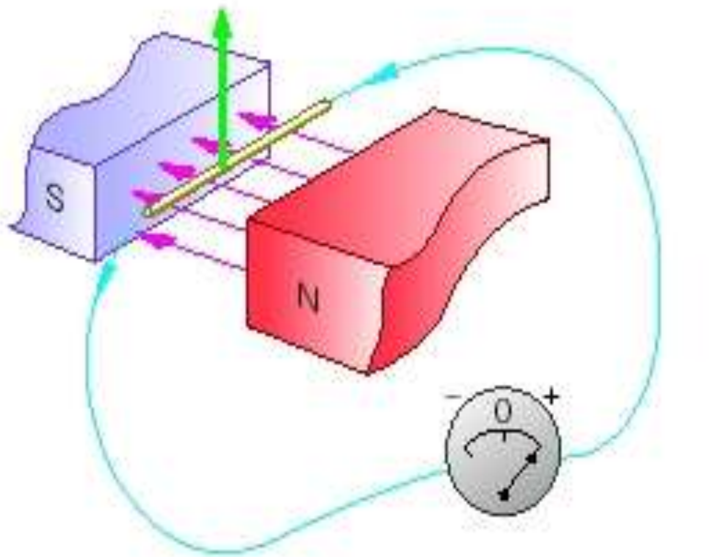
DC Generator

DC Generator

Mechanical energy is converted to electrical energy

Three requirements are essential

1. Conductors
2. Magnetic field
3. Mechanical energy

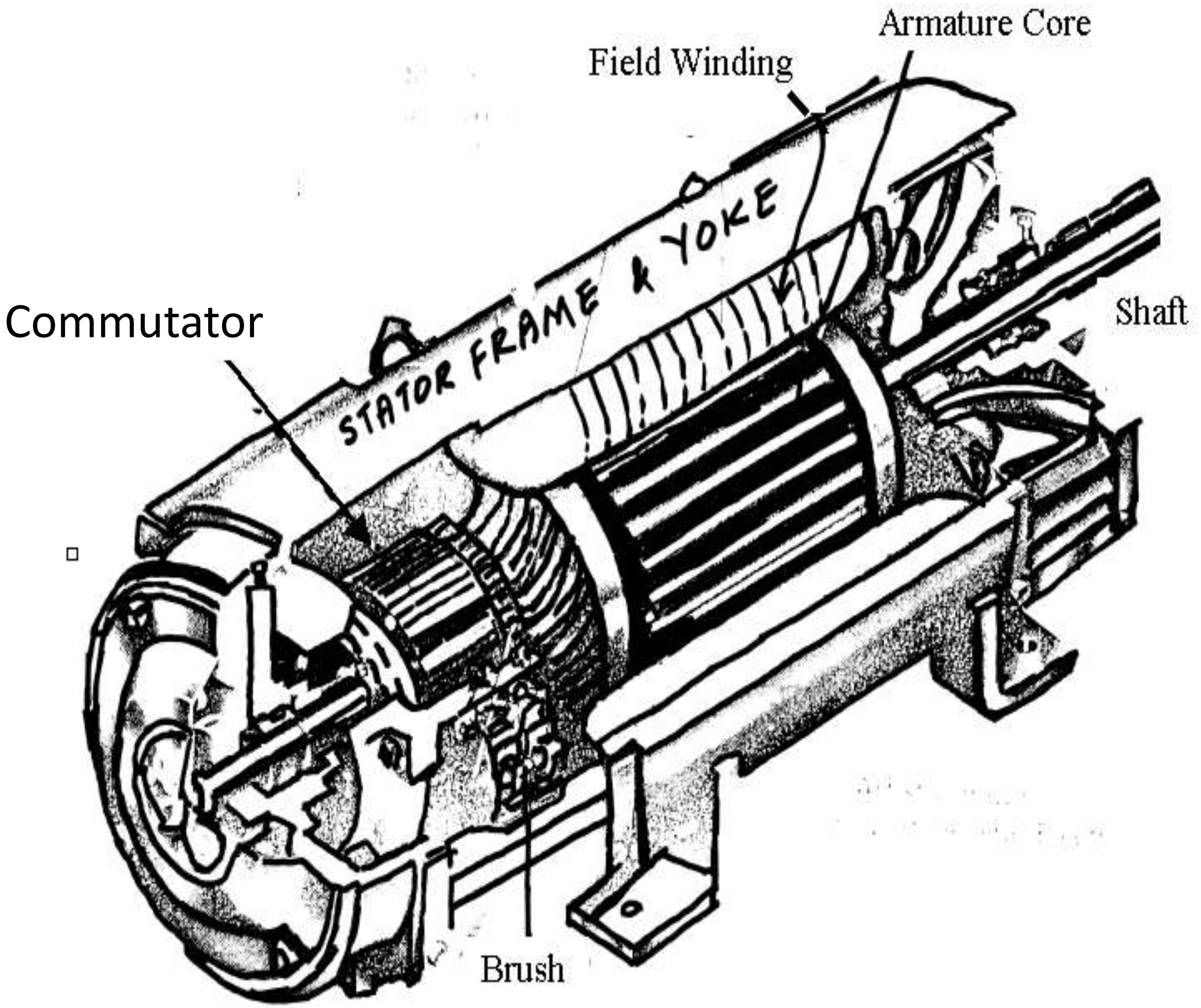


How it works??

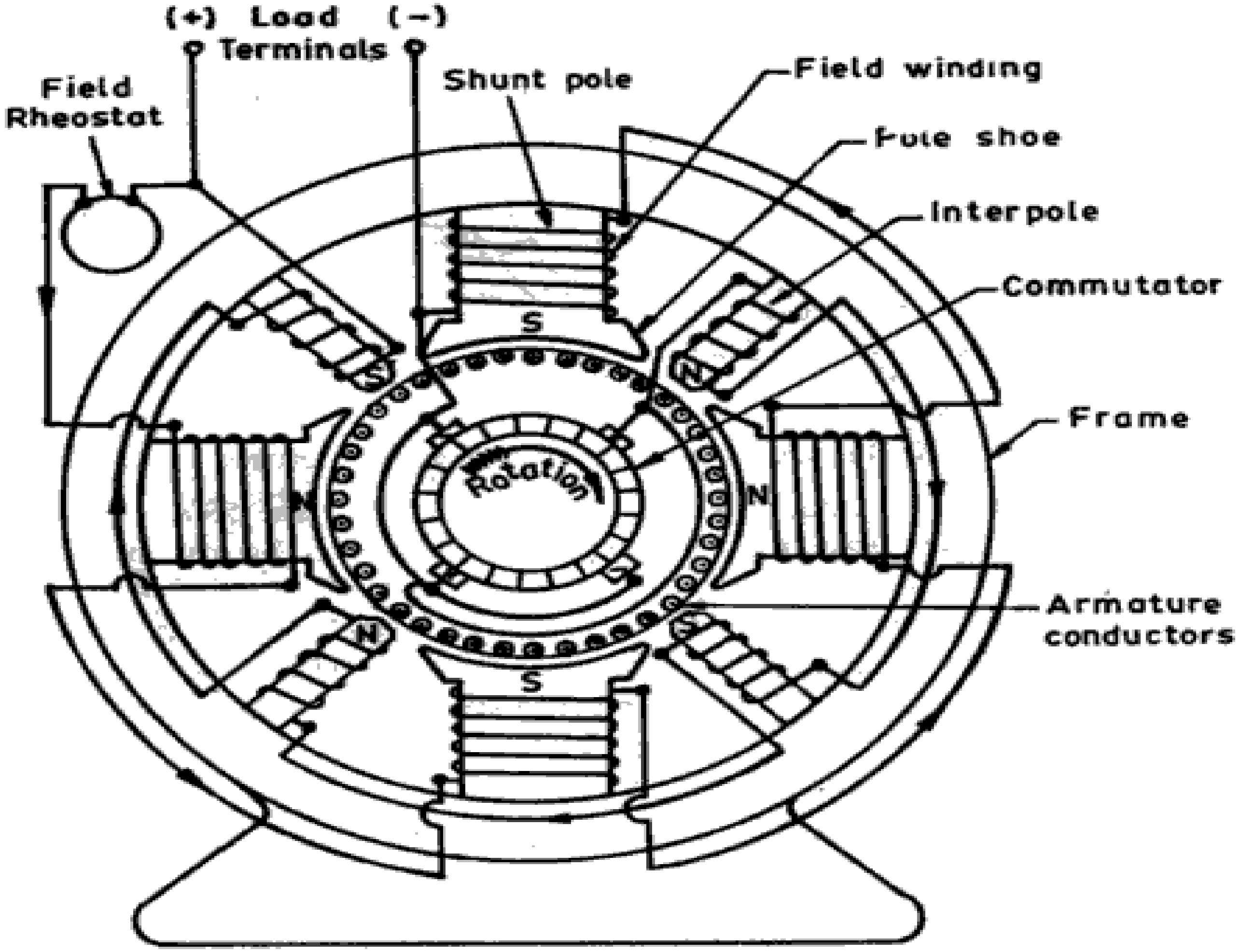
- A generator works on the principles of Faraday's law of electromagnetic induction

- Whenever a conductor is moved in the magnetic field , an emf is induced and the magnitude of the induced emf is directly proportional to the rate of change of flux linkage.

- This emf causes a current flow if the conductor circuit is closed .

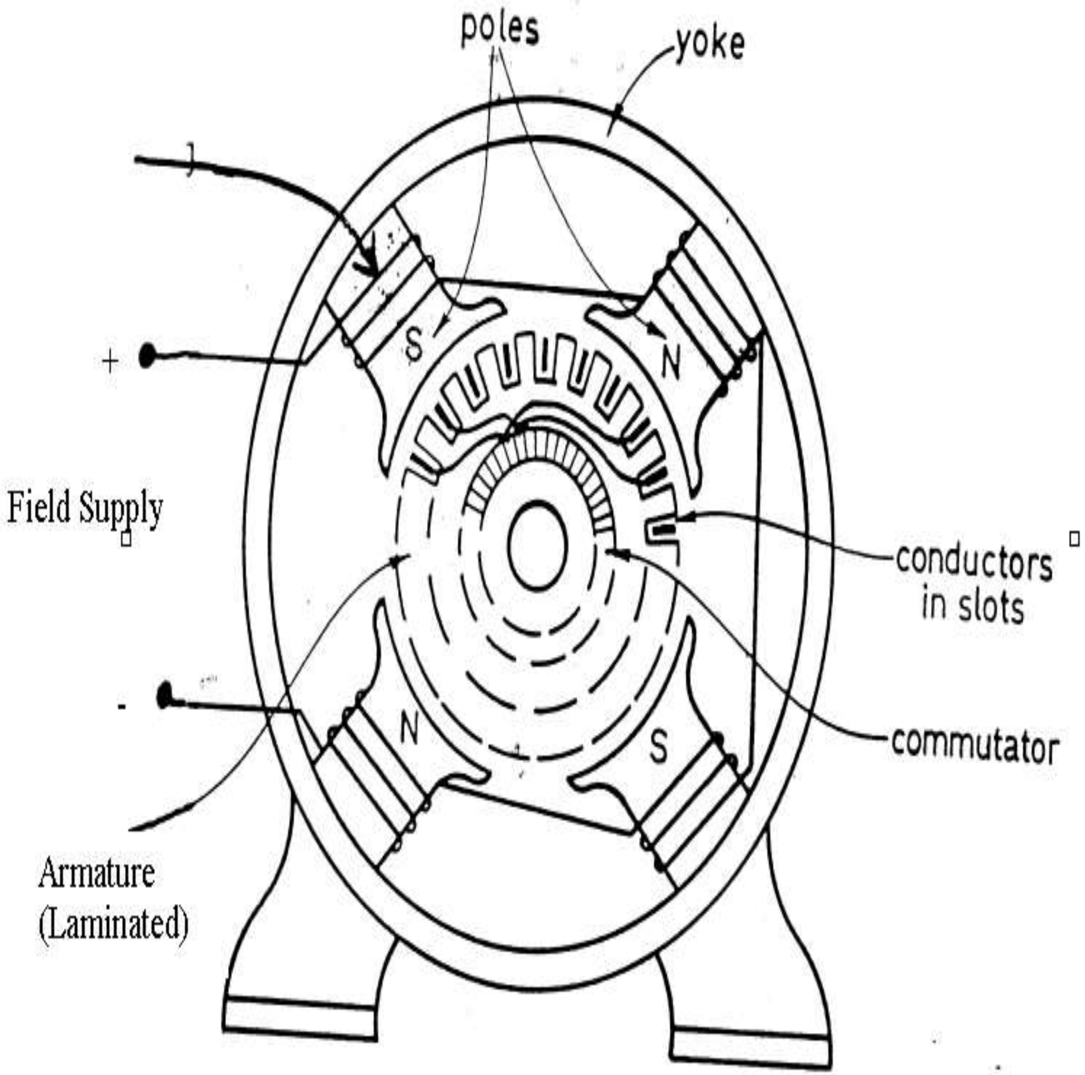

Armature Core
Field Winding
STATOR FRAME & YOKE
Commutator
Shaft
Brush

Sectional View

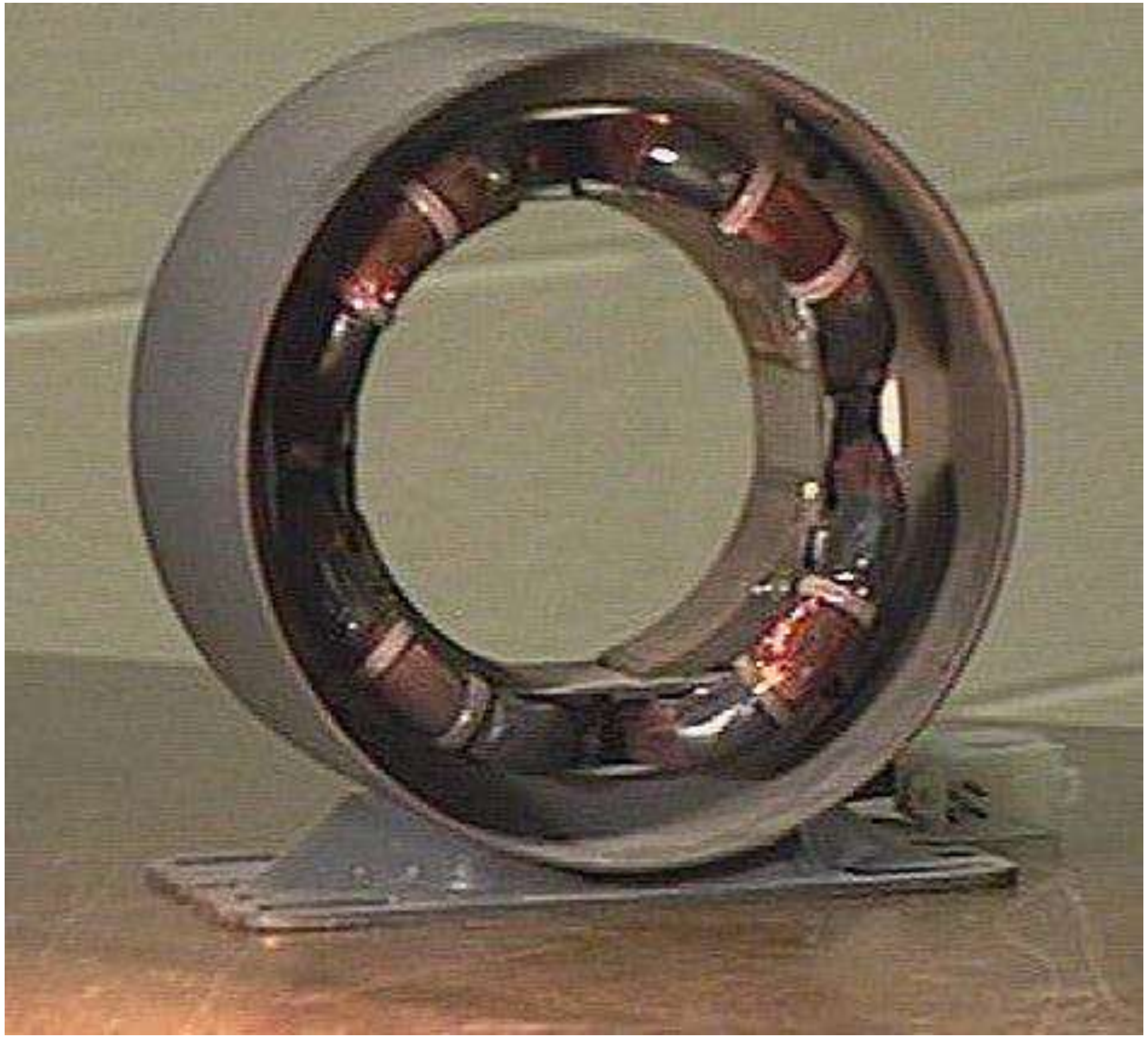


Construction

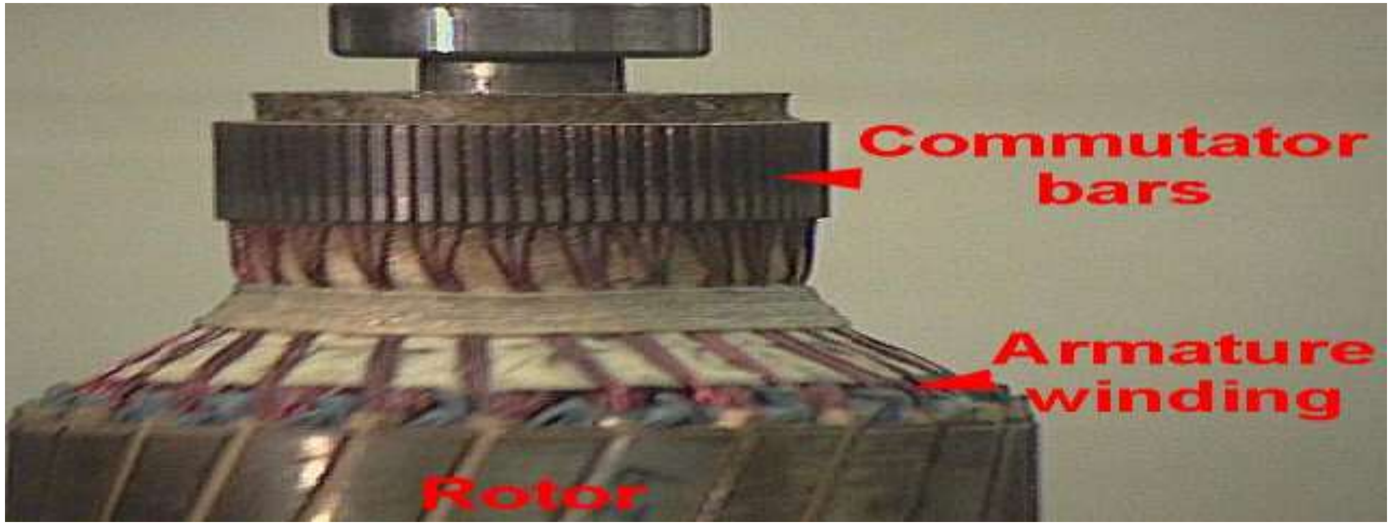
- Field system
- Armature core
- Armature winding
- Commutator
- Brushes



Field winding



Rotor and rotor winding



Armature winding

There are 2 types of winding

Lap and Wave winding

Lap winding

- $A = P$

- The armature windings are divided into no. of sections equal to the no of poles

Wave winding

- $A = 2$

- It is used in low current output and high voltage.

- 2 brushes

How field works

- It is for uniform magnetic field within which the armature rotates.
- Electromagnets are preferred in comparison with permanent magnets
- They are cheap , smaller in size , produce greater magnetic effect and
- Field strength can be varied

Field System Components

- Yoke
- Pole cores
- Pole shoes
- Field coils

Armature core

- The armature core is cylindrical
- High permeability silicon steel stampings
- Impregnated
- Lamination is to reduce the eddy current loss

Commutator

- Connect with external circuit
- Converts ac into unidirectional current
- Cylindrical in shape
- Made of wedge shaped copper segments
- Segments are insulated from each other
- Each commutator segment is connected to armature conductors by means of a cu strip called riser.
- No of segments equal to no of coils

Brush (Carbon)

- Carbon brushes are used in DC machines because they are soft materials
- It does not generate spikes when they contact commutator
- To deliver the current thro armature
- Carbon is used for brushes because it has negative temperature coefficient of resistance
- Self lubricating , takes its shape , improving area of contact

Brush rock and Holder

EMF equation

Let,

- Ø= flux per pole in weber
- Z = Total number of conductor
- P = Number of poles
- A = Number of parallel paths
- N =armature speed in rpm

- Eg = emf generated in any on of the parallel path

- Flux cut by 1 conductor in 1 revolution = $P * \phi$
- Flux cut by 1 conductor in 60 sec = $P \phi N / 60$
- Avg emf generated in 1 conductor = $P\phi N/60$
- Number of conductors in each parallel path = Z / A

$$E_g = P\phi NZ/60A$$

Types of DC Generator

DC generators are generally classified according to their method of excitation .

- Separately excited DC generator
- Self excited D C generator

Sub Classification

- ➢ Series wound generator
- ➢ Shunt wound generator
- ➢ Compound wound generator
  - Short shunt & Long shunt
  - Cumulatively compound

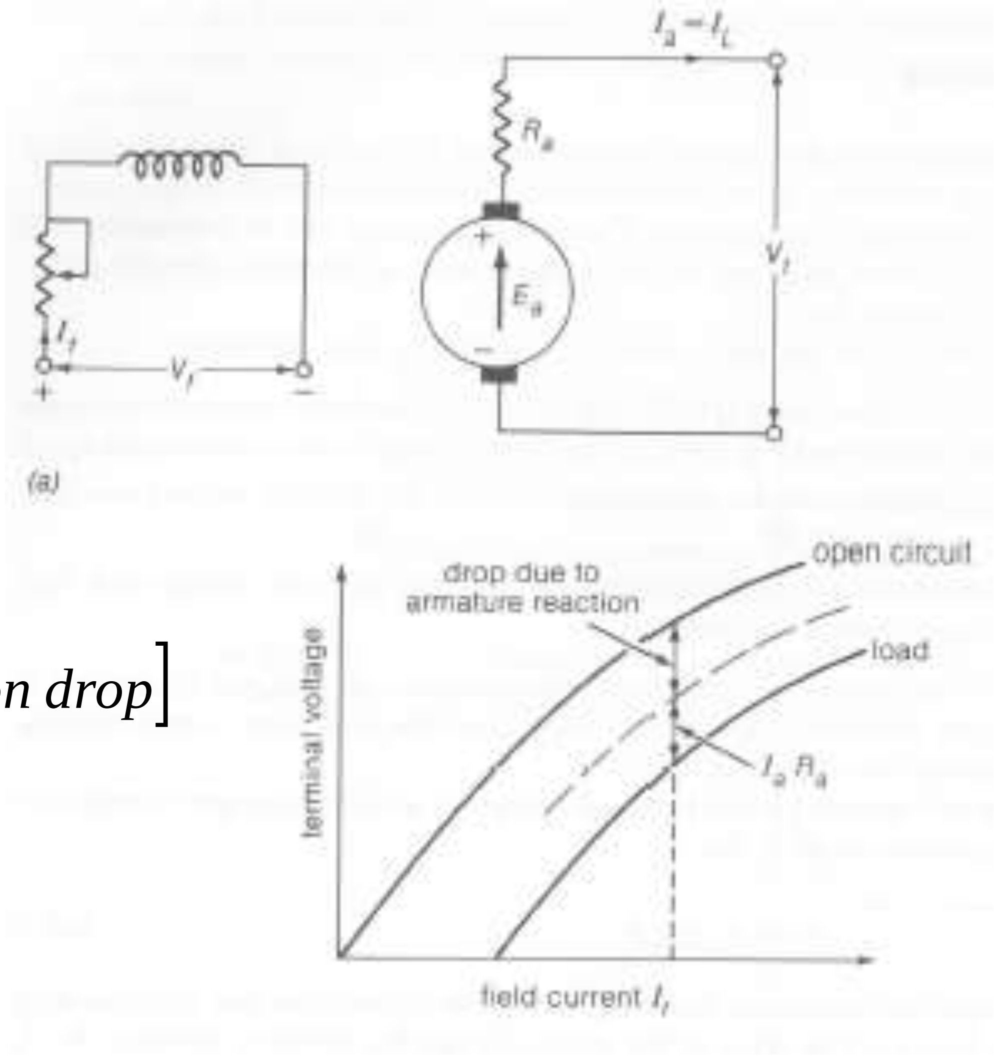
    &

    Differentially compound

Characteristics

- No load saturation characteristic (E_o/I_f)
- Internal or Total characteristic (E/ I_a)
- External characteristic (V/I)

DC Generator Characteristics



The terminal voltage of a dc generator is given by

$$V_t = E_a - I_a R_a$$
$$= \left[f\left(I_f, \omega_m\right) - Armature\ reaction\ drop \right]$$
$$- I_a R_a$$

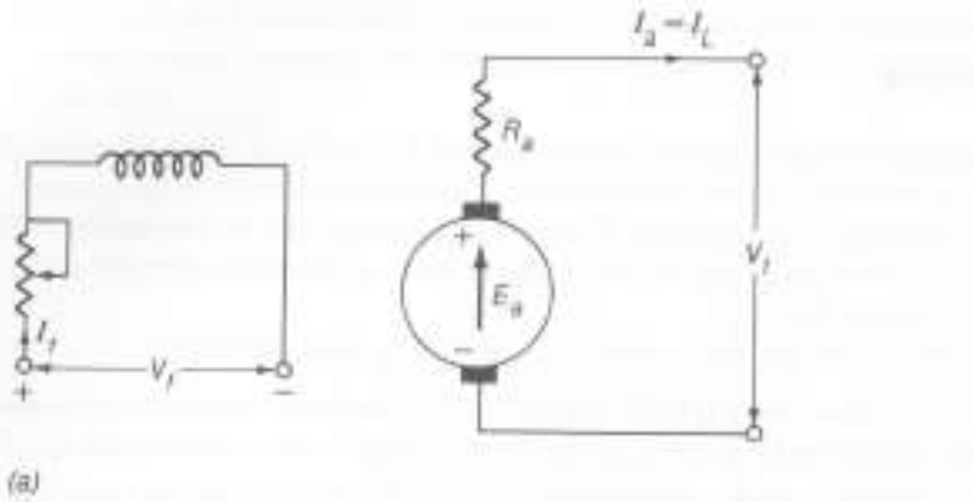
Open-circuit and load characteristics

DC Generator Characteristics

In general, three characteristics specify the steady-state performance of a DC generators:

1. Open-circuit characteristics: generated voltage versus field current at constant speed.
2. External characteristic: terminal voltage versus load current at constant speed.
3. Load characteristic: terminal voltage versus field current at constant armature current and speed.

