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Chapter 2

DC Machines & Transformers

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Content

Unit 2 (DC Machines and Transformers): Fundamentals of magnetic circuits, DC Machines: Constructional details, working principle and methods of excitation of DC machine as a generator and a motor. Transformers: Necessity of transformer, construction, principle of operation, ideal transformer, practical transformer, **Simulation** using standard circuit simulation tools

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DC Machines

Introduction

- Motor converts electrical energy into mechanical energy
- Generator converts mechanical energy to electrical energy

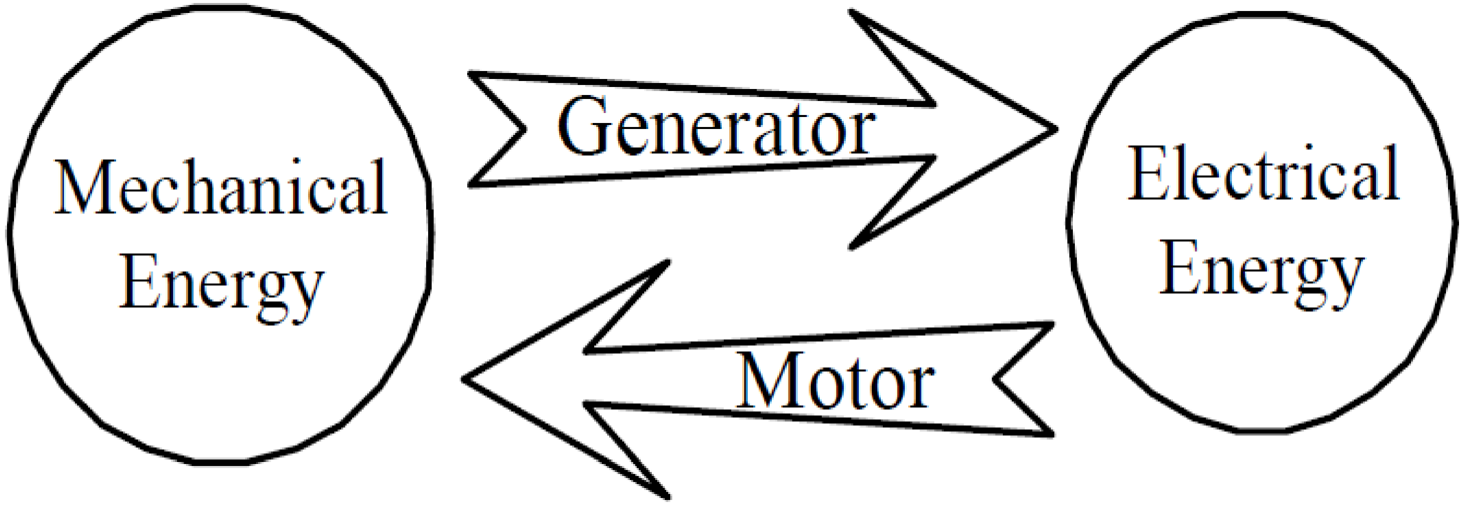
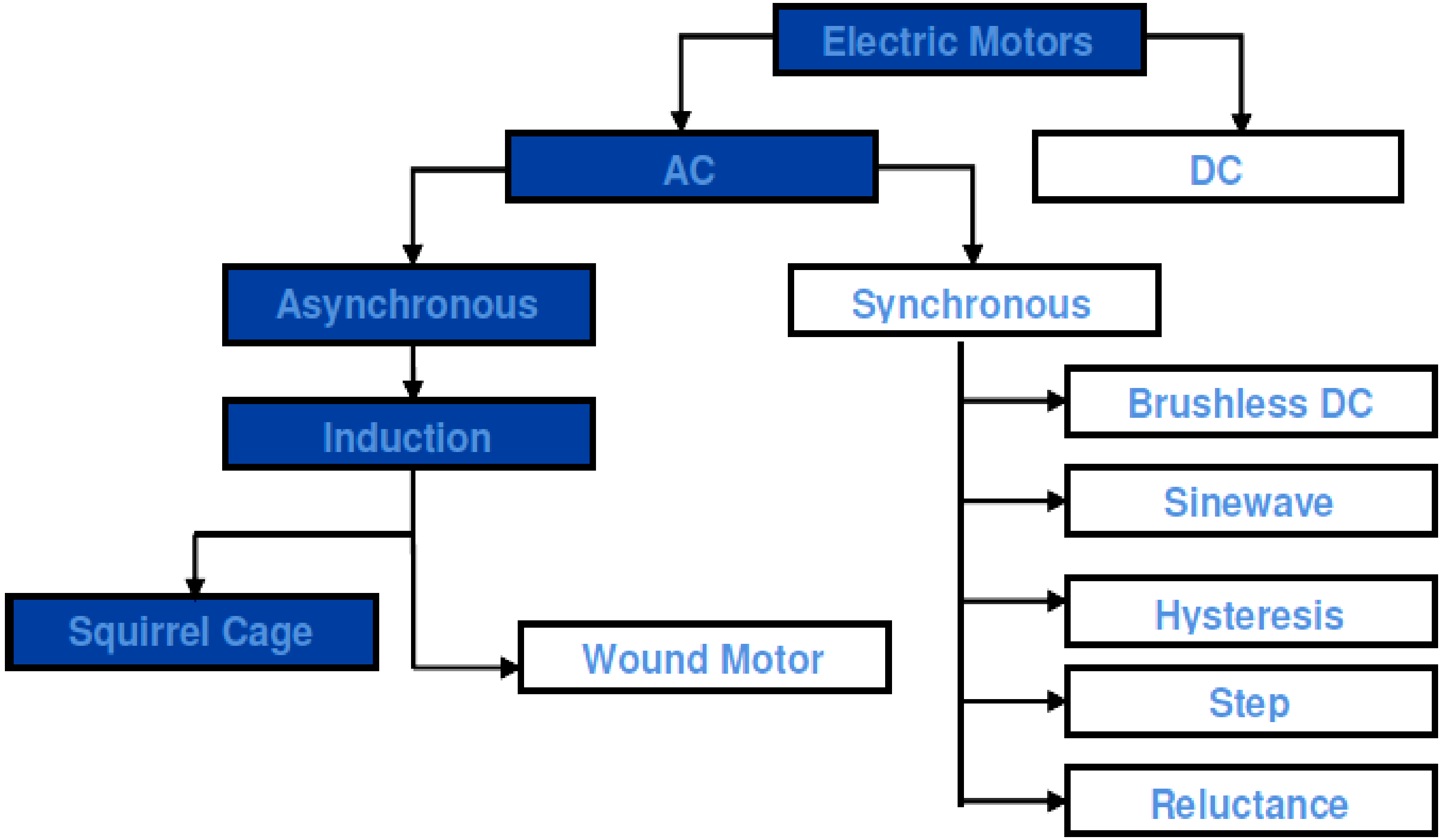


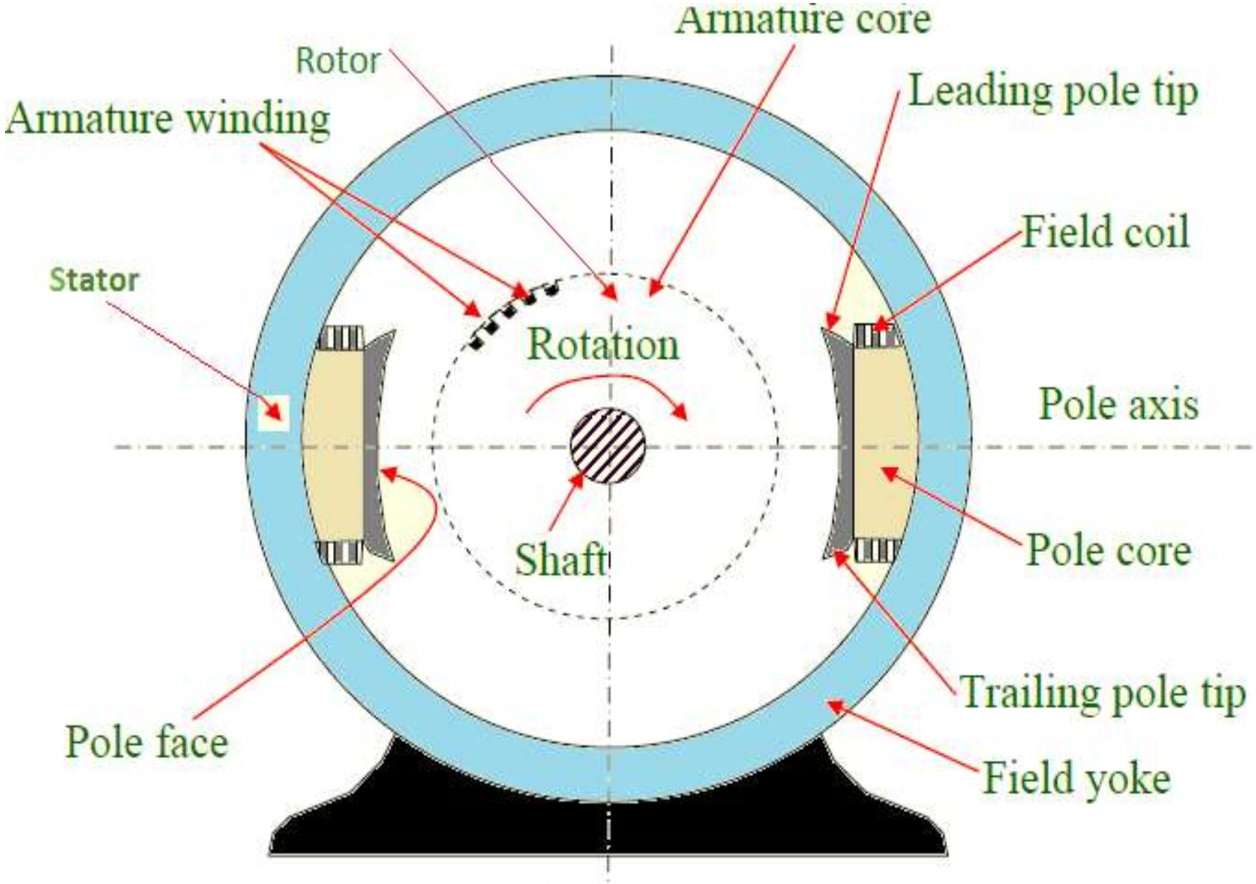
Fig. The Energy directions in generator and motor actions.

