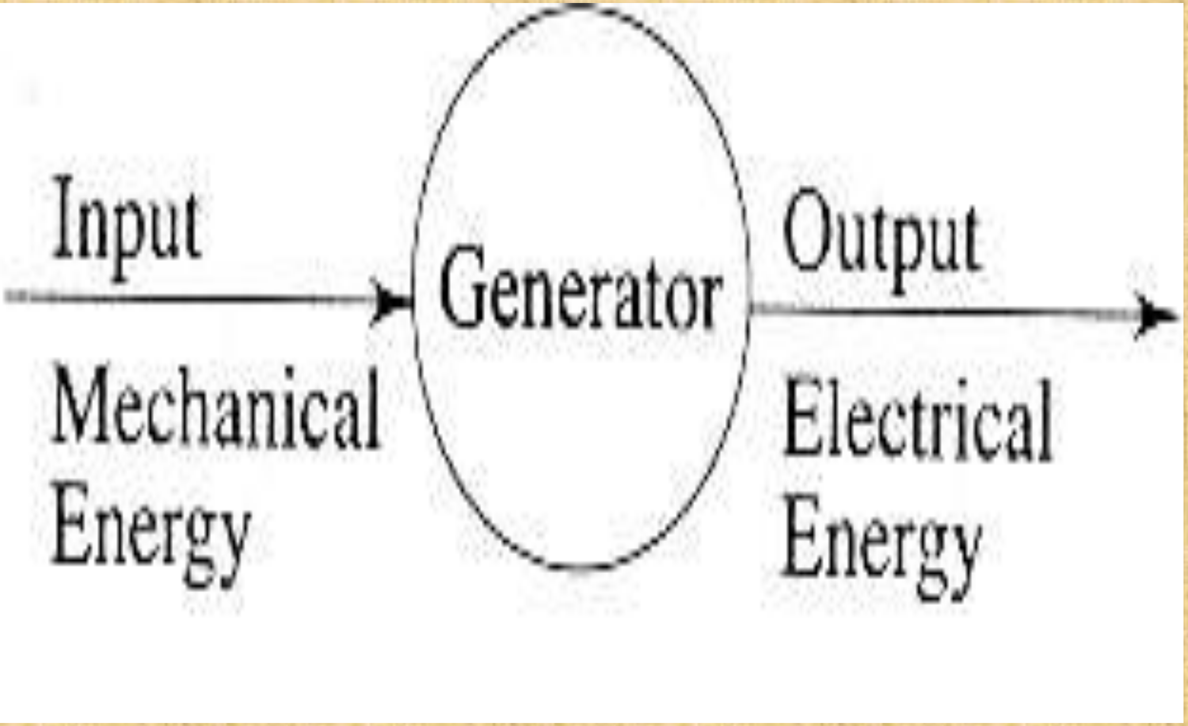
UNIT - I

D.C. GENERATORS

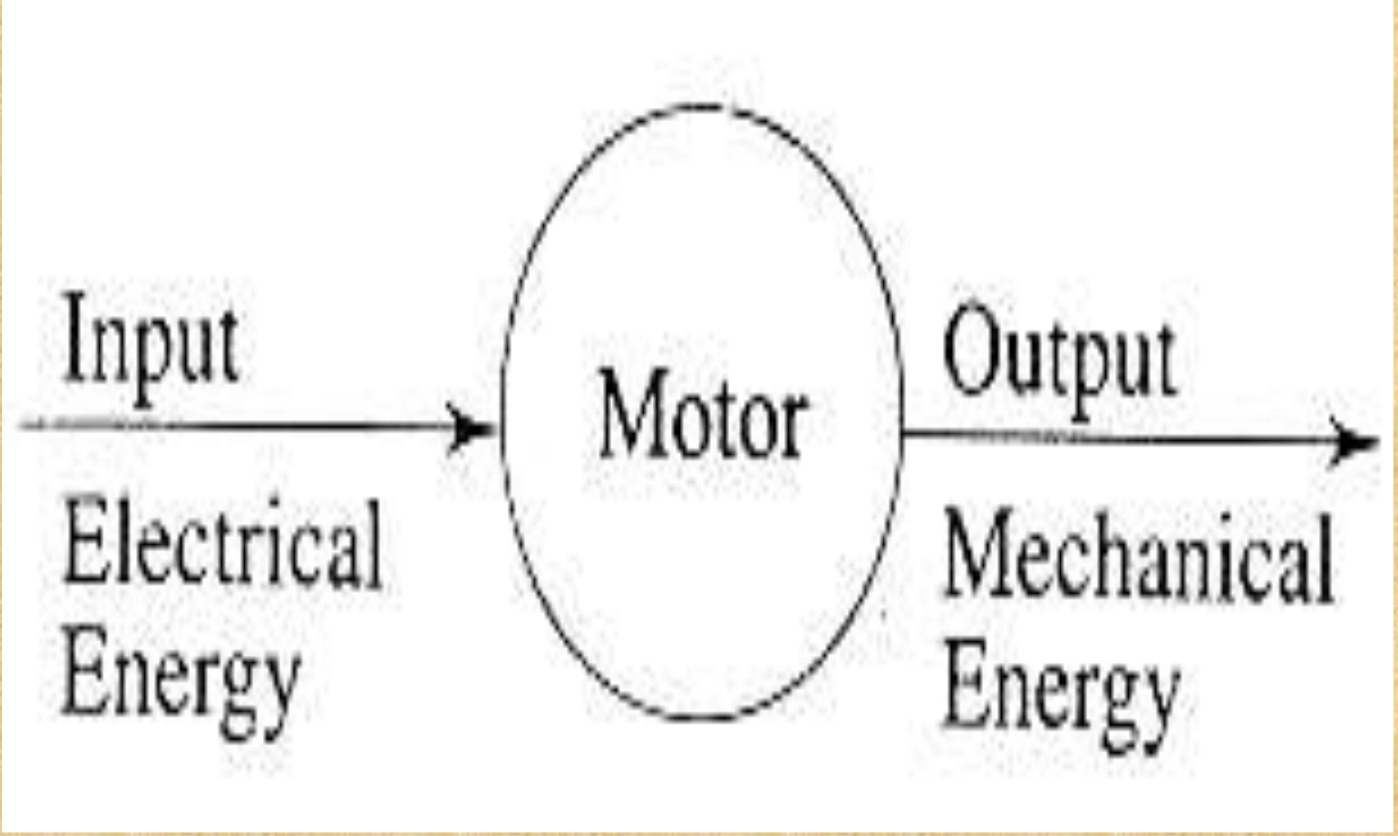
D.C. GENERATORS-CONSTRUCTION & OPERATION

- DC Generators
- Principle of operation
- Action of Commutator
- Constructional details of DC Machine
- Types of DC generators
- EMF Equation

DC Generator



DC motor



D.C. GENERATORS PRINCIPLE OF OPERATION

- DC generator converts mechanical energy into electrical energy. when a conductor move in a magnetic field in such a way conductors cuts across a magnetic flux of lines and e.m.f. produces in a generator and it is defined by faradays law of electromagnetic induction e.m.f. causes current to flow if the conductor circuit is closed.

Faradays laws

First Law :

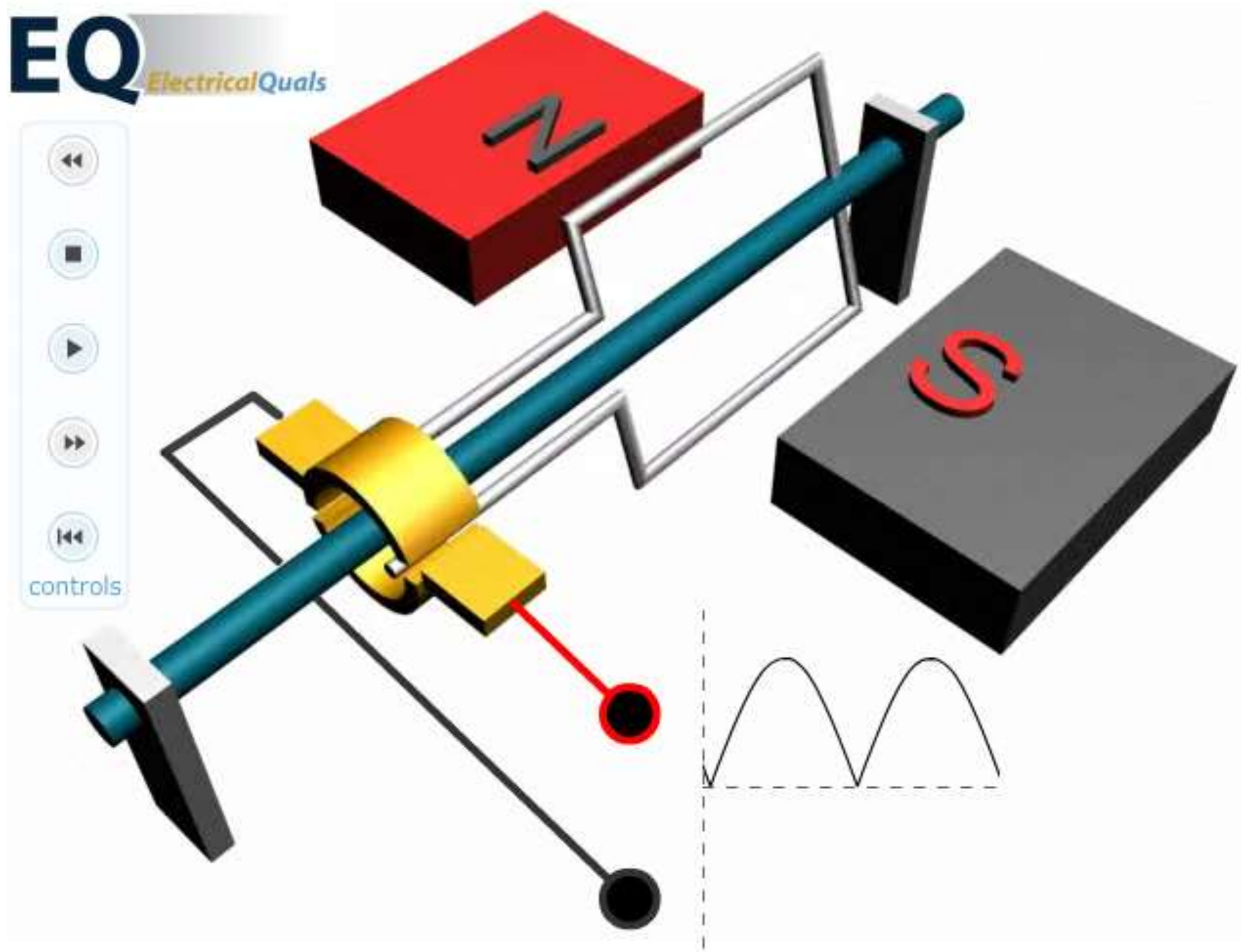
Whenever the magnetic flux linked with a circuit changes, an e.m.f. is always induced in it.

or

Whenever a conductor cuts magnetic flux, an e.m.f. is induced in that conductor.

Second Law :

The magnitude of the induced e.m.f. is equal to the rate of change of flux linkages.



EQ
ElectricalQuals
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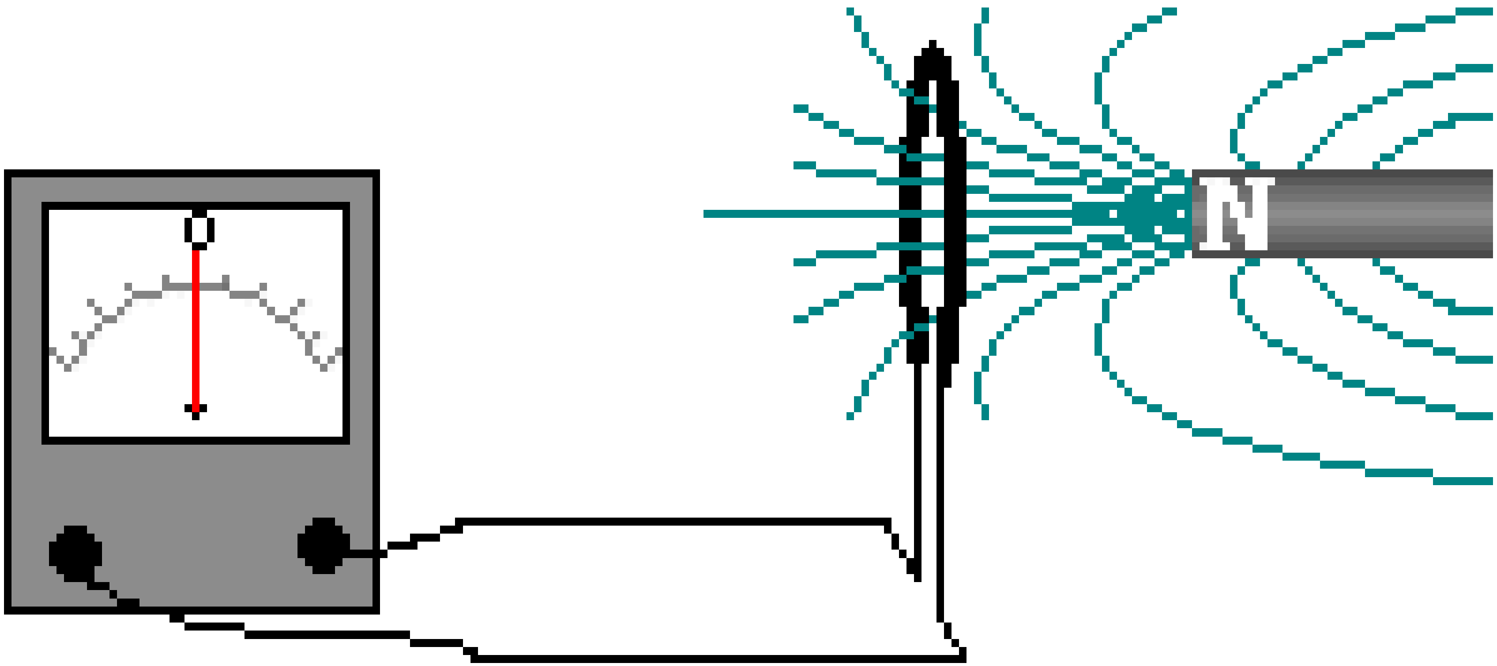
N
S

Faradays Law of Electromagnetic Induction

A changing magnetic flux through a loop or loops of wire induces an electromotive force (voltage) in each loop.



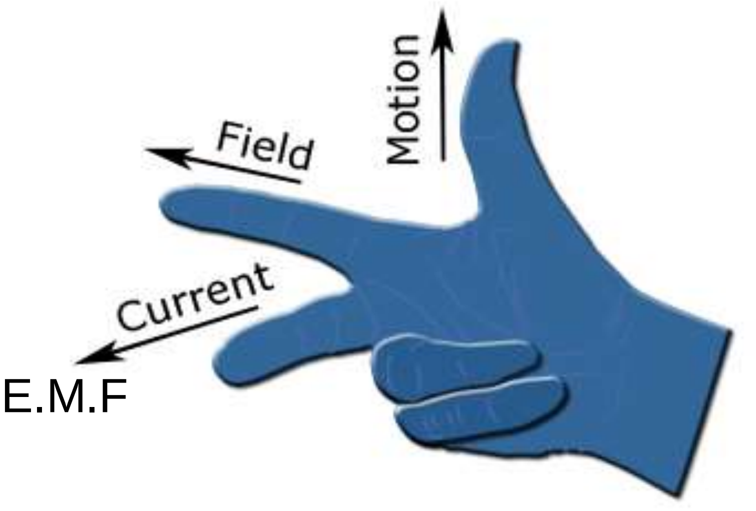
<u>Lenz's Law</u>

"The induced currents in a conductor are in such a direction as to oppose the change in magnetic field that produces them.."

OR

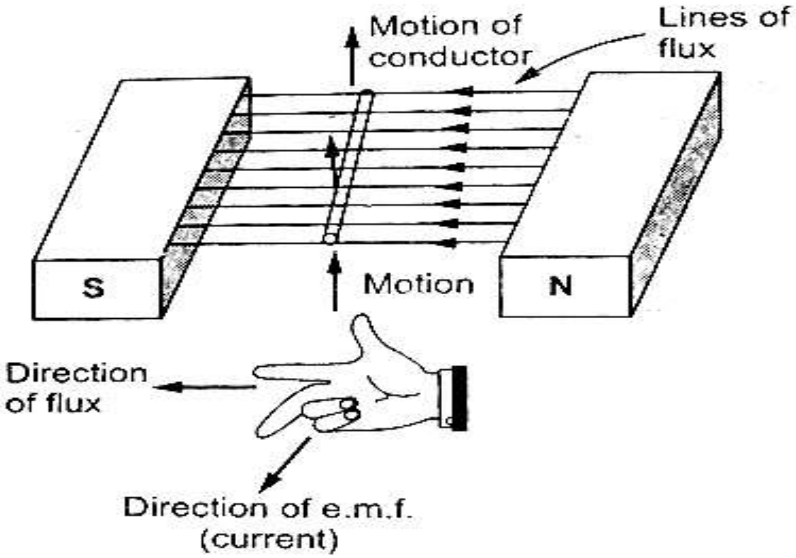
"The direction of induced E.M.F in a coil (conductor) is such that it opposes the cause of producing it.."

Fleming's Right Hand Rule



- **The Thumb represents the direction of Motion of the conductor.**
- **The First finger (four finger) represents Field.**
- **The Second finger (Middle finger) represents Current**

Fleming's Right Hand Rule

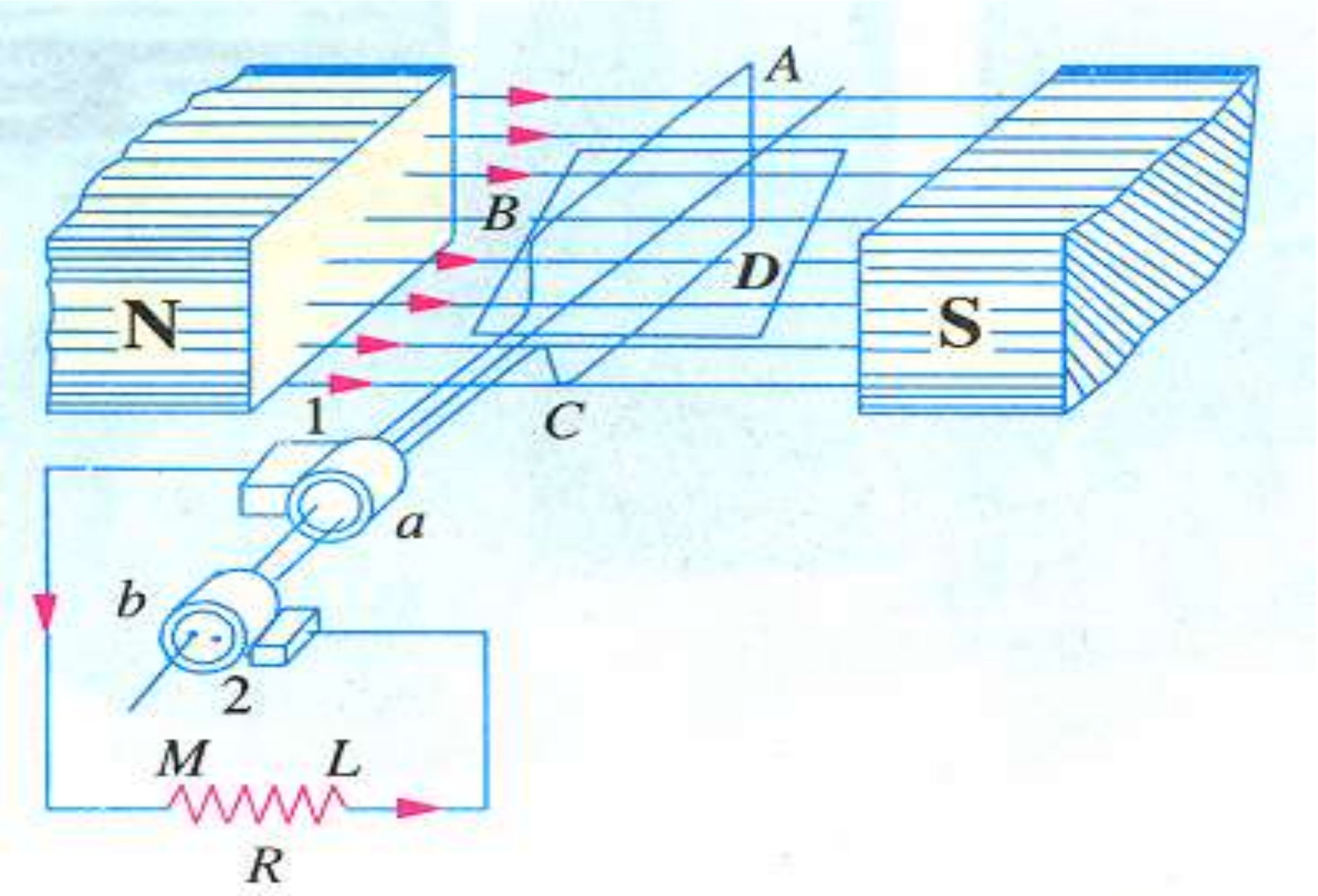


The following are the basic requirements to be satisfied for generation of E.M.F

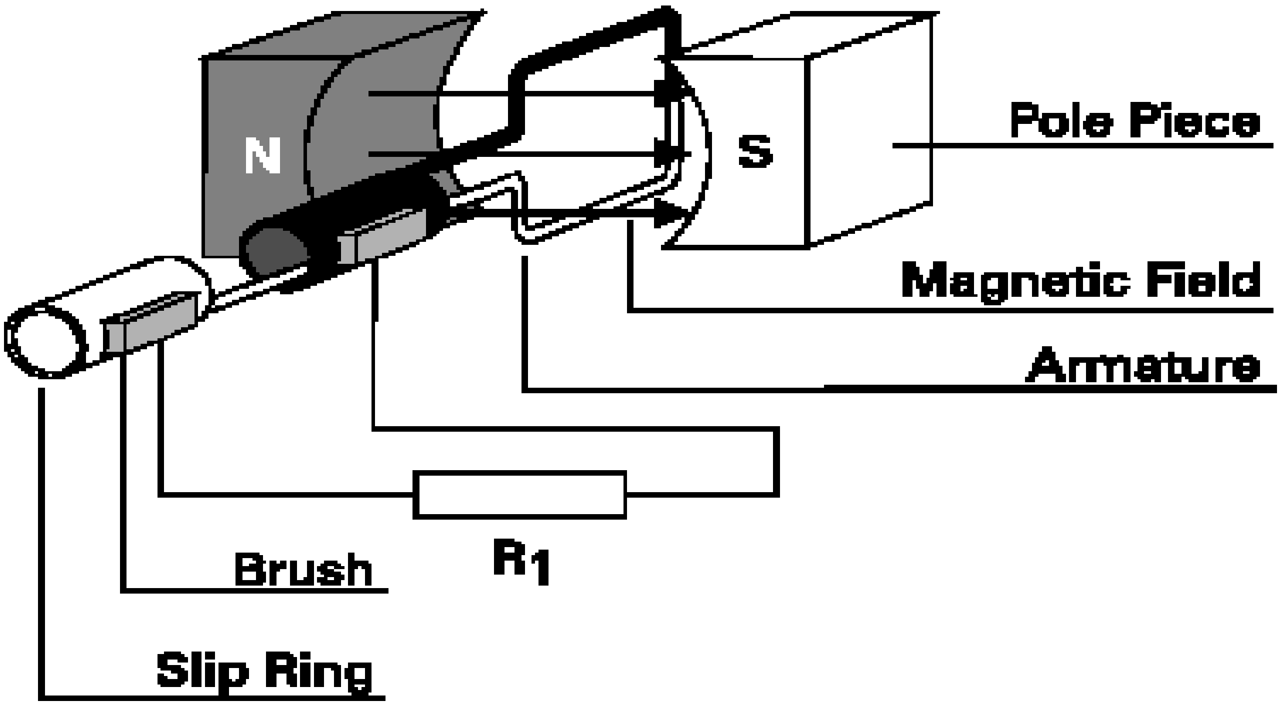
1. A uniform Magnetic field
2. A System of conductors
3. Relative motion between the magnetic field and conductors

- **Magnetic field :-**
  Permanent Magnet
  (or)
  Electro Magnet (practical)
- **Conductor :- Copper (or) Aluminum bars placed in slots cut around the periphery of cylindrical rotor**
- **Relative motion:-**
  By Prime Mover
  Turbine
  I.C Engine (Internal combustion)

Simple loop generator



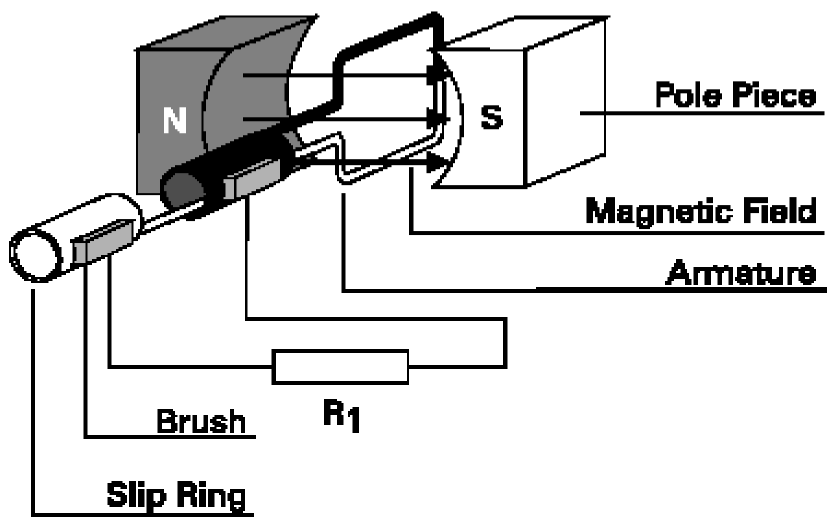
Basic Generator



Generators

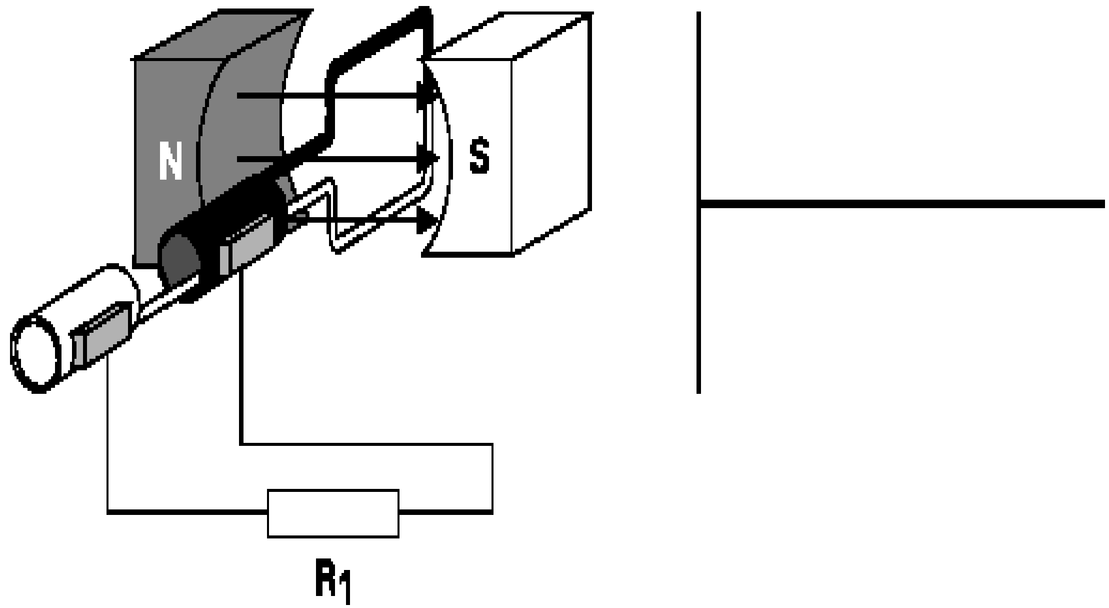
Basic generator

A basic generator consists of a magnetic field, an armature, slip rings, brushes and a resistive load. The magnetic field is usually an electromagnet. An armature is any number of conductive wires wound in loops which rotates through the magnetic field. For simplicity, one loop is shown. When a conductor is moved through a magnetic field, a voltage is induced in the conductor. As the armature rotates through the magnetic field, a voltage is generated in the armature which causes current to flow. Slip rings are attached to the armature and rotate with it. Carbon brushes ride against the slip rings to conduct current from the armature to a resistive load.



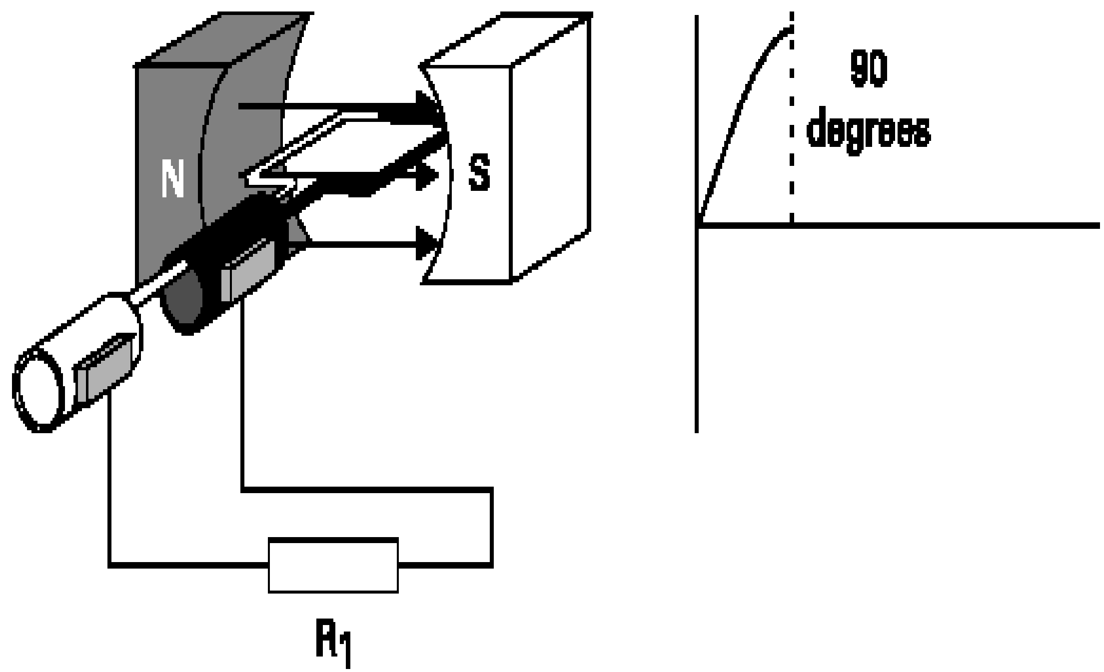
Basic generator operation

An armature rotates through the magnetic field. At an initial position of zero degrees, the armature conductors are moving parallel to the magnetic field and not cutting through any magnetic lines of flux. No voltage is induced.



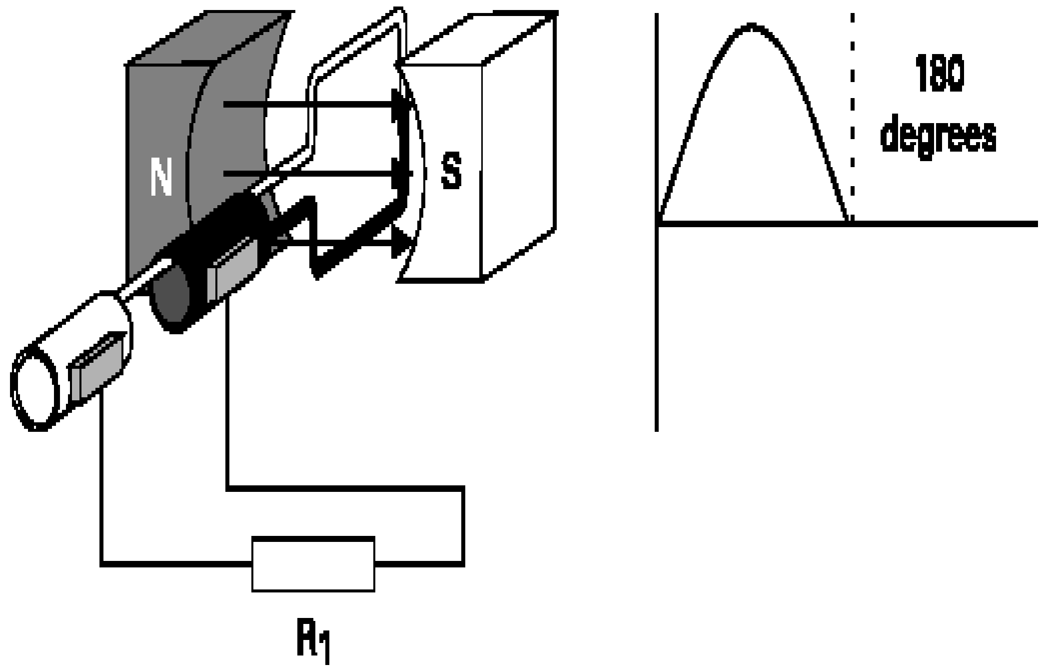
Generator operation from zero to 90 degrees

The armature rotates from zero to 90 degrees. The conductors cut through more and more lines of flux, building up to a maximum induced voltage in the positive direction.



