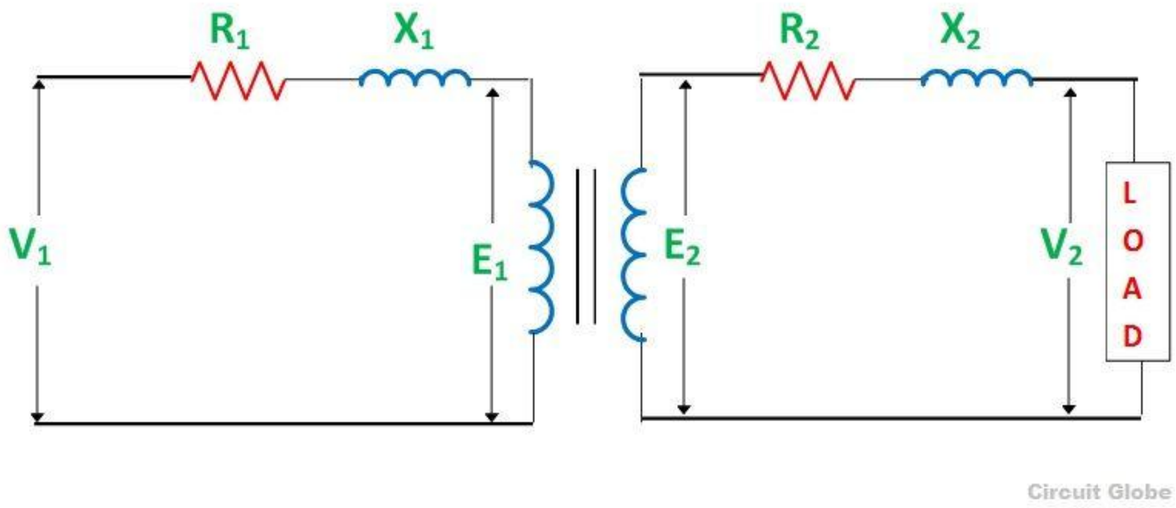
The voltage regulation by considering the primary terminal voltage of the transformer is expressed as,

$$\%\ \text{Voltage Regulation} = \frac{V_1 - E_1}{V_1} \times 100$$

Let us understand the voltage regulation by taking an example explained below

If the secondary terminals of the transformer are open circuited or no load is connected to the secondary terminals, the no-load current flows through it. If the no current flows through the secondary terminals of the transformer, the voltage drops across their resistive and reactive load become zero. The voltage drop across the primary side of the transformer is negligible.

If the transformer is fully loaded, i.e., the load is connected to their secondary terminal, the voltage drops appear across it. The value of the voltage regulation should always be less for the better performance of transformer.



- The primary voltage of the transformer is always greater than the emf induces on the primary side. $V_1>E_1$
- The secondary terminal voltage at no load is always greater than the voltage at full load condition. $E_2>V_2$

By considering the above circuit diagram, the following equations are drawn

$$V_1 = I_1R_1Cos\varphi_1 + I_1X_1Sin\varphi_1 + E_1$$

$$E_2 = I_2R_2Cos\varphi_2 + I_2X_2Sin\varphi_2 + V_2$$

The approximate expression for the no-load secondary voltage for the different types of load is

For inductive load

$$E_2 = I_2R_{02}Cos\varphi_2 + I_2X_{02}Sin\varphi_2 + V_2$$

OR

$$E_2 - V_2 = I_2R_{02}Cos\varphi_2 + I_2X_{02}Sin\varphi_2$$

For Capacitive load

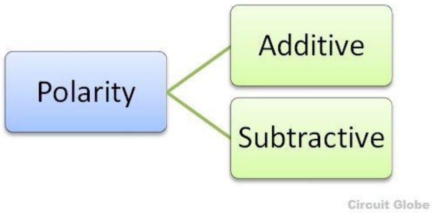
$$E_2 = I_2R_{02}Cos\varphi_2 - I_2X_{02}Sin\varphi_2 + V_2$$

OR

$$E_2 - V_2 = I_2R_{02}Cos\varphi_2 - I_2X_{02}Sin\varphi_2$$

Polarity Test of Transformer

Polarity means the direction of the induced voltages in the primary and the secondary winding of the transformer. If the two transformers are connected in parallel, then the polarity should be known for the proper connection of the transformer.There are two types of polarity one is Additive, and another is Subtractive.



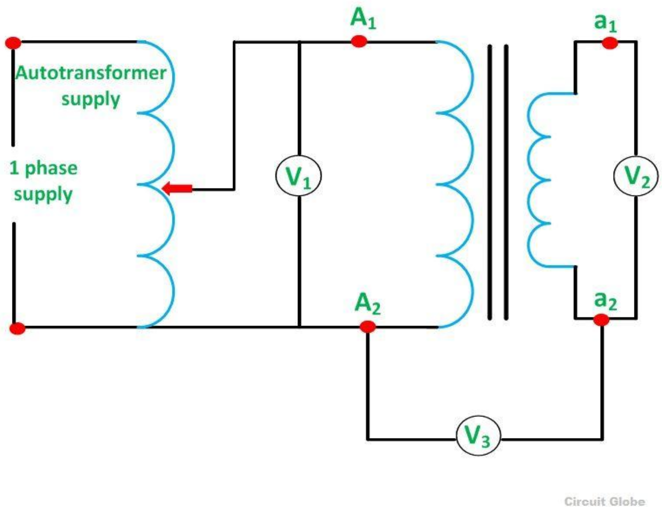
Additive Polarity: In additive polarity the same terminals of the primary and the secondary windings of the transformer are connected

Subtractive Polarity: In subtractive polarity different terminals of the primary and secondary side of the transformer is connected.

Explanation with Connection Diagram

Each of the terminals of the primary as well as the secondary winding of a transformer is alternatively positive and negative with respect to each other as shown in the figure below. Let A_1 and A_2 be the positive and negative terminal respectively of the transformer primary and a_1, a_2 are the positive and negative terminal of the secondary side of the transformer.

If A_1 is connected to a_1 and A_2 is connected to a_2 that means similar terminals of the transformer are connected, then the polarity is said to be additive. If A_1 is connected to a_2 and A_2 to a_1, that means the opposite terminals are connected to each other, and thus the voltmeter will read the subtractive polarity.



It is essential to know the relative polarities at any instant of the primary and the secondary terminals for making the correct connections if the transformers are to be connected in parallel or they are used in a three phase circuit.

In the primary side, the terminals are marked as A_1 and A_2 and from the secondary side the terminals are named as a_1 and a_2. The terminal A_1 is connected to one end of the secondary winding, and a voltmeter is connected between A_2 and the other end of the secondary winding.

When the voltmeter reads the difference that is (V_1 – V_2), the transformer is said to be connected with opposite polarity know as Subtractive polarity and when the voltmeter reads (V_1 + V_2), the transformer is said to have additive polarity.

Steps to Perform Polarity Test

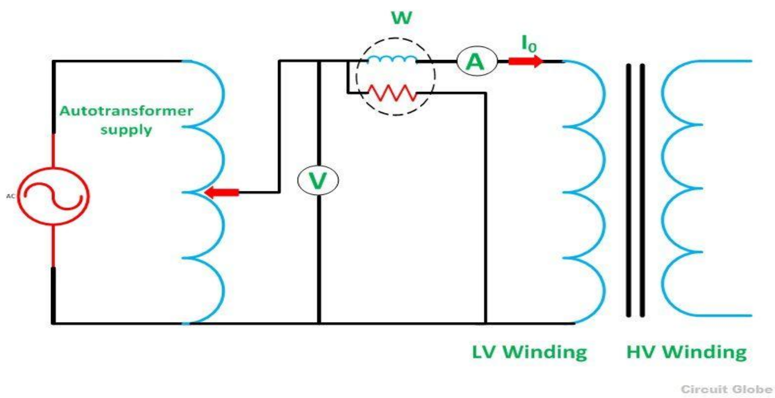
- Connect the circuit as shown in the above circuit diagram figure and set the autotransformer to zero position.
- Switch on the single phase supply
- Records the values of the voltages as shown by the voltmeter V_1, V_2 and V_3.
- If the reading of the V_3 shows the addition of the value of V_1 and V_2 that is $V_3 = V_1+V_2$ the transformer is said to be connected in additive polarity.
- If the reading of the V_3 is the subtraction of the readings of V_1 and V_2, then the transformer is said to be connected in subtractive or negative polarity.

Open Circuit and Short Circuit Test on Transformer

The open circuit and short circuit test are performed for determining the parameter of the transformer like their efficiency, voltage regulation, circuit constant etc. These tests are performed without the actual loading and because of this reason the very less power is required for the test. The open circuit and the short circuit test gives the very accurate result as compared to the full load test.

Open Circuit Test

The purpose of the open circuit test is to determine the no-load current and losses of the transformer because of which their no-load parameter are determined. This test is performed on the primary winding of the transformer. The wattmeter, ammeter and the voltage are connected to their primary winding. The nominal rated voltage is supplied to their primary winding with the help of the ac source.



The secondary winding of the transformer is kept open and the voltmeter is connected to their terminal. This voltmeter measures the secondary induced voltage. As the secondary of the transformer is open the no-load current flows through the primary winding.

The value of no-load current is very small as compared to the full rated current. The copper loss occurs only on the primary winding of the transformer because the secondary winding is open. The reading of the wattmeter only represents the core and iron losses. The core loss of the transformer is same for all types of loads.

Calculation of open circuit test
Let,

W_0 – wattmeter reading
V_1 – voltmeter reading
I_0 – ammeter reading
Then the iron loss of the transformer $P_i = W_0$ and

$$W_0 = V_1 I_0 \cos\varphi_0 \qquad ....(1)$$

The no-load power factor is

$$\cos\varphi_0 = \frac{W_0}{V_1 I_0}$$

Working component I_w is

$$I_w = \frac{W_0}{V_1} \dots\dots\dots\dots(2)$$

Putting the value of W_0 from the equation (1) in equation (2) you will get the value of working component as

$$I_w = I_0 \cos\varphi_0$$

Magnetizing component is

$$I_m = \sqrt{I_0^2 - I_w^2}$$

No load parameters are given below

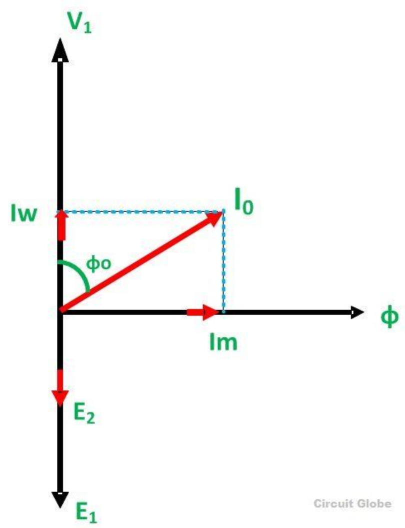
Equivalent exciting resistance is

$$R_0 = \frac{V_1}{I_w}$$

Equivalent exciting reactance is

$$X_0 = \frac{V_1}{I_m}$$

The phasor diagram of transformer at no load or when an open circuit test is performed is shown below



The iron losses measured by the open circuit test is used for calculating the efficiency of the transformer.

Short Circuit Test

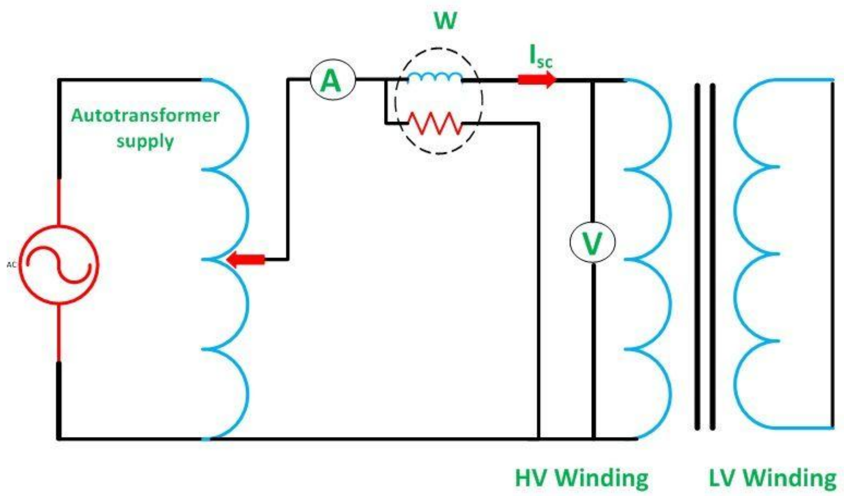
The short circuit test is performed for determining the below mention parameter of the transformer.

