Technical and Vocational Stream
Learning Resource Material

Electrical Machine

(Grade 10)

Electrical Engineering

Government of Nepal
Ministry of Education, Science and Technology
Curriculum Development Centre
Sanothimi, Bhaktapur

Publisher: Government of Nepal
Ministry of Education, Science and Technology
Curriculum Development Centre
Sanothimi, Bhaktapur

Layout by Khados Sunuwar

Preface

The curriculum and curricular materials have been developed and revised on a regular basis with the aim of making education objective-oriented, practical, relevant and job oriented. It is necessary to instill the feelings of nationalism, national integrity and democratic spirit in students and equip them with morality, discipline, self-reliance, creativity and thoughtfulness. It is essential to develop linguistic and mathematical skills, knowledge of science, information and communication technology, environment, health and population and life skills in students. It is also necessary to bring the feeling of preserving and promoting arts and aesthetics, humanistic norms, values and ideals. It has become the need of the present time to make them aware of respect for ethnicity, gender, disabilities, languages, religions, cultures, regional diversity, human rights and social values to make them capable of playing the role of responsible citizens with applied technical and vocational knowledge and skills. This learning resource material for Electrical engineering has been developed in line with the Secondary Level Electrical engineering Curriculum with an aim to facilitate the students in their study and learning on the subject by incorporating the recommendations and feedback obtained from various schools, workshops, seminars and interaction programs attended by teachers, students, parents and concerned stakeholders.

In bringing out the learning resource material in this form, the contribution of the Director General of CDC Mr. Yubaraj Paudel and members of the subject committee Dr. Nandabikram Adhikari, Er. Chitra Bahadur Khadka, Mr. Damberdhwaj Angdembe, Er. Sanju Shrestha is highly acknowledged. This learning resource material is compiled and prepared by Er. Rupesh Maharjan, Er. Jaya Prakash maharjan, Er. Rakesh Singh, Er. Bigyan Pokharel. The subject matter of this material is edited by Mr. Badrinath Timsina and Mr. Khilanath Dhamala. Similarly, the language is edited by Mr. Saroj Kumar Mandal. CDC extends sincere thanks to all those who have contributed to developing this material in this form.

This learning resource material contains a wide coverage of subject matters and sample exercises which will help the learners to achieve the competencies and learning outcomes set in the curriculum. Each chapter in the material clearly and concisely deals with the subject matters required for the accomplishment of the learning outcomes. The Curriculum Development Centre always welcomes creative and constructive feedback for the further improvement of the material.

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Table of Content

Guidelines to Teachers

A. Facilitation Methods

The goal of this course is to combine the theoretical and practical aspects of the contents needed for the subject. The nature of contents included in this course demands the use of practical or learner focused facilitation processes. Therefore, the practical side of the facilitation process has been focused much. The instructor is expected to design and conduct a variety of practical methods, strategies or techniques which encourage students engage in the process of reflection, sharing, collaboration, exploration and innovation new ideas or learning. For this, the following teaching methods, strategies or techniques are suggested to adopt as per the course content nature and context.

Brainstorming

Brainstorming is a technique of teaching which is creative thinking process. In this technique, students freely speak or share their ideas on a given topic. The instructor does not judge students' ideas as being right or wrong, but rather encourages them to think and speak creatively and innovatively. In brainstorming time, the instructor expects students to generate their tentative and rough ideas on a given topic which are not judgmental. It is, therefore, brainstorming is free-wheeling, non-judgmental and unstructured in nature. Students or participants are encouraged to freely express their ideas throughout the brainstorming time. Whiteboard and other visual aids can be used to help organize the ideas as they are developed. Following the brainstorming session, concepts are examined and ranked in order of importance, opening the door for more development and execution. Brainstorming is an effective technique for problem-solving, invention, and decision-making because it taps into the group's combined knowledge and creative ideas.

Demonstration

Demonstration is a practical method of teaching in which the instructor shows or demonstrates the actions, materials, or processes. While demonstrating something the students in the class see, observe, discuss and share ideas on a given topic. Most importantly, abstract and complicated concepts can be presented into visible form through demonstration. Visualization bridges the gap between abstract ideas and concrete manifestations by utilizing the innate human ability to think visually. This enables students to make better decisions, develop their creative potential, and obtain deeper insights across a variety of subject areas.

Peer Discussion

Peer conversation is a cooperative process where students converse with their peers to exchange viewpoints, share ideas, and jointly investigate subjects that are relevant or of mutual interest. Peer discussion is an effective teaching strategy used in the classroom to encourage critical thinking, active learning, and knowledge development. Peer discussions encourage students to express their ideas clearly, listen to opposing points of view, and participate in debate or dialogue, all of which contribute to a deeper comprehension and memory of the course material. Peer discussions also help participants develop critical communication and teamwork skills by teaching them how to effectively articulate their views, persuasively defend their positions, and constructively respond to criticism.

Peer conversation is essential for professional growth and community building outside of the classroom because it allows practitioners to share best practices, work together, and solve problems as a group. In addition to expanding their knowledge horizon and deepening their understanding, peer discussions help students build lasting relationships and a feeling of community within their peer networks.

Group Work

Group work is a technique of teaching where more than two students or participants work together to complete a task, solve a problem or discuss on a given topic collaboratively. Group work is also a cooperative working process where students join and share their perspectives, abilities, and knowledge to take on challenging job or project. Group work in academic contexts promotes active learning, peer teaching, and the development of collaboration and communication skills. Group work helps individuals to do more together than they might individually do or achieve.

Gallery Walk

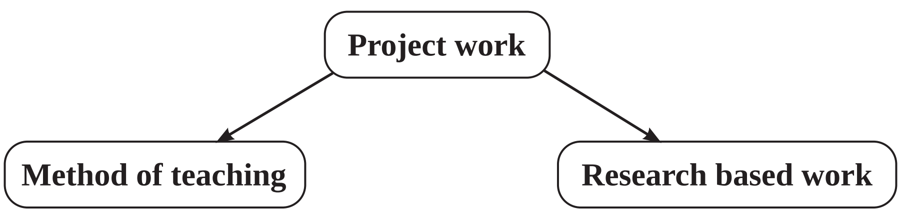
Gallery walk is a critical thinking strategy. It creates interactive learning environment in the classroom. It offers participants or students a structured way to observe exhibition or presentation and also provides opportunity to share ideas. It promotes peer-to-peer or group-to-group engagement by encouraging participants to observe, evaluate and comment on each other's work or ideas. Students who engage in this process improve their communication and critical thinking abilities in addition to their comprehension of the subject matter, which leads to a deeper and more sophisticated investigation of the subjects at hand.

Interaction

The dynamic sharing of ideas, knowledge, and experiences between people or things is referred to as interaction, and it frequently takes place in social, academic, or professional settings. It includes a broad range of activities such as dialogue, collaboration or team work, negotiation, problem solving, etc. Mutual understanding, knowledge sharing, and interpersonal relationships are all facilitated by effective interaction. Interaction is essential for building relationships, encouraging learning, and stimulating creativity in both in-person and virtual contexts. Students can broaden their viewpoints, hone their abilities, and jointly achieve solutions to difficult problems by actively interacting with others.

Project Work

Project work is a special kind of work that consists of a problematic situation which requires systematic investigation to explore innovative ideas and solutions. Project work can be used in two senses. First, it is a method of teaching in regular class. The next is: it is a research work that requires planned investigation to explore something new. This concept can be presented in the following figure.



Project work entails individuals or teams working together to achieve particular educational objectives. It consists of a number of organized tasks, activities, and deliverables. The end product is important for project work. Generally, project work will be carried out in three stages. They are:

- Planning
- Investigation
- Reporting

B. Instructional Materials

Instructional materials are the tools and resources that teachers use to help students. These resources/materials engage students, strengthen learning, and improve conceptual comprehension while supporting the educational goals of a course or program. Different learning styles and preferences can be accommodated by the variety of instructional resources available. Here are a few examples of typical educational resource types:

- Daily used materials
- Related Pictures
- Reference books
- **Slides and presentation:** PowerPoint slides, keynote presentations, or other visual aids that help convey information in a visually appealing and organized manner.
- **Audiovisual materials:** Videos, animations, podcasts, and other multimedia resources that bring concepts to life and cater to auditory and visual learners.
- **Online Resources:** Websites, online articles, e-books, and other web-based materials that can be accessed for further reading and research.

Maps, charts, and graphs: Visual representations that help learners understand relationships, patterns, and trends in different subjects.

Real-life examples and Case Studies: Stories, examples, or case studies that illustrate the practical application of theoretical concepts and principles.

C. Assessment

Formative Test

Classroom discussions: Engage students in discussions to assess their understanding of concepts.
Quizzes and polls: Use short quizzes or polls to check comprehension during or after a lesson.
Homework exercises: Assign tasks that provide ongoing feedback on individual progress.
Peer review: Have students review and provide feedback on each other's work.

Summative Test

Exams: Conduct comprehensive exams at the end of a unit or semester.
Final Projects: Assign projects that demonstrate overall understanding of the subject.

Peer Assessment

Group projects: Evaluate individual contributions within a group project.
Peer feedback forms: Provide structured forms for students to assess their peers.
Classroom Presentations: Have students assess each other's presentations.

Objective Test

Multiple-choice tests: Use multiple-choice questions to assess knowledge.

True/False questions: Assess factual understanding with true/false questions.

Matching exercises: Evaluate associations between concepts or terms.

Portfolio Assessment

Compilation of work: Collect and assess a variety of student work samples.

Reflection statements: Ask students to write reflective statements about their work.

Showcase events: Organize events where students present their portfolios to peers or instructors.

Observational Assessment

Classroom observations: Observe students' behavior and engagement during class.
Performance observations: Assess practical skills through direct observation.
Field Trips: Evaluate students' ability to apply knowledge in real-world settings.

List of Abbreviation

DC	Direct Current
AC	Alternating Current
EMF	Electromotive force
MMF	Magneto motive force
EMI	Electromagnetic induction
O.C.C	Open circuit characteristics
LV	Low voltage
HV	High voltage
kV	Kilovolt
kW	Kilowatt
kVA	Kilovolt ampere
Tw	Two winding
KVL	Kirchhoff's voltage law
RPM	Revolution per minute
Mm	Millimeter
T-S	Torque slip
HP	Horse power
VDF	Variable frequency drive

Electromagnetism

Unit 1

1.1 Electromagnetism

1.1.1 Introduction to Electromagnetism

Study of relationship between electric current (electricity) and magnetic field or, interaction of electric current with the magnetic field is called electromagnetism. In order word when the electric current generates magnetic field or when a changing magnetic field generates the electric field production of magnetic property (magnetism) in a current carrying conductor is known as electromagnetism. Magnetic field developed around the conductor is known as electromagnetic field. Magnetic effect of current is a fundamental principle in electromagnetism widely used in a variety of applications such as, electric motors, generators, transformers, MRI machines etc.

1.1.2 Magnetic Field Around a Straight Current Carrying Conductor

When an electric current flows through a straight conductor, it creates a magnetic field around the conductor. Magnetic field around a straight current carrying conductor has a cylindrical symmetry with magnetic field lines forming concentric circles around the conductor. Consider a long straight conductor CD carrying current "*I*" in the direction shown in figure. Magnetic field at point P located at a perpendicular distance r from a conductor if given by,

$$B = \frac{\mu_o I}{2\pi r} ------(1.1)$$

Where μ_o is permeability of free space = $4\pi \; x \; 10^{-7} \; Hm^{-1}$

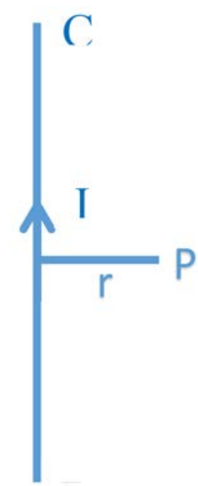


Fig.1.1: Magnetic field around a straight conductor

As a distance from a conductor increases the magnitude of *B* decreases. Direction of magnetic field is determined by right hand thumb rule.

1.1.2.1 Magnetic Field Around the Solenoid

Solenoid is a coil of wire that wound in a cylindrical shape. When current is passed through the solenoid, magnetic field is set up around it. Fields of all the turns of the solenoid add together to form the total field. Nature of magnetic field is similar to that of bar magnet with North Pole and South Pole at either end of the solenoid.

Magnitude of magnetic field around solenoid is given by,

$$B = \mu_o NI - - - - - - -(1.2)$$

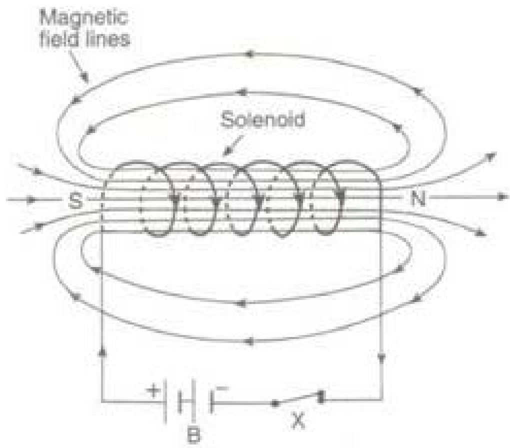


Fig. 1.2: Magnetic field around solenoid

Where N is number of turns per unit length, I current through solenoid and μ_0 is permeability of free space. Note that B does not depend upon diameter or length of the solenoid. Magnetic field inside the solenoid is nearly uniform and proportional to the number of the turns and current flowing through it. Magnetic field is negligible outside the coil except ends where magnetic poles are formed. Direction of magnetic field or poles at the end of the solenoid is determined using right hand grip rule.

In right hand thumb rule curl fingers indicates direction of current whereas thumb indicates point towards North Pole along the axis of the solenoid.

1.1.2.2 Force on a Current Carrying Conductor Placed in Magnetic Field

When a current carrying conductor is placed in a magnetic field, conductor experiences a force due to interaction between the magnetic field and the current. In order word due to interaction between placed magnetic field and produced magnetic field in current carrying conductor. The magnitude of the force on the conductor depends on

a. Magnetic flux density (*B*)

b. Current (*I*) flowing through the conductor

c. Length (*L*) of the conductor that is placed in magnetic field

Force is given by,

$$F = BIL\sin\theta ----------- (1.3)$$

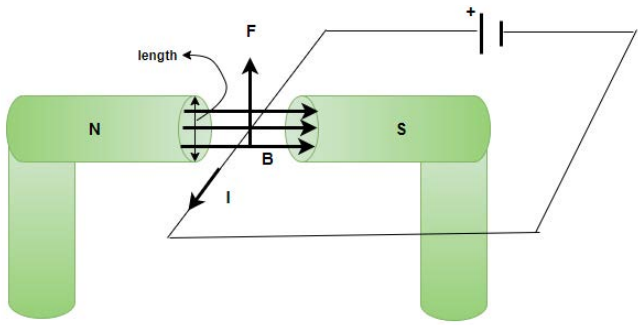


Fig. 1.3: Force on a current carrying conductor placed in magnetic field

The force is maximum when the conductor is perpendicular to the magnetic field

$$F = BIL\sin 90^0 ------------- (1.4)$$

$$F = BIL \ Newton$$

Where *F* is force experienced by the conductor, *I* is current flowing through the conductor, *L* is the length of conductor that is placed in magnetic field and *B* is magnetic flux density. This force is known as Lorentz force (due to electromagnetic field). The direction of force is given by Fleming's Left Hand Rule. The force on the conductor can be used to move the conductor or to do work. In fact the principle behind electric motors is based on this force.

1.1.3 Force Between Two Parallel Current Carrying Conductors

When two parallel current carrying conductors are placed near to each other, they produce magnetic fields that interact with each other, resulting a force between the two conductors. The force between two parallel current carrying conductors is given by,

$$F = \frac{\mu_o I_1 I_2 L}{2\pi r} ----------- (1.5)$$

Force per unit length, $\frac{F}{L} = \frac{\mu_o I_1 I_2}{2\pi r}$

The force between the conductors can be attractive or repulsive depending upon the direction of currents. When currents are flowing in the same direction the magnetic field produced by the conductors reinforce each other, resulting attractive force between two conductors. When current are flowing opposite direction the magnetic fields produced by the conductor cancel each other resulting repulsive force between two conductors.

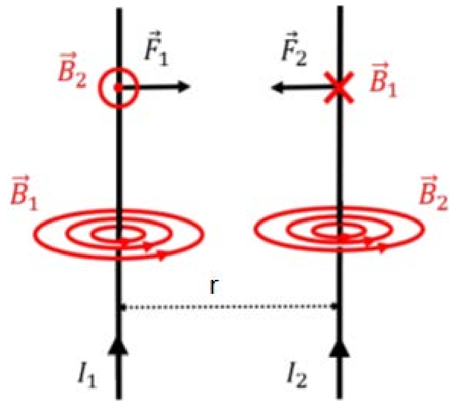


Fig. 1.4: Force between two parallel current carrying conductor

1.1.4 Series and Parallel Magnetic Circuits

Magnetic circuit

The closed path through which magnetic flu passes is known as magnetic circuit.

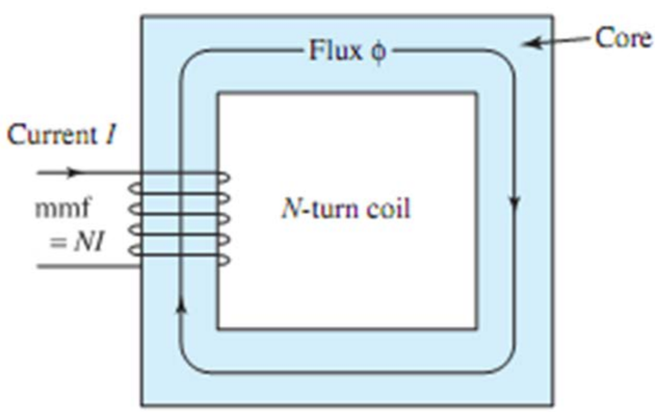


Fig. 1.5: Magnetic circuit

Series Magnetic Circuit

Magnetic circuit that consists of series of magnetic cores is called series magnetic circuit. Magnetic reluctance (S) of each component in the series magnetic circuit is determined by the material properties of the component such as permeability and cross sectional area. Reluctance of each component is given by

$$S = \frac{l}{\mu a} - - - - - - - - - - - - - - - - (1.6)$$

Where μ is permeability of the material and a is the cross sectional area of the component. The total reluctance of series magnetic circuit is the sum of reluctances of each component and given by,

$$S_{total} = S_1 + S_2 + \ \ldots \ldots\ldots \ + S_n - - - - - - (1.7)$$

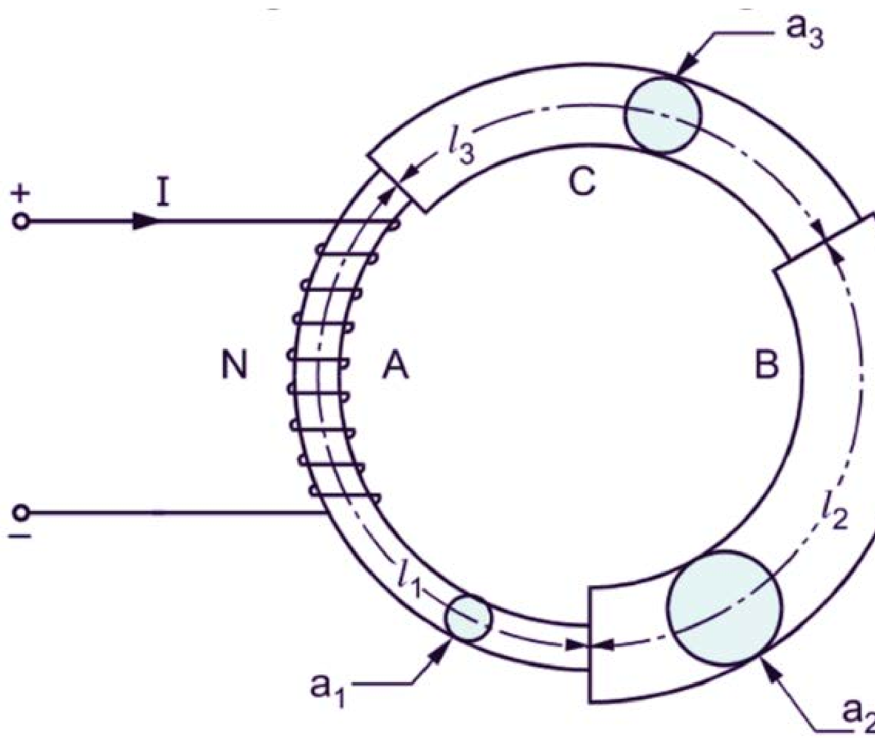


Fig. 1.6: Series magnetic circuit

Parallel Magnetic Circuit

Parallel magnetic circuit is a magnetic circuit where multiple magnetic components are arranged in parallel. Thus magnetic flux split between the components. Total magnetic flux is equal to the sum of the flux through each component and total magnetic field strength is determined by the magnetic field strength of each component.

A coil of N turns wound on limb AF carries a current of I amperes. The flux $\emptyset_1$, set up by the coil divides at B into two parts they are $\emptyset_2$ and$\emptyset_3$. So that $\emptyset_1 = \emptyset_2 + \emptyset_3$, $\emptyset_2$ passes along the path BE and $\emptyset_3$ follows the path BCDE as shown in figure1.7.

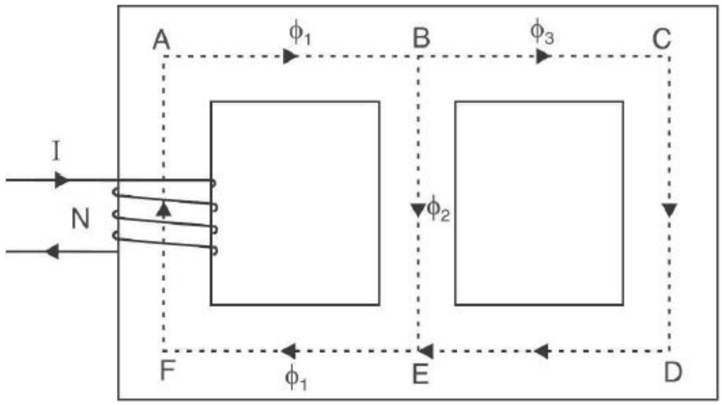


Fig. 1.7: Parallel magnetic circuit

1.1.5 Concept of Hysteresis Loop and Hysteresis Loss

Hysteresis Loop

Hysteresis loop is a graphical representation of magnetic behavior of ferromagnetic material subjected to an alternating magnetic field. Loop shows the relationship between H and B during a complete cycle of magnetization and demagnetization of the material. Nature of the loop is a closed curve as shown in figure 1.8.

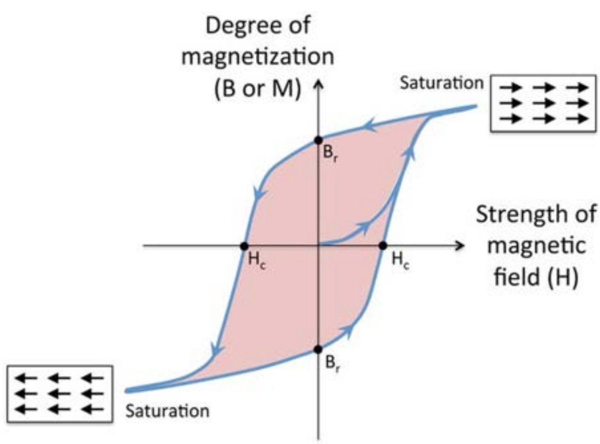


Fig. 1.8: Hysteresis loop

Hysteresis Loss

The area enclosed by the B-H curve (hysteresis loop) represents the hysteresis loss. Energy loss as heat during each cycle of magnetization and demagnetization. Energy loss due to frictional forces between the magnetic domains in material that resists changes in the direction of magnetization and demagnetization. Loss occurs as heat. Smaller the area of loop, smaller the hysteresis loss.

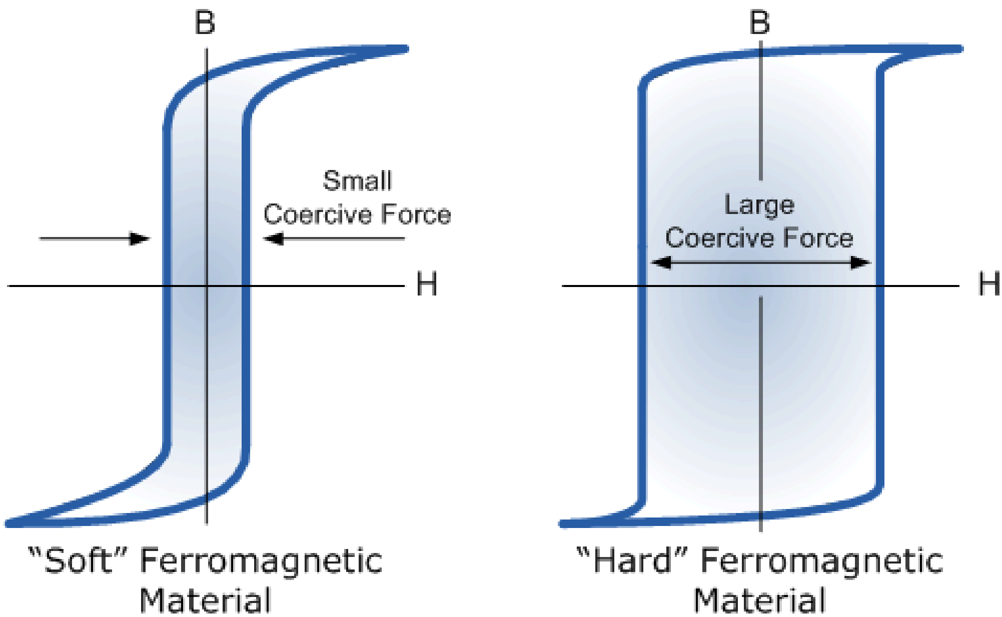


Fig. 1.9: Hysteresis loop area sizes

1.2 Electromagnetic Induction

The production of electromotive force (emf) or voltage across a conductor due to relative motion between the conductor and the magnetic field is known as electromagnetic induction. This process was first discovered by Michael Faraday in 1831 A.D. Thus produced current is known as induced current. Motors, generators etc. are based on this principle.