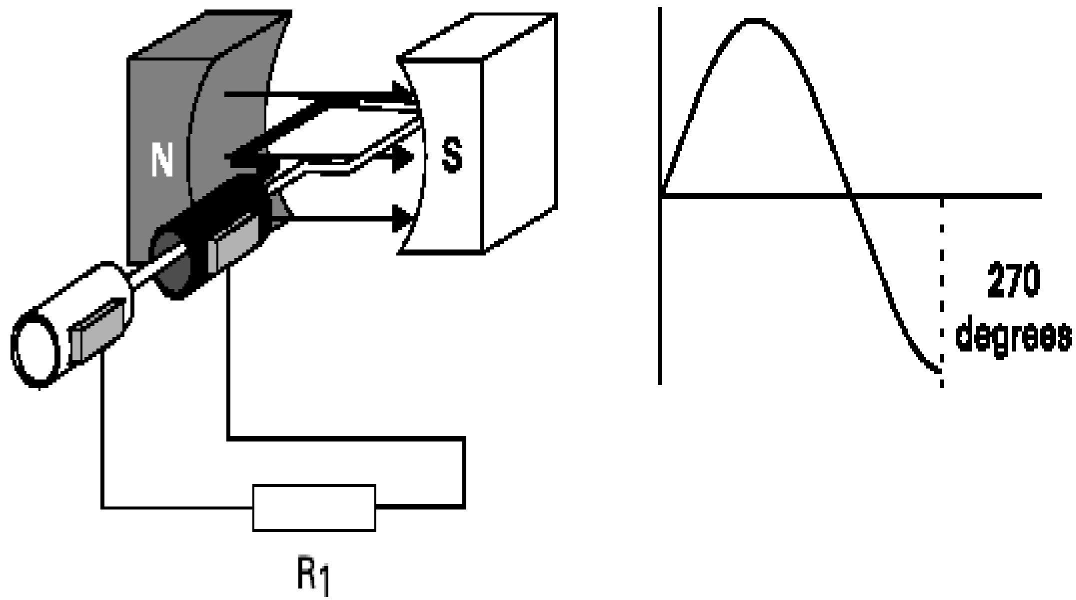
Generator operation from 90 to 180 degrees

The armature continues to rotate from 90 to 180 degrees, cutting less lines of flux. The induced voltage decreases from a maximum positive value to zero.



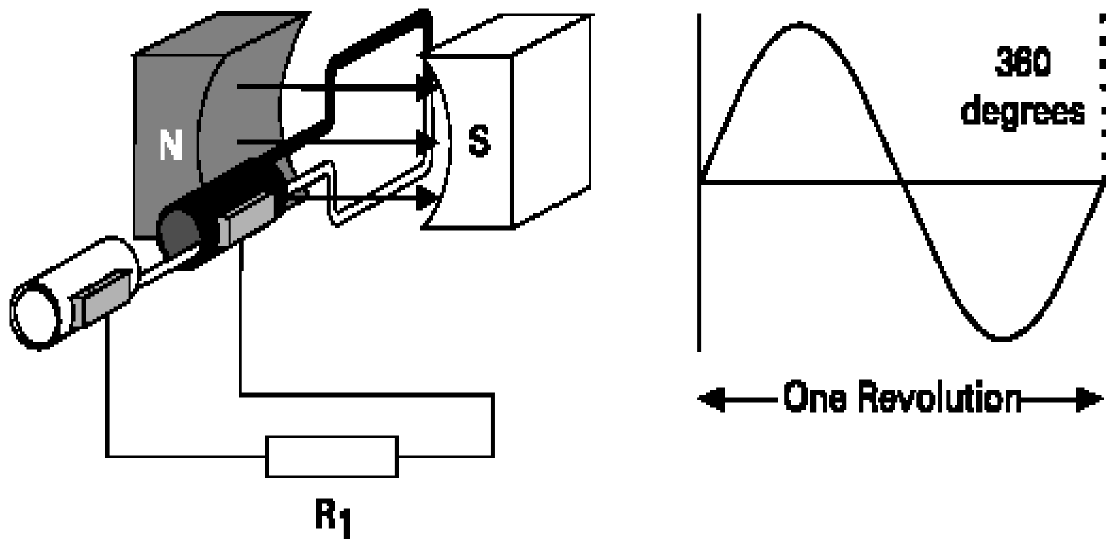
Generator operation from 180 to 270 degrees

The armature continues to rotate from 180 degrees to 270 degrees. The conductors cut more and more lines of flux, but in the opposite direction. Voltage is induced in the negative direction building up to a maximum at 270 degrees.

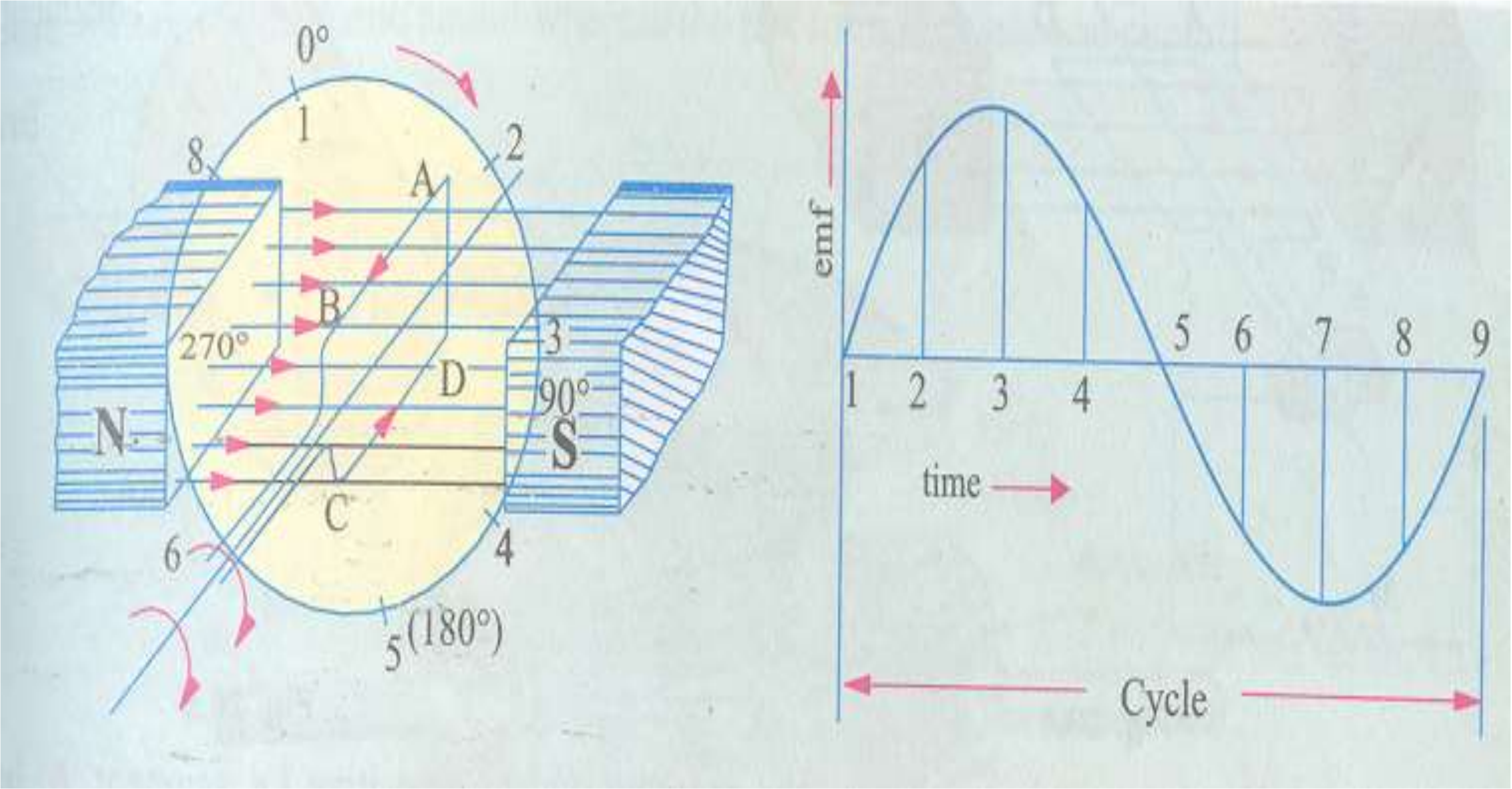


Generator operation from 270 to 360 degrees

The armature continues to rotate from 270 to 360 degrees. Induced voltage decreases from a maximum negative value to zero. This completes one cycle. The armature will continue to rotate at a constant speed. The cycle will continuously repeat as long as the armature rotates.



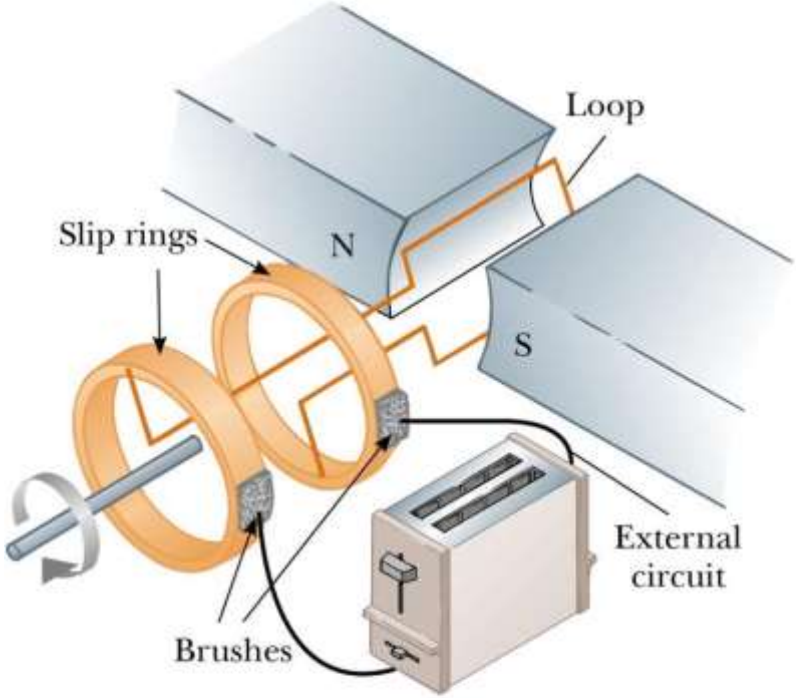
Simple loop generator with slip ring



Generators

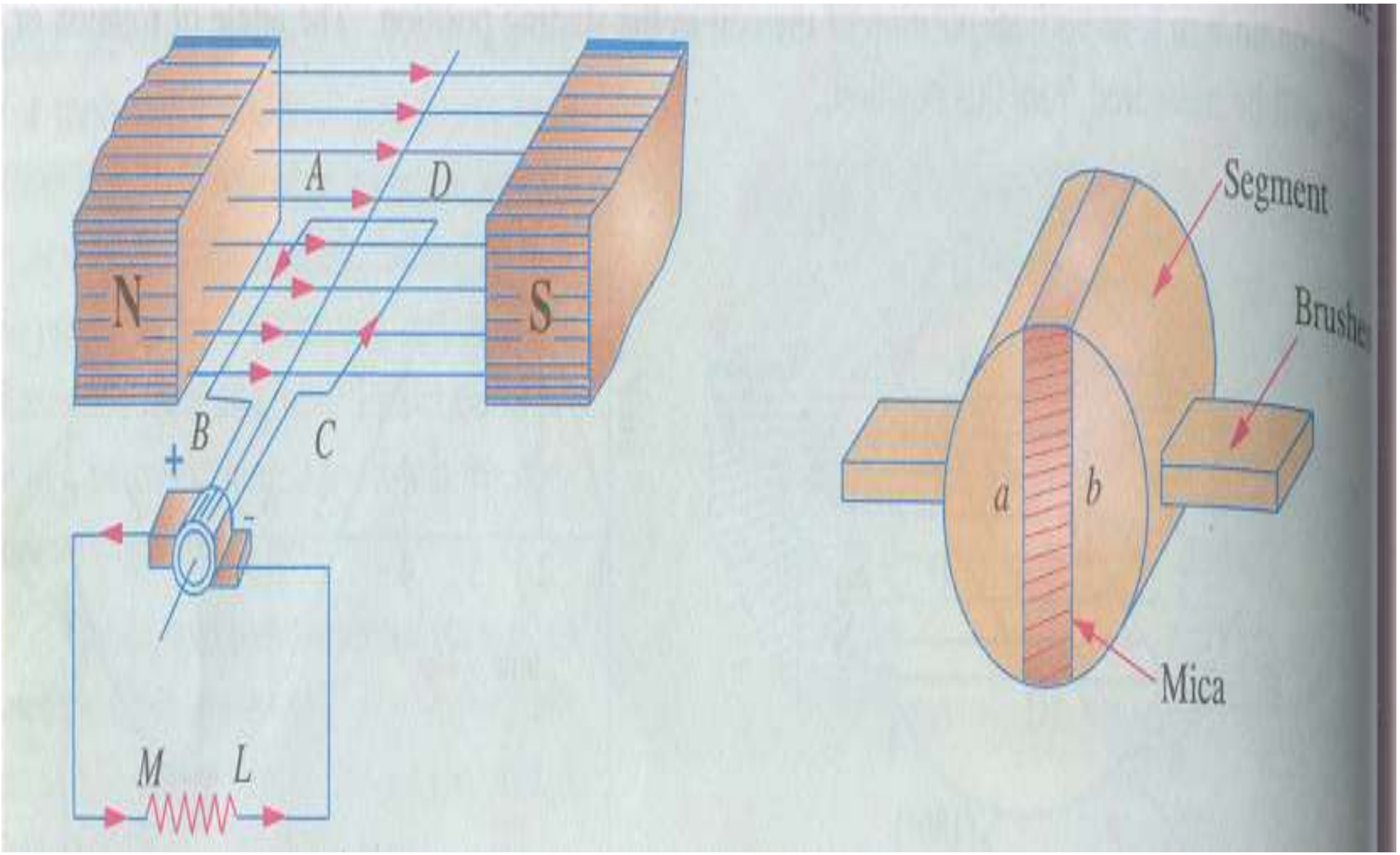
Basic operation of the generator

- As the loop rotates, the magnetic flux through it changes with time
- This induces an e.m.f and a current in the external circuit
- The ends of the loop are connected to slip rings that rotate with the loop
- Connections to the external circuit are made by stationary brushes in contact with the slip rings

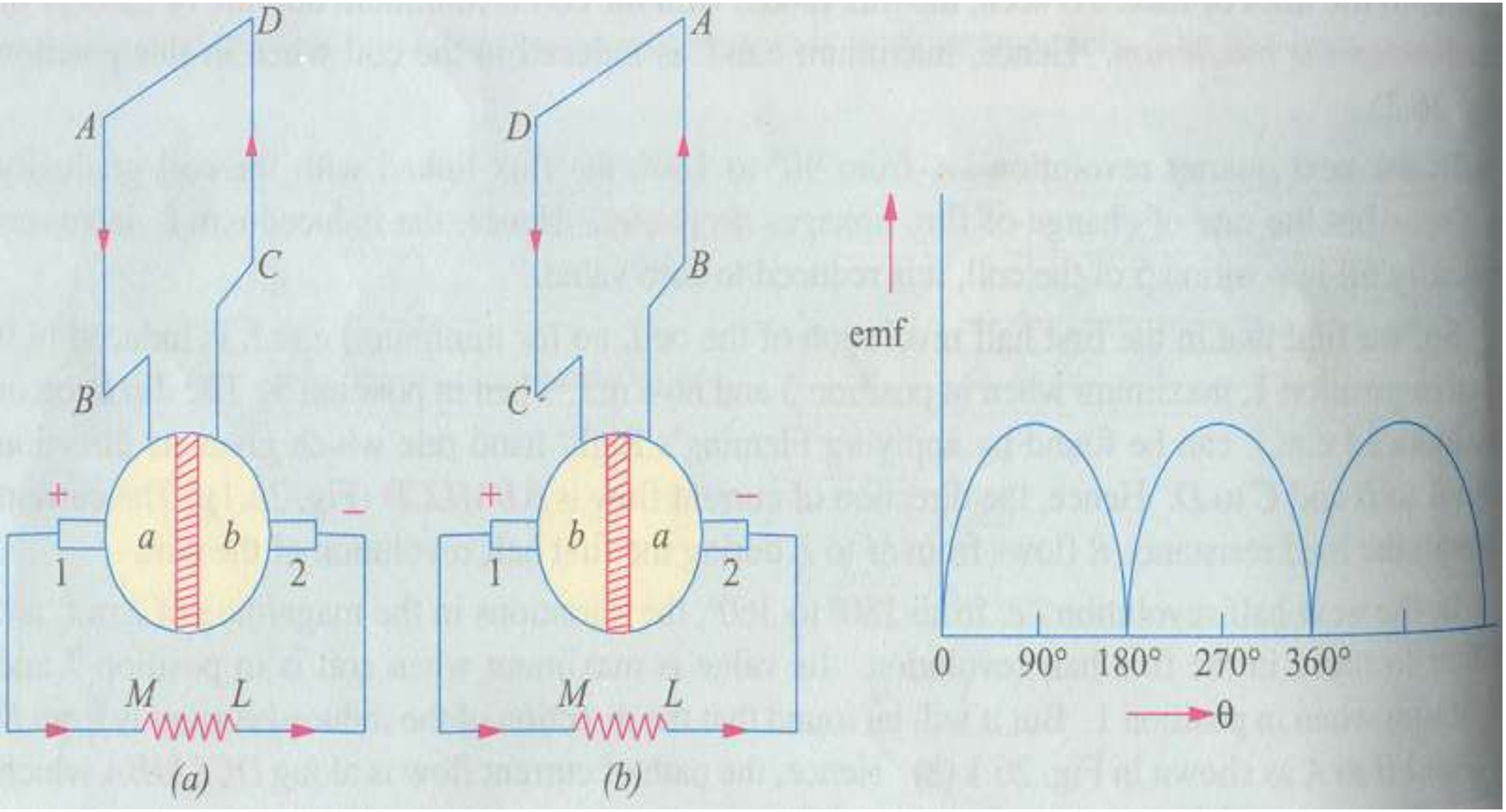


(a)

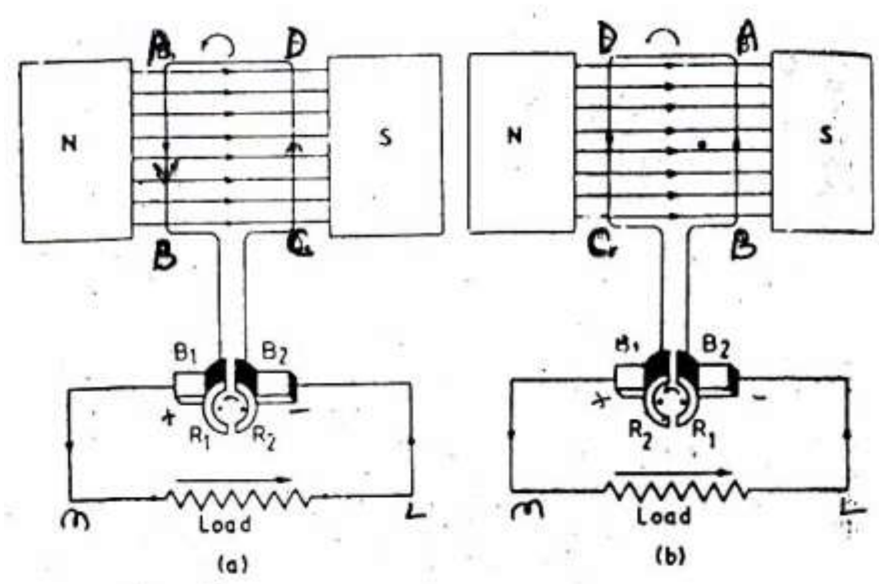
Simple loop generator with split ring



Simple loop generator with split ring



Working Principle of D.C Generator



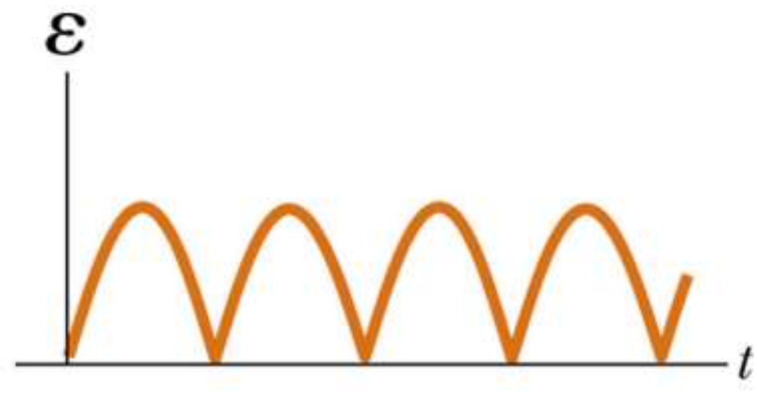
Schematic diagram of a simple DC Generator

1st half cycle(0^0 to 180^0) Path of current $ABR_1B_1\underline{ML}R_2B_2CD$

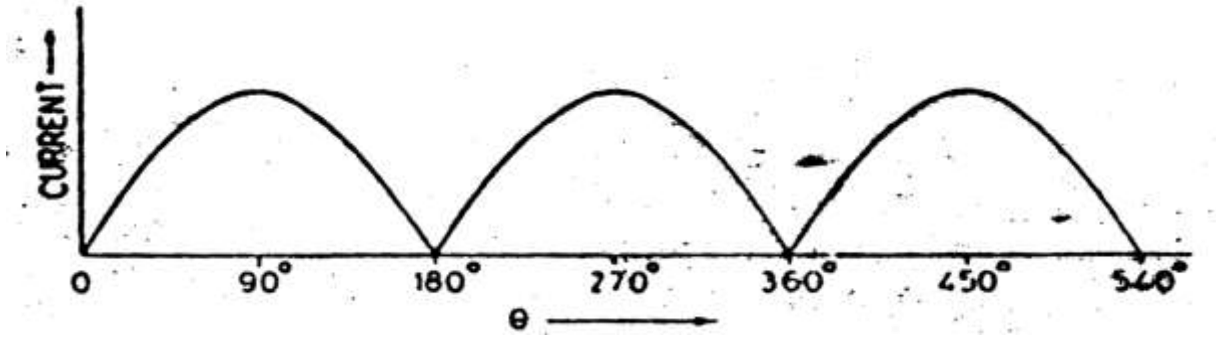
2st half cycle(180^0 to 360^0) Path of current $DCR_2B_1\underline{ML}B_2R_1BA$

DC Generators, cont

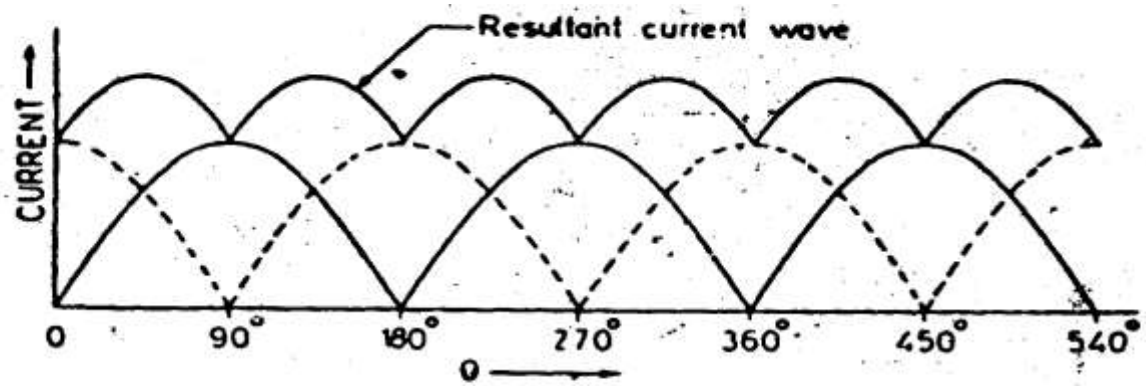
- The output voltage always has the same polarity
- The current is a pulsating current
- To produce a steady current, many loops and commutators around the axis of rotation are used
  - The multiple outputs are superimposed and the output is almost free of fluctuations



(b)



Unidirectional current wave shape



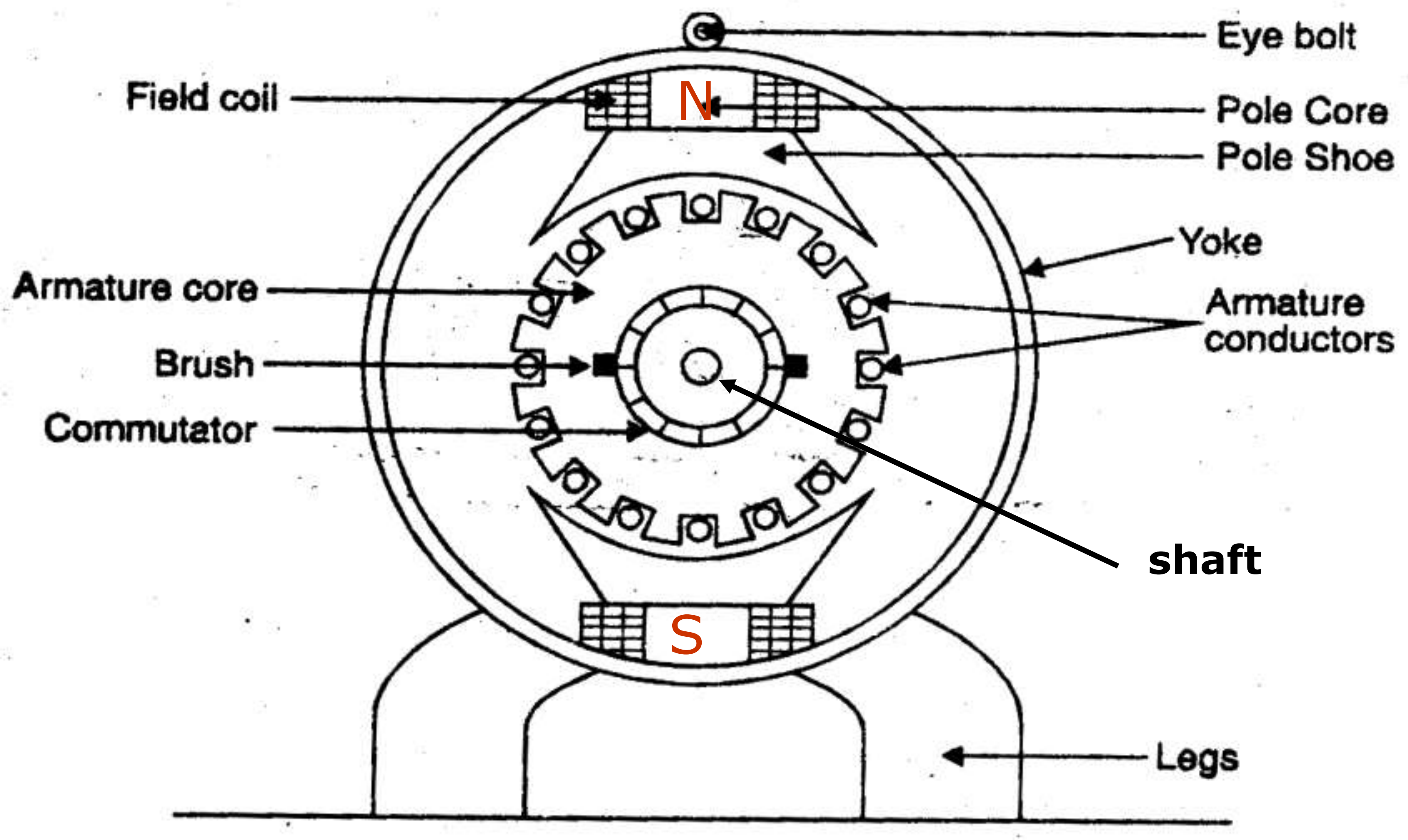
Resultant current wave shape when number of conductors used result current wave shape

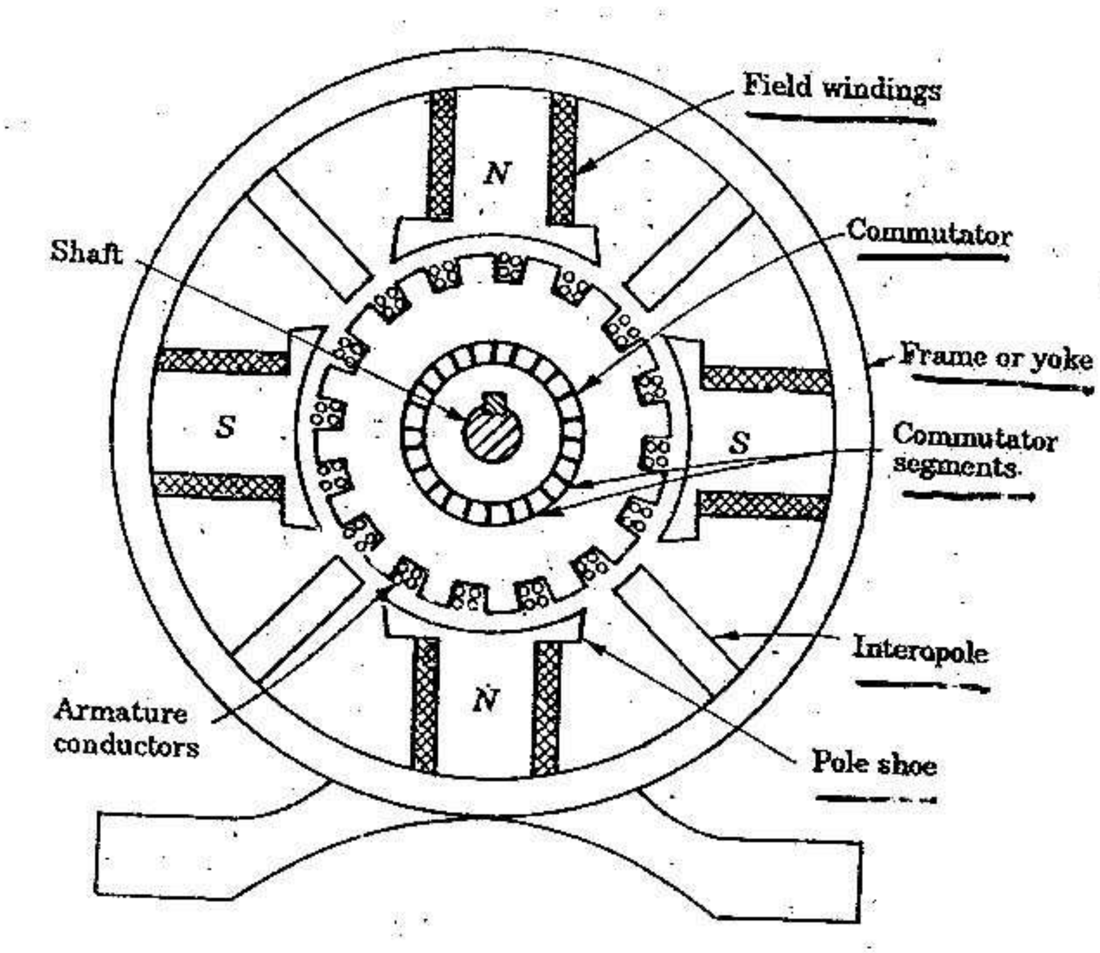
Constructional Details Of DC Machine

- **Yoke:**
- **Rotor:**
- **Stator:**
- **Field electromagnets:**
- **Pole core and pole shoe:**
- **Brushes:**
- **Shaft:**
- **Armature:**
- **Coil:**
- **Commutator:**
- **Bearings:**

Construction details of DC generator

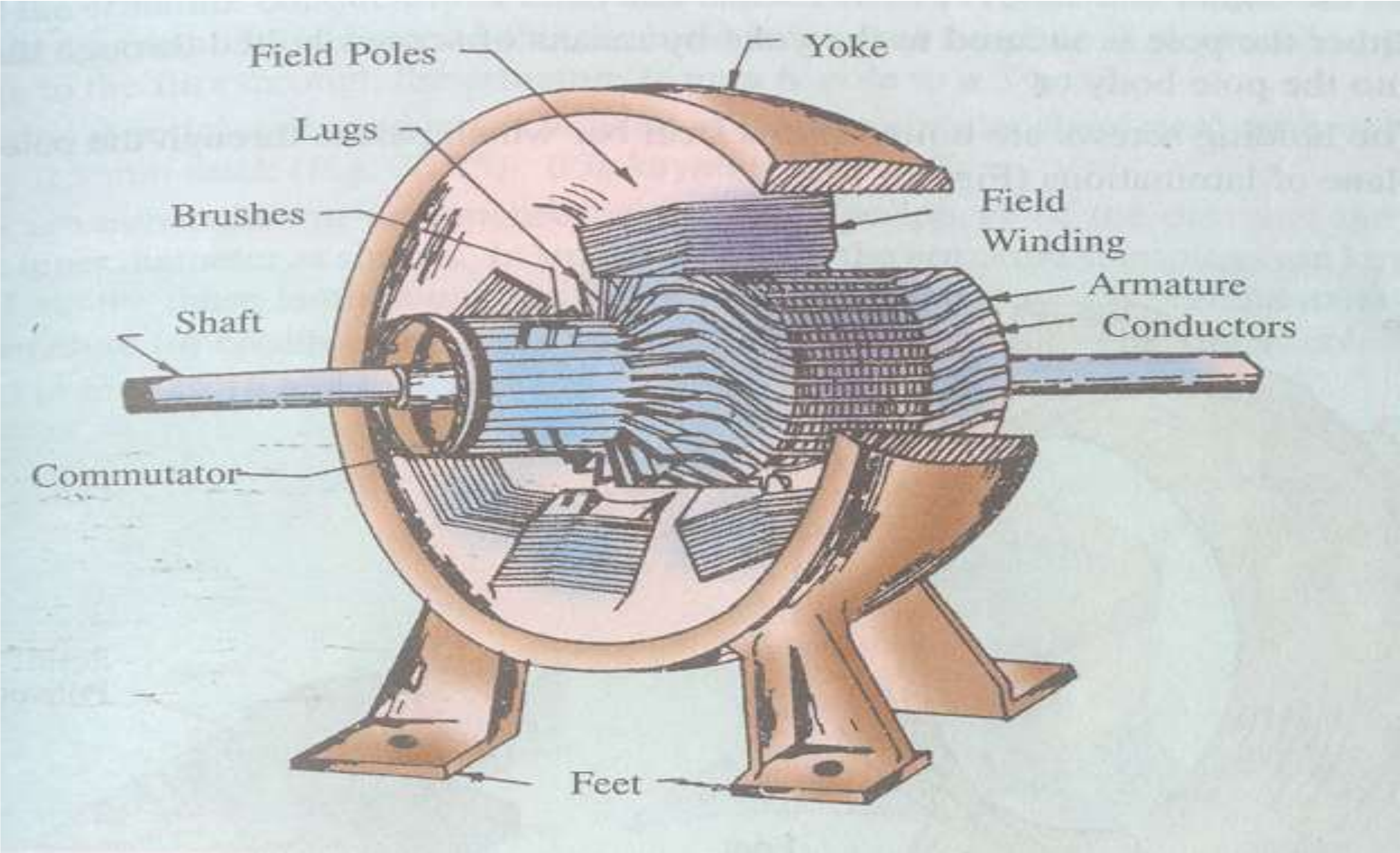
Cross section view of dc machine





Main parts of a 4-pole d. c machine

Practical Dc Machine



UNIT 2
DC MOTOR

INTRODUCTION

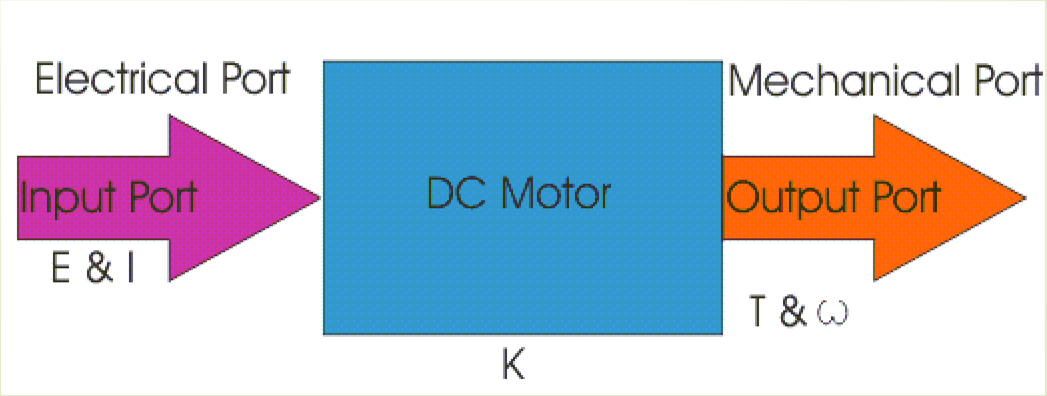
- Electrical motors are everywhere around us. Almost all the electro-mechanical movements we see around us are caused either by an A.C. or a **DC motor**. Here we will be exploring this kind of motors. This is a device that converts DC electrical energy to a mechanical energy.