It determines the copper loss occur on the full load. The copper loss is used for finding the efficiency of the transformer.

The equivalent resistance, impedance, and leakage reactance are known by the short circuit test. The short circuit test is performed on the secondary or high voltage winding of the transformer. The measuring instrument like wattmeter, voltmeter and ammeter are connected to the High voltage winding of the transformer. Their primary winding is short circuited by the help of thick strip or ammeter which is connected to their terminal.

The low voltage source is connected across the secondary winding because of which the full load current flows from both the secondary and the primary winding of the transformer. The full load current is measured by the ammeter connected across their secondary winding.

The circuit diagram of the short circuit test is shown below



The low voltage source is applied across the secondary winding which is approximately 5 to 10% of the normal rated voltage. The flux is set up in the core of the transformer. The magnitude of the flux is small as compared to the normal flux.

The iron loss of the transformer depends on the flux. It is less occur in the short circuit test because of the low value of flux. The reading of the wattmeter only determines the copper loss occur on their windings. The voltmeter measures the voltage applied to their high voltage winding. The secondary current induces in the transformer because of the applied voltage.

Calculation of Short Circuit Test
Let,

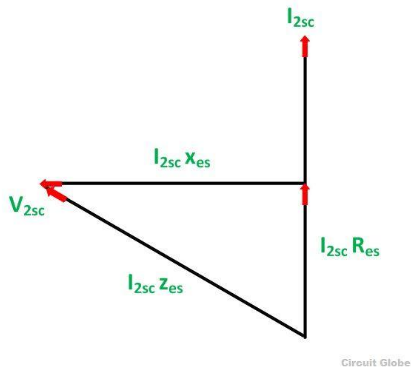
W_c – Wattmeter reading
V_{2sc} – voltmeter reading
I_{2sc} – ammeter reading
Then the full load copper loss of the transformer is given by

$$P_c = \left(\frac{I_{2fl}}{I_{2sc}}\right)^2 W_c \qquad \text{And} \qquad I_{2sc}^2 R_{es} = W_c$$

Equivalent resistance referred to secondary side is

$$R_{es} = \frac{W_c}{I_{2sc}^2}$$

The phasor diagram of the short circuit test of the transformer is shown below



From the phasor diagram

$$I_{2sc}Z_{es} = V_{2sc}$$

Equivalent impedance referred to the secondary side is given by

$$Z_{es} = \frac{V_{2sc}}{I_{2sc}}$$

The Equivalent reactance referred to the secondary side is given by

$$X_{es} = \sqrt{(Z_{es})^2 - (R_{es})^2}$$

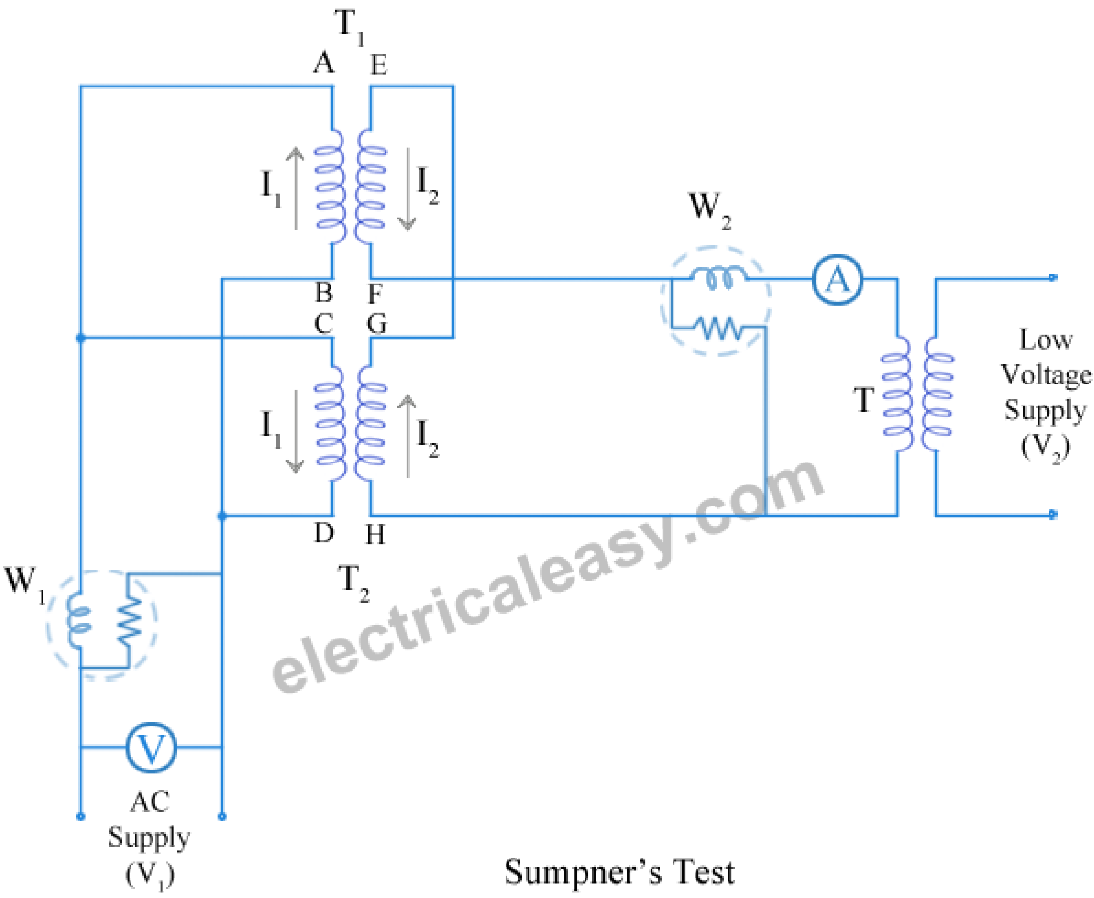
The voltage regulation of the transformer can be determined at any load and power factor after knowing the values of Z_{es} and R_{es}.

In the short circuit test the wattmeter record, the total losses including core loss but the value of core loss are very small as compared to copper loss so, the core loss can be neglected.

Sumpner's test

Sumpner's test or back to back test on transformer is another method for determining transformer efficiency, voltage regulation and heating under loaded conditions. Short circuit and open circuit tests on transformer can give us parameters of equivalent circuit of transformer, but they cannot help us in finding the heating information. Unlike O.C. and S.C. tests, actual loading is simulated in Sumpner's test. Thus the Sumpner's test gives more accurate results of regulation and efficiency than O.C. and S.C. tests.

Sumpner's test can be employed only when two identical transformers are available. Both transformers are connected to supply such that one transformer is loaded on another. Primaries of the two identical transformers are connected in parallel across a supply. Secondaries are connected in series such that emf's of them are opposite to each other. Another low voltage supply is connected in series with secondaries to get the readings, as shown in the circuit diagram shown below.



Sumpner's Test

In above diagram, T_1 and T_2 are identical transformers. Secondaries of them are connected in voltage opposition, i.e. E_{EF} and E_{GH}. Both the emf's cancel each other, as transformers are identical. In this case, as per superposition theorem, no current flows through secondary. And thus the no load test is simulated. The current drawn from V_1 is $2I_0$, where I_0 is equal to no load current of each transformer. Thus input power measured by wattmeter W_1 is equal to iron losses of both transformers.

i.e. iron loss per transformer $Pi = W_1/2$.

Now, a small voltage V_2 is injected into secondary with the help of a low voltage transformer. The voltage V_2 is adjusted so that, the rated current I_2flows through the secondary. In this case, both primaries and secondaries carry rated current. Thus short circuit test is simulated and wattmeter W_2shows total full load copper losses of both transformers.

i.e. copper loss per transformer $P_{Cu} = W_2/2$.

From above test results, the **full load efficiency of each transformer** can be given as –

$$\text{\% full load efficiency of each transformer} = \frac{\text{output}}{\text{output} + \frac{W_1}{2} + \frac{W_2}{2}} \times 100$$

Parallel Operation of Transformers

Sometimes, it becomes necessary to connect more than one transformers in parallel, for example, for supplying excess load of the rating of existing transformer. If two or more transformers are connected to a same supply on the primary side and to a same load on the secondary side, then it is called as parallel operation of transformers.

Necessity of Parallel Operation Of Transformers

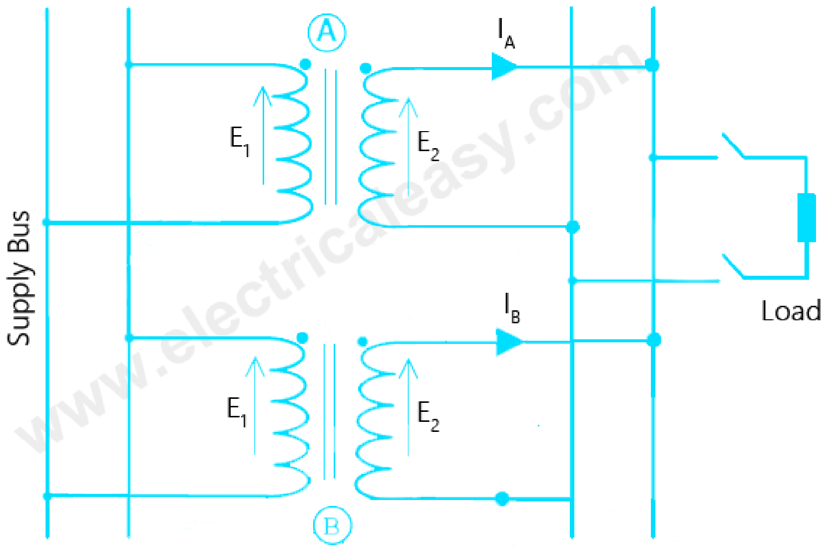
Why parallel operation of transformers is needed?

Increased Load: When load is increased and it exceeds the capacity of existing transformer, another transformer may be connected in parallel with the existing transformer to supply the increased load.

Non-availability of large transformer: If a large transformer is not available which can meet the total requirement of load, two or more small transformers can be connected in parallel to increase the capacity.

Increased reliability: If multiple transformers are running in parallel, and a fault occurs in one transformer, then the other parallel transformers still continue to serve the load. And the faulty transformer can be taken out for the maintenance.

Transportation is easier for small transformers: If installation site is located far away, then transportation of smaller units is easier and may be economical.



Parallel Operation of Single Phase Transformers

Conditions for Parallel Operation

When two or more transformers are to be operated in parallel, then certain conditions have to be met for proper operation. These conditions are -

- Voltage ratio of all connected transformers must be same. If the voltage ratio is not same, then the secondaries will not show equal voltage even if the primaries are connected to same busbar. This results in a circulating current in secondaries, and hence there will be reflected circulating current on the primary side also. In this case, considerable amount of current is drawn by the transformers even without load.
- The per unit (pu) impedance of each transformer on its own base must be same. Sometimes, transformers of different ratings may be required to operate in parallel. For, proper load sharing, voltage drop across each machine must be same. That is, larger transformer has to draw equivalent large current. That is why per unit impedance of the connected transformers must be same.
- The polarity of all connected transformers must be same in order to avoid circulating currents in transformers. Polarity of a transformer means the instantaneous direction of induced emf in secondary. If polarity is opposite to each other, huge circulating current flows.
- The phase sequence must be identical of all parallel transformers. This condition is relevant to poly-phase transformers only. If the phase sequences are not same, then transformers cannot be connected in parallel.
- The short-circuit impedances should be approximately equal (as it is very difficult to achieve identical impedances practically).

Auto Transformer

Auto transformer is kind of electrical transformer where primary and secondary shares same common single winding. So basically it's a one winding transformer.

Theory of Auto Transformer

In Auto Transformer, one single winding is used as primary winding as well as secondary winding. But in two windings transformer two different windings are used for primary and secondary purpose. A diagram of auto transformer is shown below.

The winding AB of total turns N_1 is considered as primary winding. This winding is tapped from point ′C′ and the portion BC is considered as secondary. Let's assume the number of turns in between points ′B′ and ′C′ is N_2.