DC Generator Characteristics



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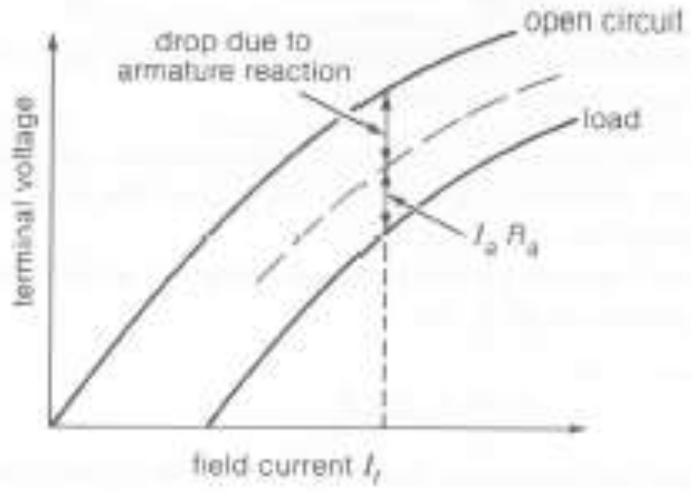
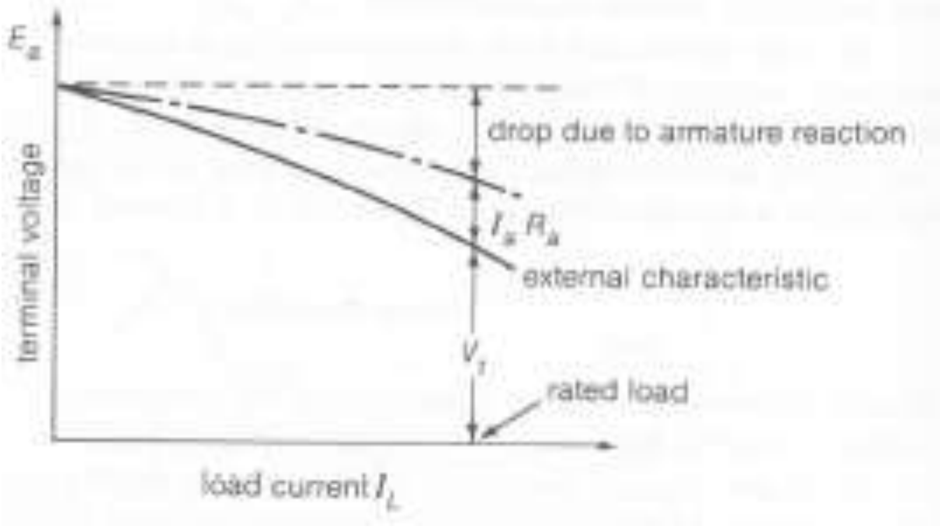


Open-circuit and load characteristics

DC Generator Characteristics

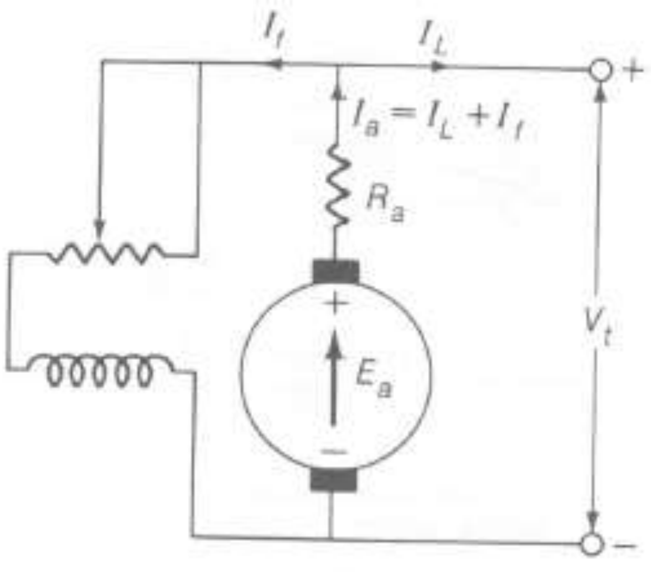
It can be seen from the external characteristics that the terminal voltage falls slightly as the load current increases. *Voltage regulation* is defined as the percentage change in terminal voltage when full load is removed, so that from the external characteristics,

$$Voltage\ regulation = \frac{E_a - V_t}{V_t} \times 100$$



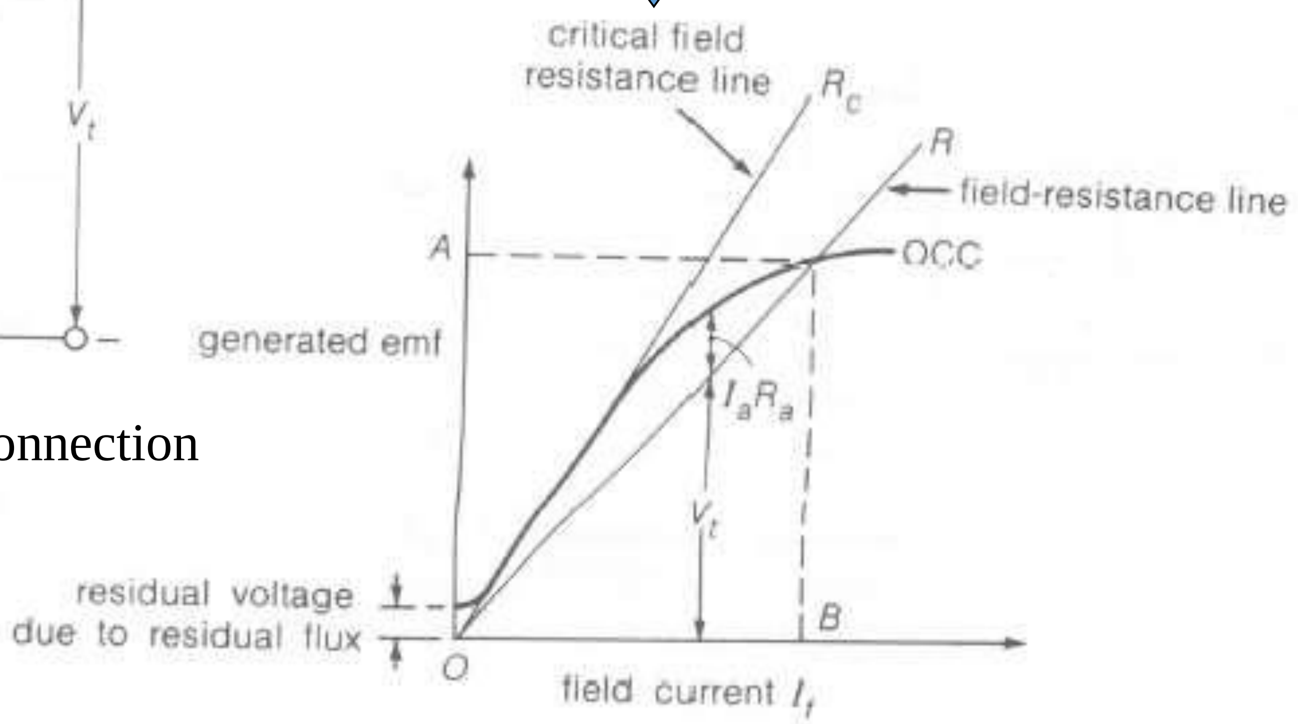
External characteristics

Self-Excited DC Shunt Generator



Schematic diagram of connection

Maximum permissible value of the field resistance if the terminal voltage has to build up.



Open-circuit characteristic

Critical field resistance

For appreciable generation of emf, the field resistance must be always less certain resistance, that resistance is called as the critical resistance of the machine .

General terms used in Armature reaction

Magnetic neutral axis :

It is perpendicular to the lines of force between the two opposite adjacent poles.

Leading pole Tip (LPT) :

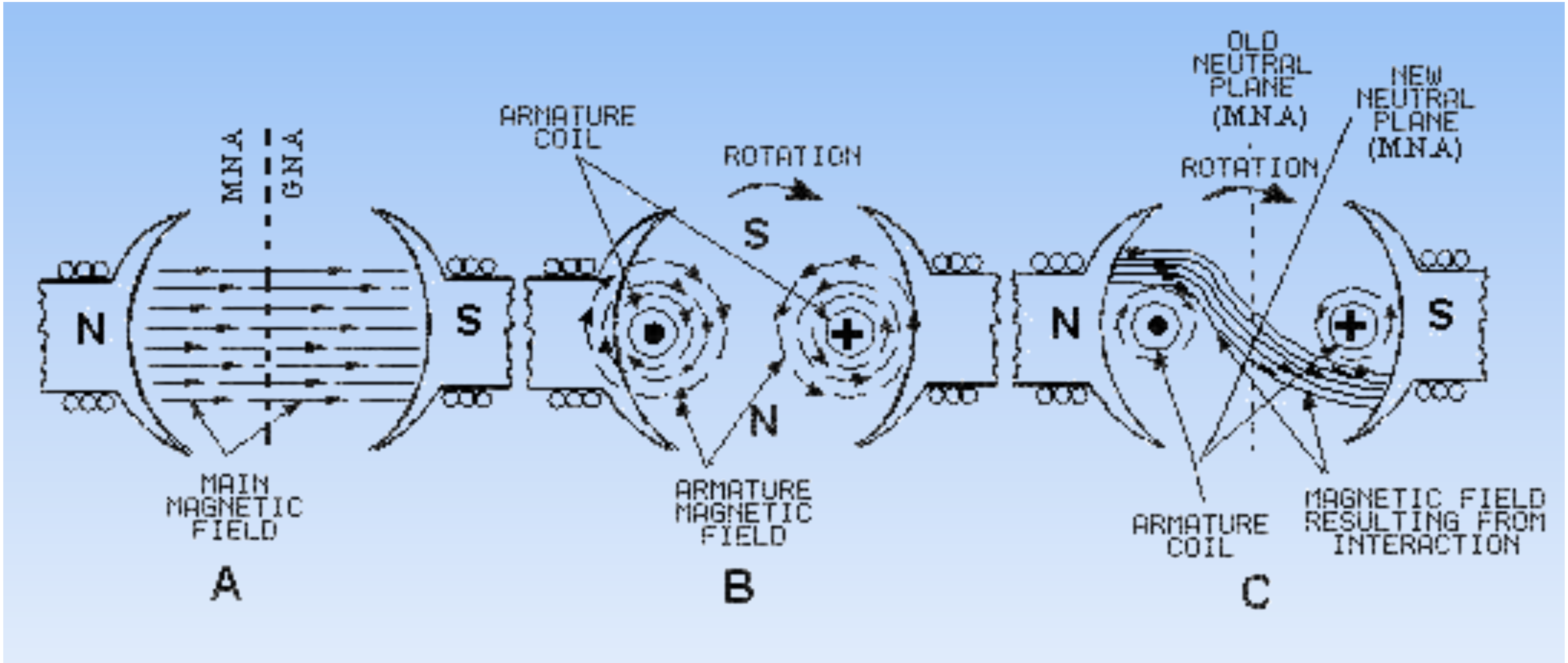
It is the end of the pole which first comes in contact with the armature.

Trailing pole tip :

It is the end of the pole which comes in contact later with the armature.

Armature Reaction

Interaction of Main field flux with Armature field flux



Effects of Armature Reaction

- It decreases the efficiency of the machine
- It produces sparking at the brushes
- It produces a demagnetizing effect on the main poles
- It reduces the emf induced
- Self excited generators some times fail to build up emf

Armature reaction remedies

1.Brushes must be shifted to the new position of the MNA

2.Extra turns in the field winding

3.Slots are made on the tips to increase the reluctance

4. The laminated cores of the shoe are staggered

5. In big machines the compensating winding at pole shoes produces a flux which just opposes the armature mmf flux automatically.

Commutation

- ✓ The change in direction of current takes place when the conductors are along the brush axis .
- ✓ During this reverse process brushes short circuit that coil and undergone commutation
- ✓ Due to this sparking is produced and the brushes will be damaged and also causes voltage dropping.

Losses in DC Generators

1. Copper losses or variable losses
2. Stray losses or constant losses

Stray losses : consist of (a) iron losses or core losses and (b) windage and friction losses .

Iron losses : occurs in the core of the machine due to change of magnetic flux in the core . Consist of hysteresis loss and eddy current loss.

Hysteresis loss depends upon the frequency ,

Flux density , volume and type of the core .

Hysteresis loss depends upon the frequency ,

Flux density , volume and type of the core .

Eddy current losses : directly proportional to the flux density , frequency , thickness of the lamination .

Windage and friction losses are constant due to the opposition of wind and friction .

Applications

Shunt Generators:

a. in electro plating

b. battery recharging

c. Exciters for AC generators.

Series Generators :

A. Boosters

B. Lighting arc lamps

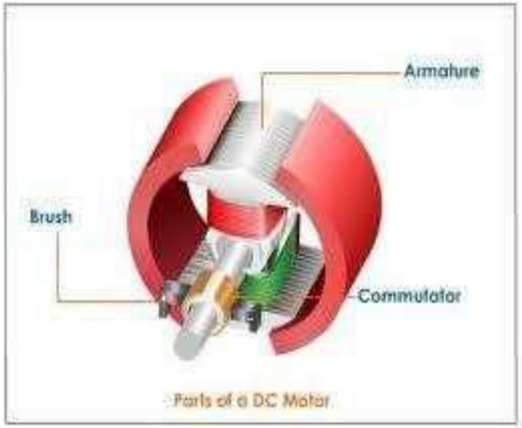
Unit-2
DC Motors

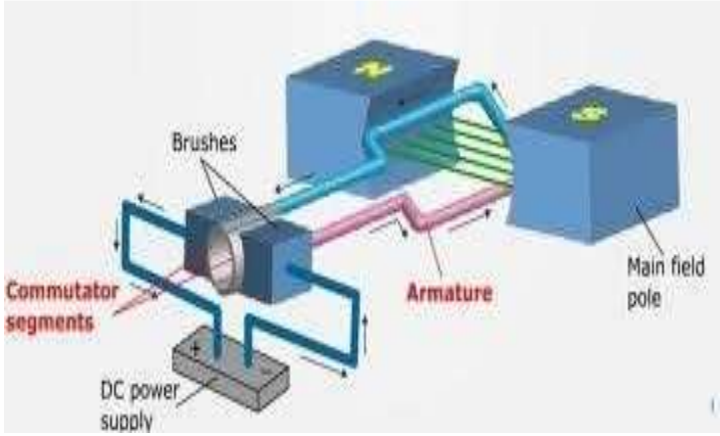
DC MOTOR

Motor: It is a machine which converts electrical energy into mechanical energy.

Principle of operation of DC Motor:

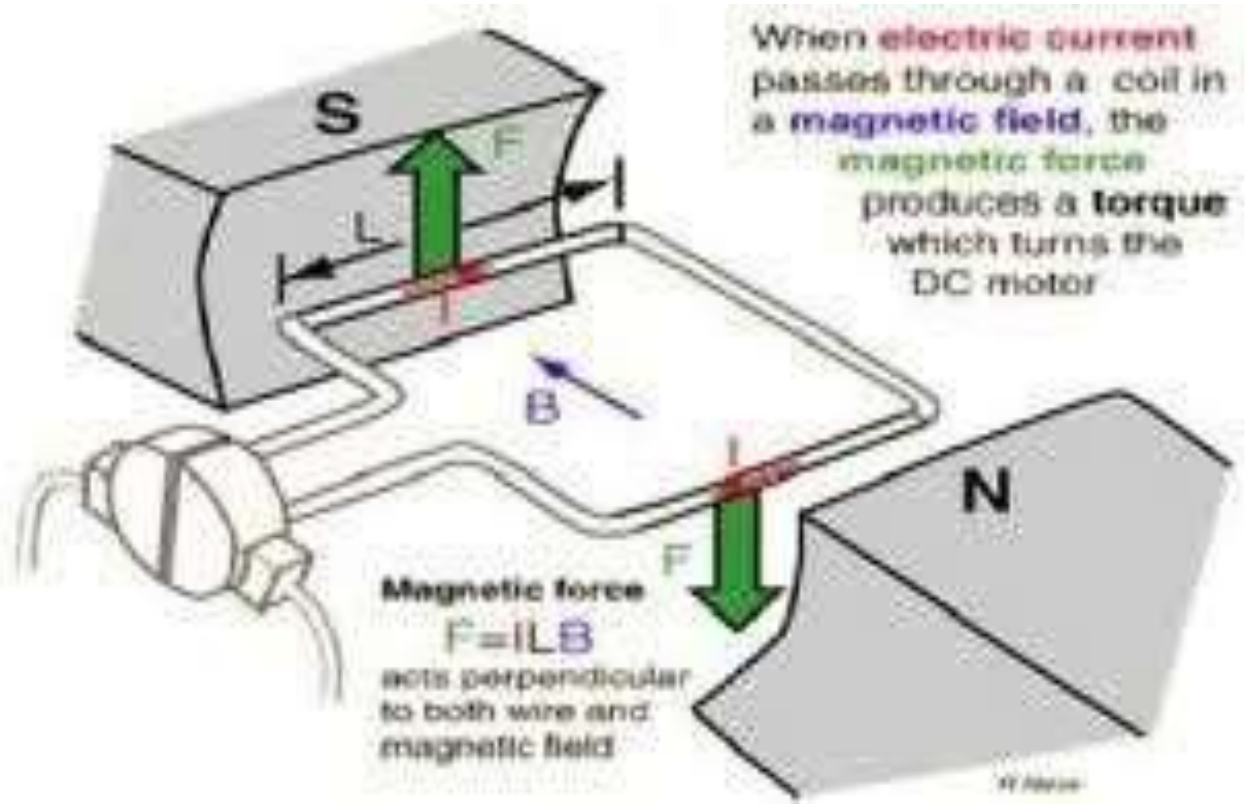
When current carrying conductor is placed in a magnetic field it experience a force.





The direction of force is given by Fleming's Left Hand Rule

Force acting on the armature conductor(Lorentz force):



Back emf:

- When the armature winding of dc motor is start rotating in the magnetic flux produced by the field winding, it cuts the lines of magnetic flux and induces the emf in the armature winding.
- According to Lenz's law (*The law that whenever there is an induced electromotive force (emf) in a conductor, it is always in such a direction that the current it would produce would oppose the change which causes the induced emf.*), this induced emf acts in the opposite direction to the armature supply voltage. Hence this emf is called as back emfs.

$$E_b = \frac{N\emptyset Z}{60}\frac{P}{A} \text{ Volts}$$

N= speed in rpm

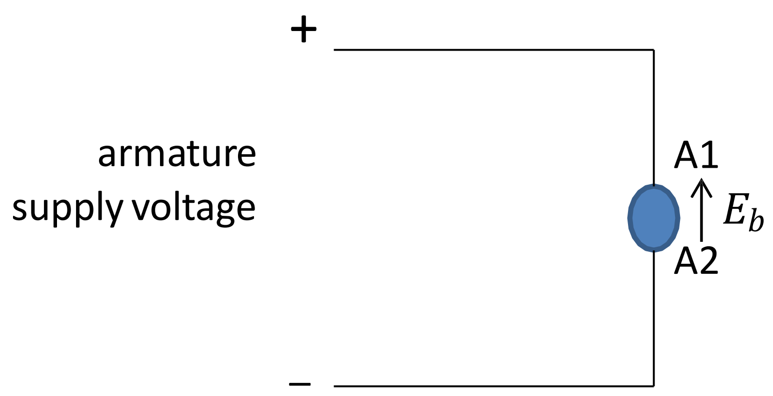
$\emptyset$= flux per pole

Z= no of conductors

P=no of pole pairs

A=area of cross section of conductor

E_b= back emf



Significance of Back EMF

The presence of **back emf** makes the d.c. motor a *self-regulating machine* i.e., it makes the motor to draw as much armature current as is just sufficient to develop the torque required by the load.

$Ia=(V-E_b)/R_a$

Voltage and Power equation of DC Motor:

$$V = E + IR$$

If we multiply the above equation by Ia, we will get

$$VI_a = E_b I_a + I_a{}^2 R_a$$

$VIa = electrical\ power\ supplied\ to\ the\ motor$
$EbIa = electrical\ equivalent\ of\ the\ mechanical\ power\ produced\ by\ the\ motor$
$Ia^2Ra = power\ loss\ taking\ place\ in\ armature\ winding$
Thus,

$$E_b I_a = VI_a - I_a{}^2 R_a$$

=input power-power loss

thus,

$EbIa$= Gross mechanical power produce *by the motor*

= P_m

Condition for Maximum Power

The gross mechanical power developed by a motor is

$$P_m = VI_a - I_a^2 R_a$$

Differentiating both sides with respect to I_a and equating the result to zero, we get

$$P_m = VI_a - I_a^2 R_a$$

$$\frac{\mathrm{d}P_m}{\mathrm{d}I_a} = V - 2I_a R_a = 0$$

$$\therefore I_a R_a = \frac{V}{2}$$

$$As\ V = E_b + I_a R_a \ \ and \ \ I_a R_a = \frac{V}{2}$$

$$\therefore E_b = \frac{V}{2}$$

Thus maximum efficiency of a dc motor occurs when back EMF is equal to half the applied voltage.

Important Points

- Thus gross mechanical power developed by a motor is maximum when back EMF is equal to half the applied voltage.

- This condition is, however, not realized in practice, because in that case current would be much beyond the normal current of the motor.

- Moreover, half the input would be wasted in the form of heat and taking other losses (mechanical and magnetic) into consideration, the motor efficiency will be well below 50 percent.

Torque equation of DC Motor:

$Mechanical\ power\ required\ to\ rotate\ the\ shaft\ on$
$mechanical\ side = T\omega$-----------------------------------1

T =Torque in Newton-meter

ω= angular velocity in radian /second

$gross\ Mechanical\ power\ produce\ by$ the $motor\ on$
$electrical\ side = E_b I_a$--2

E_b = back emf in volts

Ia = armature current in ampere

equating equation 1 & 2

$E_b I_a = T_\omega$

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

$\frac{2\pi N}{60}$ = Speed in rpm

And $Eb = \frac{N\emptyset ZP}{A60}$

Thus, equation (3) become

$$\frac{N\emptyset ZP}{A60} Ia = T \frac{2\pi N}{60}$$

$$T = \frac{P\emptyset ZIa}{2\pi A} = \frac{0.159P\emptyset ZIa}{A} = \left(\frac{0.159PZ}{A}\right) \emptyset Ia$$

$P, Z\ and\ A$ are constant, hence we can say

$$T \propto \emptyset\, Ia$$

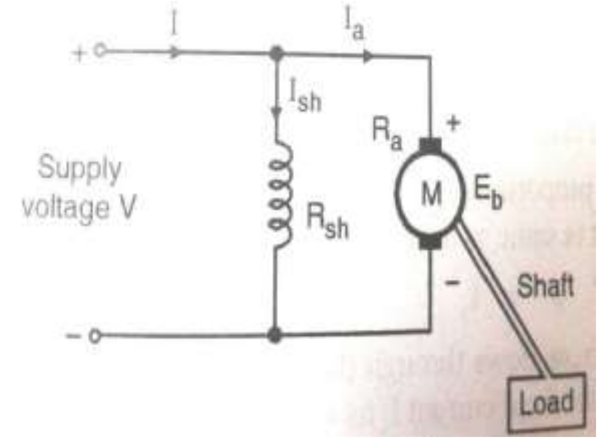
Thus torque produce by the DC Motor is proportional to the main field flux Ø and armature current Ia

Types of DC Motor:

- Classification of the d.c. motor depends on the way of connecting the armature and field winding of a d.c. motor:

1. DC Shunt Motor
2. DC Series Motor
3. DC Compound Motor
    - Short shunt compound
        - Cumulative compound motor
        - Differential compound motor
    - long shunt compound
        - Cumulative compound motor
        - Differential compound motor

DC Shunt Motor:



- In dc shunt motor the armature and field winding are connected in parallel across the supply voltage
- The resistance of the shunt winding R_{sh} is always higher than the armature winding R_a
- Since V and R_{sh} both remains constant the I_{sh} remains essentially constant, as field current is responsible for generation of flux.

  thus $\varnothing \propto I_{sh}$
- So shunt motor is also called as constant flux motor.

Torque and Speed equation of DC Shunt Motor:

As we have seen for dc motor

$$T \propto \emptyset\, Ia$$

But for dc shunt motor :$\emptyset \propto Is$ ▯

And Is ▯ is constant , thus $\emptyset$ is also constant So torque in dc shunt motor is

$$T \propto Ia$$

For dc motor

$$Eb = \frac{N\emptyset ZP}{A60}$$

Z , P, A, $\emptyset$ and 60 are constants

Thus, $N \propto Eb \propto (V - IaRa)$

Characteristics of DC Shunt Motor:

To study the performance of the DC shunt Motor various types of characteristics are to be studied.

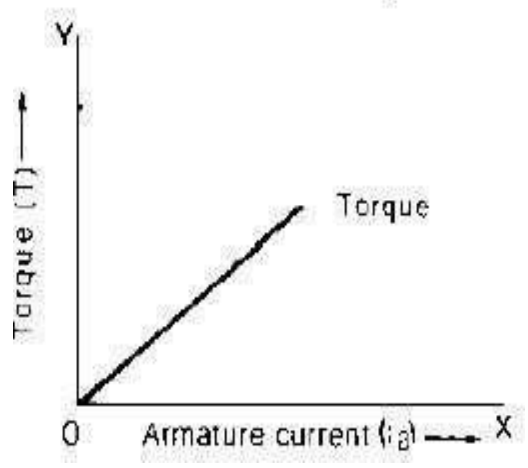
1. Torque Vs Armature current characteristics.
2. Speed Vs Armature current characteristics.
3. Speed Vs Torque characteristics.

Torque Vs Armature current characteristics of DC Shunt motor

This characteristic gives us information that, how torque of machine will vary with armature current, which depends upon load on the motor.

$$T \propto Ia$$

Thus,



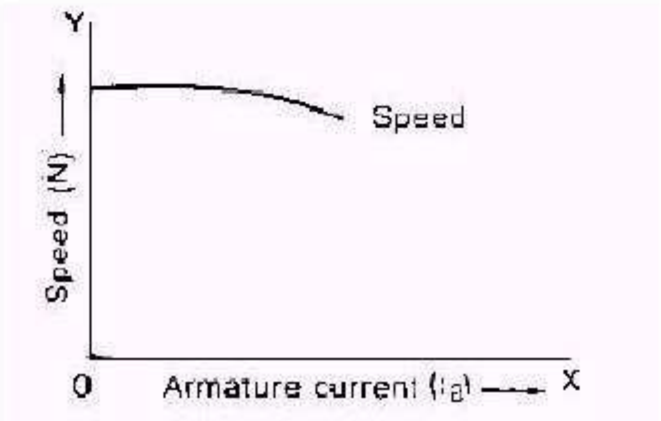
Speed Vs Armature current characteristics of DC Shunt Motor

The back emf of dc motor is $Eb = \frac{N\emptyset ZP}{A60} = V - IaRa$

$$\text{Therefore} \quad N = \frac{(V - I_a R_a)\ 60\ A}{\phi PZ} = \frac{K(V - I_a R_a)}{\phi}$$

where K = 60A/ ZP and it is constant. In dc shunt motor, when supply voltage V is kept constant the shunt field current and hence flux per pole will also be constant.