Introduction

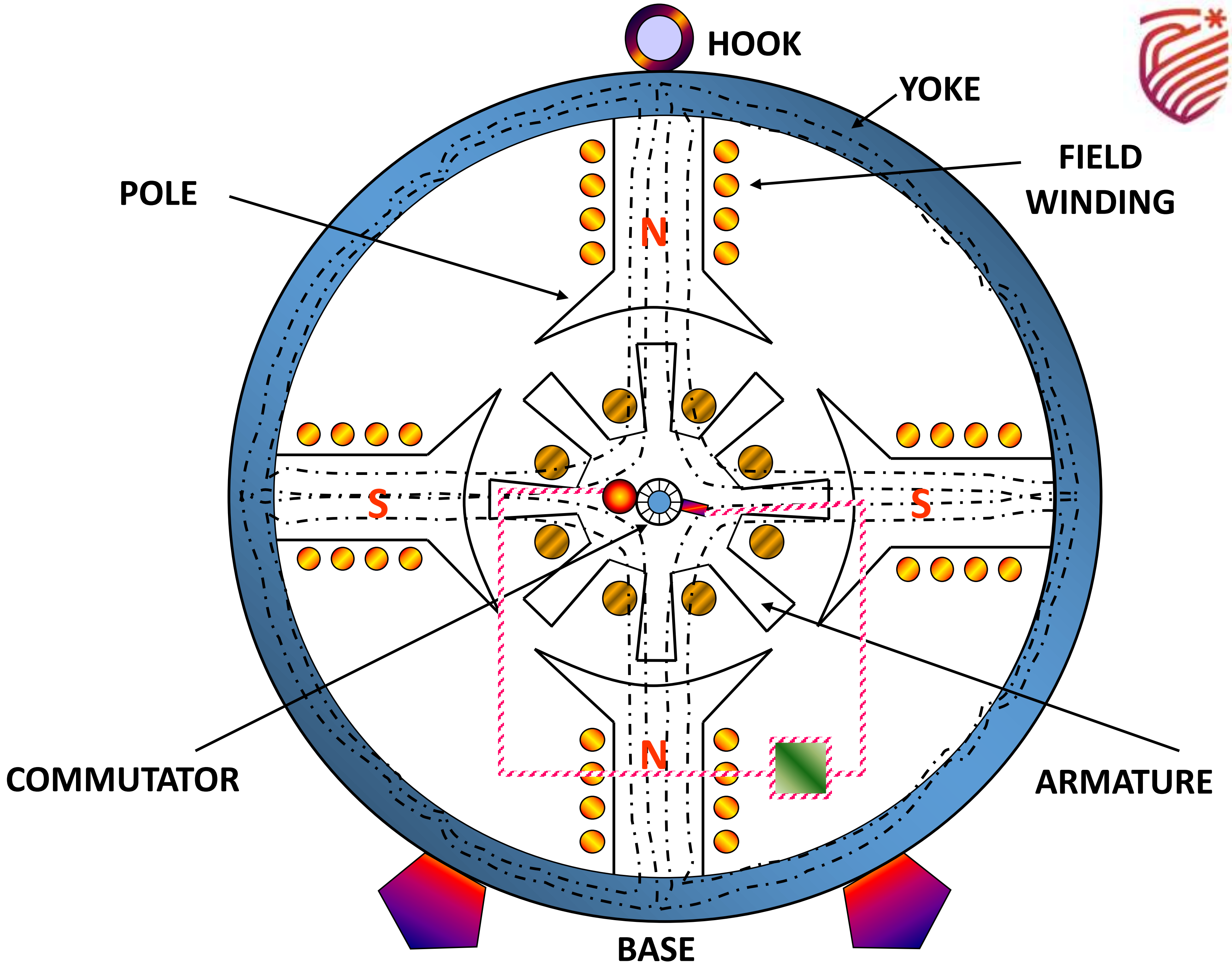


D.C. Machine Construction

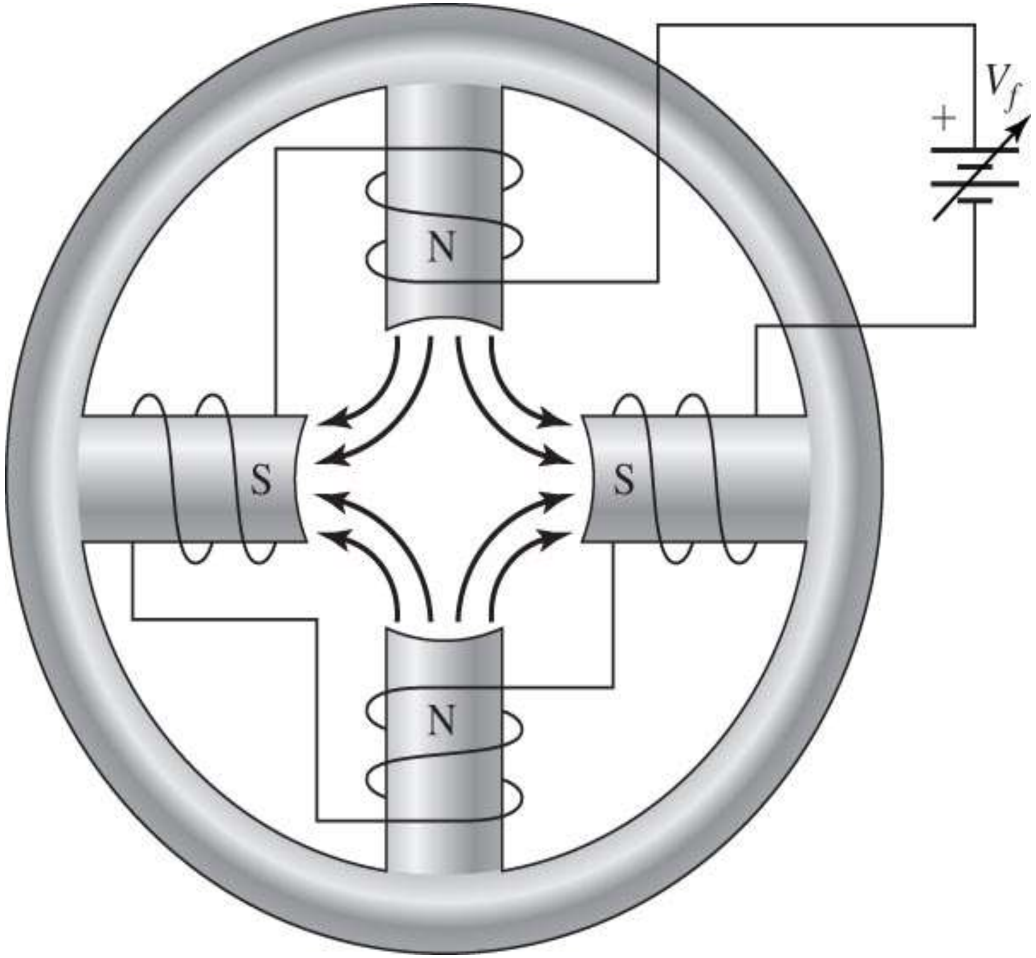
- The basic parts of any d.c. machine are shown in Figure



Construction of DC Motor


HOOK
YOKE
FIELD
WINDING
POLE
N
S
S
N
COMMUTATOR
ARMATURE
BASE

D.C. Machine Construction



How EMF is Induced ?

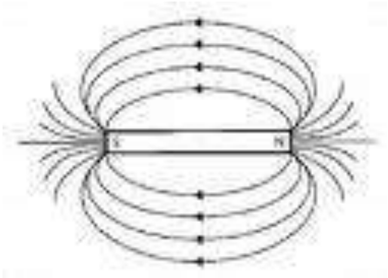
- When ever a conductor cuts the Magnetic field an EMF is induced in it (Faradays 1st law of Electro magnetic induction)

What are the types of Induced EMF ?

- Dynamically Induced EMF
- Statically Induced EMF

What are the basic requirements generating EMF ?

- Conductor
- Magnetic Field
- Relative Motion



DYNAMICALLY INDUCED EMF

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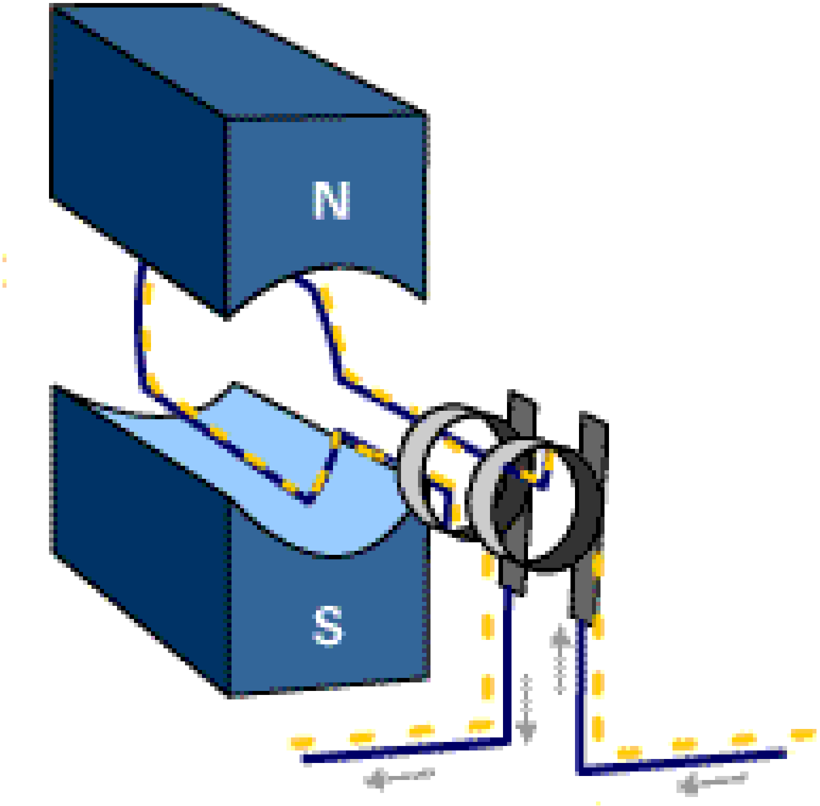
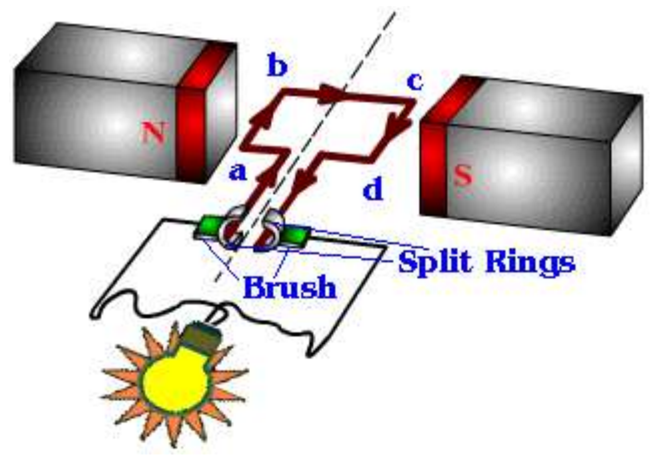
- E.m.f is induced when the flux linking a conductor changes
- In dynamically induced e.m.f the conductor moves in a stationary magnetic field.
- The e.m.f is induced in the conductor when it is in motion