If V_1 voltage is applied across the winding i.e. in between ′A′ and ′C′.

$$So\ voltage\ per\ turn\ in\ this\ winding\ is\ \frac{V_1}{N_1}$$

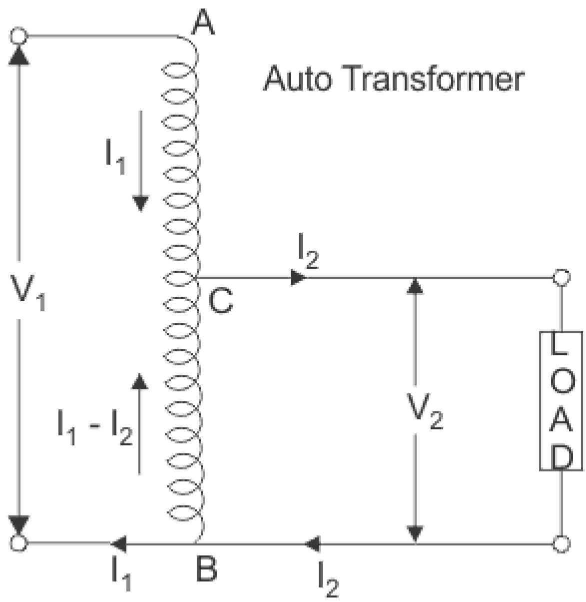
Hence, the voltage across the portion BC of the winding, will be,

$$\frac{V_1}{N_1} X N_2\ and\ from\ the\ figure\ above,\ this\ voltage\ is\ V_2$$

$$Hence,\ \frac{V_1}{N_1} X N_2 = V_2$$

$$\Rightarrow \frac{V_2}{V_1} = \frac{N_2}{N_1} = Constant = K$$

As BC portion of the winding is considered as secondary, it can easily be understood that value of constant ′k′ is nothing but turns ratio or voltage ratio of that auto transformer. When load is connected between secondary terminals i.e.between ′B′ and ′C′, load current I_2 starts flowing. The current in the secondary winding or common winding is the difference of I_2 and I_1.



Copper Savings in Auto Transformer

Now we will discuss the savings of copper in auto transformer compared to conventional two winding transformer.

We know that weight of copper of any winding depends upon its length and cross-sectional area. Again length of conductor in winding is proportional to its number of turns and cross-sectional area varies with rated current.

So weight of copper in winding is directly proportional to product of number of turns and rated current of the winding.

Therefore, weight of copper in the section AC proportional to,

$$(N_1 - N_2)I_1$$

and similarly, weight of copper in the section BC proportional to,

$$N_2(I_2 - I_1)$$

Hence, total weight of copper in the winding of auto transformer proportional to,

$$(N_1 - N_2)I_1 + N_2(I_2 - I_1)$$

$$\Rightarrow N_1I_1 - N_2I_1 + N_2I_2 - N_2I_1$$

$$\Rightarrow N_1I_1 + N_2I_2 - 2N_2I_1$$

$$\Rightarrow 2N_1I_1 - 2N_2I_1 (Since,\ N_1I_1 = N_2I_2)$$

$$\Rightarrow 2(N_1I_1 - N_2I_1)$$

In similar way it can be proved, the weight of copper in two winding transformer is proportional to,

$$N_1I_1 - N_2I_2$$

$$\Rightarrow 2N_1I_1 \qquad (Since,\ in\ a\ transformer\ N_1I_1 = N_2I_2)$$

$N_1I_1 + N_2I_2$

$\Rightarrow 2N_1I_1$ (Since, in a transformer $N_1I_1 = N_2I_2$)

Let's assume, W_a and W_{tw} are weight of copper in auto transformer and two winding transformer respectively,

$$Hence,\ \frac{W_a}{W_{tw}} = \frac{2(N_1I_1 - N_2I_1)}{2(N_1I_1)}$$

$$= \frac{N_1I_1 - N_2I_1}{N_1I_1} = 1 - \frac{N_2I_1}{N_1I_1}$$

$$= 1 - \frac{N_2}{N_1} = 1 - k$$

$$\therefore W_a = W_{tw}(1-k)$$

$$\Rightarrow W_a = W_{tw} - kW_{tw}$$

∴ Saving of copper in auto transformer compared to two winding transformer,

$$\Rightarrow W_{tw} - W_a = kW_{tw}$$

Auto transformer employs only single winding per phase as against two distinctly separate windings in a conventional transformer.

Advantages of using Auto Transformers

1. For transformation ratio = 2, the size of the auto transformer would be approximately 50% of the corresponding size of two winding transformer. For transformation ratio say 20 however the size would be 95 %. The saving in cost of the material is of course not in the same proportion. The saving of cost is appreciable when the ratio of transformer is low, that is lower than 2. Thus auto transformer is smaller in size and cheaper.
2. An auto transformer has higher efficiency than two winding transformer. This is because of less ohmic loss and core loss due to reduction of transformer material.
3. Auto transformer has better voltage regulation as voltage drop in resistance and reactance of the single winding is less.

Disadvantages of Using Auto Transformer

1. Because of electrical conductivity of the primary and secondary windings the lower voltage circuit is liable to be impressed upon by higher voltage. To avoid breakdown in the lower voltage circuit, it becomes necessary to design the low voltage circuit to withstand higher voltage.
2. The leakage flux between the primary and secondary windings is small and hence the impedance is low. This results into severer short circuit currents under fault conditions.
3. The connections on primary and secondary sides have necessarily needs to be same, except when using interconnected starring connections. This introduces complications due to changing primary and secondary phase angle particularly in the case of delta/delta connection.

4. Because of common neutral in a star/star connected auto transformer it is not possible to earth neutral of one side only. Both their sides should have their neutrality either earth or isolated.
5. It is more difficult to maintain the electromagnetic balance of the winding when voltage adjustment tappings are provided. It should be known that the provision of tapping on an auto transformer increases considerably the frame size of the transformer. If the range of tapping is very large, the advantages gained in initial cost is lost to a great event.

Applications of Auto Transformers

1. Compensating voltage drops by boosting supply voltage in distribution systems.
2. Auto transformers with a number of tapping are used for starting induction and synchronous motors.
3. Auto transformer is used as variac in laboratory or where continuous variable over broad ranges are required

On-Load Tap-Changing Transformer

Definition: The transformer which is not disconnected from the main supply when the tap setting is to be changed such type of transformer in known as on-load tap changing transformer. The tap setting arrangement is mainly used for changing the turn ratio of the transformer to regulate the system voltage while the transformer is delivering the load. The main feature of an on-load tap changer is that during its operation the main circuit of the switch should not be opened. Thus, no part of the switch should get the short circuit.

In tap changing transformer different types of an impedance circuit are used for limiting the current during the operation of a tap changing. The impedance circuit may be resistor or reactor type, and by the impedance circuit, the tap changer can be classified as the resistor and reactor type. Nowadays the current limiting is carried out by using a pair of resistors.

Location of Tapping

The tapping is provided at the HV winding of the transformer because the high voltage winding is wound on the low-voltage winding. Also, the current in the HV winding of the transformer is smaller due to which small contacts and leads are required for tapping connections.

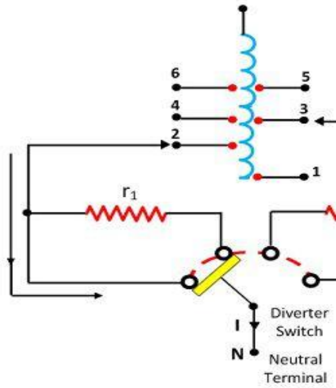
The tapping on the windings is taken out through the house board to separate the oil-filled compartment in which the on-load tap changer switch is housed. The tap changer is operated by a motor operated driving mechanism of local or remote control. The handle is operated for manual operation in case of an emergency.

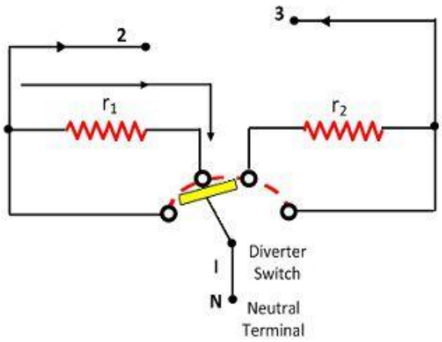
Needs for Tapping

Frequently change in load changes the voltage of the system. The tap changing in the power transformer is mainly done for keeping the output voltage within the prescribed limit. Nowadays almost all the large power transformer is provided with on-load tap changer.

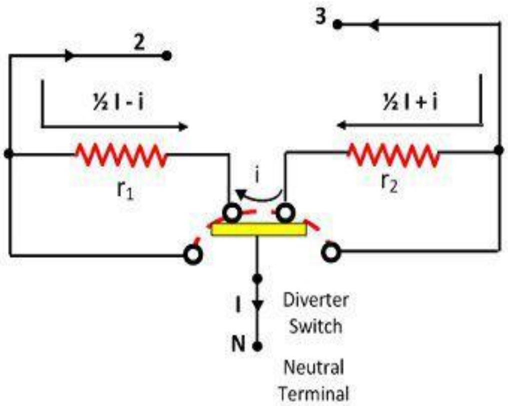
On-Load Tap Changing Transformer Using a Resistor

The on-load tap changing gear with the resistor transition, in which one winding is changed for each operating position as shown in the figure below. The sequence of operation during the shifting of one tap into the next is shown in the figure below. The backup main contactor is provided which short-circuit the resistors for normal operation.

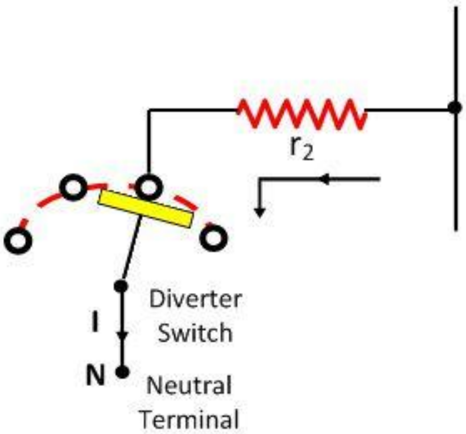




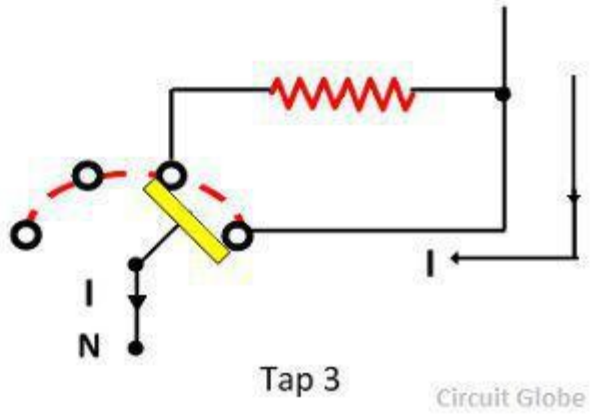
Tap 2 and r_1



Tap 2 and 3



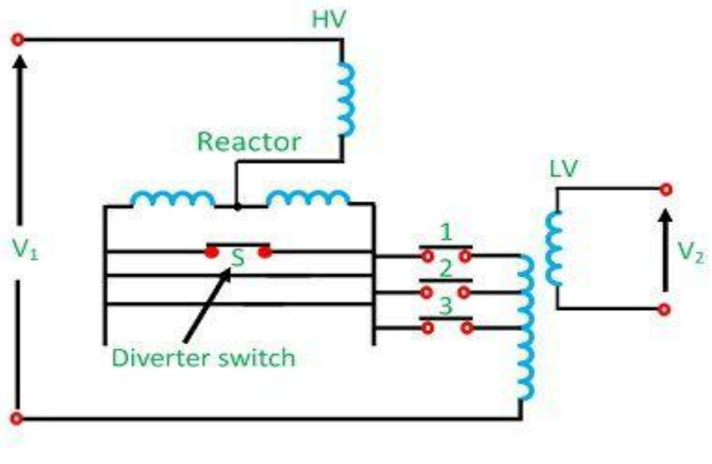
Tap 3 and r_2



The tap changer controls gear by using the push buttons. The aim of control is to maintain a given voltage level within a specified resistance or to increase it with a load to compensate for the voltage drop in the given transmission line.

On-Load Tap Changing Using a Reactor

The other type of on-load tap changer is provided with a centre tapped reactor as shown in the figure below. The function of the reactor is to prevent the short circuit of the tap winding. During the normal operation, the short-circuiting switches S remains closed. The reactor prevents the flow of large values of current in any section of the primary winding when two tapping switches are closed simultaneously.