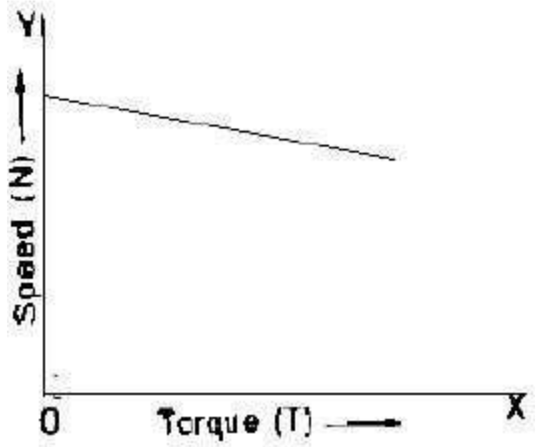
$$\therefore N \propto V - Ia\,Ra$$



- Therefore shunt motor is considered as constant speed motor.

Speed Vs Torque characteristics of DC Shunt motor

- From the above two characteristics of dc shunt motor, the torque developed and speed at various armature currents of dc shunt motor may be noted.
- If these values are plotted, the graph representing the variation of speed with torque developed is obtained.
- This curve resembles the speed Vs current characteristics as the torque is directly proportional to the armature current.



Applications of DC shunt Motor:

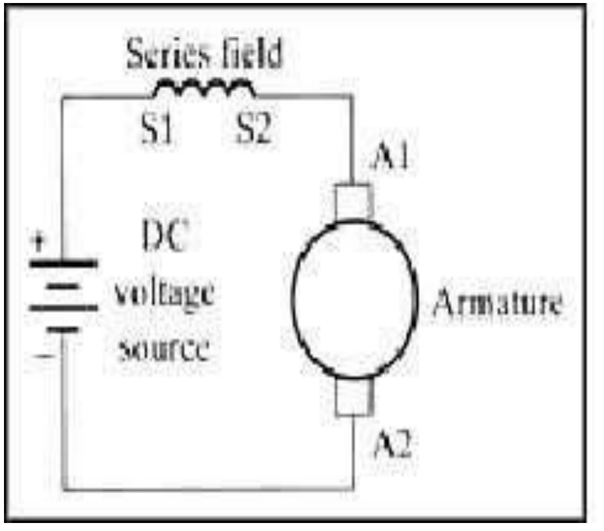
These motors are constant speed motors, hence used in applications requiring constant speed.

Like:

1) Lathe machine
2) Drilling machine
3) Grinders
4) Blowers
5) Compressors

DC Series Motor:

- In this type of DC motor the armature and field windings are connected in series.
- the resistance of the series field winding Rs is much smaller than the armature resistance Ra



- The flux produced is proportional to the field current but in this $I_f = I$ thus $\emptyset \propto Ia$
- Thus flux can never become constant in dc series motor as load changes I_f and I_a also gets changed
- Thus dc series motor is not a constant flux motor.

Torque and Speed equation of DC Series Motor:

As we have seen for dc motor

$$T \propto \emptyset\, Ia$$

But for dc series motor as $I_{f=}I_a$ but $\emptyset \propto Ia$

So torque in dc series motor is

$$T \propto Ia^2$$

For dc motor

$$Eb = \frac{N\emptyset ZP}{A60}$$

Z , P, A and 60 are constants

Thus, $N \propto \frac{Eb}{\emptyset} \propto \frac{(V - IaRa) - I_s R_s}{\emptyset} = \frac{V - Ia(Ra + R_s)}{\emptyset}$ .... as Ia=I_s

for dc series motor

Characteristics of DC Series Motor:

To study the performance of the DC series Motor various types of characteristics are to be studied.

1. Torque Vs Armature current characteristics.
2. Speed Vs Armature current characteristics.
3. Speed Vs Torque characteristics

Torque Vs Armature current characteristics of DC Series motor

- Torque developed in any dc motor is

$$T \propto \emptyset Ia$$

- In case of a D.C. series motor, as field current is equal to armature current, and for small value of I_a

$$\emptyset \propto I_a$$

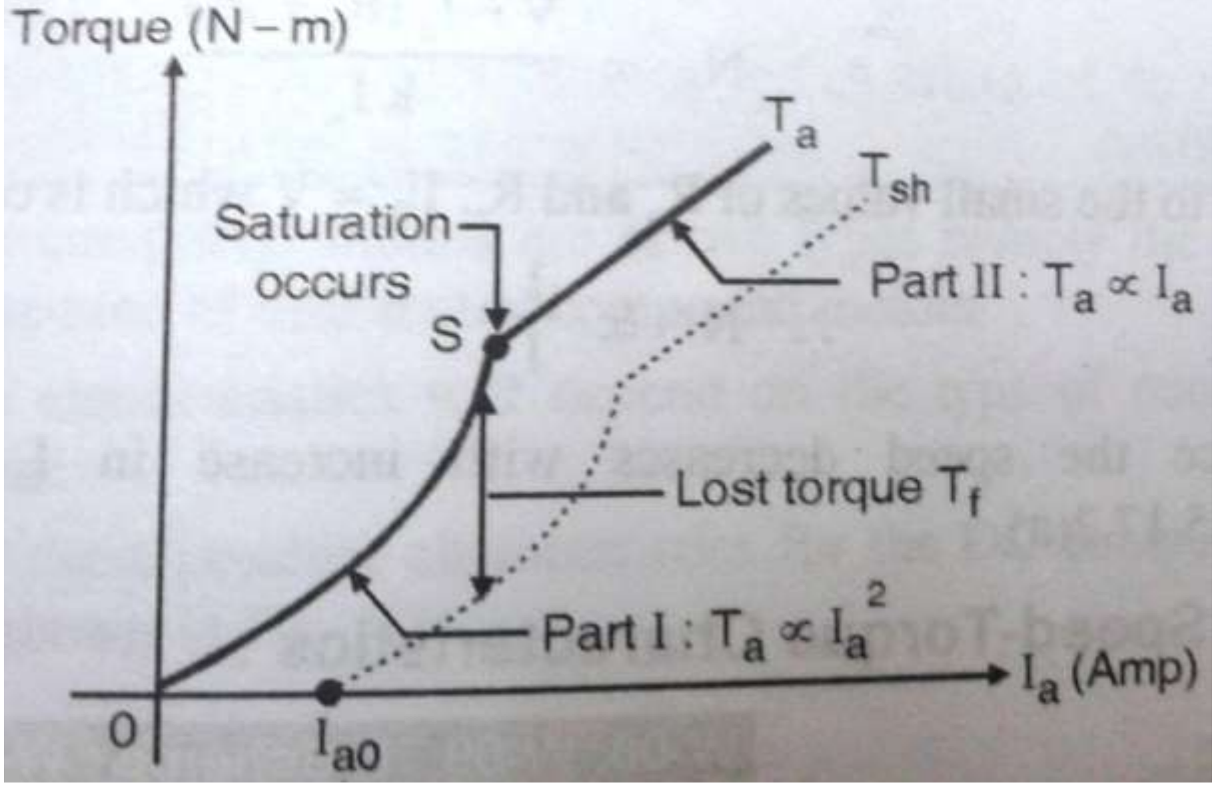
- Therefore the torque in the dc series motor for small value of I_a

$$T \propto Ia^2$$

- When I_a is large the Ø remains the constant due to saturation, thus torque is directly proportional to armature current for large value of I_a

$$T \propto I_a$$

- Thus Torque Vs Armature current characteristics begin to raise parabolically at low value of armature current and when saturation is reached it become a straight line as shown below.



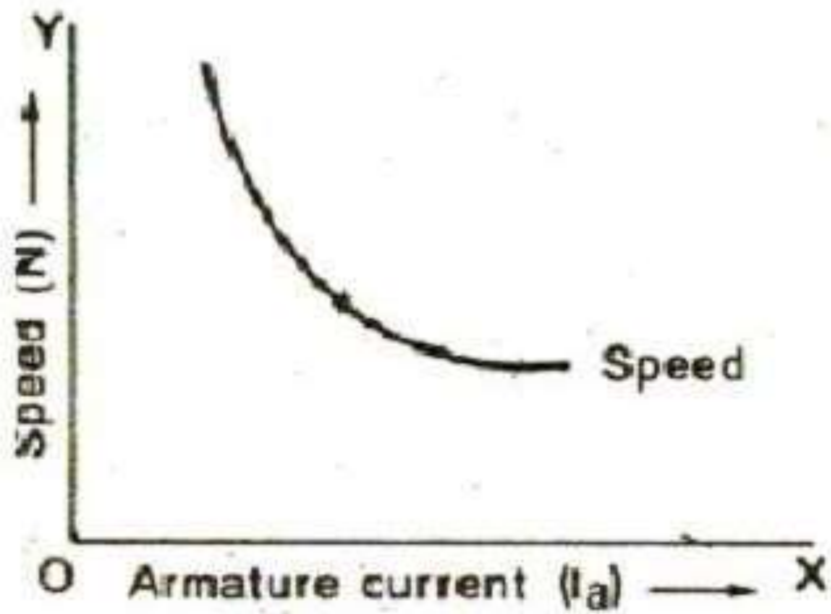
Speed Vs Armature current characteristics of DC Series Motor

Consider the following equation:

$$N = \frac{K(V - IaRa)}{\emptyset}$$

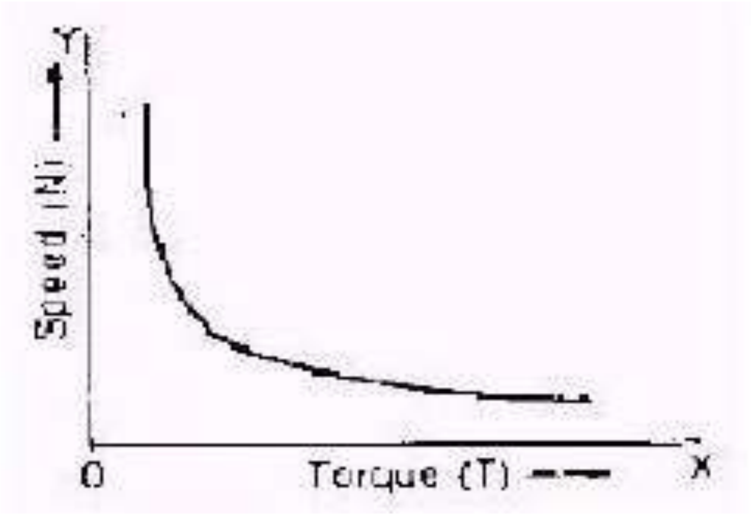
When supply voltage V is kept constant, speed of the motor will be inversely proportional to flux. In dc series motor field exciting current is equal to armature current which is nothing but a load current. Therefore at light load when saturation is not attained, flux will be proportional to the armature current and hence speed will be inversely proportional to armature current. Hence speed and armature current characteristics is hyperbolic curve upto saturation.

- As the load increases the armature current increases and field gets saturated, once the field gets saturated flux will become constant irrespective of increases in the armature current. Therefore at heavy load the speed of the dc series motor remains constant.
- This type of dc series motor has high starting torque.



Speed Vs Torque characteristics of DC Series motor

- The Speed Vs Torque characteristics of dc series motor will be similar to the Speed Vs Armature current characteristics it will be rectangular hyperbola, as shown in the fig.



Applications of DC series Motor-

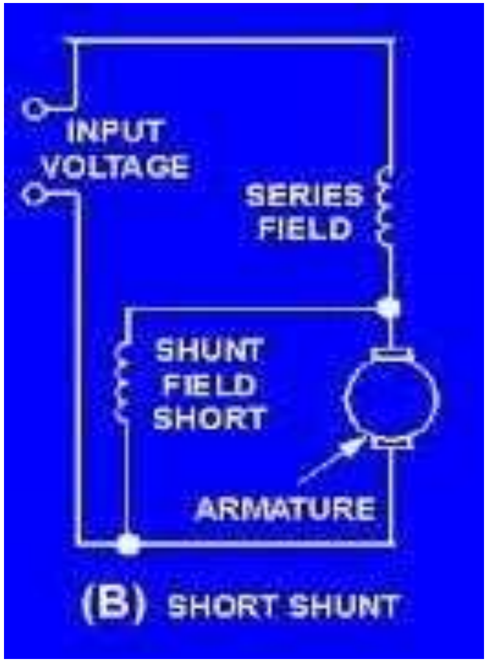
These motors are useful in applications where starting torque required is high and quick acceleration. Like:

1) Traction
2) Hoists and Lifts
3) Crane
4) Rolling mills
5) Conveyors

DC Compound Motor:

- The DC compound motor is a combination of the series motor and the shunt motor. It has a series field winding that is connected in series with the armature and a shunt field that is in parallel with the armature. The combination of series and shunt winding allows the motor to have the torque characteristics of the series motor and the regulated speed characteristics of the shunt motor. Several versions of the compound motor are:
- Short shunt Compound Motors
- Long shunt Compound Motors

Short shunt compound motor:

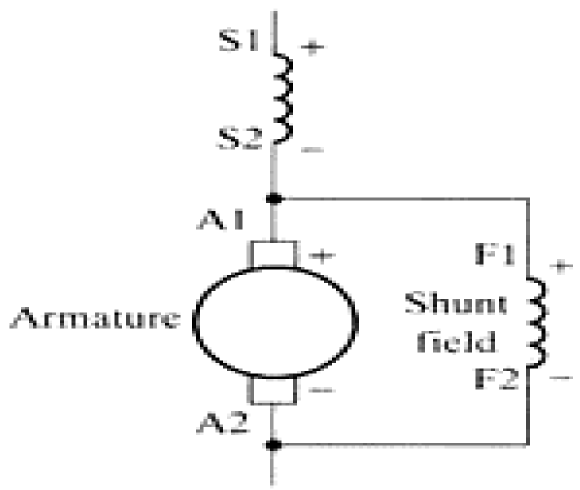


- When shunt field winding is connected in parallel with armature like dc shunt motor and this assembly is connected in series with the series field winding then this type of motor is called as short shunt compound motor.
- Depending on the polarity of the connection short shunt motor is classified as:

1. Cumulative compound motor.
2. Differential compound motor.

Cumulative compound motor (short shunt):

- Figure shows a diagram of the cumulative compound motor. It is so called because the shunt field is connected so that its coils are aiding the magnetic fields of the series field and armature.
- In this figure that the top of the shunt field is positive polarity and that it is connected to the positive terminal of the armature.

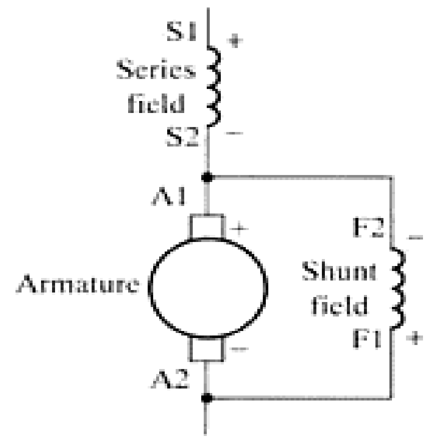


(a) Cummulative compound dc motor (short shunt)

- The cumulative compound motor is one of the most common DC motors because it provides high starting torque and good speed regulation at high speeds. Since the shunt field is wired with similar polarity in parallel with the magnetic field aiding the series field and armature field, it is called cumulative. When the motor is connected this way, it can start even with a large load and then operate smoothly when the load varies slightly.
- You should recall that the shunt motor can provide smooth operation at full speed, but it cannot start with a large load attached, and the series motor can start with a heavy load, but its speed cannot be controlled. The cumulative compound motor takes the best characteristics of both the series motor and shunt motor, which makes it acceptable for most applications.

Differential Compound Motor (short shunt):

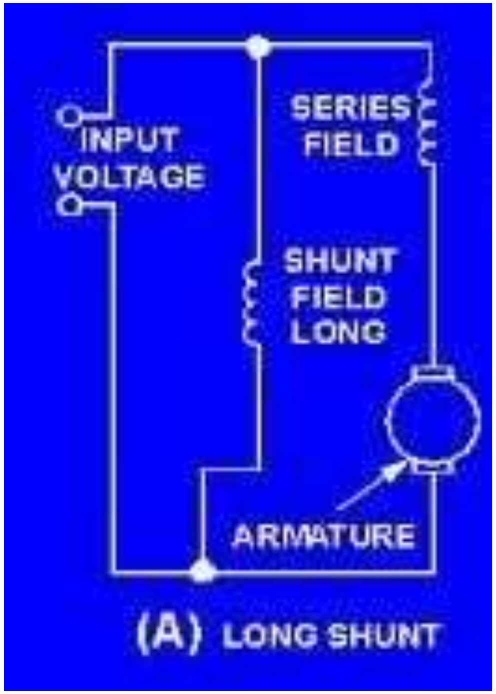
Differential compound motors use the same motor and windings as the cumulative compound motor, but they are connected in a slightly different manner to provide slightly different operating speed and torque characteristics. Figure shows the diagram for a differential compound motor with the shunt field connected so its polarity is reversed to the polarity of the armature. Since the shunt field is still connected in parallel with only the armature, it is considered a short shunt.



(b) Differential compound dc motor (short shunt)

In the above diagram you should notice that Fl and F2 are connected in reverse polarity to the armature. In the differential compound motor the shunt field is connected so that its magnetic field opposes the magnetic fields in the armature and series field. When the shunt field's polarity is reversed like this, its field will oppose the other fields and the characteristics of the shunt motor are not as pronounced in this motor. This means that the motor will tend to overspeed when the load is reduced just like a series motor. Its speed will also drop more than the cumulative compound motor when the load increases at full rpm. These two characteristics make the differential motor less desirable than the cumulative motor for most applications.

Long shunt compound motor:



- when the shunt field is connected in parallel with both the series field and the armature then this type of motor is called as long shunt compound motor.
- Depending on the polarity of connection of shunt field winding, series field winding and armature, long shunt motor is classified as:

1. Cumulative Compound Motor.
2. Differential Compound Motor.

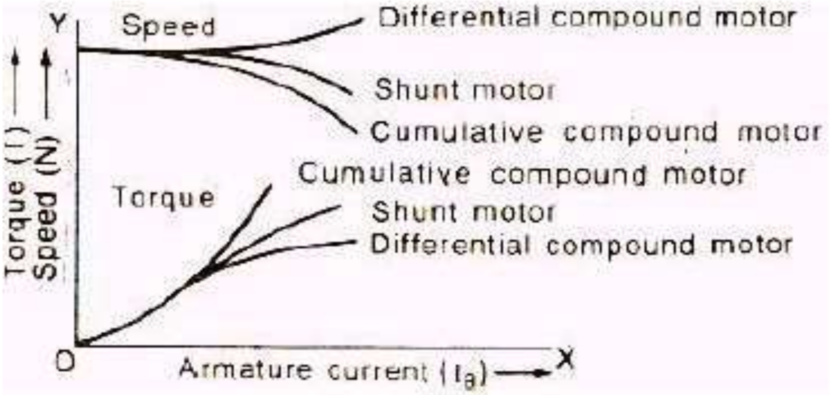
Characteristics of DC compound Motor:

To study the performance of the DC compound Motor various types of characteristics are to be studied.

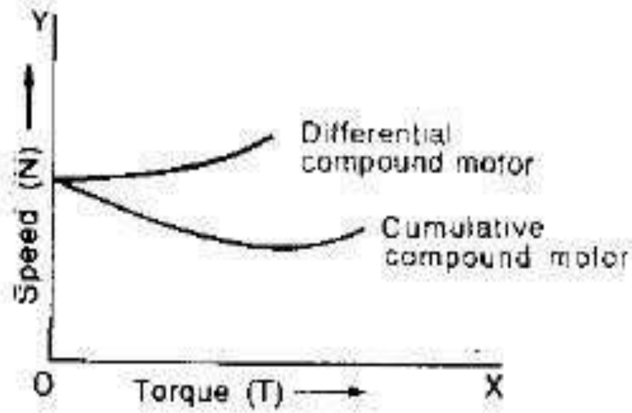
1. Torque Vs Armature current characteristics.
2. Speed Vs Armature current characteristics.
3. Speed Vs Torque characteristics

- In dc compound motors both shunt and series field acting simultaneously.
- In cumulative compound motor series field assist the shunt field.
- In such motors when armature current increases the field flux increases.
- So for given armature current the torque developed will be greater and speed lower when compared to a dc shun motor.
- In differential compound motor series field opposes the shunt field, therefore when armature current decreases the field flux decreases, so for given armature current the torque developed will be lower and speed greater when compare to the dc shunt motor.

Torque Vs Armature current and Speed Vs Armature current characteristics of dc compound motors



Speed Vs Torque characteristics are compared with that of shunt motor.



Applications of DC Compound Motor:

Cumulative Compound Motor:

- These motors have high starting torque.
- They can be operated even at no loads as they run at a moderately high speed at no load.
- Hence cumulative compound motors are used for the following applications.

1. Elevators
2. Rolling mills
3. Punches
4. Shears
5. planers

Applications of DC Compound Motor:

Differential Compound Motor:

- The speed of these motors increases with increases in the load which leads to an unstable operation.
- Therefore we can not use this motor for any practical applications.

Speed Control of DC Motor:

- The speed equation of dc motor is

$$N \propto \frac{Eb}{\emptyset} \propto \frac{(V - IaRa)}{\emptyset}$$

- But the resistance of armature winding or series field winding in dc series motor are small.
- Therefore the voltage drop $IaRa$ or $Ia(Ra + R_s)$ across them will be negligible as compare to the external supply voltage V in above equation.
- Therefore $N \propto \frac{V}{\emptyset}$, since V>>>> $IaRa$
- Thus we can say

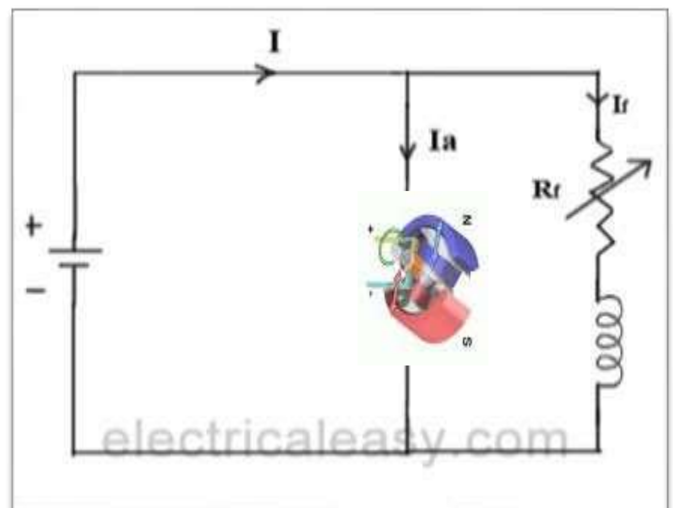
1. Speed is inversely proportional to flux Ø.
2. Speed is directly proportional to armature voltage.
3. Speed is directly proportional to applied voltage V.

So by varying one of these parameters, it is possible to change the speed of a dc motor

SPEED CONTROL OF SHUNT MOTOR

Flux Control Method

To control the flux, a rheostat is added in series with the field winding, as shown in the circuit diagram. Adding more resistance in series with field winding will increase the speed, as it will decrease the flux. Field current is relatively small and hence I^2R loss is small, hence this method is quiet efficient. Though speed can be increased by reducing flux with this method, it puts a limit to maximum speed as weakening of flux beyond the limit will adversely affect the commutation.



SPEED CONTROL OF SHUNT MOTOR

Armature Control Method

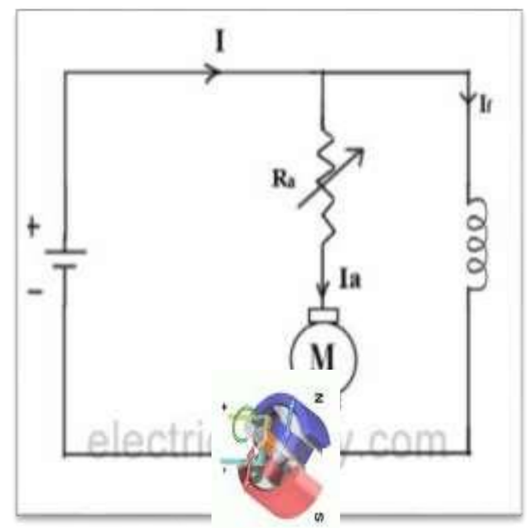
Speed of the motor is directly proportional to the back emf

E_b

and $E_b = V - I_a R_a$. That is when supply voltage V and armature

resistance R_a are kept constant,

speed is directly proportional to armature current I_a. Thus if we add resistance in series with armature, I_a decreases and hence speed decreases.

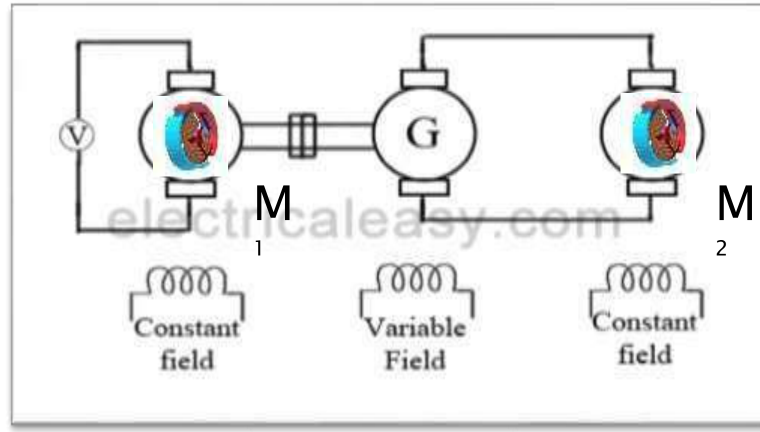


Greater the resistance in series with armature, greater the decrease in speed.

SPEED CONTROL OF SHUNT MOTOR

Voltage Control Method

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



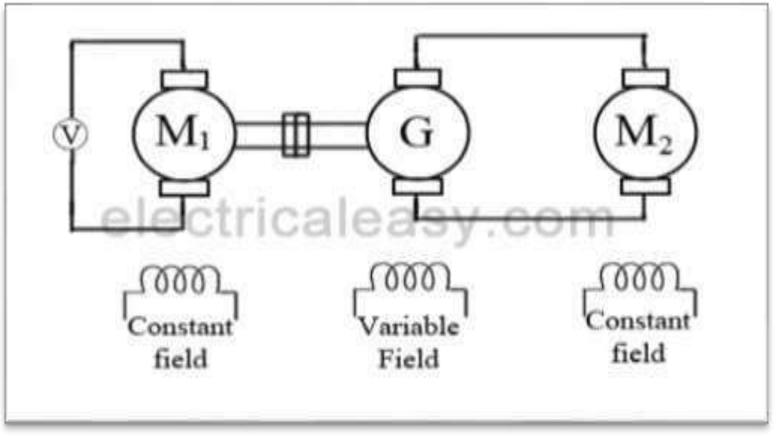
This system is used where very sensitive speed control of motor is required (e.g electric excavators, elevators etc.) The arrangement of this system is as required in the figure beside.

M2 is the motor whose speed control is required.M1 may be any AC motor or DC motor with constant speed. G is the generator directly coupled to M1

SPEED CONTROL OF SHUNT MOTOR

Voltage Control Method

In this method the output from the generator G is fed to the armature of the motor M_2 whose speed is to be controlled. The output voltage of the generator G can be varied from zero to its maximum value, and hence the armature voltage of the motor M_2 is varied very smoothly. Hence very smooth speed control of **motor** can be obtained by this method.