- Principle of DC Motor

- This DC or **direct current motor** works on the principal, when a current carrying conductor is placed in a magnetic field, it experiences a torque and has a tendency to move. This is known as motoring action. If the direction of current in the wire is reversed, the direction of rotation also reverses. When magnetic field and electric field interact they produce a mechanical force, and based on that the working principle of **dc motor** established.

Left Hand Rule
Current
Direction of Force
S
N
S

- The direction of rotation of a this motor is given by Fleming's left hand rule, which states that if the index finger, middle finger and thumb of your left hand are extended mutually perpendicular to each other and if the index finger represents the direction of magnetic field, middle finger indicates the direction of current, then the thumb represents the direction in which force is experienced by the shaft of the **dc motor**.
- Structurally and construction wise a direct current motor is exactly similar to a DC generator, but electrically it is just the opposite. Here we unlike a generator we supply electrical energy to the input port and derive mechanical energy from the output port. We can represent it by the block diagram shown below.



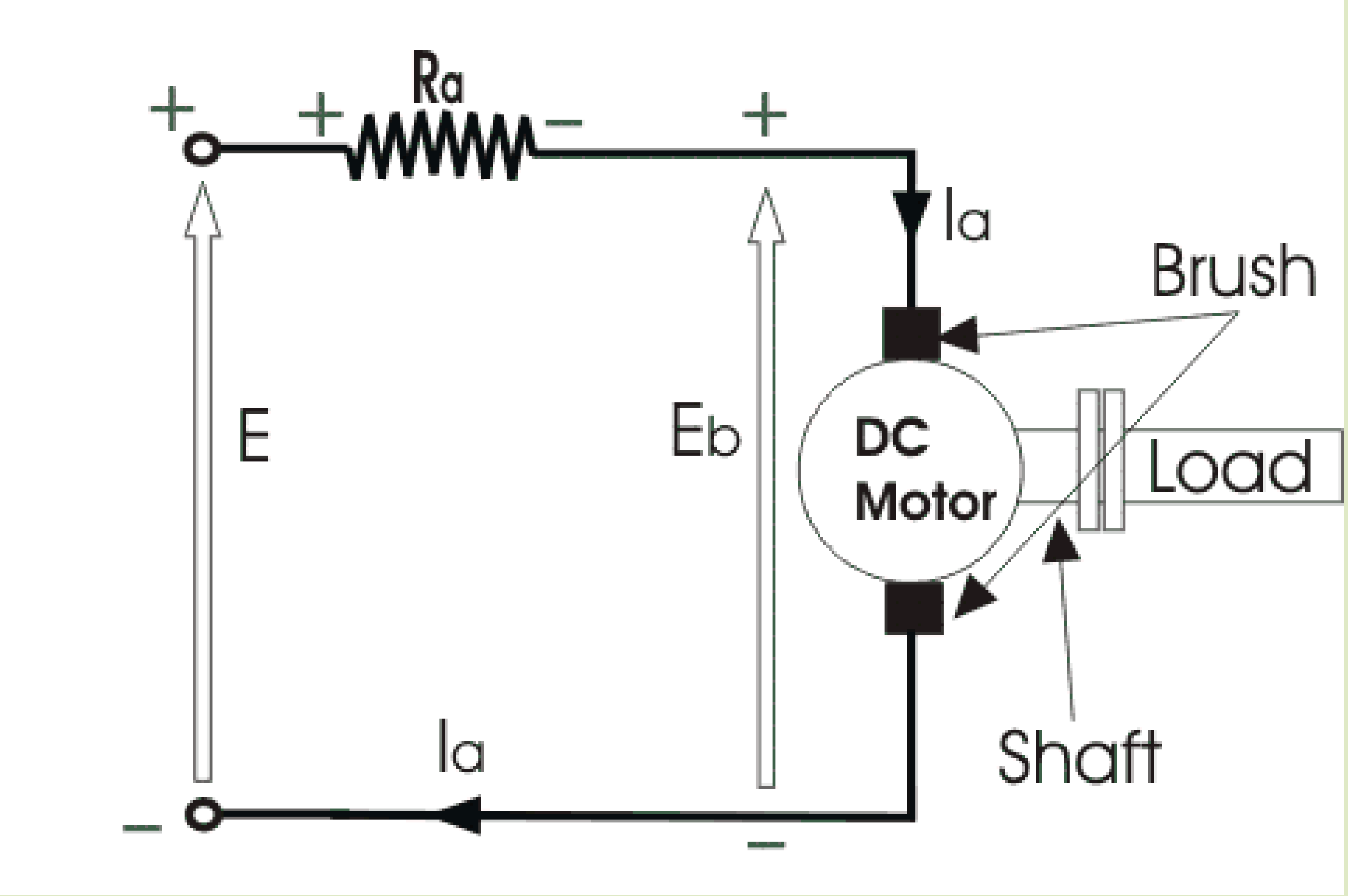
- Here in a DC motor, the supply voltage E and current I is given to the electrical port or the input port and we derive the mechanical output i.e. torque T and speed ω from the mechanical port or output port.
- The input and output port variables of the **direct current motor** are related by the parameter K.

$$T = KI \quad \text{and} \quad E = KW$$

- So from the picture above we can well understand that motor is just the opposite phenomena of a DC generator, and we can derive both motoring and generating operation from the same machine by simply reversing the ports.

Detailed Description of a DC Motor

- To understand the DC motor in details lets consider the diagram below,

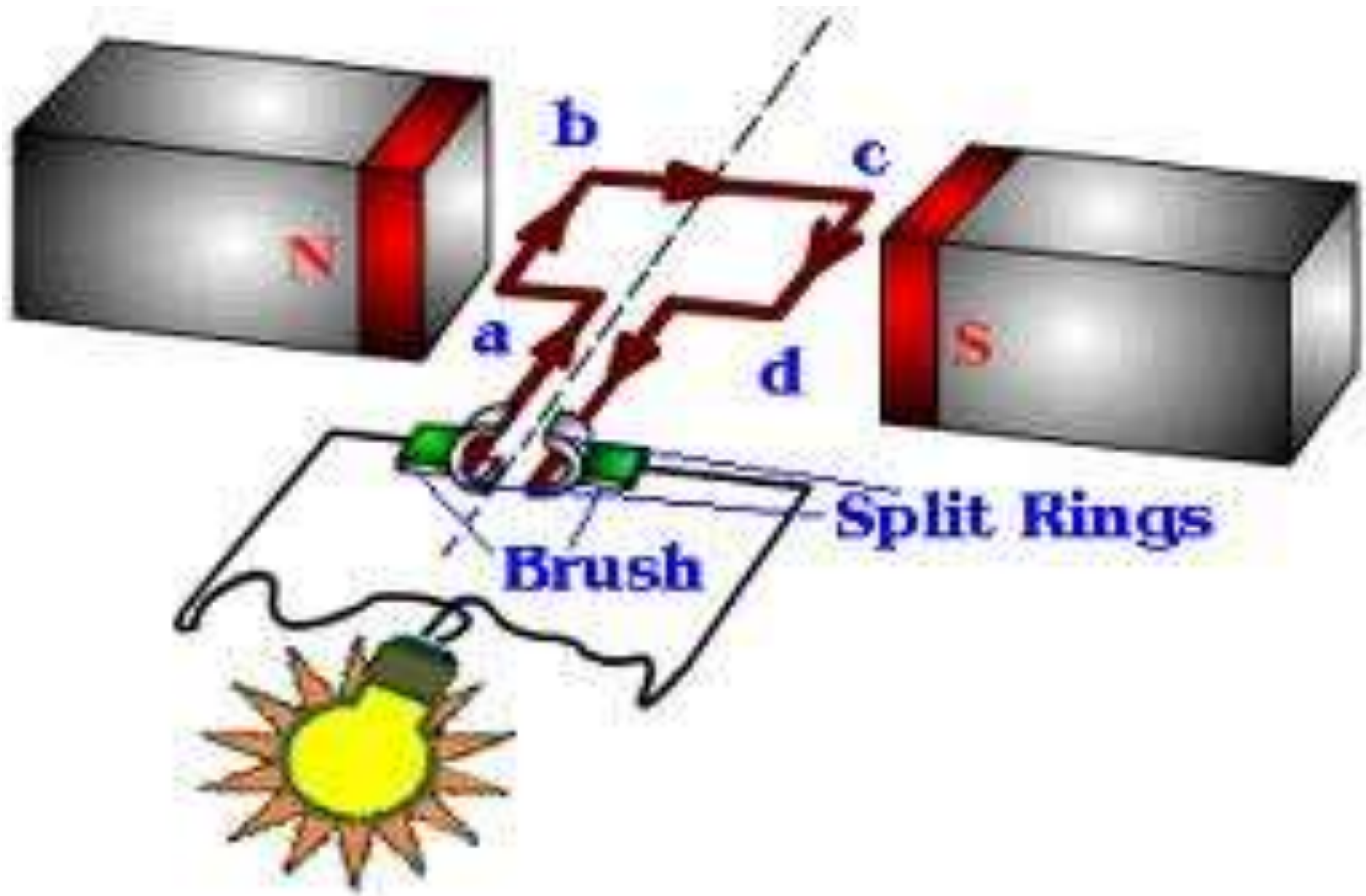


The direct current motor is represented by the circle in the center, on which is mounted the brushes, where we connect the external terminals, from where supply voltage is given. On the mechanical terminal we have a shaft coming out of the Motor, and connected to the armature, and the armature-shaft is coupled to the mechanical load. On the supply terminals we represent the armature resistance R_a in series. Now, let the input voltage E, is applied across the brushes. Electric current which flows through the rotor armature via brushes, in presence of the magnetic field, produces a torque T_g . Due to this torque T_g the dc motor armature rotates. As the armature conductors are carrying currents and the armature rotates inside the stator magnetic field, it also produces an emf E_b in the manner very similar to that of a generator. The generated Emf E_b is directed opposite to the supplied voltage and is known as the back Emf, as it counters the forward voltage.

UNIT-III

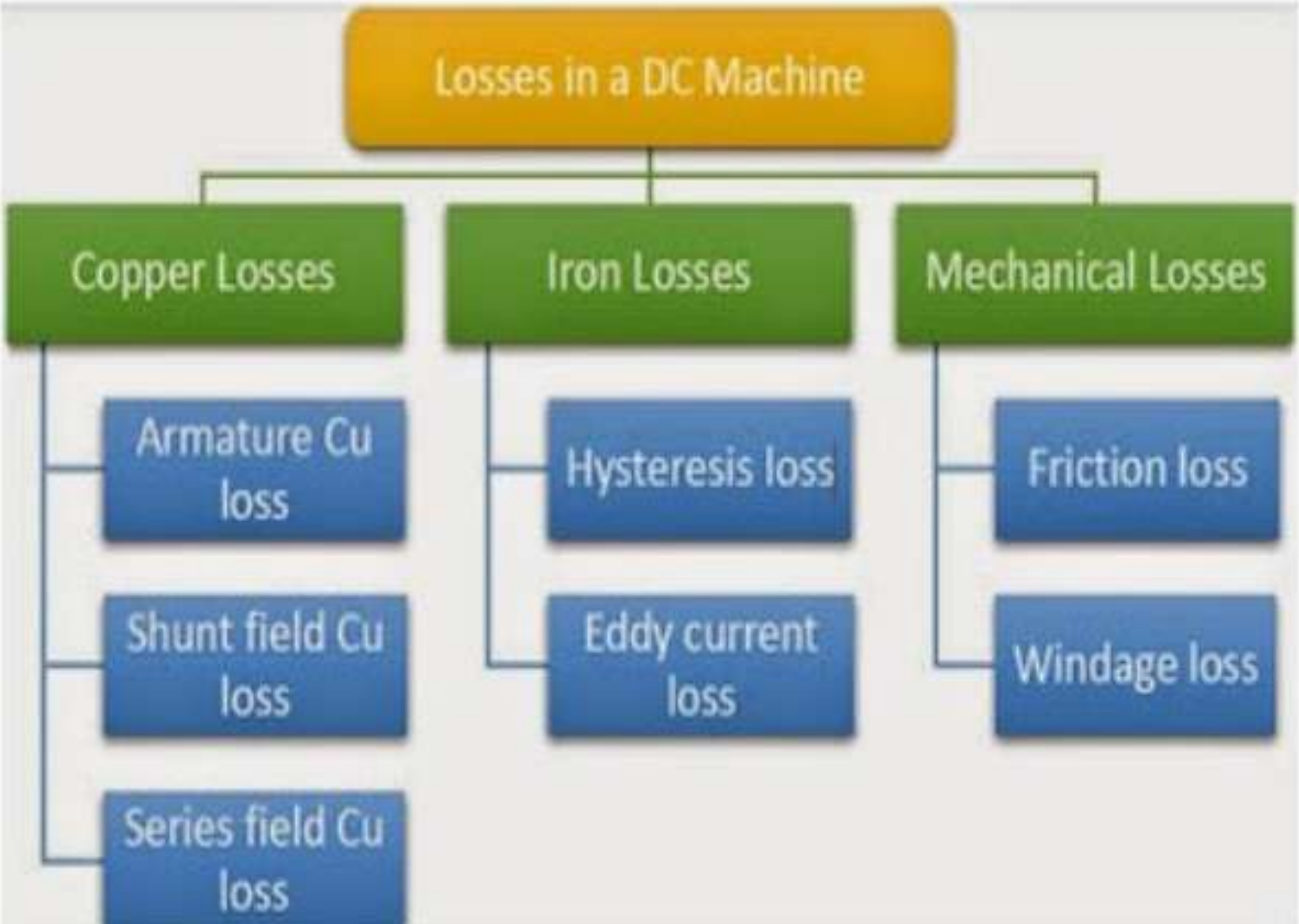
TESTING OF DC MACHINES

Working principle of DC motor



Losses In A DC Generator And DC Motor

- A dc generator converts mechanical power into electrical power and a dc motorconverts electrical power into mechanical power. Thus, for a dc generator, input power is in the form of mechanical and the output power is in the form of electrical.
- On the other hand, for a dc motor, input power is in the form of electrical and output power is in the form of mechanical. In a practical machine, whole of the input power can not be converted into output power as some power is lost in the process.
- This causes the efficiency of the machine to be reduced. Efficiency is the ratio of output power to the input power. Thus, in order to design rotating dc machines with higher efficiency, it is important to study the losses occurring in them.
- **Various losses in a rotating DC machine (DC generator or DC motor)** can be characterized as follows:


Losses in a DC Machine
Copper Losses
Iron Losses
Mechanical Losses
Armature Cu loss
Shunt field Cu loss
Series field Cu loss
Hysteresis loss
Eddy current loss
Friction loss
Windage loss

Losses In A Rotating DC Machine

- Copper losses
  - Armature Cu loss
  - Field Cu loss
  - Loss due to brush contact resistance
- Iron Losses
  - Hysteresis loss
  - Eddy current loss
- Mechanical losses
  - Friction loss
  - Windage loss
- The above tree categorizes various types of losses that occur in a dc generator or a dc motor. Each of these is explained in details below.

COPPER LOSSES

- These losses occur in armature and field copper windings. **Copper losses** consist of Armature copper loss, Field copper loss and loss due to brush contact resistance.

- **Armature copper loss** = Ia2Ra

(where, Ia = Armature current and Ra = Armature resistance)

This loss contributes about 30 to 40% to full load losses. The armature copper loss is variable and depends upon the amount of loading of the machine.

- **Field copper loss** = If2Rf

(where, If = field current and Rf = field resistance)

In the case of a shunt wounded field, field copper loss is practically constant. It contributes about 20 to 30% to full load losses.

- Brush contact resistance also contributes to the copper losses. Generally, this loss is included into armature copper loss.

IRON LOSSES (CORE LOSSES)

- As the armature core is made of iron and it rotates in a magnetic field, a small current gets induced in the core itself too. Due to this current, eddy current loss and hysteresis loss occur in the armature iron core. Iron losses are also called as *Core losses or magnetic losses.*
- Hysteresis loss is due to the reversal of magnetization of the armature core. When the core passes under one pair of poles, it undergoes one complete cycle of magnetic reversal. The frequency of magnetic reversal if given by, f=P.N/120

(where, P = no. of poles and N = Speed in rpm)

The loss depends upon the volume and grade of the iron, frequency of magnetic reversals and value of flux density.

- **Hysteresis loss** is given by, Steinmetz formula:

$$W_h = \eta B_{max}^{1.6} f V \text{ (watts)}$$

where, η = Steinmetz hysteresis constant

V = volume of the core in m^3

- **Eddy current loss**: When the armature core rotates in the magnetic field, an emf is also induced in the core (just like it induces in armature conductors), according to the Faraday's law of electromagnetic induction.
- Though this induced emf is small, it causes a large current to flow in the body due to the low resistance of the core. This current is known as eddy current. The power loss due to this current is known as eddy current loss.
- Eddy current loss $P_e = K_e B_{max} f^2 t^2 V$

where K_e = Constant depending upon the electrical resistance of core and system of units used

B_{max} = Maximum flux density in Wb/m^2

f = Frequency of magnetic reversals in Hz

t = Thickness of lamination in m

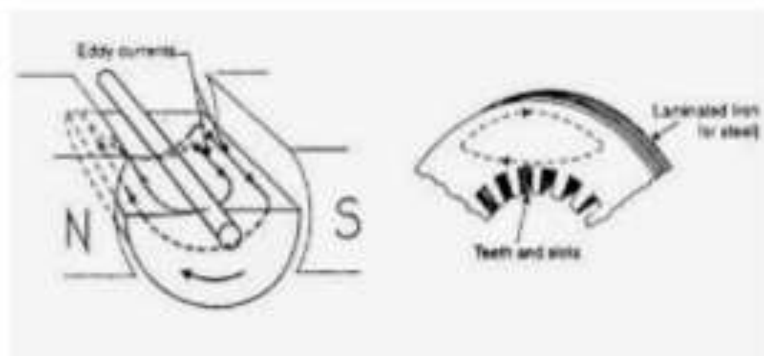
V = Volume of core in m^3

It may be noted that eddy current loss depends

upon the square of lamination thickness.

For this reason, lamination thickness

should be kept as small as possible.



Mechanical Losses

- Mechanical losses consist of the losses due to friction in bearings and commutator. Air friction loss of rotating armature also contributes to these. These losses are about 10 to 20% of full load losses.
- These losses are due to friction and windage.
  (i) friction loss e.g., bearing friction, brush friction etc.
  (ii) windage loss i.e., air friction of rotating armature.
- These losses depend upon the speed of the machine. But for a given speed, they are practically constant.
  Note. Iron losses and mechanical losses together are called stray losses.

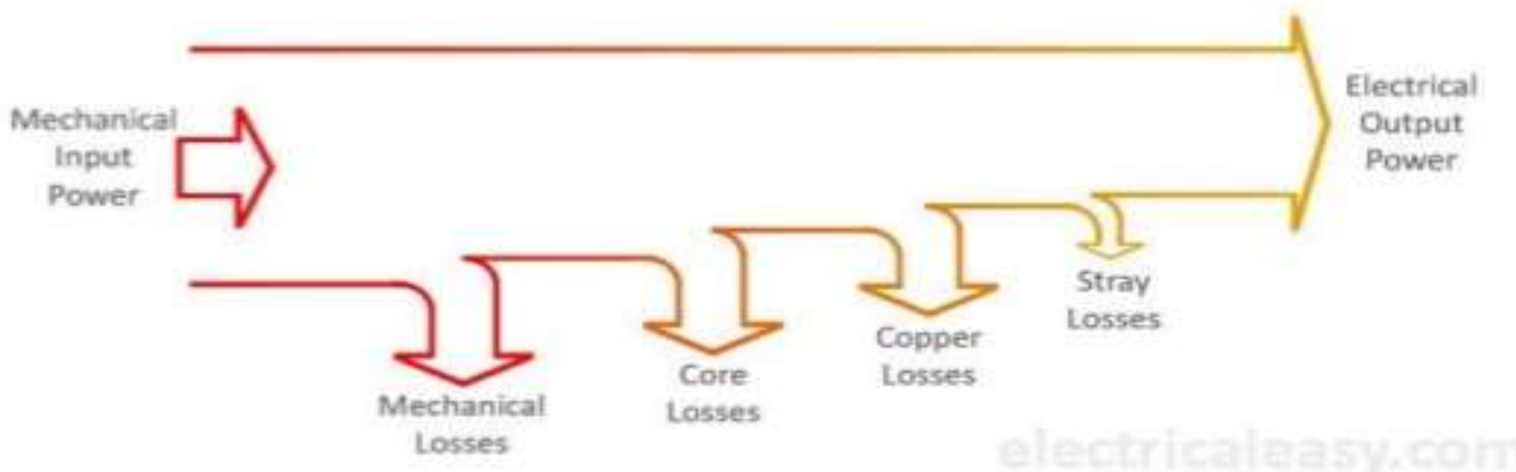
Stray Losses

- In addition to the losses stated above, there may be small losses present which are called as stray losses or miscellaneous losses. These losses are difficult to account. They are usually due to inaccuracies in the designing and modeling of the machine.

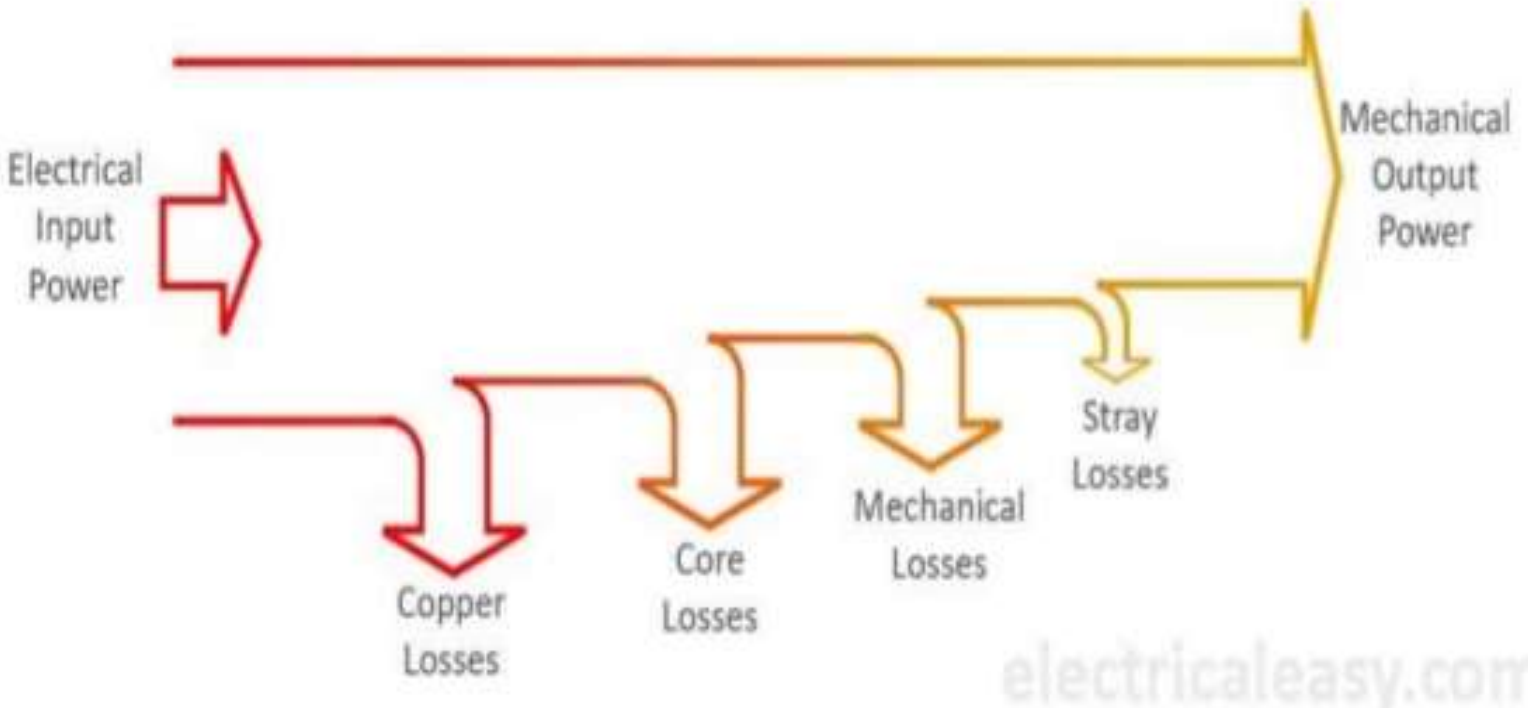
  Most of the times, stray losses are assumed to be 1% of the full load.

Power Flow Diagram

- The most convenient method to understand these losses in a dc generator or a dc motor is using the power flow diagram.
- The diagram visualizes the amount of power that has been lost in various types of losses and the amount of power which has been actually converted into the output. Following are the typical power flow diagrams for a dc



Power flow diagram of a DC generator



Power flow diagram of a DC motor

Efficiency of D.C. Machines:

Generator:

1. Mechanical efficiency (η_m)

$$\eta_m = \frac{\text{Electrical power developed by armature}}{\text{Total mechanical power input}}$$

$$= \frac{E_g I_a}{\text{B. H. P. of prime mover} \times 735.5} \quad \text{... (17)}$$

2. Electrical efficiency (η_e)

$$\eta_e = \frac{\text{Useful electrical power output}}{\text{Electrical power developed}}$$

$$= \frac{VI}{E_g I_a} \quad \text{... (18)}$$

3.Overall or commercial efficiency ($\eta_g = \eta_m \times \eta_e$)

$$\eta_{og} = \frac{\text{Useful electrical power output}}{\text{Total mechanical power input}}$$

$$= \frac{VI}{\text{B. H. P. of prime mover } \times \ 735.5} \qquad \ldots (19)$$

The overall efficiency of generator can also be expressed as follows:

$$\eta_{og} = \frac{\text{Useful power output}}{\text{Useful power output } + \text{ total losses}}$$

$$= \frac{\text{VI}}{\text{VI + total losses}} \qquad \ldots (20)$$

where E_g = generated e.m.f. V = terminal voltage

I = load current, I_a = armature current.

For good generators the value of overall or commercial efficiency may be as high as 95%.

Motor:

1. Electrical efficiency (η_e)

$$\eta_e = \frac{\text{Mechanical power developed}}{\text{Total electrical power input}}$$

$$= \frac{E_b I_a}{VI} \qquad \text{...(21)}$$

2. Mechanical efficiency (η_m)

$$\eta_m = \frac{\text{Useful mechanical power output}}{\text{Mechanical power developed}}$$

$$= \frac{\text{B. H. P. of motor} \times 735.5}{E_b I_a} \qquad \text{...(22)}$$

3. Overall or commercial efficiency ($\eta_{om} = \eta_m \times \eta_e$)

$$\eta_{om} = \frac{\text{Useful mechanical power output}}{\text{Total electrical power input}}$$

$$= \frac{\text{B. H. P. of motor} \times 735.5}{VI} \quad \text{... (23)}$$

η_{om} can also be expressed as follows:

$$\eta_{om} = \frac{\text{Useful power output}}{\text{Total power input}}$$

$$= \frac{\text{Total power input} - \text{total losses}}{\text{Total power input}}$$

$$= \frac{\text{Total power input} - \text{total losses}}{\text{Total power input}}$$

$$= \frac{VI - \text{total losses}}{VI}$$

V = supply voltage

I = load current

where E_b = back e.mf.

I_a = armature current.