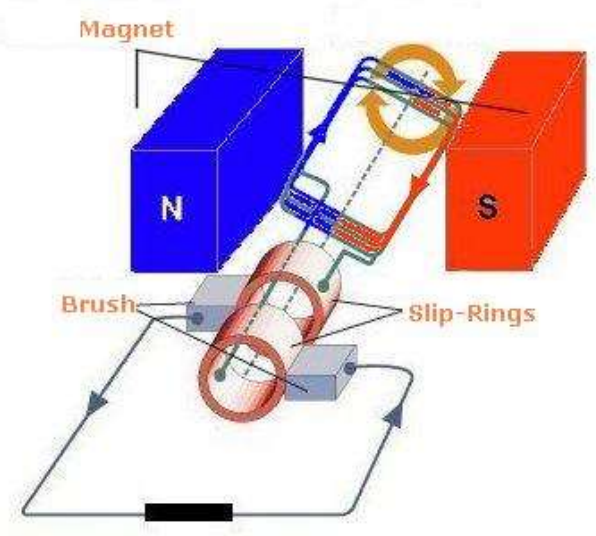


DYNAMICALLY INDUCED EMF

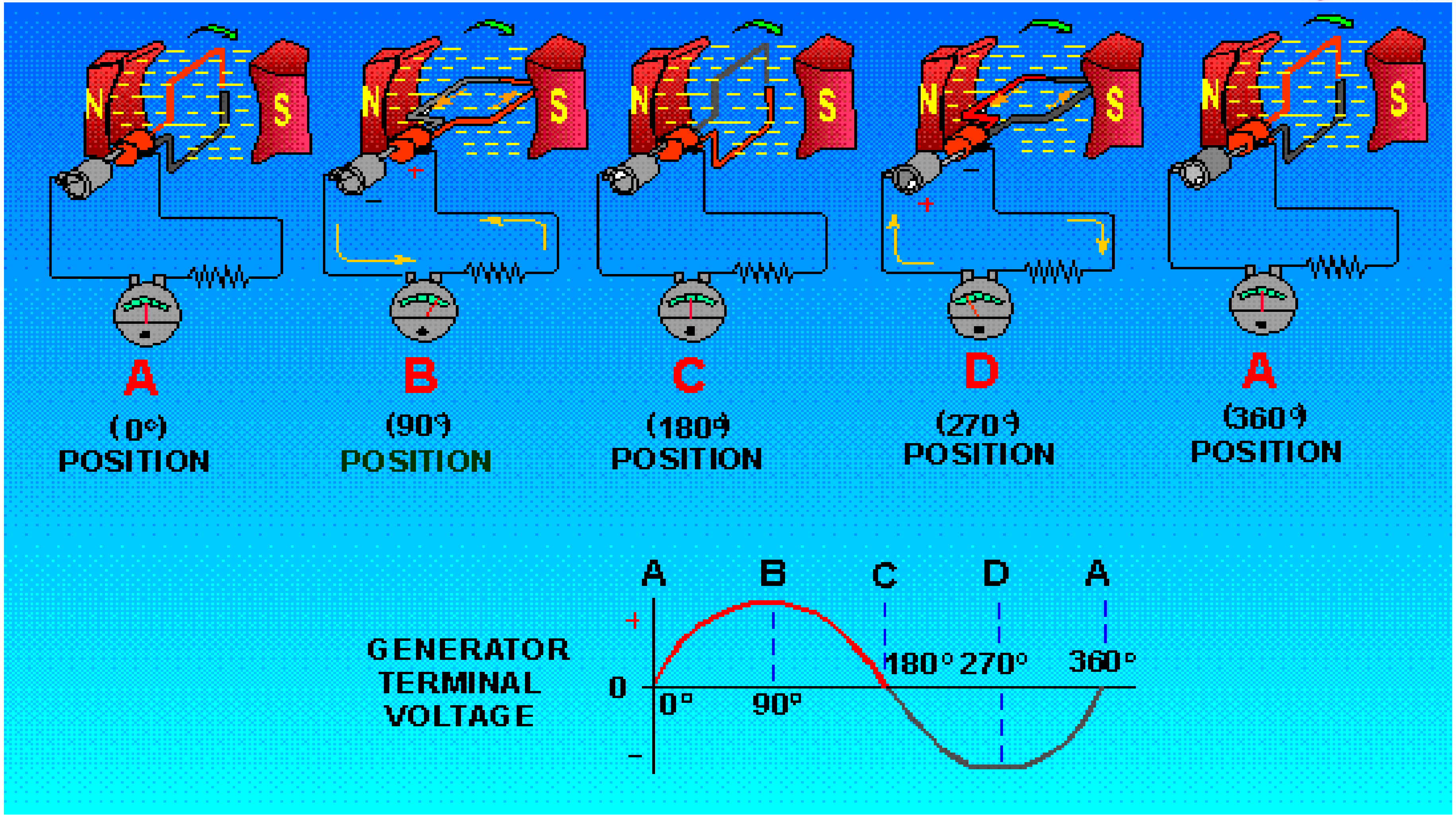
- Conductors are moved through a stationary magnetic field – ***D.C.generator***

- Conductors are stationary and the field is moving –***A.C.generators***

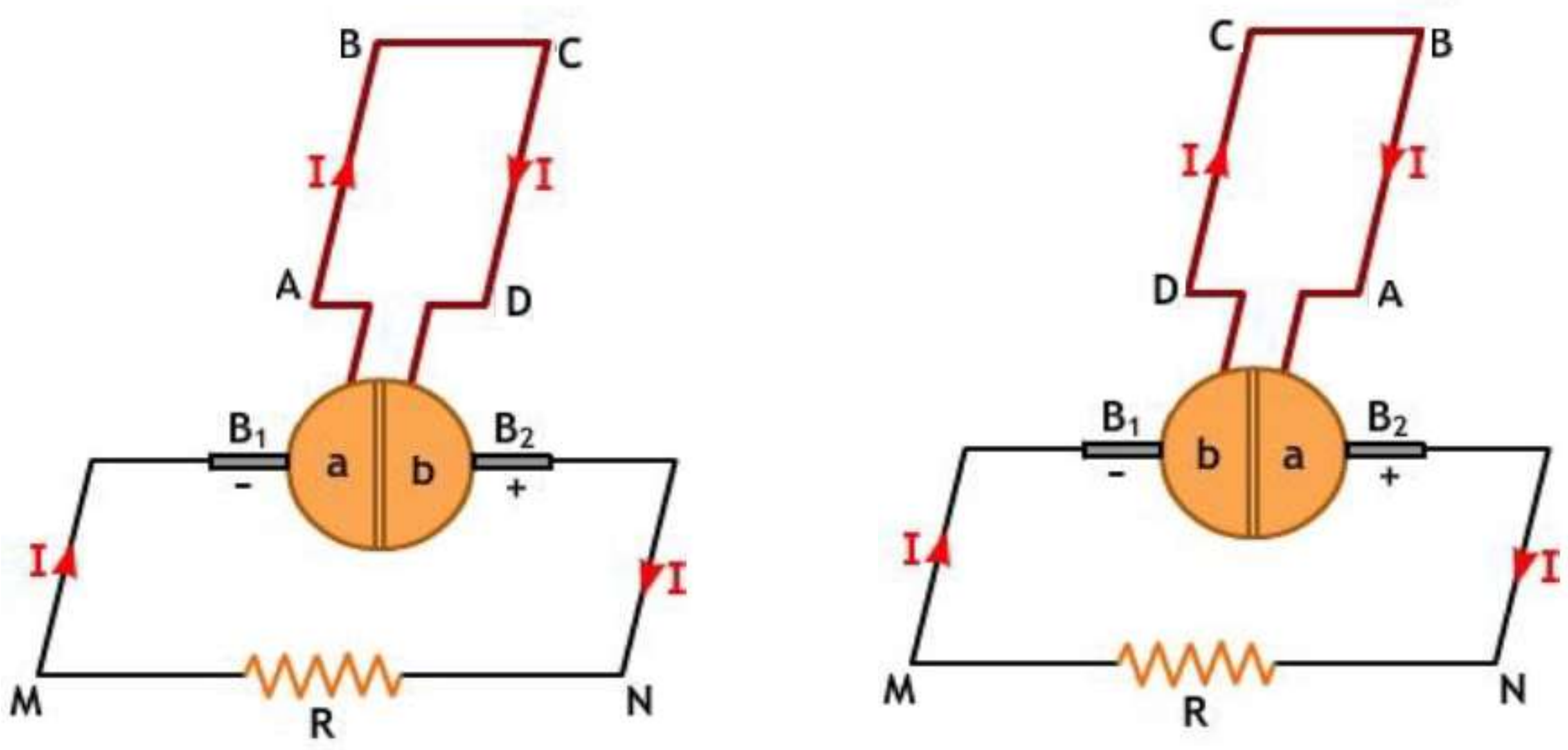




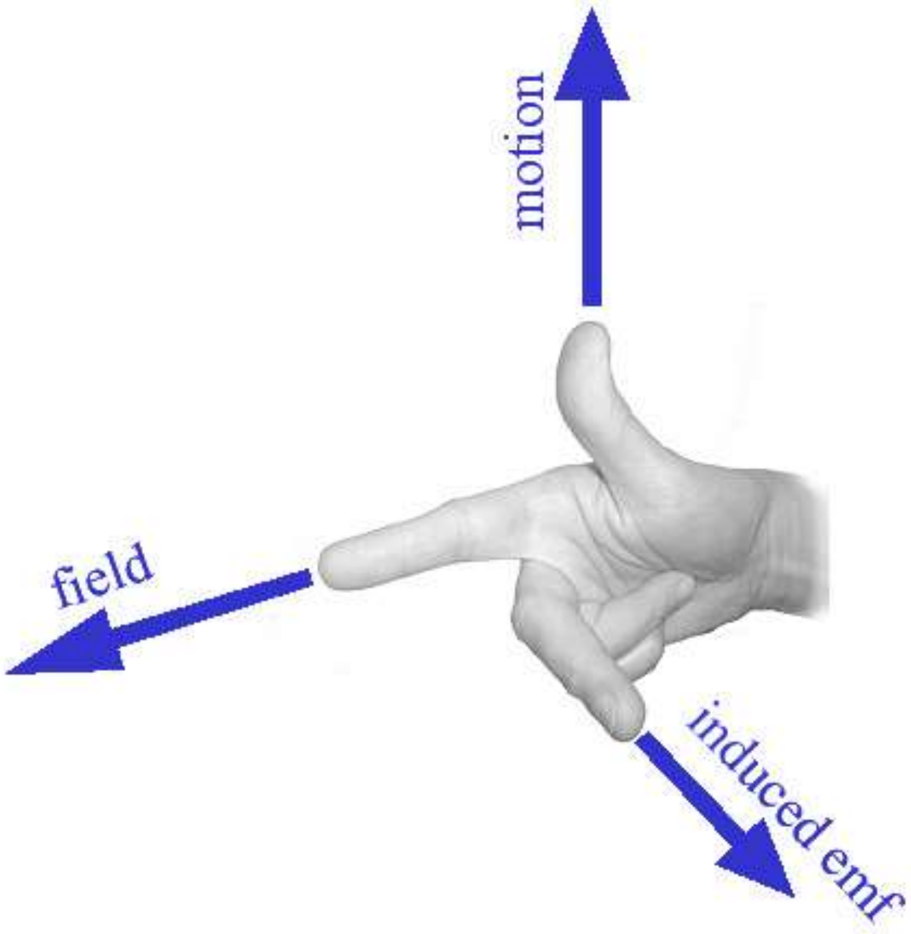
Generation Principle



Action of Commutator



FLEMINGS RIGHT HAND RULE



Thumb points motion

Forefinger points field

Middle finger points Induced Emf

D.C. Machine Construction

a) a stationary part called the **stator having,**

I. a steel ring called the **yoke, to which are attached**

II. the magnetic **poles, around which are the**

III. field windings, i.e. many turns of a conductor wound round the pole core; current passing through this conductor creates an electromagnet

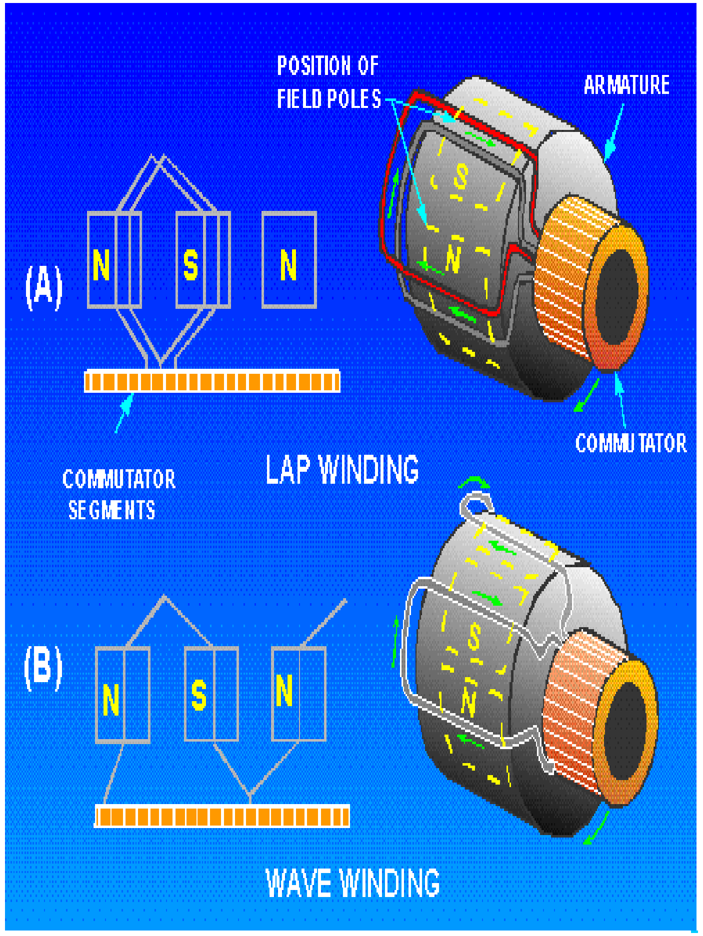
D.C. Machine Construction

- A rotating part called the **armature mounted in bearings housed in the stator** and having,
  I. Yoke
  II. armature winding
  III. Commutator

- Armature windings can be divided into two groups, These are called **wave windings** and **lap windings**

Wave and Lap Windings

- In **wave windings** there are two paths in parallel irrespective of the number of poles. Wave wound generators produce high voltage, low current outputs
- In **lap windings** there are as many paths in parallel as the machine has poles. Lap wound generators produce high current, low voltage output.