SPEED CONTROL OF SERIES MOTOR

Flux Control Method

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

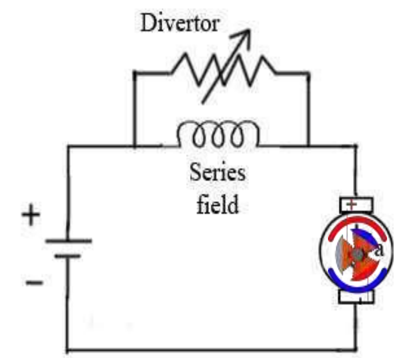


fig (a) Field Divertor

Divertor is connected across the armature as in fig (b).
For a given constant load torque, if armature current is reduced then flux must increase. As, Ta α ØIa
This will result in increase in current taken from the supply and hence flux Ø will increase and subsequently speed of the **motor** will decrease.

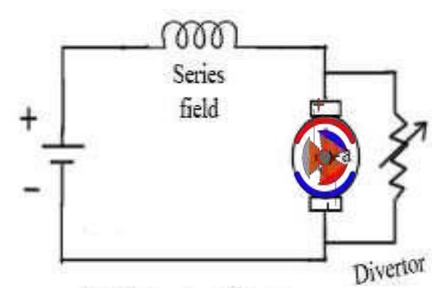


fig (b) Armature Divertor

SPEED CONTROL OF SERIES MOTOR

Flux Control Method

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

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

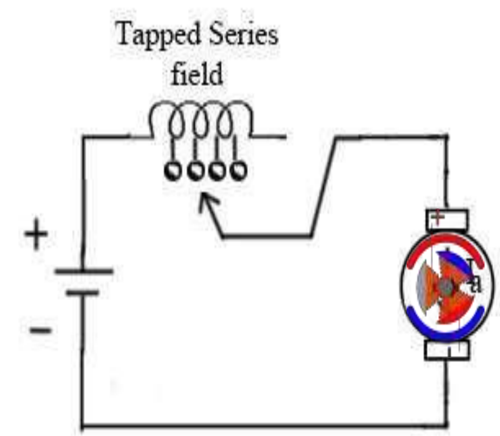


fig (c) Tapped field

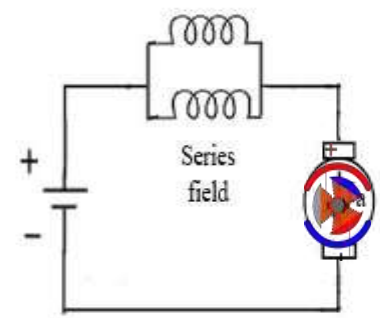


fig (d) Paralleling Field coils

SPEED CONTROL OF SERIES MOTOR

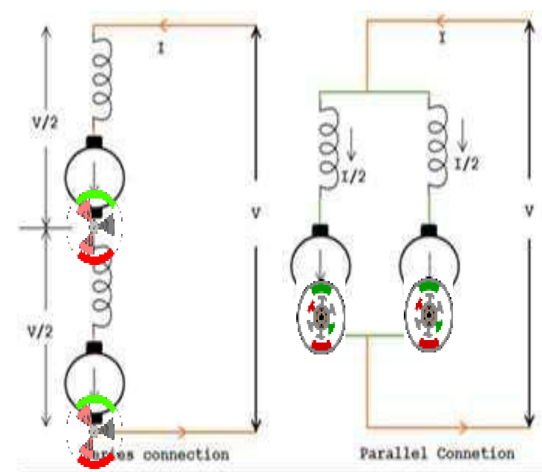
Variable Resistance In Series With Armature

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

Series-Parallel Control

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

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



Reversal of Direction of Rotation:

- The direction of the magnetic flux in the air gap depends on the direction of the field current.
- And the direction of the force exerted on the armature winding depends on the direction of flux and the direction of armature current.
- Thus in order to reverse the direction of dc motor, we have to reverse the direction of force.
- This can be achieved either by changing the terminals of the armature or the terminals of the field winding.

Need of Starter:

We know that, $V = E_b + I_a R_a$............for a dc shunt motor

and $V = E_b + I_a(R_a + R_s)$....for a dc series motor

Hence the expression for I_a are as follows:

$$I_a = \frac{V - E_b}{R_a} \text{......................... for dc shunt motor}$$

$$I_a = \frac{V - E}{(R_a + R_s)} \text{....................for dc series motor}$$

At the time of starting the motor, speed N=0 and hence the back emf E_b=0. Hence the armature current at the time of starting is given by,

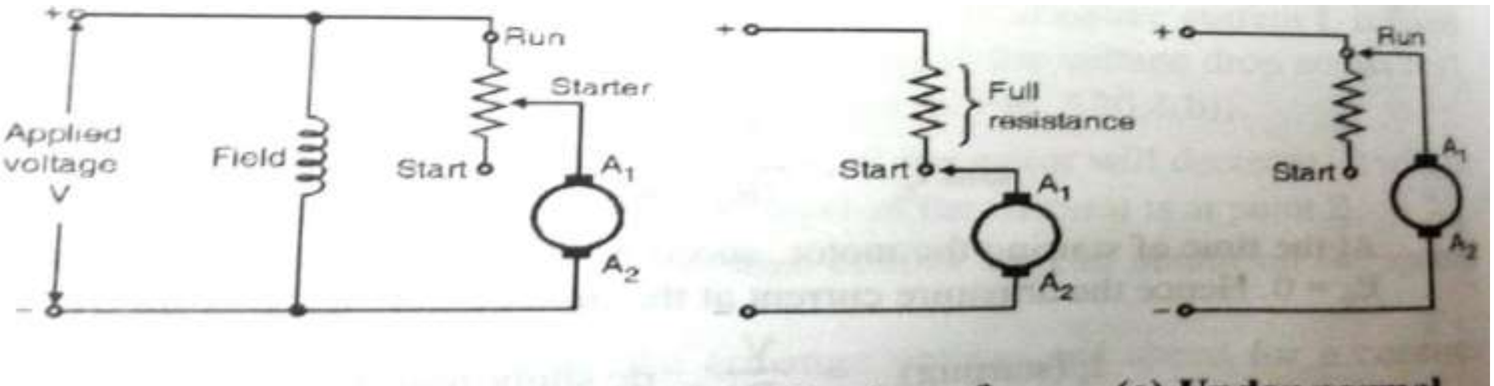
$$I_{a(starting)} = \frac{V}{R} \text{............for dc shunt motor}$$

$$I_{a(starting)} = \frac{V}{(R_a + R_s)} \text{......for dc series motor}$$

- Since the the values of R_a *and* R_s are small, the starting currents will be tremendously large if the rated voltage is applied at the time of starting.
- The starting current of the motor can be 15 to 20 times higher than the full load current.
- Due to high starting current the supply voltage will fluctuate.
- Due to excessive current, the insulation of the armature winding may burn.
- The fuses will blow and circuit breakers will trip.
- For dc series motors the torque $\mathrm{T} \propto {I_a}^2$. So an excessive large starting torque is produced. This can put a heavy mechanical stress on the winding and shaft of the motor resulting in the mechanical damage to the motor.
- So to avoid all these effects we have to keep the starting current of motor below safe limit. This is achieved by using starter.

Principle of starter:

- Starter is basically a resistance which is connected in series with the armature winding only at the time of starting the motor to limit the starting current.
- The starter of starter resistance will remain in the circuit only at the time of starting and will go out of the circuit or become ineffective when the motor speed upto a desire speed.



(a) Principle of starter
(b) At the time of starting
(c) Under normal operating condition

- At the time of starting, the starter is in the start position as shown in fig. so the full starter resistance appears in series with the armature. This will reduce the starting current.
- The starter resistance is then gradually cut off. The motor will speed up, back emf will be developed and it will regulate the armature current. The starter is not necessary then.
- Thus starter is pushed to the Run position as shown in fig under the normal operating condition. The value of starter resistance is zero in this position and it does not affect the normal operation.

Types of starters:

1. Two point starter
2. Three point starter
3. Four point starter

Three Point Starter

Construction of 3 Point Starter

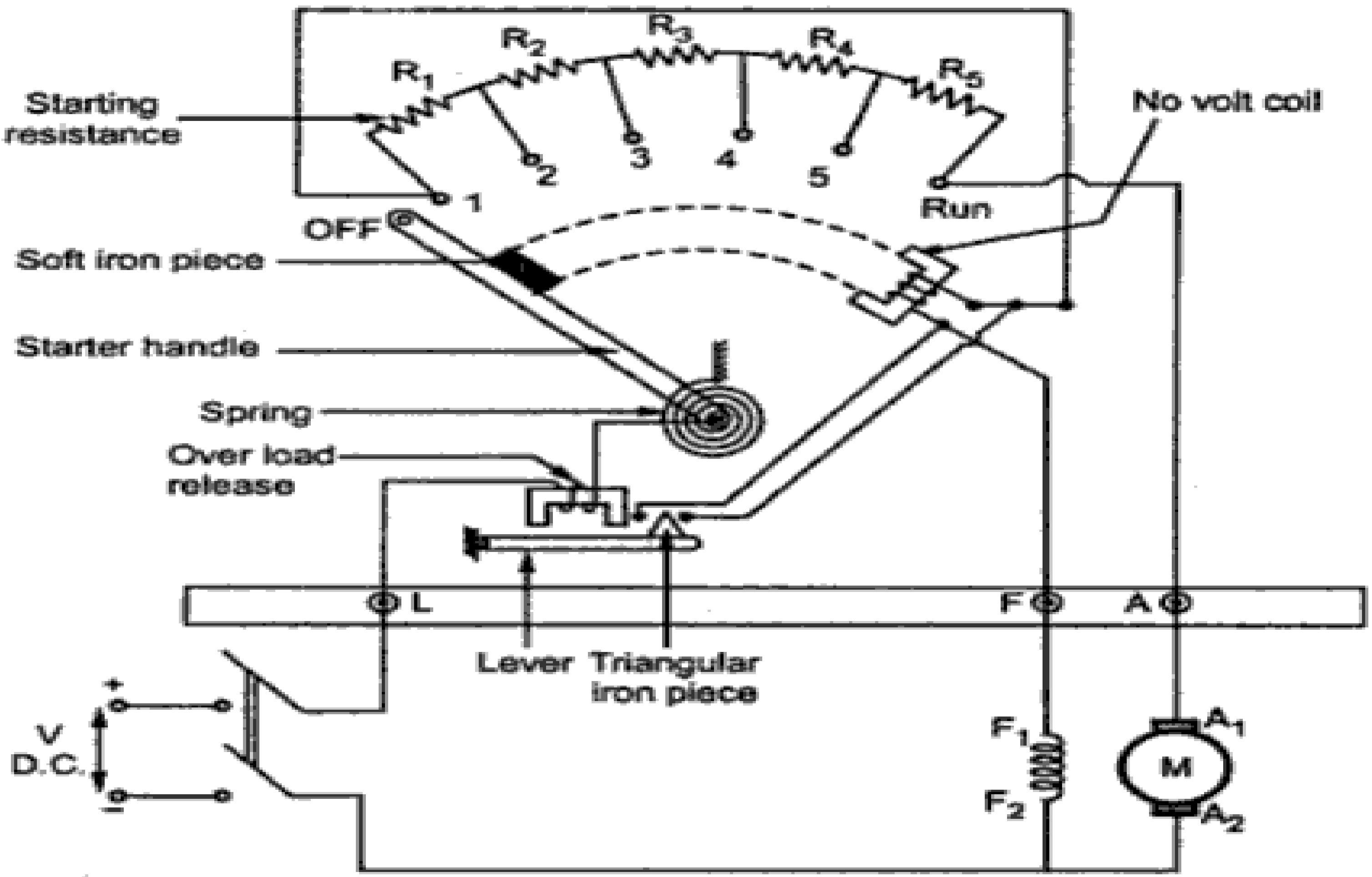
The Three Terminals are L, A & F

L is known as Line terminal, which is connected to the positive supply.

A is known as the armature terminal and is connected to the armature windings.

F is known as the field terminal and is connected to the field terminal windings.

Three point starter



3 point Starter

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

Working of Three Point Starter

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

$$I_a = \frac{E}{(R_a + R_{st})}$$

As the handle is moved further, it goes on making contact with studs 2, 3, 4, etc., thus gradually cutting off the series resistance from the armature circuit as the motor gathers speed. Finally, when the starter handle is in 'RUN' position, the entire starting resistance is eliminated, and the motor runs with normal speed. This is because back emf is developed consequently with speed to counter the supply voltage and reduce the armature current.

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

Function of No Voltage Coil (NVC)

- The field winding is supplied through NVC and field current makes it an electromagnet.

- When the handle is at the RUN position, the soft iron piece on handle gets attracted by the magnetic force produced by NVC.

- Whenever there is supply failure or field supply is broken then NVC loses its magnetism and unable to hold the handle.

- The spring action brings back the handle to OFF position.

- NCV perform the similar action during low voltage condition and Save the device.

Functions of Overload release (OLR)

- The motor current is supplied through OLR coil, which makes it an electromagnet.

- Below the OLR coil, there is an arm which is fixed at its fulcrum or lying horizontally.

- At the end of the arm, a small triangular iron piece is fitted which is in the proximity of two ends of the shorting cable of NVC.

- It is so designed that, till the full load current OLR coil magnetism and gravitational force are balanced and OLR is unable to lift the lever.

- Whenever motor draws high current the magnetism of the OLR coil pull the arm and triangular piece of the arm shorts both point of NVC coil.

- NVC coil loses its magnetism and leaves the handle. the handle than retracts back to OFF position because of spring action. The motor will stop.

Drawbacks of a 3 Point Starter

1. The 3 point starter suffers from a serious drawback for motors with a large variation of speed by adjustment of the field rheostat.

2. To increase the speed of the motor, the field resistance should be increased. Therefore, the current through the shunt field is reduced.

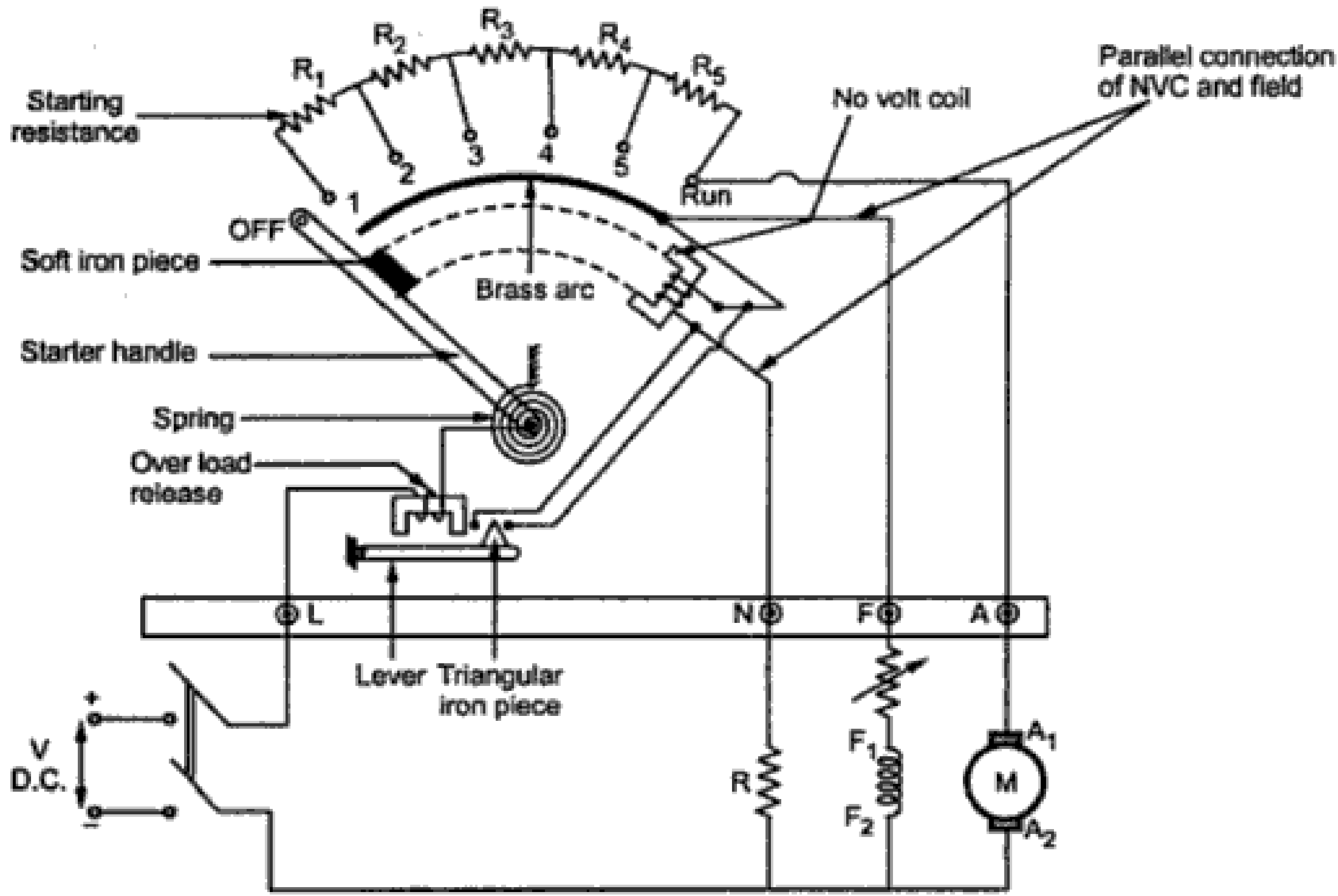
3. The field current may become very low because of the addition of high resistance to obtain a high speed.

Drawbacks of a 3 Point Starter

4. A very low field current will make the holding electromagnet too weak to overcome the force exerted by the spring.

5. The holding magnet may release the arm of the starter during the normal operation of the motor and thus, disconnect the motor from the line. This is not a desirable action.

Four point starter



4 point Starter

Drawback of a 4 Point Starter

The only drawback of the 4 point starter is that it cannot limit or control the high current speed of the motor.

Unit-III

Testing of DC Machines

Why testing are required ?

Machines are tested for finding out

- Performance of the machine
- Losses & efficiency of the machine
- Quality of the materials used
- Modification in manufacturing process

LOSSES IN DC MACHINE

LOSSES MEANS…………

- *The basic function of a dynamo is the conversion of energy, either from mechanical to electrical form or from electrical to mechanical form. Whole of the input to the dynamo is not converted into useful output energy but a part of the input energy is converted into heat and is lost for the useful output purpose of the machine. The energy converted into heat is called the ENERGY LOSS.*

TYPES OF LOSSES……….

- Copper Losses or Electrical Losses
- Core Losses or Iron Losses
- Brush Losses
- Mechanical Losses
- Stray-Load Losses

COPPER OR ELECTRICAL LOSSES…

These losses are the winding losses because these occurs in the winding of the machine.

Armature current losses= = $I_a^2R_a$

Copper losses in shunt field of a machine=$I_{sh}^2R_{sh}$

Copper losses in interpole winding=$I_a^2R_i$

Copper losses in a series field machine=$I_{se}^2R_{se}$

Copper losses in a compensating windings=$I_a^2R_c$

CORE LOSSES OR IRON LOSSES…

These losses are also called as magnetic losses. These losses are constant about 20% of a full load losses

Core losses are of two types

1. *Hysteresis losses*
2. *Eddy current losses*

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

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

where, η = Steinmetz hysteresis constant

V = volume of the core in m^3

B_{max} = Maximum flux Density in armature winding F = Frequency of magnetic reversals

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.

Eddy Current loss $P_e = K_e B^2_{max} f^2 t^2 V$ Watts

Where, k_e = constant

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

T = Thickness of lamination in m

V = Volume of core in m^3

Note: Constant (**K_e**) depend upon the resistance of core and system of unit used

BRUSH LOSSES…

Power loss at the brush contacts between the copper commutator and the carbon brushes.

MECHANICAL LOSSES..

The losses associated with mechanical effects are called as MECHANICAL LOSSES. They consists of bearing friction loss and windage loss.

These losses are usually very small.

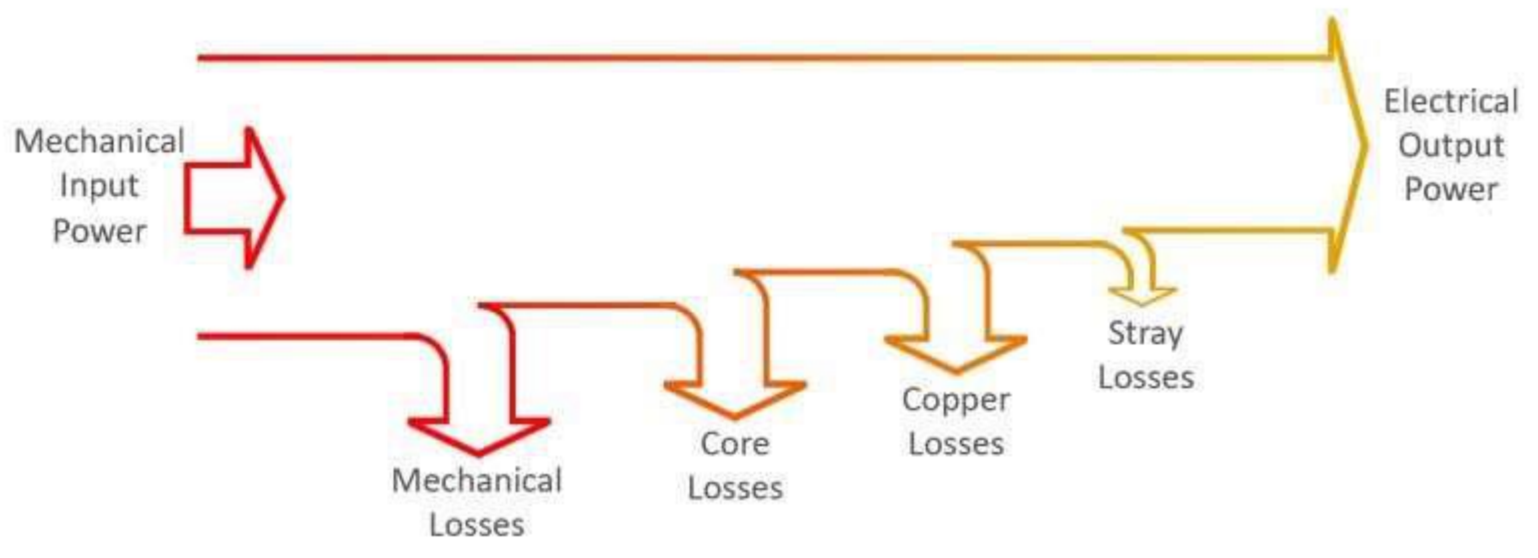
STRAY LOSSES…

Stray losses are results from

1. The distortion of flux because of Armature reaction
2. Short circuit currents in the coil, undergoing commutation etc

Stray losses are assumed as 1% of full load output power

The power-flow diagram of DC Generator



Power flow diagram of a DC generator

Efficiency Of DC Generator

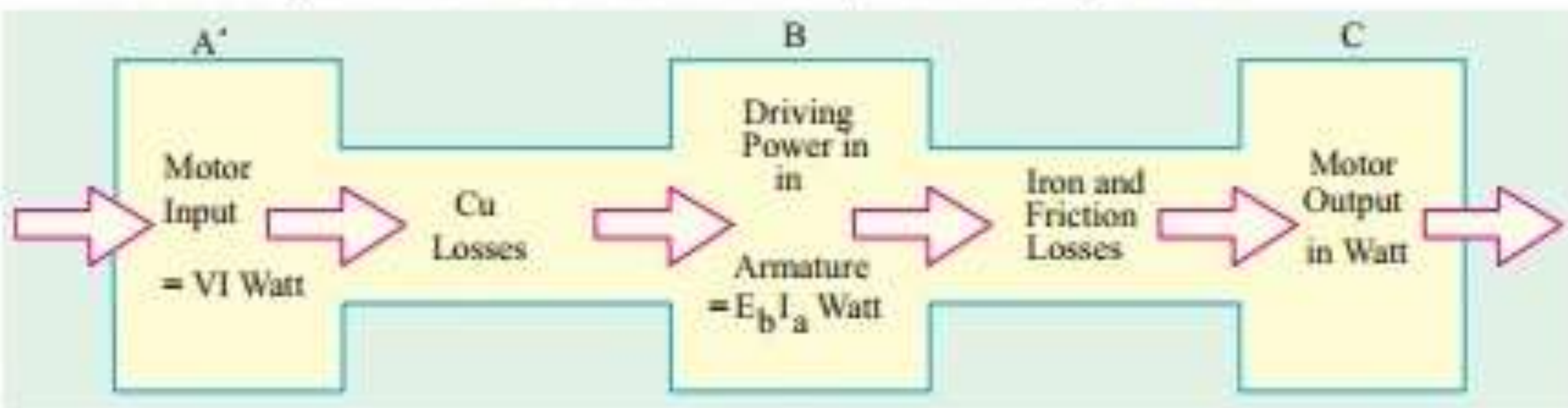
Mechanical Power Input (A) → Iron and Friction Losses → **Electrical Power developed in armature. EIa, Watt (B)** → Copper Losses → **Electrical Power Output VI, Watts (C)**

Mechanical Efficiency = B / A
Electrical Efficiency = C / B
Overall/Commercial Efficiency = C / A

The power-flow diagram of DC Motor

Overall or commercial efficiency $\eta_c = \frac{C}{A}$, Electrical efficiency $\eta_e = \frac{B}{A}$, Mechanical efficiency $\eta_m = \frac{C}{B}$.