9.3.1. Condition for maximum efficiency. Condition for maximum efficiency for a D.C. generator or D.C. motor is same. For a D.C, generator the condition for maximum efficiency is derived as follows:

Generator power output = VI,

If flux and speed are constant all losses except armature copper loss are constant, Losses = armature copper loss + constant loss

$= (I + I_{sh})^2R_a + P_c$

$= I^2R_a + P_c$

[Neglecting I_{sh} in comparison with load current I]

where I_{sh} is the shunt field current and P, denotes constant losses which include iron loss, field winding loss and mechanical loss, Efficiency, $\eta = \frac{\text{Output}}{\text{Input}} = \frac{\text{Output}}{\text{Output + losses}}$

$$= \frac{VI}{VI + I^2R_a + P_c} \qquad \dots (25)$$

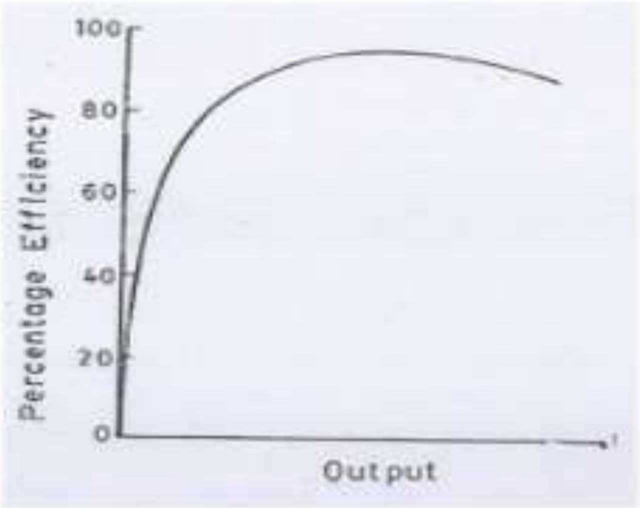
η is maximum when $\frac{d\eta}{dI} = 0 = \frac{(VI + I^2R_a + P_c)V - VI(V + 2IR_a)}{(VI + I^2R_a + P_c)^2}$

or $\quad I^2R_a = P_c \qquad \dots (26)$

Hence, efficiency will be maximum when variable losses are equal to constant losses

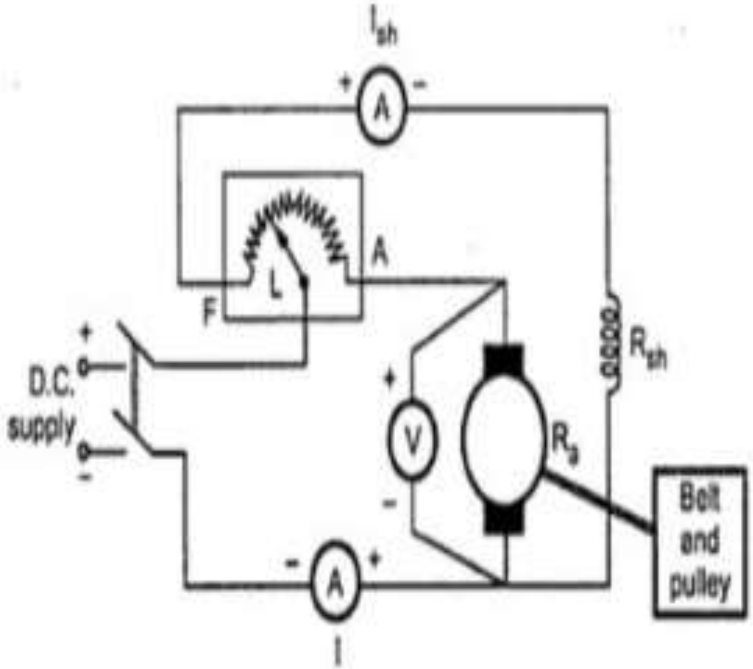
Further (from eqn. 26) $\quad I = \sqrt{\frac{P_c}{R_a}} \qquad \dots (27)$

- Thus the efficiency increases with increase in load current, reaches a maximum value when load current equals the value given by eqn. (27) and then starts decreasing,
- Efficiency curve: The efficiency of a machine is different at different values of power output. As the output increases, the efficiency increases till it reaches a maximum value.
- As the output is further increased, the efficiency starts decreasing. A graph of efficiency vs. output is called efficiency curve. A typical efficiency curve is shown in Fig. 96.
- The machines are so designed as to give maximum efficiency at or near the rated output of the machine. Since the generators operate at a constant terminal voltage V, the efficiency curve of a generator can be drawn between efficiency and load current I:

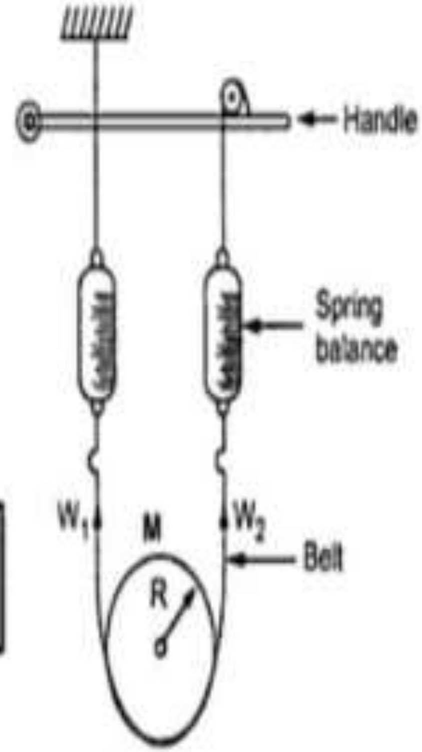


BRAKE TEST ON DC SHUNT MOTOR

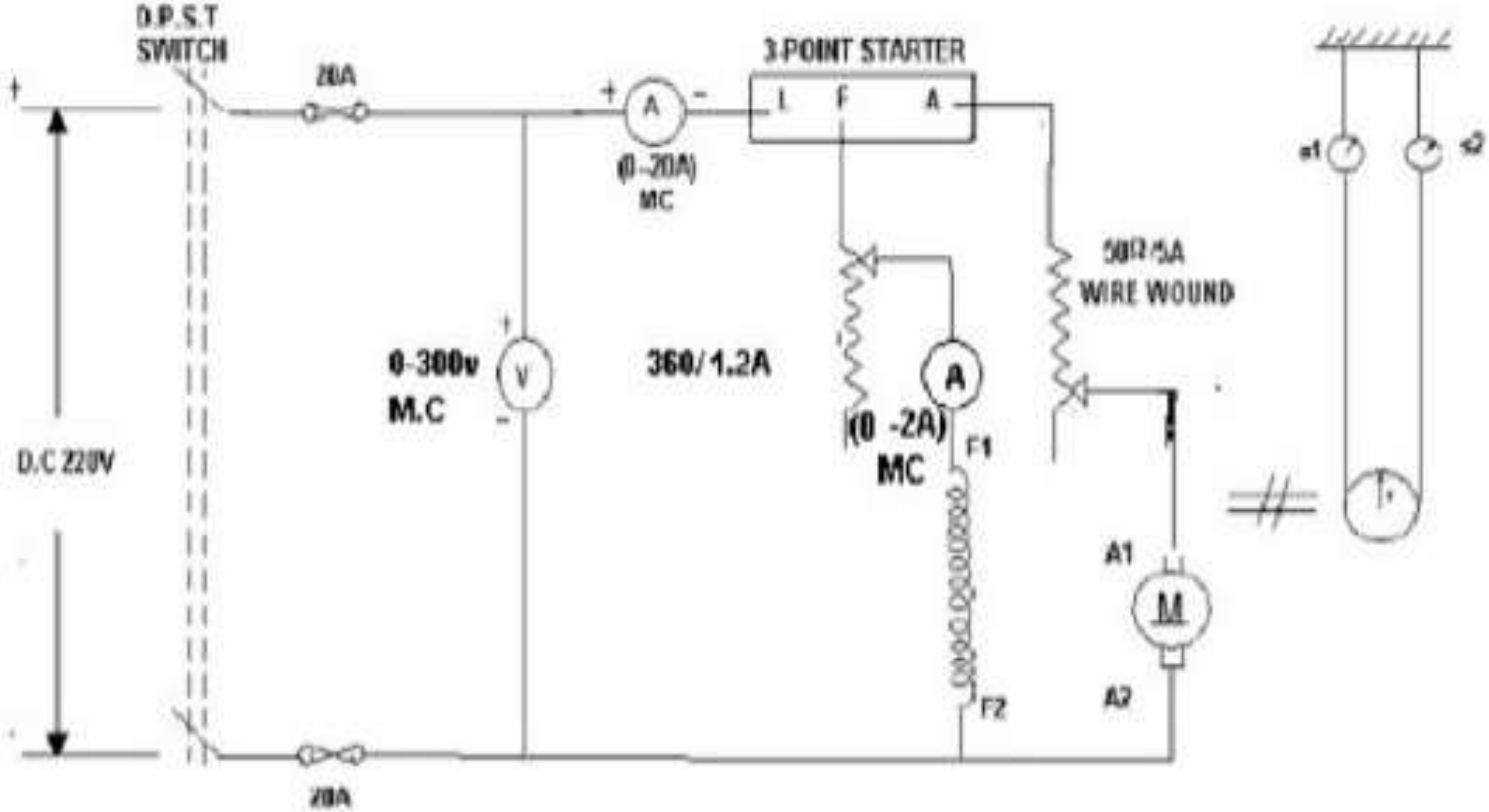
- Another method of testing the d.c. motor is brake test method. This is a direct method of testing the motor.
- In this method, the motor is put on the direct load by means of a belt and pulley arrangement. Brake adjusting the tension of belt, the load is adjusted to give the various values of currents. The load is finally adjusted to get full load current.
- The power developed gets wasted against the friction between belt and shaft. Due to the braking action of belt the test is called brake test.
- The Fig. 1(a) shows the experimental setup for performing brake test on a d.c. shunt motor while the Fig. 1(b) shows the belt and pulley arrangement mounted on the shaft of the motor.



(a) Experimental setup



(b) Belt and pulley arrangement



NAME PLATE DETAILS
VOLTAGE -220V
CURRENT- 19A
SPEEED-1500RPM

The tension in the belt can be adjusted using the handle. The tension in kg can be obtained from the spring balance readings.

Let R = Radius of pulley in meter

N = Speed in r.p.m.

W1 = Spring balance reading on tight side in kg

W2 = Spring balance reading on slack side in kg

So net pull on the belt due to friction at the pulley is the difference between the two spring balance readings.

$$\text{Net pull} = W_1 - W_2 \text{ kg} = 9.81\,(W_1 - W_2) \text{ N}$$

As radius R and speed N are known, the shaft torque developed can be obtained as,

$$T_{sh} = \text{net pull} \times R = 9.81\,(W_1 - W_2)\,R \quad \text{N-m}$$

Hence the output power can be obtained as,

$$P_{out} = T_{sh} \times \omega = 9.81\,(W_1 - W_2)\,R \times \frac{2\pi N}{60} \text{ W}$$

Now let, V = Voltage applied in volts

I = Total line current drawn in amps.

then

$$P_{in} = VI \quad W$$

Thus if the readings are taken on full load condition then the efficiency can be obtained as,

$$\% \eta = \frac{P_{out}}{P_{in}} \times 100$$

Adjusting the load step by step till full load, number of readings can be obtained. The speed can be measured by tachometer. Thus all the motor characteristics can be plotted.

Advantages

The advantages of brake test,

1. Actual efficiency of the motor under working conditions can be found out.
2. The method is simple and easy to perform.
3. Can be performed on any type of d.c. motor.

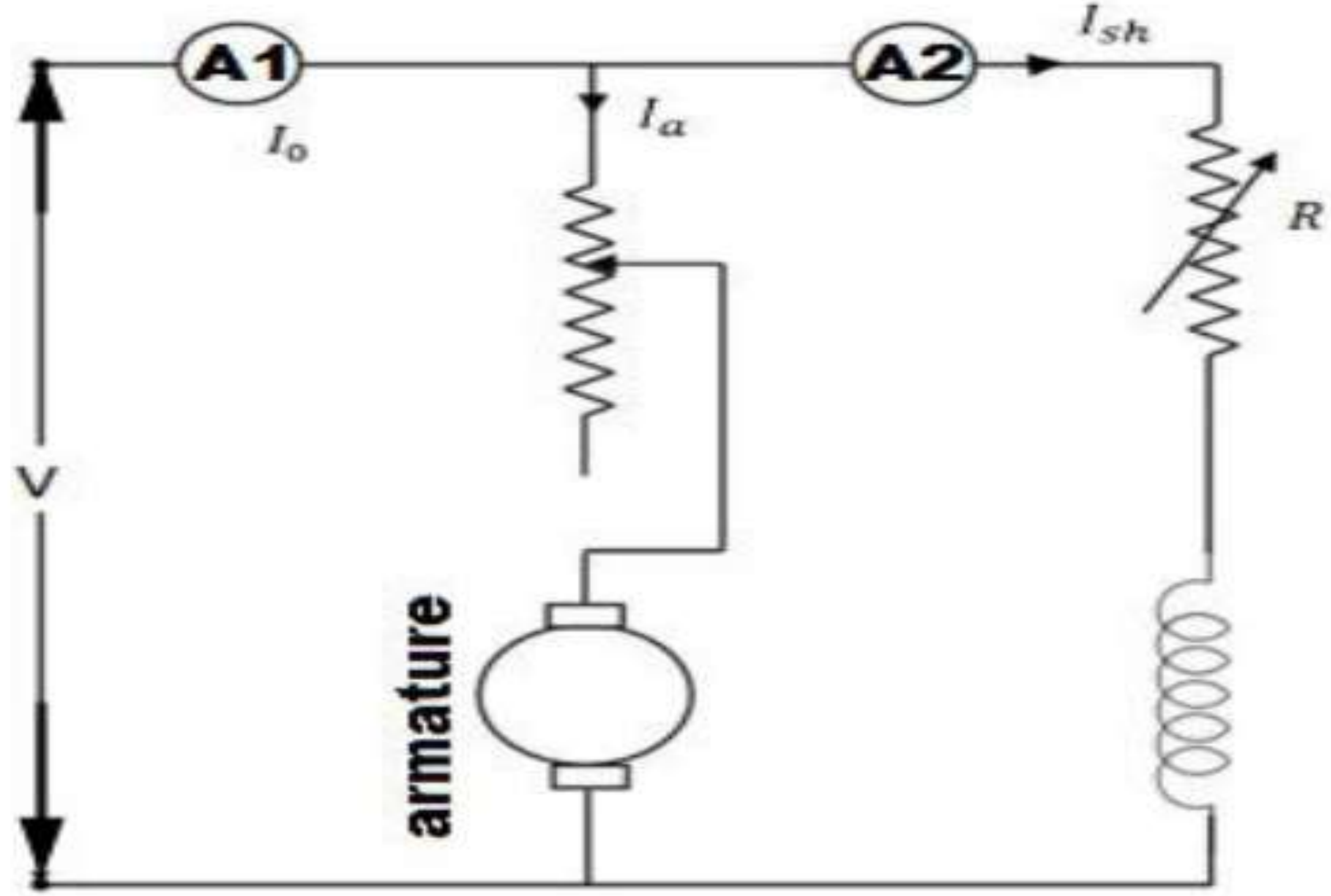
Disadvantages

The disadvantages of brake test,

1. Due to friction, heat generated and hence there is large dissipation of energy.
2. Some type of cooling arrangement is necessary
3. Convenient only for small machines due to limitations regarding heat dissipation arrangements.
4. The power developed gets wasted hence method is expensive.
5. The efficiency observed is on lower side.

Swinburne Test of DC Machine

- This method is an indirect method of testing a dc machine. It is named after Sir James Swinburne. Swinburne's test is the most commonly used and simplest method of testing of shunt and compound wound dc machines which have constant flux.
- In this test the efficiency of the machine at any load is pre-determined. We can run the machine as a motor or as a generator. In this method of testing no load losses are measured separately and eventually we can determine the efficiency.
- The circuit connection for Swinburne's test is shown in figure below. The speed of the machine is adjusted to the rated speed with the help of the shunt regulator R as shown in fig.



A1
A2
I_{sh}
I_a
I_o
R
V
armature

Calculation of Efficiency:

Let, I0 is the no load current (it can be measured by ammeter A1) Ish is the shunt field current (it can be measured by ammeter A2)

Then, no load armature current = (I0 - Ish) Also let, V is the supply voltage. Therefore, No load power input = VI0 watts.

In Swinburne's test no load power input is only required to supply the losses. The losses occur in the machine mainly are: Iron losses in the core Friction and windings losses Armature copper loss.

Since the no load mechanical output of the machine is zero in Swinburne's test, the no load input power is only used to supply the losses. The value of armature copper loss = (I0 - Ish)2 Ra Here, Ra is the armature resistance.

Now, no to get the constant losses we have to subtract the armature copper loss from the no load power input. Then, Constant losses WC = VI0 -(I0 - Ish)2 Ra After calculating the no load constant losses now we can determine the efficiency at any load.

Let, I is the load current at which we have to calculate the efficiency of the machine. Then, armature current (Ia) will be (I - Ish), when the machine is motoring. And Ia = (I + Ish), when the machine is generating.

Calculation of Efficiency When the Machine is Motoring on Load:

Power input = VI Armature copper loss, PCU = I2 Ra = (I - Ish)2Ra Constant losses, WC = VI0 -(I0 - Ish)2 Ra Total losses = PCU + WC ∴ Efficiency of the motor:

$$\eta_m = \frac{output}{input} = \frac{input - losses}{input} = \frac{VI - (P_CU + W_C)}{VI}$$

Calculation of Efficiency When the Machine is Generating on Load:

Power input = VI Armature copper loss, PCU = I2 Ra = (I + Ish)2 Ra Constant losses, WC = VI0 - (I0 - Ish)2 Ra Total losses = PCU + WC ∴ Efficiency of the generator:

$$\eta_g = \frac{output}{input} = \frac{input - losses}{input} = \frac{VI - (P_CU + W_C)}{VI}$$

Advantages of Swinburne's Test:

The main advantages of this test are :

1. This test is very convenient and economical as it is required very less power from supply to perform the test.

2. Since constant losses are known, efficiency of Swinburne's test can be pre-determined at any load.

Disadvantages of Swinburne's Test

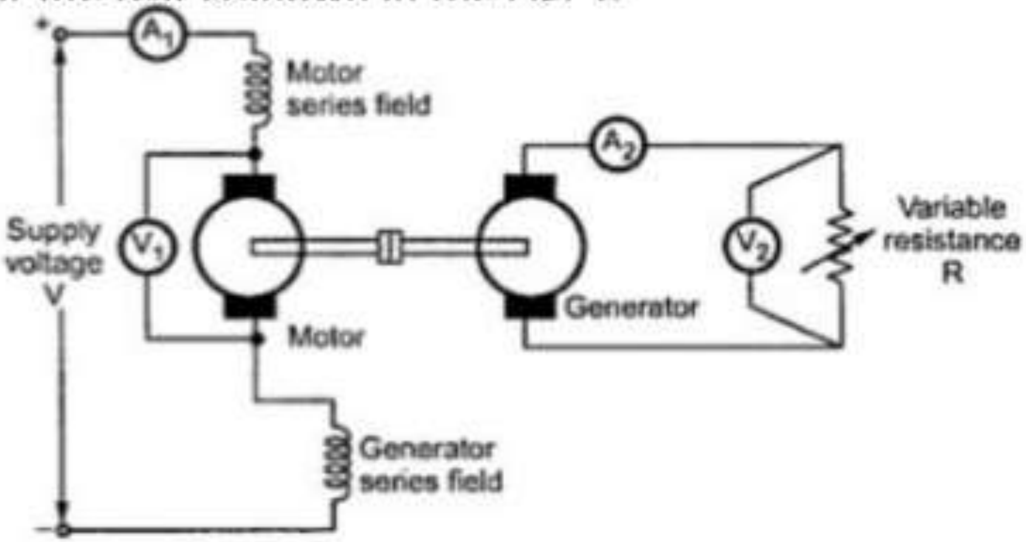
The main disadvantages of this test are :

- Iron loss is neglected though there is change in iron loss from no load to full load due to armature reaction.
- We cannot be sure about the satisfactory commutation on loaded condition because the test is done on no-load.
- We can't measure the temperature rise when the machine is loaded. Power losses can vary with the temperature.
- In DC series motors, the Swinburne's test cannot be done to find its efficiency as it is a no load test.

Field's Test for Series Motor

- This is one of the methods of testing the d.c. series motors. Unlike shunt motors, the series motor can not be tested by the methods which area available for shunt motors as it is impossible to run the motor on no load. It may run at dangerously high speed on no load. In case of small series motors brake test may be employed.

- The series motors are usually tested in pairs. The field test is applied to two similar series motors which are coupled mechanically. The connection diagram for the test is shown in the Fig. 1.



- As shown in the Fig. 1 one machine is made to run as a motor while the other as a generator which is separately excited. The field of the two machines are connected in series so that both the machines are equally excited. This will make iron losses same for the two machines. The two machines are running at the same speed. The generator output is given to the variable resistance R.
- The resistance R is changed until the current taken by motor reaches full load value. This will be indicated by ammeter A1. The other readings of different meters are then recorded.

Let V = Supply voltage

I_1 = Current taken by motor

I_2 = Load current

V_2 = Terminal p.d. of generator

R_a, R_{se} = Armature and series field resistance of each machine

Power taken from supply = VI_1

Output obtained from generator = $V_2 I_2$

Total losses in both the machines, $W_T = VI_1 - V_2 I_2$

Armature copper and field losses, $W_{CU} = (R_a + 2R_{se}) I_1^2 + I_2^2 R_a$

Total stray losses = $W_T - W_{CU}$

$$\text{Stray losses per machine, } W_s = \frac{W_T - W_{cu}}{2}$$

Since the two machines are equally excited and are running at same speed the stray loses are equally divided.

FOR MOTOR :

Input to motor = V1 I1
Total losses = Armature Cu loss + Field Cu loss + Stray loss
= I12 (Ra + Rse) + Ws
Output of motor = Input - Total losses = V1 I1 - [I12 (Ra + Rse) + Ws]

$$\text{Efficiency of motor, } \eta_m = \frac{\text{Output}}{\text{Input}}$$

$$\boxed{\eta_m = \frac{V_1 I_1 - [I_1^2 (R_a + R_{se}) + W_s}{V_1 I_1}}$$

For Generator :

Efficiency of generator is of little importance because it is running under conditions of separate excitation. Still it can be found as follows.

Output of generator = V2 I2

Field Cu loss = I12 Rse

Armature Cu loss = I22 Ra

Total losses = Armature Cu loss + Field Cu loss + Stray loss

= I22 Ra + I12 Rse + Ws

Input to generator = Output + Total losses = V2 I2 + [I22 Ra + I12 Rse + Ws]

$$\text{Efficiency of generator, } \eta_g = \frac{\text{Output}}{\text{Input}}$$

$$\therefore \quad \eta_g = \frac{V_2 I_2}{V_2 I_2 + [I_2^2 R_a + I_1^2 R_{se} + W_s]}$$

The important point to be noted is that this is not regenerative method though the two machines are mechanically coupled because the generator output is not fed back to the motor as in case of Hopkinson's test but it is wasted in load resistance.

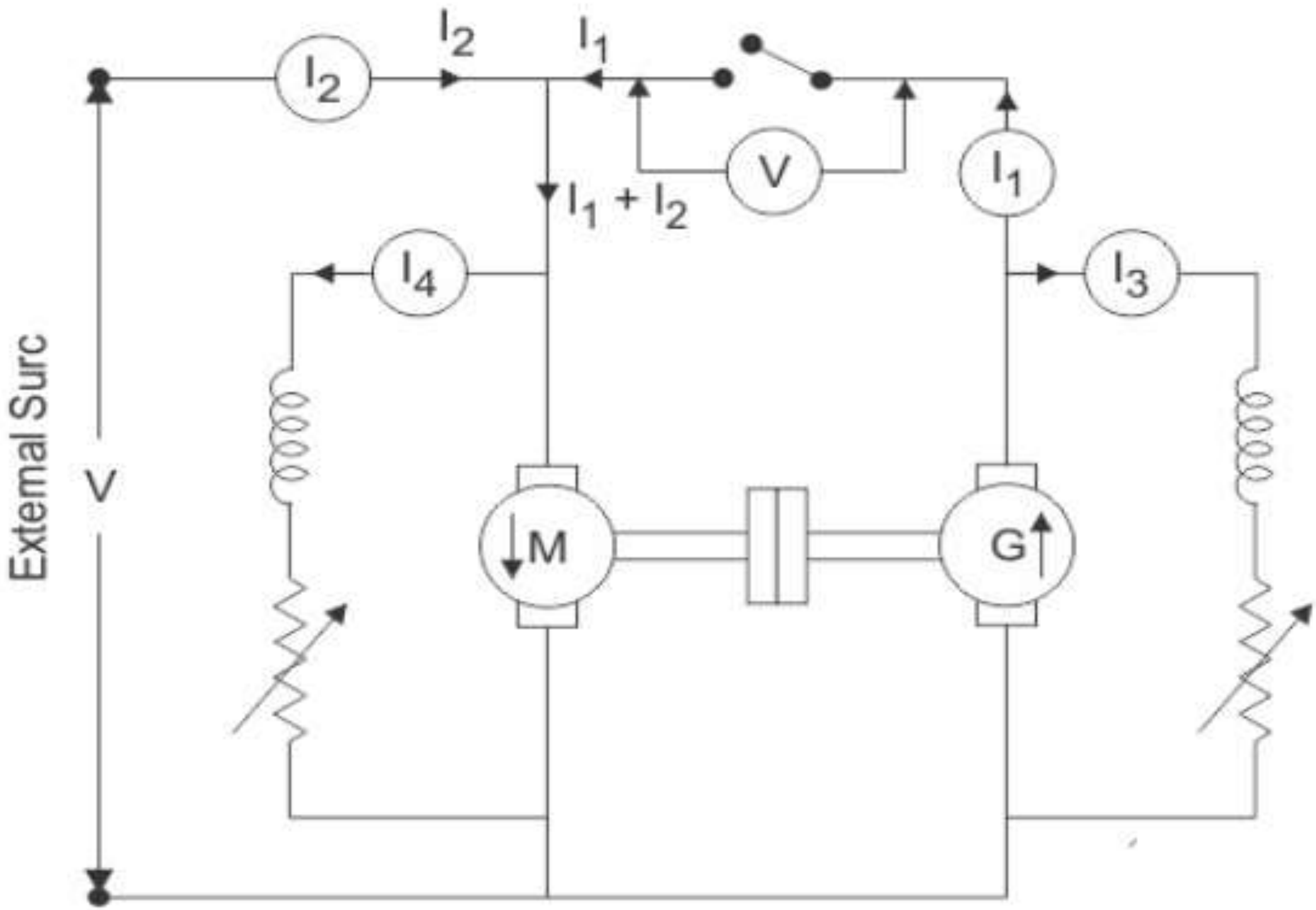
HOPKINSON TEST

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

Connection Diagram of Hopkinson's Test:

MOTOR-GENERATOR COUPLED

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



Hopkinson's Test of DC Machine

Calculation of Efficiency by Hopkinson's Test

- Let, V = supply voltage of the machines.
- Then, Motor input = V(I1 + I2) I1 = The current from the generator I2 = The current from the external source And, Generator output = VI1..................(1) Let, both machines are operating at the same efficiency 'η'. Then, Output of motor = η x input = η x V(I1 + I2) Input to generator = Output of the motor = η X V(I1 + I2) Output of generator = η x input = η x [η x V(I1 + I2)] = η2 V(I1 + I2) ...(2) From equation 1 an 2 we get, VI1 = η2 V(I1 + I2)

$$or, \quad \eta = \sqrt{\frac{I_1}{I_1 + I_2}}$$

or I1 = η2 (I1 + I2)

- **Now, in case of motor,**
- armature copper loss in the motor = (I1 + I2 - I4)2 Ra. Ra is the armature resistance of both motor and generator. I4 is the shunt field current of the motor. Shunt field copper loss in the motor will be = VI4
- Next, in case of generator armature copper loss in generator = (I1 + I3)2Ra I3 is the shunt field current of the generator. Shunt field copper loss in the generator = VI3 Now, Power drawn from the external supply = VI2 Therefore, the stray losses in both machines will be W = VI2 - (I1 + I2 - I4)2 Ra + VI4 + (I1 + I3)2 Ra + VI3 Let us assume that the stray losses will be same for both the machines. Then, Stray loss / machine = W/2

Efficiency of Generator:

- Total losses in the generator, WG = (I1 + I3)2 Ra + VI3 + W/2
- Generator output = VI1
- Then, efficiency

$$\eta_G = \frac{output}{input} = \frac{output}{output + losses} = \frac{VI_1}{VI_1 + W_G}$$

Efficiency of Motor:

- Total losses in the motor, WM = (I1 + I2 - I4)2 Ra + VI4 + W/2
- Motor input
- Then, effici

$$\eta_M = \frac{output}{input} = \frac{input - losses}{input} = \frac{V(I_1 + I_2) - W_M}{V(I_1 + I_2)}$$

Advantages of Hopkinson's Test

The merits of this test are…

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

Disadvantages of Hopkinson's Test

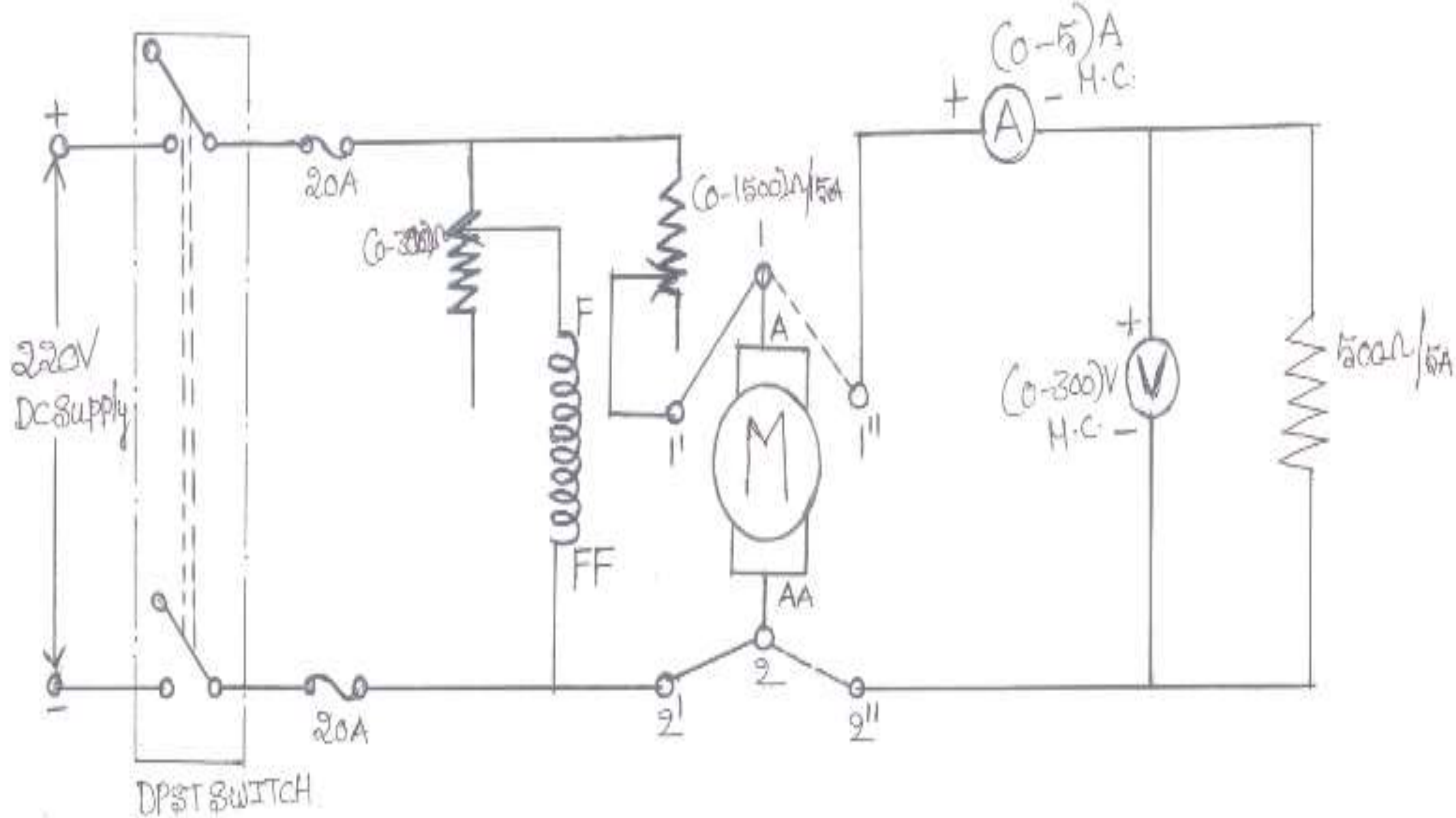
The demerits of this test are

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

RETARDATION TEST ON DC SHUNT MOTOR

- This test is also known as running down test.
- It is used for finding out the stray power losses of shunt wound DC machines.
- In this method of testing dc machines, machine under test is speeded up slightly above its normal speed and supply to the armature is cut off.
- Consequently the armature slows down and its kinetic energy is utilized to meet the rotational losses.
- The voltmeter connected across the armature shows the instantaneous back emf of the motor.
- Since back emf of the motor is directly proportional to speed, therefore, the voltmeter can be suitably calibrated to indicate speed.
- When the supply to armature is cut off, the speed of the motor decreases.

CIRCUITDIAGRAM:



•Connect the circuit as per the circuit diagram.
•Run the motor at a speed slightly higher than rated speed by adjusting field external rheostat..
•Disconnect the armature circuit from supply by opening switch ‘S’.
•Note down the time taken for the machine to come down to zero speed.
•Now, once again start the motor and run at a speed slightly higher than rated speed.
•Disconnect the armature circuit from supply and connect it across the rheostat by throwing switch ‘S’ into the position 1”& 2”.
•Note down the readings of voltmeter and ammeter for two speeds and time taken for the machine to come down to zero speed.

Without load:

S .no	Speed (rpm)	Time (sec)

With load:

S .no	Speed (rpm)	Time (sec)

Time taken = seconds (with load)

Speed (rpm)	V	I_L	V_{avg}	I_{avg}
N_1=				
N_2=				

PRECAUTIONS:

- Loose connection should be avoided.
- Operate the 3- point starter carefully.
- Don't run the motor above safe speed.

CALCULATIONS:

Rotational losses $W = W' \frac{(dt_2)}{(dt_1 - dt_2)}$

Where W'=average load power=$V_{avg}I_{avg}$ watts

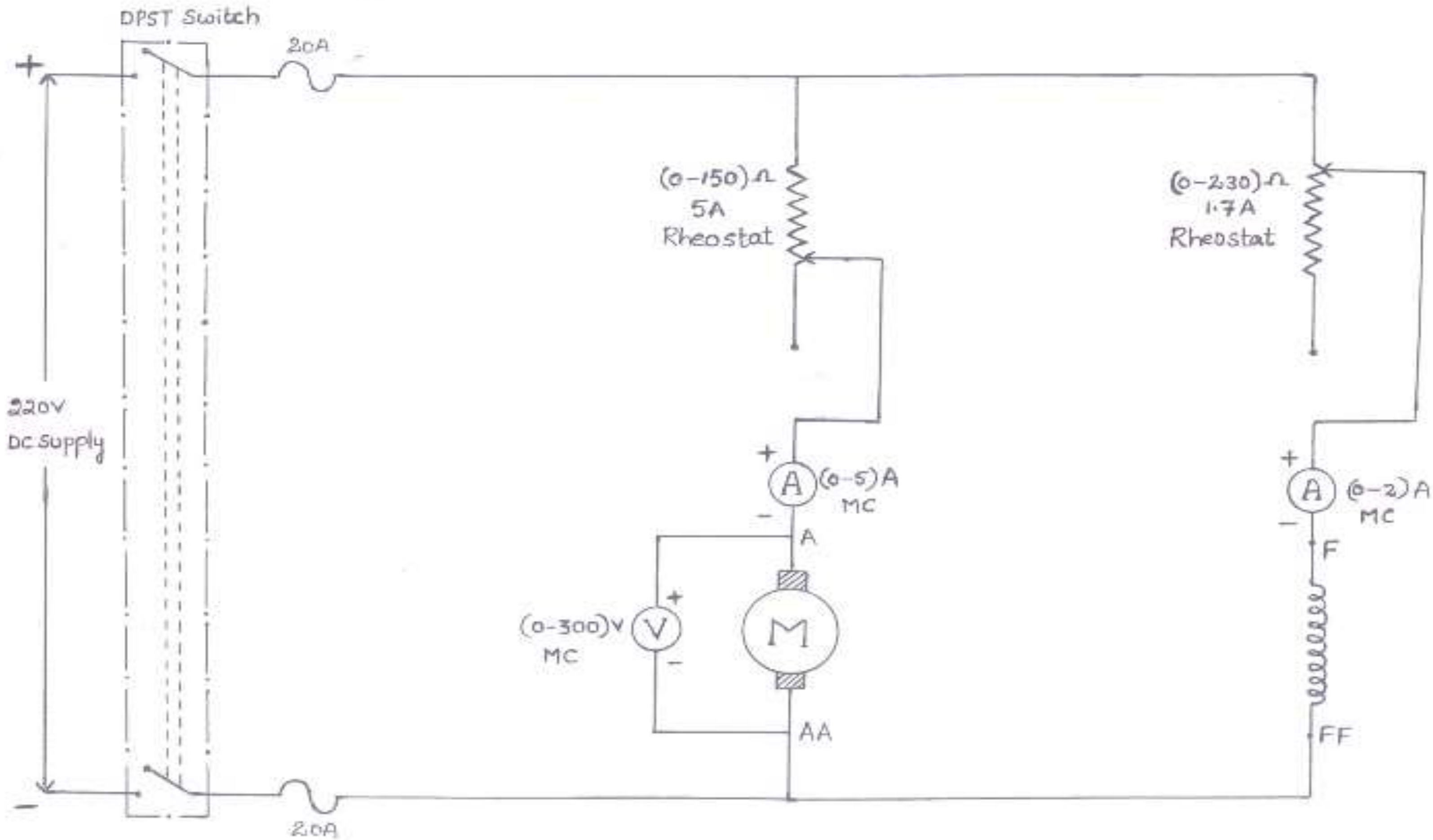
dt_2 is the time taken for the speed to come down from N_1 to N_2 with load.

dt_1 is the time taken for the speed to come down from N_1 to N_2 under no-load.