On-load tap changing using reactor

For understanding the applications of the on-load tap changer consider that the tapping switches are closed and the output voltage is minimised. For raising the output voltage, the short-circuiting switch S is opened, the second tapping switch is closed, and the first tapping switch is opened, and finally the short-circuit switch is closed.

When the short-circuiting switch is in the open position, and the two tapping switches are in closed position, the reactor is shunted between the two tapping position of the transformer windings. But the large circulating current is not established on account of its high reactance.

The line current is not affected by this reactance because the current is equally divided and flows in the opposite direction in the two halves of the reactor. The reactor carries the full current when only the one switch is closed.

The sliding contacts are so attached at the end of the reactor that makes one before other breaks and in normal operating condition both contact touches the same tapping stud. Usually, the tapping is located at the midway between the end turn of the winding to prevent the surge voltages for getting into the load ratio control elements.

MODULE 6

Three Phase Transformer

Three phase transformers are more economical for supplying large loads and large power distribution. The three phase power is used in almost all fields of electrical power system such as power generation, transmission and distribution sectors, also all the industrial sectors are supplied or connected with three phase system. Therefore, to step-up (or increase) or step-down (or decrease) the voltages in the three phase systems, three phase transformers are used. As compared with the single phase transformer, there are numerous advantages with 3 phase transformer such as smaller and lighter to construct for the same power handling capacity, better operating characteristics, etc.

Three phase transformers are used to step-up or step-down the high voltages in various stages of power transmission system. The power generated at various generating stations is in three phase nature and the voltages are in the range of 13.2KV or 22KV. In order to reduce the power loss to the distribution end, the power is transmitted at somewhat higher voltages like 132 or 400KV. Hence, for transmission of the power at higher voltages, three phase step-up transformer is used to increase the voltage. Also at the end of the transmission or distribution, these high voltages are step-down to levels of 6600, 400, 230 volts, etc. For this, a three phase step down transformer is used.

A three phase transformer can be built in two ways,

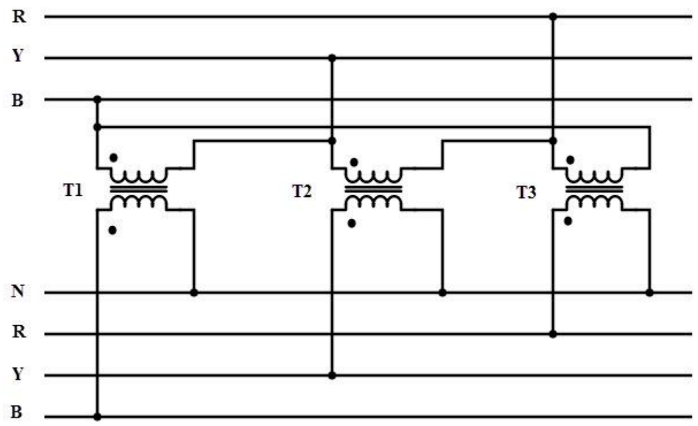
1. Bank of three single phase transformers
2. Single unit of three phase transformer

1. Bank of three single phase transformers

The former one is built by suitably connecting three single phase transformers having same ratings and operating characteristics. In this case if the fault occurs in any one of the transformers, the system still retained at reduced capacity by other two transformers with open delta connection. Hence, continuity of the supply is maintained by this type of connection. These are used in mines because easier to transport individual single phase transformers.

2. Single unit of three phase transformer

Instead of using three single phase transformers, a three phase bank can be constructed with a single three phase transformer consisting of six windings on a common multi-legged core. Due to this single unit, weight as well as the cost is reduced as compared to three units of the same rating and also windings, the amount of iron in the core and insulation materials are saved. Space required to install a single unit is less compared with three unit bank. But the only disadvantage with single unit three phase transformers is if the fault occurs in any one of the phase, then entire unit must be removed from the service.

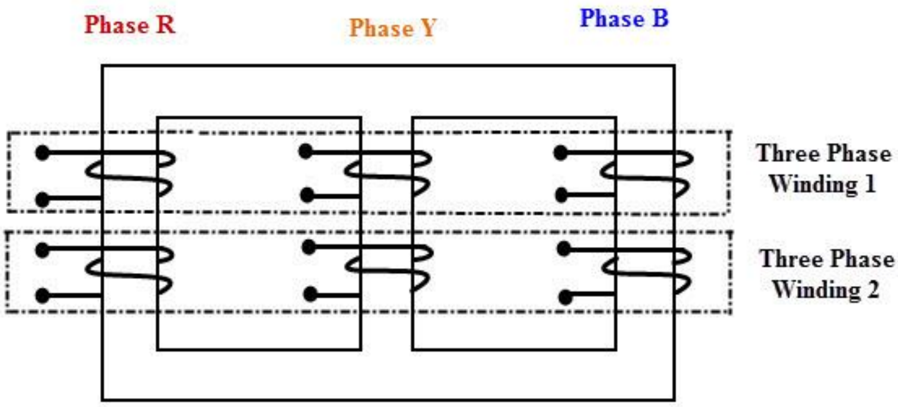


Construction of Three Phase Transformers

A three phase transformer can be constructed by using common magnetic core for both primary and secondary windings. As we discussed in the case of single phase transformers, construction can be core type or shell type. So for a bank of three phase core type transformer, three core type single phase transformers are combined. Similarly, a bank of three phase shell type transformer is getting by properly combining three shell type single phase transformers. In a shell type transformer, EI laminated core surrounds the coils whereas in core type coil surrounds the core.

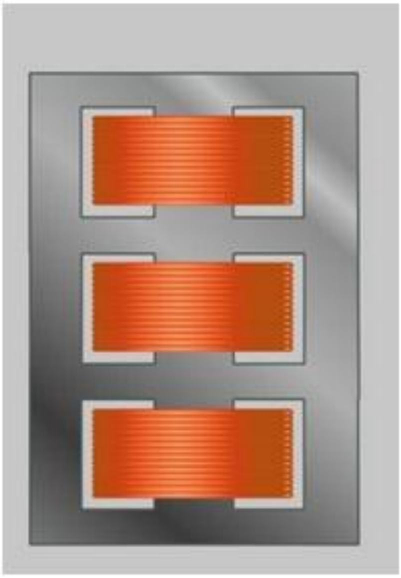
- **Core Type Construction**

  In core type three phase transformer, core is made up of three limbs or legs and two yokes. The magnetic path is formed between these yokes and limbs. On each limb both primary and secondary windings are wounded concentrically. Circular cylindrical coils are used as the windings for this type of transformer. The primary and secondary windings of one phase are wounded on one leg. Under balanced condition, the magnetic flux in each phase of the leg adds up to zero. Therefore, under normal conditions, no return leg is needed. But in case of unbalanced loads, high circulating current flows and hence it may be best to use three single phase transformers.



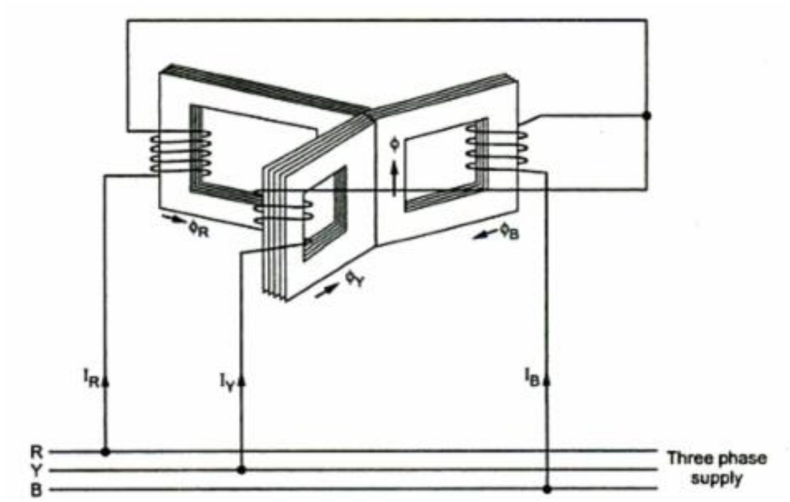
- **Shell Type Construction**

  In shell type, three phases are more independent because each phase has independent magnetic circuit compared with core type transformer. The construction is similar to the single phase shell type transformer built on top of another. The magnetic circuits of this type of transformer are in parallel. Due to this, the saturation effects in common magnetic paths are neglected. However, shell type constructed transformers are rarely used in practice.



Working of Three Phase Transformers

Consider the below figure in which the primary of the transformer is connected in star fashion on the cores. For simplicity, only primary winding is shown in the figure which is connected across the three phase AC supply. The three cores are arranged at an angle of 120 degrees to each other. The empty leg of each core is combined in such that they form center leg as shown in figure.



When the primary is excited with the three phase supply source, the currents IR, IY and IB are starts flowing through individual phase windings. These currents produce the magnetic fluxes ΦR, ΦY and ΦB in the respective cores. Since the center leg is common for all the cores, the sum of all three fluxes are carried by it. In three phase system, at any instant the vector sum of all the currents is zero. In turn, at the instant the sum of all the fluxes is same. Hence, the center leg doesn't carry any flux at any instant. So even if the center leg is removed it makes no difference in other conditions of the transformer.

Likewise, in three phase system where any two conductors acts as return for the current in third conductor, any two legs acts as a return path of the flux for the third leg if the center leg is removed in case of three phase transformer. Therefore, while designing the three phase transformer, this principle is used.

These fluxes induce the secondary EMFs in respective phase such that they maintain their phase angle between them. These EMFs drives the currents in the secondary and hence to the load. Depends on the type of connection used and number of turns on each phase, the voltage induced will be varied for obtaining step-up or step-down of voltages.

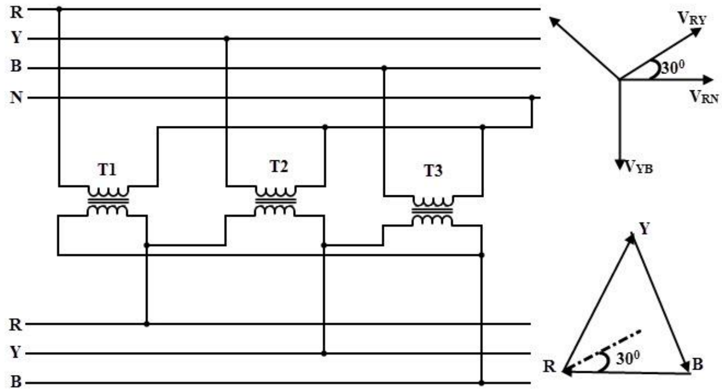
Three Phase Transformer Connections

As discussed above, either by a single three phase transformer or by three single phase transformers combination, three phase transformations can be carried out. The way of connecting the windings for three phase transformation is same whether the three windings of a three phase transformer or three windings of three single phase transformers are used. The primary and secondary windings are connected in different ways, such as in delta or star or combination of these two. The voltage and current ratings of the three phase transformer is depends on suitable connection. The most commonly used connections are

1. Star-delta
2. Delta-star
3. Delta-delta

4. Star-star

Star – Delta Connection



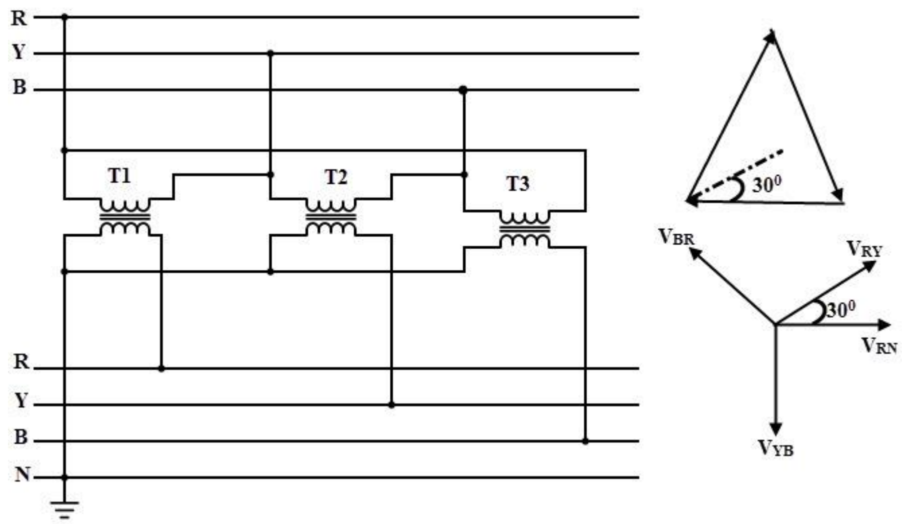
This type of connection is commonly used to step-down the voltages to a lower value in transmission end substations. Utility companies use this connection to reduce the voltage levels for distribution systems.