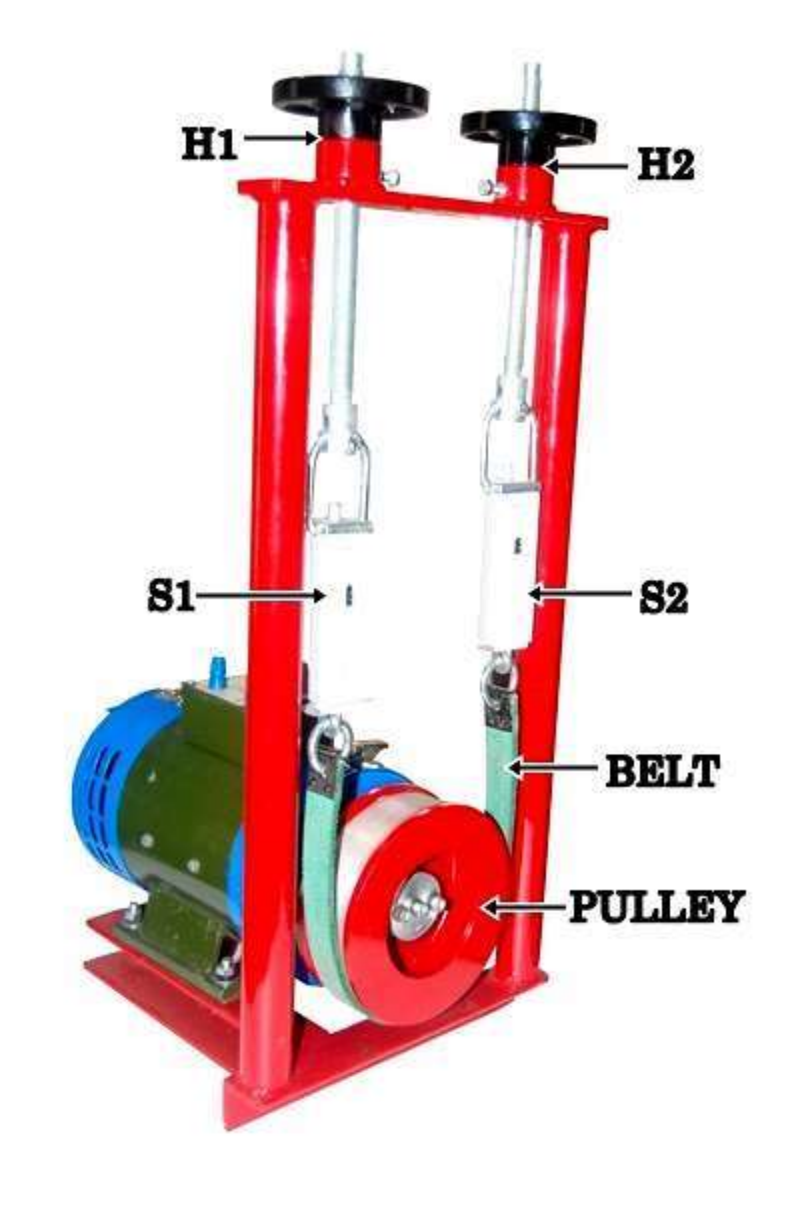
The efficiency curve for a motor is similar in shape to that for a generator



TYPES OF TESTING OF ADC MOTOR

- **DIRECT METHOD**
- **INDIRECT METHOD OR SWINBURNE’S METHOD**
- **REGENERATIVE METHOD OR HOPKINSON’S METHOD**

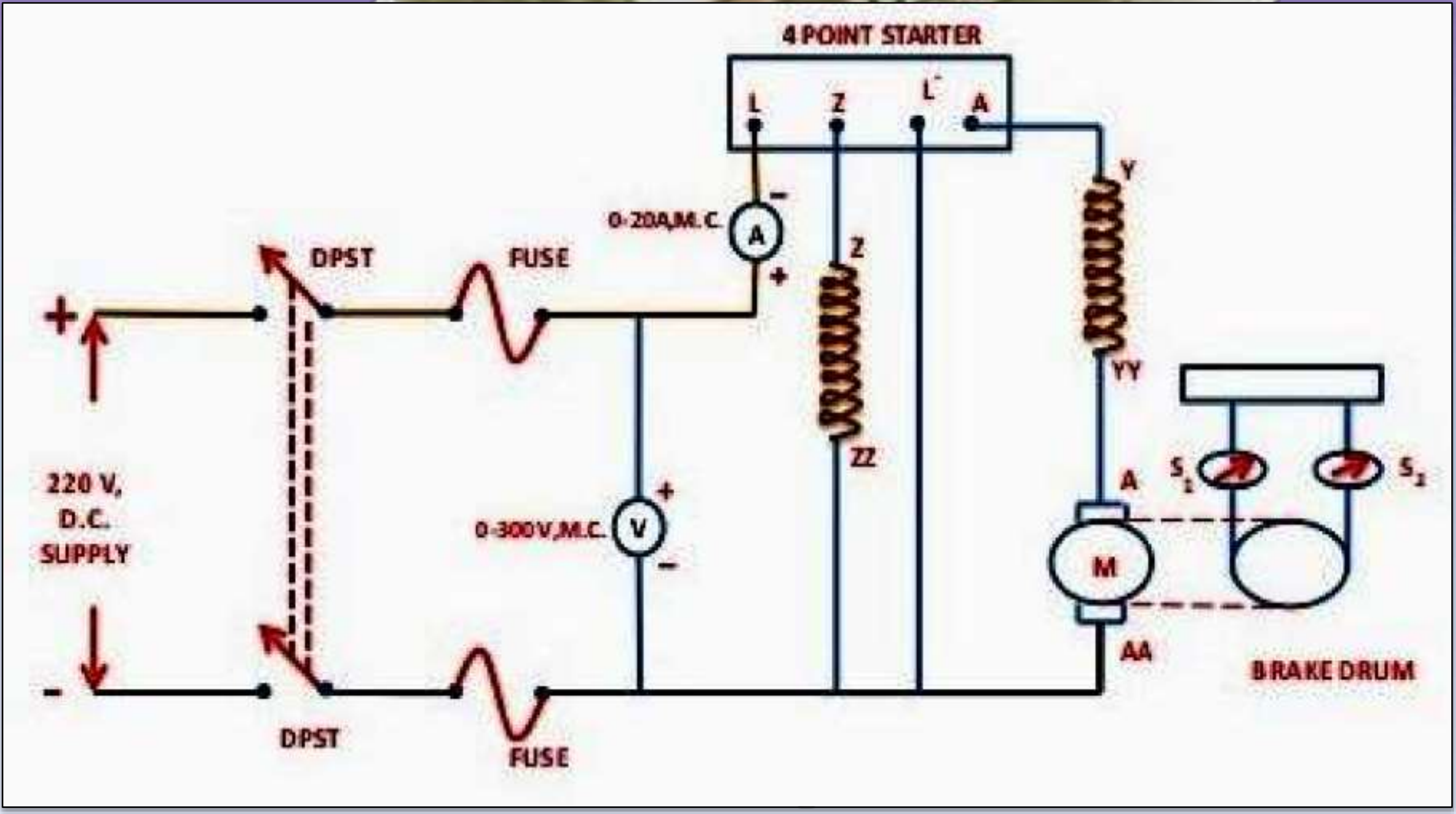
DIRECT METHOD



- Suitable for small D.C. Machines
- Brake test for D.C. Motors
- Belt pulley arrangement attached to spring balances S_1 & S_2
- Loads on pulley adjusted by hand WHEELS H_1 & H_2

EFFICIENCY CALCULATION

- Motor output power= $\omega*(S_1 – S_2)*r*9.81$ watts
- Motor input power= $V_t * I_l$ watts
- Motor efficiency, $\boldsymbol{\eta_m = [\{\omega*(S_1 – S_2)*r*9.81\}*100/(V_t * I_l)]\%}$



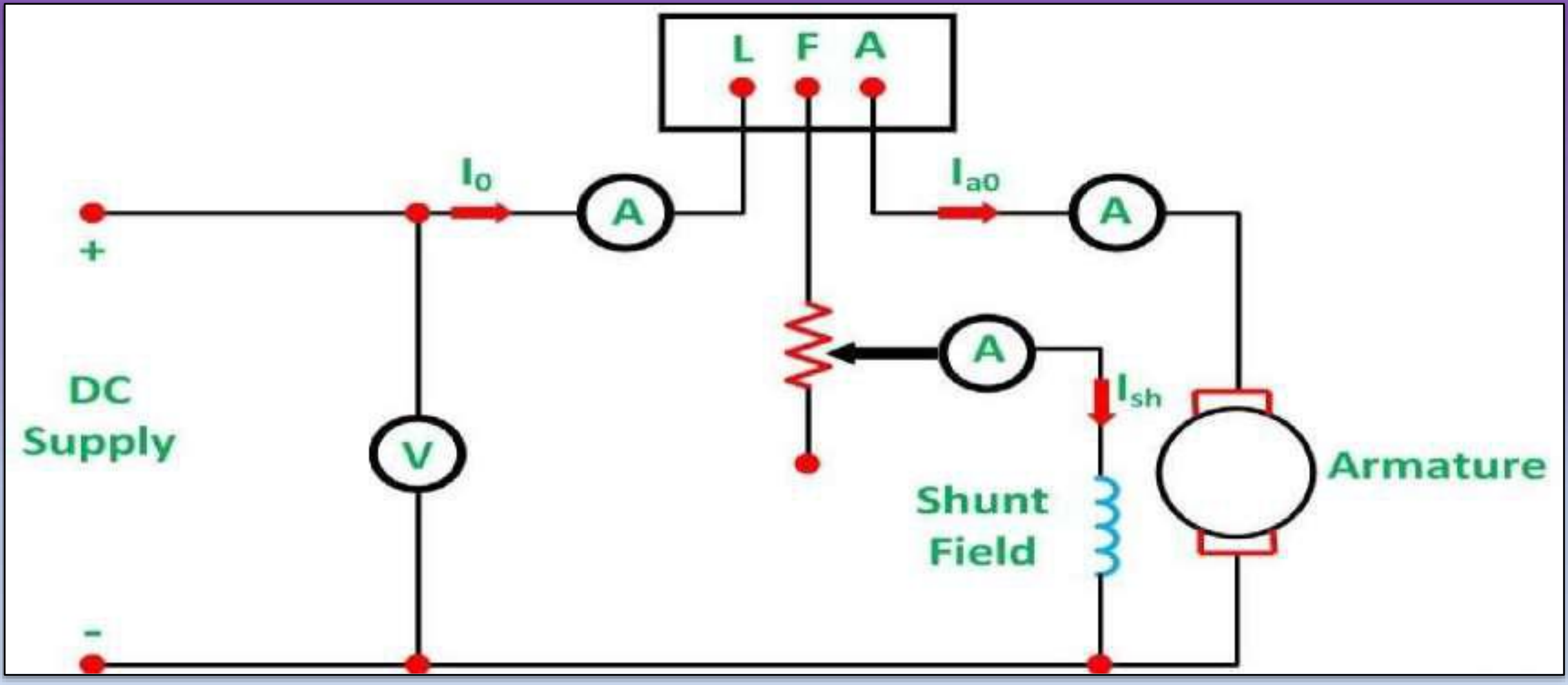
PRECAUTION

- THE BRAKE SHOULD BE SUFFICIENTLY TIGHT FOR A DC SERIES MOTOR

DISADVANTAGES

- Size of the motor is restricted
- Spring balance readings are not steady
- More power Consumption

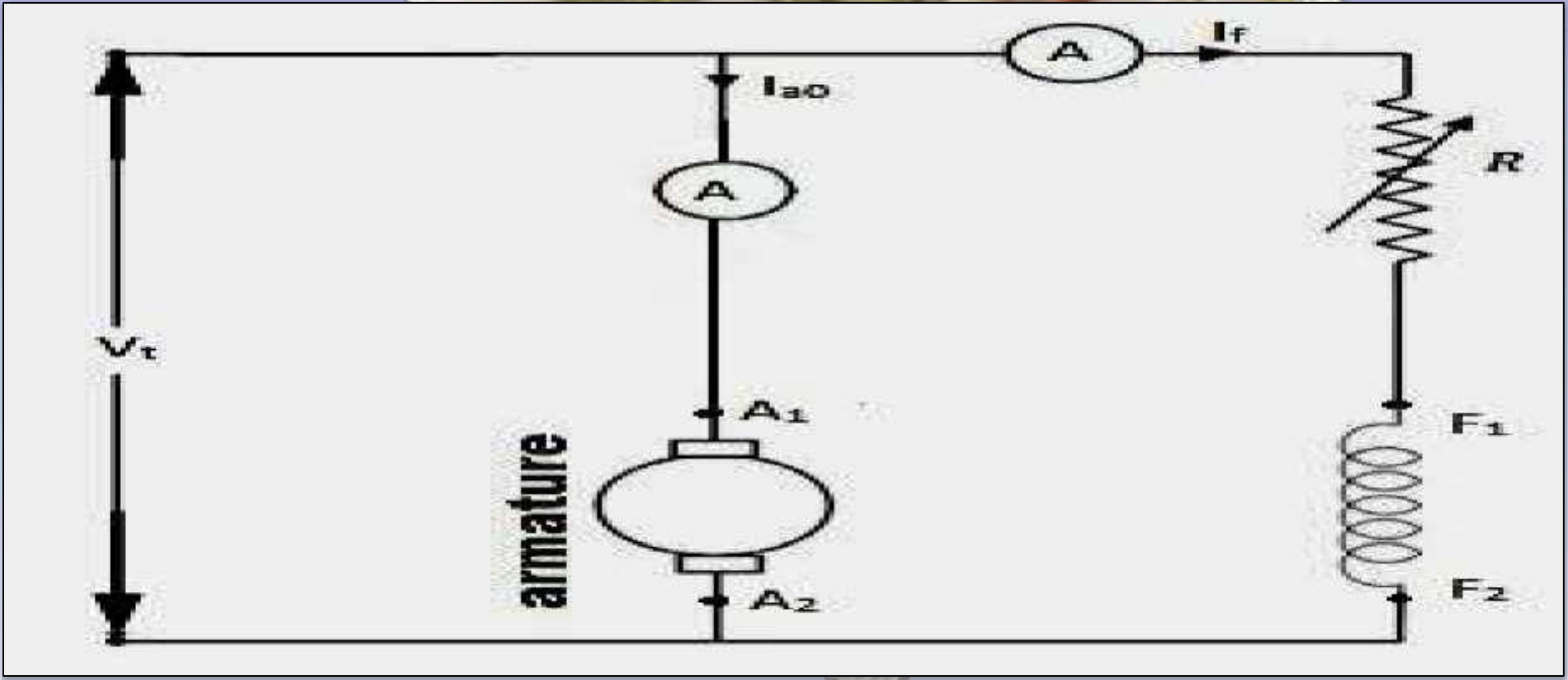
SWINBURNE'S METHOD OF TESTING A DCMOTOR



- Most commonly used and simplest method of testing of shunt and compound wound dc machines
- No load losses are measured separately

EFFICIENCY CALCULATION

- Power absorbed by armature at no load= $V_t * I_{a0}$
- Armature circuit loss = $I_{a0}^2 * r_a$
- No load rotational losses, $W_0 = (V_t * I_{a0}) – (I_{a0}^2 * r_a)$
- Shunt field loss= $V_t * I_f$
- Power input = $V_t * I_L$
- $I_L = I_a + I_f$
- Efficiency of the motor: η_m **=1- [{W_0 + ($I_{a0}^2 * r_a$)+ ($V_t * I_f$)}/ ($V_t * I_L$)]%**



ADVANTAGES

- Required very less power
- Since constant losses are known, efficiency of Swinburne's test can be pre-determined at any load

DISADVANTAGES

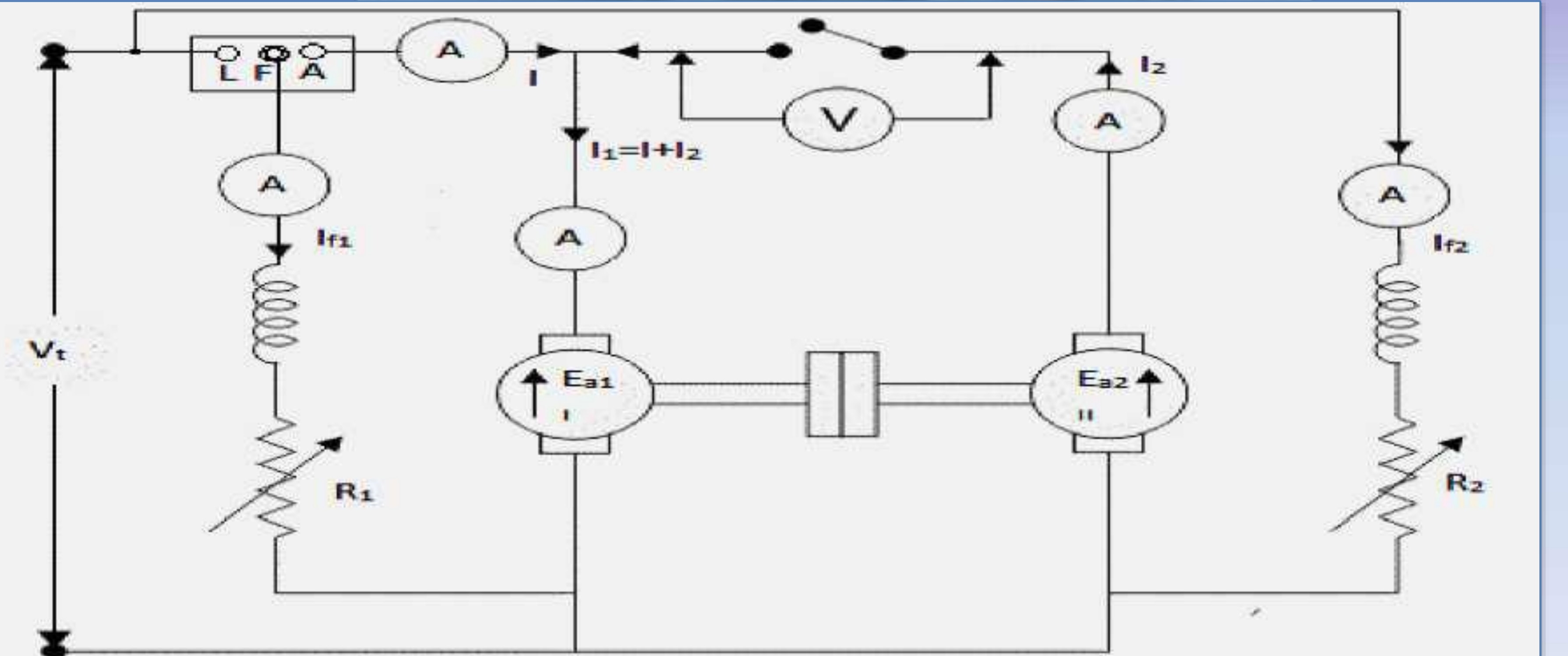
- Iron loss is neglected
- We cannot be sure about the satisfactory commutation on loaded condition
- We can’t measure the temperature rise when the machine is loaded
- In dc series motor, the Swinburne’s test cannot be done

HOPKINSON'S METHOD OF TESTING A DCMOTOR

- Two identical dc machines are coupled, both mechanically & electrically
- One of these two machines is operated as a generator to supply the electrical power to the motor and the other is operated as a motor to drive the generator
- Due to the drop in the generator output voltage we need an extra voltage source to supply the proper input motor-generator set

EFFICIENCY CALCULATION

- Input to motor armature= $V_t * I_1$
- Motor armature circuit loss= $I_1^2 * r_a$
- Motor shunt field loss= $V_t * I_{f1}$
- No-load rotational loss in two machines, $W_0 = (V_t * I) - r_a * (I_1^2 + I_2^2)$
- No-load rotational loss in each machine= $W_0/2$
- Total motor loss, $W_m = (W_0/2) + (V_t * I_{f1}) + (I_1^2 * r_a)$
- Motor efficiency: $\boldsymbol{\eta_m = [1 - \{W_m / V_t * (I_1 + I_{f1})\}] * 100\%}$



Hopkinson's Test of DC Machine

ADVANTAGES

- Very small power required
- Temperature rise and commutation can be observed
- Change in iron loss due to flux distortion can be taken into account due to the advantage of its full load condition

DISADVANTAGES

- Difficult to find two identical machines
- Both machines cannot be loaded equally all the time
- It is not possible to get separate iron losses for the two machines
- It is difficult to operate the machines at rated speed because field currents vary widely

Unit-4
Single Phase Transformers

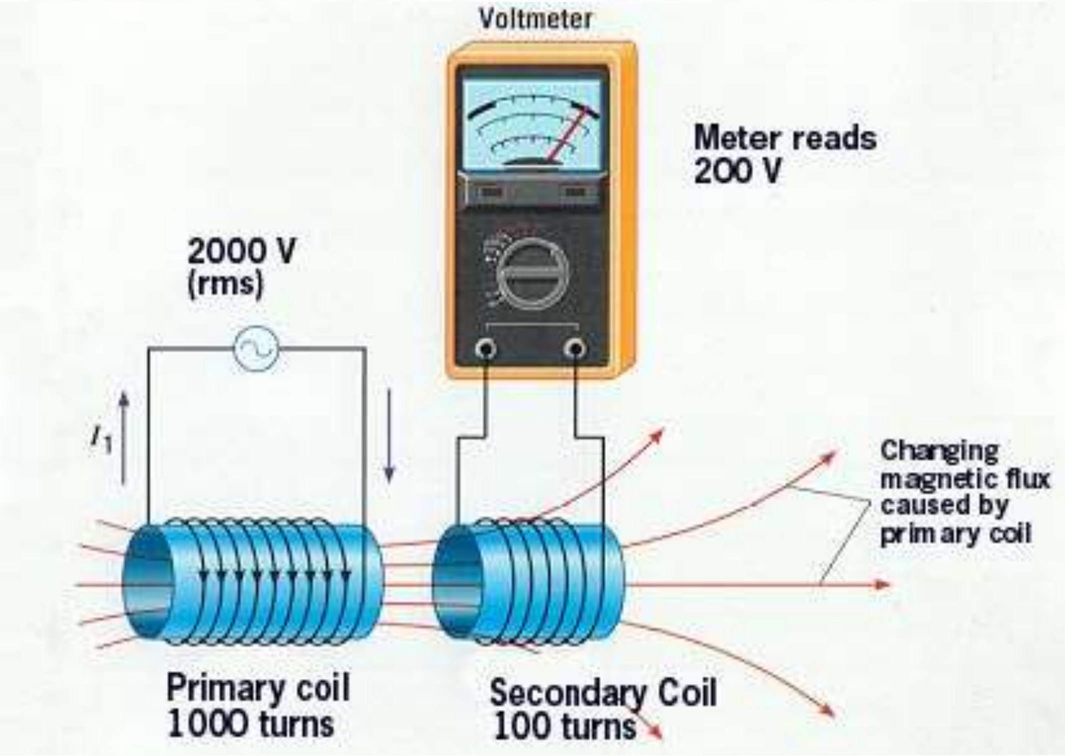
Transformer

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

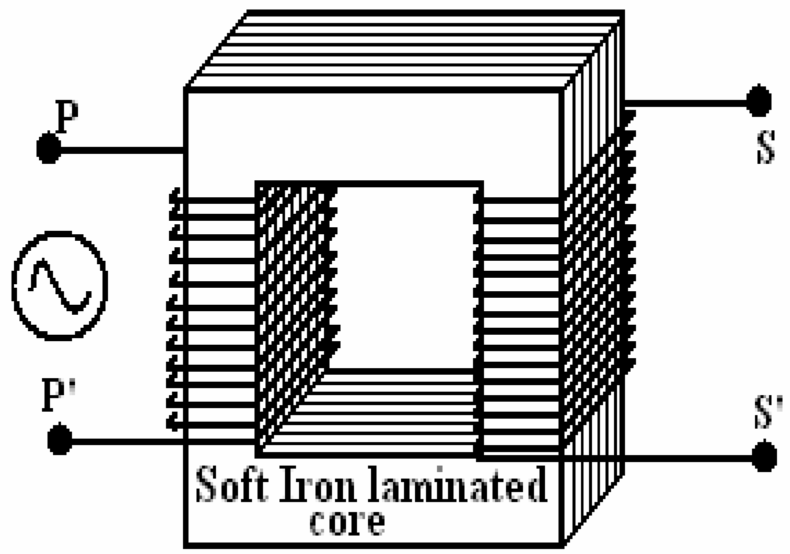


It is based on principle of MUTUAL INDUCTION.

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.



Single Phase Transformer

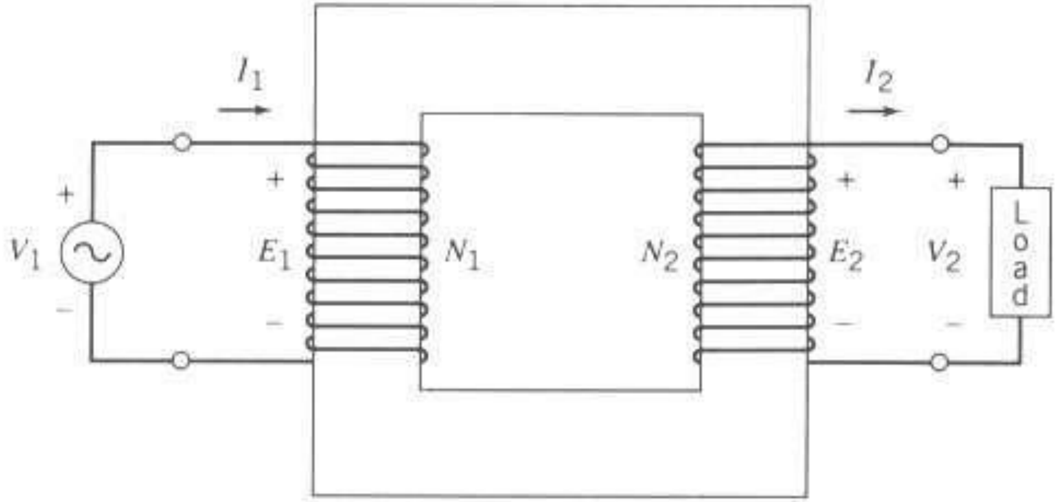


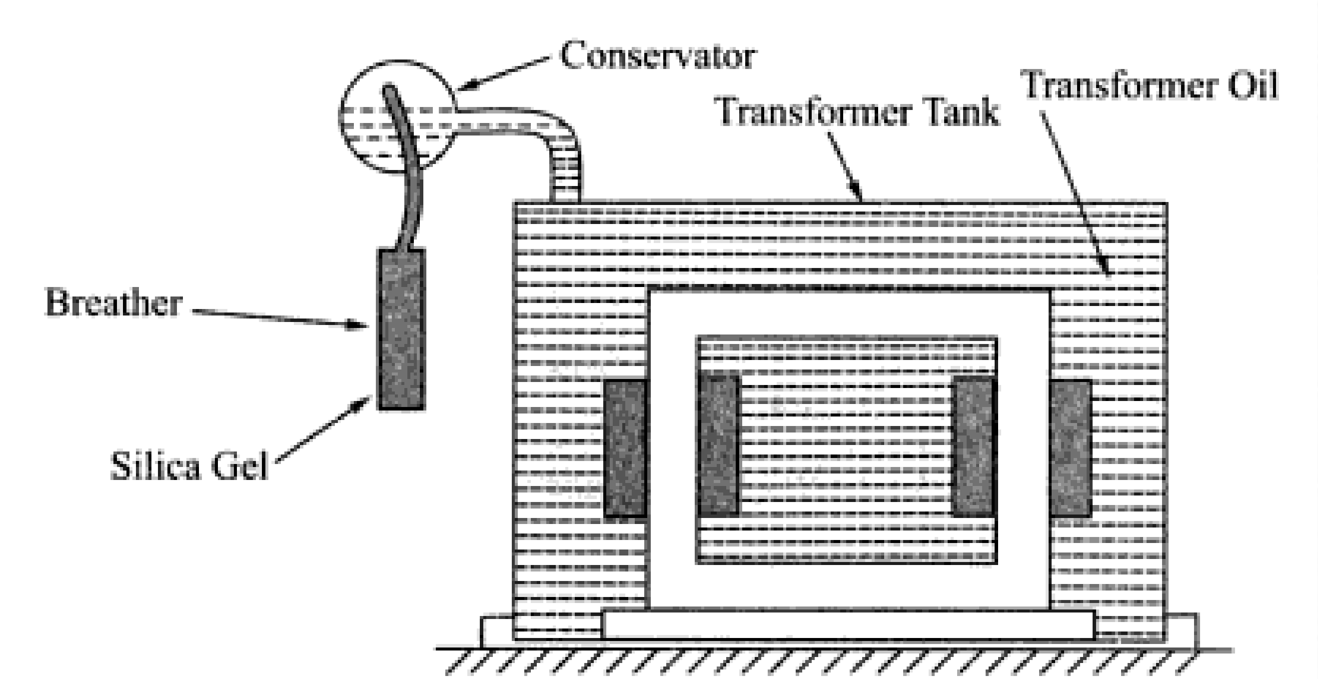
FIGURE 4.8 A transformer circuit.