1.2.1 Faraday's Laws of Eectromagnetic Induction

First law

When the conductor is placed in varying, changing magnetic field, emf is induced. If the conductor circuit is closed, a current is induced, which is called induced current.

Second Law

Magnitude of induced emf is directly proportional to the rate of flux linkage. The negative sign indicates that the direction of the induced emf and the change in the direction of magnetic fields have opposite signs.

$$E \propto \frac{d\emptyset}{dt}$$

$$or, E = -N\frac{d\emptyset}{dt} - - - - - - - - - - - - - - - (1.8)$$

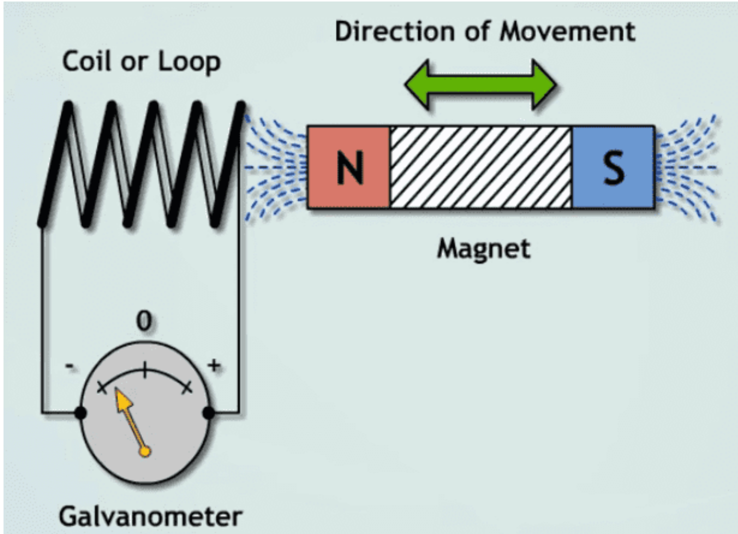


Fig. 1.10: Faraday's laws of Electromagnetic induction

Methods to Increase Induced emf

a. By increasing strength of magnet

b. By increasing number of turns of coil

c. By increasing the speed of the relative motion between the coil and the magnet

1.2.2 Lenz law

We have,

$$E \propto \frac{d\emptyset}{dt}$$

$$or, E = -N\frac{d\emptyset}{dt}$$

An induced emf generated by electromagnetic induction is such that it sets up a current which always opposes the cause that is responsible for generating the emf. Induced emf always opposes the cause that produces it.

1.2.3 Fleming's Right and Left Hand Rule

Fleming's Right Hand Rule

This rule is used to find direction of induced current. When thumb, fore finger and middle finger are kept mutually perpendicular to each other so that thumb indicates the motion or force, fore finger indicates the magnetic field and middle figure indicates the induced current. This rule is applicable for generators.

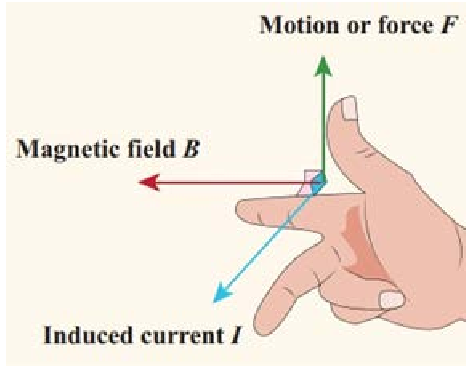


Fig. 1.11: Fleming's right hand rule

Fleming's Left Hand Rule

This rule is used to find direction of force. When thumb, fore finger and middle finger are kept mutually perpendicular to each other so that thumb indicates the motion or induced force, fore finger indicates the magnetic field and middle finger indicates the current flowing. This rule is applicable for motors.

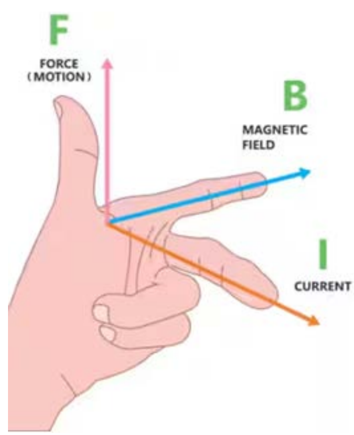


Fig. 1.12: Fleming's left hand rule

1.2.4 Principle of Self and Mutual Induction

Self-Induction

Self-induction is a phenomenon in which a changing current in a coil of wire induces an emf in the same coil, opposing original current. This effect is caused by magnetic field that is generated by the current in the coil which induces a voltage that opposes the original current.

The property of a coil by virtue of which it opposes any change in amount of current flowing through it is called its self-inductance. This opposition occurs because a changing produces self-induced emf which opposes change in current.

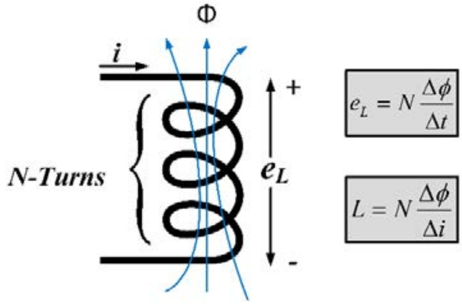


Fig. 1.13: Self-Inductance

Self-induced emf is given by,

$$e_s = -L\frac{dI}{dt} - - - - - - - - - - - - - (1.9)$$

where L is called self-inductance and dI/dt is change in current

Another expression for self-inductance

$$L = \frac{N\emptyset}{I} - - - - - - - - - - - - (1.10)$$

where $N\Phi$ is flux linkage.

Mutual Induction

Mutual induction is a phenomenon that occurs when a changing magnetic field created by one coil of wire induces an emf in second coil of wire.

The property of two coils by virtue of which each opposes any change of current flowing in the other is called mutual inductance. This opposition occurs because a changing current in one coil produces mutually induced emf in the other coil which opposes the change of current in the first coil. Mutually induced emf in second coil due to coil 1 is given by,

$e_2 = -M_{21}\frac{dI_1}{dt}$, where M_{21}mutual inductance.

Another expression for mutual inductance,

$M_{21} or (M) = \frac{N_2 \emptyset_{21}}{I_1}$, $\emptyset_{21}$ is flux passing through coil 2 due to coil 1.

Mutual inductance in terms of coefficient of coupling is given by,

$$M = k\sqrt{L_1 L_2} - - - - - - - - - - - - (1.12)$$

,where k is coefficient of coupling.

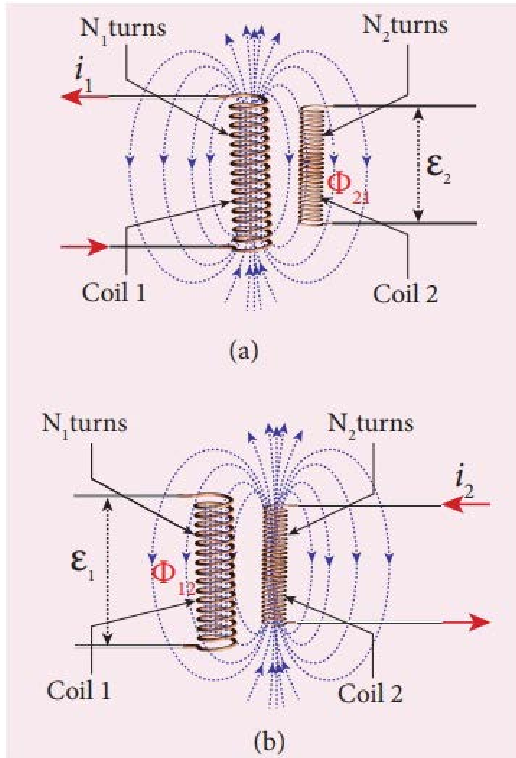


Fig. 1.14: Mutual inductance

1.2.5 Inductances in Series and Parallel

Series Combination

When three inductors having inductances L_1, L_2 and L_3 are connected in series as shown in figure. Considering no linkage between each other, then equivalent inductance is given by,

$$L_{eq} = L_1 + L_2 + L_3$$

When inductors are connected together in series so that the magnetic field of one links with the other then this is referred to as mutual inductance. Effect of mutual inductance either increase or decrease total inductance depending upon the distance and orientation of coils.

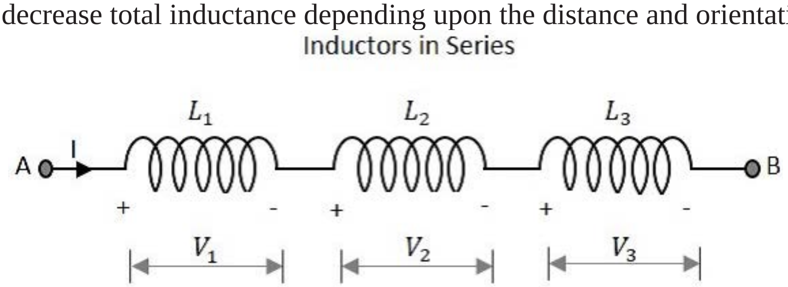


Fig. 1.15: Series combination

Aiding

If the magnetic flux produced by the current flows through the coils in the same direction then the coils are said to be cumulatively Coupled

$L_{eq} = L_1 + L_2 + 2M$

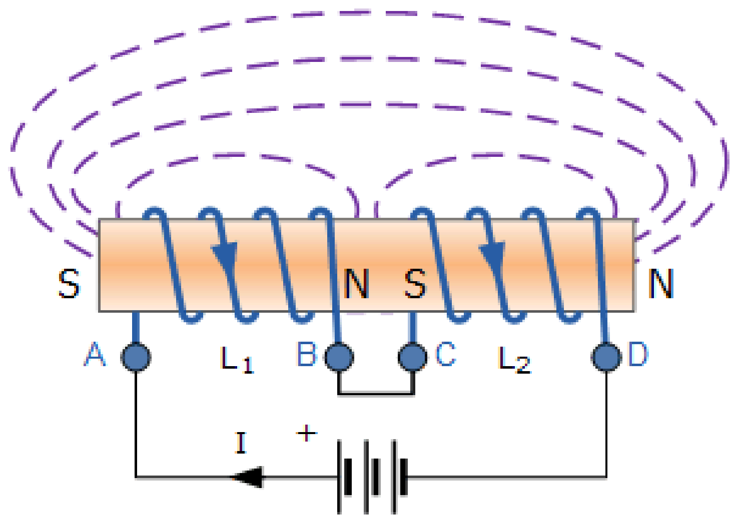


Fig. 1.16: Series aiding

Opposing

If the current flows through the coils in opposite directions then the coils are said to be differentially coupled

$L_{eq} = L_1 + L_2 - 2M$

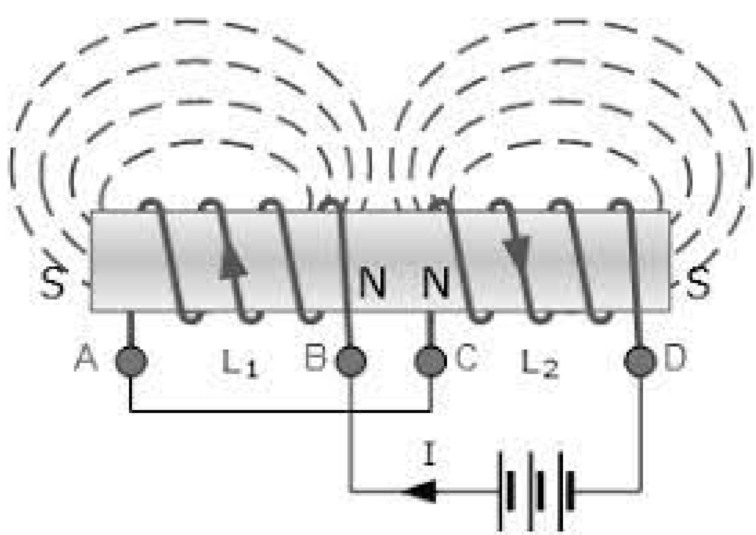


Fig. 1.17: Series opposing

Parallel Combination

When three inductors having inductances L_1, L_2 and L_3 are connected in parallel as shown in figure then equivalent inductance is given by,

$$\frac{1}{L_{eq}} = \frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3}$$

Considering mutual induction between inductors then,

Parallel Aiding, $L_T = \frac{L_1 L_2 - M^2}{L_1 + L_2 - 2M}$

Parallel Opposing, $L_T = \frac{L_1 L_2 - M^2}{L_1 + L_2 + 2M}$

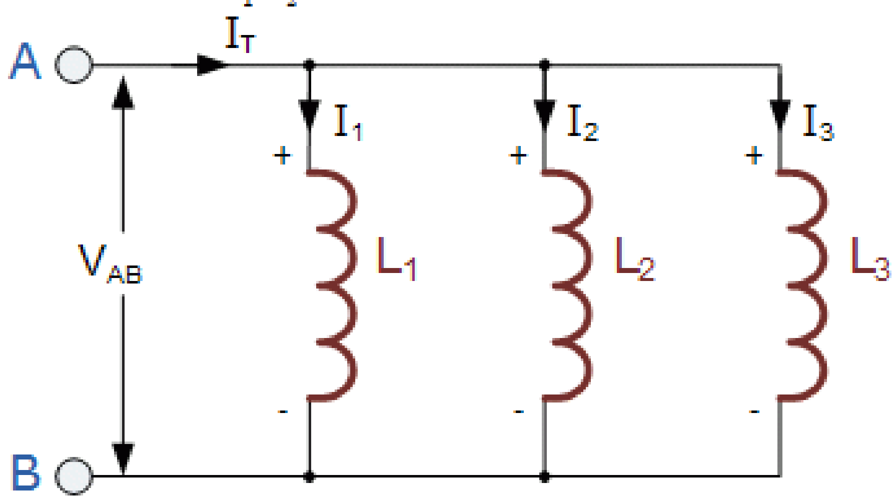


Fig. 1.18: Parallel combination

1.2.6 Energy Stored in a Magnetic Field

When a current flows through a coil of wire, a magnetic field is generated around the coil. This magnetic field stores energy in the form of electromagnetic potential energy. The energy stored in an inductor is given by,

$U = \frac{1}{2} L I^2$ Joules

Exercise

Choose the correct answer from the given alternatives.

1. What will be the current passing through the ring shaped air cored coil number of turns is 800 and ampere turns are 3200?

   a. 0.25 b. 2.5 c. 4.0 d. 0.4

2. Force between two conductors is attractive when...........

   a. Current flow in same direction
   b. Current flow in opposite direction
   c. Either direction
   d. All of the above

3. Mmf is analogous to........

   a. Electric current in electric circuit
   b. Current density in conductor
   c. Electromotive force
   d. Electric field

4. Dot notation indicates...........

   a. Current flows out
   b. Current flows in
   c. Both a and b
   d. Current flows randomly

5. Magnetic field around a straight current carrying conductor is given by........

   a. $B = \frac{\mu_0 nI}{2\pi r}$ b. $B = \frac{\mu_0 I}{2\pi r}$ c. $B = \mu_0 nI$ d. both b and c

6. Cross notation indicates........

   a. Current flows out
   b. Current flows in
   c. Both a and b
   d. Current flows randomly

7. Magnetic field in a solenoid is given by............

   a. $B = \frac{\mu_0 nI}{2\pi r}$ b. $B = \frac{\mu_0 I}{2\pi r}$ c. $B = \mu_0 nI$ d. both b and c

8. Force between two conductors is repulsive when............

   a. Current flow in same direction
   b. Current flow in opposite direction
   c. Either direction
   d. All of the above

9. Hysteresis loop provides............

   a. Iron loss b. Eddy current loss c. Hysteresis loss d. Copper loss

10. Energy stored in magnetic field is given by..........

a. $1/2L^2I$ b. $1/2L^2I^2$ c. $1/2I^2L$ d. $1/2I^3L$

Short answer questions

1. What are the rules that used to find the induced current direction and direction of produced magnetic field in current carrying conductor? Describe them.
2. Explain the force between two parallel current carrying conductors in magnetic field.
3. What is series magnetic circuit? Explain with necessary diagram.
4. Write short note on a) Faraday's laws of electromagnetic induction b) Lenz's Law c) Fleming's right hand rule d) Maxwell's screw rule
5. Define electromagnetism. Explain the magnetic field around a straight current carrying conductor and a solenoid.

Long answer questions

1. Define self and mutual inductance. What happen to the equivalent inductances when the mutual inductance between the inductor is considered in series combination? Elaborate them with necessary circuit diagram.
2. Write down the expression for the energy stored in solenoid and explain the magnetic field around the solenoid when current passes through it with diagram. Also mention the rules that find outs the direction of magnetic field.

Project Works

1. Study of electromagnetism with electromagnetism related videos.
2. Demonstrate Faraday's laws of electromagnetism.
3. Presentation about Fleming's left hand rule and Fleming's right hand rule
4. Study of the force between two parallel plates with videos.
5. Study of the force experience by the current carrying conductor placed in magnetic field with animated videos.

Unit 2 Transformers

2.1 Introduction of Transformer

Transformer is an AC static electrical device (that means- no rotating or movable parts). It transfers energy from one circuit to another without electrical connection between two circuits. While transforming there will be change in voltage and current magnitude but no change in frequency (frequency is constant in both circuit). It consists of two coils or windings called primary winding and secondary winding or high voltage winding and low voltage winding or H.V winding and L.V winding.

Two windings are electrically isolated (means there is no electrical connection between two windings) .Energy is transformed according to Faraday's law of electromagnetic induction. Generally energy transfer take place with change in voltage level (means there is change in voltage level between two windings). It works in AC circuits only.

Function of a Transformer

a. To change (raise or lower) (increase or decrease) (high or low) the voltage and current in AC circuits.

b. Can isolate two circuits electrically.

c. Can increase or decrease the value of capacitance, inductance or resistance thus can acts as impedance transferring device.

d. Extensively used in power transmission and distribution system.

Applications

a. Power supply

b. Industries

c. Substations

d. Hydropower etc.

2.2 Constructional Details of a Single Phase Transformer

2.2.1 Cores and Windings of a Single Phase Transformer

Generally consists of iron or steel core. Core are laminated and thin. Core has two members (parts) – yoke and limb. Windings are placed on limbs of the core horizontal member is called yoke and coils or windings are generally made up of insulated copper wire.

Steel Core

Magnetic current or magnetic flux is set up in the core the induced magnetic flux in the primary side is fully (100%) linked with secondary side Thin laminates sheets of silicon steel alloy (4-5% of silicon) Hence very high permeability (measures of magnetization) Different shapes (L, I, U and E).

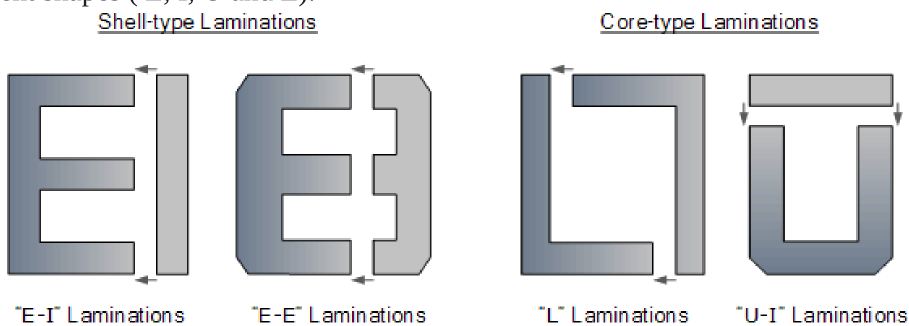


Fig. 2.1: Different types of core sheet

Bobbins

It is a spindle or cylinder, with or without flanges on which wire is wound. It supports the windings, align the cores and provides the termination of connection. Bobbins design are differ with the core shape.

Fig. 2.2: Bobbins

Windings

There are two types of winding. Primary winding and secondary winding (primary is input side and output is secondary side).

Primary Winding

Primary winding is connected to the power supply and when supply is given it generates magnetic field around the winding. It consists of a specific number of turns of high conductivity copper or aluminum wire. It has higher number of turns than secondary winding if transformer is step down transformer and has lower number of turns if the transformer is step up transformer.

Fig. 2.3: Windings

Secondary Winding

Secondary winding is connected to the load and deliver current to the connected devices. It consists of a specific number of turns. The windings are carefully insulated from each other and from the core to prevent electrical short circuits and ensure electrical isolation. It has higher number of turns than primary winding if transformer is step up transformer and has lower number of turns if the transformer is step down transformer.

2.2.2 Classification of Single phase transformer on the basis of core (Shell type and Core type Transformer)

On the Basis of Use

a. Step Up Transformer

b. Step Down Transformer

a. Step up Transformer

This type of transformer increases the voltage level and primary winding has less number of winding turns than secondary ($Np < Ns$).

b. Step down Transformer

This type of transformer decreases the voltage level and primary winding has large number of winding turns than secondary ($Np>Ns$)

On the Basis of Construction

a. Shell Type Transformer

b. Core Type Transformer

a. Shell type transformer

On a central limb of a core, both primary and secondary windings are wound.

Features/Characteristics

a. Provides double magnetic flux

b. More economical for LV transformer

c. Has three limbs

d. Natural cooling cannot be provided

e. Repair and maintenance is hard

f. Better mechanical protection to the coil

b. Core Type Transformer

Windings are usually cylindrical in form and concentric.

Features/Characteristic

a. Provides single magnetic flux

b. Suitable for HV transformer

c. Has two limbs

d. Natural cooling can be provided

e. Repair and maintenance is easy

f. Less mechanical protection to coil

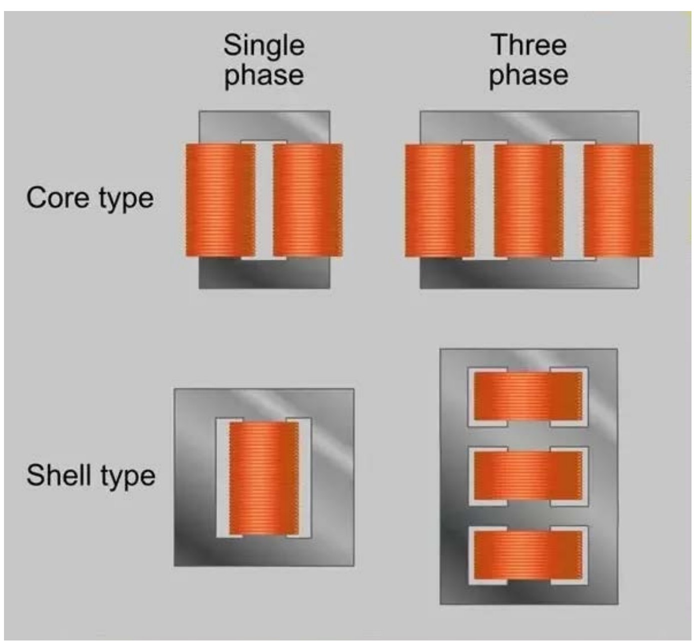


Fig. 2.4: Core types

2.3 Operation of Transformer

2.3.1 Working Principle of aTransformer

When an alternating voltage is applied to the primary side having (N_1 or N_p) number of turns, an alternating flux (ϕ) is set up in the core. This flux (ϕ) links the both windings in which secondary winding has (N_2 or N_s) number of turns and induces emf (E_1 or E_p) and (E_2 or E_s) in primary and secondary sides respectively. These emfs are induced, according to Faraday's law of electromagnetic induction. Hence the main principle of transformer is the MUTUAL induction.

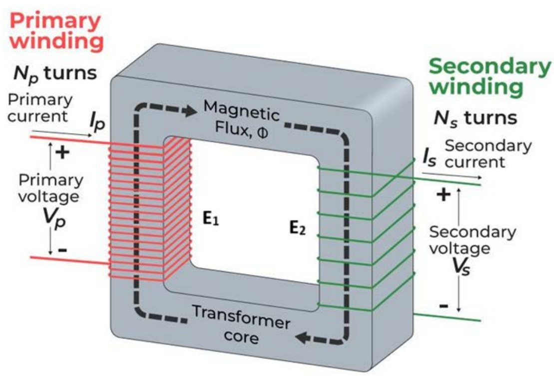


Fig. 2.5: Working of transformer

If the load is connected to the secondary side then current I_2 will flow to the load. Thus power transfer from primary side to secondary side. According to the Faraday's law of electromagnetic induction, emf induced in the primary side is given by,

$$E_1 = -N_1 \frac{d\emptyset}{dt}$$

Where, $\frac{d\emptyset}{dt}$ is the rate of change of flux.