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Generated EMF Equation of a Generator

$$Average\ EMF \text{ generated/conductor} = \frac{d\phi}{dt}\ volt$$

Now, flux cut/conductor in one revolution,

$$d\phi = \phi * P \quad web.$$

Number of revolution per second =N/60;

Then, time for one revolution, dt=60/N second

Hence according to *Faraday's laws* of electromagnetic induction,

$$EMF \text{ generated/conductor} = \frac{d\phi}{dt} = \frac{\phi P N}{60} Volt$$

Generated EMF Equation of a Generator

For a wave-wound generator

No. of parallel paths is 2

No. of conductors (in series) in one path=$Z/2$

Then, EMF generated/path= $\dfrac{\phi PN}{60} * \dfrac{Z}{2} = \dfrac{\phi ZPN}{120}\ Volt$

Generated EMF Equation of a Generator

For a lap-wound generator

No. of parallel paths $=P$

No. of *conductors (in series) in one path*$=Z/P$

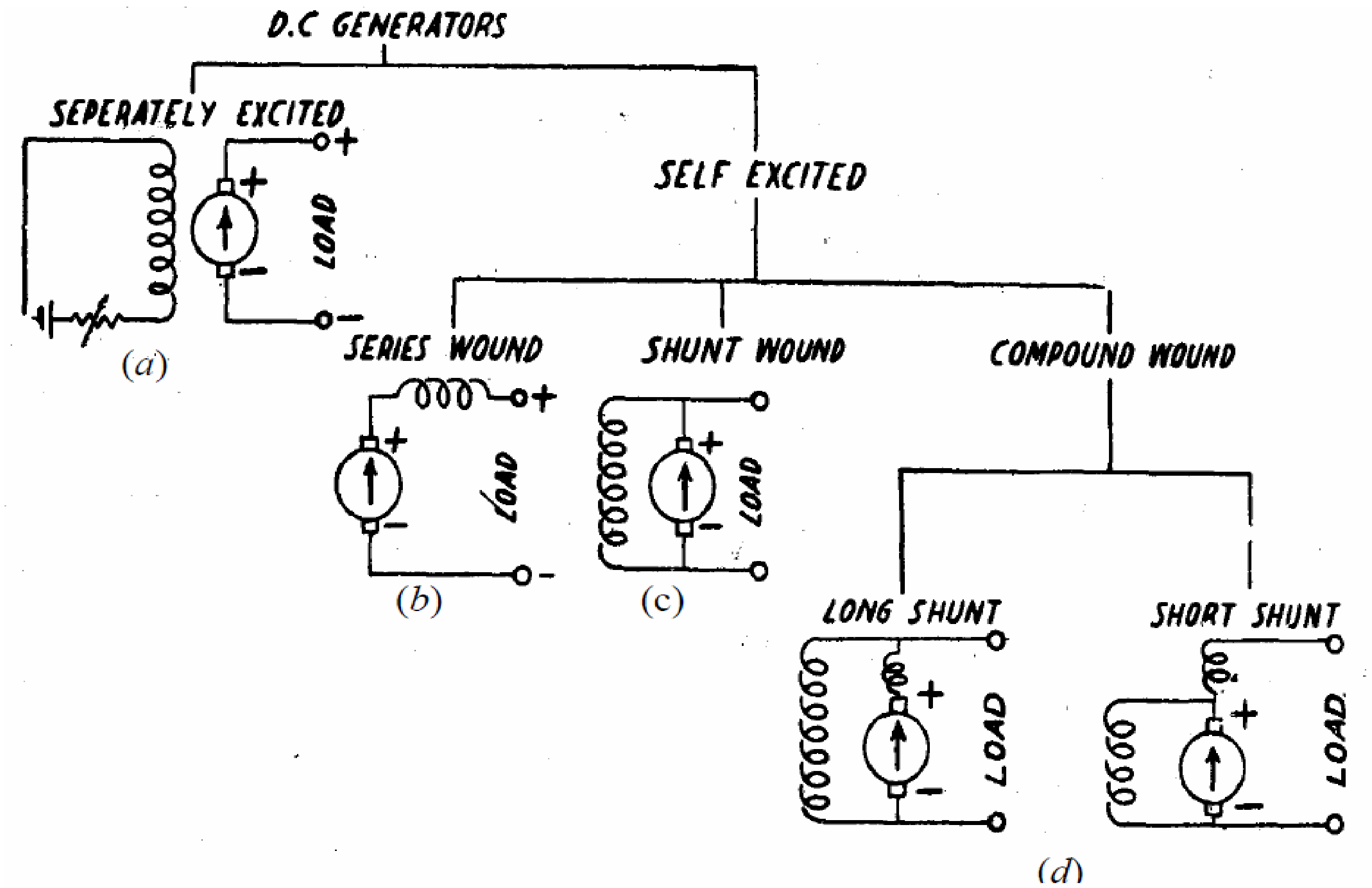
$$\text{Then, } EMF \text{ generated/path} = \frac{\phi PN}{60} * \frac{Z}{P} = \frac{\phi ZN}{60}\ Volt$$

$$\text{In general, generated } EMF = \frac{\phi PN}{60} * \frac{Z}{A}\ Volt$$

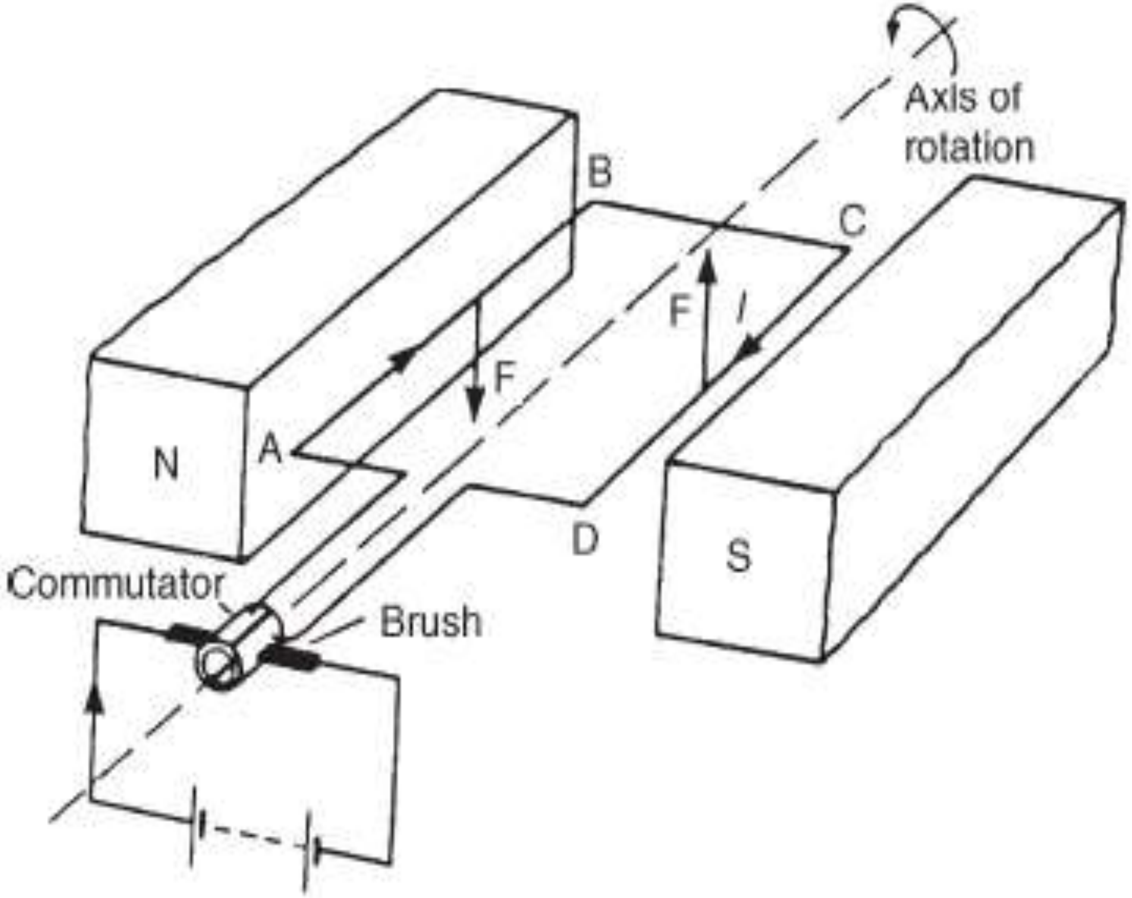
Where $A=2$ *for wave-winding.*

And $A=P$ *for lap-winding.*

Types of DC Generators



Principle of operation of a simple DC Motor



Principle of operation of a simple DC Motor

- Force F to be exerted on the current-carrying conductor which, by Fleming's left-hand rule, is downwards between points A and B and upward between C and D for the current direction shown
- The current direction is reversed every time the coil swings through the vertical position and thus the coil rotates anti-clockwise for as long as the current flows

Back e.m.f.

- When a DC motor rotates, an e.m.f. is induced in the armature conductors. By Lenz's law this induced e.m.f. E opposes the supply voltage V and is called a back e.m.f., and the supply voltage, V is given by

$$V = E + I_a R_a \quad or \quad E = V - I_a R_a$$

Summary

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- DC Machines work on the principle of Faraday’s law, Flemings Left Hand and Flemings Right Hand rule
- DC Motor and Generator have same construction
- Commutator is essential for Motor to have unidirectional rotation
- Commutator is essential for Generator to have unidirectional e.m.f at the terminal

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Transformers

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Topics

- Transformers Introduction
- Constructional Details
- Transformer Operation
- Classification of Transformers
- Application Examples of Transformer

Transformer

- **Transformer** is a static device that changes ac electric power at one voltage level to ac electric power at another voltage level through the action of a magnetic field.
- Transformer works on the principle of **Faraday's Law Of Electromagnetic Induction**.
- **Faraday's Law,** "Rate of change of flux linkage with respect to time is directly proportional to the induced EMF in a conductor or coil"