- In this, the primary winding of the transformer is connected in star and secondary in delta connection.
- The neutral point on the primary or high voltage side can be grounded which is desirable in most of the cases.
- The line voltage ratio between secondary and primary is 1/√3 times the transformation ratio of each transformer.
- There exists 30 degrees phase difference between primary and secondary line voltages.
- Since the actual primary coil voltage is 58% of the primary line voltage, the insulation requirements for HV windings is reduced by using this winding.

In this connection balanced three phase voltage are obtained at the secondary or LV side, even when the unbalanced currents are flowing the in the primary or HV side due to neutral wire. The neutral wire grounding also provides lightning surge protection.

- The primary winding is star star (Y) connected with grounded neutral and the secondary winding is delta connected.
- This connection is mainly used in step down transformer at the substation end of the transmission line.
- The ratio of secondary to primary line voltage is 1/√3 times the transformation ratio.
- There is 30° shift between the primary and secondary line voltages.

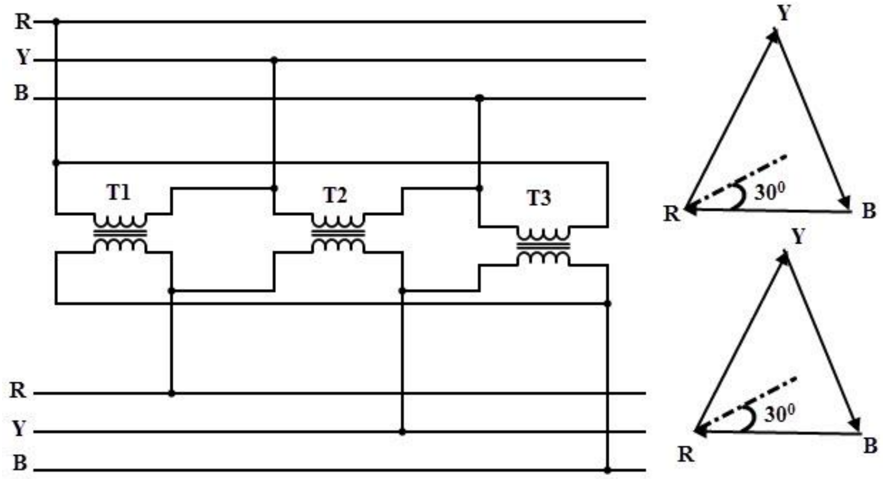
Delta – Star Connection



- This connection is used to step-up the voltage level and is commonly employed in sending end or starting of high tension transmission system.
- In this, the primary is connected in delta fashion and secondary in star fashion so that three phase 4 wire system at secondary is possible.
- The secondary voltage to the load is √3 times the delta connected primary voltage. Also the load and secondary currents will be the same due to the same series circuit.
- This connection provides three single phase circuits at both lower and higher voltages and one three phase circuit at higher voltage so that single and three phase loads can be supplied.
- Dual voltages are obtained delta-star connection. Low single phase voltages are obtained by wiring between any phase and ground. Higher single phase voltages are obtained by wiring between any two phases. And by connecting all three phases to the load, three phase voltage is obtained.
- The insulation requirement on high voltage side is lowered due to the star (less number of turns per phase) connected secondary.
- Similar to star-delta, this connection causes to create a 30 degrees phase difference between primary and secondary line voltages.
- By using this connection, it is not possible to connect it parallel with delta-delta and star-star transformers due to the primary and secondary voltage phase difference.

➢ The primary winding is connected in delta and the secondary winding is connected in star with neutral grounded. Thus it can be used to provide 3-phase 4-wire service.
➢ This type of connection is mainly used in step-up transformer at the beginning of transmission line.
➢ The ratio of secodary to primary line voltage is √3 times the transformation ratio.
➢ There is 30° shift between the primary and secondary line voltages.

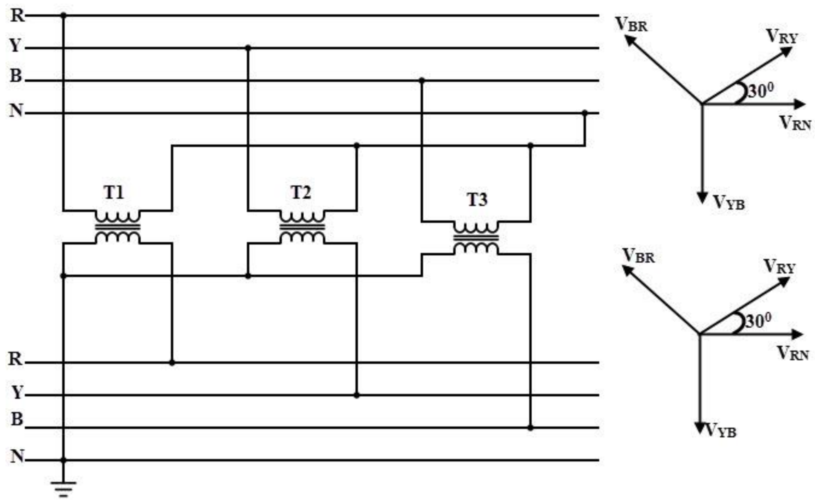
Delta-delta



- This type of connection is used when the supply source is delta connected and the secondary load needs single voltage with high current. This is generally employed for three phase power loads (like three phase motor).
- In this, both primary and secondary windings are connected in delta fashion.
- The voltage across the load is equal to the secondary voltage and voltage across the primary winding is equal to source voltage. In this, the current flow through the load will be 1.732 times the secondary current and the feeder current will equal to the 1.732 times current through the primary winding. Due to these high supply and load currents, it is recommended to place transformer much closer to both source and load circuits.
- In this, there exists no phase difference between the primary and secondary voltages.
- The three phase voltages remains constant even with unbalanced load, thus allows unbalanced loading.
- The main advantage of this connection is if the one transformer is defective or removed for service (open delta connection), then remaining two transformers continue to deliver thee phase power at reduced load capacity.

➢ This connection is generally used for large, low-voltage transformers. Number of required phase/turns is relatively greater than that for star-star connection.
➢ The ratio of line voltages on the primary and the secondary side is equal to the transformation ratio of the transformers.
➢ This connection can be used even for unbalanced loading.
➢ Another advantage of this type of connection is that even if one transformer is disabled, system can continue to operate in open delta connection but with reduced available capacity.

Star – Star Connection



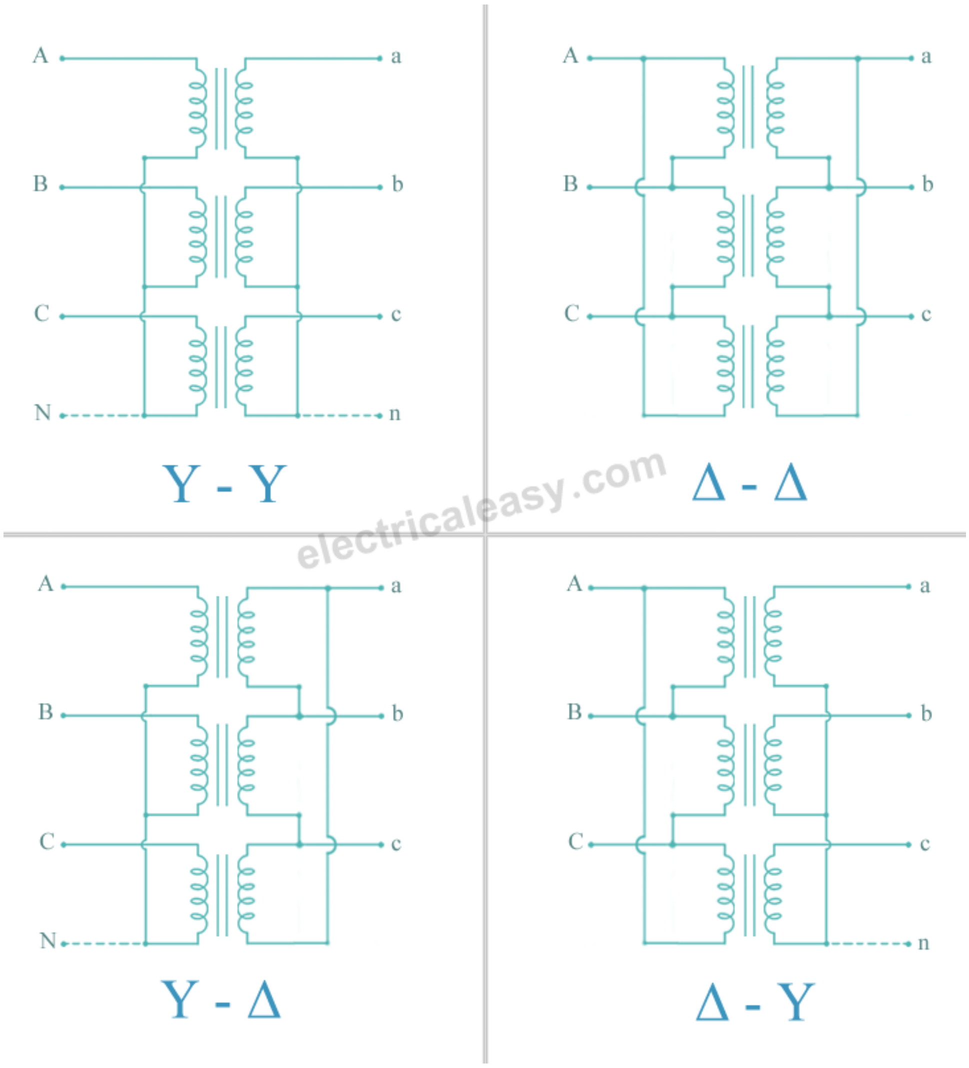
- In this, both primary and secondary windings are connected in star fashion and also there exist no phase difference between the primary and secondary voltages.
- In this, current flowing through both primary and secondary windings are equal to the currents of the lines to which they are connected (supply source and load). And voltages between line phases on either end equal to 1.732 times respective winding voltages.
- Due to neutral availability, it is well suited for three phase four wire system.
- This type connection satisfactorily works if the load is balanced. But if the load is unbalanced, the neutral point shift causes unequal phase voltages.
- Large third harmonic voltages would appear in both primary and secondary windings without the neutral tie. This may lead to the insulation failures.
- This connection considerably generates interference with communication lines and hence with this connection configuration, telephone lines cannot be run in parallel.
- Due to these disadvantages, the star-star connection is rarely used and not employed in practice.

➢ Star-star connection is generally used for small, high-voltage transformers. Because of star connection, number of required turns/phase is reduced (as phase voltage in star connection is $1/\sqrt{3}$ times of line voltage only). Thus, the amount of insulation required is also reduced.

➢ The ratio of line voltages on the primary side and the secondary side is equal to the transformation ratio of the transformers.

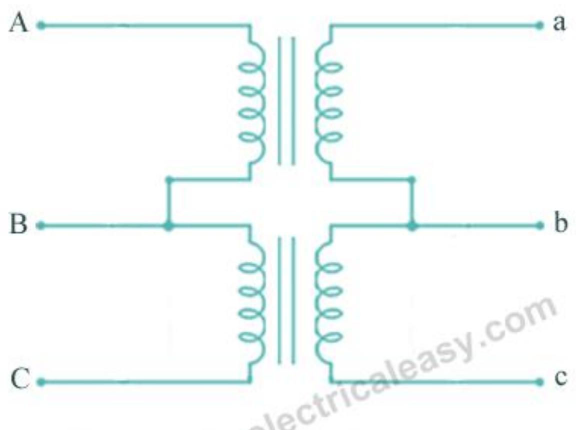
➢ Line voltages on both sides are in phase with each other.

➢ This connection can be used only if the connected load is balanced.



Open Delta (V-V) Connection

Two transformers are used and primary and secondary connections are made as shown in the figure below. Open delta connection can be used when one of the transformers in Δ-Δ bank is disabled and the service is to be continued until the faulty transformer is repaired or replaced. It can also be used for small three phase loads where installation of full three transformer bank is un-necessary. The total load carrying capacity of open delta connection is 57.7% than that would be for delta-delta connection.