Now, for secondary side,

$$E_2 = -N_2 \frac{d\emptyset}{dt}$$

$$\frac{E_2}{E_1} = \frac{-N_2 \frac{d\emptyset}{dt}}{-N_1 \frac{d\emptyset}{dt}}$$

Since, both side have common flux ϕ. From 1 and 2,

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

$$\frac{E_2}{E_1} = \frac{N_2}{N_1} = \text{K} - - - - - - - - - - - - (2.1)$$

Where, K is transformation Ratio.

2.3.2. EMF Equation of a Transformer

The average value of emf E_2 is given by,

$$e_2 = -N_2\frac{d\emptyset}{dt}$$

Where, $\frac{d\emptyset}{dt}$ is rate of change of magnetic flux. From fig, it is clear that the magnetic flux changes from 0 to $\emptyset_m$ during the time interval of T/4 or (1/4f), where T is the time period of ac waveform. Hence,

$$\frac{d\emptyset}{dt} = \frac{0-\emptyset_m}{\frac{T}{4}} = -4f\emptyset_m$$

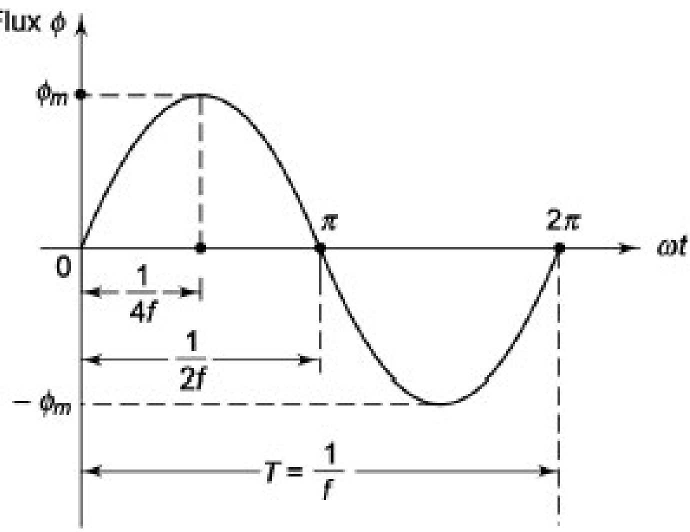


Fig. 2.6: Magnetic flux waveform

Therefore,

$$e_2 = -N_2\frac{d\emptyset}{dt} = 4N_2f\emptyset_m \quad \text{volts}$$

We know, form factor for sine wave = $\frac{RMS\ value}{Average\ value}$ = 1.11

RMS value = Average value x 1.11

Therefore, RMS value of emf induced in sec. winding is given by

$$E_2 = 4N_2f\emptyset_m \times 1.11 = 4.44N_2f\emptyset_m \ volts - - - - - - - - - - (2.2)$$

Since the same flux is linked with the pri. Coil so RMS value of primary side can be written as,

$E_1 = 4N_1f\emptyset_m$ x 1.11 = $4.44N_1f\emptyset_m$ $volts$ ---------- (2.3)

Numerical

Numerical related relations.

a. $E_1 = 4N1f\emptyset_m$ x 1.11 = $4.44N1f\emptyset_m$ volts.

b. $E_2 = 4N2f\emptyset_m$ x 1.11 = $4.44N2f\emptyset_m$ volts.

c. $\frac{E_2}{E_1} = \frac{V_2}{V_1}$

d. $\frac{V_2}{V_1} = \frac{N_2}{N_1}$

e. $V_1I_1 = V_2I_2$

f. $\frac{V_2}{V_1} = \frac{I_1}{I_2}$

g. $\frac{V_2}{V_1} = \frac{N_2}{N_1} = \frac{I_1}{I_2}$

h. $\emptyset_m$ =BA where, B= flux density and A=Cross sectional area

Example 1

A 3000/200V, 50Hz single phase transformer is built on a core having an effective cross-sectional area of $150cm^2$ and has 80 turns in the low voltage winding. Calculate the maximum flux density in the core.

Solution,

Given, supply frequency (f) = 50 Hz

No. of turns in low voltage winding (N2)=80

Cross section area (A) = 150 cm2= $150 \times 10^{-4}\ m^2$

We know,

$$E_2 = 4.44N_2f\emptyset_m$$

$$or, \emptyset_m = \frac{E_2}{4.44N_2f}$$

$$\emptyset_m = \frac{200}{4.44 \times 80 \times 50} = 0.01126 \text{ wb}$$

Maximum flux density in the core (Bm) = $\frac{\emptyset_m}{A}$

$= \frac{0.01126}{150\ x\ 10^{-4}}$

= 0.75 T

Example 2

A step up transformer having 400/1100V of primary no of turns is 200. Calculate secondary no of turns? Flux density = 80wb/m^2.

Solution,

Primary side Voltage (E_1) = 400 V

Secondary side voltage (E_2) = 1100 V

Primary No. of turns (N_1) = 200 turns

Flux Density (B) = 80 wb/m^2

Secondary No. of turns (N_2) =?

We know,

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

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

= 550 turns

Example 3

A 200 kVA, 3000/240V, 50Hz single phase transformer has 80 turns on the secondary winding. Assuming an ideal transformer, calculate:

i. Primary and secondary current at full load

ii. Maximum value of flux

iii. Number of primary turns

Solution,

Transformer kVA rating = 200 kVA

Primary side Voltage (V_1) = 3000 V

Secondary side voltage (V_2) = 240 V

Frequency (f) = 50 Hz

Secondary turns (N_2) = 80

We know,

Transformer kVA rating = $V_1I_1 = V_2I_2$

So,

Primary current (I_1) = $\frac{kVA\,rating}{V_1} = \frac{200 \times 1000}{3000}$ =66.6 A

Secondary current (I_2) = $\frac{kVA\,rating}{V_2} = \frac{200 \times 1000}{240}$ =833.33 A

We know,

Maximum flux ($\emptyset_m$) = $\frac{V_2}{4.44N_2f}$ = 0.0135 wb

Primary number of turn (N_1) = $N_2 \; x \frac{V_1}{V_2}$ = 1000 turns

2.3.3. Transformation Ratio

The transformation ratio of a transformer is the ratio of the number of turns in the secondary winding to the number of turns in the primary winding. It is denoted by k and given by,

$$K = \frac{N_2}{N_1} = \frac{V_2}{V_1}$$

It determines the voltage transformation capability of the transformer. It also called turn ratio of the transformer.

Cases:

If $K>1$ i.e. $N_2 > N_1$, then transformer is Step Up transformer.

If $K<1$ i.e. $N_2 < N_1$, then transformer is Step Down transformer.

If $K=1$ i.e. $N_2 = N_1$, then transformer is Isolation transformer.

2.3.4 Basic concept of Transformer on Load and No-load condition (Mathematical interpretation not required)

The no load current can be resolved into two components as follow:

I_w= component of I_o in phase with $V_1 = I_o\cos\phi_o$ = loss component

I_μ= component of I_o which lags V_1 by $90^0 = I_o\sin\phi_o$ = magnetizing component

Loss component I_w is responsible for producing heat loss in the core Magnetizing component Iμ is responsible for producing magnetic flux in the core. The power consumed by the transformer at no load is given by:

$W_0 = V_1 I_0 \cos\phi_0$ watts, where $\cos\phi_0$ is the no load power factor of the transformer.

Transformer on Load

When load is connected I_2 current flows in sec. side. Secondary mmf N_2I_2 will set up own magnetic flux ϕ_2, opposite to main flux ϕ_m. At no load current at primary side is I_o but when load is connected additional current I'_2 will flow in primary winding to balance the power between primary and secondary circuit. The additional current I'_2 also set up its own flux ϕ'_2 and direction will be opposite to ϕ_2. Hence two additional flux ϕ_2 and ϕ'_2 cancel each other. That is why, magnetic flux within the transformer core is constant at any load condition.

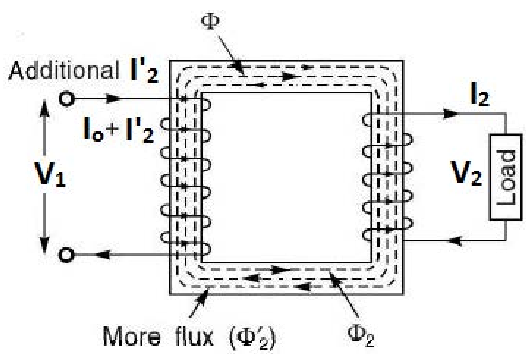


Fig. 2.7: Transformer ON loading condition

2.3.5. Equivalent Circuit Diagram of a Transformer

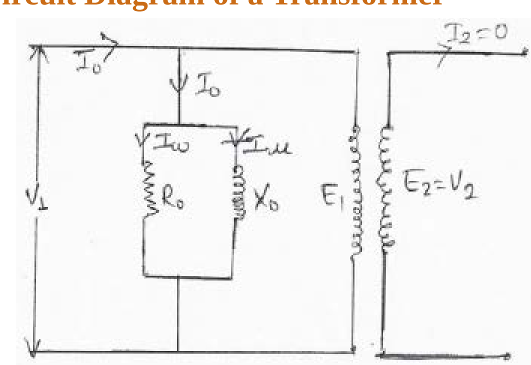


Fig. 2.8: No load equivalent circuit

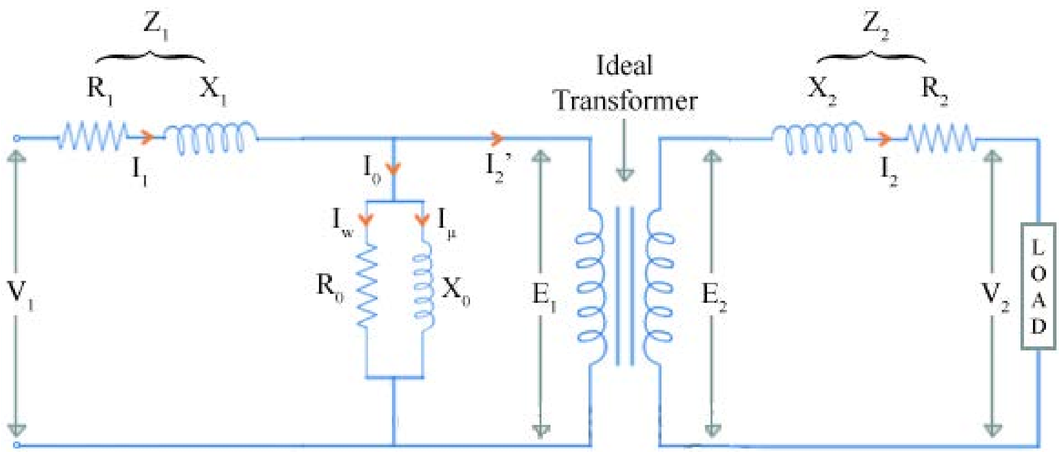


Fig. 2.9: ON load equivalent circuit

2.4 Losses and Efficiency

2.4.1 Losses and Efficiency of a Transformer

The output of a transformer is always less than input (practical t/f) because there are some power losses within the transformer while it transfers power from one circuit to another circuit. There are mainly two types of power losses in the transformer:

a. Copper Loss

b. Iron Loss (Core loss)

2.4.2 Types of Losses of a Transformer Copper Loss

a. Copper Loss

Power loss due to heating of primary and secondary winding. Main cause of heat generation is due to resistance of the windings. Copper loss depends upon the load connected to the transformer. This loss can be determined by short circuit test of transformer.

$$Total\ Cu\ losses = I_1^2 R_1 + I_2^2 R_2$$

Hence Cu losses vary as the square of load current. It is variable losses of transformer.

b. Iron or Core Loss

It is the power loss due to heating of iron core. Main causes for this heating are eddy current loss and hysteresis loss. This power loss is equal to the no-load power loss and remains constant at any load. This can be determined by open- circuit test of transformer.

Iron losses = Eddy current loss + Hysteresis loss

Eddy current loss = $K_e B_m^2 f^2 t^2 V$ watts

Hysteresis loss = $K_h B_m^{1.6} fV$ watts

Both eddy current loss and hysteresis loss depends upon maximum flux density B_m in the core and supply frequency f. Since, transformers are connected to constant-frequency, constant voltage supply, both f and Bm are constant. Hence, core or iron losses are practically the same at all loads.

Iron or Core losses, Pi = hysteresis loss + eddy current loss= constant losses

The hysteresis loss can be minimized by using steel of high silicon content whereas eddy current loss can be reduced by using core of thin laminations.

Total Losses

Total losses in transformer = Pi +Pc

Where, Pi = iron or core loss

Pc= copper loss

So,

Total losses in transformer = Pi +Pc

= (eddy current loss + hysteresis loss) + Pc

= Constant loss + Cu loss

= Constant loss + variable loss

Eddy Current Loss

Flux produced in core is alternating in nature and when emf induced in the core at the same time some circulating current will flow in the core.

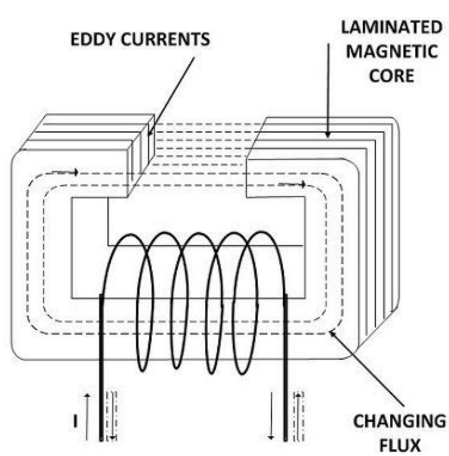


Fig. 2.10: Eddy current

This circulating current is known as eddy current. This current produces heat in the core. Power loss due to this heat is known as eddy current loss. To reduce this loss, thin steel silicon laminated core is used.

Eddy current loss is given by;

$W_e = KB_m^2 f^2 t^2 V$ (watts)

Where,

K= constant depending upon nature of core

B_m= maximum value of magnetic flux density in the core

f= frequency of the exciting current

t= thickness of each lamination

V= volume of iron core

Hysteresis Loss

Hysteresis loss is due to the reversal of magnetization of transformer core whenever it is subjected to alternating nature of magnetizing force. Whenever the core is subjected to an alternating magnetic field, the domain present in the material will change their orientation after every half cycle. The power consumed by the magnetic domain for changing the orientation after every half cycle is called Hysteresis loss. The relationship between the magnetizing force, H, and the flux density, B, is shown on a hysteresis curve, or loop.

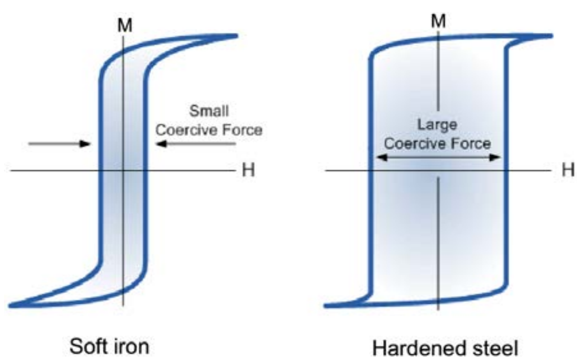


Fig. 2.11: Hysteresis loss according to loop area

Hysteresis loss is given by;

$W_h = K_h B_m^{1.6} fV$ watts

Where,

K_h= hysteresis coefficient

B_m= maximum value of magnetic flux density in the core

f= frequency of the exciting current

V= volume of iron core

2.4.3 Types of Efficiency of a Transformer

The efficiency of a transformer is categorized into two parts:

a. Commercial efficiency

b. All day efficiency

a. Commercial Efficiency

Commercial or ordinary efficiency of a transformer is defined as the ratio of output power to the input power.

$$Commercial\ efficiency(\eta_{commercial}) = \frac{Output\ power}{Input\ power}$$

b. All Day Efficiency

The ratio of output in kWh to the input in kWh of a transformer over a 24-hour period is known as all day efficiency. It is also known as energy efficiency.

$$All\ day\ efficiency(\eta_{all-day}) = \frac{kWh\ output\ in\ 24hr}{kWh\ input\ in\ 24\ hr}$$

Since the distribution transformer does not supply the rated load for the whole day. So the all-day efficiency of such transformer will be lesser than ordinary or commercial efficiency.

2.4.4 Short Circuit and Open Circuit Test of a Transformer

Large rating transformer cannot be tested by direct loading because of:

a. during test large amount of energy has to be wasted.

b. It is not feasible or practicable to have a large load for test in lab.

Therefore transformer test is done from the knowledge of equivalent circuit parameters.

Two Types of Test

a. Open circuit test or no load test

b. Short circuit test or impedance test

a. Open Circuit Test or no Load Test

This test provides exciting shunt branch parameters of equivalent circuit, no load power loss, no load current and no load power factor of the transformer. The rated voltage and frequency is applied to primary side (usually low voltage side) while secondary side is left open circuited. Since the no load current I_o is very small (usually

2-10 % of rated current), copper loss can be neglected and the watt meter reading can be considered as no load power loss or iron loss of the transformer.

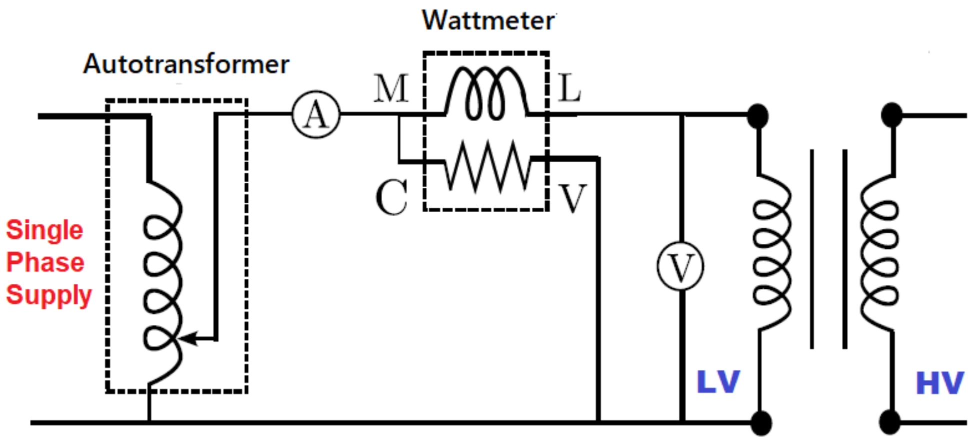


Fig. 2.12: Open circuit test

Let V_1= voltmeter reading (applied voltage)

I_o= ammeter reading (no load current)

W_o= wattmeter reading (iron losses or no load power) = P_i

Where input power, $W_0 = V_1 I_0 \cos \emptyset_0$

No load power factor, $\cos \emptyset_0 = \frac{W_0}{V_1 I_0}$

$$I_w = I_0 \cos \emptyset_0$$

$$I_\mu = I_0 \sin \emptyset_0$$

Hence open circuit test provides Pi, I_0, $\cos \emptyset_0$, I_w and I_μ.

Short Circuit Test or Impedance Test

This test provides copper loss, series resistance and leakage reactance of the transformer. For this test usually LV side is short circuited by a thick wire and HV side is supplied with variable low voltage so that full load current flows through the transformer, Since test voltage is very small (about 5% of normal rated voltage) , iron loss can be neglected therefore wattmeter readings can be considered as full load copper loss.

Voltmeter reading (applied voltage)

I_1= Ammeter reading (full load primary current)

W_{sc}= Wattmeter reading (full load copper loss) = P_c

Where,

$$W_{sc} = I_1^2 R_{01}$$

Where, R_{01} is total resistance of transformer referred to primary

Total impedance $Z_{01} = \frac{V_{sc}}{I_1}$

Total reactance $X_{01} = \sqrt{Z_{01}{}^2 - R_{01}{}^2}$

Hence short circuit test provides Cu loss, R_{01}, Z_{01}, X_{01}.

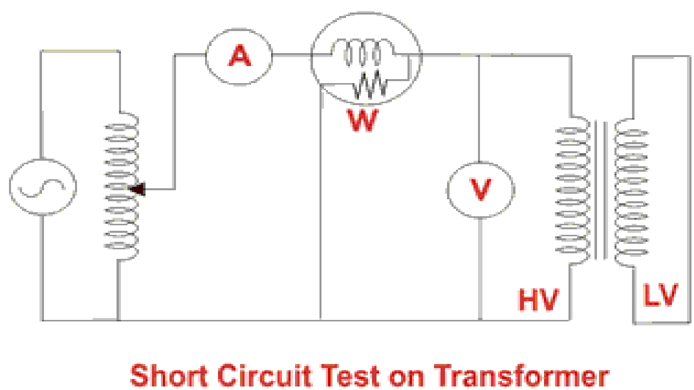


Fig. 2.13: Short circuit test

2.5 Three-phase Transformer

Large scale generation of electric power is usually three phase at 11 kV or higher voltage level. Transmission of power is generally accomplished at further higher voltage for economy. Therefore three phase step up transformers are necessary at the sending end of the transmission line. In the earlier days, it was common practice to use interconnected three units of single phase transformers to step up or step down the three phase voltage. Nowadays we use three phase transformer (single unit). Three phase transformer are widely used in power transmission, distribution networks, industrial systems and commercial applications.

2.5.1 Construction of Three Phase Transformers

Construction is similar to the single phase transformer. Core is typically made up of laminated sheets of silicon steel to minimize core losses. Thin laminations are insulated from each other to reduce eddy current losses. Core provides low reluctance path for magnetic flux generated by the primary windings. Three phase transformer has three primary windings and three secondary windings one for each phase. Windings are usually made up of copper or aluminum conductors. Each limb consists of primary and secondary winding and insulated from each other. Varnish or enamel as insulating materials are used to insulate the windings and prevent electrical breakdown between turns and phases. They also mechanical support and protection to the windings.

Core Type Three Phase Transformer

Core type three phase transformer has three limbs to wound windings. Windings are wound around each limb of the core forming separate concentric coils for each phase. Primary and secondary are electrically insulated from each other. This type of transformer are widely used and can handle a wide range of power ratings.

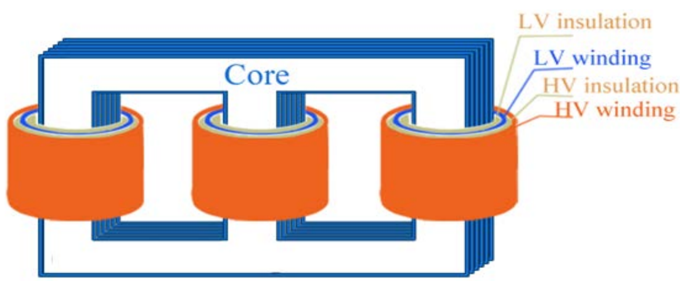


Fig. 2.14: Three phase core type transformer

Shell Type Three Phase Transformer

Shell type three phase transformer core is constructed in shell structure enclosing the windings. Windings are surrounded by the magnetic core material or yoke. Primary and secondary are electrically insulated from each other. Generally used for lower power ratings and can be physically larger compared to core type transformer.