SEPARATION OF LOSSES IN DC SHUNT MOTOR

- It is the simplest indirect method of testing dc machines in which the losses are measured separately and efficiency at any desired load is predetermined.
- In this test various losses in a dc machine can be found into their components.
- The dc machine is run at no-load by varying the speed and keeping the excitation constant.
- If 'N' is the speed of the shunt motor at any given time, then the frictional losses are found to be proportional to 'N'.
- similarly the windage losses are found to be proportional to N^2.

CIRCUITDIAGRAM:



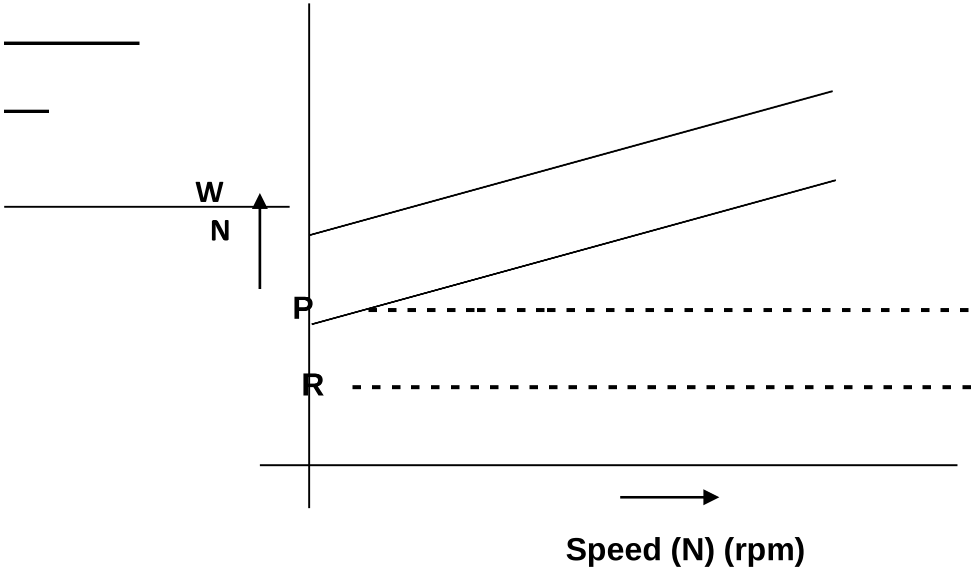
- Connect the circuit as per the circuit diagram.
- Keep the all rheostat at minimum resistance position.
- Start the motor with the help of 3- point starter.
- Adjust the speed of the motor to rated speed by adjusting the
- field rheostat.
- Note down the speed, voltage across armature and armature current.
- Keeping the field excitation constant.
- The speed of the motor can be varied by controlling the armature voltage by varying the armature resistance.
- The experiment is repeated at ¾ of the field current

S.No	Speed N(rpm)	Armature Voltage V (volts)	Armature Current I (Amp)	Cu losses $I_a^2R_a$ (Watts)	Input VI_a (Watts)	Constant losses W (Watts)	W/N

¾ Field current I_f =

S.No.	Speed (rpm)	Armature Voltage (V)	Armature Current (A)	Armature Cupper losses $I^2_aR_a$ (W)	Input VI_a (W)	Constant Losses = VI_a-I_aR_a (W)	$\frac{W}{N}$

MODEL GRAPH:



PRECAUTIONS:

•Loose connection should be avoided.
2. Operate the 3- point starter carefully.
3. Don’t run the motor above safe speed.

TUTORIALS

1. A 220 V d.c shunt motor has armature and field resistance as 0.8 Ω and 200 Ω. During Swinburne's test, current drawn from the supply is found to be 2.5 A. Estimate the efficiency of the machine,

(i) When it is running as a motor drawing a line current of 40 A from the 220 V supply.
(ii) When it is running as a generator delivering a load current of 40 A at 220 V.
(iii) Estimate the efficiency of the motor and for Generator.

2. Two similar coupled machines of same rating, each having an armature resistance of 0.5 Ω are connected for Hopkinson's test. Test data recorded as follows:

Supply voltage = 230 Volts

Total line current drawn from the supply = 8 A

Field current of the machine running as generator = 3 A

Field current of the machine running as motor = 2 A

Generator armature current = 17 A

(i) Estimate the rotational loss of each machine.

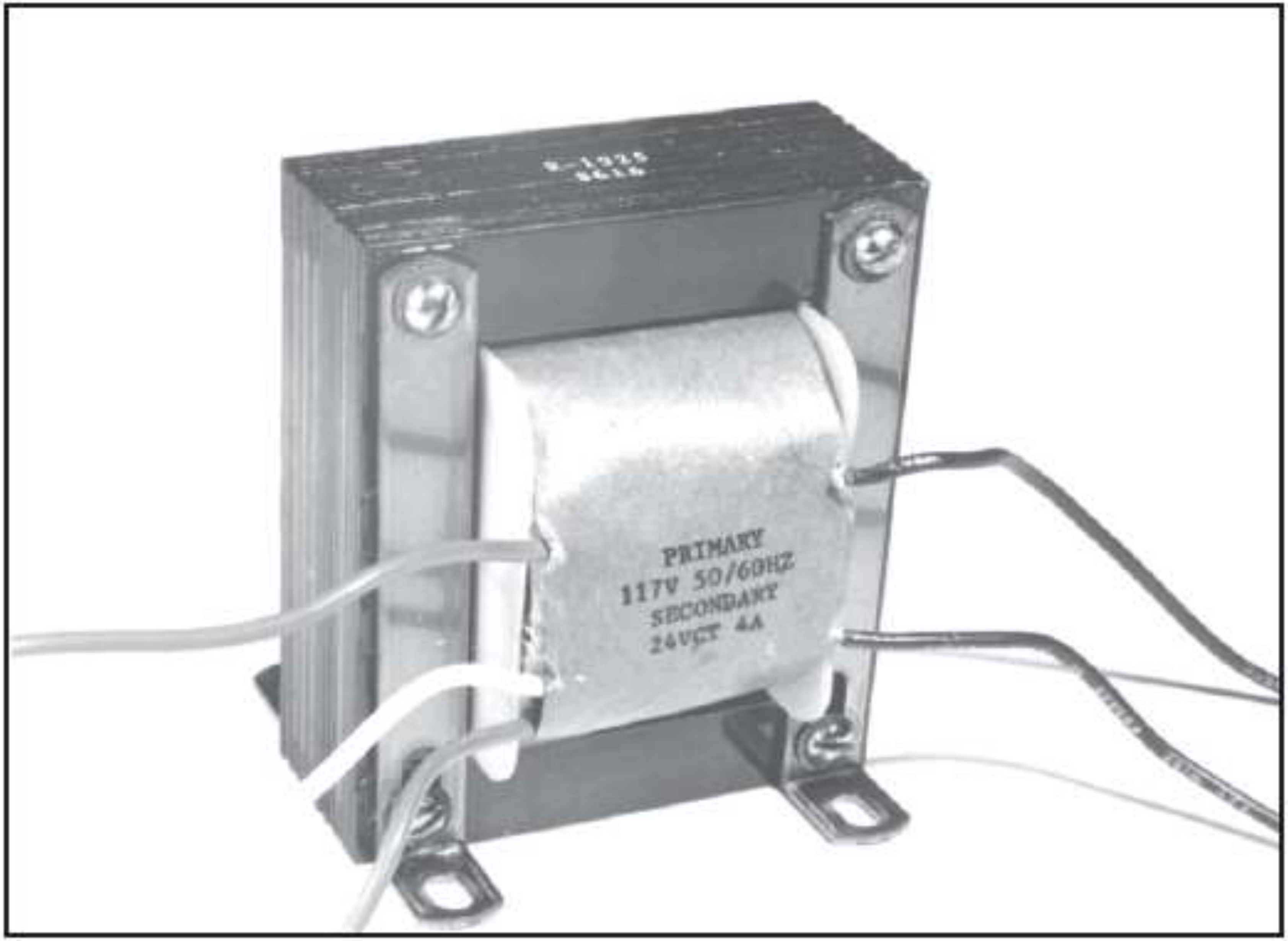
(ii) Estimate the efficiency of the Generator.

UNIT-4
Single Phase Transformers

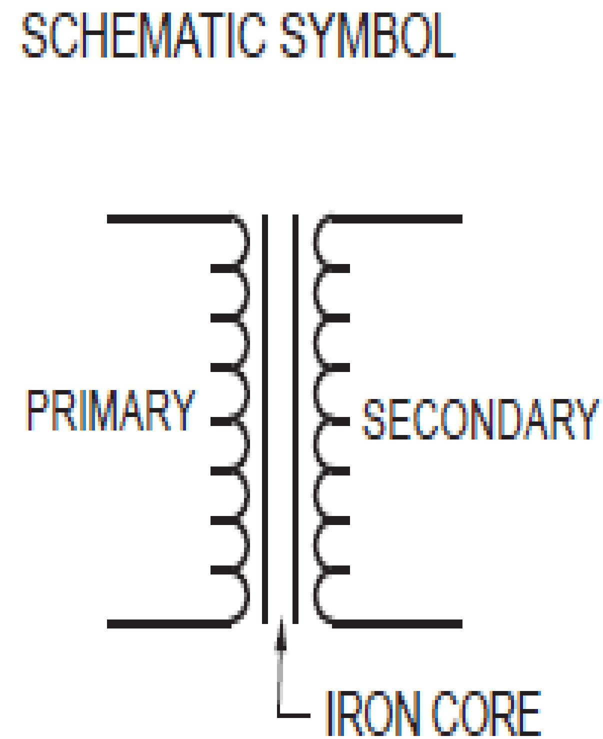
What are transformers?

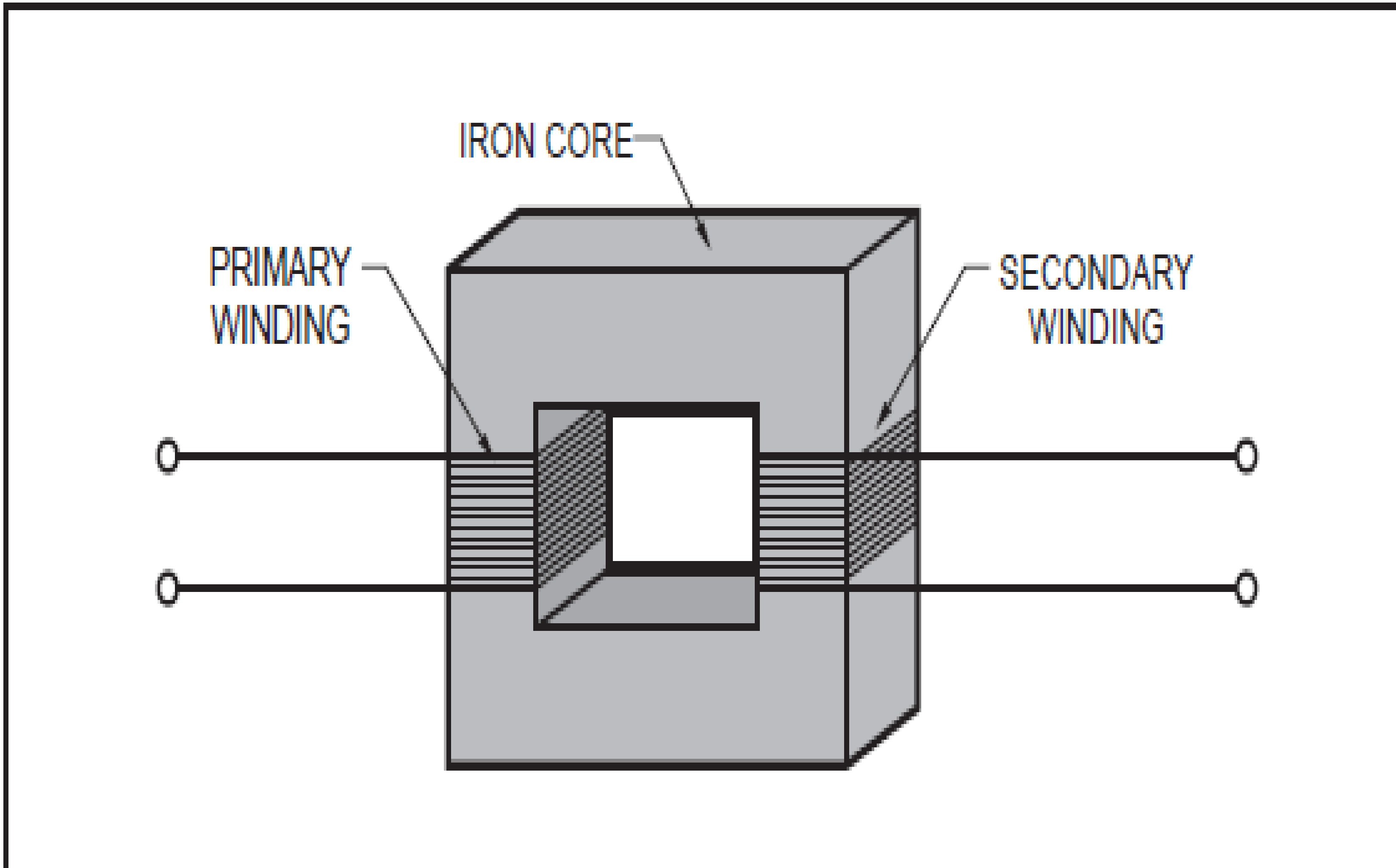
- Transformers are electrical devices used to convert or "transform" AC voltage from one level to another. (high to low or low to high)
- Input and output are AC
- They do this by the principle of electromagnetic induction

Transformer



Symbol of Transformer



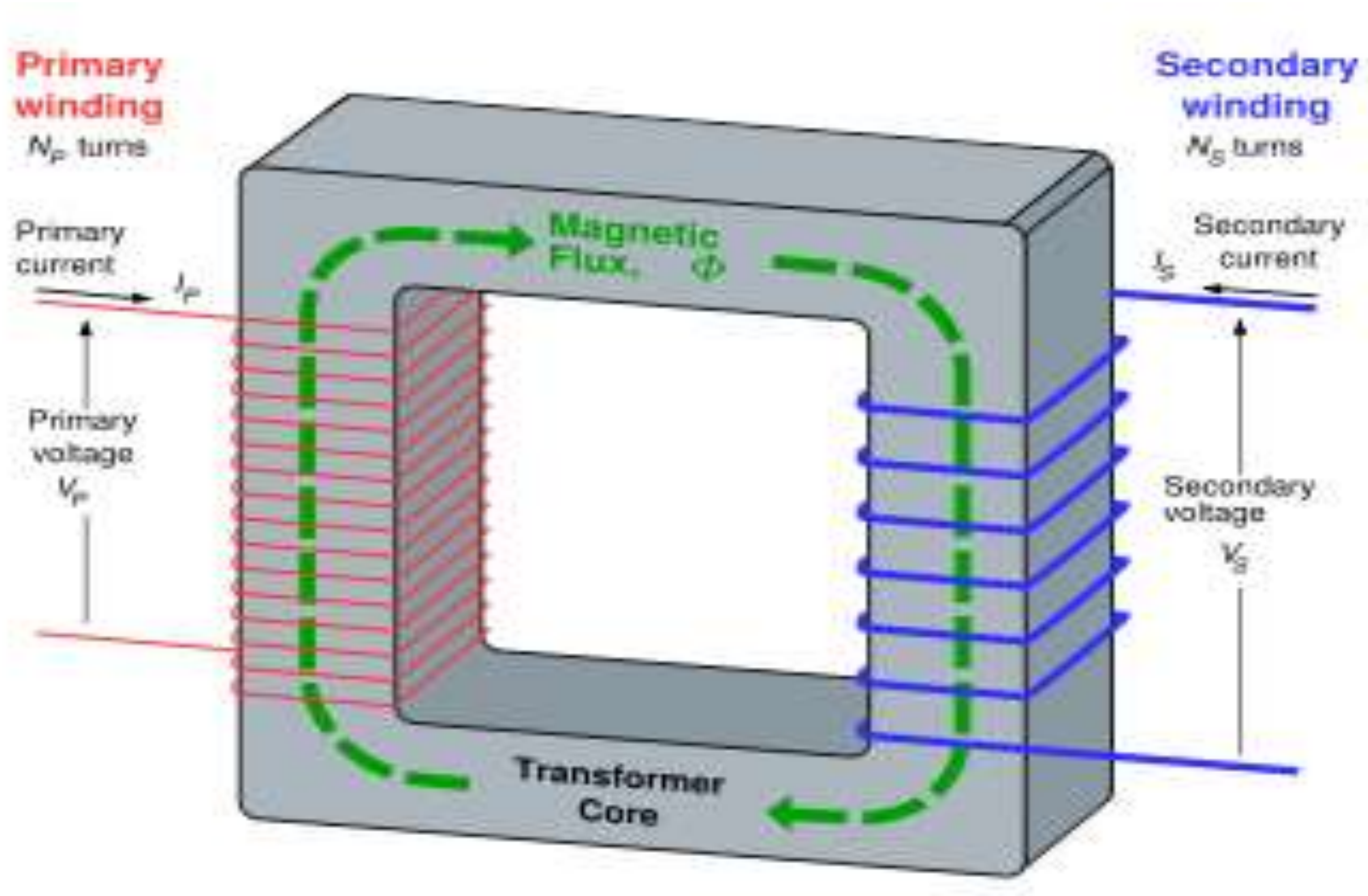

IRON CORE
PRIMARY
WINDING
SECONDARY
WINDING

Parts of a Transformer

A transformer consists of 3 basic components

- Primary Coil or Primary Winding : It is an electrical wire wrapped around the core on the input side
- Secondary Coil or Secondary Winding: It is an electrical wire wrapped around the core on the output side
- Core : A ferromagnetic material that can conduct a magnetic field through it. Example: Iron

Transformer Structure



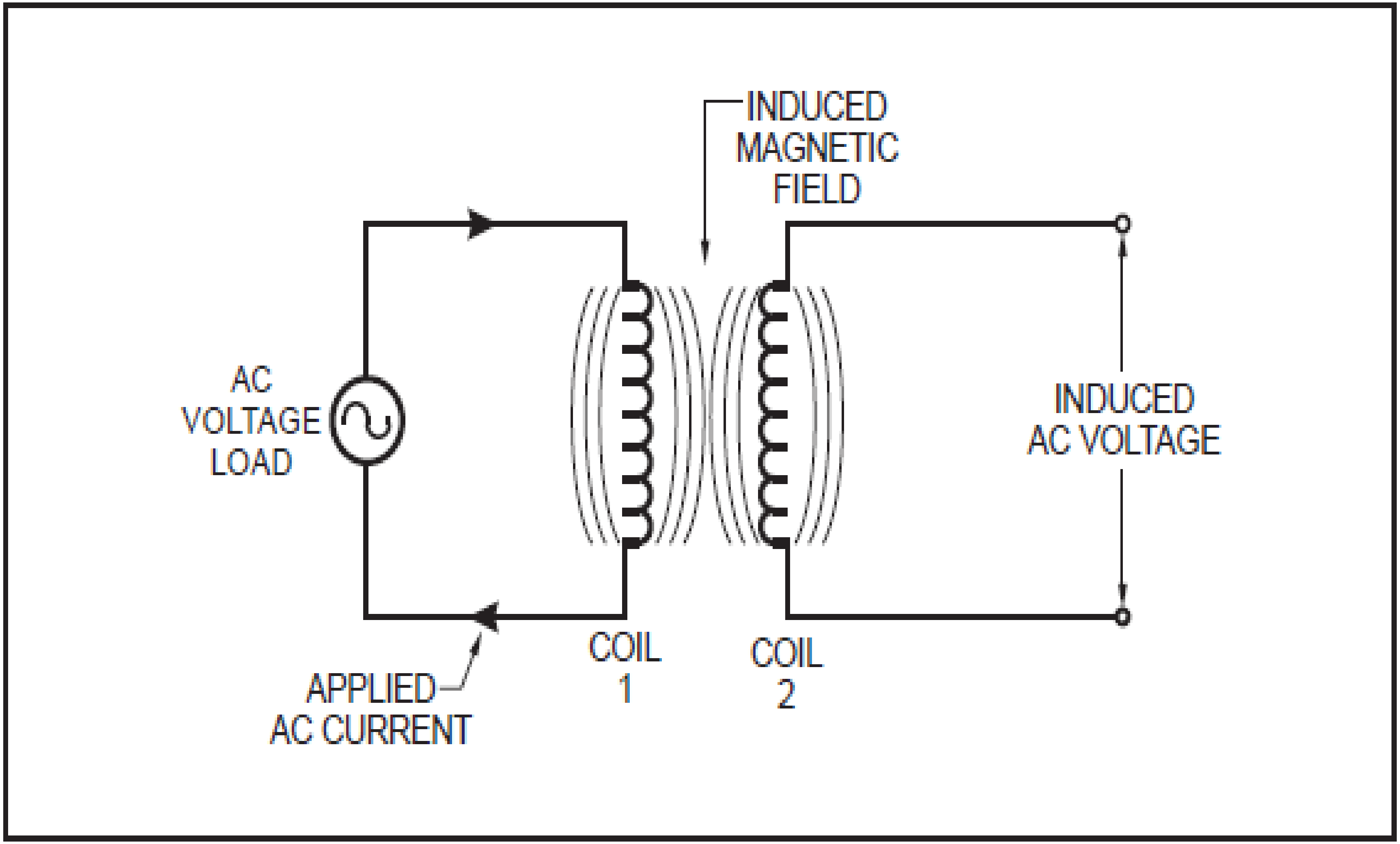
Transformer Operation

- An electrical transformer normally consists of a ferromagnetic core and two coils called "windings".
- A transformer uses the principle of mutual inductance to create an AC voltage in the secondary coil from the alternating electric current flowing through the primary coil.
- The voltage induced in the secondary can be used to drive a load.

What is Mutual Inductance?

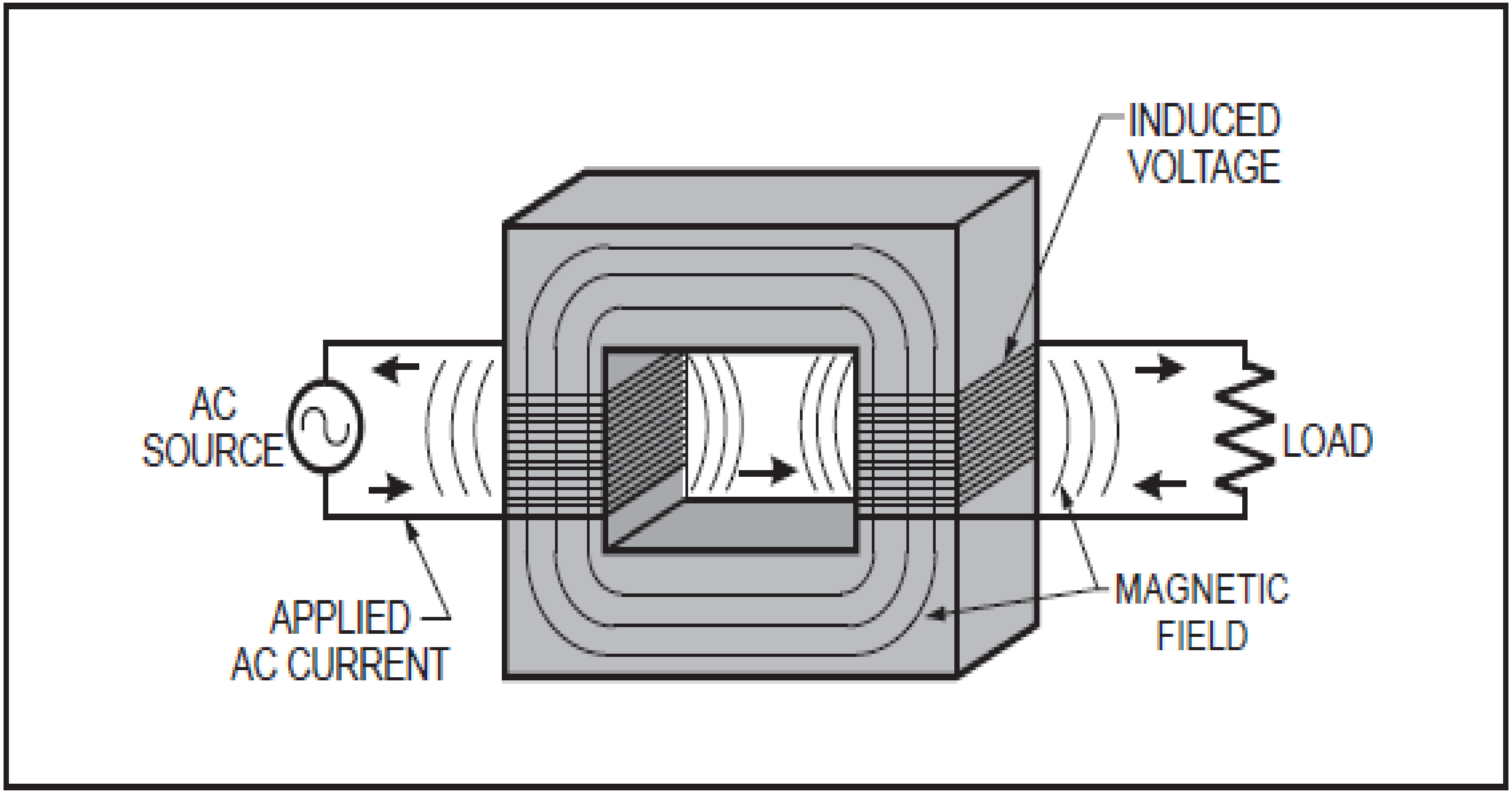
- The principle of mutual inductance says that when two electrical coils are placed near to each other, AC electrical current flowing in one coil induces an AC voltage in the other coil.
- This is because current in the first coil creates a magnetic field around the first coil which in turn induces a voltage in second coil

Mutual Inductance



- The transformer improves the efficiency of the transfer of energy from one coil to another by using a core to concentrate the magnetic field.
- The primary coil creates a magnetic field that is concentrated by the core and induces a voltage in the secondary coil

Transformer Operation



Turns Ratio

- The voltage at the secondary coil can be different from the voltage at the primary. This happens when the number of turns of the coil in primary and secondary are not the same
- The Turns Ratio (TR) is the ratio of the number of turns in the primary coil to the number of turns in the secondary coil

TURNS RATIO FORMULA

$$TR = \frac{N_P}{N_S}$$

Where

N_P = *number of turns in the primary*
N_S = *number of turns in the secondary*

TRANSFORMER OUTPUT VOLTAGE FORMULA

$$V_S = \frac{V_P}{TR}$$

Where

V_S = *secondary voltage (Volts)*
V_P = *primary voltage (Volts)*
TR = *turns ratio*

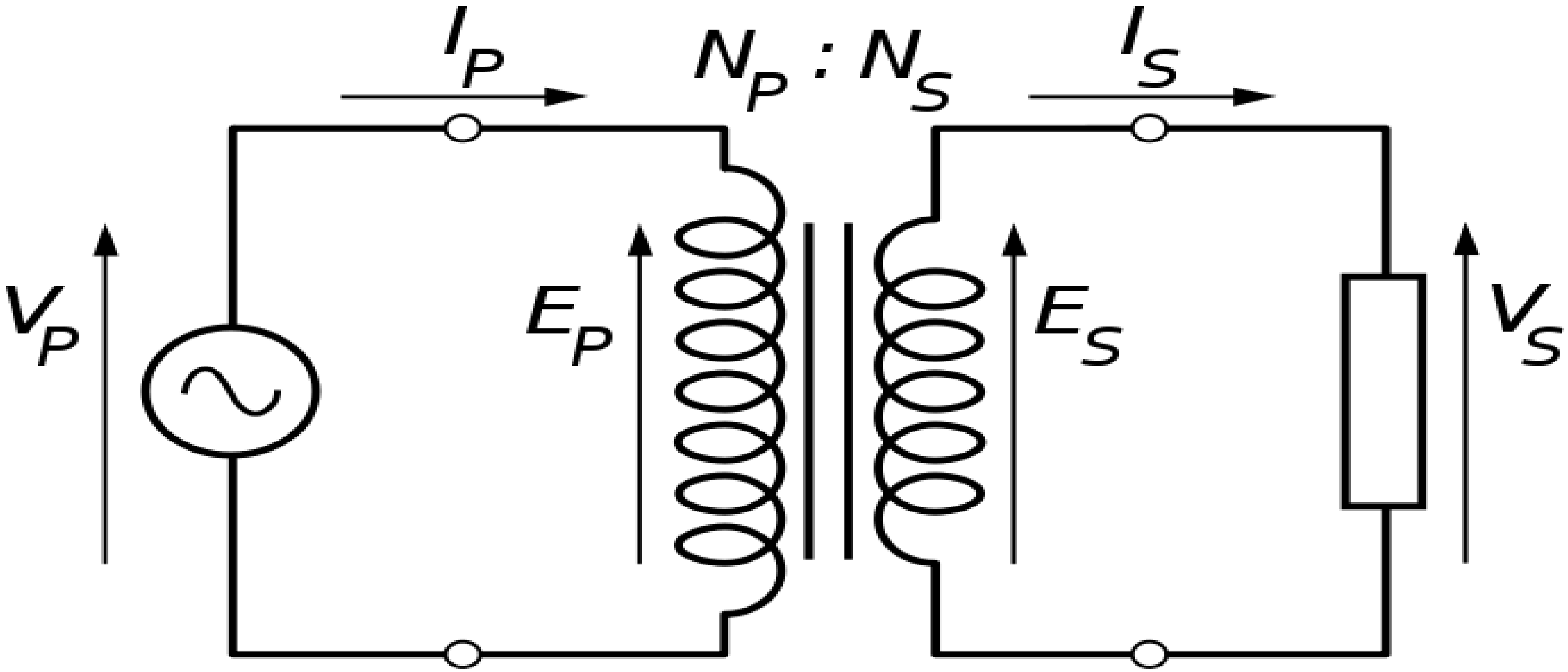
Formulas

- TR= Vp / Vs
- Also TR= Np /Ns
- So we can say

Vp / Vs = Np /Ns

Also Vp/Vs=Is /Ip

Transformer Voltages & Currents



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

Problems

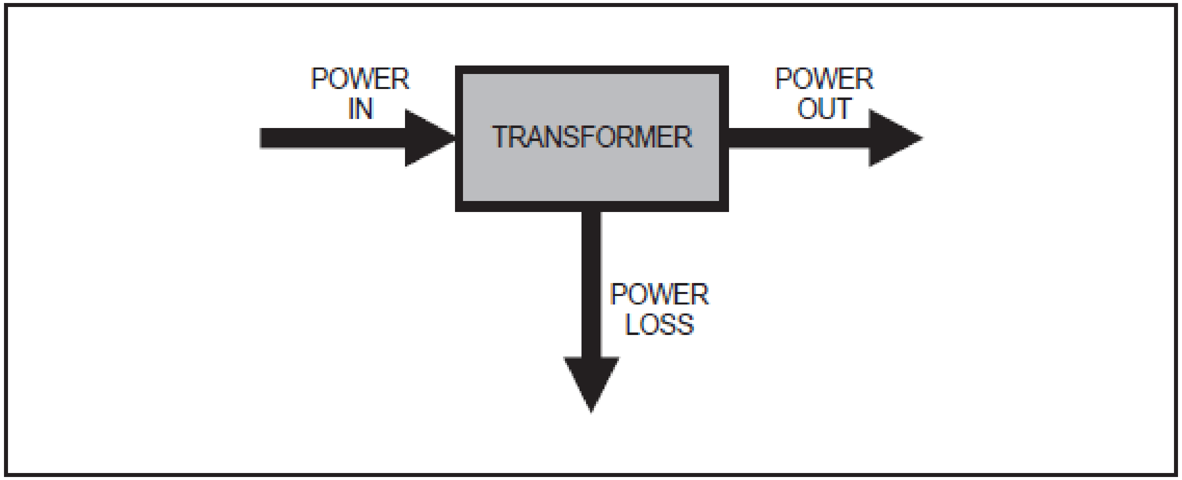
1. A transformer has a primary voltage of 230v and turns ratio of 5:1. Calculate the secondary voltage
2. A transformer has 200 turns in the primary, 50 turns in the secondary, and 120 volts applied to the primary (V_p). What is the voltage across the secondary (V_s)?

More Problems….

1. There are 400 turns of wire in an iron-core coil. If this coil is to be used as the primary of a transformer, how many turns must be wound on the coil to form the secondary winding of the transformer to have a secondary voltage of one volt if the primary voltage is five volts?
2. A 12 volts transformer has 20 turns in the primary, 5 turns in the secondary. What is the voltage across the primary side (V_P)?

Input Power and Output Power of a Transformer

- Under ideal conditions input power and output power should be the same. But there is power loss between the primary and secondary and so practically they are not exactly equal.
- So, $P_{in} = P_{out} + P_{loss}$



Transformer Efficiency

- The power loss is converted to heat . The heat produced can be found by calculating the transformer efficiency.