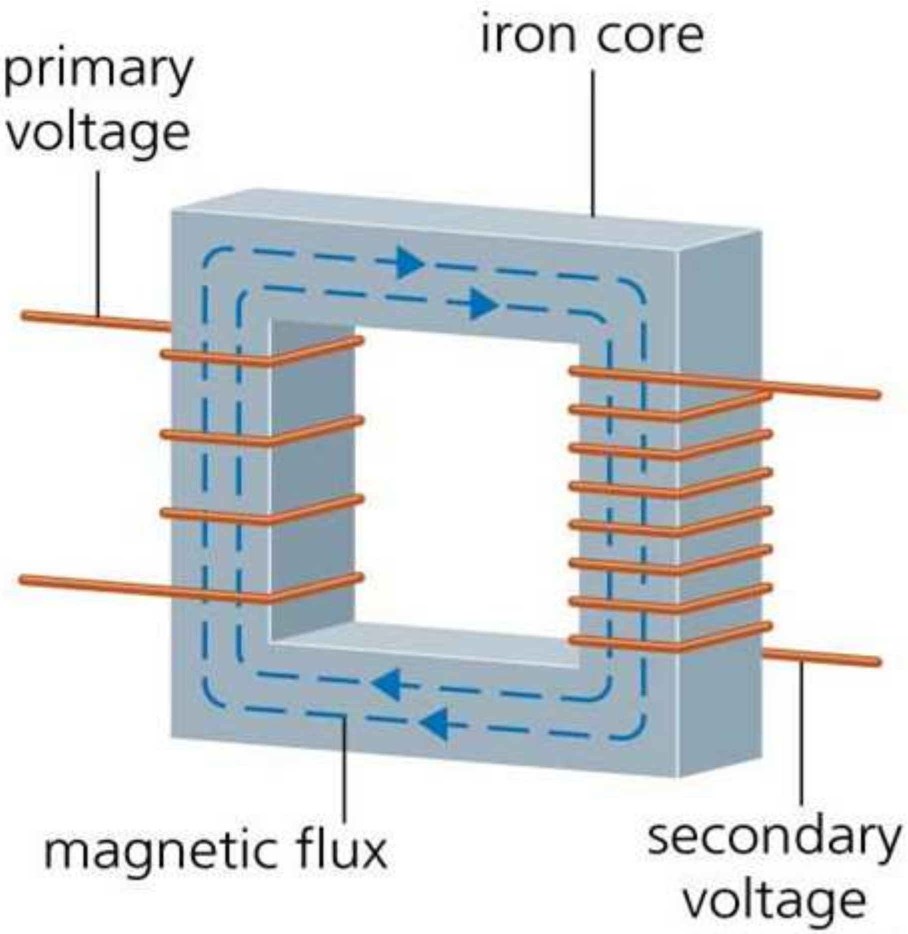
Transformer Uses

Changing

- Voltage Levels
- Current Levels
- Impedance values

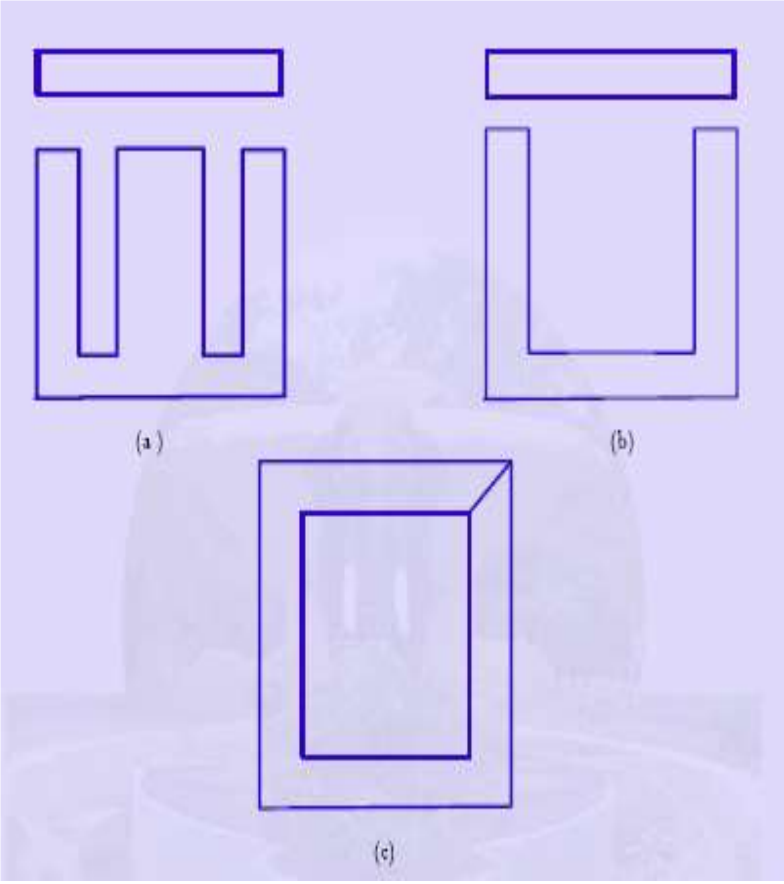
Constructional Details

Basic Structure of Transformer



Constructional Details

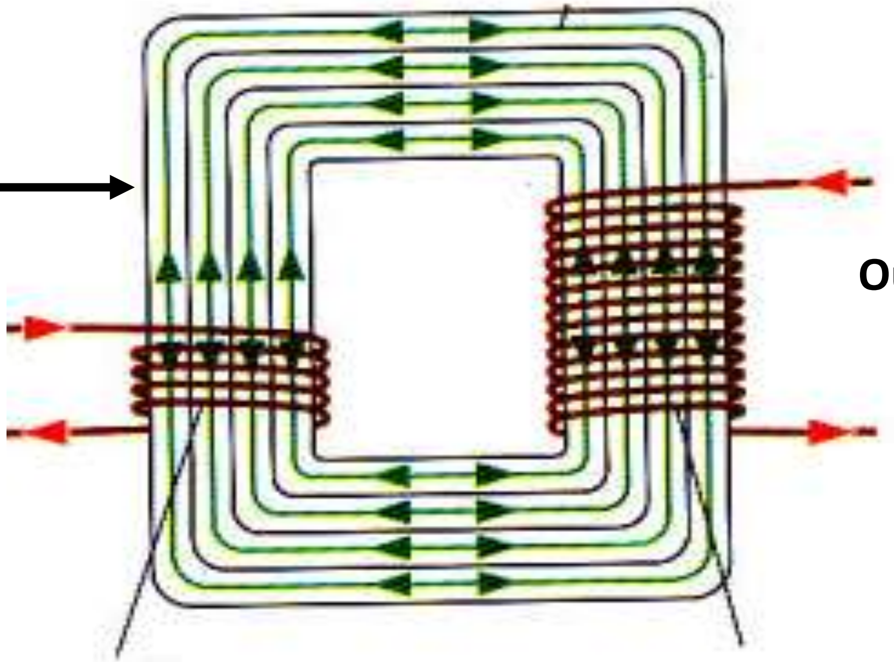
- Requirements of magnetic material are,
  - **High permeability**
  - **Low reluctance**
  - **High saturation flux density**
  - **Smaller area under B-H curve**
- For small transformers, the laminations are in the form of E,I, C and O.



How Transformer Works

Laminated Soft Iron Core

Input Voltage (A.C.)

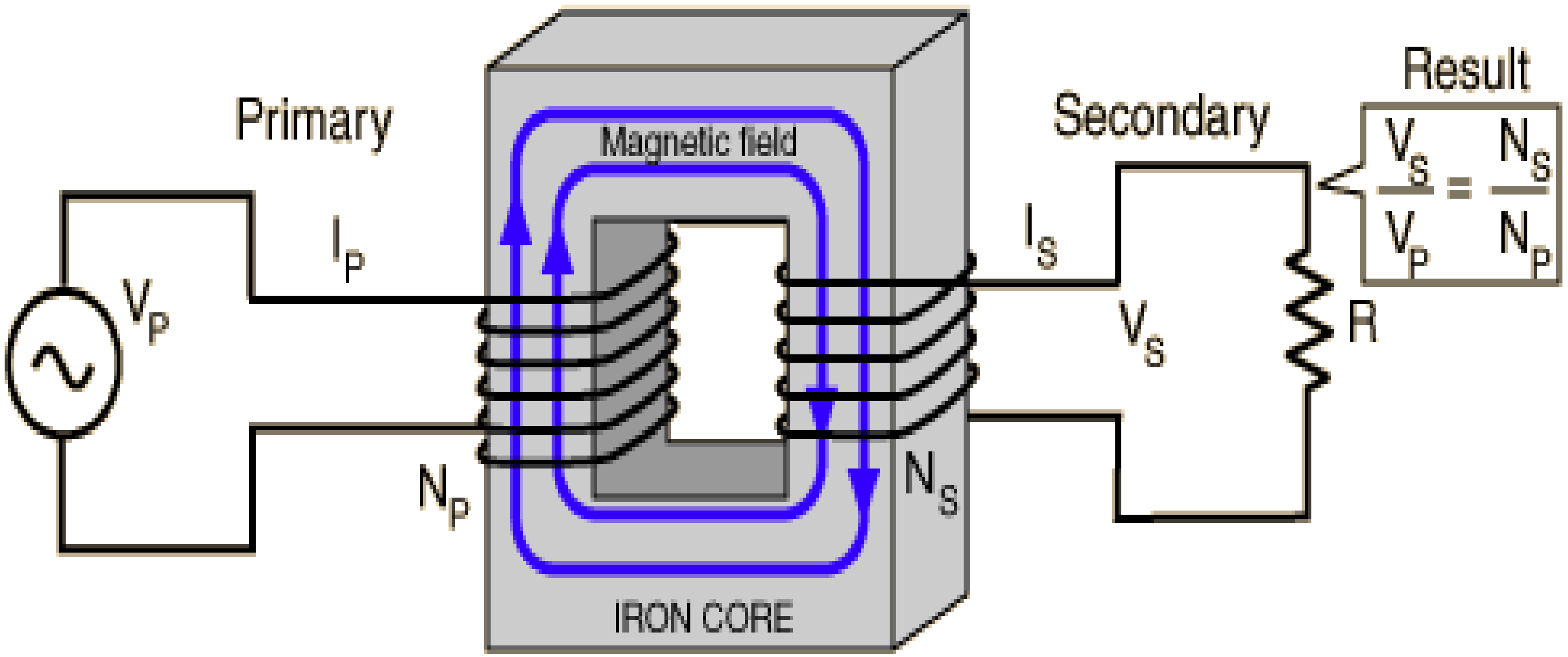


Output Voltage (A.C.)