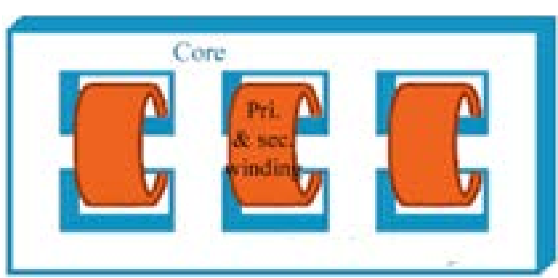


Fig. 2.15: Three phase shell type transformer

2.5.2 Types and Connections of Three Phase Transformers

Following are the different types of connection of three phase transformer:

a. Star-Star connection [Y-Y]

b. Star-Delta connection [Y-Δ]

c. Delta-Delta connection [Δ- Δ]

d. Delta-Star connection [Δ-Y]

a. Star-Star Connection [Y-Y]

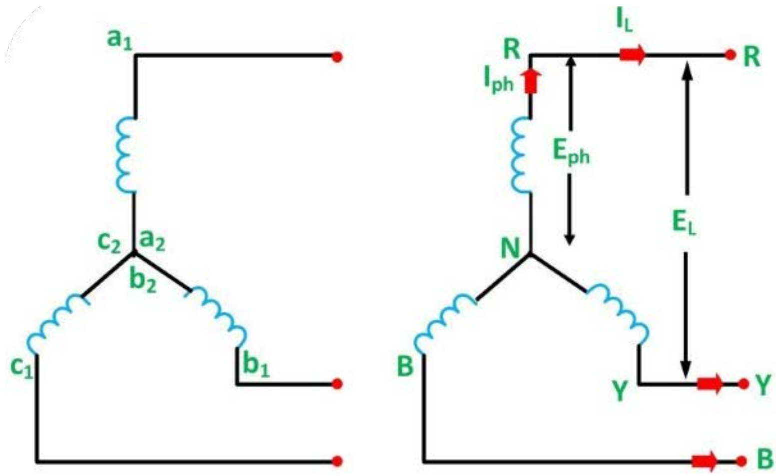


Fig. 2.16: Star-Star connection

i. Both sides of the transformers are star connected

ii. This type of transformer is most economical for small, high voltage transformers as the number of turns per phase and amount of insulation is minimum

iii. Phase coil is under pressure of 1/√3 times of system line voltage but line current and phase current is same

b. Star-Delta Connection [Y-Δ]

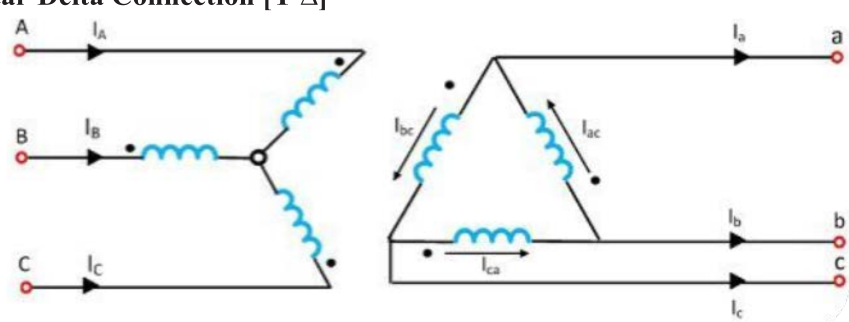


Fig. 2.17: Star-Delta connection

i. Primary side is star connected whereas secondary side is delta connected

ii. Most suitable for stepping down the voltage at the receiving end of a transmission line.

c. **Delta-Delta Connection [Δ- Δ]**

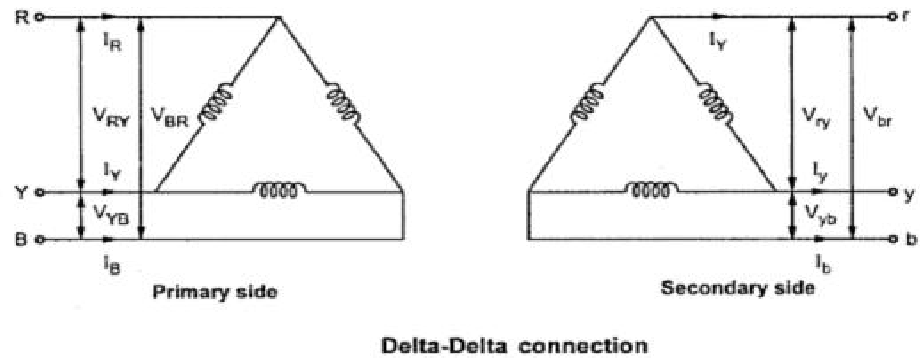


Fig. 2.18: Delta-Delta connection

i. Both sides are delta connected

ii. Economical for large , low voltage transformer in which the insulation problem is not serious as it increases the number of turns per phase and reduces necessary cross sectional area of the conductor

iii. Phase coil is under pressure of full supply line voltage but the phase current is 1/√3 times of system line current

d. **Delta-Star Connection [Δ-Y]**

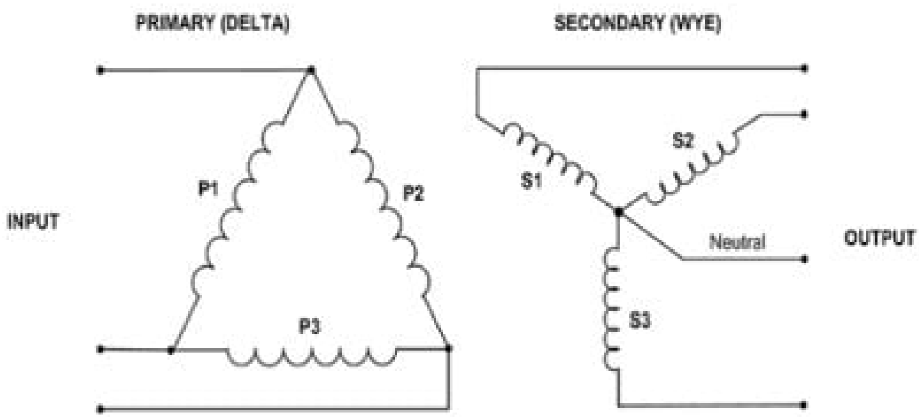


Fig. 2.19: Delta-Star connection

i. Primary side is delta connected whereas secondary side is star connected

ii. Most suitable for stepping up the voltage at the sending end of transmission line

iii. Also suitable for distribution transformers at the consumer end where 3 phase 4 wires system with earthed neutral is necessary to supply single as well as three phase loads

2.5.3 Differences Between Single Phase and Three Phases Transformer

Basis	Single phase transformer	Three phase transformer
Number of phases	One	Three
Primary windings	One	Three
Secondary windings	One	Three
Common applications	Residential, commercial, small scale industrial	Large scale industrial, commercial, power transmission and distribution
Power generation	Not typically used in large scale transmission system	Used in power transmission systems
Voltage waveform	Single sinusoidal waveform	Three sinusoidal waveforms with a phase difference of 120^0 degrees
Common uses	Local distribution networks, small scale power systems	Power plants, substations, transmission lines
Overall system size	Smaller in size	Larger in size

2.5.4 Single Unit Three Phase Transformer and Three Units of Single Phase Transformer

Basis	Single unit 3phase transformer	Three units of 1phase transformer
Construction	Single core with three windings	Separate cores and windings for each transformer
Size and Weight	Smaller and lighter	Larger and heavier
Installation	Fewer connections and wiring	More connections and wiring
Efficiency	Generally higher efficiency	Lower efficiency
Cost	Initially more expensive	Initially less expensive
Overall space requirement	Compact	Larger

Disadvantages of Three Units of Single Phase Transformer over Single Unit of Three Phase Transformer

a. For same amount of power, this system is more expensive than single unit of three phase transformer in long term

b. This system will be less efficient

c. This system occupy more space

d. More connections and wiring required

e. Assembling time is higher

f. Hard to installation

Advantages of Three Units of Single Phase Transformer over Tingle Unit of Three Phase Transformer

a. Three units of single phase transformers would be easier for transportation

b. Better reliability of supply

2.5.5 Different Parts of Power Transformers

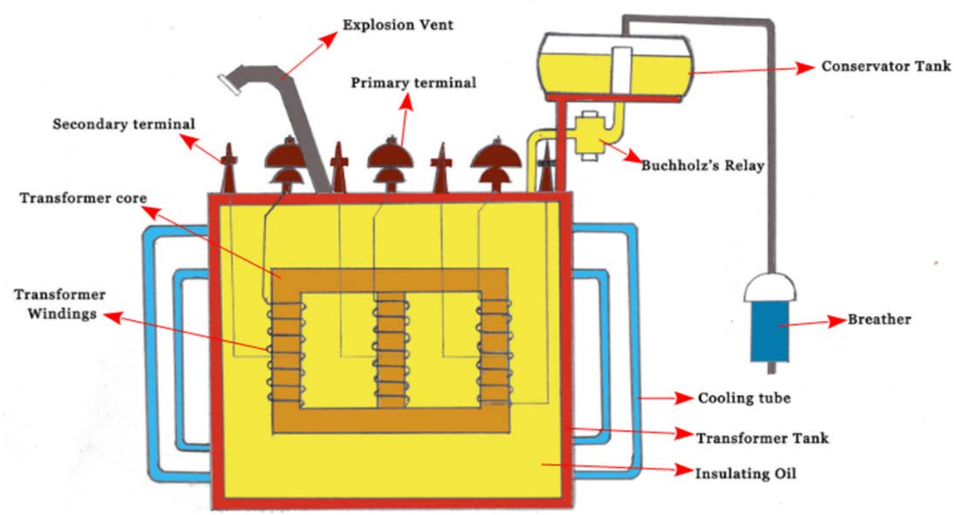


Fig. 2.20: Power transformer parts

Different parts of the power transformer are:

a. Transformer tank

b. Conservator tank

c. Breather

d. Buchholz relay

e. Explosion vent

f. Cooling tube

g. Bushing

h. Tap changer

a. **Transformer Tank**

Tank is used for the housing of core and windings and for mounting various accessories required for the operation of transformer and typically made up of steel or other durable materials.

Fig. 2.21: Transformer Tank

b. **Conservator Tank**

It is small cylindrical tank mounted on the top of the oil transformer and connected to the main tank by a small pipe. It serves as a reservoir for insulating oil. It allows for the expansion and contraction of the insulating oil due to temperature variation.

Fig. 2.22: ***Conservator tank***

c. **Breather**

It is a device through which all the movement of the air from the transformer takes place maintain the air inside it dry and free from moisture. As the transformer oil expands or contracts the breather ensure that dry air enters or exits the conservator tank, preventing moisture entering the transformer.

Fig. 2.23: Breather

d. **Buchholz Relay**

It is a protective device that give alarm when the oil level is low or any internal fault (such as transformer core insulation failure or short circuits) occurs and when detects abnormal oil flow of evolution of gases take place.

Fig. 2.24: Buchholz relay

e. Explosion Vent

It is a bent pipe with a glass cover at the end fitted on the top of the transformer tank. It provides protection against excessive pressure build up inside the transformer when sudden fault or short circuit. Hence it is a pressure relief device that opens up at a predetermined pressure allowing the release of gases and pressure buildup.

f. Cooling Tube

They are the bent pipe kept on the outside of the transformer tank which is used to cool the transformer. It helps to dissipate heat generated during transformer operation. They are often integrated with cooling fans or oil cooling system to enhance the cooling process.

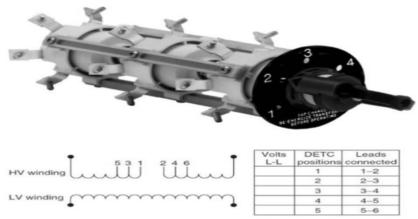
g. Bushing

An insulating device used for connecting external elements to internal windings of the transformer. It provides insulation and support for conductors and generally made up of porcelain, ceramic, glass etc. to withstand high voltage and provide insulation.

Fig. 2.25: Bushing

h. Tap Changer

It is used to adjust the turn ration of the transformer winding. It enables the control of the transformer output voltage compensating for the variations in the input voltage or load conditions.



Volts L-L	DETC positions	Leads connected
	1	1–2
	2	2–3
	3	3–4
	4	4–5
	5	5–6

Fig. 2.26: Tap changer

2.6 Parallel Operation of Transformers

The process of connecting the transformer with another one if its capacity is not enough to supply the power demanded by the load is known as parallel operation of transformer. The primary windings are connected to supply bus-bars and whereas secondary windings are connected to load bus-bars.

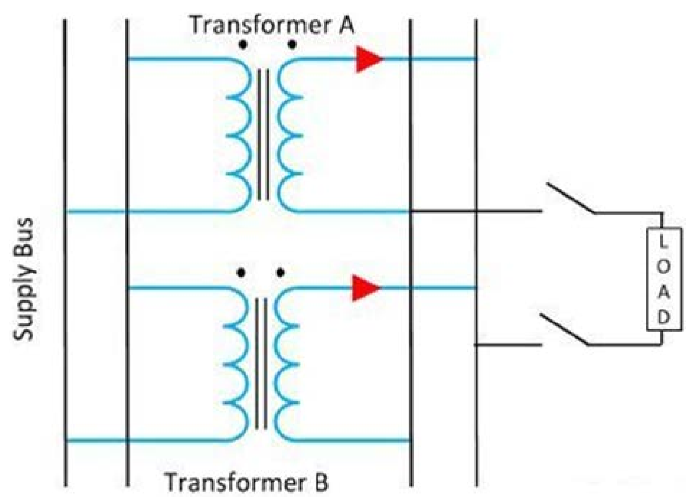


Fig. 2.27: Parallel connection of transformer

2.6.1 Necessary and Sufficient Conditions required for parallel operation of transformers

Necessary Conditions

a. Terminal voltage and frequency of both transformers must be same

b. Polarities of both transformers must be same

c. Transformation ratio must be same

Sufficient or Desirable Conditions

a. Rating of the transformers should be same

b. Impedance ratio should be same

Advantages of Parallel Operation of Transformer

a. If one transformer fails, the continuity of the supply can be maintained through other transformer

b. When load on the substation becomes more than the capacity of the existing transformers another transformer can be added in parallel

c. Any transformer can be taken out from the circuit for repair or routine maintenance without interrupting supply to the consumer

2.7 Auto Transformer

It is a transformer with one winding only which is common to both primary and secondary side. Hence it a one winding transformer. Primary and secondary windings are connected electrically as well as magnetically. Provides variable ac power supply with different tapping position. Such a transformer is economical where the transformation ratio is very close to unity

2.7.1 Working Principle of an Auto Transformer

Figure shows the connection of step-down autotransformer. The winding AB having N_1 turns in primary winding and winding BC having N_2 turns is the secondary winding. The power from primary is transferred to secondary conductively as well as inductively.

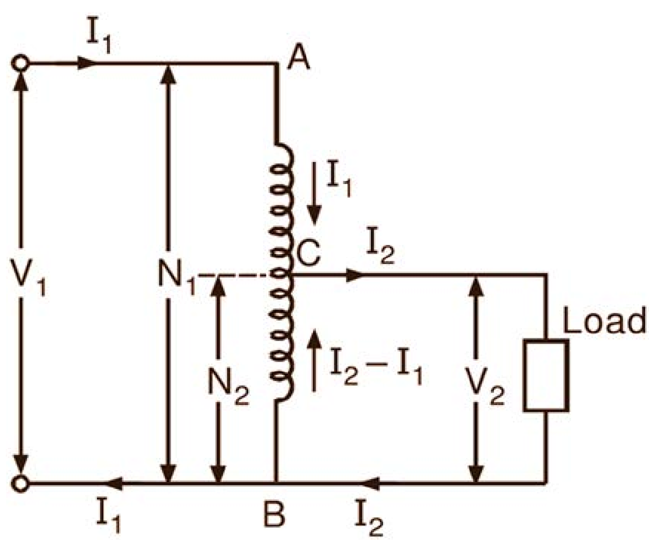


Fig. 2.28: Auto transformer

One single winding is share as primary winding as well as secondary winding. Input connected at fixed positions but on the other side we employ few taps to get variable output voltages. Variable turns ratio at secondary can be obtained by changing the tap position provided in the winding. By changing the tap position the number of turns in secondary winding can be adjusted thus different output voltage can be produced.

$\frac{V2}{V1} = \frac{N2}{N1}$, $V_2 = \frac{N2}{N1} \; x \; V_1$

2.7.2 Applications of an Auto Transformer

Advantages of auto transformer over two winding transformer

a. Requires less Copper than a two-winding transformer of similar rating

b. Auto transformer has smaller size than a two-winding transformer of the same rating

c. Most economical than two winding transformer when it is operating while the turn ratio is nearly equal to unity, Wauto=(1-K) x Wtw

d. Auto transformer has better voltage regulation than a two-winding transformer of the same rating as voltage drop in resistance and reactance on single winding is less.

e. Operates at a higher efficiency because of less ohmic loss and core loss due to single winding and small size

Disadvantages of Auto Transformer Over Two Winding Transformer

a. There is a direct connection between the primary and secondary. Therefore the output is no longer isolated from the input.

b. An autotransformer is not safe for stepping down a high voltage to a low voltage.

c. The short circuit current is much larger than the two-winding transformer of the same rating.

Applications

a. They are used for reducing the voltage supplied to a.c. motors during the starting period.

b. They are used in variable voltage power supply.

c. They are used to compensate for voltage drops in transmission and distribution lines.

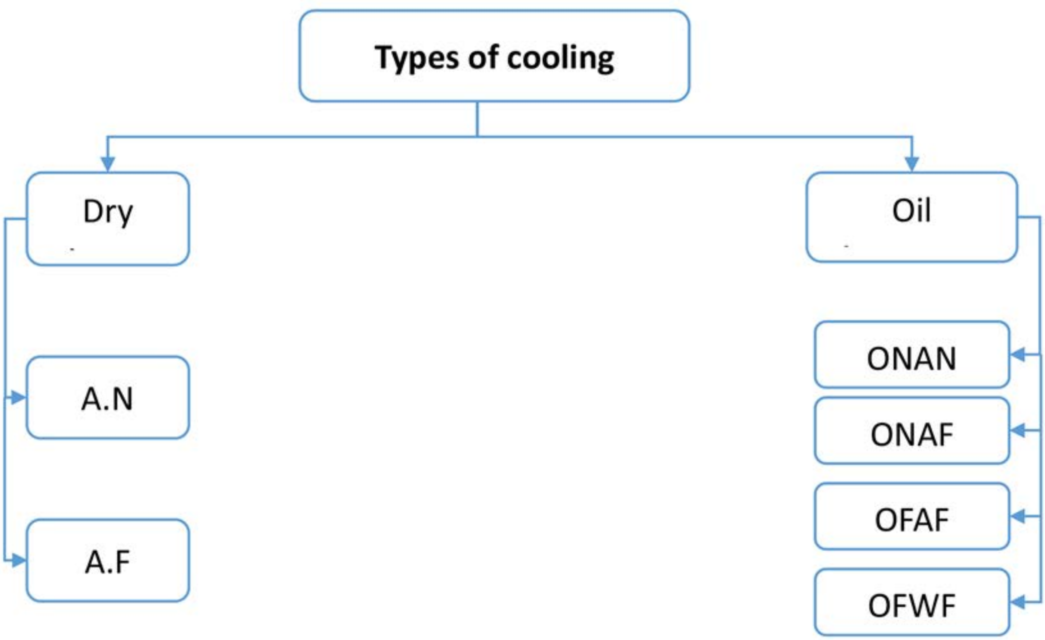
2.8 Cooling of Transformer

In all the electrical machines, the losses produce heat. That means cooling must be provided to keep the temperature low. In generators and motors, the rotating unit serves as a fan causing air to circulate and carry away the heat. However, a transformer has no rotating parts. Therefore, some other methods of cooling must be used to cool down the transformer. Heat is produced in a transformer by the iron losses in the core and I2R loss in the winding. To prevent undue temperature rise, this heat is removed by cooling.

While transferring from one circuit to another, some energy is lost within the core and winding. This lost energy must be dissipated in the form of heat. Losses in the transformer are of the order of 1% of its full load kW rating. But for the higher kVA rating, the magnitude of losses becomes higher. Greater the rating of the transformer, there will be more difficult to dissipate the heat.

2.8.1 Methods of Cooling of Transformers

Depending upon the size, type of application, there are different types of cooling method of transformer. Regarding the cooling method, the transformer is of two types: dry and oil-immersed transformer.



Dry type transformer

a. Air Natural cooling

b. Air Force cooling

a. Air Natural Cooling

Atmospheric air is used as cooling agent. This type of cooling method is used for small rating below 25kVA.

b. Air Force Cooling

The air is forced onto the tank surface to increase the rate of heat dissipation. The fans are switched on when the temperature of the winding increases above the permissible level.

Oil type Transformer

a. Oil Natural Air Natural cooling [ONAN]

b. Oil Natural Air Force cooling [ONAF]

c. Oil Forced Air Forced cooling [OFAF]

d. Oil Forced Water Forced cooling [OFWF]

a. Oil Natural Air Natural Cooling [ONAN]

In this cooling types both core and the winding are immersed in the insulating oil within the iron tank. Thus, the heat produced in core and windings is passed onto the oil by conduction. The heated oil transfers its heat to the tank surface which dissipates it to the surroundings.

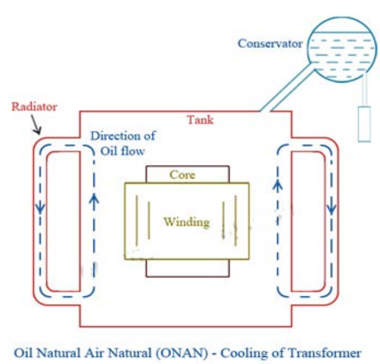


Fig. 2.29: ONAN

b. Oil Natural Air Force Cooling [ONAF]

In this type, both the core and windings are immersed in the insulating oil within iron tank. The cooling is improved by forced air over cooling surface. Air is forced over the external surface of tank such as tubes, radiators by means of fans mounted external to the transformer. Medium to large capacity transformers are cooled by this method.

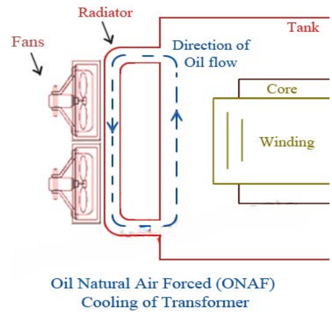


Fig. 2.30: ONFA

c. Oil Forced Air Forced Cooling [OFAF]

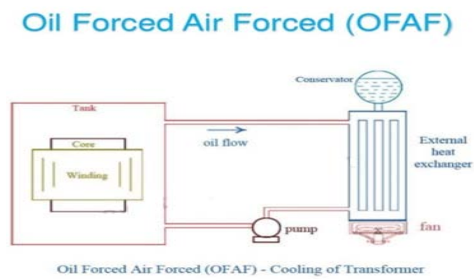


Fig. 2.31: OFAF

In this method, the oil is cooled by air blast from fans in the external heat exchanger. It is not necessary that the oil pump and fans may be used at all times.

d. Oil Forced Water Forced Cooling [OFWF]

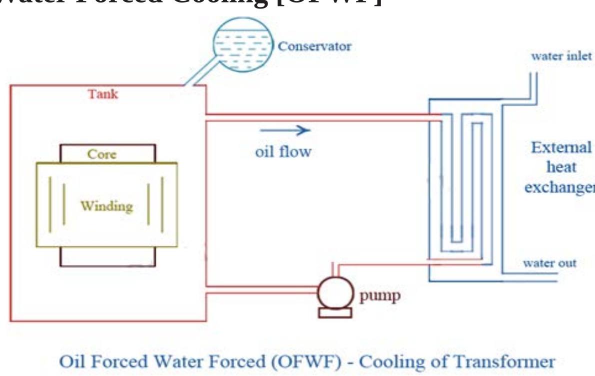


Fig. 2.32: OFWF

In this method, the heated oil is pumped out from the main tank to the radiator where the oil is cooled by the water passing through the tubes. Pressure of the oil is kept higher than that of water in this cooling method.

Exercise

Choose the correct answer from the given alternatives.

1. Auto transformer is most economical when the value of K is..........

   a. Equal to 1 b. Very less than 1 c. Close to unity d. Any value

2. In a transformer operation which quantity remains fixed?

   a. Voltage b. Current c. Frequency d. All of above

3. The oil used in transformer serve as.........

   a. Coolant b. Insulator c. Both a and b d. None of the above

4. The test is done to find copper loss in transformer is............

   a. Short circuit test b. Open circuit test

   c. Both a and b d. None of the above

5. Which type of core has good mechanical support?

   a. Shell type b. Core type c. Both a and b d. All of above

6. Constant loss in transformer is

   a. Hysteresis loss b. Eddy current loss c. Iron loss d. Copper loss

7. For isolation transformer the value of K equals to..........

   a. Greater than 1 b. Less than 1 c. Unity d. All of the above

8. The test is done to find iron loss in transformer is...........

   a. Short circuit test b. Open circuit test

   c. Both a and b d. None of the above

9. The test is done to find copper loss in transformer is...........

   a. Short circuit test b. Open circuit test

   c. Both a and b d. None of the above

10. The function of buchholz relay in transformer is...........

    a. To absorb moisture b. To provide connection

    c. To cool down d. To give an alarm signal

Write short answer to the following questions.

1. Why is transformer rated in kVA? What are the losses in transformer? Draw equivalent circuit of transformer in loaded operation.
2. Explain power transformer in detail.
3. What are the conditions required for the parallel operation of the transformers? Write down the advantages of it.
4. When is short circuit test of transformer done? Explain auto transformer along with its advantages.
5. What are the types of transformer on the basis of use? Differentiate between core type and shell type transformer.

Write long answer to the following questions.

1. Explain working principle of transformer. Describe Open circuit test in transformer.
2. Derive emf equation of transformer. A single phase, 50Hz transformer has 80 turns on the primary winding and 280 in the secondary winding. The net cross-sectional area of the core can be taken 200cm2. The voltage applied across the primary winding is 240 volts. Calculate maximum flux density and induced emf in secondary winding.

Numerical

1. A step up transformer having 400/1100V of primary no of turns is 200. Calculate secondary no of turns? Flux density = 80wb/m^2.
2. A single phase 2200/250V, 50Hz transformer has net core area of 36cm^2 and maximum flux density 6 wb/m^2. Calculate the no of turns of primary and secondary.
3. A single phase, 50Hz transformer has 80 turns on the primary winding and 280 in the secondary winding. The voltage applied across the primary winding is 240 volts. Calculate:
    a. The maximum flux density in the core
    b. Induced emf in the secondary winding
    c. The net cross-sectional area of the core can be taken 200cm^2.
4. An ideal 25kVA transformer has 500 turns on the primary winding and 40 turns in secondary winding. The primary is connected to 3000V, 50 Hz supply. Calculate
    a. Primary and secondary current
    b. Secondary emf

c. Maximum core flux

Project Works

1. Pictures and videos presentation of different types of transformers (core type and shell type)
2. Study of operation of transformer by animated videos.
3. Disassembled of small 12V transformer and observed the different parts such as bobbins, windings, cores, laminations etc.
4. Polarity test of the transformer.
5. Group presentation of different parts of the power transformer

Unit 3 DC Machines

3.1 Introduction of DC Machines

3.1.1 Definition of DC Machines

DC machines are the rotating electrical machines which can be used as either motors or generators. DC machine is a device which converts mechanical energy into electrical energy and vice-versa. When the device acts as a generator (or dynamo), mechanical energy is converted into electrical energy. On the other hand, when the device acts as the motor, the electrical energy is converted into mechanical energy. The process of the inter conversion is reversible. Therefore, this type of machine can work either as” motor” or “generator”.