TRANSFORMER EFFICIENCY FORMULA

$$\text{Transformer Efficiency } \% = \frac{\text{Power Out}}{\text{Power In}} \times 100$$

Where

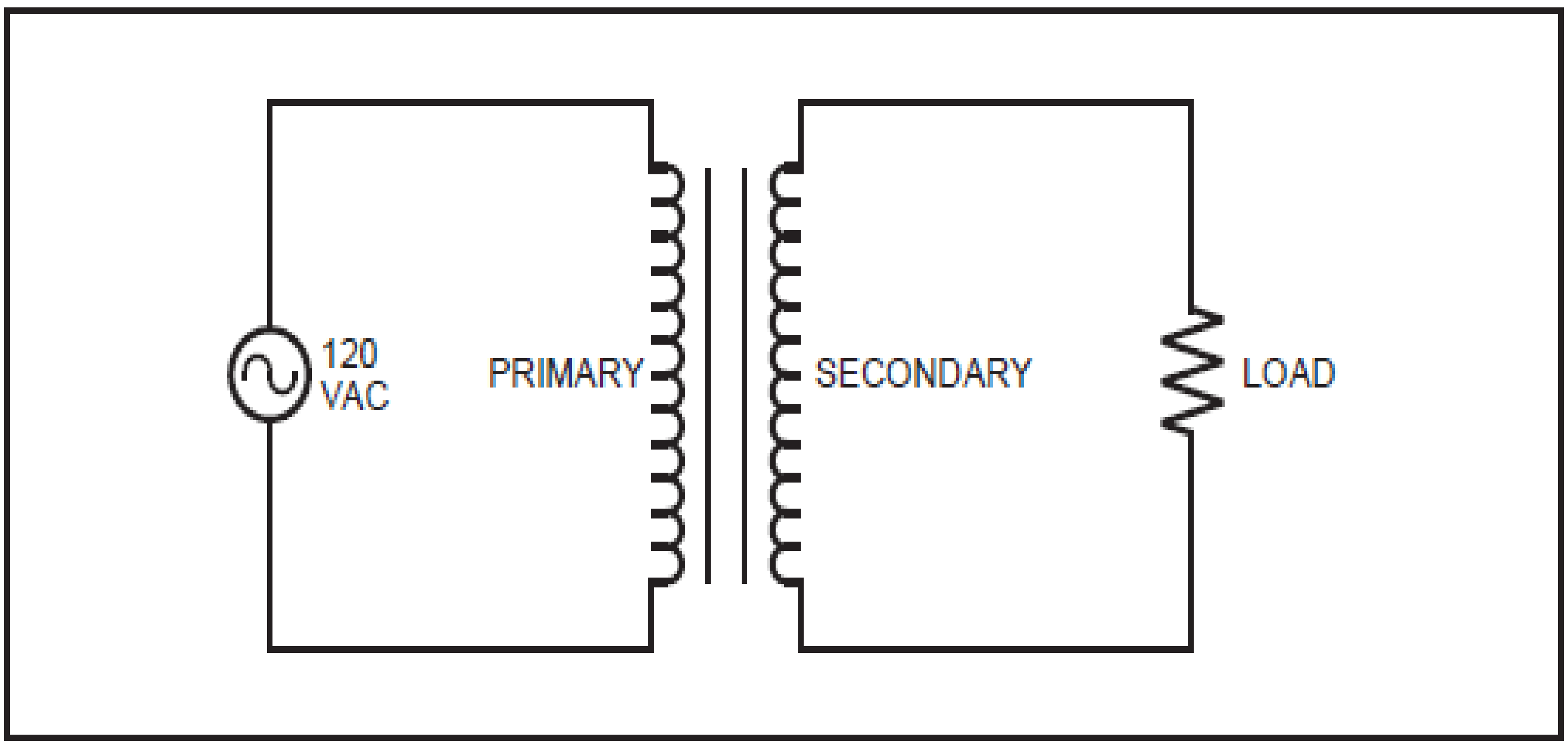
Power Out = output power (Watts or VA)
Power In = input power (Watts or VA)

Transformer Types

- Isolation Transformer
- Autotransformer

Isolation Transformer

- In isolation transformer, the primary and secondary are physically isolated (no electrical connection)

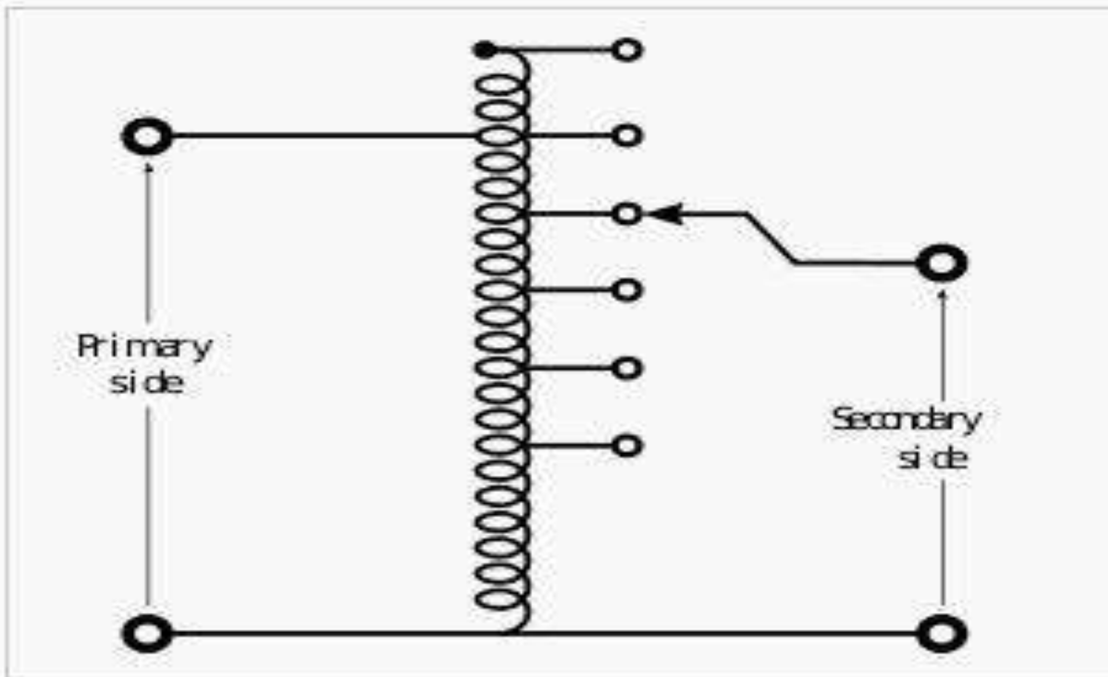


Advantages of Isolation Transformer

- Voltage spikes that might occur on the primary are greatly reduced or eliminated in the secondary
- If the primary is shorted somehow, any load connected to the secondary is not damaged
- Example: In TV monitors to protect the picture tube from voltage spikes in main power lines

Autotransformers

- An autotransformer uses only one coil for the primary and secondary.
- It uses taps on the coil to produce the different ratios and voltages.



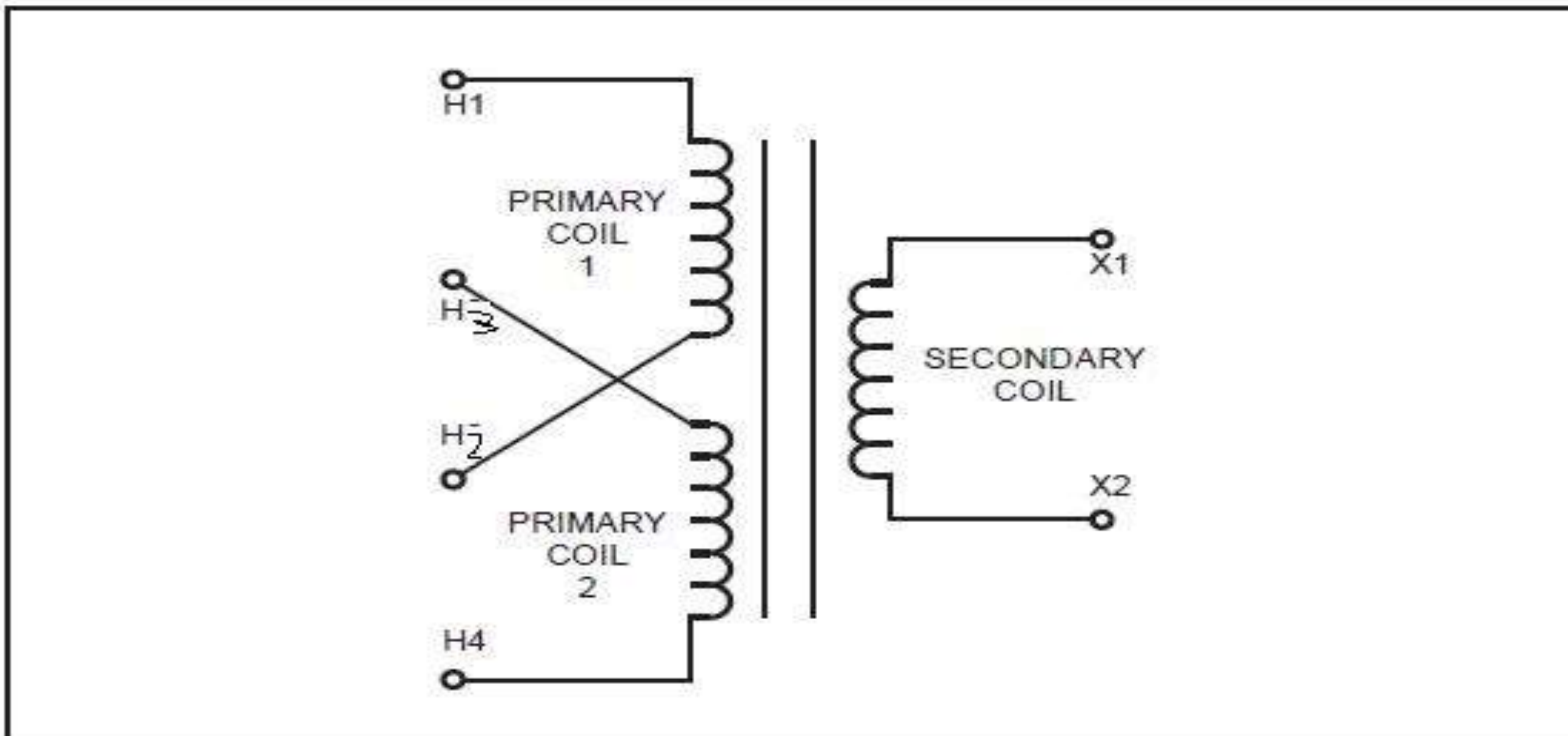
Single-phase tapped autotransformer with output voltage range of 40%–115% of input

The Control Transformer

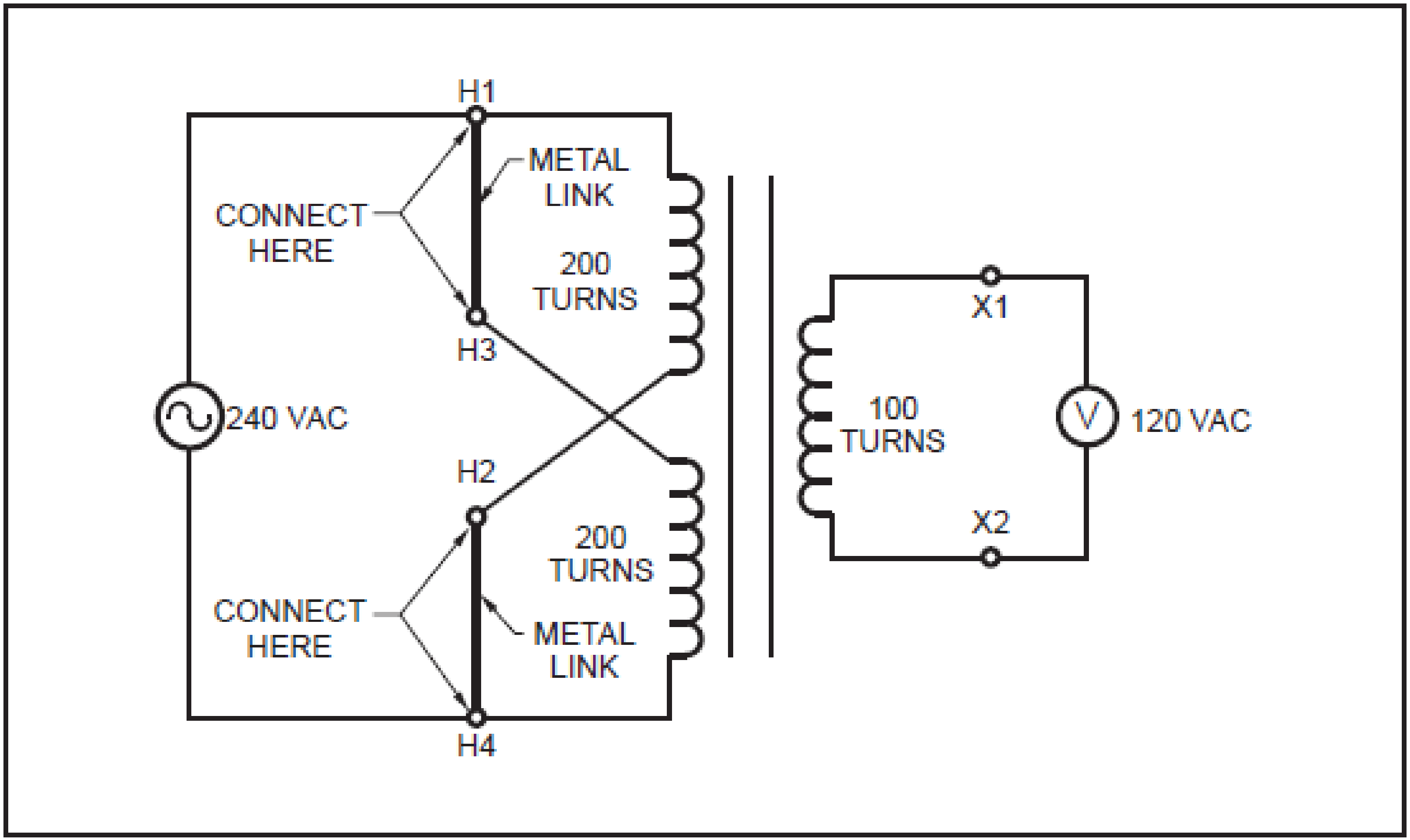
- A control transformer is used to reduce voltage from the main power line to a lower voltage that operates a machine’s electrical control system.

The Control Transformer

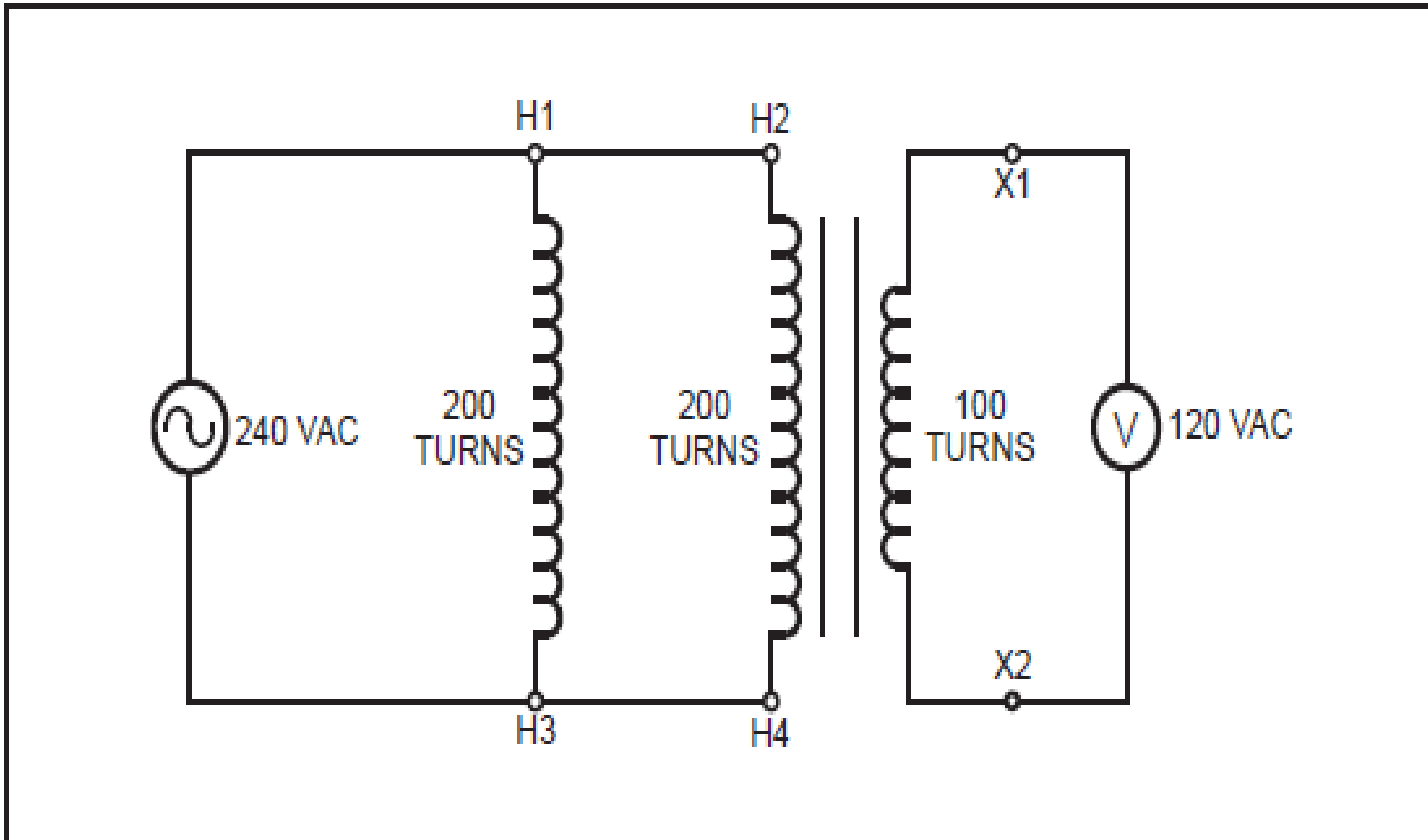
- The most common type of control transformer has two primary coils (H1H2 and H3H4) and one secondary coil (X1X2). Note that the primary windings are crossed



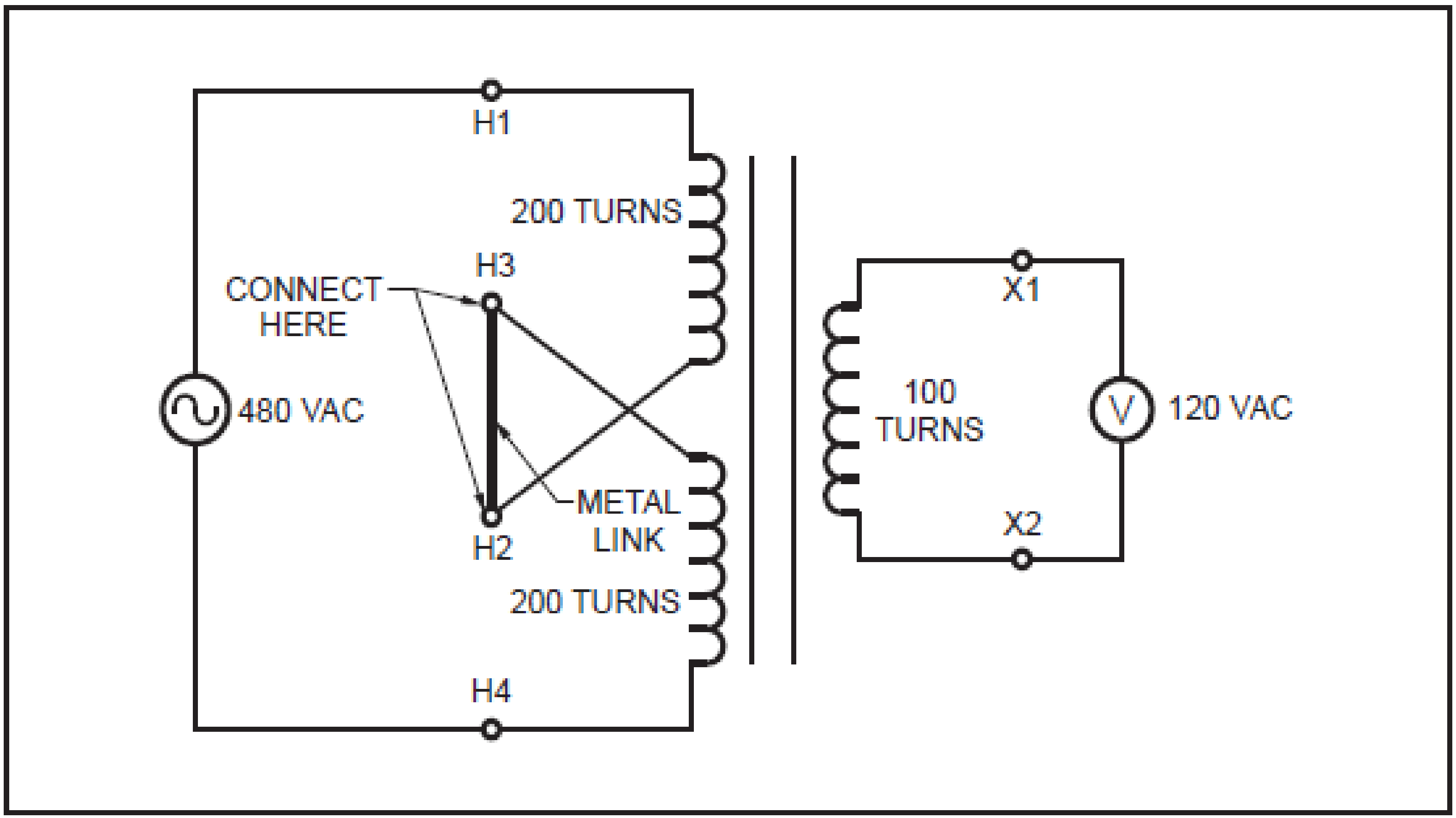
To get 120V at the secondary from 240 V at the primary using a control transformer



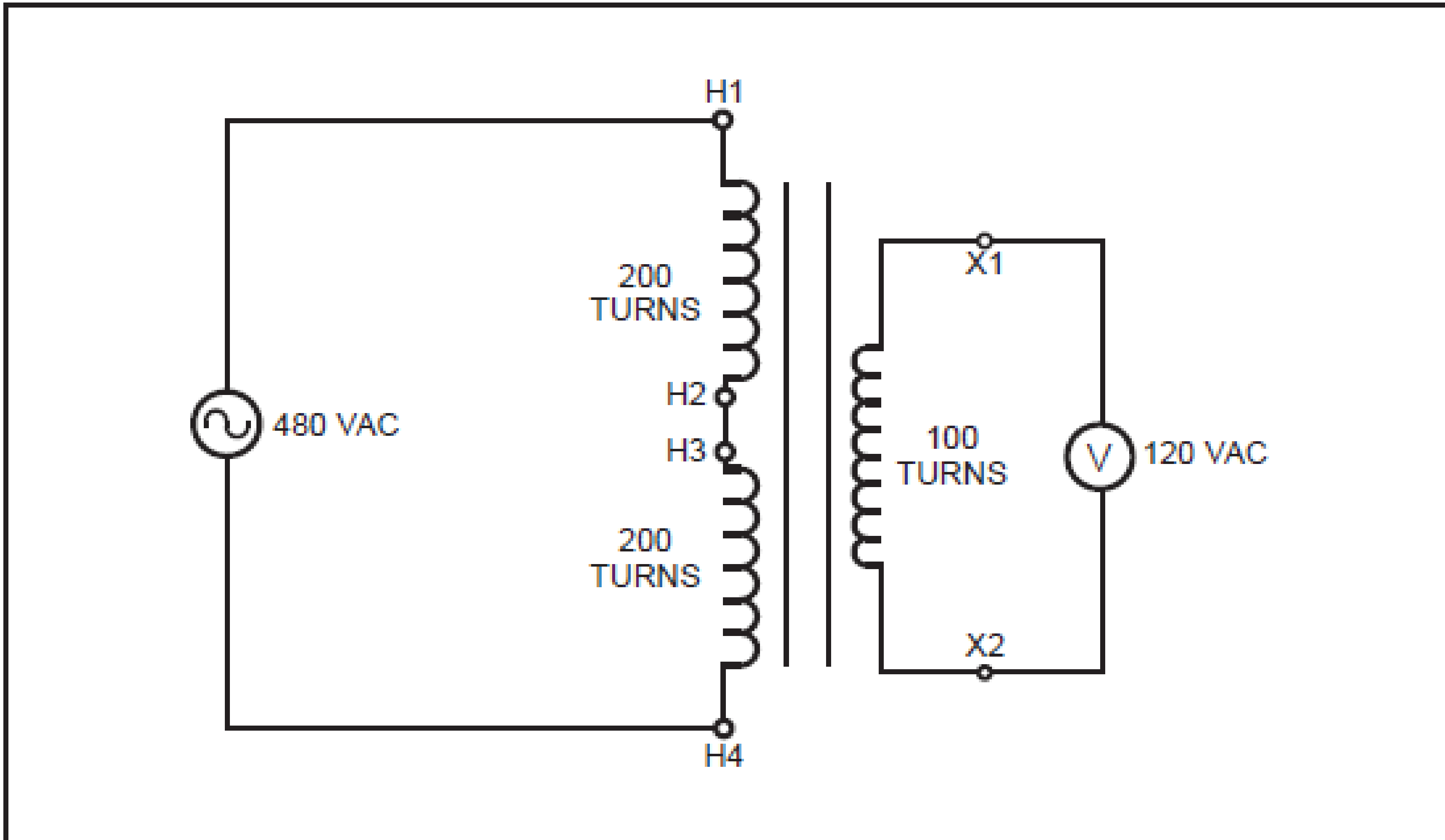
It is actually a parallel connection of the primary coils



To get 120V at the secondary from 480 V at the primary using a control transformer

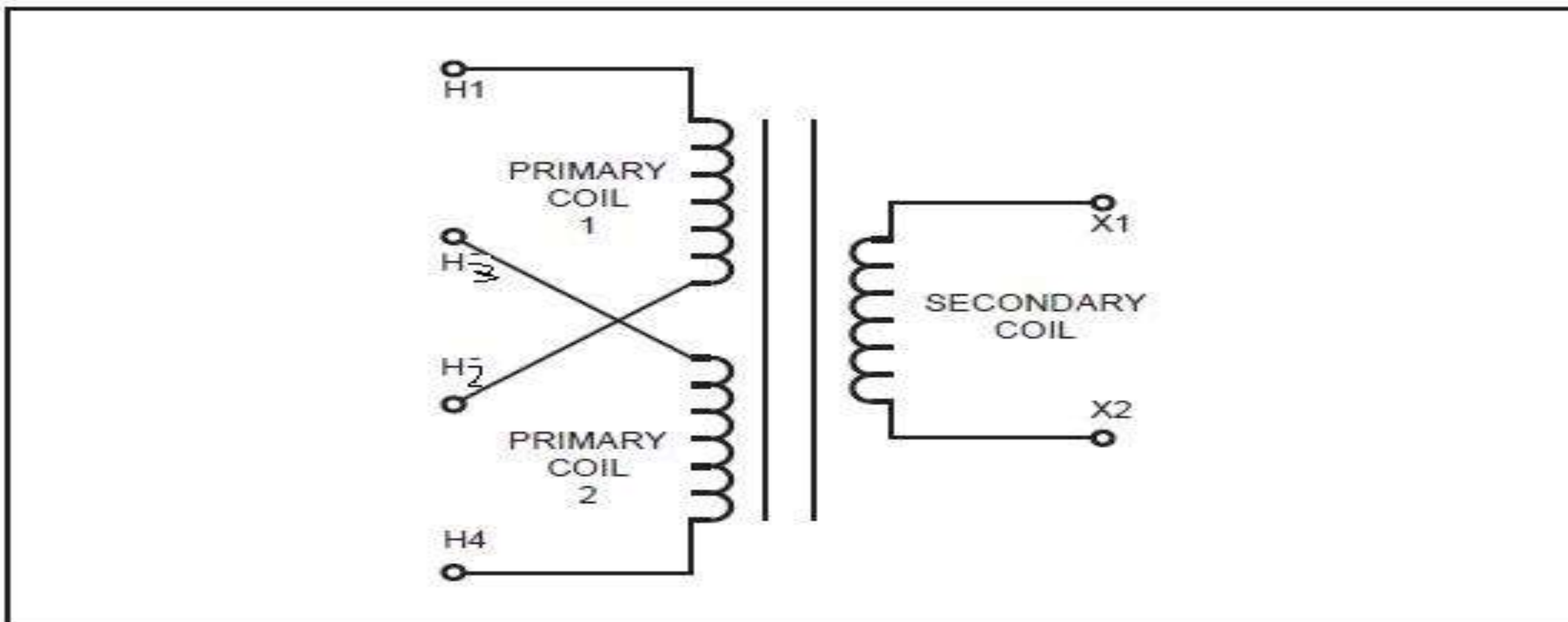


This is actually a series connection of the primary coils



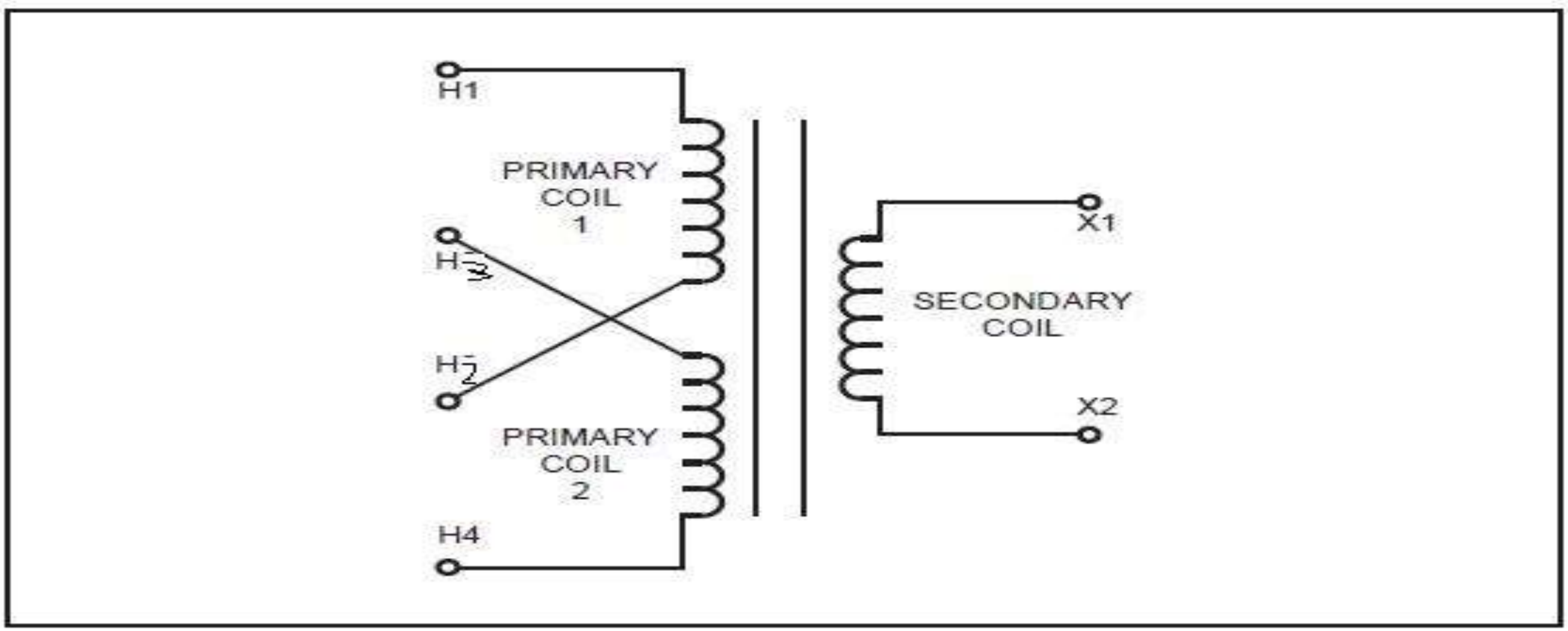
Problem 1

- Connect the primary coils in parallel and calculate the secondary voltage if the primary voltage is 48 Volts and the number of turns in each primary is 50 turns and the secondary has 25 turns.