- A single phase transformer
  - Two or more winding, coupled by a common magnetic core

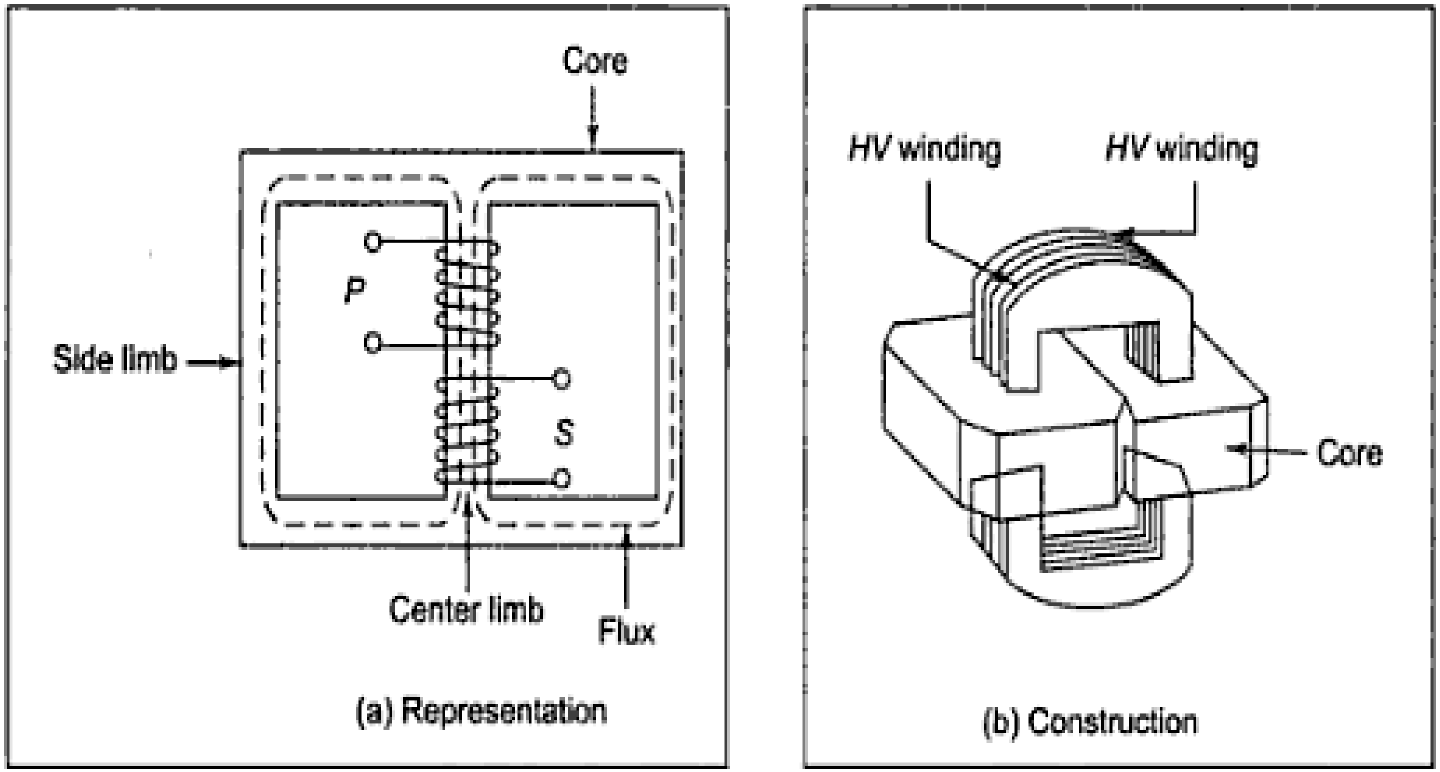
PARTS OF TRANSFORMER

1. Laminated Core
2. Windings
3. Main Tank / Oil Tank
4. Transformer Oil
5. Conservator Tank
6. Buchholz Relay
7. Breather
8. Radiator

Transformer with conservator and breather



Constructional detail : Shell type

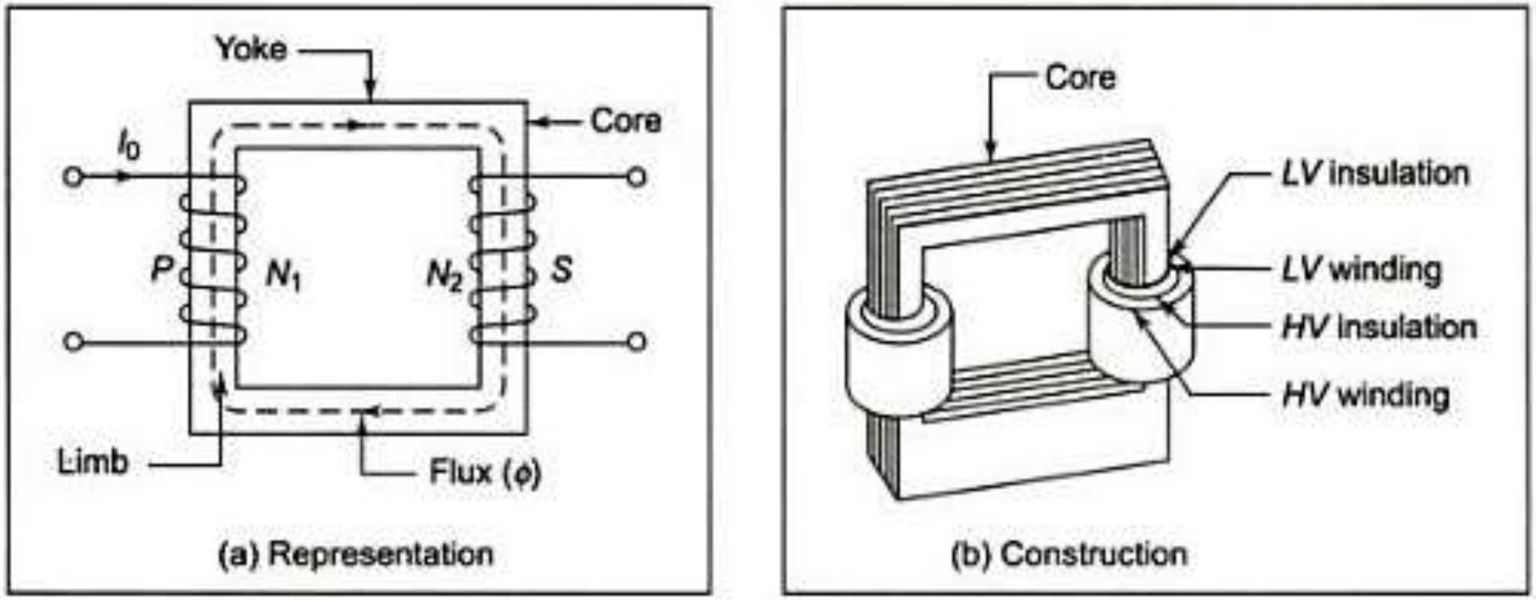


(a) Representation

(b) Construction

- Windings are wrapped around the center leg of a laminated core.

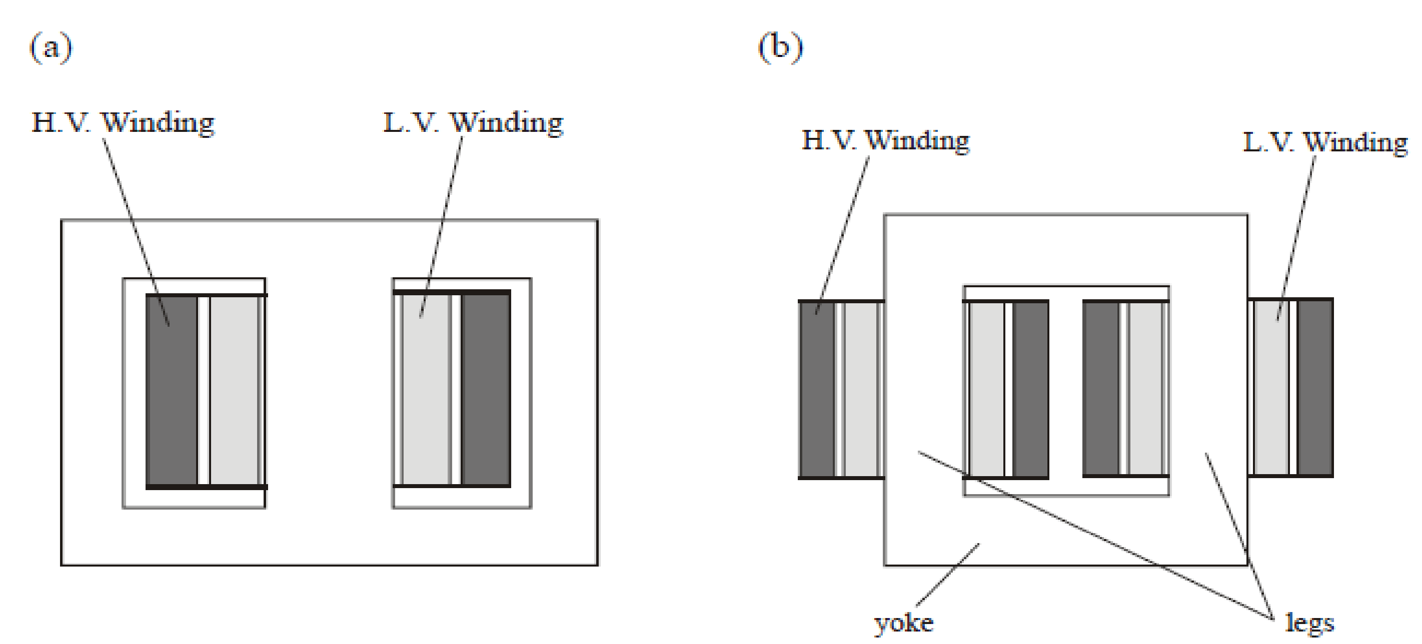
Core type



(a) Representation (b) Construction

- Windings are wrapped around two sides of a laminated square core.

Sectional view of transformers

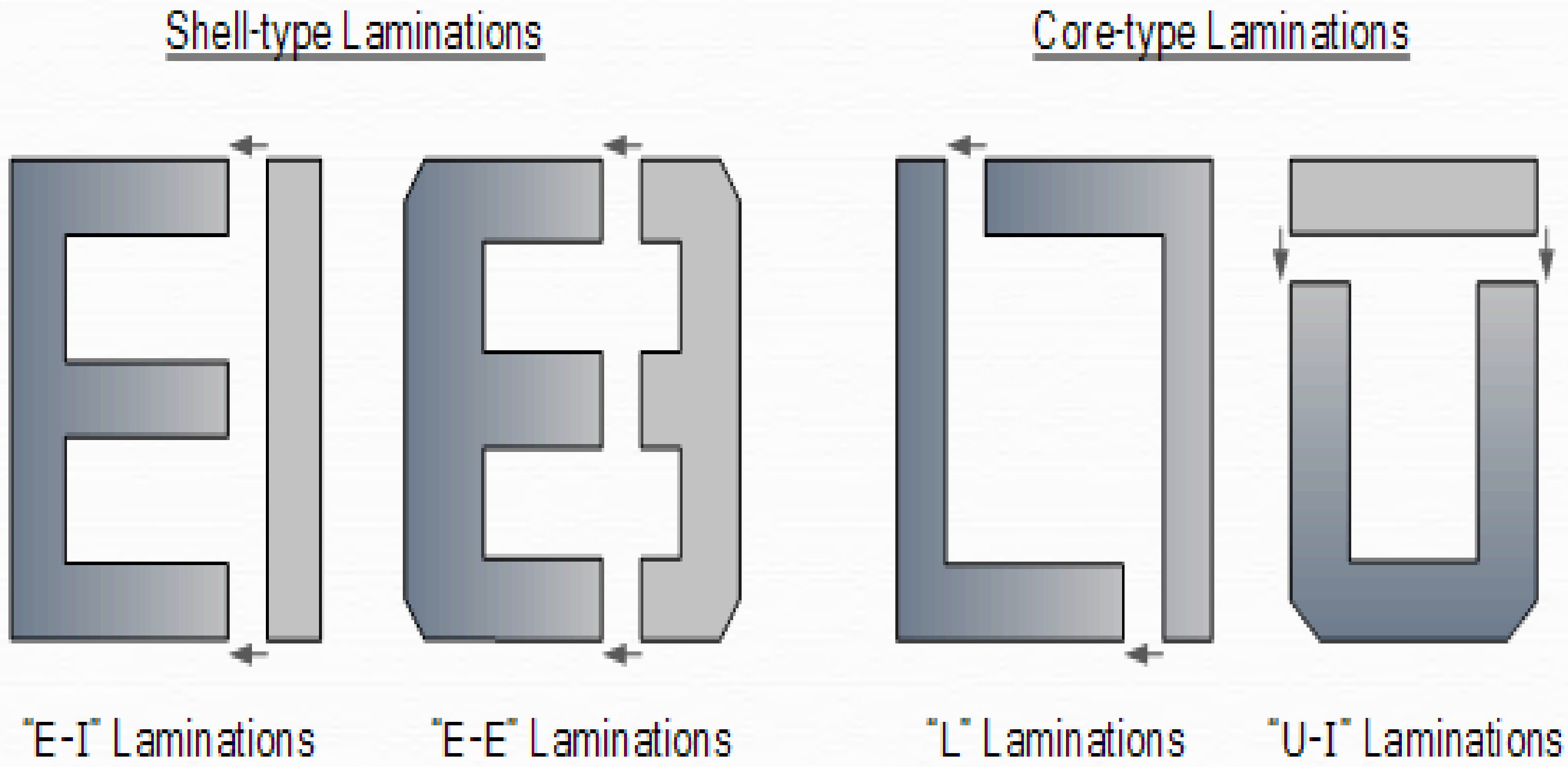


(a) Shell-type transformer, (b) core-type transformer

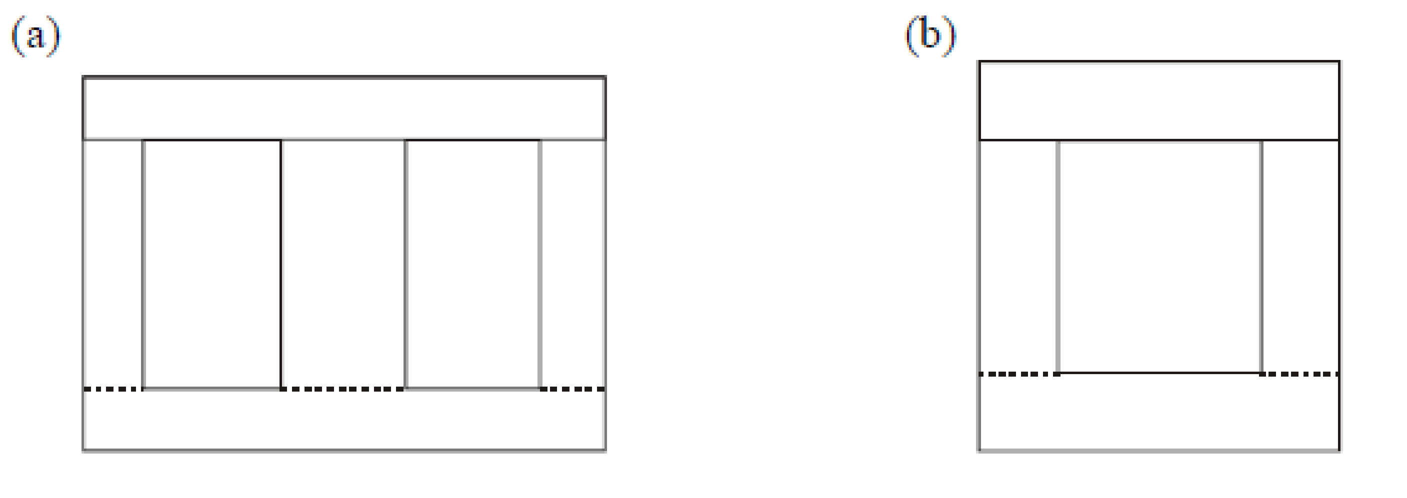
Note:

High voltage conductors are smaller cross section conductors than the low voltage coils

Lamination Shapes of Transformer



Construction of transformer from stampings



(a) Shell-type transformer, (b) core-type transformer

Core type

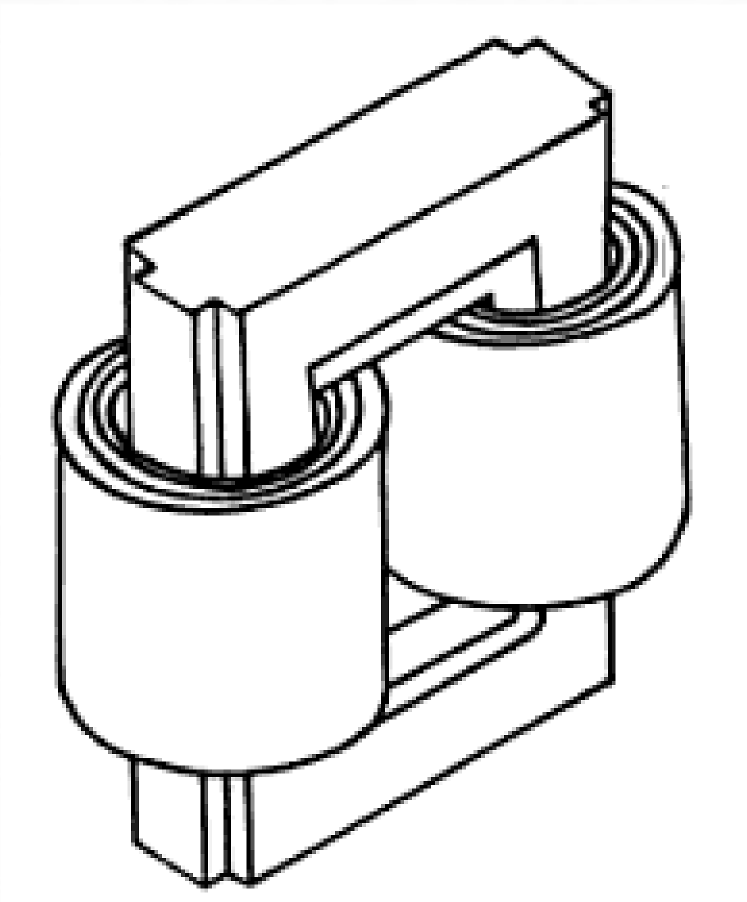


Fig1: Coil and laminations of core type transformer

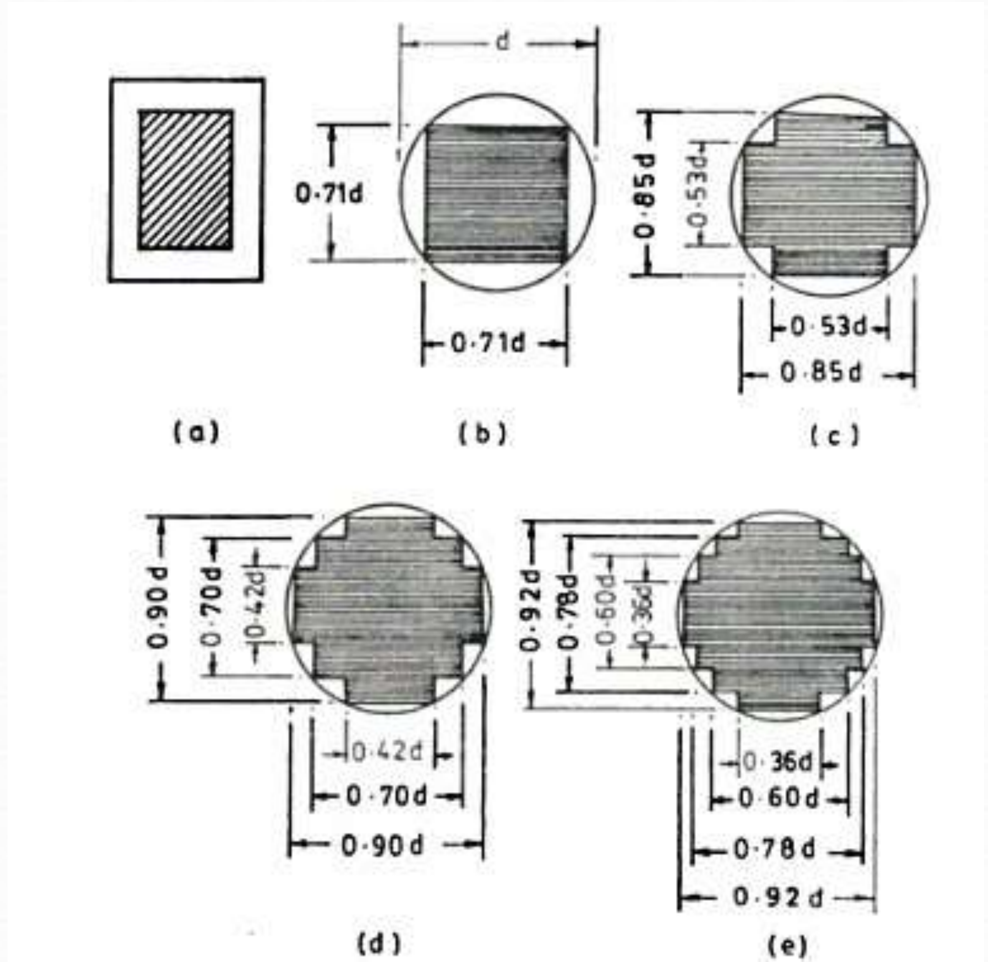


Fig2: Various types of cores

Shell type

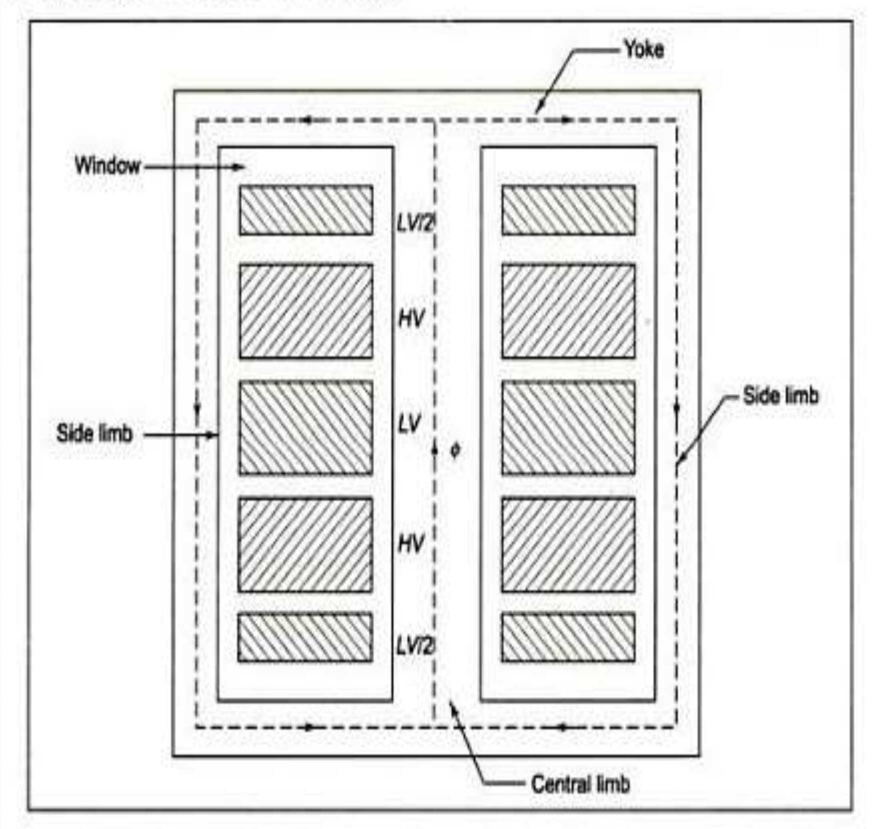


Fig: Sandwich windings

- The HV and LV windings are split into no. of sections
- Where HV winding lies between two LV windings
- In sandwich coils leakage can be controlled

Basis for Comparison	Core Type Transformer	Shell Type Transformer
Definition	The winding surround the core.	The core surround the winding.
Lamination Shape	The lamination is cut in the form of the L strips.	Lamination are cut in the form of the long strips of E and L.
Cross Section	Cross-section may be square, cruciform and three stepped	The cross section is rectangular in shape.
Copper Require	More	Less
Other Name	Concentric Winding or Cylindrical Winding.	Sandwich or Disc Winding

Cont...

Basis for Comparison	Core Type Transformer	Shell Type Transformer
Limb	Two	Three
Insulation	More	Less
Flux	The flux is equally distributed on the side limbs of the core.	Central limb carry the whole flux and side limbs carries the half of the flux.
Winding	The primary and secondary winding are placed on the side limbs.	Primary and secondary windings are placed on the central limb
Magnetic Circuit	Two	One

Cont...

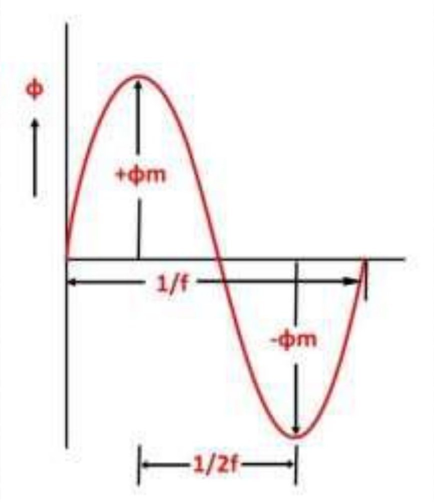
Basis for Comparison	Core Type Transformer	Shell Type Transformer
Losses	More	Less
Maintenance	Easy	Difficult
Mechanical Strength	Low	High
Output	Less	High
Natural Cooling	Does not Exist	Exist

EMF equation of a transformer

Let

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

As shown in the above figure that the flux changes from $+\phi_m$ to $-\phi_m$ in half a cycle of 1/2f seconds.



By Faraday's Law

Let E_1 is the emf induced in the primary winding

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

Where $\Psi = N_1\varphi$

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

Since φ is due to AC supply $\varphi = \varphi_m$ Sinwt

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

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

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

So the induced emf lags flux by 90 degrees.