Almost, generator and motor are very much similar to each other in essential parts and construction but slight modification is done for their operation. DC generators convert mechanical energy given to it into electrical energy whereas DC motors convert the electrical energy given to it into mechanical energy.

3.1.2 Types of DC Machines

There are two types of DC machines: a. DC generator and b. DC motor

DC Generator

DC generators are the machine that convert mechanical energy into electrical energy. They works on the principle of Faraday’s law of electromagnetic induction. When the armature is rotated by the means of external source within in the magnetic field produced by field winding them emf is induced in the armature. They are also known as dynamo.

DC Motor

DC motors are the machine that convert electrical energy into the rotational or mechanical energy. Torque or rotational motion is produced by the interaction between the magnetic field created by the field pole and the current carrying armature winding.

3.2 Constructional Details of DC Machine

3.2.1 Construction of DC Machines

The main parts of DC machines are as follows:

a. **Yoke**

b. **Field Poles**

c. **Field Winding**

d. **Armature**

e. **Commutator**

f. **Armature Winding**

g. **Carbon Brush**

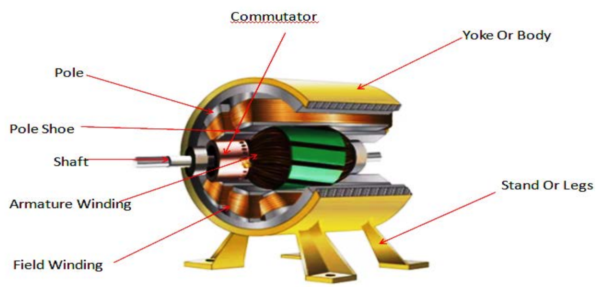


Fig. 3.1: Parts of DC Machine

a. **Yoke**

Yoke It is the outermost frame of the machine. It provides mechanical support for the field pole and acts a protecting cover for the whole machine. It also carries the magnetic flux produced by the field poles. In small machines, cast iron yokes are used because of cheapness. In large machine, steel yokes are used because of its high permeability property.

b. **Field Poles**

They are the iron core projected from yoke. The upper part of the pole, which is connected to the yoke, is known as pole –core. The lower and wider part is known as pole-shoe. The field poles are usually formed of laminations (thin sheet of steel) and are bolted to the frame or yoke. The pole shoe serves two purposes:

i. It spreads out the magnetic flux in the air gap and also being larger cross section reduces the reluctance of the magnetic path.

ii. It supports the field winding.

c. **Field Winding**

Field winding is the copper wire or strip wound on the field pole. The windings are insulated from the pole core and each turns of windings are also insulated from each other to protect from turn to turn short circuit. When DC current is passed through these coils, they will magnetize the pole core and produce magnetic field in the central space of the machine.

d. **Armature**

Armature is the rotating part of the machine. It is found in cylindrical or drum shape. It consists of armature core, commutator, armature winding and shaft and made up of laminated silicon steel sheet insulated with varnish. Bearing holds the shaft on the central empty space of the machine in such way that there is a small air gap few mm between armature and the pole- shoes. It is rotated in uniform magnetic field. It consists of coils of insulated wires wound around a core and so arranged that electric currents are induced in these wires when the armature is rotated in a magnetic field.

e. **Commutator**

Commutator is a form of rotating switch placed between the armature and the external circuit and so arranged that it will reverse the connections to the external circuit at the instant of each reversal of current in the armature coil. It is made of number of copper segments insulated from each other. It is also known as mechanical rectifier as it coverts ac into dc.

Purpose of Commutator

a. It provides the electrical connections between the rotating armature coils and the stationary external circuit.

b. Converts ac into dc along with the carbon brush.

c. It keeps the rotor or armature mmf stationary in space.

f. **Armature Winding**

Armature windings is placed in armature core. An arrangement of conductors to develop desired emf by relative motion in a magnetic field. Conductors may be connected in series and parallel combinations depending upon the current and voltage rating of the machine. Enamel insulated copper wire wound on the slots of the armature core.

g. Carbon Brush

It is rectangular in shape which rest on the commutator. Main function of the carbon brush is to collect the current from the commutator and supply it to the external load circuit. Brushes are held under pressure over the commutator by the combination of brush holders and springs whose tension may be adjusted.

3.3 DC Generators

3.3.1 Basic Operating Principle of DC Machine as a Generator

DC machine converts mechanical energy into electrical energy when it is operated as generator. Generator is based on principle of Faraday's law of electromagnetic induction which state that whenever conductor cuts the magnetic flux emf is induced. Which cause the flow of current if the circuit is closed. Direction of induced current is given by Fleming's right hand rule. When the armature of dc generator is rotated by prime mover (external force) and the field windings are excited then according to Faraday's law of EMI, emf is induced in armature conductor. Thus induced emf is collected through commutator and carbon brush arrangement.

3.3.2 Emf Equation of a DC Generator

Let,

Ø= flux per pole in weber

Z= total number of conductors in armature\

A= Number of parallel paths

P= Number of poles

N= Speed of armature in rpm

E_g= Generated emf

Since, Z conductors are arranged in A parallel paths, number of conductors per path = $\frac{Z}{A}$

Induced emf in one turns in one revolution is given by, $E=\frac{d\emptyset}{dt}$

Flux linkage in one revolution, $d\emptyset=P\emptyset$

Time taken in one revolution, $dt=\frac{60}{N}$

Now,

$E=\frac{P\emptyset}{\frac{60}{N}}=\frac{P\emptyset N}{60}$

Total emf induced $E_g=\frac{P\emptyset N}{60}x\frac{Z}{A}$

$E_g=\frac{Z\emptyset N}{60}x\frac{P}{A}\ volts -------------(3.1)$

$Where, A = P\ for\ lap\ winding\ and$

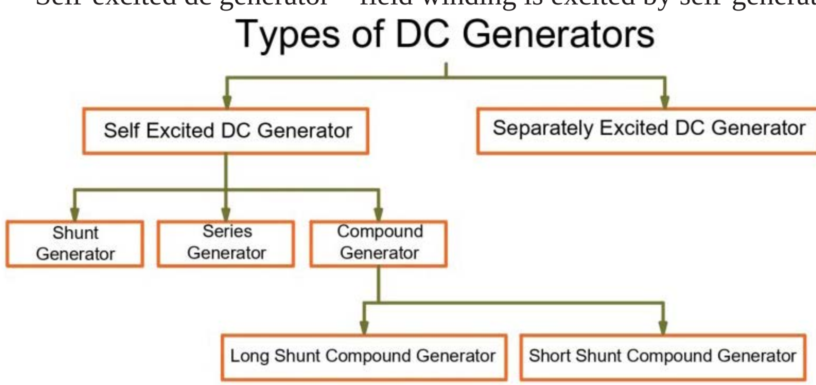
$A\ = 2\ for\ wave\ winding$

3.3.3 Types of DC Generator

On the basis of field excitation there are two types:

a. Separately excited dc generator – field winding is excited by external dc source

b. Self-excited dc generator – field winding is excited by self-generated emf



a. Separately Excited DC Generator

In this type of dc generator field winding is excited by external dc source. DC source maybe battery, rectifier circuit etc. There is no electrical connection between field winding and armature winding.

From figure 3.2,

$I_a=I_l$

Applying KVL, $E_g - I_aR_a - I_LR_L = 0$

or, $E_g - I_aR_a - V =$

or, $V = E_g - I_aR_a$

Power generated= E_gI_a

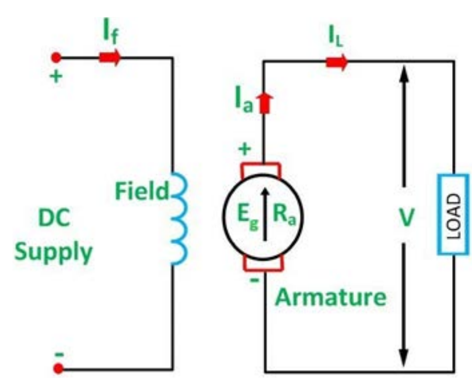


Fig. 3.2: Separately excited DC generator

Power delivered to load or output power,

$= E_g I_a - I^2_a R_a = VI_L = VI_a$

b. Self-Excited DC Generator

i. DC Series Generator

In this types of generator series field winding is connected in series with the armature winding. Thus field winding current equals to armature winding current.

From figure 3.3,

$I_a = I_{se} = I_L$

Applying KVL,

$E_g - I_a R_a - I_a R_{se} - I_L R_L = 0$

or, $E_g - I_a(R_a + R_{se}) - V = 0$

or, $V = E_g - I_a(R_a + R_{se})$

Power generated= $E_g I_a$

Power delivered to load or output power,

$= E_g I_a - I^2_a R_a(R_a + R_{se}) = VI_L = VI_a$

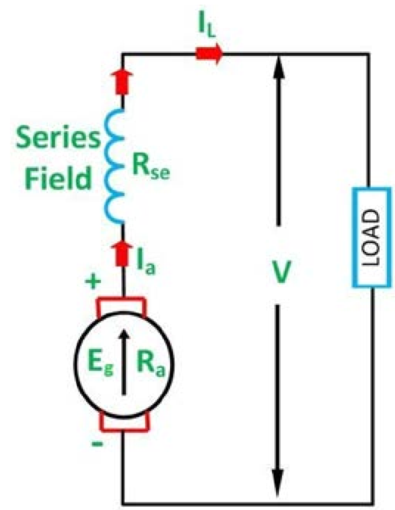


Fig. 3.3: DC series generator

Series dc generator shows rising voltage characteristics as the load increases field current also increase $E_g \propto \emptyset$ *and* $\emptyset \propto If$. Limited voltage regulation capabilities that is output voltage decreases significantly under heavy load conditions.

ii. DC shunt Generator

In this type of generator, shunt field wi
winding. Only fraction of armature cu

From figure 3.4,

$I_a = I_{sh} + I_L$

$I_{sh} = \frac{V}{R_{sh}}$

Applying KVL,

$E_g - I_a R_a - I_L R_L = 0$

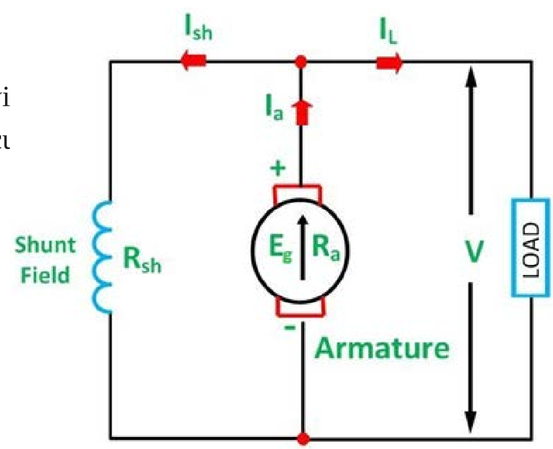


Fig. 3.4: DC shunt generator

or, $E_g - I_a R_a - V = 0$

or, $V = E_g - I_a R_a$

Power generated= $E_g I_a$

Power delivered to load or output power,

$= E_g I_a - I_a^2 R_a = V I_L = V I_a$

DC shunt generator offers better voltage regulation as compare to series dc generator. In DC shunt generator there is less voltage variation with low load to high load. By adjusting field current through shunt winding output voltage can be controlled.

iii. DC compound Generator

This type of generator has both series filed winding and shunt field winding. Hence it has combined features of series and shunt dc generators. There are two types as the shunt field connection nature with the series and armature windings

a. Long Shunt Compound DC Generator

In this type shunt field winding is parallel with the both series field and armature winding.

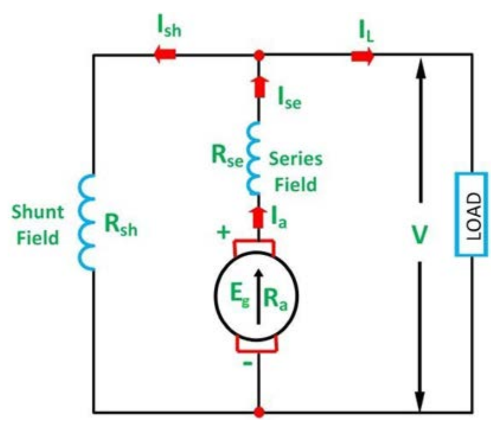


Fig. 3.5: Long shunt compound DC generator

From figure 3.5,

Series field current, $I_a = I_{se} = I_L + I_{sh}$

Shunt field current, $I_{sh} = \frac{V}{R_{sh}}$

Applying KVL, $E_g - I_a R_a - I_a R_{se} - I_L R_L = 0$

or, $E_g - I_a(R_a + R_{se}) - V = 0$

or, $V = E_g - I_a(R_a + R_{se})$

Power generated= $E_g I_a$

Power delivered to load or output power,

$= E_g I_a - I^2_a R_a(R_a + R_{se}) = VI_L = VI_a$

b. Short Shunt Compound Generator

In this type, shunt field winding is parallel with the armature winding only.

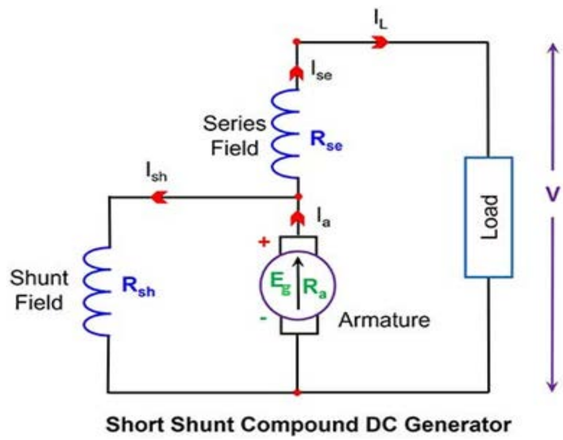


Fig. 3.6: Short shunt compound DC generator

From figure 3.6, $I_a = I_{sh} + I_L(I_{se})$

Series field current $I_{se} = I_L$

Shunt field current, $I_{sh} = \frac{V + I_a R_{se}}{R_{sh}}$

Applying KVL,

$E_g - I_a R_a - I_{se} R_{se} - I_L R_L = 0$

or, $E_g - I_a(R_a - I_{se} R_{se}) - V = 0$

or, $V = E_g - I_a R_a - I_{se} R_{se}$

Power generated = $E_g I_a$

Power delivered to load or output power,

$= E_g I_a - I^2_a R_a - I^2_{se} R_{se} = VI_L = VI_a$

3.3.4 Basic Concept of Voltage Build up in DC Generator

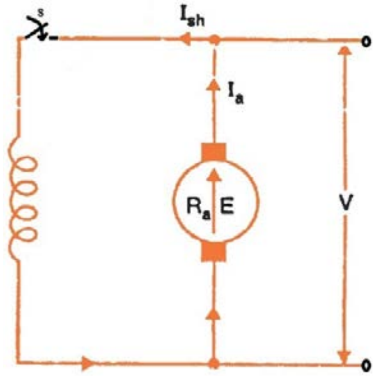


Fig. 3.7: DC shunt generator

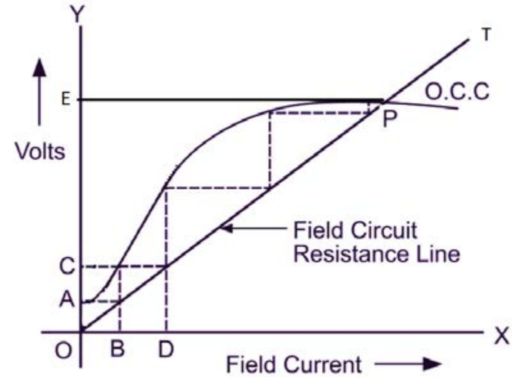


Fig. 3.8: Voltage build up curve

Figure shows the open circuit characteristics (O.C.C) or no load characteristics of a DC shunt generator. Straight line OT represents the shunt field resistance. When the armature rotates at a constant speed of, small emf OA is induced in the armature due to presence of the residual flux and that of flux cut by the armature conductors.

When switch S is closed, current OB flows through the field winding, current increases the magnetic flux produced by the windings resulting increased in emf generated OC in the armature. Consequently, field current increases to OD. This process continues up to the point P where OCC intersects the shunt field resistance line OT. Thus OE represents the maximum voltage build up in the generator. There is no further voltage build up after point T due to the saturation of the field i.e. no further addition flux is produced by the field winding.

3.3.5 Applications of Different Types of DC Generator

Series DC Generator

1. Supplying field excitation current in DC locomotives for regenerative breaking
2. Used as a booster in distribution networks
3. Arc lighting

Shunt DC Generator

1. Battery charging for electric vehicles and backup system
2. Use for giving excitation to the alternators
3. Laboratory and testing equipment

Comound DC Generator

1. Lighting and heavy power supply
2. Arc welding
3. Electric propulsion system for ships and submarines

3.4 DC Motor

3.4.1 Basic Operating Principle of a DC Machine as Motor

Motor converts electrical energy into mechanical power. DC motor is based on fundamental principle, when a current carrying conductor is placed in a magnetic field it experiences a mechanical force. This force generate the motion in the motor.

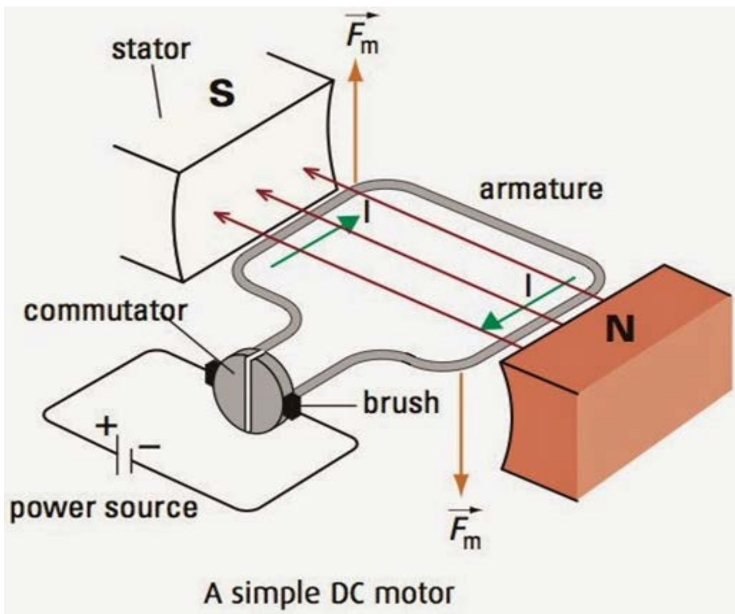


Fig. 3.9: A simple DC motor

Interaction between the magnetic field produced by the stator and the current flowing through the armature windings results in a force known as Lorentz force i.e. F=BIL newton. The force exerted on the conductor can be determined using Fleming's left hand rule. This force causes a torque that helps to rotate motor.

Commutator in dc motor serves the same purpose as it does in a generator. Facilitates reversal of current in each conductor as it transitions from one pole to another contributing the development of a continuous and unidirectional torque. Motor torque depends on strength of magnetic field, armature current.

3.4.2 Torque Equation and back emf of a DC Motor

Let, N=speed of armature in RPM

r= radius of armature coil

T_a= torque developed

When the current carrying conductor is placed in a magnetic field, a force is exerted on the conductor. Work done by this force in one complete rotation= F x $2\pi r = (F\ x\ r)2\pi = Ta\ x 2\pi$

The time required for N revolution= 60 sec

Time required for 1 revolution = 60/N sec

Power developed by the armature is equal to the rate of doing work, $P_a = \frac{work}{time}$

$$P_a = \frac{T_a x 2\pi}{\frac{60}{N}}$$

$$P_a = \frac{2\pi N T_a}{60} - - - - - - - - - (3.2)$$

Emf in induced in rotating armature conductor as it cut flux and called back emf which is given by, $E_b = \frac{Z\emptyset N}{60} x \frac{P}{A} - - - - - - - - - - (3.3)$

The power developed by armature, $P_a = E_b$ x $I_a - - - - - - - - - - (3.4)$

Now, from 3.2, 3.3, and 3.4, we get, $\frac{2\pi N T_a}{60} = \frac{Z\emptyset N}{60} x \frac{P}{A} x Ia$

$$T_a = \frac{Z\emptyset I_a}{2\pi} x \frac{P}{A}\ N - m - - - - - - - - - - - - - - - (3.5)$$

This is the required torque equation of DC motor. Since Z, P and A are constant for particular motor so torque is directly proportional to the product of magnetic flux and armature current, i.e.

$$T_a \propto \emptyset I_a - - - - - - - - - - - - (3.6)$$

Back Emf

When the motor rotates, the armature conductors cuts the magnetic flux produced by the field poles. Hence, according to Faraday's law of electromagnetic induction, emf induced across the armature conductor. Thus induced emf is called back emf or counter emf. The direction of this emf is opposite to the applied voltage "*V*". It is denoted by "E_b".

Significance of Back emf

a. Back emf protects the armature from damage.

We know, $I_a = \frac{V - E_b}{R_a}$, then if there is no emf , motor will draw very high current which may damage motor permanently.

b. Back emf acts as energy converting agent that means without it energy conversion is not possible.

c. Back emf helps to produce required amount of torque according to change in load

3.4.3 Types of DC Motor

Based on excitation

a. Separately excited dc motor

b. Self-excited dc motor

  i. Series dc motor

  ii. Shunt dc motor

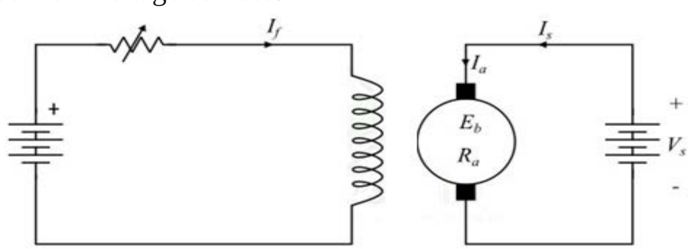
  iii. Compound dc motor

a. Long shunt compound dc motor

b. Short shunt compound dc motor

a. Separately Excited DC Motor

In this type of dc motor field winding and armature winding are powered by separate and independent voltage sources.



Separately Excited DC Motor

Fig. 3.10: Separately excited DC motor

From figure 3.10,

$$I_a = I_s = I_l = I$$

Applying KVL,

$$V - I_aR_a - E_b = 0E_b = V - I_aR_a$$

b. Self Mxcited DC Motor

i. DC Series Motor

In this type of motor field winding is connected in series with armature winding.To provide low resistance field winding has few number of turns of thick wire. Thus allow required current for the motor.

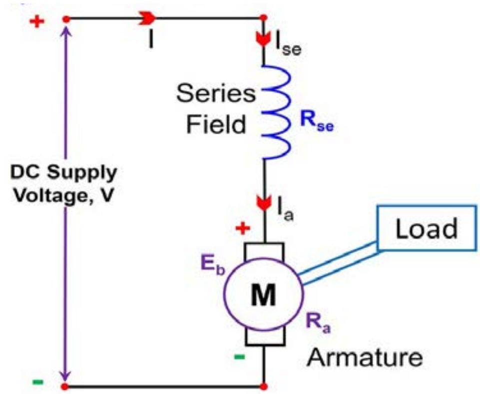


Fig. 3.11: DC series motor

From figure 3.11,

$$I_a = I_s = I_L = I_f = I$$

Applying KVL,

$$V - I_a R_a - I_a R_{se} - E_b = 0 \; E_b = V - I_a (R_a + R_{se})$$

ii. DC Shunt Motor

In this type of dc motor field winding is connected in parallel with the armature winding. Field winding has large number of turns with fine wire. Thus provide large resistance. Therefore field current is much less than armature current.

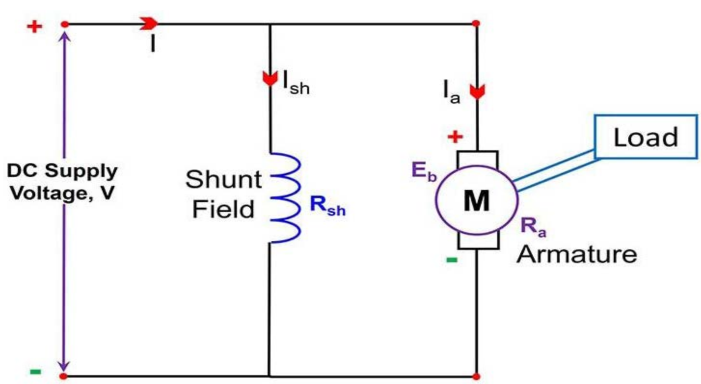


Fig. 3.12: DC shunt motor

From figure 3.12,

$$I_a + I_{sh} = I_L = I_s I_{sh} = \frac{V}{R_{sh}}$$

Applying KVL

$$V - I_a R_a - E_b = 0$$
$$E_b = V - I_a R_a$$

iii. Compound DC Motor

a. Long shunt dc Compound Motor

In this type of motor the shunt field is connected parallel with armature and series field winding both.