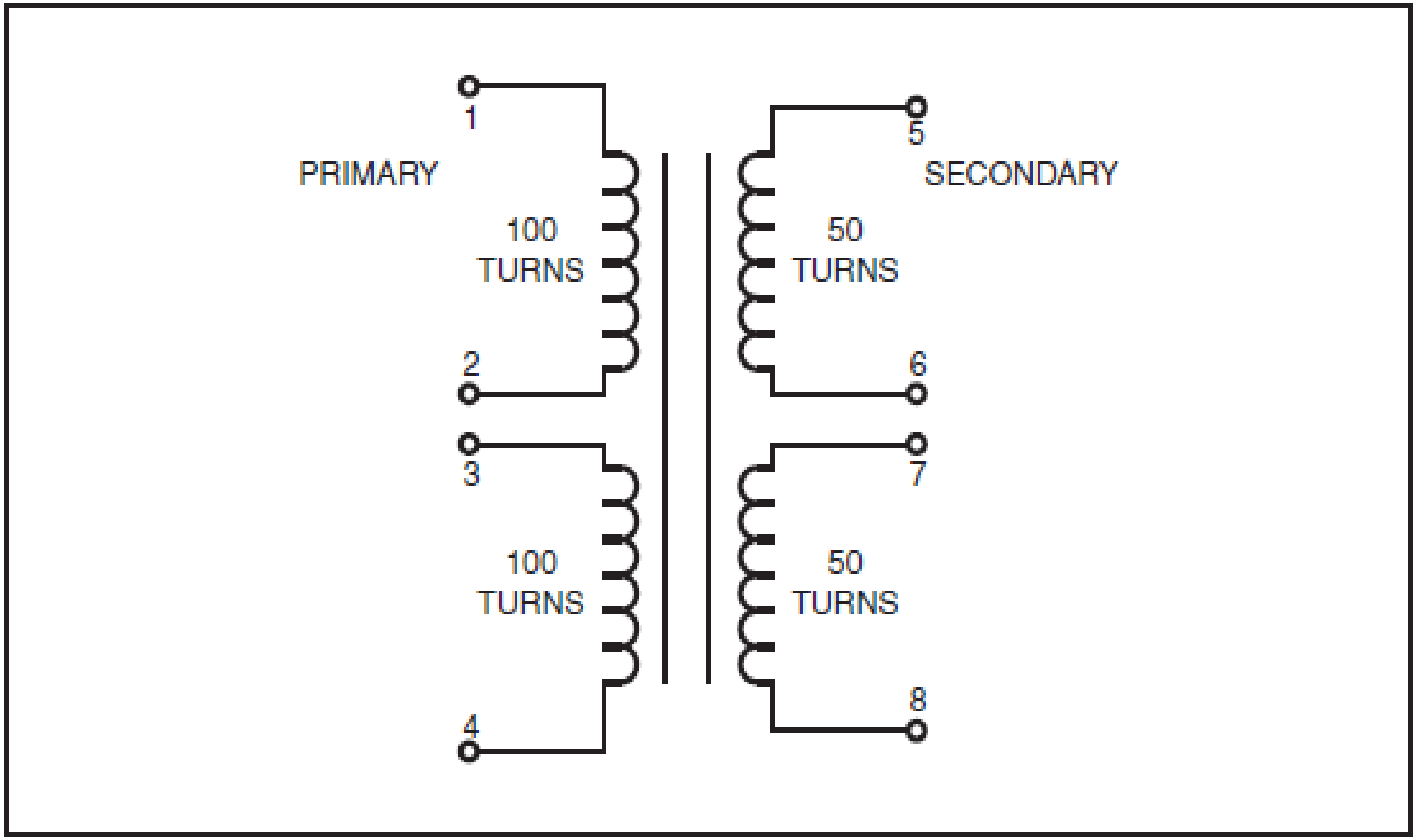


Problem 2

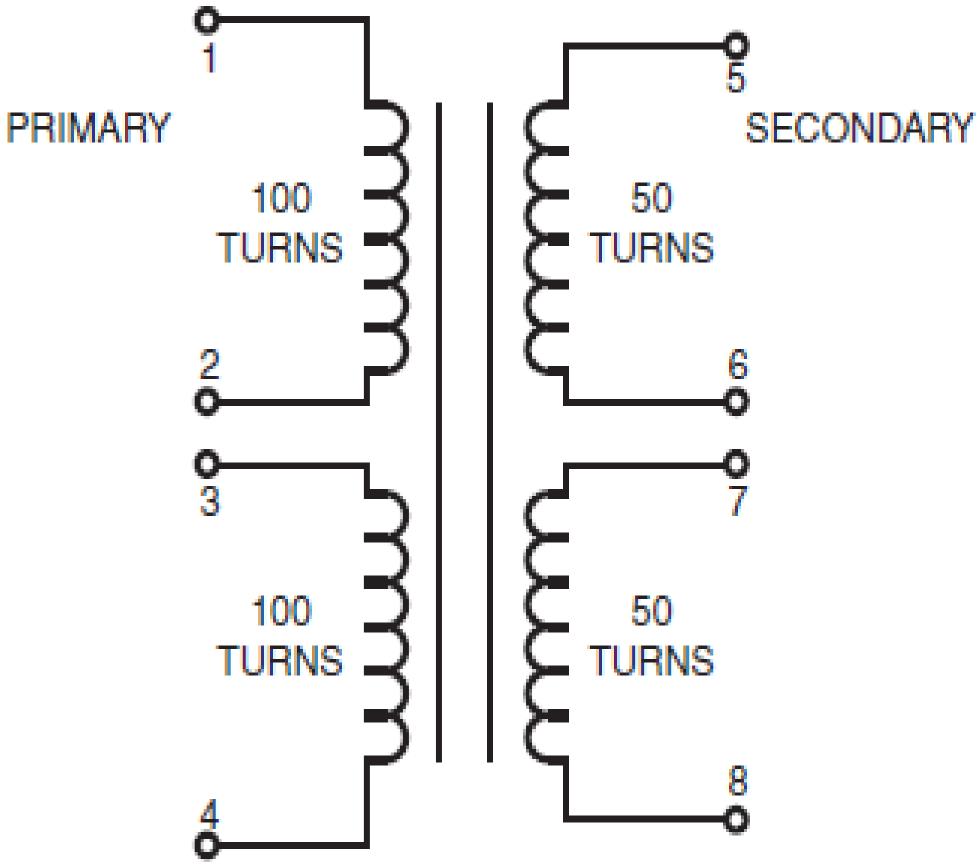
- Connect the primary coils in series and calculate the secondary voltage if the primary voltage is 48 Volts and the number of turns in each primary is 50 turns and the secondary has 25 turns.



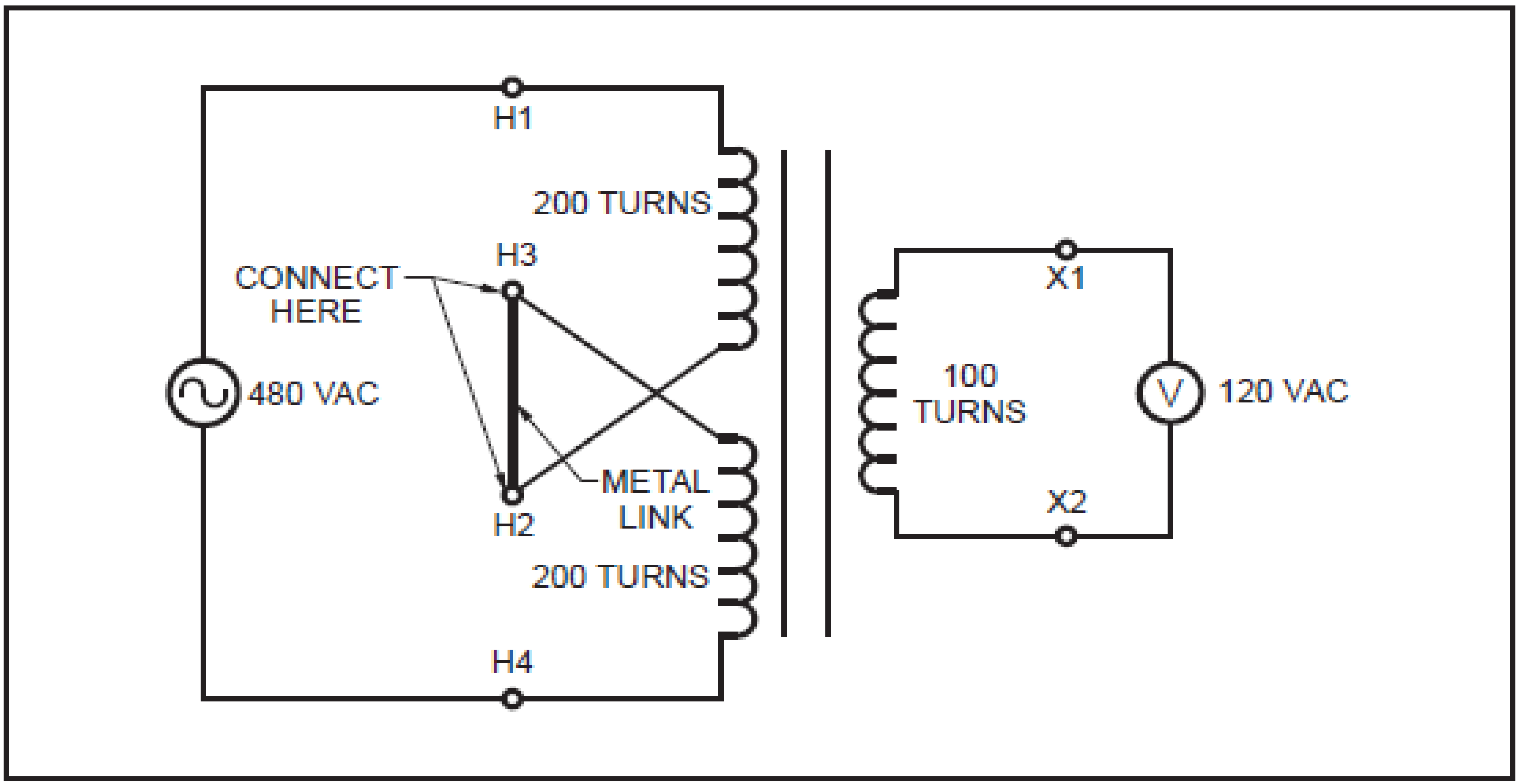
Problem 3: Make connections in the transformer coils to produce a turns ratio of 1:1. Use both primary and secondary coils.



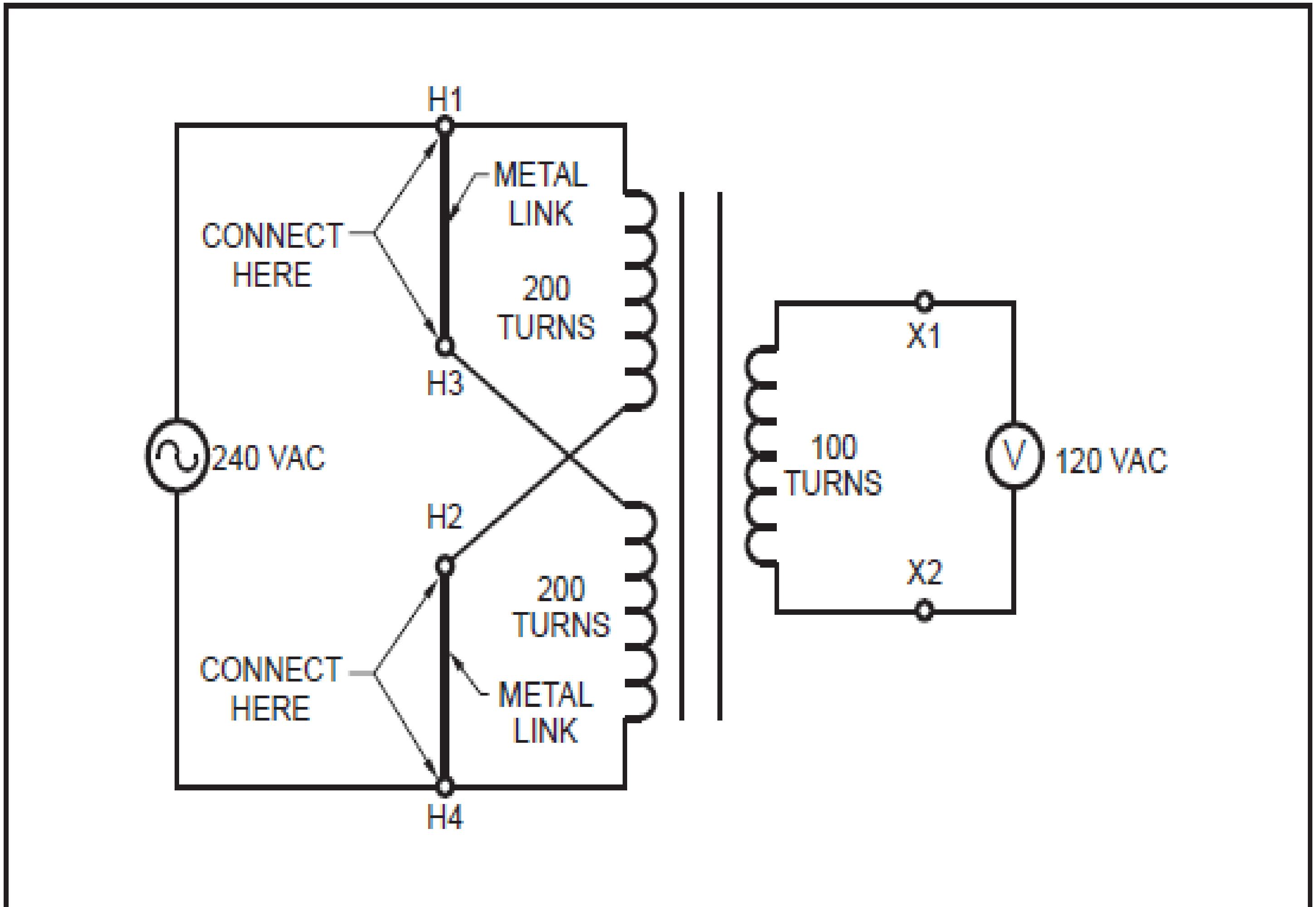
Problem 4:Make connections in the transformer coils to produce a turns ratio of 2:1. Use both primary and secondary coils.



Problem 5: What is the turns ratio in the circuit?



Problem 6: What is the turns ratio in this circuit?



UNIT-V

Testing of Transformers

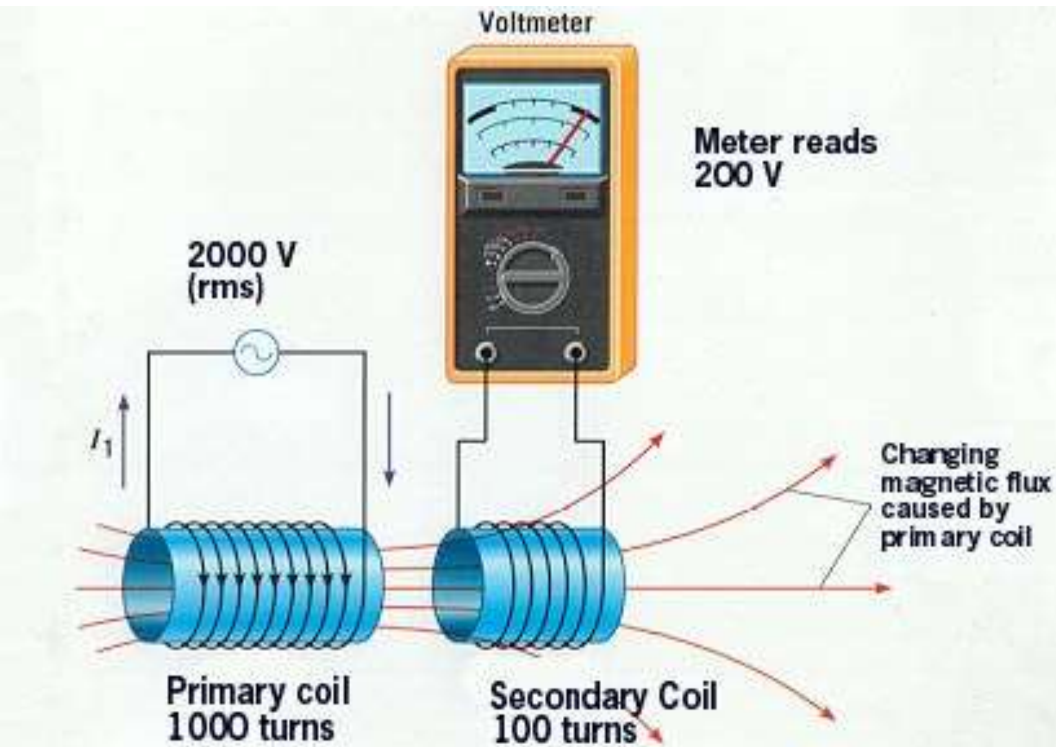
Transformer

An A.C. device used to change high voltage low current A.C. into low voltage high current A.C. and vice-versa without changing the frequency

In brief,

1. Transfers electric power from one circuit to another
2. It does so without a change of frequency
3. It accomplishes this by electromagnetic induction
4. Where the two electric circuits are in mutual inductive influence of each other.

Principle of operation

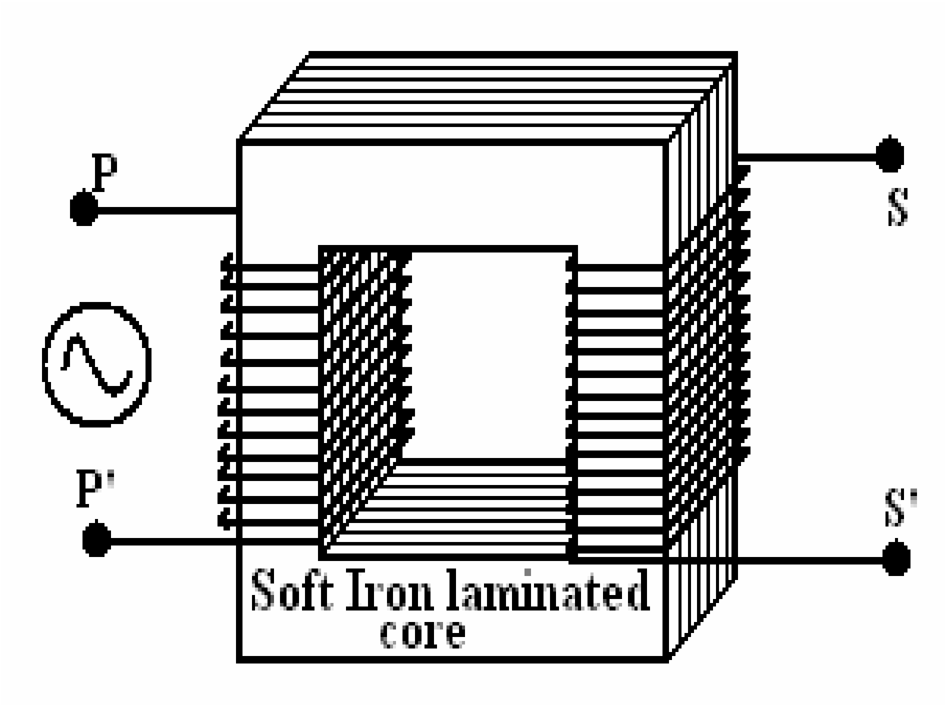


It is based on principle of MUTUAL INDUCTION.

According to which an e.m.f. is induced in a coil when current in the neighbouring coil changes.

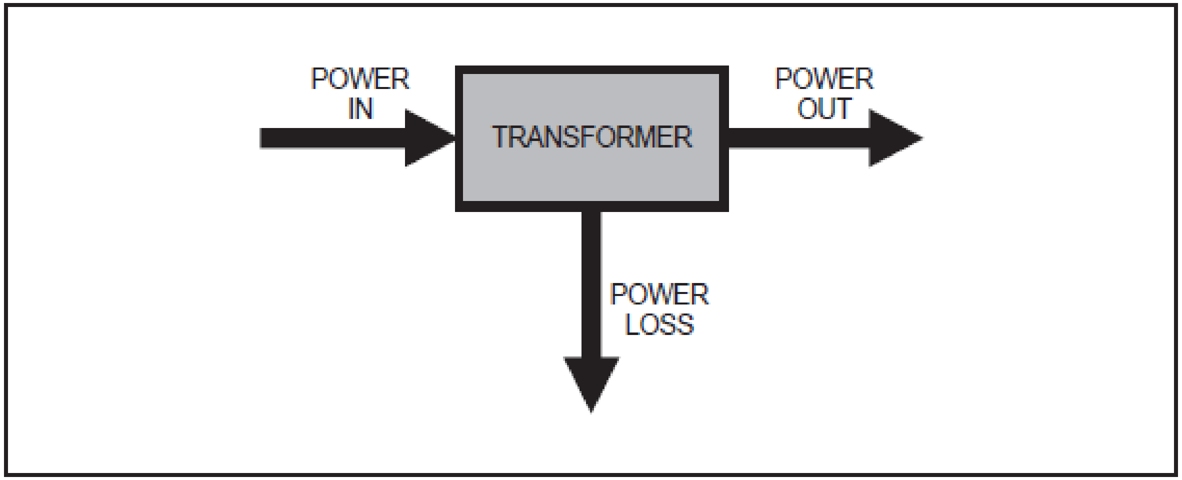
Working of a transformer

1. When current in the primary coil changes being alternating in nature, a changing magnetic field is produced
2. This changing magnetic field gets associated with the secondary through the soft iron core
3. Hence magnetic flux linked with the secondary coil changes.
4. Which induces e.m.f. in the secondary.



Input Power and Output Power of a Transformer

- Under ideal conditions input power and output power should be the same. But there is power loss between the primary and secondary and so practically they are not exactly equal.
- So, $P_{in} = P_{out} + P_{loss}$



Transformer Efficiency

- The power loss is converted to heat . The heat produced can be found by calculating the transformer efficiency.

TRANSFORMER EFFICIENCY FORMULA

$$Transformer\ Efficiency\ \% = \frac{Power\ Out}{Power\ In} \times 100$$

Where

Power Out= output power (Watts or VA)
Power In = input power (Watts or VA)

Transformer Efficiency

Transformer efficiency is defined as (applies to motors, generators and transformers):

$$\eta = \frac{P_{out}}{P_{in}} \times 100\%$$

$$\eta = \frac{P_{out}}{P_{out} + P_{loss}} \times 100\%$$

Types of losses incurred in a transformer:

Copper I^2R losses

Hysteresis losses

Eddy current losses

Therefore, for a transformer, efficiency may be calculated using the following:

$$\eta = \frac{V_S I_S \cos\theta}{P_{Cu} + P_{core} + V_S I_S \cos\theta} x100\%$$

Losses in a transformer

Core or Iron loss:

Hysteresis loss $W_h = \eta B^{1.6}{}_{max} f V$ watt;

eddy current loss $W_e = \eta B^2{}_{max} f^2 t^2$ watt

Copper loss:

Total Cu loss $= I_1{}^2 R_1 + I_2{}^2 R_2 = I_1{}^2 R_{01} + I_2{}^2 R_{02}$.

Condition for maximum efficiency

$$\text{Cu loss} = I_1^2 R_{01} \quad \text{or} \quad I_2^2 R_{02} = W_{cu}$$

$$\text{Iron loss} = \text{Hysteresis loss} + \text{Eddy current loss} = W_h + W_e = W_i$$

Considering primary side,

$$\text{Primary input} = V_1 I_1 \cos\phi_1$$

$$\eta = \frac{V_1 I_1 \cos\phi_1 - \text{losses}}{V_1 I_1 \cos\phi_1} = \frac{V_1 I_1 \cos\phi_1 - I_1^2 R_{01} - W_i}{V_1 I_1 \cos\phi_1}$$

$$= 1 - \frac{I_1 R_{01}}{V_1 \cos\phi_1} - \frac{W_i}{V_1 I_1 \cos\phi_1}$$

Differentiating both sides with respect to I_1, we get

$$\frac{d\eta}{dI_1} = 0 - \frac{R_{01}}{V_1 \cos\phi_1} + \frac{W_i}{V_1 I_1^2 \cos\phi_1}$$

For η to be maximum, $\frac{d\eta}{dI_1} = 0$. Hence, the above equation becomes

$$\frac{R_{01}}{V_1 \cos\phi_1} = \frac{W_i}{V_1 I_1^2 \cos\phi_1} \quad \text{or} \quad W_i = I_1^2 R_{01} \quad \text{or} \quad I_2^2 R_{02}$$

or **Cu loss = Iron loss**

Contd.,

The output current corresponding to maximum efficiency is $I_2 = \sqrt{(W_i/R_{02})}$.

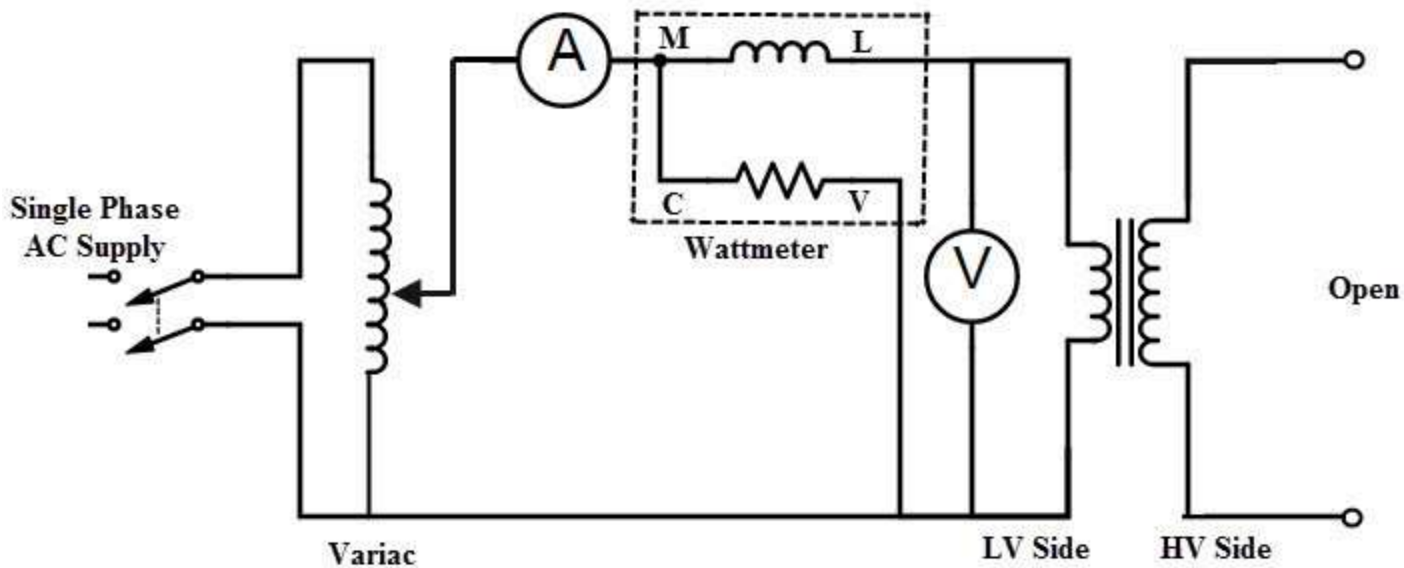
The load at which the two losses are equal $= \text{Full load} \times \sqrt{\left(\dfrac{\text{Iron loss}}{\text{F.L. Cu loss}}\right)}$

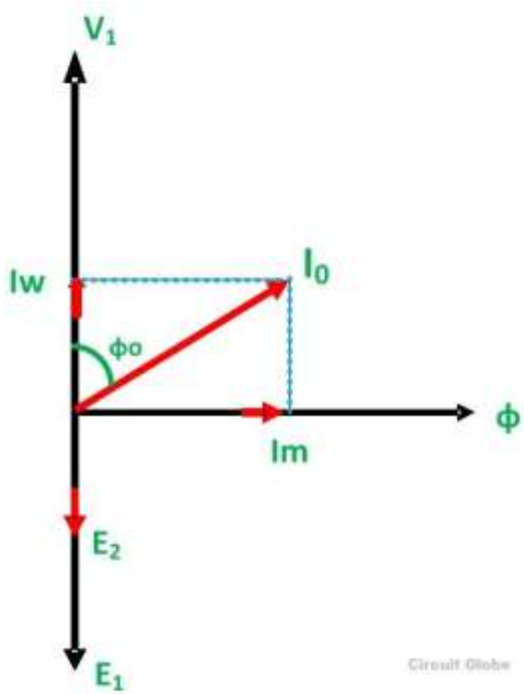
Transformer Tests

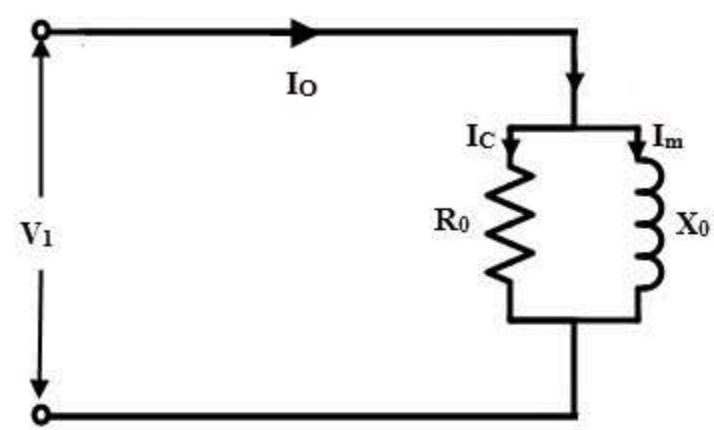
- The performance of a transformer can be calculated on the basis of equivalent circuit
- The four main parameters of equivalent circuit are:
  - R_{01} as referred to primary (or secondary R_{02})
  - the equivalent leakage reactance X_{01} as referred to primary (or secondary X_{02})
  - Magnetising susceptance B_0 (or reactance X_0)
  - core loss conductance G_0 (or resistance R_0)
- The above constants can be easily determined by two tests
  - Oper circuit test (O.C test / No load test)
  - Short circuit test (S.C test/Impedance test)
- These tests are economical and convenient
  - these tests furnish the result without actually loading the transformer

Open-circuit Test

Circuit diagram, equivalent circuit, phasor diagram

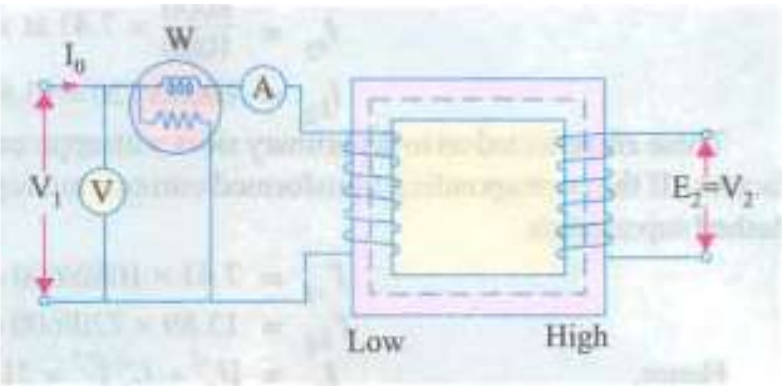






Open-circuit Test

In Open Circuit Test the transformer's ***secondary winding is open-circuited***, and its ***primary winding is connected to a full-rated line voltage***.



$$\text{Core loss} = W_{oc} = V_0 I_0 \cos\phi_0$$

$$\cos\phi_0 = \frac{W_{oc}}{V_0 I_0}$$

$$\mathrm{I_c} \, or \, \mathrm{I_w} = I_0 \cos\phi_0$$

$$\mathrm{I_m} \, or \, \mathrm{I_\mu} = I_0 \sin\phi_0 = \sqrt{I_0^2 - I_w^2}$$

$$\mathrm{I_0 = V_0 Y_0}; \quad \therefore \mathrm{Y_o} = \frac{I_0}{V_0}$$

$$R_0 = \frac{V_0}{I_w}$$

$$X_0 = \frac{V_0}{I\mu}$$

$$G_0 = \frac{I_w}{V_0}$$

$$B_0 = \frac{I\mu}{V_0}$$

$$\mathrm{W_{oc} = V_0^2 G_0}; \quad \therefore \text{Exciting conductance } \mathrm{G_0} = \frac{\mathrm{W_{oc}}}{\mathrm{V_0^2}}$$

$$\& \quad \text{Exciting susceptance } \mathrm{B_0} = \sqrt{Y_0^2 - G_0^2}$$

- Usually conducted on H.V side
- To find

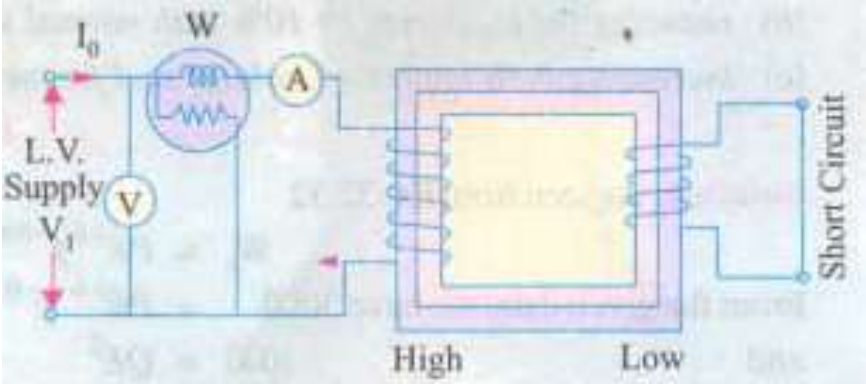
  (i) No load loss or core loss

  (ii) No load current I_o which is helpful in finding G_o(or R_o) and B_o (or X_o)

Short-circuit Test

In Short Circuit Test the ***secondary terminals are short circuited***, and the ***primary terminals are connected to a fairly low-voltage source***

The input voltage is adjusted until the current in the short circuited windings is equal to its rated value. The input voltage, current and power is measured.