Maximum valve of emf

$$E_1 max = N_1 w \varphi_m \dots\dots\dots (4)$$

But w = 2πf

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

Root mean square RMS value is

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

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

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

For a sinusoidal wave

$$\frac{\text{R.M.S value}}{\text{Average value}} = \text{Form factor} = 1.11$$

$$E_1 = 4.44 f N_1 \varphi_m \text{ ... ... (8)}$$

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

Or

$$E_2 = 4.44 f N_2 \varphi_m \text{ ... ... (9)}$$

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

Or

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

Ideal Transformers

- **Zero leakage flux:**

  -Fluxes produced by the primary and secondary currents are confined within the core

- **The windings have no resistance:**

  - Induced voltages equal applied voltages

- **The core has infinite permeability**

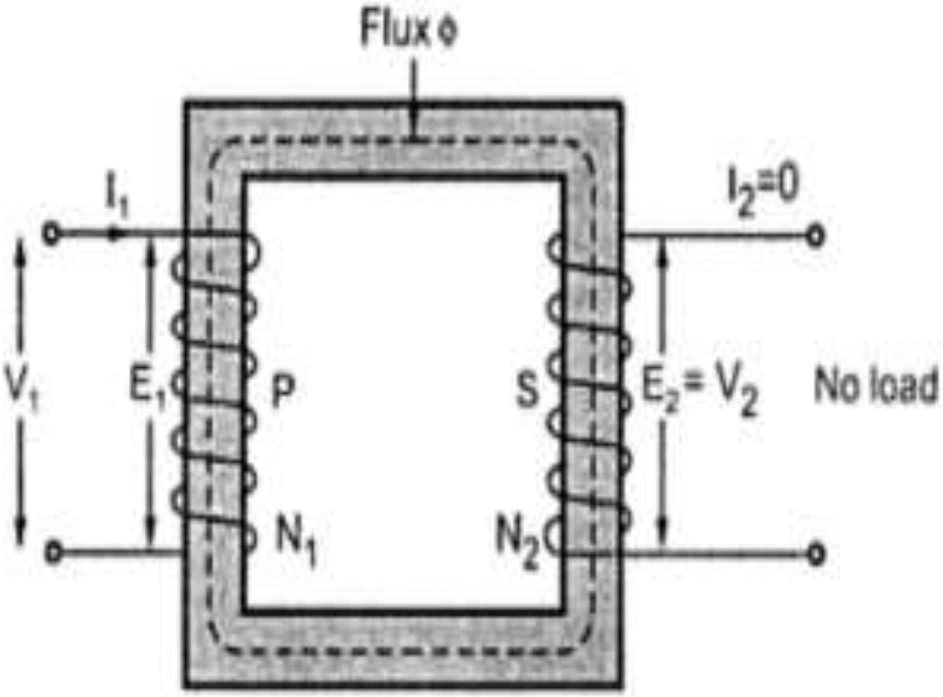
  - Reluctance of the core is zero

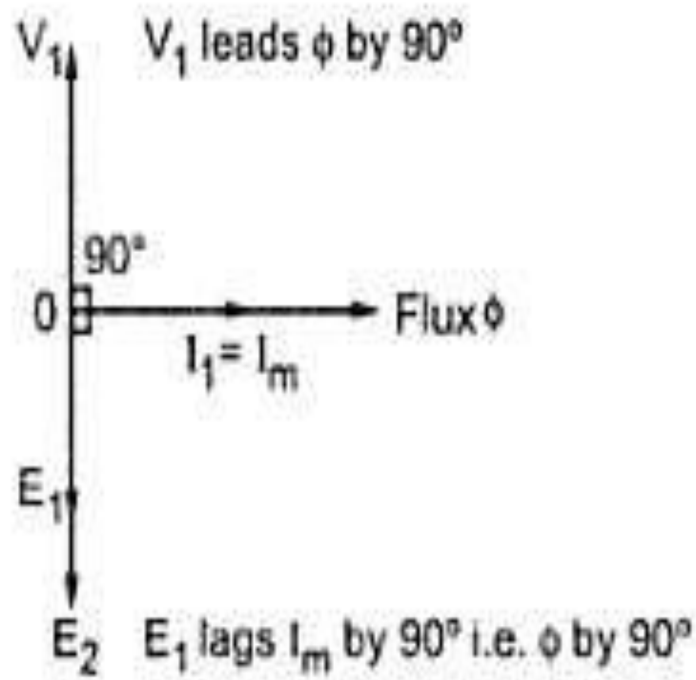
  - Negligible current is required to establish magnetic flux

- **Loss-less magnetic core**

  - No hysteresis or eddy currents

Ideal transformer





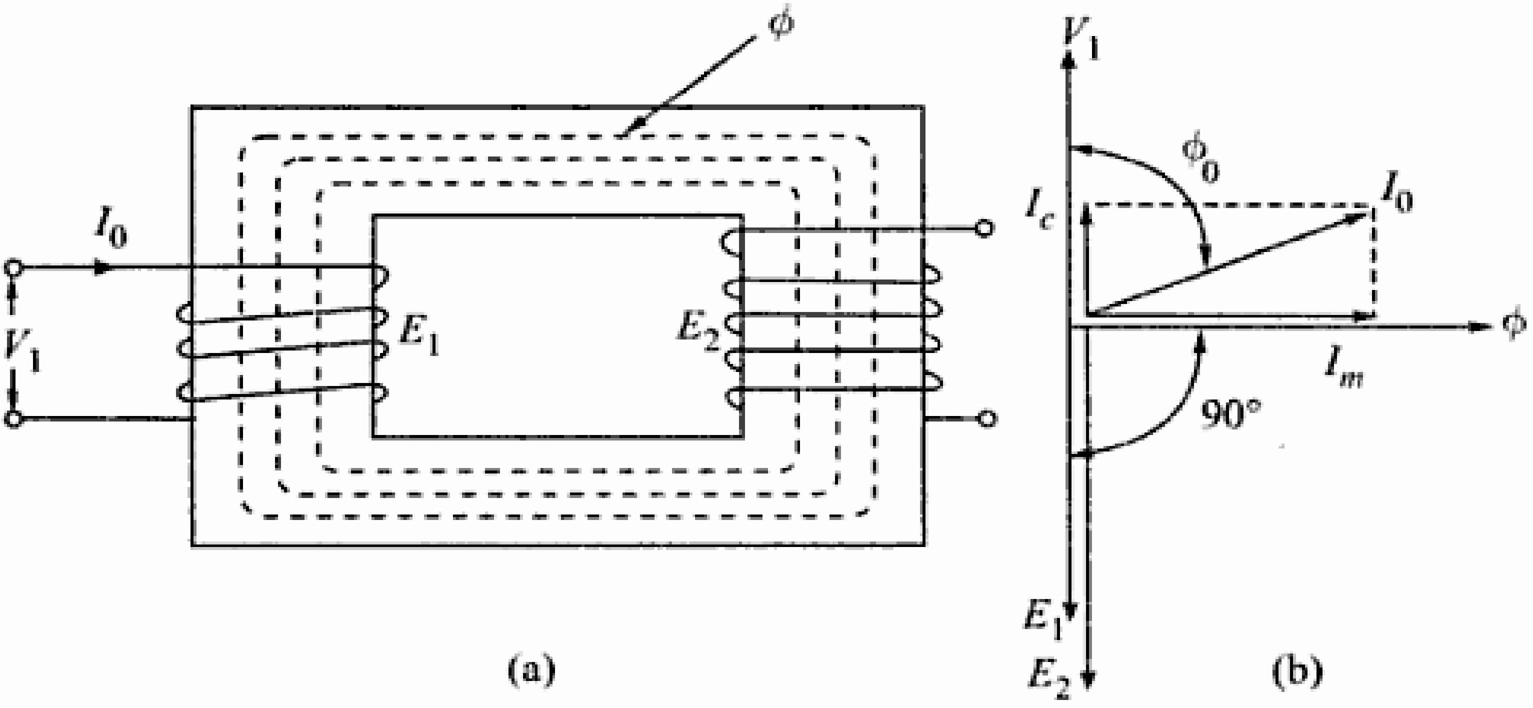
V_1 – supply voltage ; I_1- noload input current ;

V_2- output voltgae; I_2- output current

I_m- magnetising current;

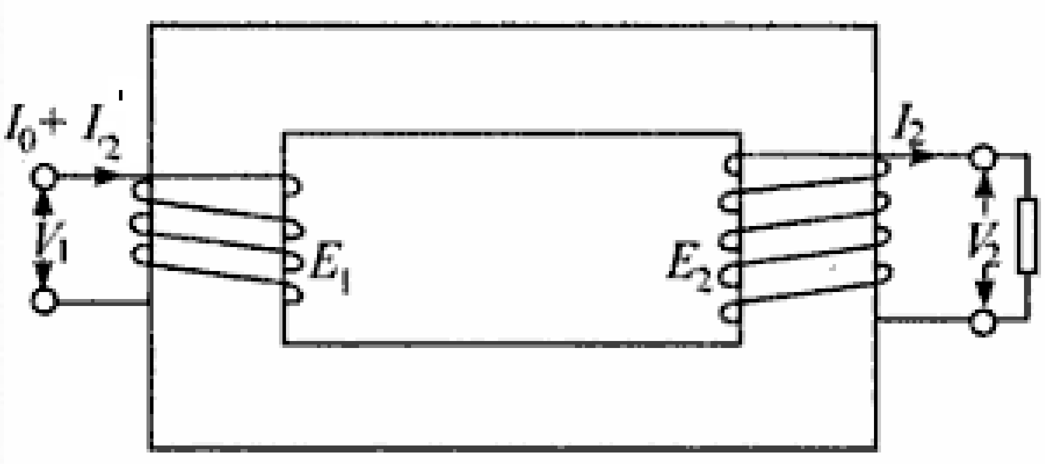
E_1-self induced emf ; E_2- mutually induced emf

Phasor diagram: Transformer on No-load



(a) Transformer on no-load (b) Phasor diagram of a transformer on no-load

Transformer on load assuming no voltage drop in the winding



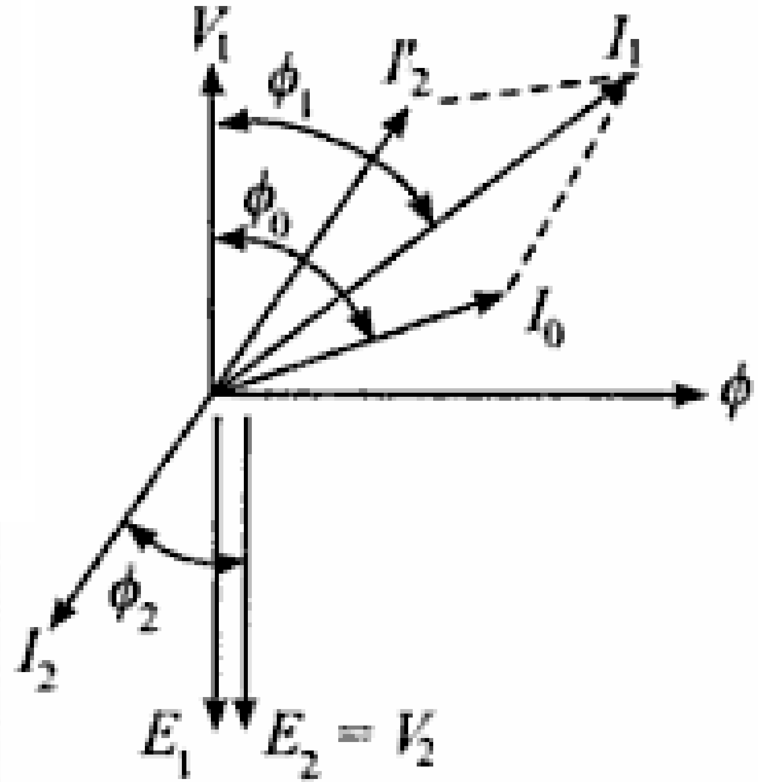


Fig shows the Phasor diagram of a transformer on load by assuming

1. No voltage drop in the winding
2. Equal no. of primary and secondary turns

Transformer on load

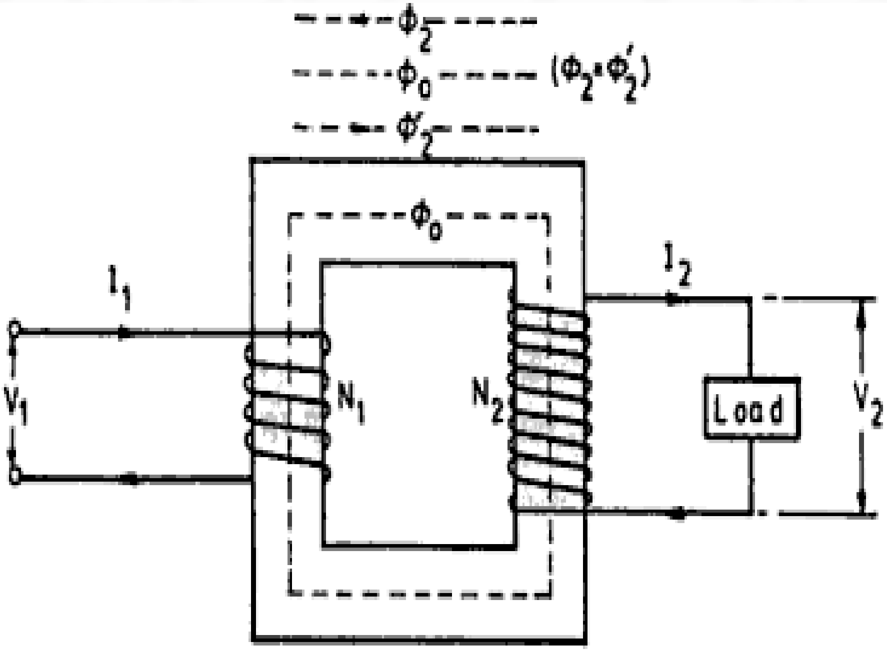


Fig. a: Ideal transformer on load

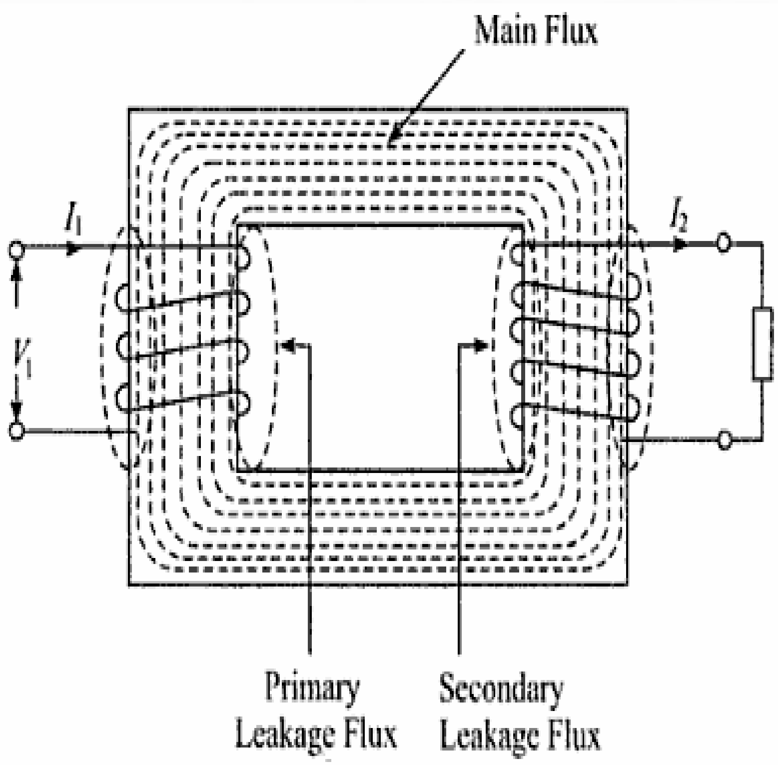
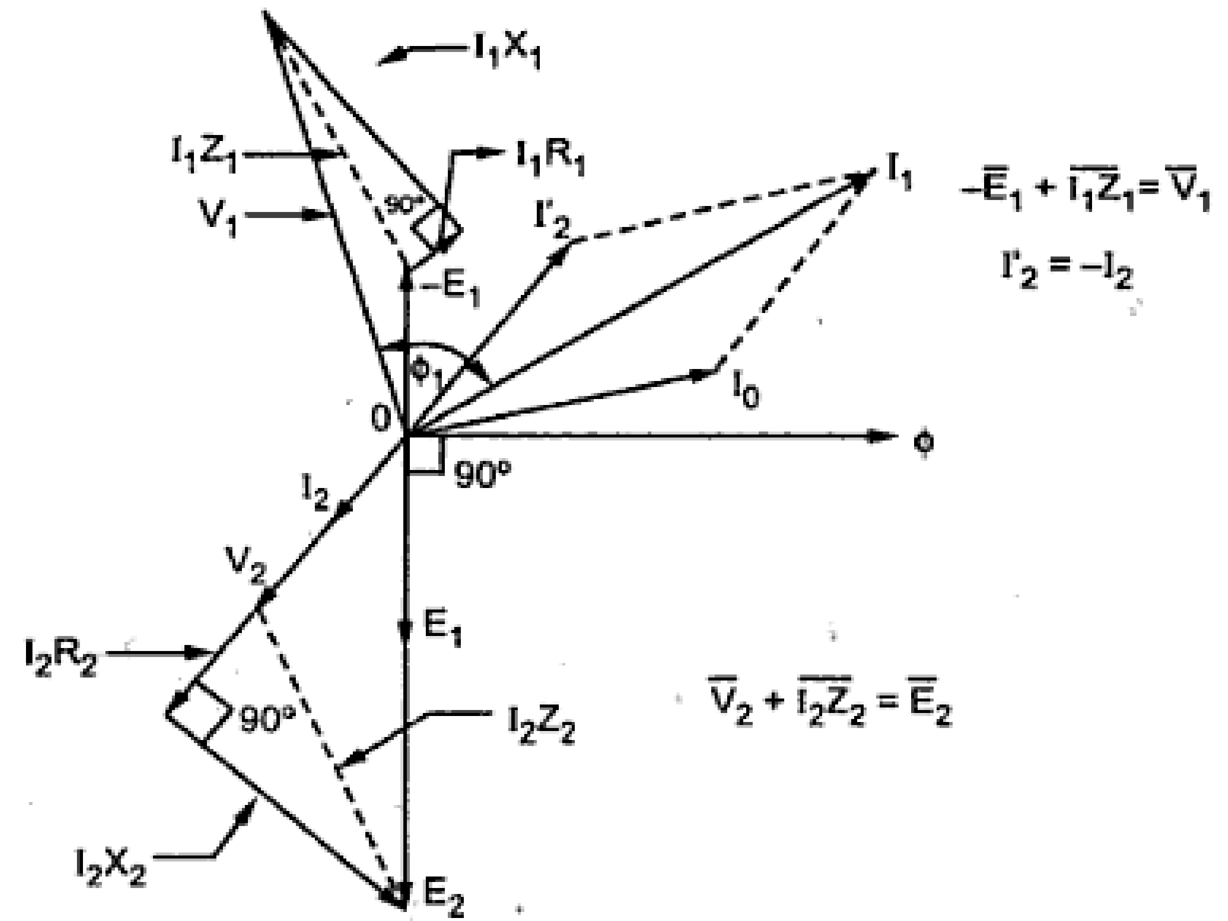
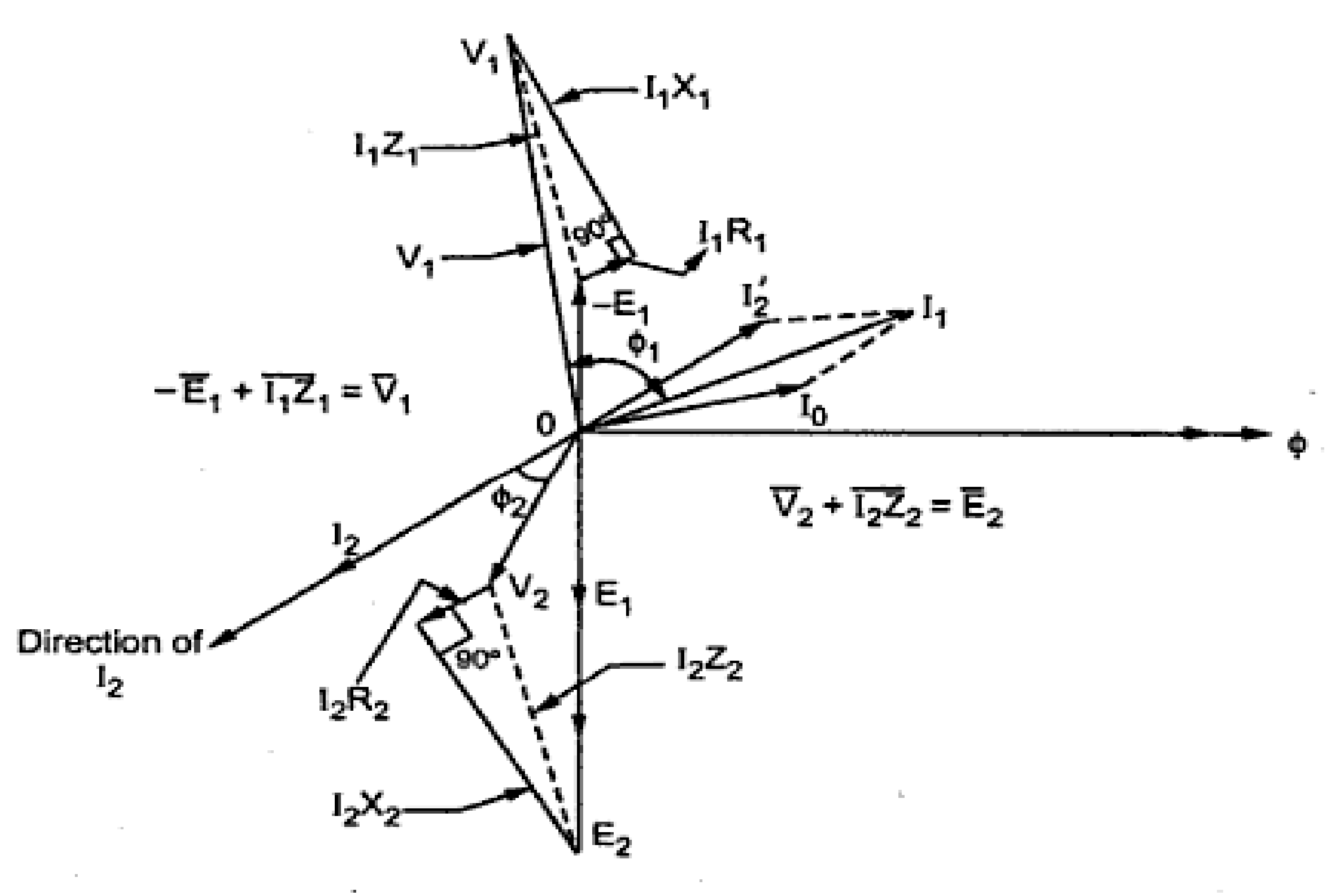


Fig. b: Main flux and leakage flux in a transformer

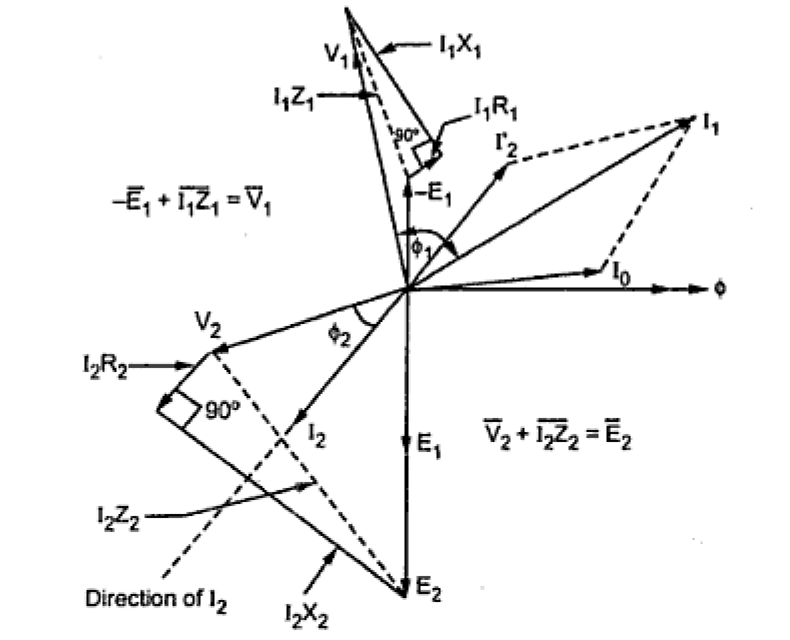
Phasor diagram of transformer with UPF load



Phasor diagram of transformer with lagging p.f load

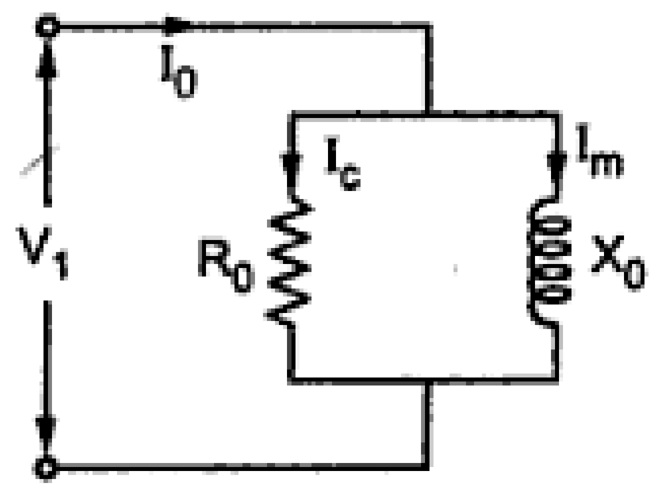


Phasor diagram of transformer with leading p.f load



Equivalent circuit of a transformer

No load equivalent circuit:



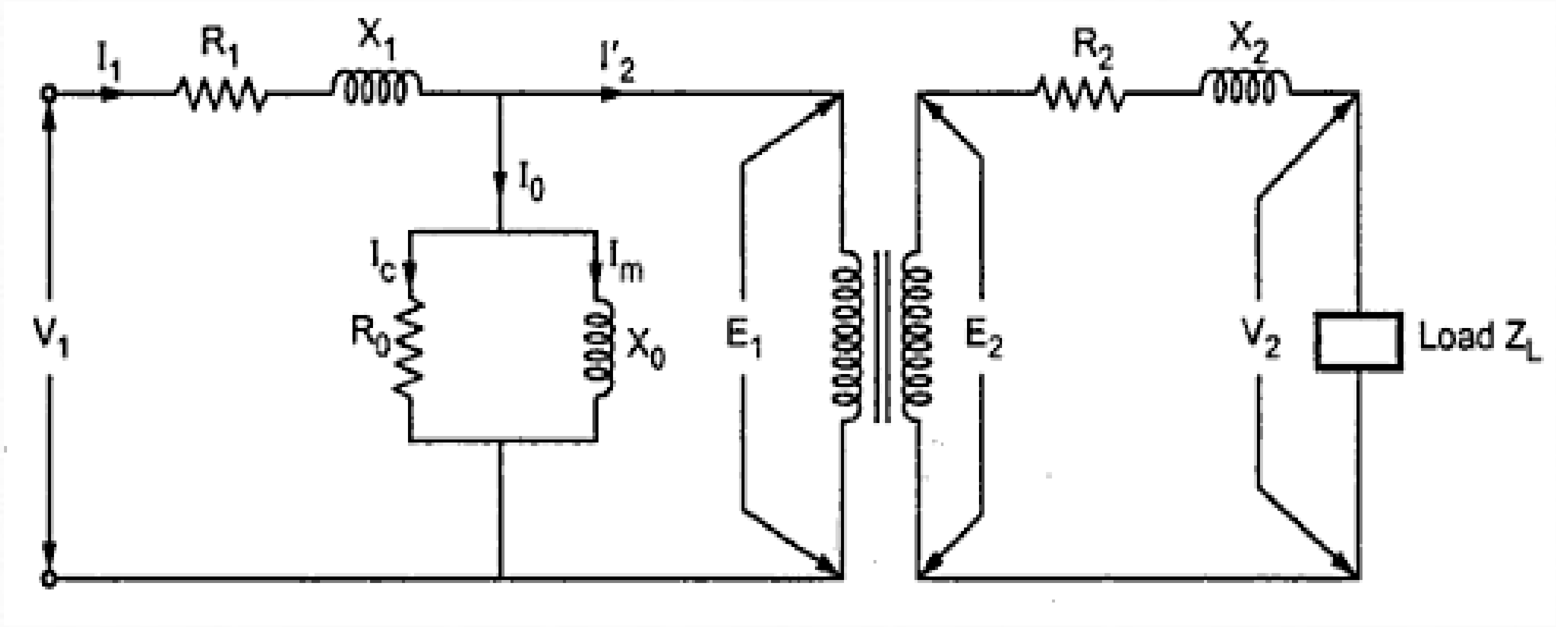
$$R_0 = \frac{V_1}{I_c}$$

$$X_0 = \frac{V_1}{I_m}$$

$I_m = I_0 \sin \phi_0$ = Magnetising component

$I_c = I_0 \cos \phi_0$ = Active component

Equivalent circuit parameters referred to primary and secondary sides respectively