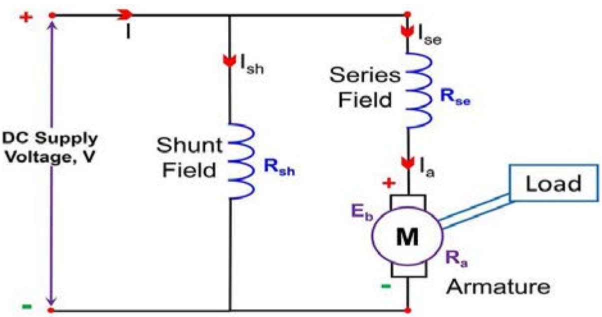


Fig. 3.13: Long shunt compound DC motor

From figure 3.13,

$I_{sh} = \frac{V}{R_{sh}}$, $I_a + I_{sh} = I_L$ i.e. $I_a = I_L - I_{sh}$ $(I_{se} = I_a)$

Applying KVL,

$$V - I_a R_a - I_a R_{se} - E_b = 0 \; E_b = V - I_a (R_a + R_{se})$$

b. Short Shunt DC Mompound Motor

In this type of motor the shunt field winding is parallel with the armature winding only and series field winding is connected series with the source.

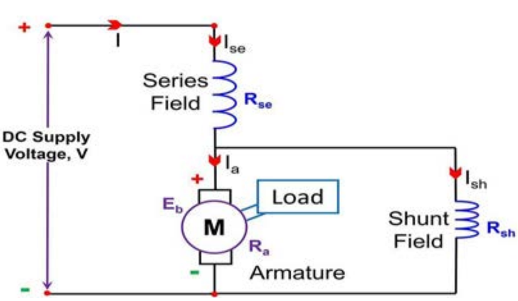


Fig. 3.14: Short shunt compound DC motor

From figure 3.14,

$I_a = I_L - I_{sh}$ $(I_L = I_{se})$ $I_{sh} = \frac{V - I_L R_{se}}{R_{sh}}$

Applying KVL,

$V - I_a R_a - I_{se} R_{se} - E_b = 0$ $E_b = V - I_a R_a - I_{se} R_{se}$

3.4.4 DC Motor Starter and it Necessity

For motor under normal operating conditions, the voltage equation is given as $E_b = V - I_a R_a$

The motor armature current is given by $I_a = \frac{V - E_b}{R_a}$

At N=0 (i.e. at rest condition) E_b=0($E_b \propto N$) $I_a = \frac{V}{R_a}$

If full voltage is applied, heavy armature current draws due to relatively small Ra. Hence following effects can be seen.

a. blow out the fuses

b. damage the commutator, brushes and even armature winding

c. produces large voltage drops in the supply voltage line

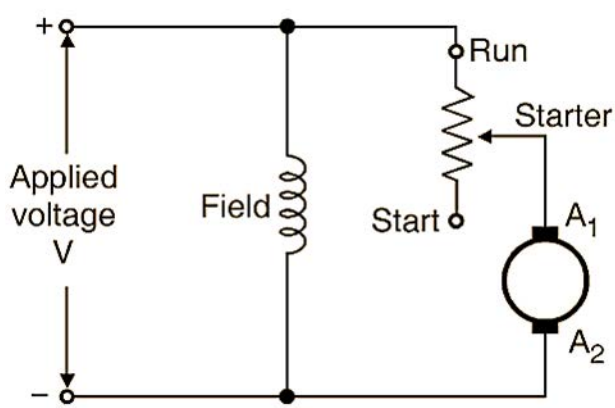


Fig. 3.15: DC motor starter

Hence the motor starter is used to reduce that starting current to protect the motor from several possible damages. A variable resistance, also known as starting resistance or starter is connected in series with the armature to prevent starting heavy current.

i.e. at starting $I_a = \frac{V - 0}{R_a + Rv}$

Hence armature current is reduced by adding variable resistance. As motor accelerates, back emf induced and Ia decreases i.e. $I_a = \frac{V-E_{b1}}{R_a+Rv}$. When motor gains the normal speed entire external resistance is removed from the circuit.

3.4.5 Speed Control of DC Motor

The magnitude of back emf developed by the armature is given by, $E_b = \frac{Z\emptyset N}{60} x \frac{P}{A}$

Or, $N = \frac{E_b x 60 x A}{Z x P x \emptyset}$

So,

$N \propto \frac{E_b}{\emptyset}$, since A, Z and P are constant for particular motor.

But, $E_b = V - I_a R_a$

$\therefore N \propto \frac{V - I_a R_a}{\emptyset}$

From the above expression we can observe that the factors that control the speed of dc motor are:

a. flux per pole ($\emptyset$)

b. armature resistance (R_a)

c. applied voltage (V)

Speed Control Methods of DC Shunt Motor

a. Flux control method

b. Armature control method

a. Flux Control Method

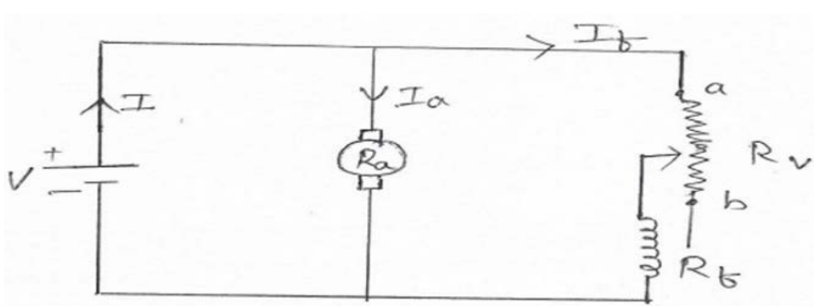


Fig. 3.16: Flux control method

We know the speed is inversely proportional to the flux per pole i.e. $N \propto \frac{1}{\emptyset}$. So varying flux, speed can be varied. To achieve this variable resistance R_v is added in series with the field winding as shown in figure. Then the field current I_f is given by $I_f = \frac{V}{R_f + R_v}$. From this expression we can see that I_f decreases as the R_v is added thus produced flux per pole also decreases. Hence from the relation ($N \propto \frac{1}{\emptyset}$), as the flux per pole decreases, speed of the motor increases. Thus by using this method speed can be control above the rated speed of the motor.

b. Armature Control Method

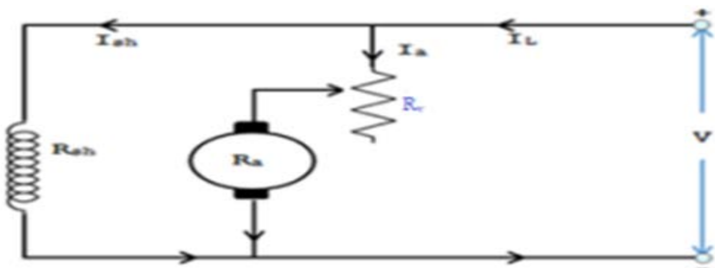


Fig. 3.17: Armature control method

In this method, variable resistance R_v is connected series with the armature. Before connecting R_v back emf E_b is given by, E_b=V- $I_a R_a$. When R_v is connected then back emf E_b is given by E_b=V- $I_a(R_a+R_v)$. As a result E_b decreases as $I_a(R_a+R_v)$ drop increases after connecting variable resistance R_v. Since the speed of motor is directly proportional to the back emf i.e. $N \propto E_b$, hence speed of the motor decreases. Therefore this method is suitable for controlling speed below normal rated speed. Highest speed obtainable is equal to normal rated speed when value of variable resistance R_v=0.

Speed Control Methods of DC Series Motor

a. Flux control method

   i. Field diverter method

   ii. Armature diverter method

   iii. Tapped field control method

i. Field Control Method

In this method, variable resistance R_v is connected in parallel to the series field winding. By adjusting Rv current flowing through field winding is controlled. Thus current can be reduced flowing through R_{se} as shown in figure. As a result flux also decreases. We know $N \propto \frac{1}{\emptyset}$, then speed increases. Therefore from this method speed above rated speed can be achieved.

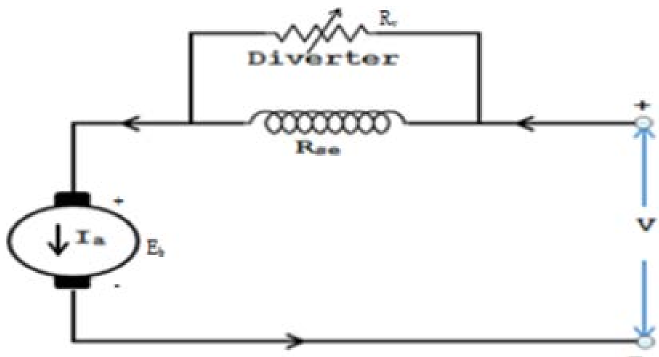


Fig. 3.18: Field diverter method

ii. Armature Diverter Method

In this method, variable resistance R_v is connected in parallel to the armature winding. Then some of the current can be diverted with the help of Rv as shown in figure. For constant load torque, if I_a decrease then flux per pole must increase to produce constant torque , $T_a \propto \emptyset I_a$. This results increase in main line current from the source. Thus speed deceases as flux increases. ($N \propto \frac{1}{\emptyset}$). This method is suitable to control the speed below the rated speed of the motor.

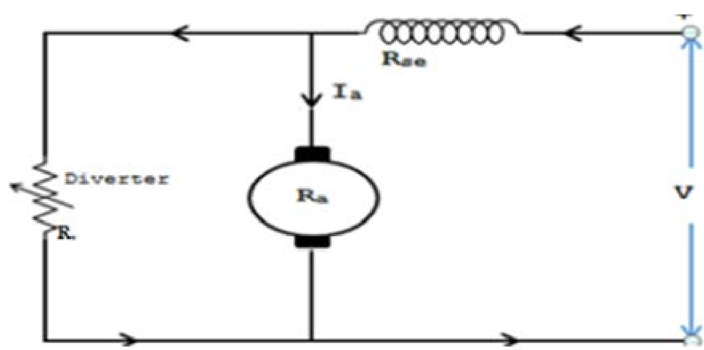


Fig. 3.19: Armature diverter method

iii. Tapped Field Control Method

In this method, series field winding is provided with number of tapping. Number of turns can be varied by the help of tap changer from point a to b as shown in figure. When the tapping at point a, motor runs at its minimum speed as field current will be maximum as $N \propto \frac{1}{\emptyset}$. From point a to b, field current gradually decreases consequently speed also increases gradually. At point b, field current will be minimum then speed will be maximum. In this way speed of the motor can be varied and suitable for controlling the speed of motor below rated speed.

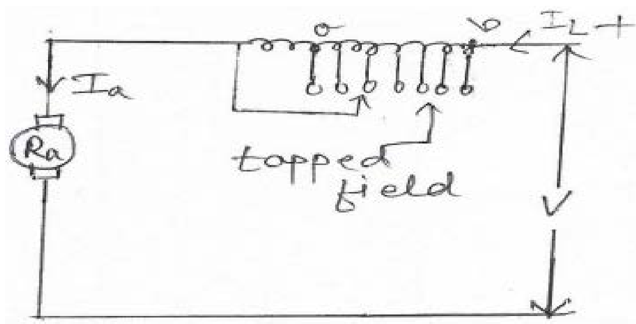


Fig. 3.20: Tapped field method

3.4.6 Application of different types of DC motor

DC Series motor

a. Trains
b. Electric vehicle
c. Mixers
d. Vacuum cleaner
e. Power tools etc.

DC Shunt motor

a. Pumps
b. HVAC system
c. Battery charge
d. Blowers etc.

DC Compound motor

a. Elevators and lift
b. Rolling mills
c. Spinning and weaving machine etc.

Exercise

Choose the correct answer from the given alternatives.

1. In DC generator, the emf induced in the armature is

   a. DC b. AC c. Both a and b d. None of the above

2. The role of commutators in DC machine is to convert

   a. AC into DC b. DC into AC c. AC to AC d. DC to DC

3. The core of DC machine is made up of

   a. Silicon steel b. Nickel steel c. Carbon steel d.Any of the above

4. The field winding of a DC machine are usually made up of

   a. Mica b. Carbon c. Copper d. Cast iron

5. The armature resistance of DC machine is generally of the range

   a. 0 ohm b. 50 ohm c. 25 ohm d. 0.5 ohm

6. The output power of a DC motor is given by

   a. EI_a b. E_bI c. $E_bI_a^2$ d. E_b^2Ia

7. Speed of DC motor can be controlled by varying

   a. Applied voltage b. Flux per pole

   c. Armature resistance d. All of the above

8. As a load increases, speed of the DC motor

   a. Remains constant b. Increase slightly

   c. Decrease slightly d. All of the above

9. DC motor output power is taken from the

   a. Armature b. Field c. Shaft d. Yoke

10. A thick wire is used in dc series motor field winding than that in dc shunt motor

    a. To create more flux b. To reduce resistance

    c. To carry heavy current d. Both b and c

Write short answer to the following questions.

1. Derive the emf equation of DC generator.
2. List the different types of DC generator and explain them.
3. Draw the circuit diagrams of self-excited DC motor and explain them.
4. Why is motor starter necessary? Explain it with mathematical expression.
5. What are the types of speed control of DC shunt motor and explain them.

Write long answer to the following questions.

1. Define back emf. What are the roles of back emf in dc motor? Explain the types of speed control methods of dc series motor.
2. Explain the constructional detail of dc machine. Explain the factors the affect the speed control of dc motor with expression.

Numerical

1. A 6 pole lap wound dc generator has 720 conductors, flux of 80 mwb/pole is driven at 1000 rpm. Find the generated emf.
2. A 4 pole dc generator has 51slots and each contains 20 conductors. Flux per pole is 7mWb and runs at 1500 rpm. Find the produced emf of the machine if its armature is wave wound.
3. A 4 pole dc machine has lap-connected armature having 60 slots and 8 conductors per slot. The flux per pole is 30 mWb. If the armature is rotated at 1000rpm, find the emf available across its armature terminals.

Practical Works

1. Study of constructional details of dc machine. (In lab by disassembling simple dc motor and identifying different types of parts)
2. Study the operation of DC generator. (Animated videos)
3. Study the operation of DC motor. (Animated videos)
4. Draw circuit diagram of different types of DC generator.
5. Draw circuit diagram of different types of DC motor.

Three Phase Induction Machine

Unit 4

4.1 Concept of Three Phase Induction Motor

Electrical machines are electromechanical energy conversion devices. Mechanical energy can be used perform work such as rotating a pump impeller, fan, blower, driving a compressor, lifting materials etc. Most of the industrial load are inductive especially 3-ph induction motors are widely used in industrial applications. An induction motor works on transforming action similar to the transformer. The power is transferred from stator to rotor winding through induction. The stator works as the primary while the rotor works as the secondary. Three phase induction motor is also called asynchronous motor.

The features of three phase induction motor are simple design, robust, low price, easy maintenance, high power to weight ratio. Three phase induction motor runs essentially as constant speed from no load to full load. Speed depends on the frequency of power source. Speed control of three phase induction motor is difficult and three phase induction motor are self-started.

4.2 Constructional Details of Induction Motor

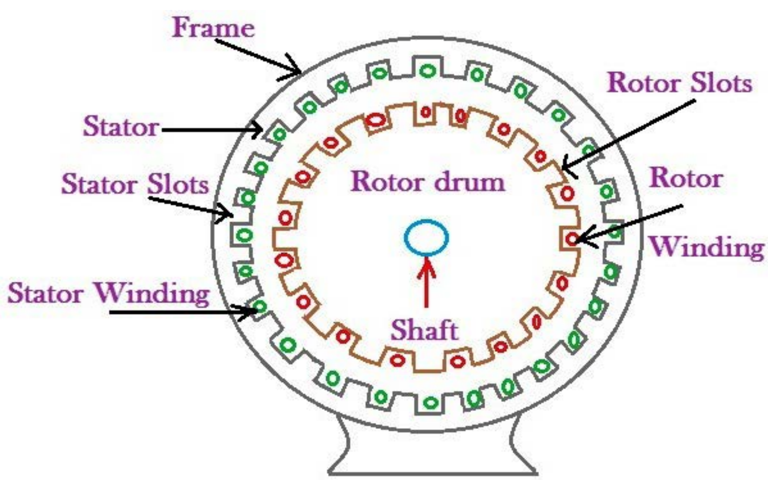


Fig. 4.1: Constructional details of three phase induction motor

The main parts of the three phase induction motor are stator and rotor. Stator is a stationary part where as rotor is a rotating part. Stator consists of frame or yoke, stator core and stator winding or field winding.

Yoke is the outer body of the motor that protects the inner part of the motor and supports stator core and stator winding. Stator core is made up of high grade silicon steel which carries the alternating magnetic field. To reduce eddy current loss, core is laminated and to reduce the hysteresis loss it is made up of silicon steel.

Stator winding has three phase winding and when these winding are excited, produces rotating magnetic flux. Three windings are uniformly distributed and spaced 120^0 electrically apart. (120^0 phase difference).

Rotor comprises a cylindrical laminated iron core with slots around the core carrying the rotor conductors. Generally it has cylindrical in shape with the central shaft. The shaft is supported by bearing at both ends so that rotor rotates freely keeping an air gap of about 1mm to 4mm between rotor and stator. There are two types of rotor.

a. Squirrel cage rotor

b. Phase wound rotor or slip ring rotor

a. Squirrel Cage Rotor

Generally this type of rotor has laminated cylindrical core with parallel slots. In that slots copper (Cu) or aluminum (Al) bar conductors are placed and short circuited at each end by Cu or Al rings called short circuited rings. Rotor winding is permanently short circuited, that is why it is not possible to add any external resistance.

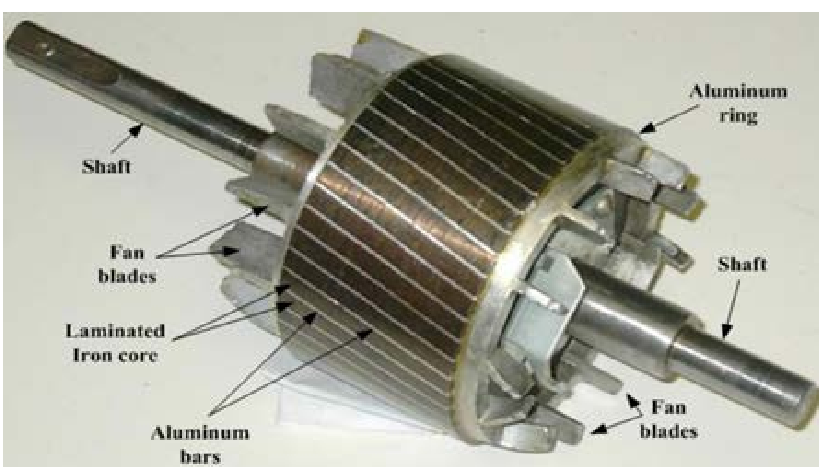


Fig. 4.2: Squirrel cage rotor

b. Phase Wound Rotor or Slip Ring Rotor

This type of rotor consists of a laminated core having open slots at the outer periphery and carries a 3 phase insulated winding. Rotor is wound for the same number of poles as that of stator. Three finish terminals are connected together forming a star point and the three star terminals are connected to three slip rings fixed on the shaft.

Fig. 4.3: Slip ring rotor

4.2.1 Differences Between Squirrel Cage and Slip Ring Three Phase Induction Motor

Phase Wound or Slip ring rotor	Squirrel cage rotor
1. Rotor consists of three phase winding similar to the stator.	1. Rotor consists of conductor bars which are shorted at the ends with the help of end rings.
2. External resistance can be added.	2. External resistance cannot be added.
3. Speed control is possible.	3. Speed control is possible from stator side.
4. Slip rings and brushes are present.	4. Slip rings and brushes are not present.
5. Complicated construction and costly.	5. Robust construction and cheap.
6. Maintenance cost is high.	6. Low maintenance cost.
7. High starting torque can be obtained.	7. Has low starting torque.

4.3 Three Phase Induction Machine as Motor

4.3.1 Concept of Synchronous Speed, Rotating Magnetic Field, Rotor Speed, Slip

Synchronous Speed

Simply the speed of rotating magnetic field is called synchronous speed and denoted by Ns. Mathematically, $N_s = \frac{120f}{P}$, where f is the frequency and P is the number of poles.

Rotating Magnetic Field

Rotating magnetic field is produced when three phase supply is provided to stator winding. The field is such that its pole does not remain in fixed position on stator but goes on shifting its position in stator. That is why called rotating magnetic field.

Rotor Speed

Rotor speed is the actual speed at which the rotor of induction motor rotates. Rotor speed is always less than that of synchronous speed due to presence of slip.

Slip

Difference between synchronous speed with actual speed of the rotor expressed as the fraction of synchronous speed is called slip. It is denoted by S and expressed in terms of percentage. Mathematically, $S = \frac{N_s - N}{N_s}$ x 100 %, where, N_s is synchronous speed and N is rotor speed.

4.3.2 Operating Principle of Three Phase Induction Motor

When three phase supply is given to three phase stator winding, rotating magnetic field is produced. This field passes through the air gap and cut the rotor conductor which is stationary. Due to relative speed between rotating magnetic field and stationary rotor, according to the Faraday's law of electromagnetic induction emf is developed in rotor. Since the rotor conductor is short circuited, current flows through it, then rotor conductor experience the force. Due to this force, torque is developed which then rotates the rotor. Direction of motion of rotor and rotating magnetic field are same.

4.3.3 Equivalent Circuit of Three Phase Induction Motor

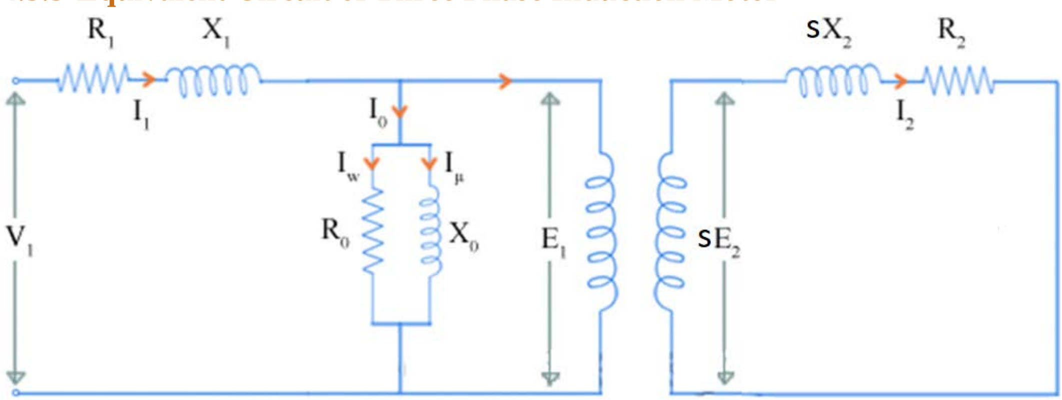


Fig. 4.4: Equivalent circuit of three phase induction motor

V1= supply voltage to stator winding per phase

I1= stator current per phase

Io= no load stator current

E1= stator emf per phase

E2= rotor emf per phase

R1= stator winding resistance

X1= stator reactance

R2= rotor winding resistance

X2= rotor reactance

I2= rotor circuit current

Ro= no load resistance

Xo= no load reactance

S= slip

4.4 Torque –slip Characteristics of Three Phase Induction Motor

Standstill torque is given by, $T_s = \dfrac{KE_2^{\,2} R_2}{R_2^{\,2} + X_2^{\,2}}$

Running torque is given by, $T_r = \dfrac{KSE_2^{\,2} R_2}{R_2^{\,2} + (SX_2)^2}$

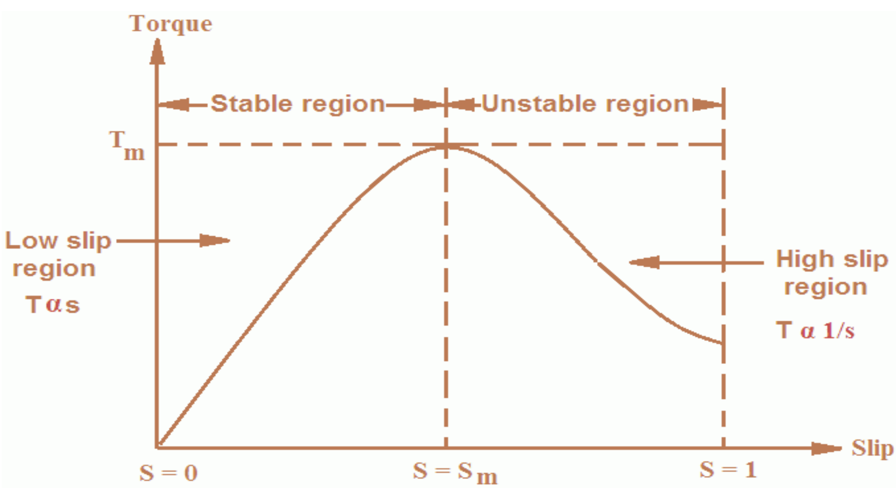


Fig. 4.5: Torque slip characteristics

The curve drawn between torque and slip at particular value of rotor resistance R_2.

a. At S=0, T=0 hence T-S curve starts from origin

b. At normal speed (Stable region) , slip is small so that $(SX_2)^2$ is negligible as compared to R2 then, $T \propto \frac{S}{R_2}$, As R_2 is constant so, $T \propto S$. Hence, T-S curve is straight line from zero slip to a slip that corresponds to full load.

c. As slip increases beyond the full load slip, torque increases and becomes maximum at $= \frac{R_2}{X_2}$ S

d. As slip increases beyond that corresponding to maximum torque, the term $(SX_2)^2$ increases very rapidly so that $R_2{}^2$ can be neglected then $\propto \frac{S}{(SX_2)^2}$, As X_2 is constant then $T \propto \frac{1}{S}$. Hence T-S curve is a rectangular hyperbola.

e. The maximum torque remains the same and independent of the value of the rotor resistance. Therefore, the addition of resistance to the rotor circuit does not change the value of the maximum torque but it only changes the value of slip at which maximum torque occurs.