Open Delta (V-V) Connection

Scott Connection

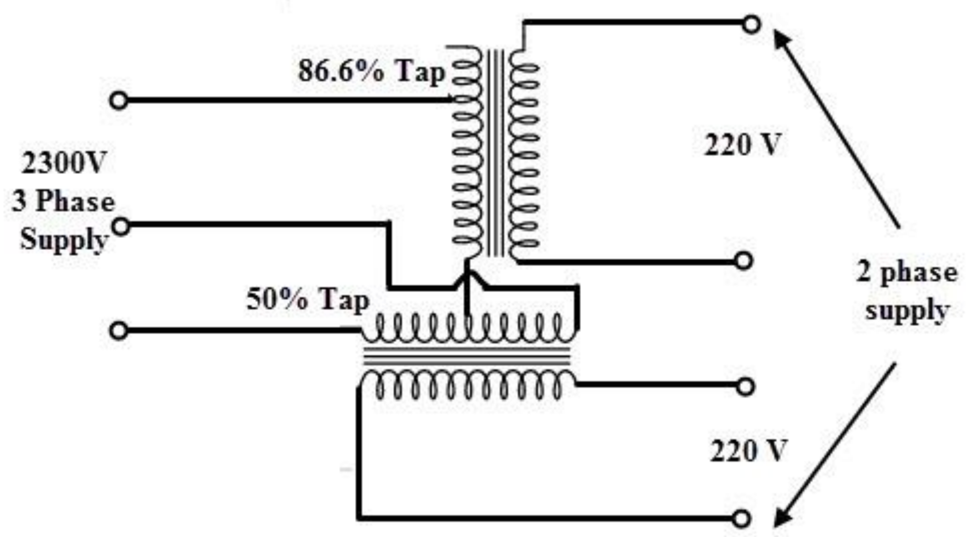
This connection is used to convert the three phase power into two phase power using two single phase transformers.

One transformer called as main transformer having center or 50 percent tap and is connected between the two lines of the three phase wires. The other transformer called as teaser transformer having 86.6 tap and is connected between the third phase wire and 50 percent tap of the main transformer.

The secondary winding of each transformer provides the phases of two phase systems.

The secondary voltages in the two transformers will be equal in magnitude if both transformers are wound for equal number of turns on secondary. And produced voltages are 90 degrees out of phase with each other.

This connection is mainly used to supply the power to the two phase motor.



Advantages of Three Phase Transformers

Being prewired and ready to install, these can be easier to install.

- To provide the same KVA, the core material required is very less compared to a bank of three single phase transformers.
- It is lighter and smaller.
- It requires less space to install.
- Higher efficiency
- Low cost compared with three units of single phase transformers.
- Transportation is easy and also transportation cost is less.
- Bus bar structure and switchgear installation for single three phase unit is simpler.
- Only three terminals are required to be brought out in case of a three phase transformer compared to six terminals from three single phase transformers.

Disadvantages of Three Phase Transformers

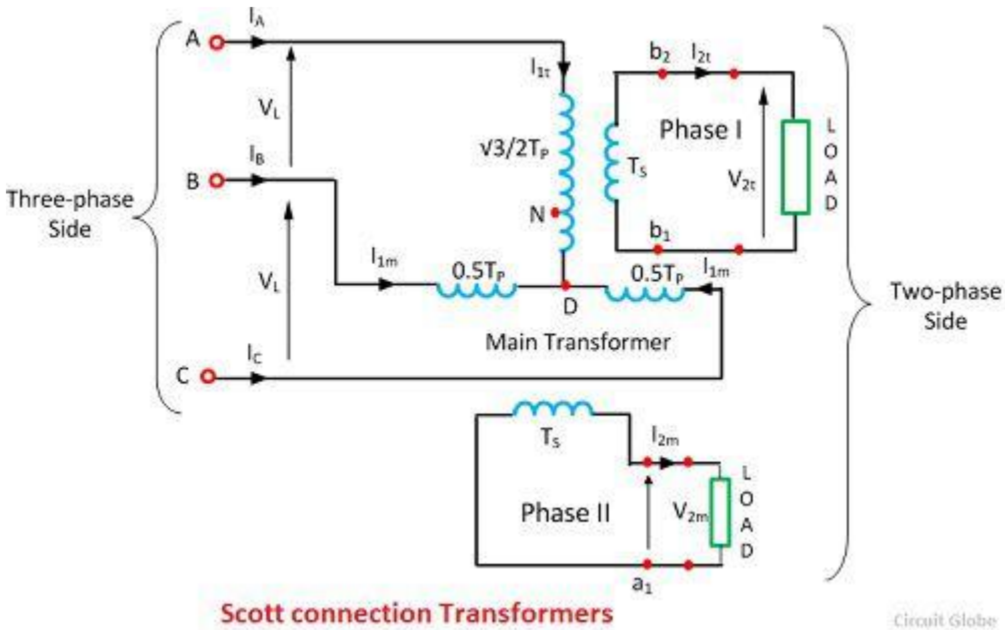
In case of fault or loss of one phase results to the complete unit shut down. This is because in three phase transformer, a common core is shared for all three units. If one unit is defective, the core of this defective unit would immediately saturate because the absence of an opposing magnetic field. This causes the greater escape of magnetic flux to the metal enclosures from the core. This further raises the heating of the metallic parts and in some cases this heat would enough to cause to fires. Therefore, a three phase transformer (or entire unit) must be shut down if any one phase is defective.

- Cost of repair is more for three phase transformer.
- To restore the service, spare unit cost is more compared with one single transformer spare unit.
- When these are self cooled, the capacity of the transformer is reduced.

Scott-T Transformer Connection

Definition: The Scott-T Connection is the method of connecting two single phase transformer to perform the 3-phase to 2-phase conversion and vice-versa. The two transformers are connected electrically but not magnetically. One of the transformers is called the main transformer, and the other is called the auxiliary or teaser transformer.

The figure below shows the Scott-T transformer connection. The main transformer is centre tapped at D and is connected to the line B and C of the 3-phase side. It has primary BC and secondary a_1a_2. The teaser transformer is connected to the line terminal A and the centre tapping D. It has primary AD and the secondary b_1b_2

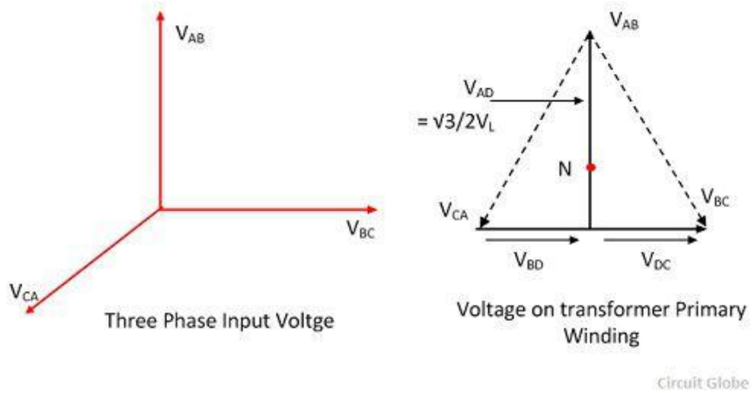


The identical, interchangeable transformers are used for Scott-T connection in which each transformer has a primary winding of T_p turns and is provided with tapping at $0.289T_p$, $0.5T_p$ and $0.866\ T_p$.

Phasor Diagram of Scott Connection Transformer

The line voltages of the 3-phase system V_{AB}, V_{BC}, and V_{CA} which are balanced are shown in the figure below. The same voltage is shown as a closed equilateral triangle. The figure below shows the primary windings of the main and the teaser transformer.

$$|V_{AB}| = |V_{BC}| = |V_{CA}| = |V_L|$$



The D divides the primary BC of the main transformers into two halves and hence the number of turns in portion BD = the number of turns in portion DC = $T_p/2$. The voltage V_{BD} and V_{DC} are equal, and they are in phase with V_{BC}.

$$V_{BD} = V_{DC} = \frac{1}{2}V_{BC} = \frac{1}{2}V_L < 0^\circ$$

The voltage between A and D is

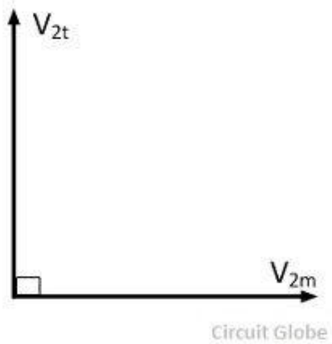
$$V_{BD} = V_{DC} = \frac{1}{2}V_{BC} = \frac{1}{2}V_L < 0°$$

$$V_{AD} = V_{AB} + V_{BD}$$

$$V_{AD} = V_L\left(-\frac{1}{2} + j\frac{\sqrt{3}}{2}\right) + \frac{1}{2}V_L$$

$$V_{AD} = V_L\left(j\frac{\sqrt{3}}{2}\right) = 0.866V_L < 90°$$

The teaser transformer has the primary voltage rating that is √3/2 or 0.866 of the voltage ratings of the main transformer. Voltage VAD is applied to the primary of the teaser transformer and therefore the secondary of the voltage V_{2t} of the teaser transformer will lead the secondary terminal voltage V_{2m} of the main transformer by 90º as shown in the figure below.



Then,

$$\frac{V_{S_1}}{V_{AD}} = \frac{T_S}{T_{AD}}$$

$$V_{2t} = \frac{T_S}{T_{AD}}V_{AD} = \frac{T_S}{\frac{\sqrt{3}}{2}T_P} \times \frac{\sqrt{3}V_t}{2}$$

$$\frac{T_S}{T_P}V_L = v_{2m}$$

For keeping the voltage per turn same in the primary of the main transformer and the primary of the teaser transformer, the number of turns in the primary of the teaser transformer should be equal to $\sqrt{3}/2T_p$.

Thus, the secondaries of both transformers should have equal voltage ratings. The V_{2t} and V_{2m} are equal in magnitude and 90º apart in time; they result in the balanced 2-phase system.

Position of Neutral Point N

The primary of the two transformers may have a four wire connection to a 3-phase supply if the tapping N is provided on the primary of the teaser transformer such that

The voltage across AN = V_{AN} = phase voltage = $V_l/\sqrt{3}$.

Since the voltage across the portion AD.

$$V_{AD} = \frac{\sqrt{3}}{2} V_L$$

the voltage across the portion ND

$$V_{ND} = V_{AD} - V_{AN} = \frac{\sqrt{3}}{2} V_L - \frac{V_L}{\sqrt{3}} = \frac{V_L}{2\sqrt{3}}$$

The same voltage turn in portion AN, ND and AD are shown by the equations,

$$T_{AN} = \frac{T_P}{\sqrt{3}} = 0.577 T_P$$

$$T_{ND} = \frac{T_P}{2\sqrt{3}} = 0.288 T_P$$

$$T_{ND} = \frac{\sqrt{3} T_P}{2} = 0.866 T_P$$

$$\frac{T_{AN}}{T_{ND}} = \frac{T_P}{\sqrt{3}} + \left(\frac{T_P}{2\sqrt{3}}\right) = 2$$

The equation above shows that the neutral point N divides the primary of the teaser transformer in ratio.

AN : ND = 2 : 1

Applications of Scott Connection

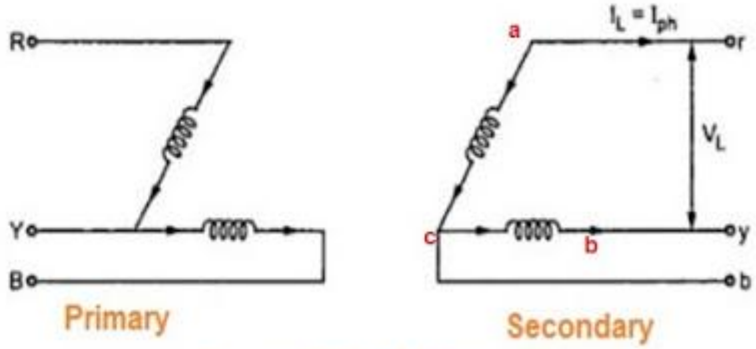
The following are the applications of the Scott-T connection.

1. The Scott-T connection is used in an electric furnace installation where it is desired to operate two single-phase together and draw the balanced load from the three-phase supply.
2. It is used to supply the single phase loads such as electric train which are so scheduled as to keep the load on the three phase system as nearly as possible.
3. The Scott-T connection is used to link a 3-phase system with a two–phase system with the flow of power in either direction.