Primary Coil

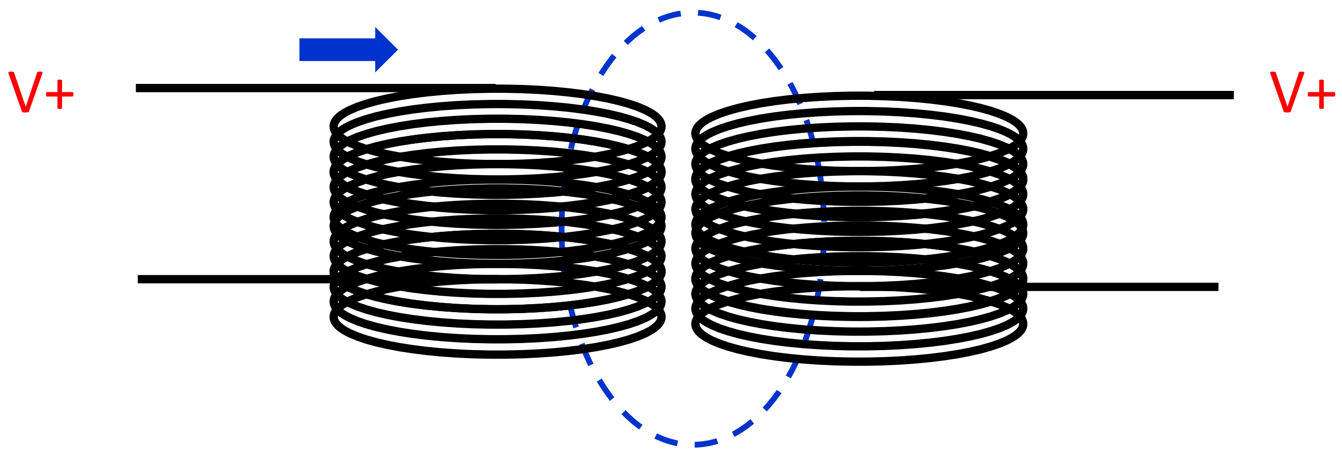
Secondary Coil

Transformer Operation



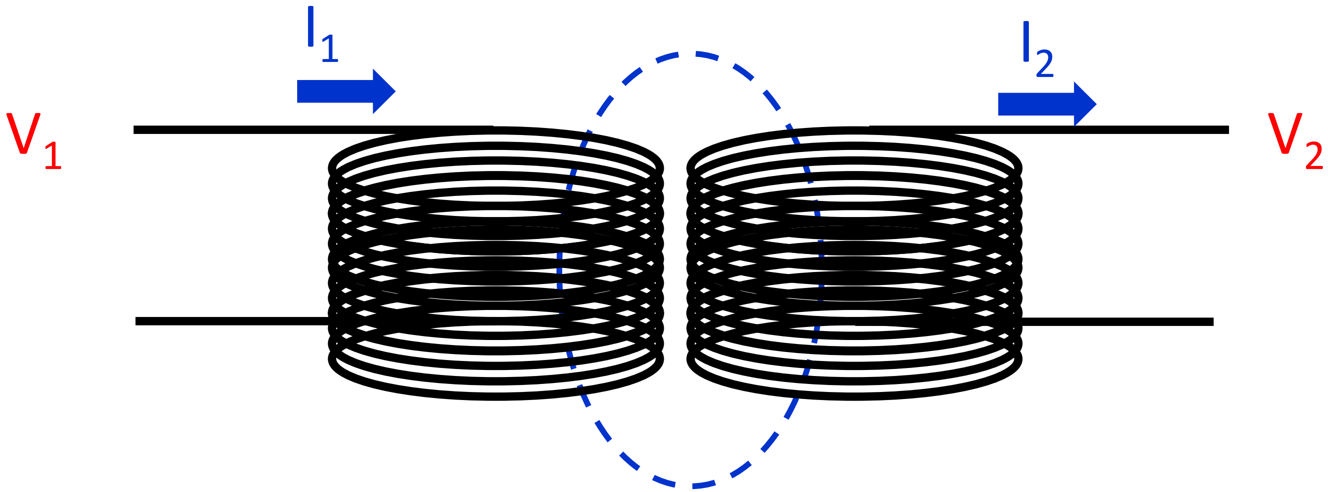
Transformer Operation

- Primary coil is supplied with a AC voltage.
- Current drawn produces a magnetic field
- Magnetic field transported to a secondary coil via a magnetic circuit
- Magnetic field induces a voltage in secondary coil

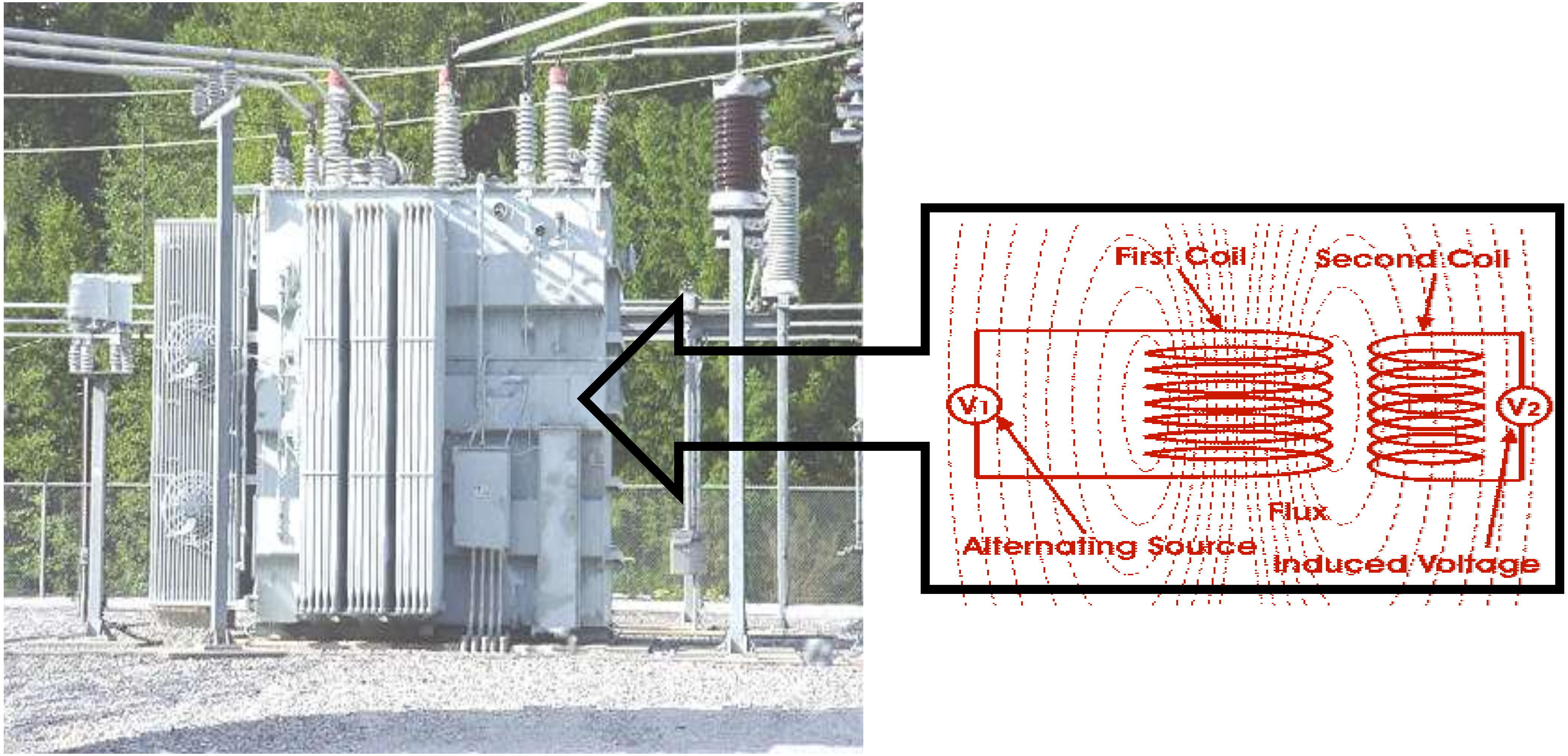


Transformer Operation

- Primary coil normally has a subscript of 1
- Secondary coil has a subscript of 2



Working Transformer



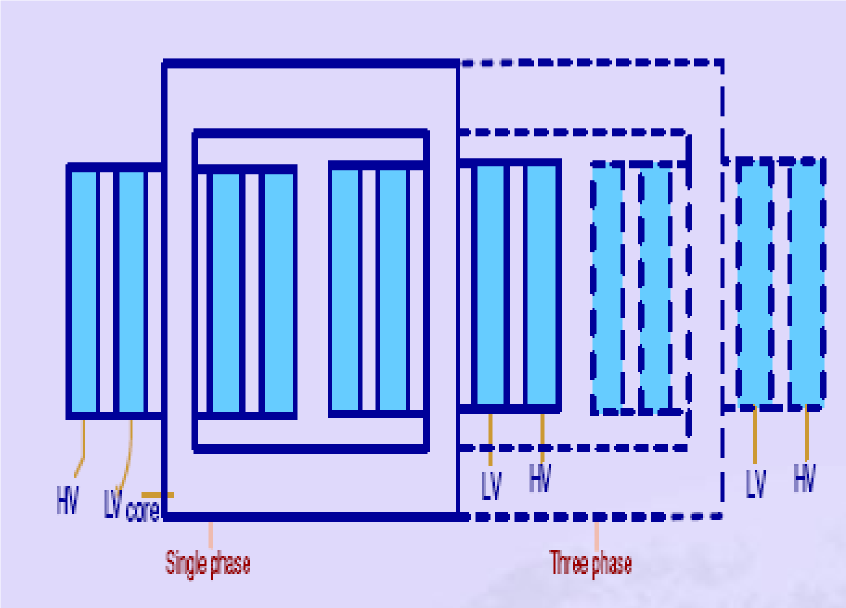
Ultra high Voltage Transformer

Classification of Transformers

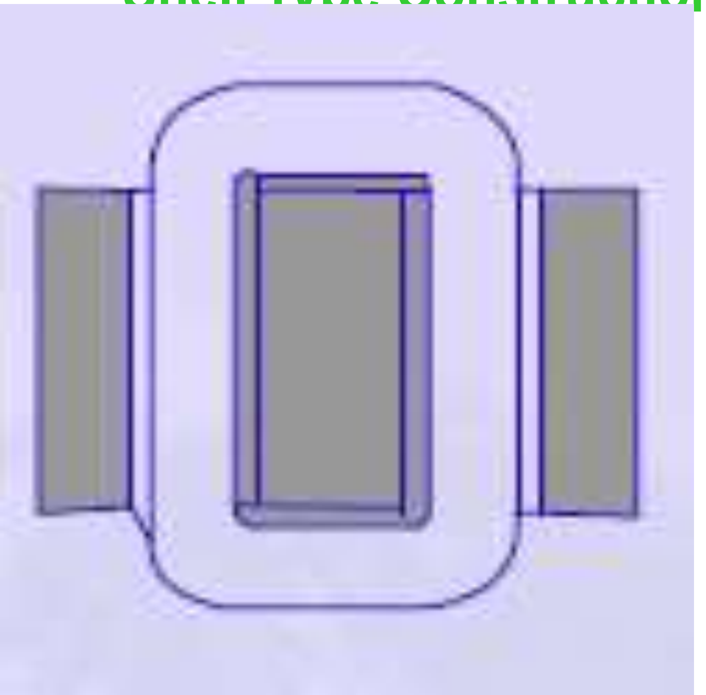
- Transformers
  - Based on Core
    - Core Type
    - Shell Type
  - Based on Transformer Ratio
    - Step Up
    - Step Down
    - One-to-one (Isolation)