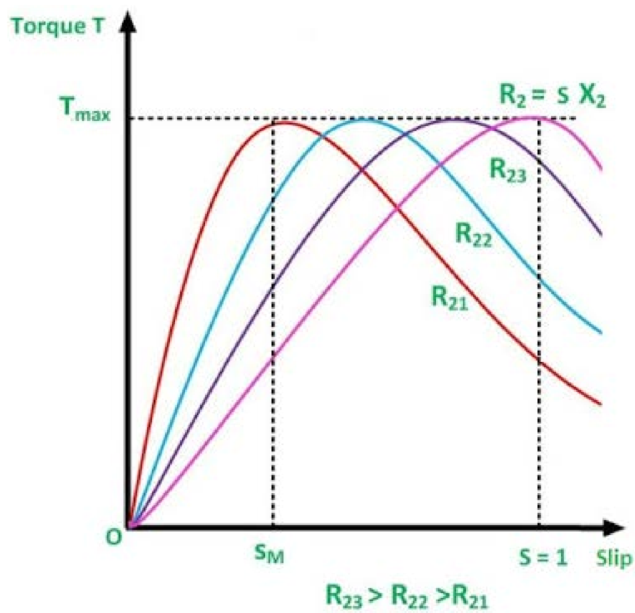


Fig. 4.6: T-S curve with different values of rotor resistance

4.5 Staring of Three Phase Induction Motor

When three phase induction motor is started without starter motor draws high current at starting .High starting current is objectionable because it will produce large line voltage drop that in turn affect the operation of other electrical equipment. Hence motor starter is required. The purpose of starter is not to start the motor as the name implies. It performs two functions:

a. to reduce the heavy staring current

b. to provide under voltage protection

The types of starting methods as follows:

a. Primary rheostat method

b. Auto transformer method

c. Star/Delta method

Primary Rheostat Method

External variable resistors are connected in series with each phase of stator winding as shown in figure. These resistors are used to drop some voltage at staring hence reduce supplied voltage. At starting whole resistance are connected and as speed picks up then resistance is gradually cut out and completely cut when motor runs with the normal speed. Applicable for motor up to 5 HP. Drawbacks of this method are lower starting torque due to reduce voltage and power is wasted in starting resistors.

Auto Transformer Method

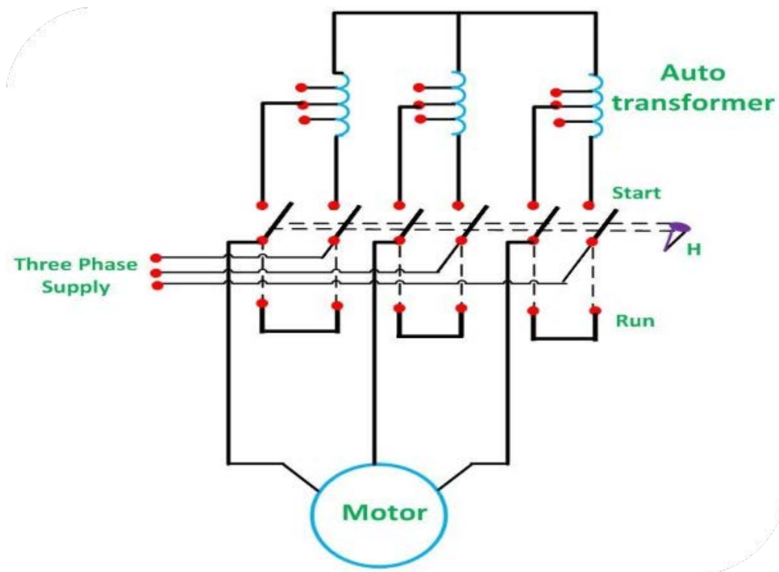


Fig. 4.7: Auto transformer method

Three auto transformers connected in star with double switch and three or four tapping. When switch is at START position, then terminals are connected to auto transformer. Hence according to tap position voltage is reduced thus starting current is reduced. When switch is at RUN position, terminals are connected to supply voltage or full voltage. When the motor runs up-to 80% of its normal speed the connections are changed so that full voltage appears across the stator winding without auto transformer. This method is used for motor output rating exceeding 20KW.

Star-Delta Method

In this method TPDT switch is used to switch Star and delta connection. At starting stator winding is connected in Star connection and at normal running condition stator winding is connected in delta connection. So at starting switch handle is moved to START position so the voltage is reduced by $1/\sqrt{3}$ times the line voltage, thus starting current is reduced. When motor accelerates and gains speed, switch handle is quickly thrown over to RUN position that is in DELTA connection. So that full voltage supplied to the stator winding. This method is used for motor rating between 4-20 KW.

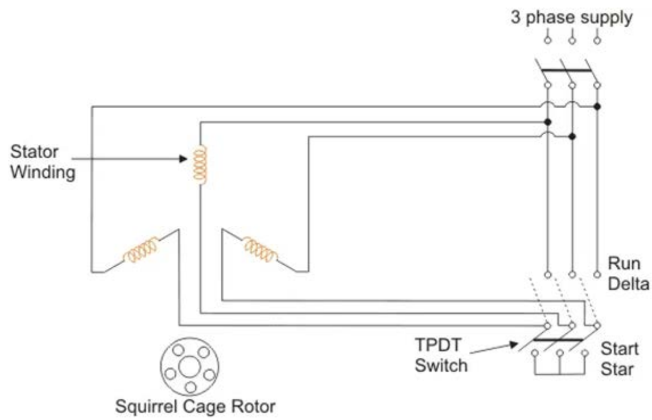


Fig. 4.8: Star-Delta method

In DELTA, $I_d = \frac{V}{Z}$

In STAR, $I_s = \frac{V}{\sqrt{3}Z}$

4.6 Speed Control of Three Phase Induction Motor

Different speed control methods of three phase induction motor are as follow:

a. Stator voltage control method

b. Rotor rheostat method

c. Frequency control method

Stator Voltage Control Method

Speed of motor is directly proportional to the magnitude of supply voltage. Thus, by varying stator supply voltage speed of motor can be controlled. This method is cheaper and simple but rarely used because large change in voltage causes small change in speed. Large change in supply voltage will result in a large change in flux density, hence, this will disturb the magnetic conditions of the motor.

Rotor Rheostat Method

In this method, to control the speed of motor an external resistance is connected to rotor circuit. This method is only applicable for slip ring induction motor. We know at normal operation, $T\propto$ /R_2. At constant load torque, if R2 is increased, slip will increase thus speed decreases.

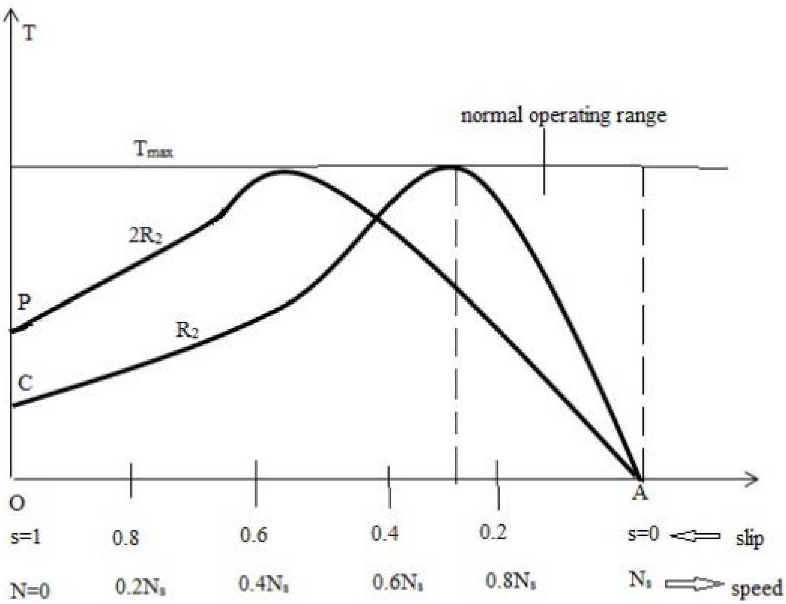


Fig. 4.9: Rotor rheostat method

Frequency ControlMethod

We know, $S = \frac{N_s - N}{N_s}$ where $N_s = \frac{120f}{P}$. So , N= N_s(1-S). Since speed is directly proportional to supply frequency, speed can be controlled by changing frequency of applied voltage. To change the frequency, VFD (Variable frequency drive) is used to vary frequency.

4.7 Application of Three phase Induction Motor

Wound Rotor or Slip Ring Induction Motor: crushers, plunger pumps, cranes and hoists, elevators, compressors and conveyors etc.

Squirrel Cage Induction Motor: Blower, fan, centrifugal pumps, punch presses etc.

4.8 Basic Introduction to Induction Generator

Induction generator is also called asynchronous generator. When the shaft of motor is run at speed more than Ns then motor acts as generator. That is when slip has negative value. Since slip , $S= (N_s - N)/N_s$. An induction generator produces electrical power when the rotor of induction motor is to rotate above synchronous speed.

Induction generator is used in micro hydropower, mini hydropower, wind power etc. Since the induction generator cannot produce reactive power so capacitor is required to provide necessary reactive power.

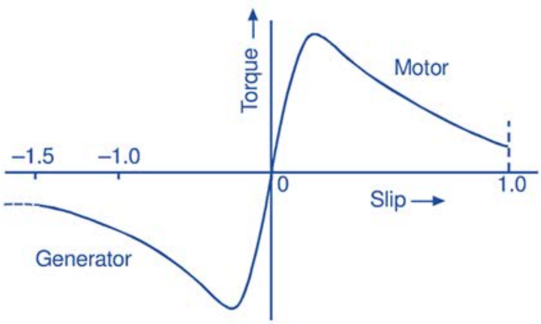


Fig. 4.10: T-S curve for Induction motor and generator

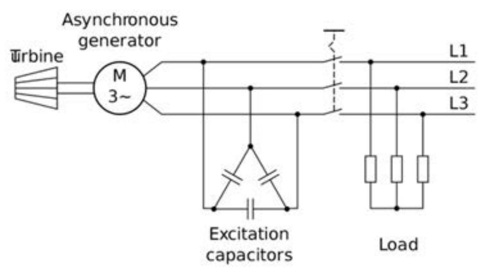


Fig. 4.11: Induction generator with excitation capacitors

Exercise

Choose the correct answer from the given alternatives.

1. Which type of rotor of three phase induction motor has slip rings?

   a. Squirrel cage rotor b. Phase wound rotor

   c. Slip ring rotor d. Both b and c

2. The key difference between the synchronous speed and the actual speed of an induction motor is called

   a. Regulation b. Efficiency c. Losses d. Slip

3. If an induction machine is runs at above synchronous speed then machine acts as

   a. A synchronous motor b. An induction motor

   c. An induction generator d. A synchronous generator

4. In equivalent circuit of three phase induction machine X_2 denotes

   a. Stator resistance b. Rotor reactance

   c. Rotor resistance d. Stator inductance

5. Which speed control method is not applicable for squirrel cage induction motor?

   a. Stator voltage control b. Frequency control

   c. Both a and b d. Rotor rheostat

6. Rotating magnetic field is produced in a

   a. Single phase induction motor b. DC series motor

   c. Ac series motor d. Three phase induction motor

7. If synchronous speed of three phase induction motor is 1800 rpm then what may be the speed of rotor

   a. 1800rpm b. 1785rpm c. 1805rpm d. 1900 rpm

8. The stator core of the induction motor is made up of

   a. Mild steel b. Laminated cast iron

   c. Silicon steel stampings d. Soft wood

9. In three phase induction motor the value of slip ranges from

a. 0 to 2 b. 0 to 1 c. 0 to 0.5 d. 1 to 2

10. At what value of slip torque becomes maximum?

a. R_2*X_2 b. R_2/X_2 c. 1 d. 0

Write short answer to the following questions.

1. Explain the construction details of three phase induction motor.
2. Define slip. Describe the torque slip characteristics of three phase induction motor.
3. Why is three phase induction motor called asynchronous motor? Write the operating principle of three phase induction motor.
4. Differentiate between squirrel cage rotor and slip ring rotor.
5. What are the starting methods of three phase induction motor? Elaborate any two of them.

Write long answer to the following questions.

1. Why is starter used in three phase induction motor? List the speed control methods of three phase induction motor. Explain them.
2. Write short notes:
   a. Slip
   b. Rotating magnetic field
   c. Synchronous speed
   d. Rotor speed

Numerical

1. An induction motor has a rated speed of 715rpm. How many poles have its rotating magnetic field?
2. A 60 Hz induction motor has 2 poles and runs at 3510rpm. Calculate synchronous speed and percent slip.
3. Calculate the speed of a 4 pole, 50Hz, 400V, 3-phase induction motor when it is operating at a slip of 1.5 percent.

Project Work

1. Study constructional details of three phase induction motor. (Animated videos)
2. Familiarization with squirrel cage rotor and phase wound rotor. (Pictures and videos)
3. Study of different types of starting methods of three phase induction motor with detail diagram.

Unit 5 Synchronous Machines

5.1 Concept of Synchronous Machines

Synchronous machines are AC machines. Synchronous machines can be operated as motor as well as generator. The machine which rotates at a constant speed equal to the synchronous speed is called synchronous machine. In synchronous generator, rotor of the generator has to be driven at constant speed equal to synchronous speed. Most of the power generating station uses synchronous generator also known as alternator. Alternators are generally constructed in larger sizes since the small size alternators are not economical thus induction generators are used were small size required.

5.2 Constructional Details of Synchronous Machines

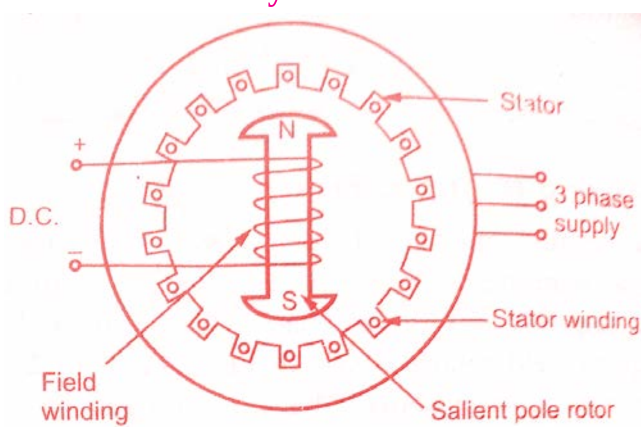


Fig. 5.1: Construction of synchronous machine

The Main Parts of Synchronous Machines are Stator, Rotor and Exciter.

Stator

It is the stationary part of the synchronous machine that consists of yoke, stator core and stator winding (armature winding). Yoke is the outer body of the machine which protects the inner part of the machine. It also supports stator core and stator winding.

Stator core is made up of steel alloy having slots on its periphery to accommodate stator winding. Core is laminated by thin sheet to reduce eddy current loss and made silicon steel to reduce hysteresis loss.

Stator winding are uniformly distributed three phase winding that kept in stator. This winding is also called armature winding.

Rotor

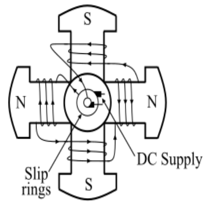


Fig. 5.2: Salient pole rotor

Rotor is the rotating part of the synchronous machine. Field windings are wound in rotor and excited by the dc source to produce magnetic poles. There are two type of rotor.

a. Salient pole rotor

b. Cylinder type of rotor

a. Salient Pole Rotor

This type of rotor has got projected magnetic pole. Construction of this type of rotor is easier and cheaper than cylinder type rotor. Generally used in generators driven by low speed prime movers such as water turbine. If driven at high speed, the salient poles would produce noise and it would cause the excessive windage loss. The following are the features of this type of rotor.

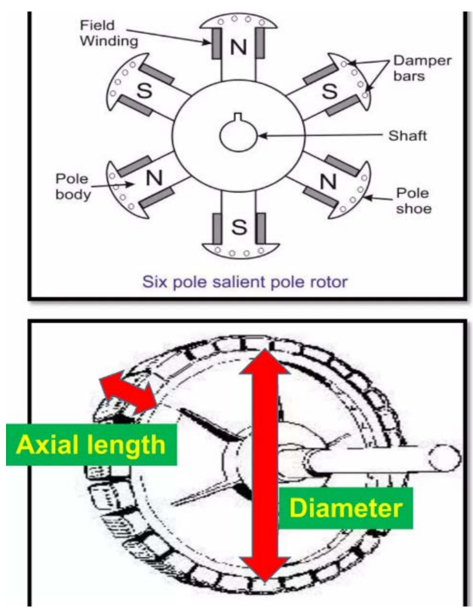


Fig. 5.3: Salient pole rotor

a. They have large diameter and short axial length.

b. The pole shoes cover about 2/3 of pole pitch.

c. Poles are laminated in order to reduce eddy current losses.

d. These are employed with hydraulic turbines or diesel engines. The speed is 100 to 375 rpm.

b. Cylinder Type Rotor

This type of rotor has smooth magnetic poles in the form of closed cylinder. Construction is more compact and robust. Generally used in the generator driven by high speed prime movers like steam engine and gas turbine. This type of rotor is also known as non-salient pole type rotor. The features of this type of rotor are as follow.

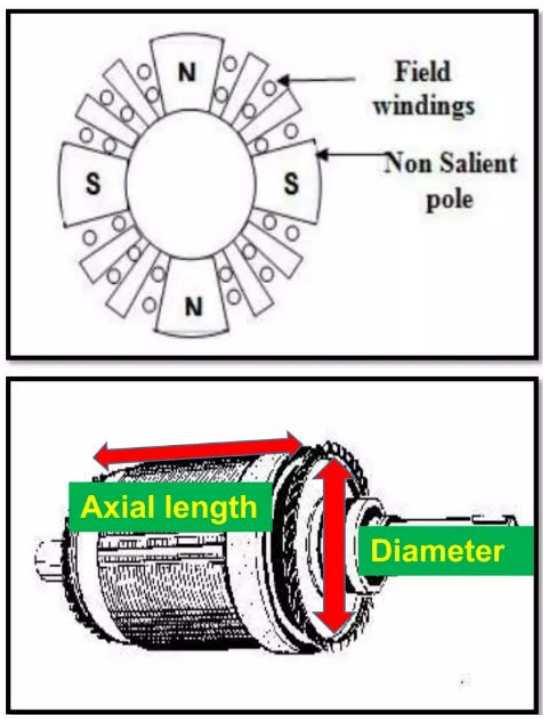


Fig. 5.4: Cylindrical type rotor

a. They are of smaller diameter and of very long axial length.

b. Robust construction and noiseless operation

c. It has less windage loss

d. It has better dynamic balancing

e. High operating speed (3000 rpm)

Comparison Between Salient Pole Rotor and Cylindrical Type Rotor

Salient Pole Rotor	Cylindrical Type Rotor
1. Poles are projecting out from the surface.	1. Poles are non-projecting.
2. Air gap is non uniform.	2. Air gap is uniform.
3. Large diameter and small axial length.	3. Small diameter and large axial length.
4. Mechanically weak.	4. Mechanically robust.
5. Suitable for low speed operation.	5. Suitable for high speed operation.
6. Prime mover used are water turbines, I.C. engines.	6. Prime mover used are steam turbine, gas turbines.
7. For same size, the rating is smaller than cylindrical typ.	7. For same size, rating is higher than salient pole type.
8. Separate damper winding is provided.	8. Separate damper winding is not necessary.

Exciter

Generally a dc shunt or compound generators are used as exciter. It provides dc current required to magnetize the magnetic pole of the rotor. DC current generated by the exciter is fed to the field winding of the alternator through slip ring and carbon brush arrangement.

5.3 Operating Principle of Pynchronous Machine as Generator

When a dc current is applied to a rotor from exciter , magnetic field is produced, then rotor is rotated by the prime mover, the stator winding are cut by the rotating magnetic flux of rotor poles. Emf is induced in stator conductor according to the Faraday's law of electromagnetic induction. Since the magnetic poles in the rotors are alternatively ("N" and "S"), so they induced alternating emf and hence current in the stator.

Field windings are the windings producing the main magnetic field (rotor windings). Armature windings are the windings where the main voltage is induced (stator windings). Frequency of generated emf is given by,

$f = \frac{PN_s}{120}$, where P is number of poles and N_s is synchronous speed

Generated emf is depends upon frequency, rotor flux and number of turns.

5.3.1 Emf Equation of Synchronous Generator

Let,

Z= Number of conductors or coil sides in series per phase

Z= 2T (where T is the number of turns in series per phase)

ϕ= Flux per pole in weber

P= Number of rotor poles

N= Rotor speed in rpm

In one revolution (i.e. 60/N second), each stator conductor is cut by Pϕ weber, i.e.

$d\phi=P\phi$ and $dt=60/N$

Therefore, average emf induced in one stator conductor is given by,

$=(d\phi)/dt$

$=(P\phi)/(60/N)$

$= (P\phi N)/60$ volts

Since there are Z conductors in series per phase,

ϕ Average emf per phase $=(P\phi N)/60 \times Z=(P\phi Z)/60 \times 120f/P=2f\phi Z$ volts

Now, RMS value of emf per phase is given by,

= average value per phase x form factor

$=2f\phi Z \times 1.11$

$=2.22f\phi Z$

$=4.44Tf\phi$ volts

Considering distribution factor (k_d) and pitch factor (k_p), then

Emf equation of synchronous generator $=4.44k_d\, k_p\, Tf\phi$ volts

5.3.2 Factors Affecting the Magnitude of emf

The magnitude of emf of synchronous generator depends up on the following factors:

a. Number of turns
b. Frequency
c. Magnetic flux
d. Distribution factor
e. Pitch factor

5.3.3 Relation Between Internal emf and Terminal Voltage

R_a = armature resistance

X_L = leakage reactance

X_{AR} = armature reaction reactance

E_a= internal emf

V= terminal voltage

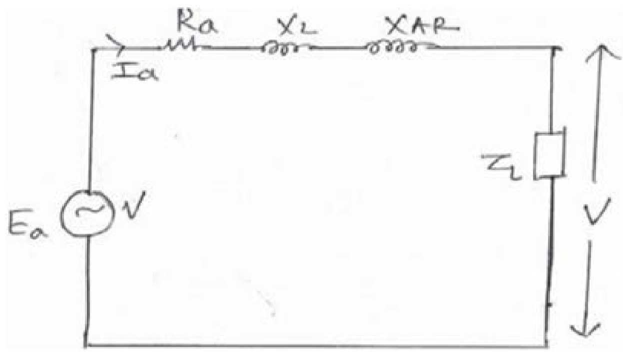


Fig. 5.5: Equivalent circuit diagram of alternator

Figure 5.5 shows the equivalent circuit diagram of alternator for one phase. During no load condition, current Ia will not flow. Thus V=E_a. At loaded condition, I_a will flow then voltage drop occurs. Hence V is not equal to E_a. Hence for loaded condition,

$$V= E_a – I_a[R_a + j(X_L + X_{AR})] \text{ ------------ } (5.1)$$

5.4 Parallel Operation and Synchronous of Alternators

5.4.1 Concept of Parallel Operation of Alternators

In power system, multiple (two or more than two) alternators are operated in parallel. Parallel operation is done to fulfill the demand. Process of connecting the two alternators in parallel is known as synchronization. In interconnected power system, many number of alternators from various power station are connected in parallel through bus bars at station and transmission line.

An alternator will be synchronized to an infinite bus bar on which many number of alternators had been already connected. An infinite bus bar is the bus bar whose voltage and frequency is independent and constant with load. Synchronous generators which have been switched onto the bus bar for synchronized are called incoming generator.

Advantages of Parallel Operation of Alternators

a. Continuity of service

b. Higher efficiency

c. Easy maintenance and repair

d. Support load growth

e. Greater reliability

5.4.2 Requirement for Parallel Operation of Alternators

During synchronization, incoming alternator must not be connected to live bus bars directly. It is because the induced emf is zero at standstill and short-circuit will result. Thus following are the conditions to be fulfilled for paralleling operation of alternators:

a. The terminal voltage (r.m.s value) of the incoming alternators must be the same as bus-bars voltage

b. The frequency of the generated voltage of the incoming alternator must be equal to the bus-bars frequency

c. The phase of the incoming alternator voltage must be identical with the phase of the bus-bars voltage. In other words, two voltages must be in phase with each other.

d. The phase sequence of the voltage of the incoming alternator must be same as that of the bus-bars.