The Scott-T connection permits conversions of a 3-phase system to a two-phase system and vice versa. But since 2-phase generators are not available, the converters from two phases to three phases are not used in practice.

Open Delta or V-Connection of Transformer

As we know, a three phase Transformer bank connected in Delta-Delta when supplies a three phases balanced load then individual Transformers share 1/3 of the total load. But if there is some fault in any one of the Transformer and due this one Transformer is taken out of service, then also three phase power can be supplied though at a reduced power level. The resulting connection obtained after the removal of one of the Transformer from a three phase Transformer bank connected in Delta-Delta is known as an Open Delta or V-connection of Transformer. Figure below depicts this open Delta or V-connection.

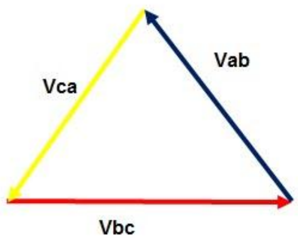


Open Delta / V-Connection

As can be seen from the figure above, one phase in Open Delta or V-connection is missing then how can we deliver three phase power?

Since only two phase voltages are available i.e. V_{ac} and V_{bc} so we need to calculate the remaining voltage V_{ab} and then only we can judge whether we can supply three phase power or not. Note that for supplying three phase power, the three voltages i.e. V_{ca}, V_{bc} and V_{ab} must be balanced in the sense that all of them are equal in magnitude and 120° displaced mutually in time domain.

Thus to find, Vabwe need to draw voltage triangle first.



From the above voltage triangle, it can be written that

V_{ab}+V_{bc}+V_{ca} = 0, bold letters mean phasor form.

So, voltage across the open Delta terminal can be found as

V_{ab} = Voltage across open delta terminal

= – (V_{bc}+V_{ca})

Here Vbc and Vcaare equal in magnitude, say V but 120° displaced. Therefore their resultant will be V and 120° apart from the reference voltage i.e. Vbc &Vca.

Thus we see that Open Delta connection, secondary line voltages form a balanced system and balanced three phase load can be supplied.

Now, we will calculate the amount of VA that can be supplied by an Open Delta connected Transformer.

VA Delivered by Open Delta:

Case1: When all the three transformers of three phase Transformer bank are in service.

Suppose,

I_{ph} = Phase current of each of Secondary

V_{ph} = Phase voltage of each of Secondary

Therefore,

Line Voltage V_L = V_{ph} (because of Delta connection)

Line Current I_L = 1.732I_{ph}

Thus,

VA Rating of Bank of three Transformers in Delta

= 1.732V_LI_L

= 1.732xV_{ph}x1.732xI_{ph}

= 3$V_{ph}I_{ph}$

Case2: Open Delta Connection

As in Open Delta connection, only two Transformers are there in service so, VA Rating of Open Delta

$= 2V_{ph}I_{ph}$

But this is not correct. Why?

Because as can be seen from the first figure,

Line Voltage in Open Delta $V_L = V_{ph}$

Line Current in Open Delta $I_L = I_{ph}$ as there is no path to bifurcate the line current. Same current is flowing in line as well as in phases.

VA Rating of Open Delta

$= 1.732 x V_L x I_L$

$= 1.732\ V_{ph}I_{ph}$

Thus,

VA Rating of Open Delta / VA Rating of Close Delta

$= 1.732V_{ph}I_{ph} / 3V_{ph}I_{ph}$

$=1 / 1.732$

$=0.577$

Thus the VA delivering capacity of Open Delta becomes 57% of that of the full capacity when all the three Transformers are in service. It shall also be noted that, though the total capacity of Transformers in Open Delta is $2V_{ph}I_{ph}$but still Open Delta can only deliver $1.732V_{ph}I_{ph}$.

The Ratio of actual available kVA rating to the sum of the kVA rating of installed Transformer is called Utilization Factor and given by

U.F = Ratio of actual available kVA / Sum of the kVA rating of installed Transformer

For Open Delta connection,

$U.F = 1.732V_{ph}I_{ph} / 2V_{ph}I_{ph}$

$= 0.866$

Thus it is beneficial to operate the bank of Transformer in Open Delta at 86% of rated capacity while the faulty Transformer is under maintenance.

Transformer Vector Groups

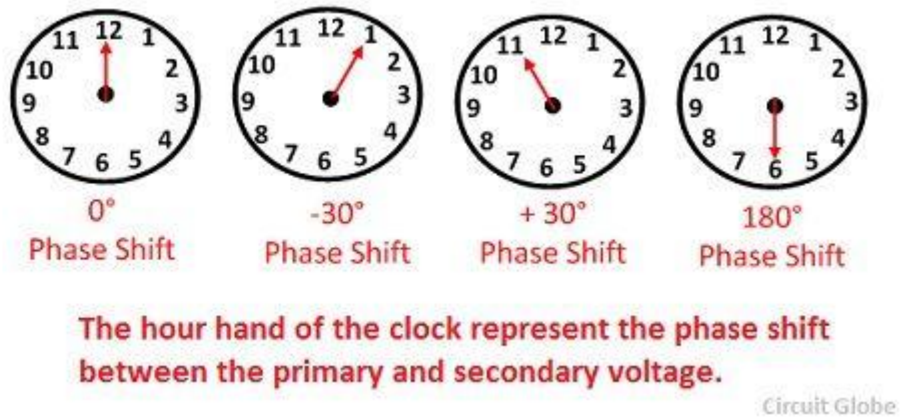
Definition: The transformer vector group show the phase difference between the primary and secondary sides of the transformer. It also determines the high voltage and low voltage windings arrangement of three phase transformers.The three phase transformer is connected in various ways. On the basis of connection, the vector group of the transformer is determined.

Three phase transformer is divided into four main groups according to the phase difference between the corresponding line voltage on the high voltage side and the low voltage sides. The phase difference is the angle by which the low voltage line lags the high line voltage, and is measured in units of 30° in clockwise direction. These groups are

- Group number 1 – no phase displacement
- Group number 2 – 180° phase displacement.
- Group number 3 – (-30°) phase displacement.
- Group number 4 – (+ 30°) phase displacement.

The connection Yd11 gives the following information – Y indicates that the high voltage is connected to star and d indicates the low voltage is connected in delta. The 11 indicates that the low line voltage lag, high line voltage by 11 X 30° = 330° measured from higher voltage phasor in a clockwise direction.

The phasor differences can also be measured by using the clock methods. Consider the minute hand of the clock shown the high voltage and the low voltage winding is represented by the hour hand. The angle of 30° is the angle between two adjacent figures on the clock dial and is taken as the unit of dial shift.



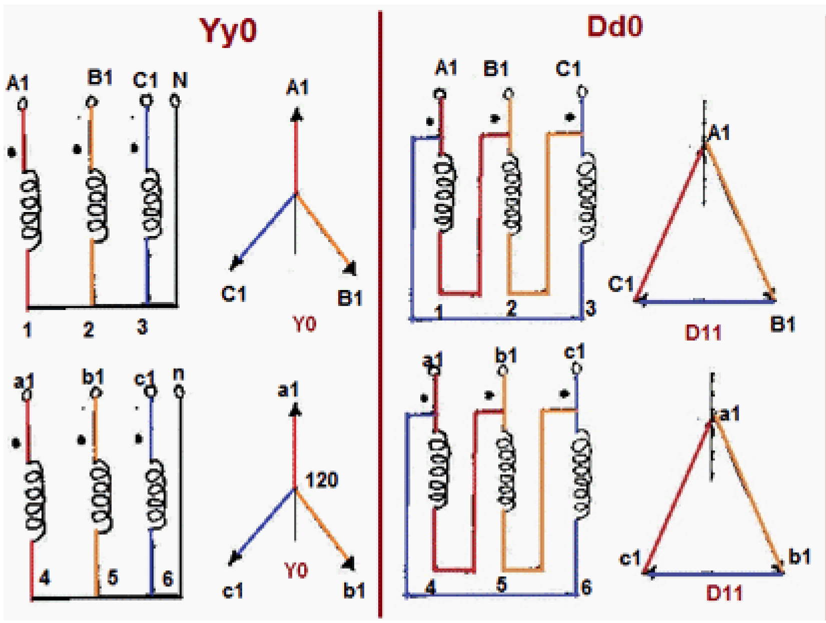
When the hour hand of the clock is at 12, then the phase displacement is zero. When the hour hand is at 1 then the phase shift -30° degree. At 6 the phase shift is 6 X 30º = 180º. Similarly, when the hour hand is at 11 the phase shift is 11 X 30º = 330º.

The number 0, 6, 1, and 11 in the group reference number indicates the primary to secondary phase shift regarding the hours of the clock. The connection designated by D y 11 is the delta-star transformer in which the low voltage line phasor is at 11 and is a phase advanced of +30° on the corresponding line voltage on the high voltage side.

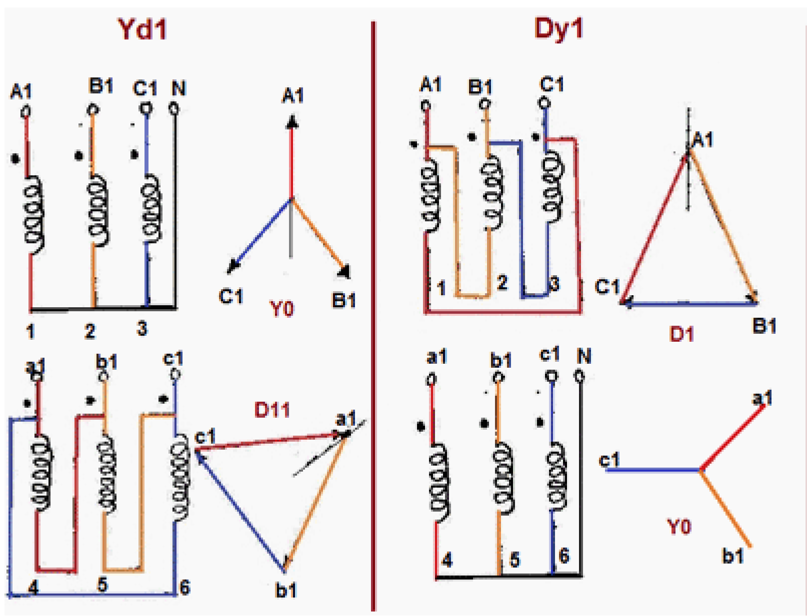
Note: The only transformer in the same group may be connected in parallel. For example, a star-star, 3-phase transformers can be parallel with another three phase transformer whose windings are either connected in Y-Y or Δ-Δ. The Δ-Δ transformer cannot be parallel with Y-Δ transformer.