Transformer Core

Core type Construction



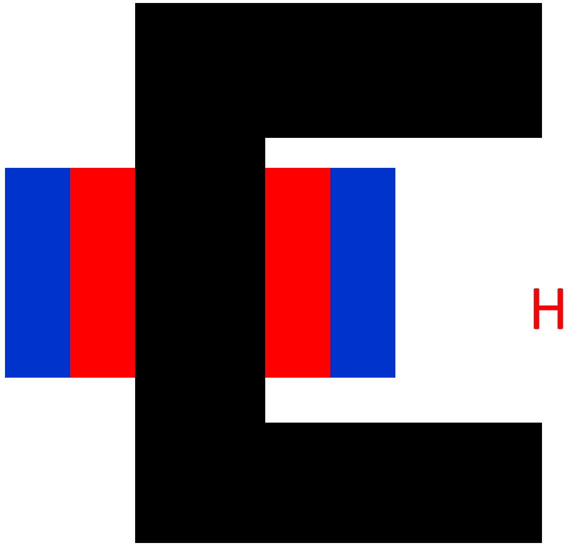
Shell Type Construction



Winding Types

- Three types

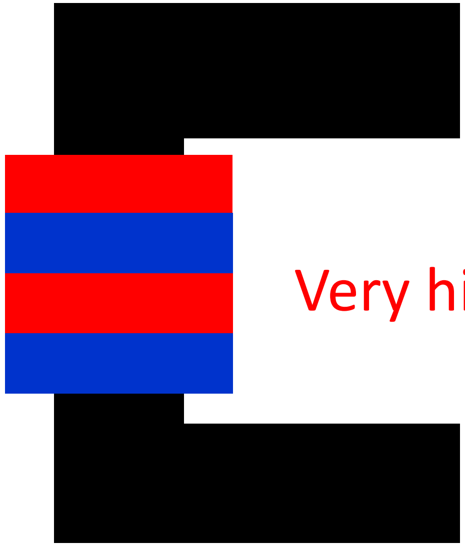
Concentric



Higher voltage closest to Iron

Winding Types

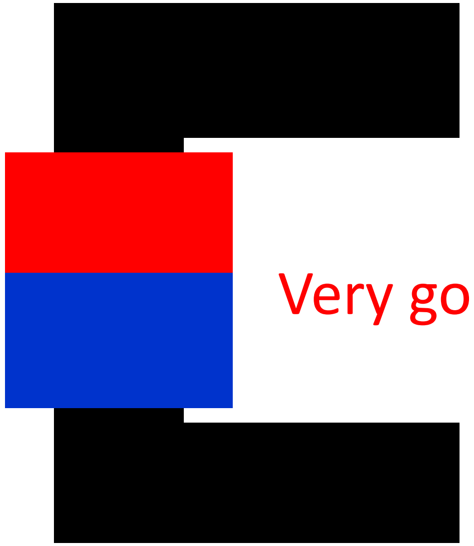
Sandwich or Pancake



Very high voltages on both windings

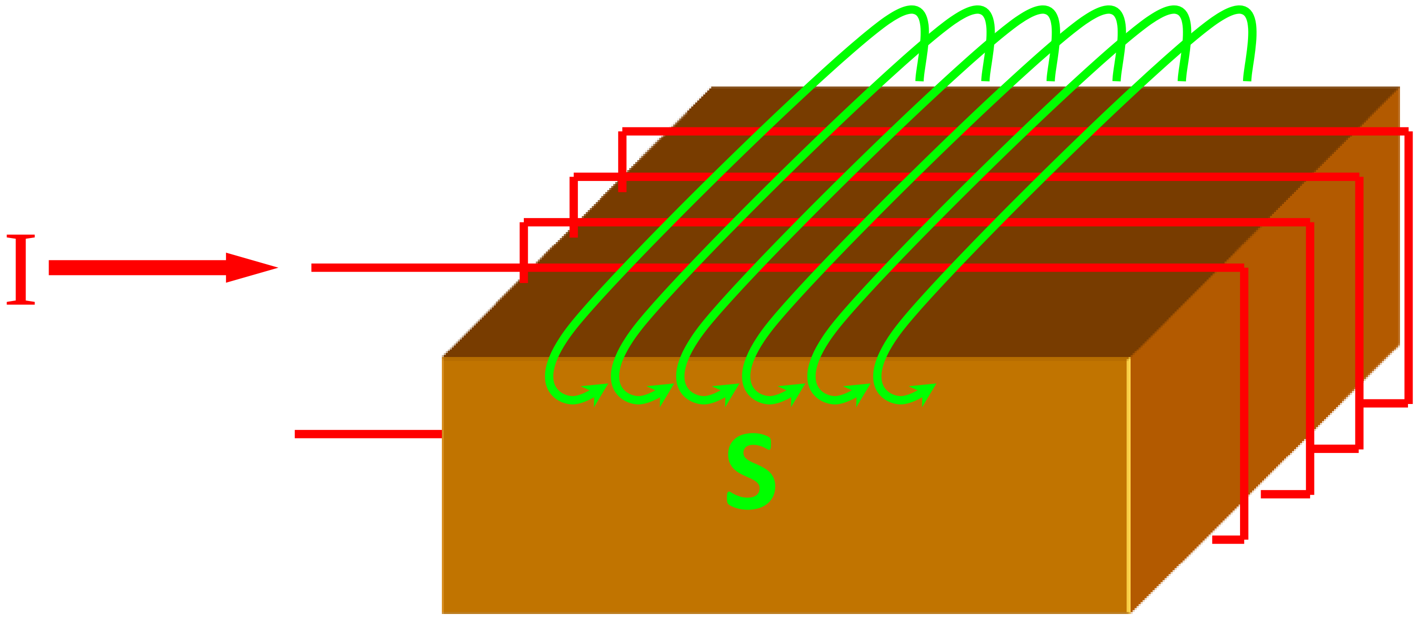
Winding Types

Side by Side



Very good insulation between windings

Why do we laminate the core?



Basic Types of Transformer

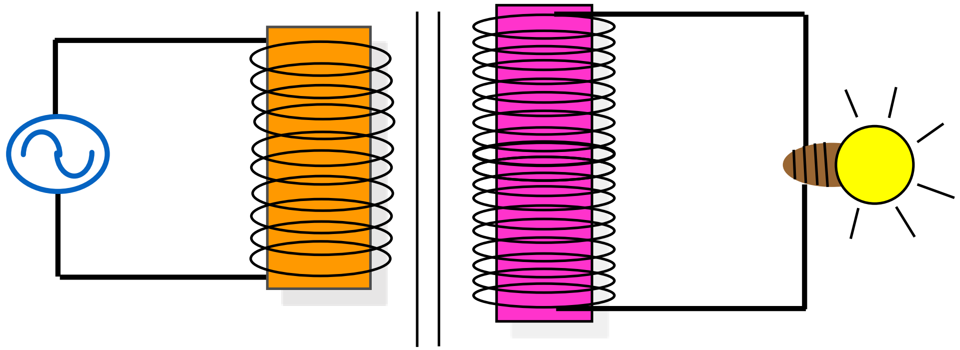
- Based on TURNS RATIO

1. **Step-up**

   turns ratio > 1

   $V_S > V_P$

   $I_S < I_P$

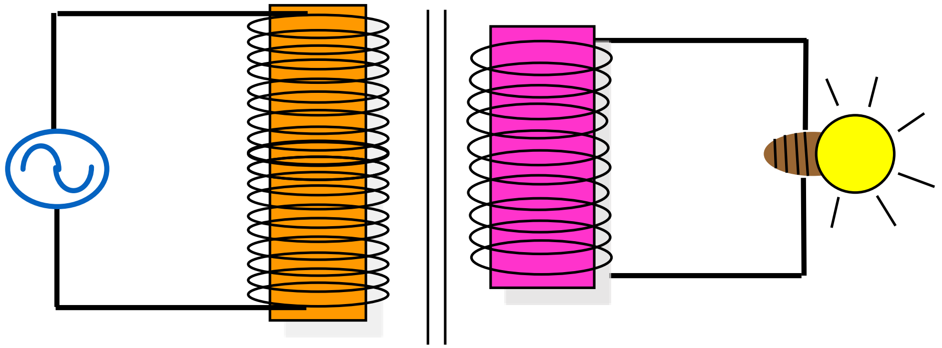


2. **Step-down**

   turns ratio < 1

   $V_S < V_P$

   $I_S > I_P$



Transformer Symbols

N_P = number of turns in the primary

N_S = number of turns in the secondary

V_P or E_P or V_1 = voltage of the primary

V_S or E_S or V_2 = voltage of the secondary

I_P or I_1 = current in the primary

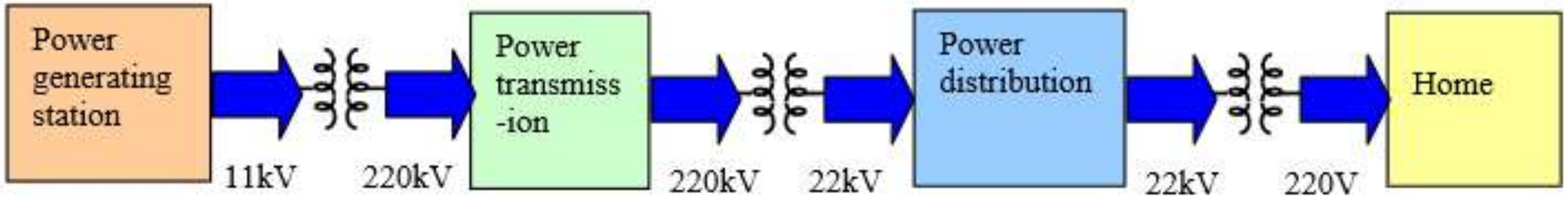
I_S or I_2 = current in the secondary

Application Example of Transformer

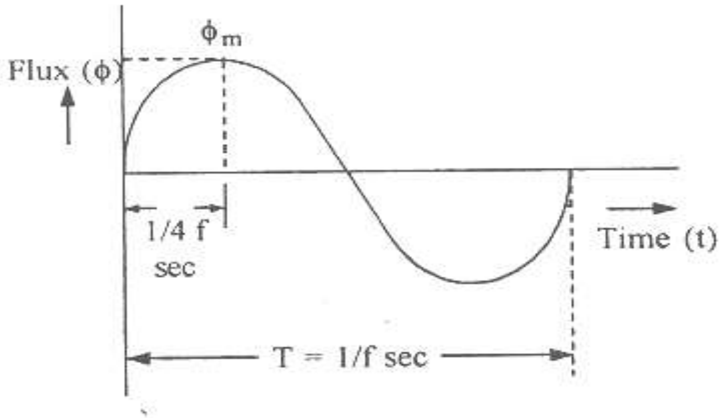
- Transformers are a necessary part of all power supplies.

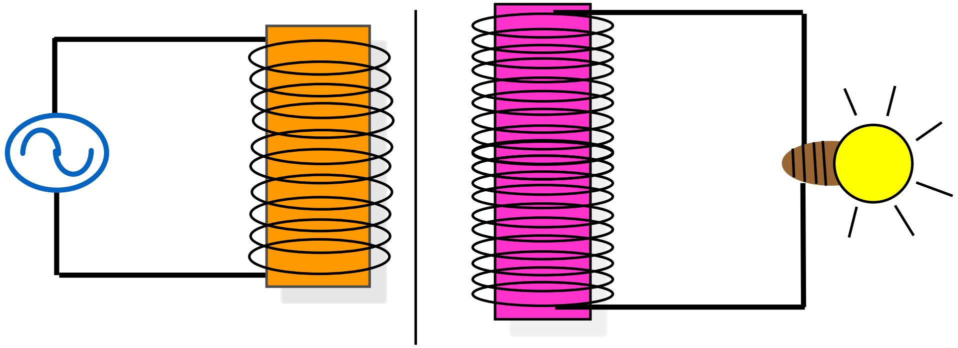
Application Example of Transformer

- Power distribution systems



EMF Induced in Transformer





Flux ϕ is produced which is given by an equation

$$\Phi = N_p i_p / S \qquad \text{.......(1)}$$

where S is the reluctance

EMF Induced in Transformer

According to Faraday law of electromagnetic induction

$$v_{\mathrm{p}} = \mathrm{N}_{\mathrm{p}} \frac{\mathrm{d}\varphi}{\mathrm{dt}} \qquad \text{......(2)}$$

Substitute $\Phi = \mathrm{N}_p i_{\mathrm{p}}/\mathrm{S}$ into the above equation , then

$$v_{\mathrm{p}} = \frac{\mathrm{N}_{\mathrm{p}}^{\ 2}}{S} \times \frac{\mathrm{d}}{\mathrm{dt}}(i_{\mathrm{p}}) \qquad \text{......(3)}$$

EMF Induced in Transformer

If i_p is sinusoidal, the flux produced also sinusoidal, i.e

$$\Phi = \Phi_m \sin 2\pi ft \qquad \text{......(4)}$$

therefore $$v_p = N_p \frac{d(\Phi_m \sin 2\pi ft)}{dt}$$

$$v_p = N_P 2\pi f\Phi_m \cos 2\pi ft = N_P 2\pi f\Phi_m \sin(2\pi ft + \pi/2) \qquad \text{......(5)}$$

The peak value = $V_{pm} = N_P 2\pi f\Phi_m$ ......(6)

and v_p is leading the flux by p/2.

The rms value $$V_p = \frac{V_{pm}}{\sqrt{2}} = 0.707 \times N_P 2\pi f\Phi_m = 4.44 N_P f\Phi_m \qquad \text{......(7)}$$

EMF Induced in Transformer

From (2) and (8) we get

$$\frac{V_s}{V_p} = \frac{N_s}{N_p}$$

$$N_p I_p = N_s I_s$$

rearrange

$$\frac{I_p}{I_s} = \frac{N_s}{N_p}$$

Transformer Rating

- If a transformer carries the 10kVA, 1100/110volts information on its name-plate. **What are the meanings of these ratings?**
- Voltage ratio indicates that the transformer has two windings,
  - high-voltage winding is rated for 1100 Volts and
  - low-voltage winding for 110 volts.
- The kVA rating means that each winding is designed for 10 kVA.
  - current rating for the high-voltage winding = 10000/1100 = 9.09A
  - Current rating for low voltage winding = 10000/110 = 90.9 A

Problem

Worked Example No.1

A 250 kVA,11000V/400V, 50Hz single –phase transformer has 80 turns on the secondary. Calculate

(a) The appropriate values of the primary and secondary currents;

(b) The approximate number of primary turns;

(c) the maximum value of the flux.