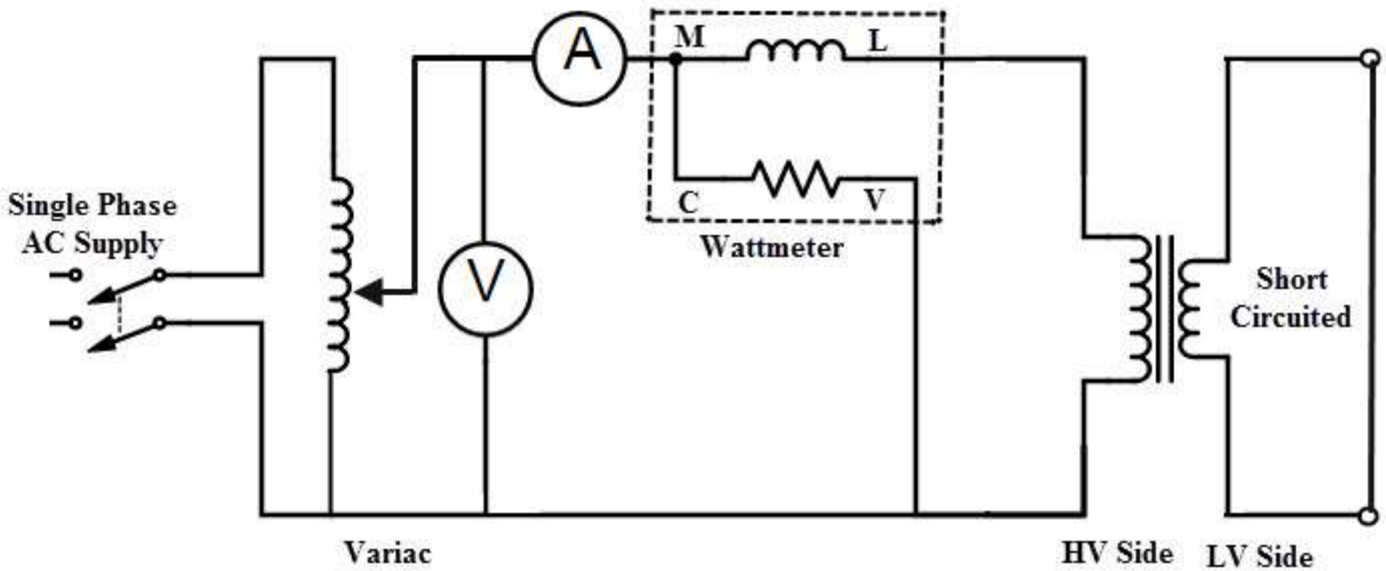


- Usually conducted on L.V side
- To find

  (i) Full load copper loss – to pre determine the efficiency

  (ii) Z_{01} or Z_{02}; X_{01} or X_{02}; R_{01} or R_{02} - to predetermine the voltage regulation

Short-circuit Test



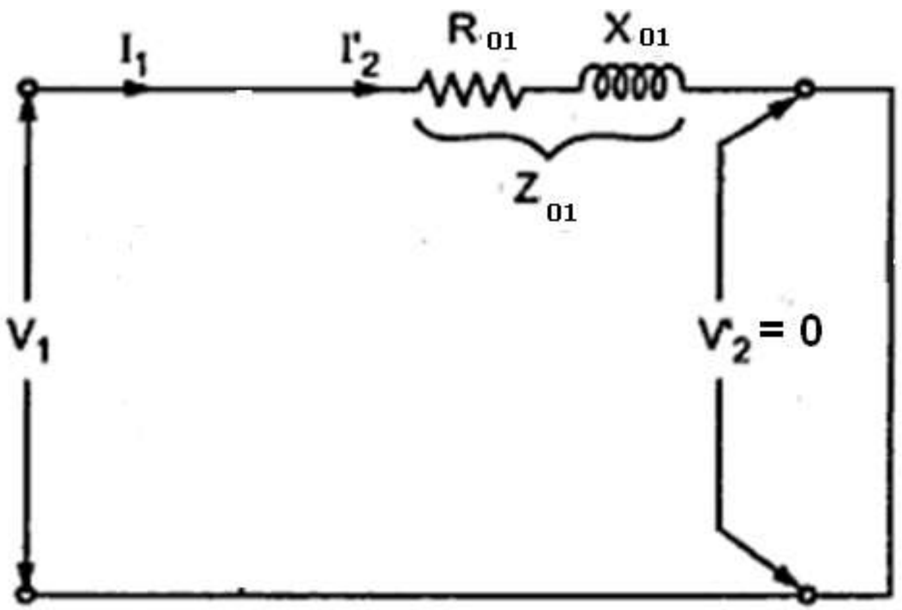
$$\text{Full load cu loss} = \mathrm{W}_{\mathrm{sc}} = I_{sc}^2 R_{01}$$

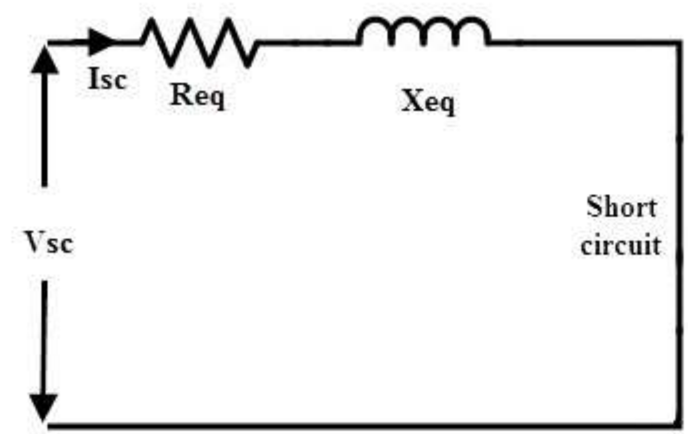
$$\mathrm{R}_{01} = \frac{\mathrm{W}_{\mathrm{sc}}}{I_{sc}^2}$$

$$Z_{01} = \frac{V_{sc}}{I_{sc}}$$

$$\therefore \mathrm{X}_{01} = \sqrt{Z_{01}^2 - R_{01}^2}$$

Equivalent circuit from SC test





Transformer Voltage Regulation

The output voltage of a transformer varies with the load even if the input voltage remains constant. This is because a real transformer has series impedance within it. Full load Voltage Regulation is a quantity that compares the output voltage at no load with the output voltage at full load, defined by this equation:

$$\text{At noload } k = \frac{V_s}{V_p}$$

$$\text{Regulation up} = \frac{V_{S,nl} - V_{S,fl}}{V_{S,fl}} \times 100\%$$

$$\text{Regulation up} = \frac{(V_P / k) - V_{S,fl}}{V_{S,fl}} x\, 100\%$$

$$\text{Regulation down} = \frac{V_{S,nl} - V_{S,fl}}{V_{S,nl}} \times 100\%$$

$$\text{Regulation down} = \frac{(V_P / k) - V_{S,fl}}{V_{S,nl}} x\, 100\%$$

Ideal transformer, VR = 0%.

Voltage regulation of a transformer

$$\text{Voltage regulation} = \frac{\text{no - load voltage} - \text{full - load voltage}}{\text{no - load voltage}}$$

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

Secondary voltage on no-load $V_2 = V_1\left(\dfrac{N_2}{N_1}\right)$

V_2 is a secondary terminal voltage on full load

Substitute we have

$$\text{Voltage regulation} = \frac{V_1\left(\dfrac{N_2}{N_1}\right) - V_2}{V_1\left(\dfrac{N_2}{N_1}\right)}$$

Calculation of Regulation

- For a fixed voltage in the primary, the secondary terminal voltage will not be maintained constant from no load to full load. This is due to the voltage drop across leakage impedance which magnitude depends on both degree of loading and the power factor.

- So the regulation gives change in secondary voltage from no load to full load at a given power factor. It is defined as the change in the secondary voltage when the transformer is operating at full load of specified power factor supplied at rated voltage to no load with primary voltage held constant.

Percentage voltage regulation, $\%R = ((E_2 - V_2) / V_2) \times 100$

The expression of voltage regulation in terms voltage drops is given as

$$\%R = ((I_1 R01 \cos \Phi +/- I_1 X01 \sin \Phi) / V_1) \times 100$$

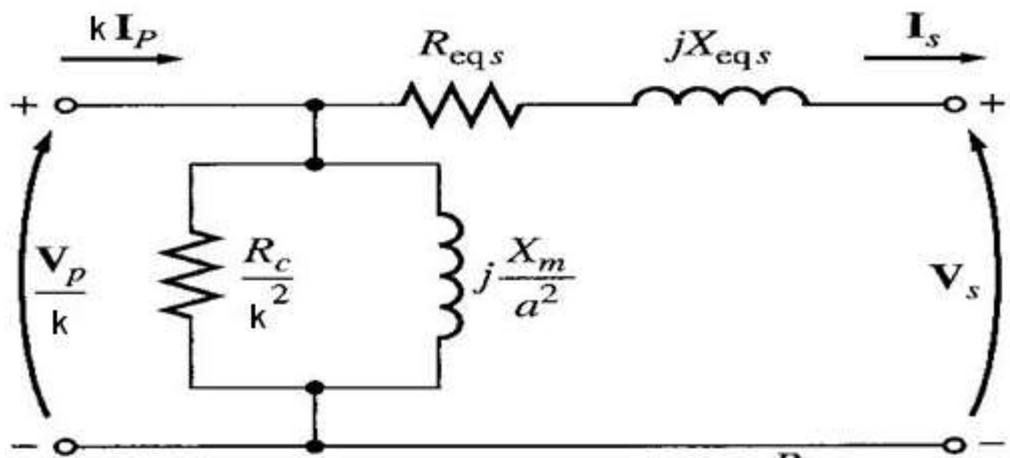
Or

$$\%R = ((I_2 R02 \cos \Phi +/- I_2 X02 \sin \Phi) / V_2) \times 100$$

- The above two equations are used based on the parameters are referred to primary or secondary sides.
- From SC test data we can find out the regulation of a transformer.
- The positive sign is used for lagging power factor and negative sign is used for leading power factor.

Transformer Phasor Diagram

To determine the voltage regulation of a transformer, it is necessary understand the voltage drops within it.



$$R_{eq\,s} = \frac{R_p}{k^2} + R_s$$

$$X_{eq\,s} = \frac{X_p}{k^2} + X_s$$

Transformer Phasor Diagram

Ignoring the excitation of the branch (since the current flow through the branch is considered to be small), more consideration is given to the series impedances (R_{eq} +jX_{eq}).

Voltage Regulation depends on magnitude of the series impedance and the phase angle of the current flowing through the transformer.

Phasor diagrams will determine the effects of these factors on the voltage regulation. A phasor diagram consist of current and voltage vectors.

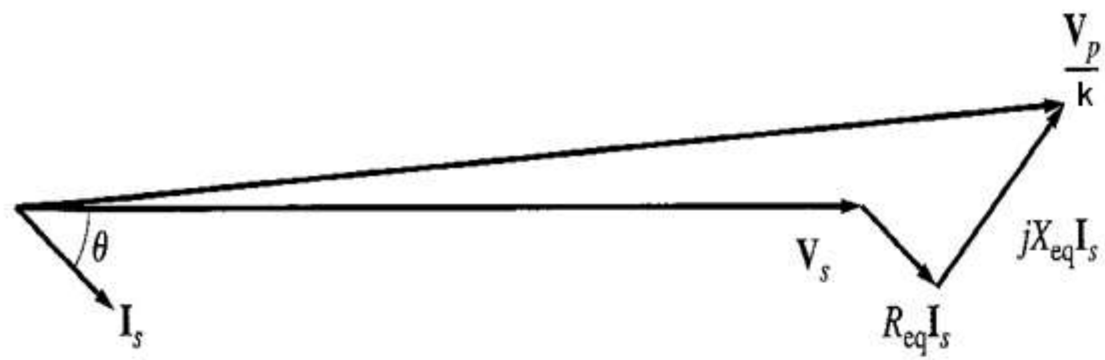
Assume that the reference phasor is the secondary voltage, V_S. Therefore the reference phasor will have 0 degrees in terms of angle.

Based upon the equivalent circuit, apply Kirchoff Voltage Law,

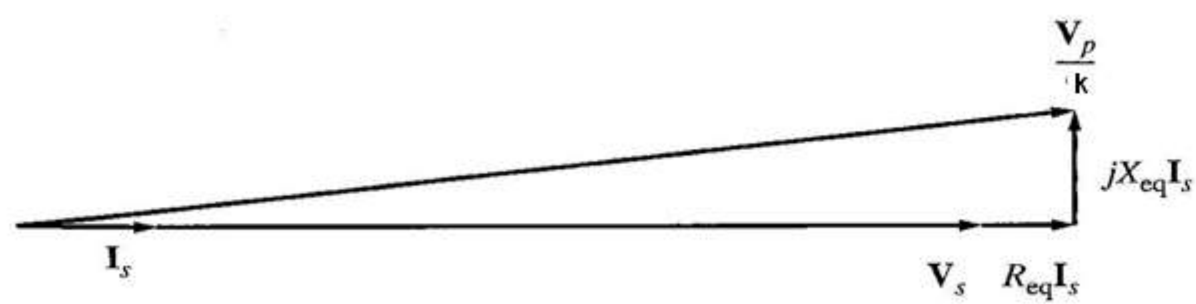
$$\frac{V_P}{k} = V_S + R_{eq} I_S + jX_{eq} I_S$$

Transformer Phasor Diagram

For lagging loads, V_P / a > V_S so the voltage regulation with lagging loads is > 0.



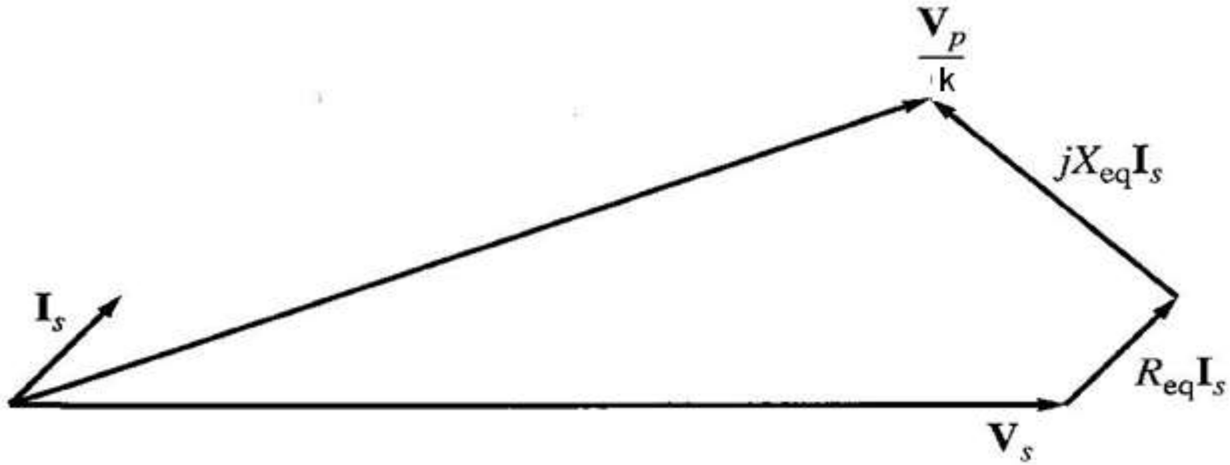
When the power factor is unity, V_S is lower than V_P so VR > 0.



(a)

Transformer Phasor Diagram

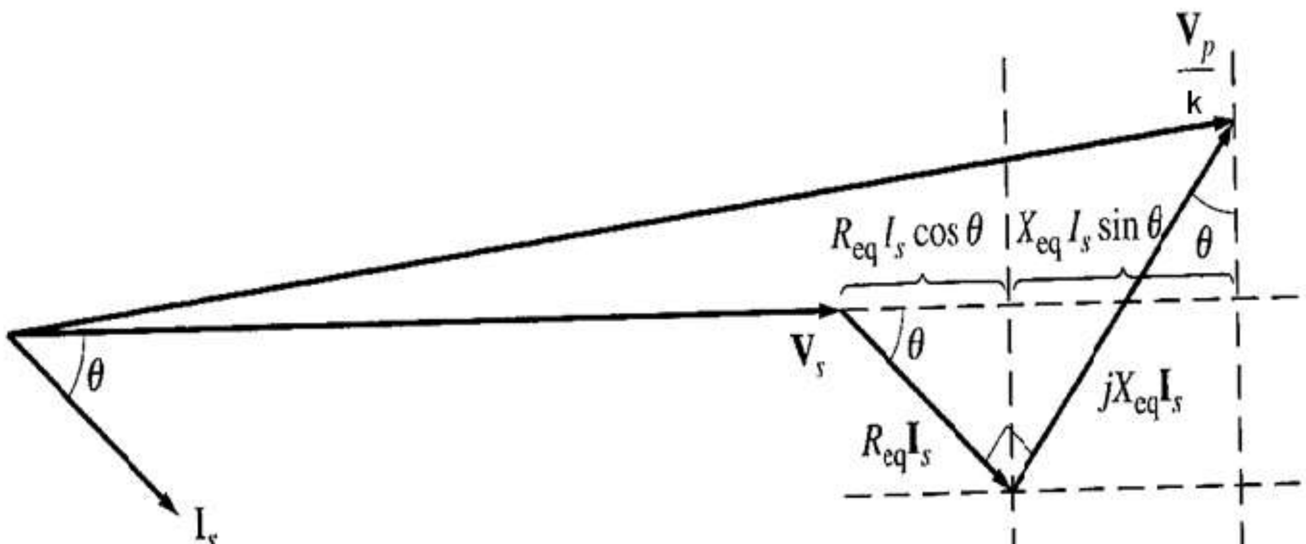
With a leading power factor, V_S is higher than the referred V_P so VR < 0



(b)

Transformer Phasor Diagram

For lagging loads, the vertical components of R_{eq} and X_{eq} will partially cancel each other. Due to that, the angle of V_P/a will be very small, hence we can assume that V_P/k is horizontal. Therefore the approximation will be as follows:



$$\frac{V_p}{k} \approx V_s + R_{eq} I_s \cos\theta + X_{eq} I_s \sin\theta$$

Formula: voltage regulation

In terms of secondary values

$$\%\,\text{regulation} = \frac{{}_0\mathrm{V}_2 - V_2}{{}_0\mathrm{V}_2} = \frac{I_2 R_{02}\cos\phi_2 \pm I_2 X_{02}\sin\phi_2}{{}_0\mathrm{V}_2}$$

where '+' for lagging and '-' for leading

In terms of primary values

$$\%\,\text{regulation} = \frac{\mathrm{V}_1 - V_2^{'}}{\mathrm{V}_1} = \frac{I_1 R_{01}\cos\phi_1 \pm I_1 X_{01}\sin\phi_1}{\mathrm{V}_1}$$

where '+' for lagging and '-' for leading

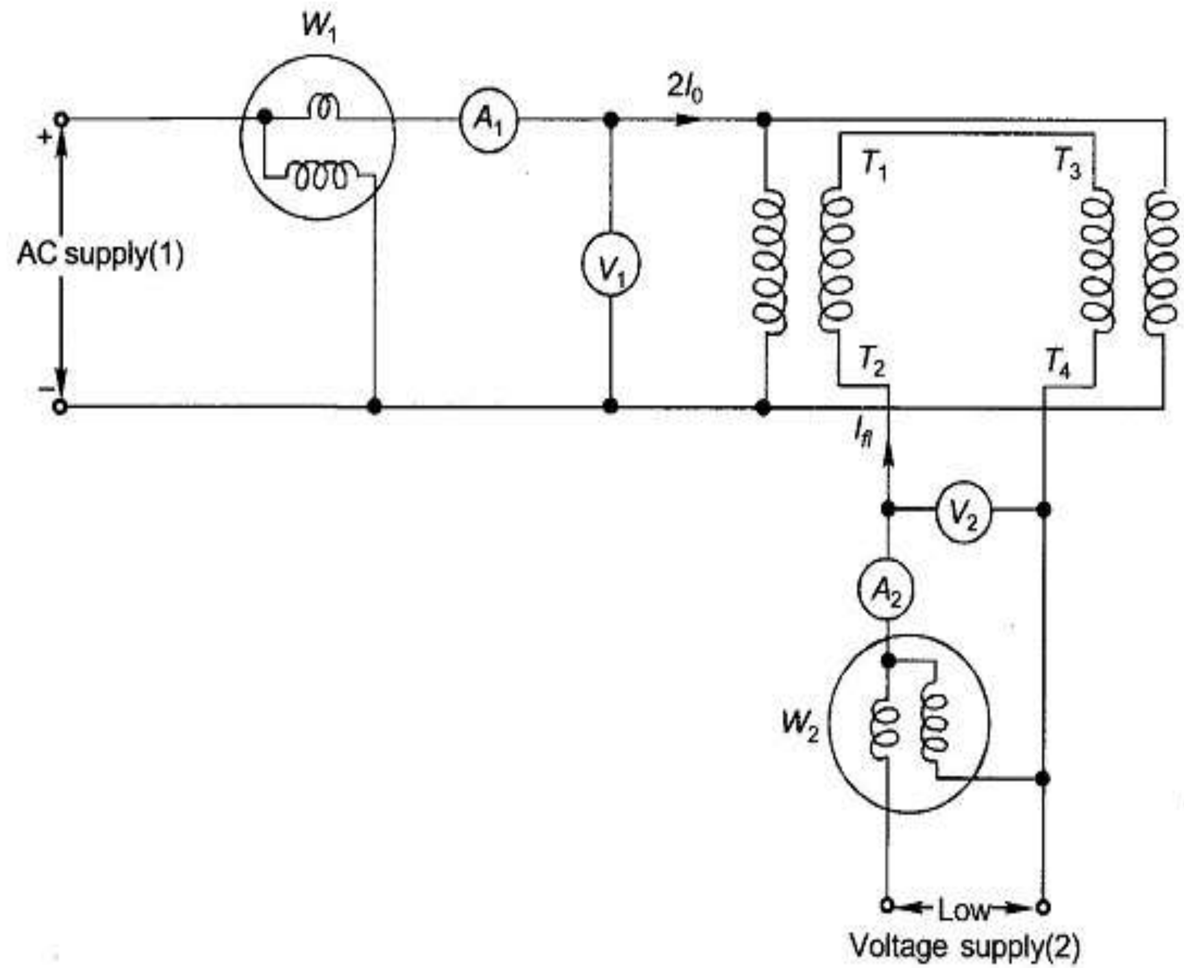
Sumpners Test (Back to Back Test/ Heat Run Test)

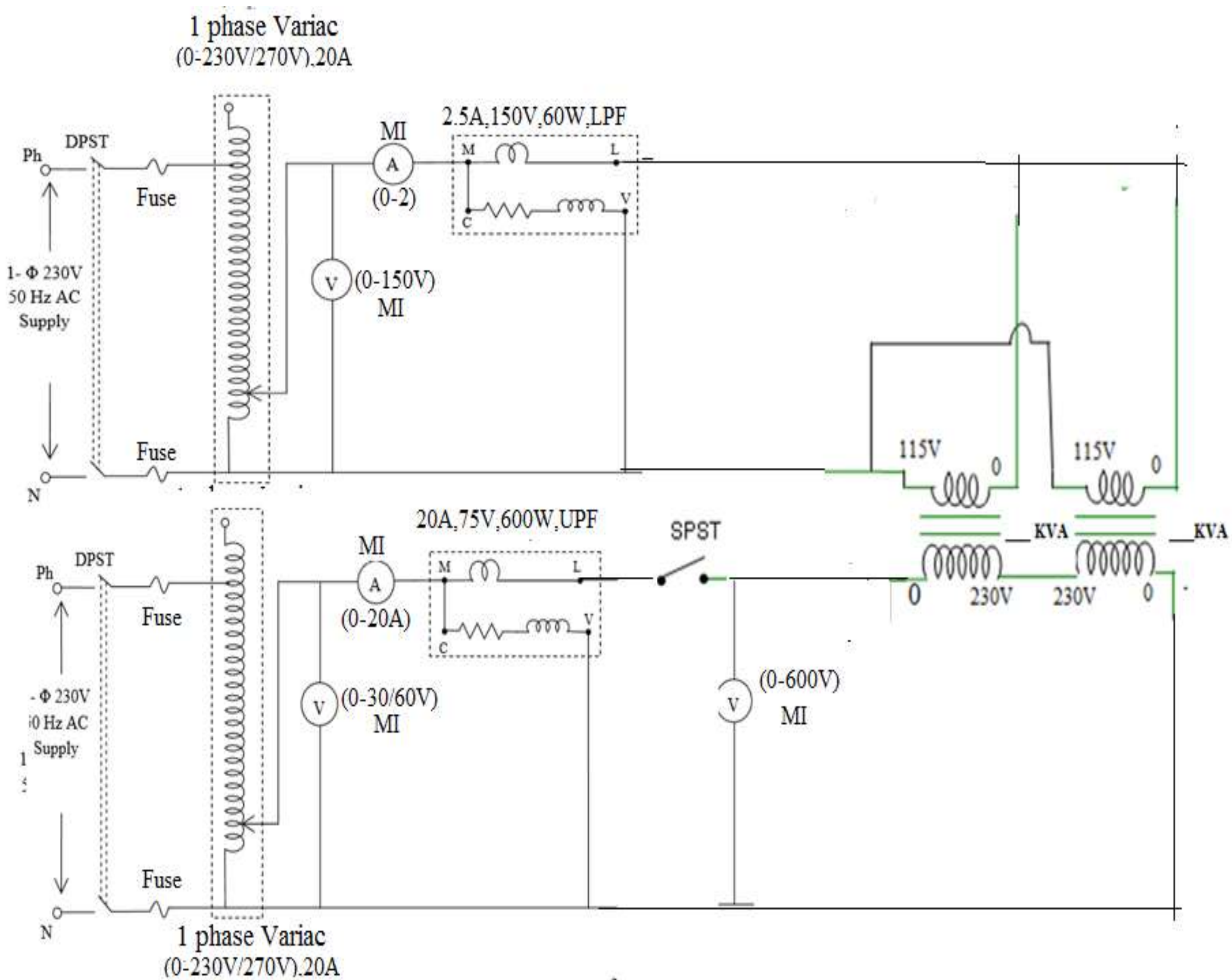
* During OC and SC test ,all the losses do not occur simultaneously, so exact temperature can't be determined

* In order to get exact temperature rise, sumpners test is required

*Basic Requirement : Two identical Transformers

Sumpner's test on two identical transformers





1 phase Variac
(0-230V/270V),20A
2.5A,150V,60W,LPF
MI
Ph
DPST
Fuse
M
L
C
V
A
(0-2)
1- Φ 230V
50 Hz AC
Supply
V
(0-150V)
MI
Fuse
N
115V
0
115V
0
20A,75V,600W,UPF
SPST
__KVA
__KVA
MI
Ph
DPST
Fuse
M
L
C
V
A
(0-20A)
0
230V
230V
0
V
(0-30/60V)
MI
V
(0-600V)
MI
Supply
Fuse
N
1 phase Variac
(0-230V/270V),20A

Conditions

*Two primeries of Transformers should be connected in parallel and excited from.supply source (same as OC test)
Seconderies of two transformers should be connected in series with subtractive polarity
* This seconderies should be supplied form auxiliary source (same as SC test)
Procedure :
(To understand the concept of sumpners test, Super position theorem should be applied)

Step1 : Short the Low voltage Auxilary supply source side and excite the Transformers by Main source alone

Step2: short the windings towards main supply side and conduct in presence of Auxilary source alone

are short circuited

(Similar to OC test)

obsevations

From" step1" , The resultant induced emf is zero when the seconderies are short circuited
(Similar to OC test)

* By this Iron losses are obtained
AMMETER reading = 2 Io
Wattmer reading = 2 Wi

Observations….

- From "Step2", Apply auxilary voltage gradually up to rated current
- (Similar to SC test)
- * By this Copper losses are obtained
- Ammeter reading = I2
- Wattmeter reading = 2 Wcu
- From "step 3", Both the sources are acting together , temperature increases gradually and remains steady after its maximum value
- This temperature can be measured using RTD

To Calculate Efficiency:

Iron loss of each Transformer = wattmeter reading (2Wi)/2

Full load Cu loss in each Transformer = Wattmeter reading (2 Wcu)/2

$$\therefore \eta_{x \text{ of FL}} = \frac{x E_2 I_2 \cos\phi_2}{x E_2 I_2 \cos\phi_2 + x^2 w_{cu} + w_i}$$

Advantages & Disadvantages of Sumpners test :

Advantages of Sumpners test :

- The power required to conduct the test is very less
- The Transformers are tested at full load conditions
- The secondery current can be varied to any value using regulating transformer.
- Hence, we can determine the coppernlosses at Full load condition or at any load (X)

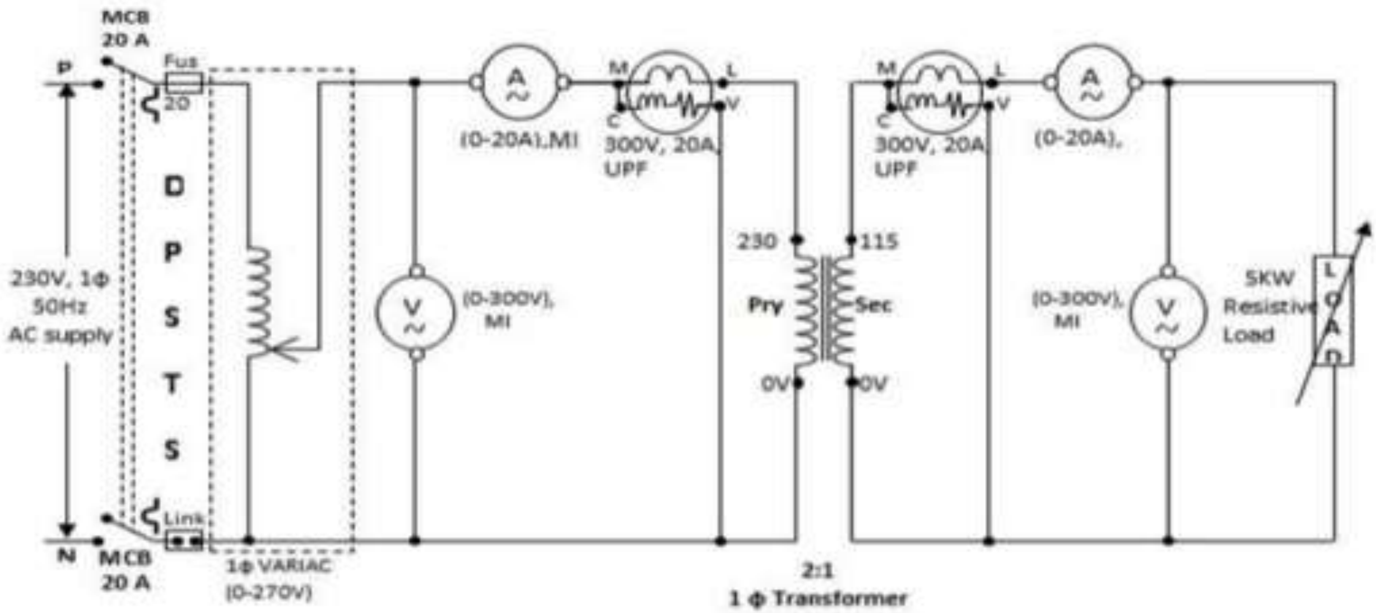
Drawbacks of Sumpners test:

- Two identical transformers are required .
- In practice, exact identical transformers can't be obtained and as two transformers are required .
- The test is not economical

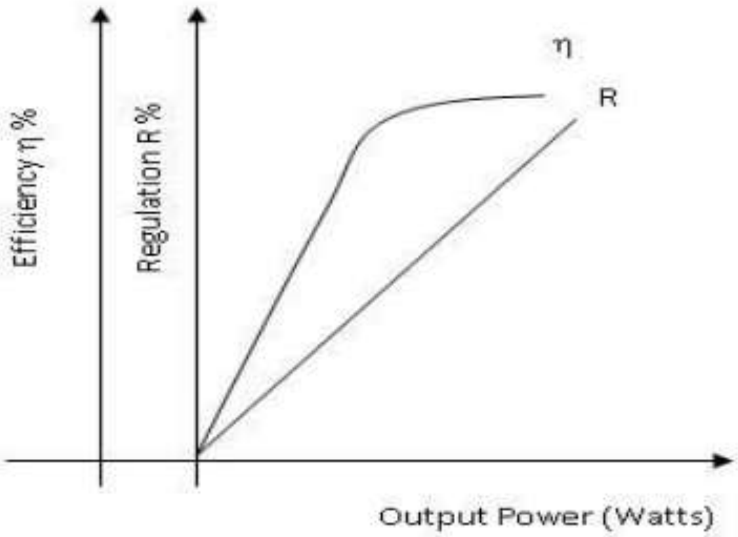
LOAD TEST ON SINGLE PHASE TRANSFORMER

- Load test on single phase Transformer aim to draw the efficiency and regulation characteristics of single phase transformer.
- Each of the terminals of primary as well as secondary winding of a transformer is alternately positive and negative with respect to each other.
- It is essential to know the relative polarities at any instant of the primary and secondary terminals for making correct connections under the following type of operation of the transformer.

CIRCUIT DIAGRAM



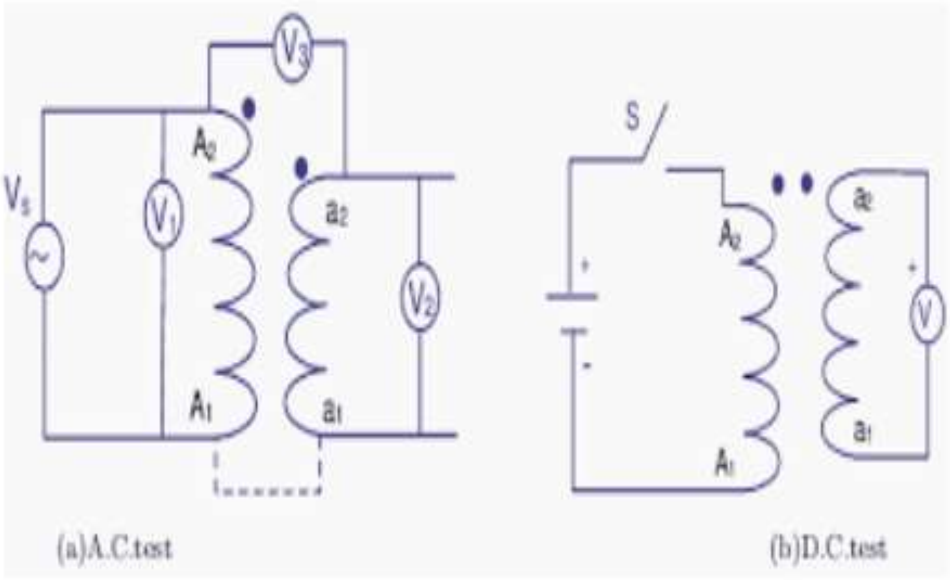
CHARACTERISTICS CURVES OF SINGLE PHASE TRANSFORMER



POLARITY TEST

- Polarity in electrical terms refers to the Positive or Negative conductors within a d.c. circuit, or to the Line and Neutral conductor within an a.c. circuit.
- the resultant voltage appearing across a voltmeter will be the sum of the high and low voltage windings.
- This is useful when connecting single phase transformers in parallel for three phase operations.

- Polarity is a term used only with single phase transformers.



- Let A1 and A2 denotes the ends of the primary winding.
- Let a1 and a2 denotes the ends of the secondary winding.
- Ends A1and a1 are joined and a voltmeter is connected across A2and a2.
- Single phase supply is given to A1 and A2.
- If the direction of the induced emf in primary (Ep) and that of the secondary (Es) is the same.

- The voltmeter will read the difference of emf(Ep ~ Es).
- If the windings are wound in the opposite direction on the magnetic core,Ep and Es will be in the opposite direction.
- The voltmeter will read Ep+Es.in this case, the polarity is know as additive.
- Generally,the polarity used is subtractive.

THANKYOU

A 5KVA 500/250 50Hz single phase transformer gave the following readings

OC Test: 500V 1A 50W (HV Side)

SC Test: 25V 10A 60W (LV Side).

Determine (i)efficiency on full load 0.8 pf lagging

(ii)voltage regulation on full load and 0.8 pf leading

(iii)Draw equivalent circuit referred to primary side.