5.4.3 Methods of Synchronization of Alternators

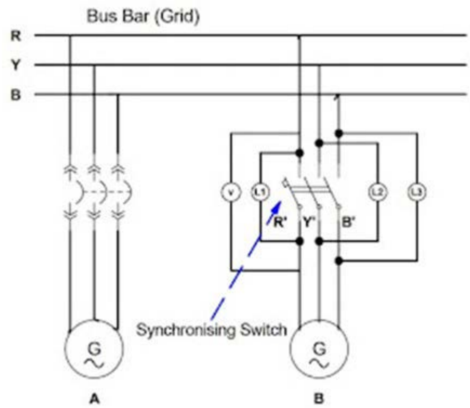
The methods of synchronization or parallel operation of alternators are as follow:

a. Dark Lamp Method

b. Synchroscope Method

a. Dark Lamp Method

In dark lamp synchronization method, three lamps L_1, L_2 and L_3 are connected as shown in figure. The lamp "L_1" is direct connected between the phase R and R' and the other two are cross connected between other two lamps. When the frequency and phase voltage of incoming generator is same as that of bus bars then lamp L_1 goes dark while cross connected lamps L_2 and L_3 will be equally bright. At this instant, parallel operation is done and switch of incoming generator can be closed to connect it to bus bar.



Advantages

i. This method required inexpensive equipment so that cost effective.

ii. Synchronization condition can easily detected with the help of three lamps.

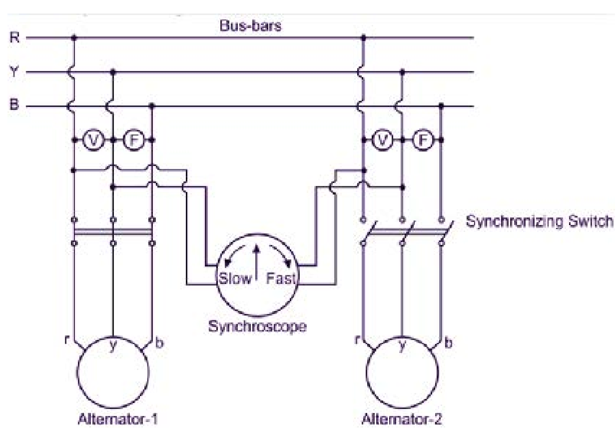
Disadvantages

i. Flicker of lamps leads to problem that which lamp has higher frequency.

ii. This method depends up on visual observation so may leads to potential errors and wrong interpretation.

b. Synchroscope Method

In Synchroscope method synchronization is done with the help of synchroscope. A synchroscope is a device used to determine the phase and frequency difference between voltages of incoming alternator and bus bar or already connected alternator. This device consists of rotating pointer that rotates when there is a difference in frequencies.



Clockwise rotation of pointer indicates that frequency of incoming alternator is higher, that means running fast than that of existing alternator. Anti-clock wise rotation of pointer indicates that the frequency of incoming alternator is lower that means running slower than that of existing alternator. Zero (0') clock position of pointer indicates that the frequency of incoming alternator is equal to the bus bar frequency or already running alternator. Then incoming alternator can be synchronized i.e. connected to the bus bar.

Advantages

i. Accuracy of synchronization is higher than dark lamp method.

ii. Provides real time feedback that means continuous monitoring and adjustment for reliable operation.

Disadvantages

i. Complex and costlier that dark lamp method.

ii. Highly skilled manpower is required.

5.5 Synchronous Motor

5.5.1 Basic of Synchronous Motor

An ac motor that rotates at constant speed i.e. synchronous speed. Alternator may operate as motor by connecting its armature winding to a 3 phase supply along with dc supply to rotor winding (field winding). Synchronous speed Ns is given by 120f/p. Since the frequency is fixed, motor speed stays constant irrespective of the load or voltage of 3 phase supply. The construction of synchronous motor and synchronous generator is almost similar. Motor is not self-starting and auxiliary means have to be used for starting it.

Operating Principle

When three phase supply is given to the stator winding, rotating magnetic field is produced. Exciter provides DC current to rotor to produce constant flux. Due to this rotating magnetic field of armature winding and constant flux of field winding , at particular condition rotor and stator poles might be at same polarity ($N_S - N_R$, $S_S - S_R$) causing the repulsive force on the rotor.

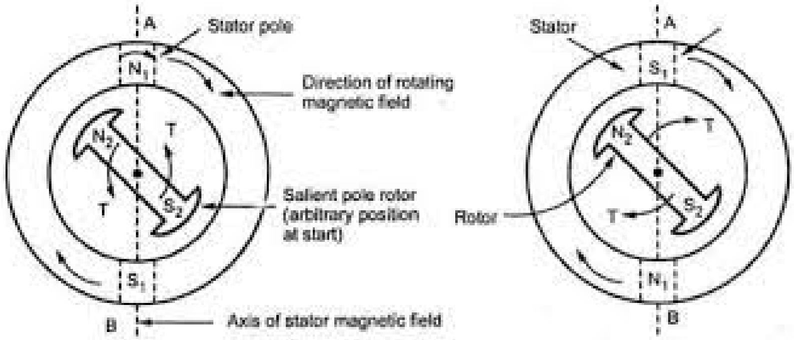


Fig. 5.6: Repulsive and attractive forces in synchronous motor

In other hand, it will be (N_S – S_R, S_S - N_R) causing attractive force. These forces cannot rotate the rotor due to inertia of rotor thus rotor remains in the stand still condition. Hence it is not self-started.

To overcome this inertia, rotor is initially fed with some mechanical input which rotates it in same direction as near to synchronous speed. After sometimes magnetic locking occurs and the motor rotates in synchronism with frequency.

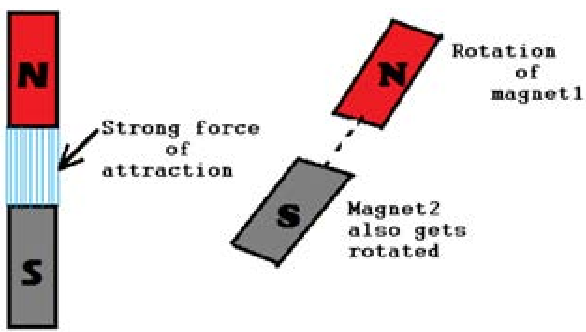


Fig. 5.7: Magnetic locking in synchronous motor

Characteristics of Synchronous Motor

a. Synchronous motors are not self- starting. They require some external means to bring their speed close to synchronous speed to before they are synchronized.

b. This motor has unique characteristics of operating under any loading of electrical factor

c. It runs at either at synchronous speed or not at all. i.e while running it maintains a constant speed equal to the synchronous speed.

d. It is used in power factor improvement.

e. The only way to change its speed is to change its supply frequency. (As Ns = 120f/P)

5.5.2 Application of Synchronous Motor

a. As synchronous motor is capable of operating under either leading or lagging power factor, it can be used for power factor improvement

b. It is used where high power at low speed is required. Such as rolling mills, chippers, mixers, pumps, compressor etc.

c. They are used to improve the voltage regulation of transmission lines.

Exercise

Choose the correct answer from the given alternatives.

1. What is the function of synchronous generator?

   a. Converts electrical energy into mech. energy

   b. Converts mech. energy to elec. energy

   c. Regulates voltage

   d. Stores electrical energy

2. In synchronous machine armature winding is placed at..........

   a. Stator b. Rotor c. Field pole d. Armature

3. What is the function of exciter?

   a. To protect motor b. To provide AC current

   c. To provide DC current d. Both B and C

4. What type of rotor is commonly used in synchronous machines?

   a. Cylindrical rotor b. Salient pole rotor

   c. Phase wound rotor d. Squirrel cage rotor

5. Which type of rotor of synchronous generator is used in high speed operation?

   a. Cylindrical type b. Salient pole type

   c. Non salient pole type d. Both A and C

6. Which type of rotor of synchronous generator is used in low speed operation?

   a) Cylindrical type b) Salient pole type

   c) Non salient pole type d) Both A and C

7. In synchronous machine stator winding is also called............

   a. Field winding b. Rotor winding

   c. Armature winding d. None of the above

8. Synchronous generator is also called..............

   a. Asynchronous generator b. Induction generator

   c. Alternator d. Any of the above

9. Motor that is used as power factor improvement............

a. Induction motor
b. Dc motor
c. Synchronous motor
d. All of the above

10. Damper windings are present in..............

a. Non salient pole rotor
b. Cylindrical rotor
c. Salient pole rotor
d. Dc motor rotor

Write short answer to the following questions.

1. Differentiate between salient pole rotor and cylindrical type rotor.
2. Define synchronization. What are the requirements for parallel operation of synchronous generators?
3. Enlist the methods of synchronization and explain them with necessary diagram.
4. What are the factors that affect the magnitude of emf of synchronous generator? Why is parallel operation of synchronous generator done?
5. Differentiate between synchronous motor and three phase induction motor.

Write long answer to the following questions.

1. Explain the constructional details of synchronous machine and operating principle of synchronous machine as generator.
2. Why is synchronous motor not self-starting? Explain operating principle of synchronous motor. Describe the methods that makes the synchronous motor starting.

Project Work

1. Study constructional details of synchronous machine. (Animated videos)
2. Familiarization with salient pole rotor and cylindrical type rotor. (Pictures and videos)
3. Study of different types of synchronizing methods of alternators with detail diagram.

Single Phase Fractional Horse Power Motors

Unit 6

6.1 Single Phase Induction Motor

6.1.1 Basic Introduction of Single Phase Induction Motor

Single phase induction motor operates with single phase AC. These motors are the most familiar motor which are used in home, shop, office etc. Construction is similar to that of three phase induction motor, difference is that the stator is provided with single phase. These motor are not self-starting thus some starting means is required.

6.1.2 Constructional Details of Single Phase Induction Motor

6.1.3 Operating Principle

When ac is supplied to stator winding, alternating flux is produced. Since the rotor is similar to the three phase induction motor, current flows which produces torque in the motor. Thus produced torque tries to rotate rotor but due to alternating flux, forward and backward torque produced which are equal in magnitude and opposite in direction. Hence resultant torque is zero. Therefore single phase induction motor cannot rotate by itself or motor is not self-staring.

6.2 Method of Making Single Phase Induction Motor Self-Starting

To make a motor rotating, a revolving magnetic field is required. Revolving magnetic field is developed with the help of auxiliary means (additional winding).That helps to make single phase motor temporarily into a two phase motor. Thus motor consists of two winding on its stator, they are main or running winding and starting or auxiliary winding. After torque developed starting winding is isolated from the connection, then only main winding is present in the circuit.

6.2.1 Types of Single Phase Induction Motor on the Basis of Making them Self-Starting

a. Split phase induction motor

b. Capacitor start induction motor

c. Capacitor start run induction motor

d. Shaded pole motor

a. Split Phase Induction Motor

This type of motor is started by two phase motor action by using auxiliary or starting winding. The stator of split phase induction motor is provided with on auxiliary or starting winding in addition to the main or running winding. The starting winding has high resistance and small reactance and the main winding has low resistance and large reactance.

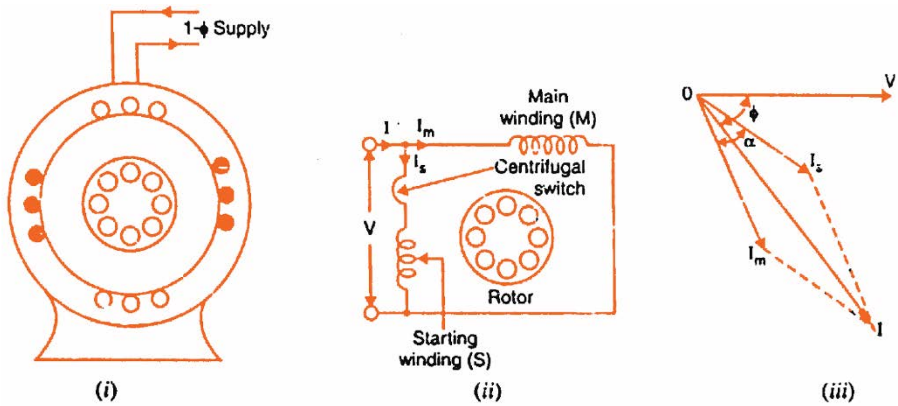


Fig. 6.1: Split phase induction motor

When single phase supply is given to the stator winding of single phase motor, then main winding carries current Im and starting winding carries current Is. Since main winding is highly inductive and starting winding have highly resistive, the current Im and Is have a phase difference (20^0 to 30^0).

Due to this phase difference, the starting torque will be developed which expression is given below:

$T_s = k\, I_m\, I_s \sin\alpha$ ——————————————— (6.1)

Where,

k =constant value whose magnitude depends upon the design of the motor

I_m = current flowing to the main winding

I_s = current flowing to the starting winding

When the motor reaches about 75% of full speed, the centrifugal switch opens and circuit gets opened.

b. Capacitor Start Induction Motor

This motor is similar as split phase except presence of capacitor. A capacitor ‘C’ is connected in series with the starting winding. The main winding has high reactance whereas the starting winding has high resistance.

When the single phase supply is given to the stator. Current "I_m" flows in the main winding and the current "I_s" flows on the starting winding.The value of capacitor is so choose that Is lead Im by about 80^0. Due to this phase difference, the starting torque will be developed which expression is given below,

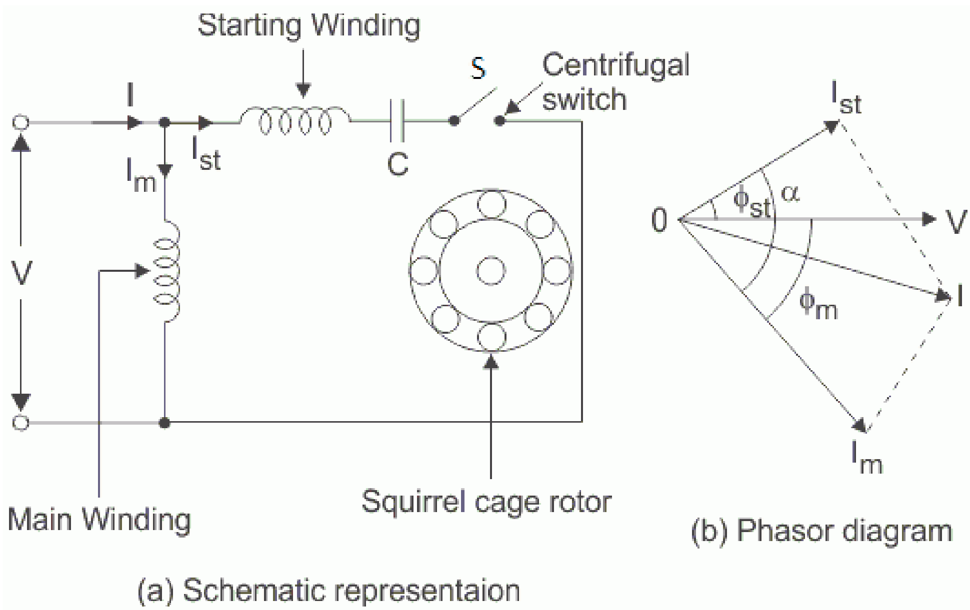


Fig. 6.2: Capacitor start induction motor

$T_s = k\, I_m\, I_s \sin\alpha$ – – – – – – – – – – – – – (6.2)

where;

k = constant value whose magnitude depends upon the design of the motor

I_m = current flowing to the main winding

I_s = current flowing to the starting winding

The starting winding is opened by the centrifugal switch when the motor attains about 75% of synchronous speed.

c. Capacitor Start Capacitor Run Induction Motor

When single phase current "I" is given to the stator "I_s" flows in the starting winding and "I_m" flows in the main winding. Two capacitors C_R and C_S are used in the starting winding. The smaller capacitor C_R required for optimum running condition is permanently connected in parallel with C_S for optimum starting required in the circuit during starting.

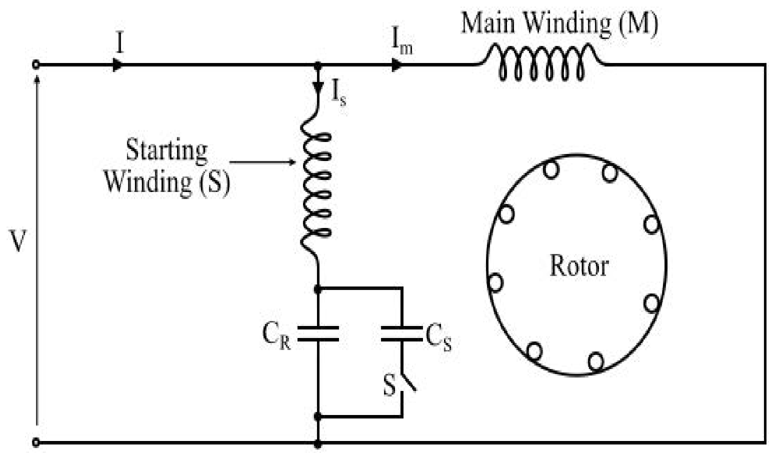


Fig. 6.3: Capacitor start capacitor run motor

The starting capacitor C_s is disconnected when the motor approaches about 75% speed. Due to the presence of C_R in the circuit, it helps to improve the power factor and the running conditions of the single phase induction motor. This type of motor has high starting torque.

d. Shaded Pole Motor

This type of motor are simple in construction and popular for starting below 40Watts (nearly 0.05hp). It has salient poles on the stator and excited by a single phase supply and it has a squirrel cage type rotor.

Construction

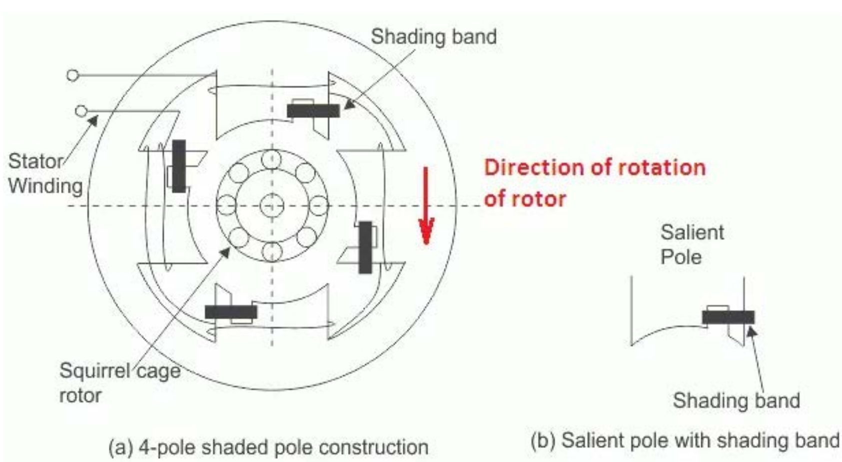


Fig. 6.4: Shaded pole motor

The main parts of the motor is stator and rotor. It has salient poles and each pole has slot cut nearly one third distance from one edge. Around the smaller part of the pole a short circuited copper coil known shading coil is placed. The part consists of shading coil is known as shaded pole and other part is called un-shaded pole. Rotor is of squirrel cage type.

Working

When a single phase supply is given to the stator of shaded pole induction motor an alternating flux is produced. This change of flux induces emf in the shaded coil. Since this shaded portion is short circuited, the current is produced in it in such a direction to oppose the main flux. The flux in shaded pole lags behind the flux in the un-shaded pole. The phase difference between these two fluxes produces resultant rotating flux. Consequently, this rotating magnetic field develops the starting torque in the motor.

Advantages

a. Such motors are built in very small size and are extremely rugged, reliable and cheap

b. They don't need any commutator, switches, brushes and slip rings etc.

c. There is the absence of the centrifugal switch and are simple in construction

Disadvantages

a. Low starting torque

b. Very little overload capacity

c. Very low efficiency

d. Low Power factor

Applications

a. Small fans

b. Exhaust fan

c. Hair dryer

d. Desk fans

6.3 Single Phase Series Motor or Universal Motor

6.3.1 Basic Introduction of Single Phase Series Motor or Universal Motor

A universal motor is such a motor which works on both ac and dc supply at almost same speed and output. Since the performance remains same for the supply thus known as universal motor. Both armature and field winding are in series. Since the armature current and flux reverse simultaneously, the torque always acts in the same direction regardless of the polarity of the supply.

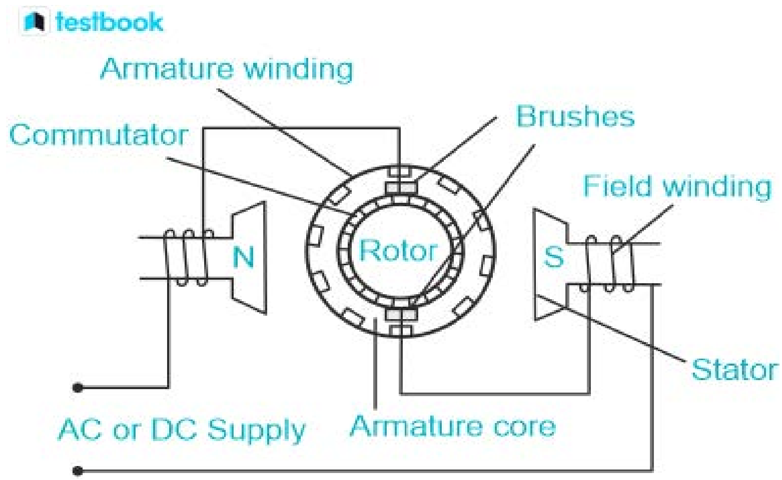


Fig. 6.5: Universal motor

Operation

Since field winding and armature winding are connected in series, the same current passes through both when motor is connected to either ac or dc supply. The field winding produces an alternating flux (Ø) that reacts with current flowing in the armature to produce a torque. The magnetic flux of the series field and armature produces by this current reverses at the same time, the torque always acts in the same direction. Since universal motors are series wound, they have high starting torque and high speed. It is noted that in this type of motor, no rotating flux is produced and the principle of operation is same as that of dc series motor.

6.3.2 Applications and Advantages of Single Phase Series Motor or Universal Motor

Advantages

a. High starting torque

b. Compact and lightweight design

c. High power to weight ratio

d. Can operate in both source (ac and dc)

Disadvantages

a. Creates noise while operating

b. Shorter lifespan as compared to other

c. Regular maintenance is required

d. Not suitable for long time operation

Applications

a. Sewing machine

b. Vacuum cleaner

c. Hand drill

d. Mixer

e. Hair dryer

f. Electric shavers

Exercise

Choose the correct answer from the given alternatives.

1. Single phase induction motors are commonly used in.............

   a. Home appliances and small tool b. Industrial machinery

   c. Automotive system d. Generating units

2. Single phase induction motors are known for their.............

   a. High efficiency b. High power factor

   c. Low maintenance d. All of the above

3. In a split phase induction motor, the auxiliary winding is connected to.........

   a. A centrifugal switch b. A starting capacitor

   c. A current relay d. A speed control device

4. What is the principle behind the operation of a shaded pole motor?

   a. To provide starting torque b. To regulate the motor speed

   c. To improve efficiency d. To protect the motor from overheating

5. Function of a capacitor in a single phase induction motor is............

   a. To increase speed b. To reduce speed

   c. To increase torque d. To reduce torque

6. Which type of single phase induction motor has a squirrel cage rotor?

   a. Capacitor start, capacitor run b. Split phase

   c. Shaded pole d. Universal

7. The constructional details of a single phase induction motor include...........

   a. Stator and rotor b. Field winding

   c. Commutator and brushes d. Slip ring and brushes

8. Which type of single phase motor is known for its simplicity and low cost?

   a. Split phase motor b. Universal motor

   c. Capacitor start motor d. Shaded pole motor

9. The motor that works on both ac and dc supply is...............

a. Split phase motor b. Universal motor
c. Capacitor start motor d. Shaded pole motor

10. Which single phase induction motor operation is similar to the dc series motor?

a. Universal motor b. Shaded pole motor
c. Capacitor run motor d. Split phase motor

Write short answer to the following questions.

1. Why is single phase induction motor not self-starting? How can it make self-starting?
2. Explain operating principle of single phase induction motor with necessary diagram.
3. What are the types of single phase motor on the basis of making self-starting? Describe any two of them.
4. Describe split phase motor and capacitor start motor with diagram.
5. What are the merits and demerits of shaded pole motor? How does it works, explain.

Write long answer to the following questions.

1. Write short notes:
   a. Shaded pole motor
   b. Universal or ac series motor
2. Why is ac series motor called universal motor? Explain operating principle of universal motor along with circuit diagram and mention its merits and demerits.

Project Work

a. Study of split phase, capacitor start and capacitor start capacitor run motor. (Circuit diagram, videos and applications)

b. Study of shaded pole motor. (Diagrams and videos with applications)

c. Study of universal motor. (Diagram and videos with applications)

References

Mehta, V. M. |. R. (2002). Principles of electrical machines. S. Chand Publishing.

Sahdev, S. K. (2017). Electrical machines. Cambridge University Press.

A Textbook of Electrical Technology (MDU). (n.d.). Goodreads.

Gieras, J. F. (2020). Electrical machines: Fundamentals of Electromechanical Energy Conversion. CRC Press.

https://www.electrical4u.com/

https://www.electricaltechnology.org/

https://electrical-engineering-portal.com/

https://energyeducation.ca/

https://www.allaboutcircuits.com/