(a) Full-load primary current $I_p = \frac{P}{V_p} = \frac{250 \times 10^3}{11000} = 22.7A$

Full-load secondary current $I_s = \frac{\mathrm{P}}{\mathrm{V_s}} = \frac{250 \times 10^{-3}}{400} = 625A$

Problem

(b) Number of primary turns

recall $$\frac{V_s}{V_p} = \frac{N_s}{N_p}$$

$$\longrightarrow \quad N_P = \frac{N_s}{V_s} \times V_P = \frac{80}{400} \times 11000 = 2200$$

(c) Maximum flux

recall $$E = 4.44\, N\, f\, \Phi_m$$

$$\Phi_m = \frac{E_s}{4.44\, N_s\, f} = \frac{400}{4.44 \times 80 \times 50} = 22.5mWb$$

Problem

(b) Number of primary turns

recall $$\frac{V_s}{V_p} = \frac{N_s}{N_p}$$

$$\longrightarrow \quad N_P = \frac{N_s}{V_s} \times V_P = \frac{80}{400} \times 11000 = 2200$$

(c) Maximum flux

recall $$E = 4.44\, N\, f\, \Phi_m$$

$$\Phi_m = \frac{E_s}{4.44\, N_s\, f} = \frac{400}{4.44 \times 80 \times 50} = 22.5mWb$$

Ideal Transformers

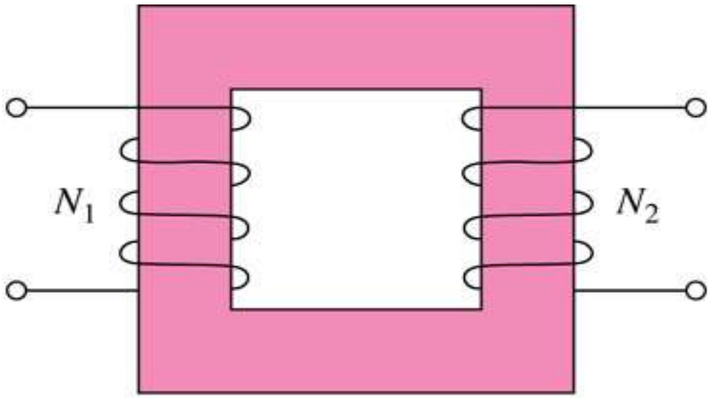
- Ideal Transformer is a unity coupled, lossless transformer in which the primary and secondary coils have infinite self inductances.

Transformer is ideal if:

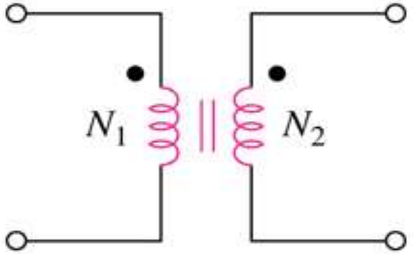
1) Large reactance coils; $L_1, L_2, M \to \infty$

2) Unity Coupling k=1.

3) Coils are lossless ($R_1=R_2=0$)



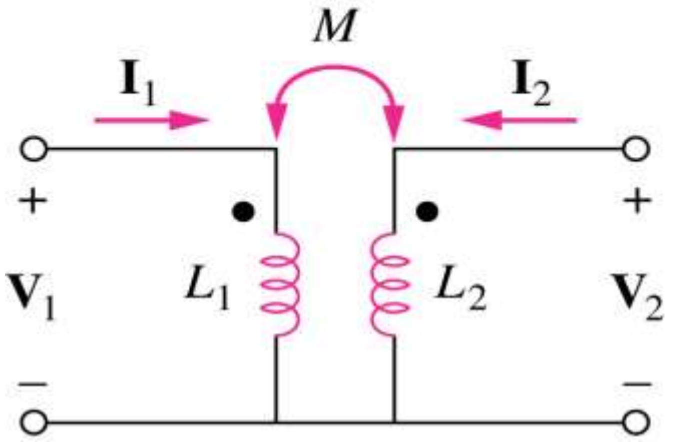
Ideal transformer



Circuit symbol for the Ideal transformer

Variables of an Ideal Transformers

- Input and Output voltages and currents of an ideal transformer are related only by the turns ratio.



$$V_1 = j\omega L_1 I_1 + j\omega M I_2 \qquad I_1 = \frac{V_1 - j\omega M I_2}{j\omega L_1}$$

$$V_2 = j\omega M I_1 + j\omega L_2 I_2 \qquad V_2 = j\omega L_2 I_2 + \frac{MV_1}{L_1} - \frac{j\omega M^2 I_2}{L_1}$$

Perfect Coupling $k = 1$, Thus we have $M = \sqrt{L_1 L_2}$ Substitute

$$V_2 = j\omega L_2 I_2 + \frac{\sqrt{L_1 L_2} V_1}{L_1} - \frac{j\omega L_1 L_2 I_2}{L_1} = \sqrt{\frac{L_2}{L_1}} V_1 = nV_1 = \frac{N_2}{N_1} V_1$$

$$\boxed{\frac{V_2}{V_1} = \frac{N_2}{N_1} = n = \text{Turns Ratio}}$$

Turns Ratio of an Ideal Transformers

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$$\frac{V_2}{V_1} = \frac{N_2}{N_1} = n = \text{Turns Ratio}$$

- A Ideal Transformer is called:

  1) Step-up transformer if n > 1.

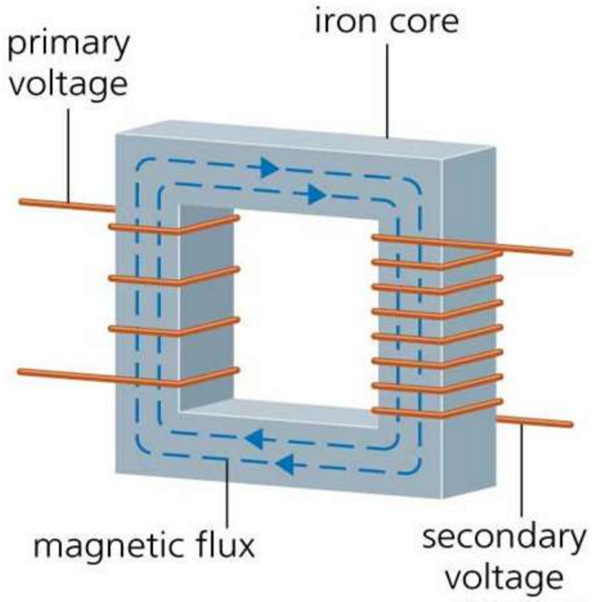
  2) Step-down transformer if n < 1.

  3) Isolation transformer if n=1.

Practical Transformer

Practical transformer has

- Copper resistance
- Leakage flux
- Finite core permeability (i.e., finite inductance)
- Core loss



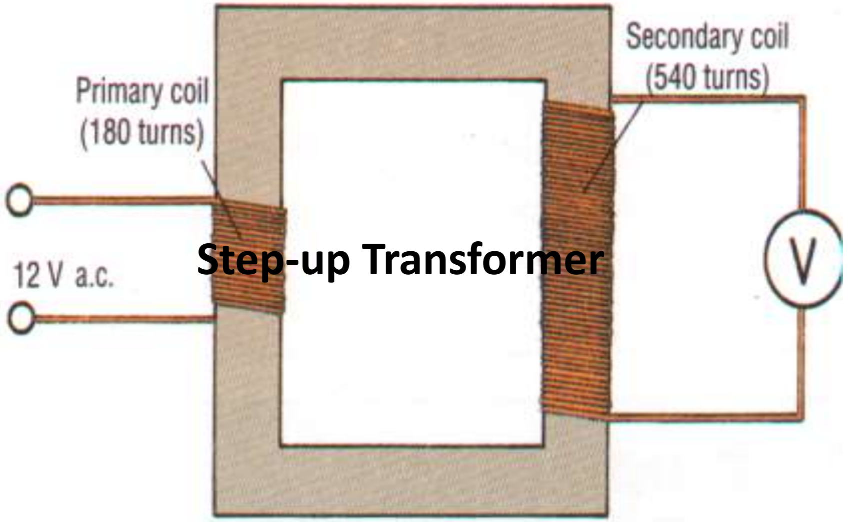
Note: Practically no transformer is ideal .knowledge of ideal transformer helps us to develop the concept of behavior of practical transformer

Problem

Worked Example No.2

The diagram shows a transformer. Calculate the voltage across the secondary coil of this transformer.

Solution



$$\frac{V_P}{V_S} = \frac{N_P}{N_S}$$

Substituting

$$\frac{12}{V_S} = \frac{180}{540}$$

Crossmultiplying

$$180.V_S = 12 \text{ x } 540$$

$$\therefore V_S = \frac{12 \text{ x } 540}{180}$$

$$\therefore V_S = 36 \text{ V}$$

Problem

Worked Example No. 3:

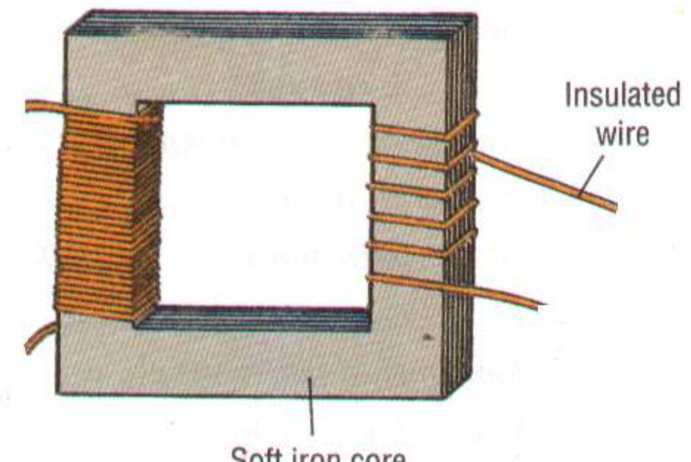
A transformer which has 1380 turns in its primary coil is to be used to convert the mains voltage of 230 V to operate a 6 V bulb. How many turns should the secondary coil of this transformer have?

Solution

$V_P = 230$ V $V_S = 6$ V

$N_P = 1380$ $N_S = ?$

Step-down Transformer



$$\frac{V_P}{V_S} = \frac{N_P}{N_S}$$

Substituting

$$\frac{230}{6} = \frac{1380}{N_s}$$

Crossmultiplying

$$2300.N_S = 6 \text{ x } 13800$$

$$\therefore N_S = \frac{6 \text{ x } 1380}{230}$$

$$\therefore N_S = 36 \text{ turns}$$

Summary

- Transformer is a very common magnetic structure found in many everyday applications.
- Transformer couples two circuits magnetically rather than through any direct connection.
- Transformers are used to raise or lower voltage and current between one circuit and the other, and plays a major role in almost all AC circuits.
- Transformer works on the principle of mutual induction
- EMF equation of Transformer is $E = 4.44\, N\, f\, \Phi_m$
- Losses are zero in an ideal transformer
- An ideal transformer divides a sinusoidal input voltage by a factor of a and multiplies a sinusoidal input current by a to obtain secondary voltage and current.
- If a transformer increases the voltage, the current decreases and vice versa.

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Problem 3:

A single-phase, 50 Hz transformer has 40 primary turns and 520 secondary turns. The cross-sectional area of the core is 270 cm2.When the primary winding is connected to a 300 volt supply, determine the

(a) maximum value of flux density in the core and

(b) voltage induced in the secondary winding

Problem 4:

A 3.3 kV/110 V, 50 Hz, single-phase transformer is to have an approximate e.m.f. per turn of 22V and operate with a maximum flux of 1.25 T. Calculate the

(a) number of primary and secondary turns and

(b) crosssectional area of the core