Different Vector Groups

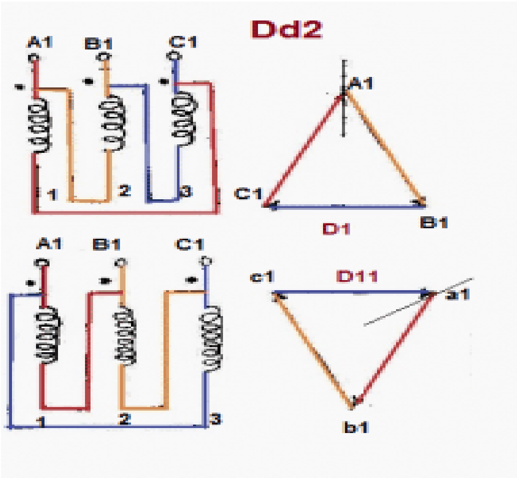
Clock Notation 0 (Phase Shift 0)



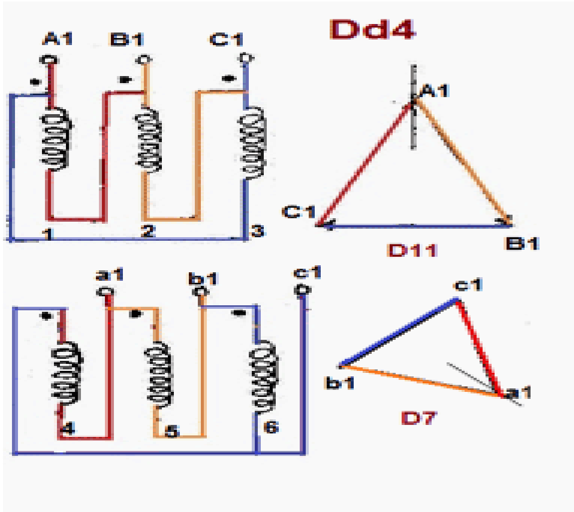
Clock Notation 1 (Phase Shift -30)



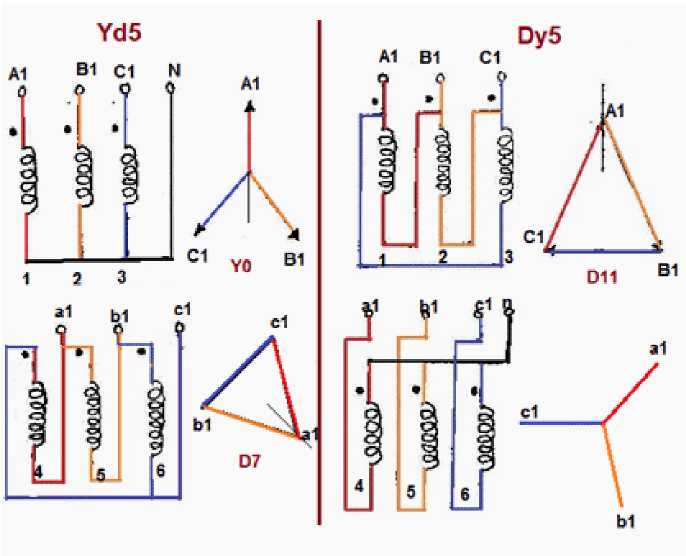
Clock Notation 2 (Phase Shift -60)



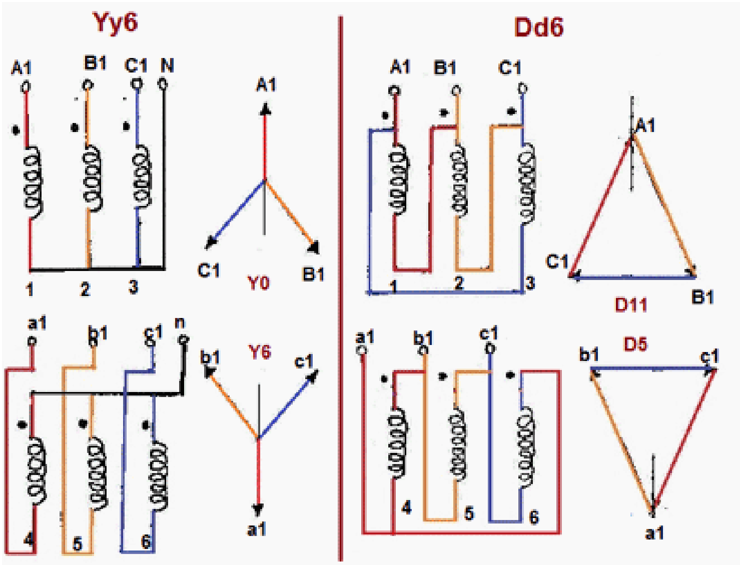
Clock Notation 4 (Phase Displacement -120)



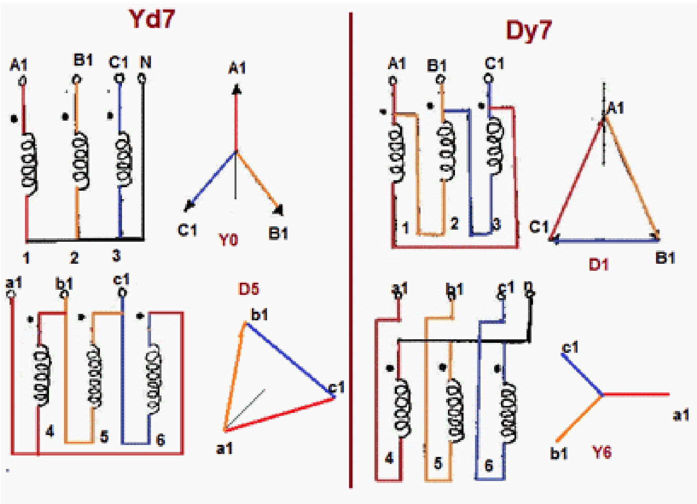
Clock Notation 5 (Phase Displacement -150)



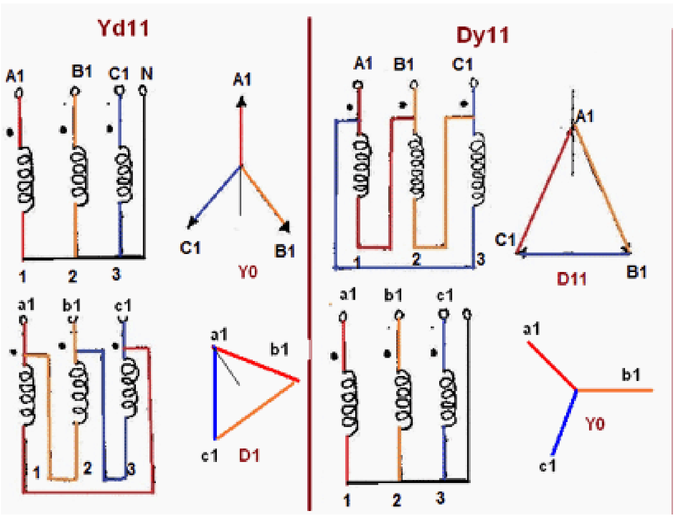
Clock Notation 6 (Phase Shift +180)



Clock Notation 7 (Phase Shift +150)



Clock Notation 11 (Phase Shift +30)



Parallel Operation of Three Phase Transformer

Parallel operation of three phase transformer is very common in three phase power generation, transmission and distribution. It is advantageous to use two or more Transformer units in parallel instead of using a single large unit. This offers flexibility for maintenance as well as operation.

Advantage of Parallel Operation of Three Phase Transformers

It increases the reliability of supply system. Let us try to understand how this happens. Suppose a fault occurs in any one of the Transformer unit. In such case, the faulty transformer may be taken out of service while the remaining transformers will feed the power supply. If there were only one large transformer unit is installed for supplying the load, the supply to the entire load will be interrupted during breakdown of the transformer. Thus the reliability of supply system is increased by parallel operation of transformers.

The size of transformer increases with the increase of its rating. Therefore, a larger transformer will be bigger in size. Therefore, its transportation form manufacturer to the Site will be difficult. Whereas, transportation and installation of small sized transformers are comparatively easy.

The maintenance opportunity in case of parallel operation is increases. One or more transformers may be taken under maintenance while the remaining transformers will supply the load at reduced power.

Condition for Parallel Operation of Three Phase Transformers

Following are the necessary conditions for parallel operation of 3 phase transformers:

- The line voltage ratio of the transformers must be same.
- The transformers should have equal per unit leakage impedance. (You may read per unit system)
- The ratio of equivalent leakage reactance to equivalent resistance should be same for all the transformers.
- The transformers should have the same polarity.

The above four conditions are also applicable for parallel operation of single phase transformers. Apart from the above four condition, there exists two more conditions which should be fulfilled for parallel operation of three phase transformers:

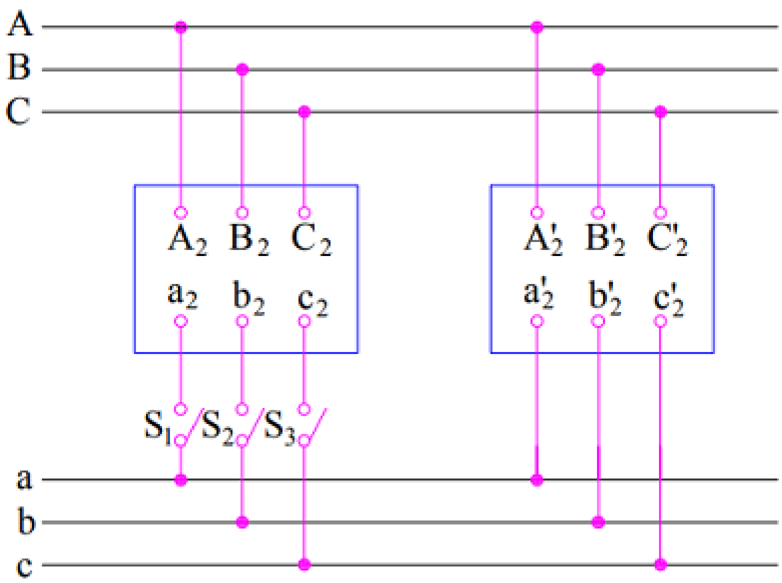
- The relative phase displacement between the secondary line voltages of all transformers should be zero. This means that transformers to be connected in parallel must belong to same Group number like Yy0 and Dd0 belong to same group number viz. Group 1.

- The phase sequence of secondary line voltages of all the transformers should be same.

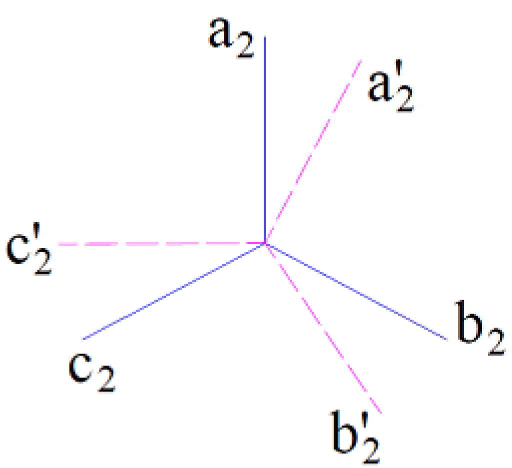
There may arise several questions in your mind at this point of time. Though I can't guess all those but can definitely guess some of them. Some of the common questions are explained below.

Why relative phase displacement between the secondary line voltages should be zero? Or what would happen if transformers of different group numbers are connected in parallel?

Let us assume that two transformers of different group numbers are connected in parallel as shown in figure below.



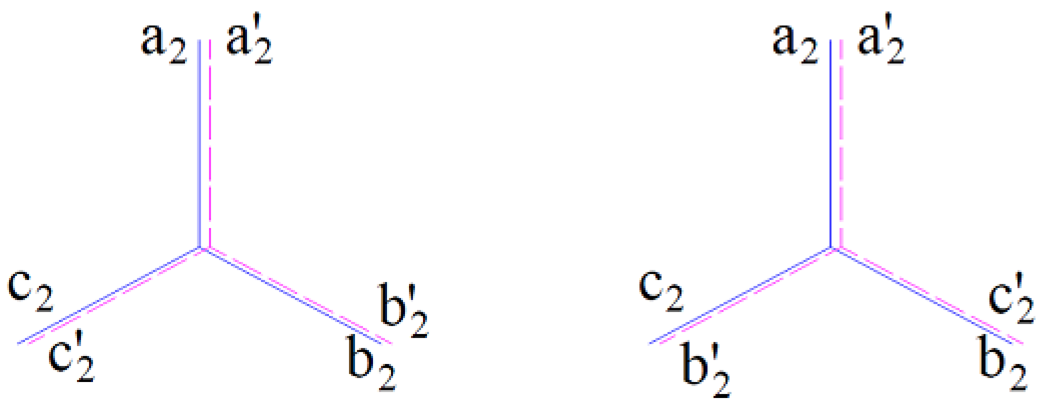
The secondary line voltages of these transforms will not be in phase rather they will be displaced from each other as shown in figure below.



A voltage across the switch S1, S2 & S3 is developed due to this displacement in secondary voltages. The voltage across the switches S1, S2 and S3 will be equal to the length of phasor joining (a2, a2'), (b2, b2') & (c2,c2') respectively. Due to this voltage when these switches are closed, a large circulating current will start flowing through the secondary winding. This may damage the transformer. Therefore it is essential that transformers belong to the same group number so that the relative phase displacement between the secondary line voltages is zero. However, the transformers of group number 3 &4 can be successfully operated in parallel.

Why phase sequence should be equal for parallel operation of 3 phase transformers?

The phase sequence of secondary line voltages of all the transformers should be same. If the phase sequence is same, there will not be any voltage across the switches S1, S2 and S3. However, an improper phase sequence may result in complete damage of the transformer. Let us consider the figure below.



In the left figure, the phase sequence of secondary line voltage of both the transformers are correct> therefore, zero voltage will be developed across the switch S1, S2 and S3. But in rightmost figure, the phase sequence is reversed for second transformer. Under this case, no voltage will be there across S1, but voltage equal to line voltage (c2-b2' and b2-c2') will be developed across the switches S2 and S3. These switches may not be designed to withstand this voltage. Therefore, parallel operation is not possible.