Contd.,

- The effect of circuit parameters shouldn't be changed while transferring the parameters from one side to another side
- It can be proved that a resistance of R_2 in sec. is equivalent to R_2/k^2 will be denoted as R_2'(ie. Equivalent sec. resistance w.r.t primary) which would have caused the same loss as R_2 in secondary,

$$I_1^2 R_2' = I_2^2 R_2$$

$$R_2' = \left(\frac{I_2}{I_1}\right)^2 R_2$$

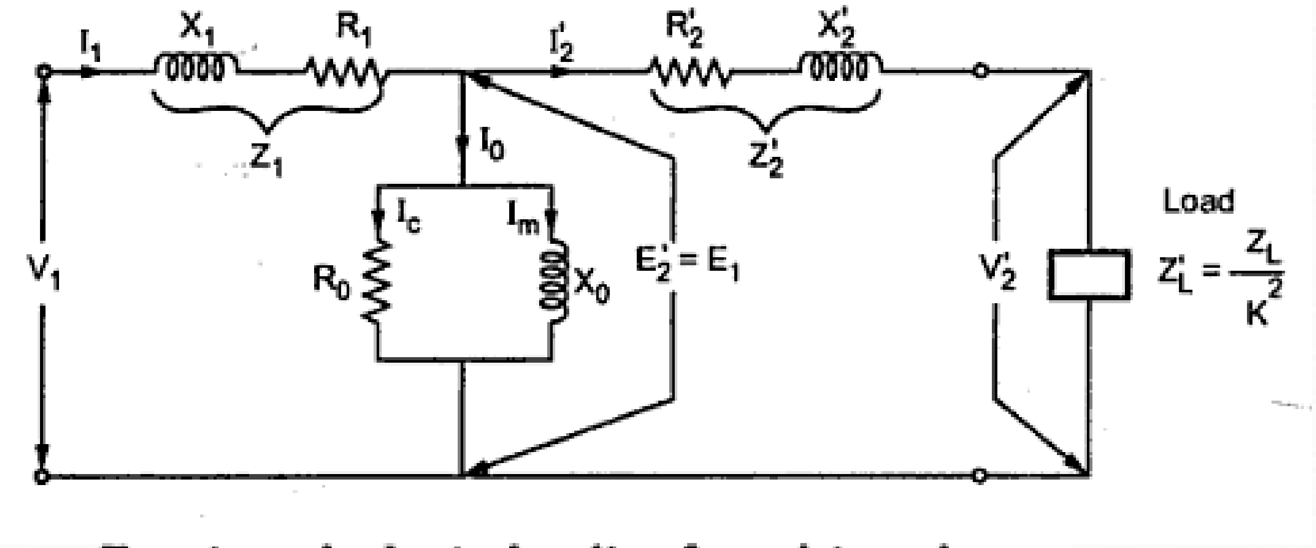
$$= \frac{R_2}{k^2}$$

Transferring secondary parameters to primary side

$$R_2' = \frac{R_2}{K^2}, \quad X_2' = \frac{X_2}{K^2}, \quad Z_2' = \frac{Z_2}{K^2}$$

While $E_2' = \frac{E_2}{K}, \quad I_2' = KI_2$

where $K = \frac{N_2}{N_1}$



Exact equivalent circuit referred to primary

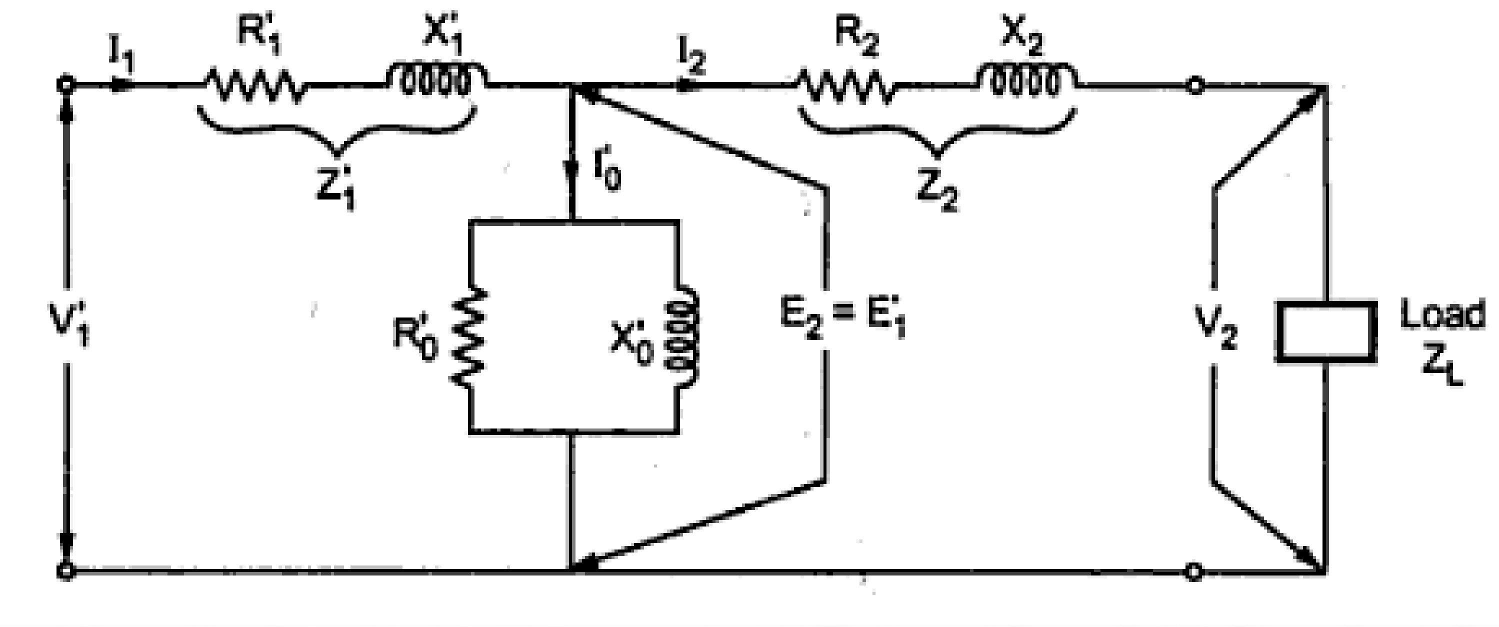
Equivalent circuit referred to secondary side

•Transferring primary side parameters to secondary side

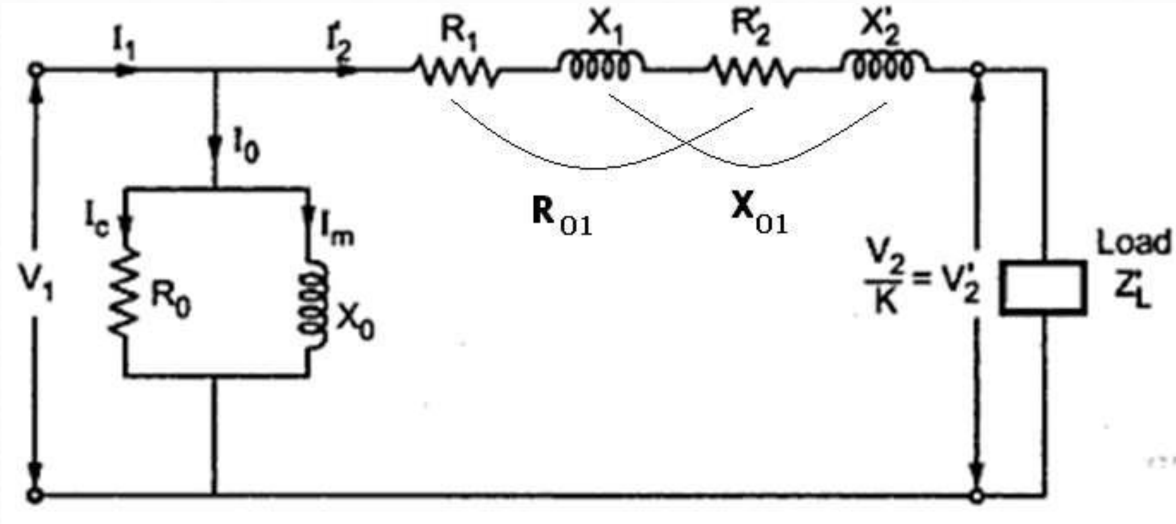
$$R_1' = K^2 R_1, \quad X_1' = K^2 X_1, \quad Z_1' = K^2 Z_1$$

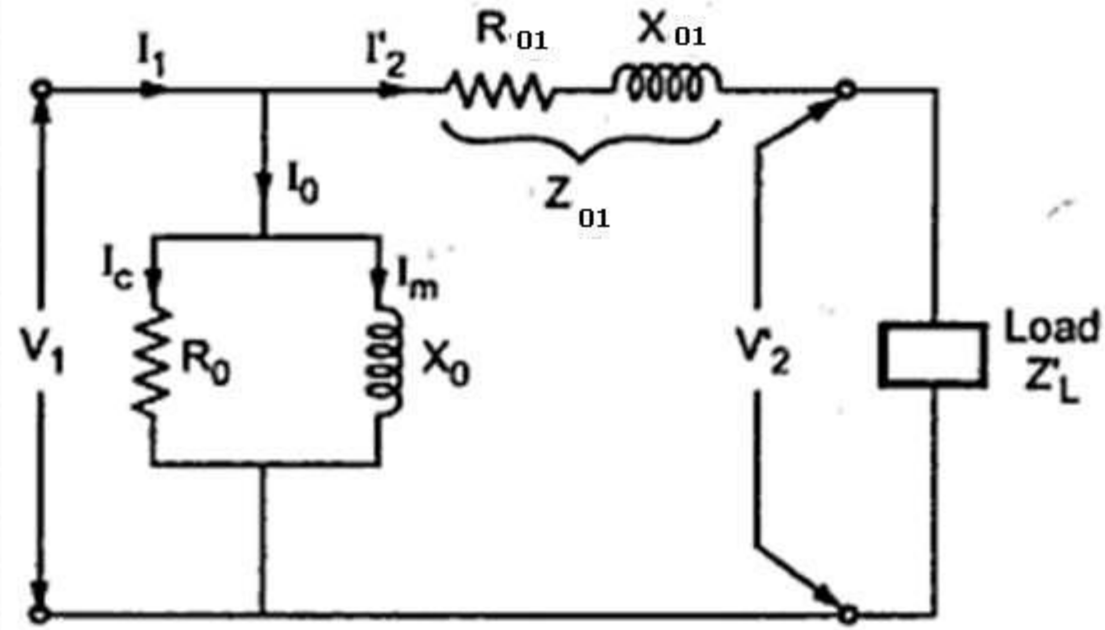
$$E_1' = K E_1, \quad I_1' = \frac{I_1}{K}, \quad I_0' = \frac{I_0}{K}$$

Similarly exciting circuit parameters are also transferred to secondary as R_o' and X_o'



Equivalent circuit w.r.t primary





where

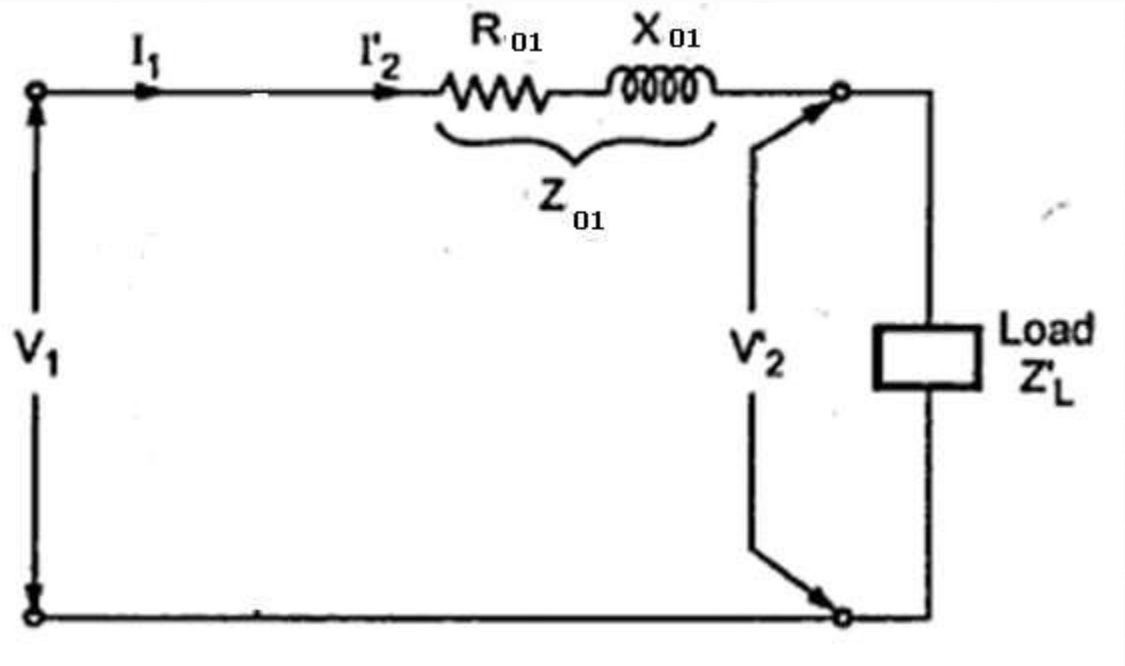
$$R_{01} = R_1 + R_2' = R_1 + \frac{R_2}{K^2}$$

$$X_{01} = X_1 + X_2' = X_1 + \frac{X_2}{K^2}$$

$$Z_{01} = R_{01} + j\,X_{01}$$

Approximate equivalent circuit

- Since the noload current is 1% of the full load current, the nolad circuit can be neglected



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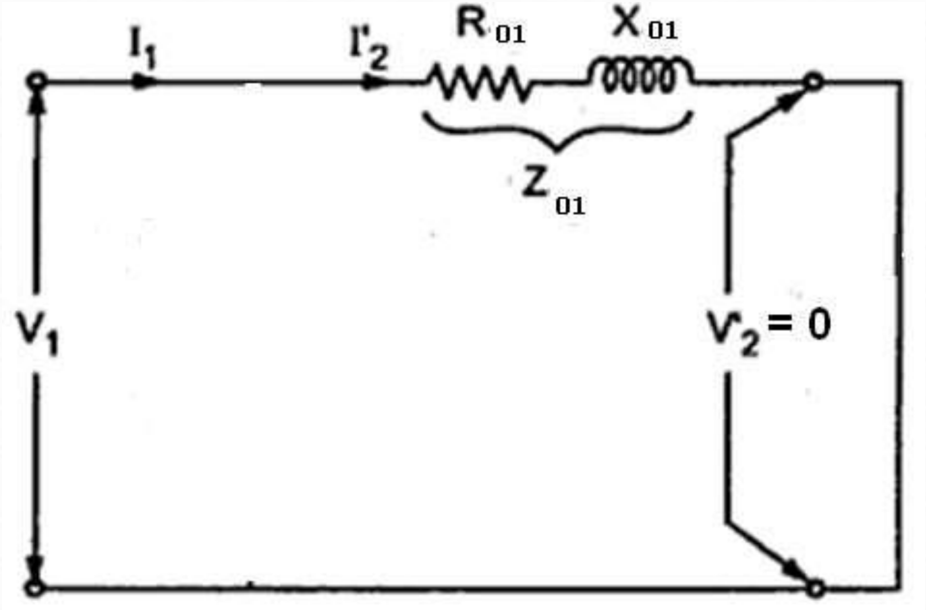


$$\text{Full load cu loss} = W_{sc} = I_{sc}^2 R_{01}$$

$$R_{01} = \frac{W_{sc}}{I_{sc}^2}$$

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

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

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

Transformer Voltage Regulation and Efficiency

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:

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

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

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

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

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

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 $V_2 = V_1\left(\dfrac{N_2}{N_1}\right)$

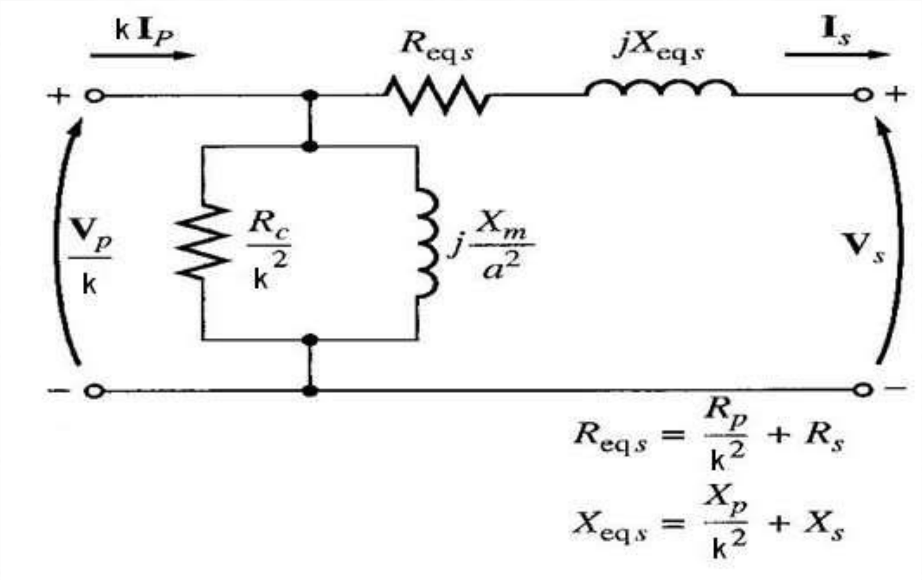
V_2 is a secondary terminal voltage on full load

Substitute we have

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

Transformer Phasor Diagram

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



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.

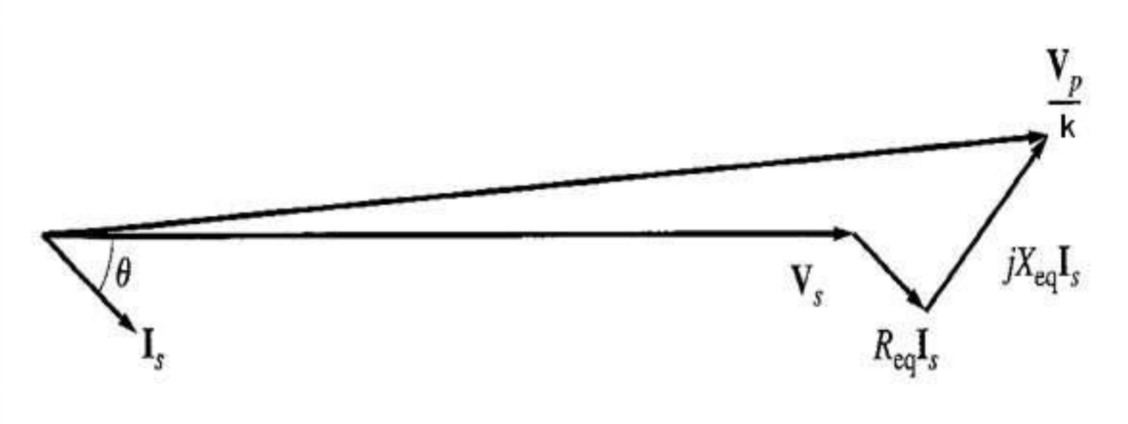
Assume that the reference phasor is the secondary voltage, V_S. Therefore the reference phasor will have 0 degrees in terms of angle.

Based upon the equivalent circuit, apply Kirchoff Voltage Law,

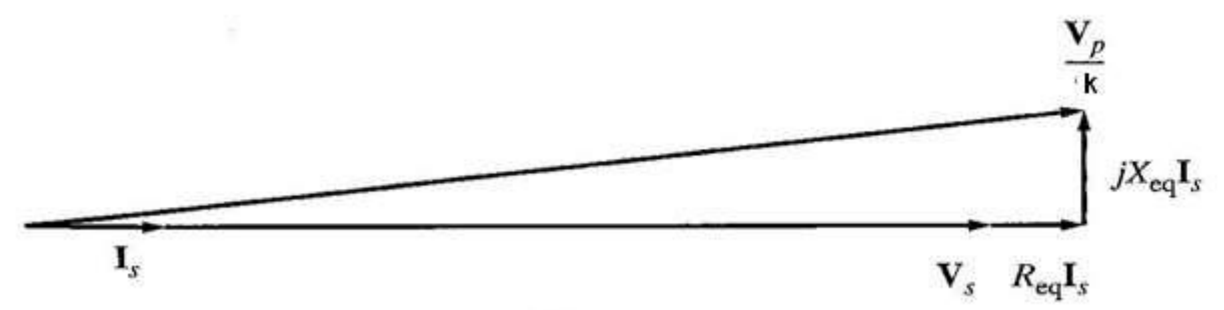
$$\frac{V_P}{k} = V_S + R_{eq} I_S + jX_{eq} I_S$$

Transformer Phasor Diagram

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



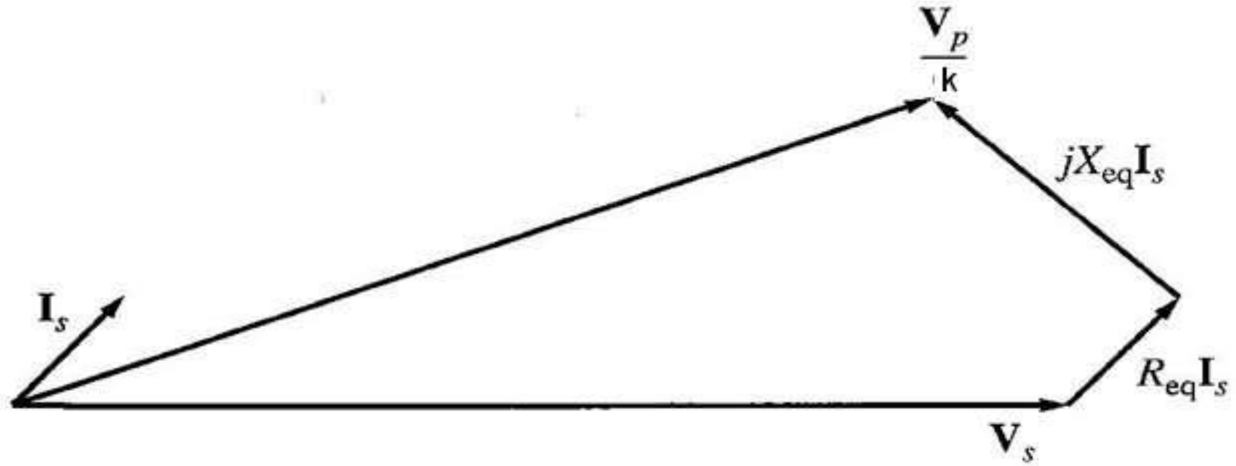
When the power factor is unity, V_S is lower than V_P so VR > 0.



(a)

Transformer Phasor Diagram

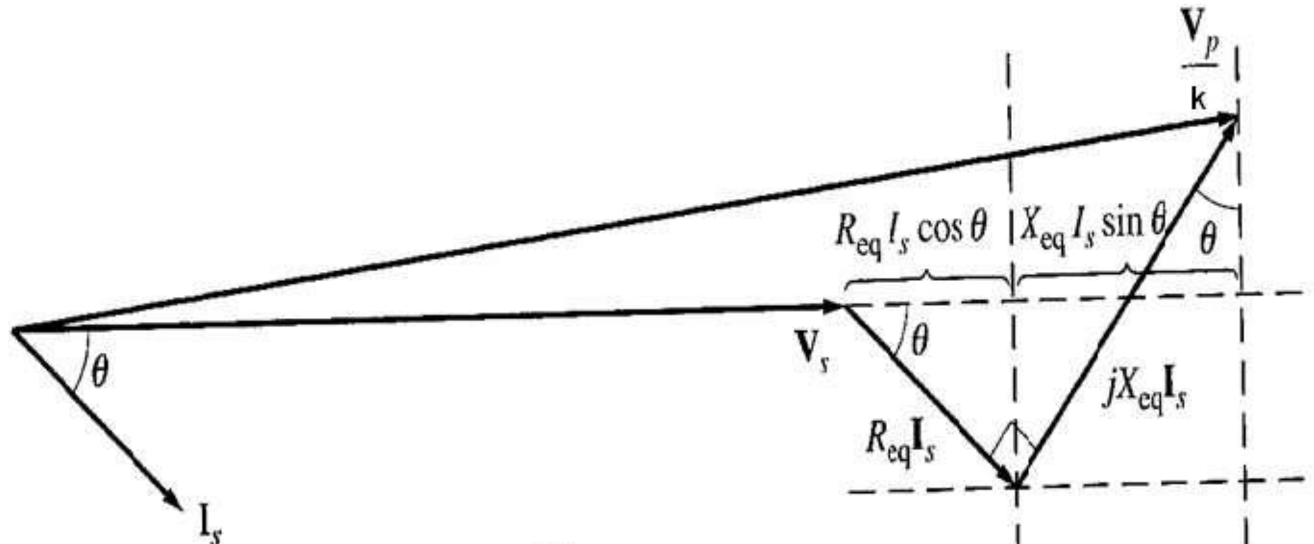
With a leading power factor, V_S is higher than the referred V_P so VR < 0



(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 va lues

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

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

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:

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

Condition for maximum efficiency

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

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

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 $= \text{Full load} \times \sqrt{\left(\frac{\text{Iron loss}}{\text{F.L. Cu loss}}\right)}$

All day efficiency

$$\text{ordinary commercial efficiency} = \frac{\text{out put in watts}}{\text{input in watts}}$$

$$\eta_{all\,\text{day}} = \frac{\text{output in kWh}}{\text{Input in kWh}}(\,for\ 24\ \text{hours})$$

- All day efficiency is always less than the commercial efficiency

APPLICATION AND USES

- The transformer used in television and photocopy machines
- The transmission and distribution of alternating power is possible by transformer
- Simple camera flash uses fly back transformer
- Signal and audio transformer are used couple in amplifier

Unit-5

Testing of Single Phase Transformer, Autotransformer and Poly phase Transformers

Testing of Transformers

We will discuss the following test in this chapter

1. Open Circuit Test
2. Short Circuit Test
3. Sumpner’s Test

Purpose of Testing

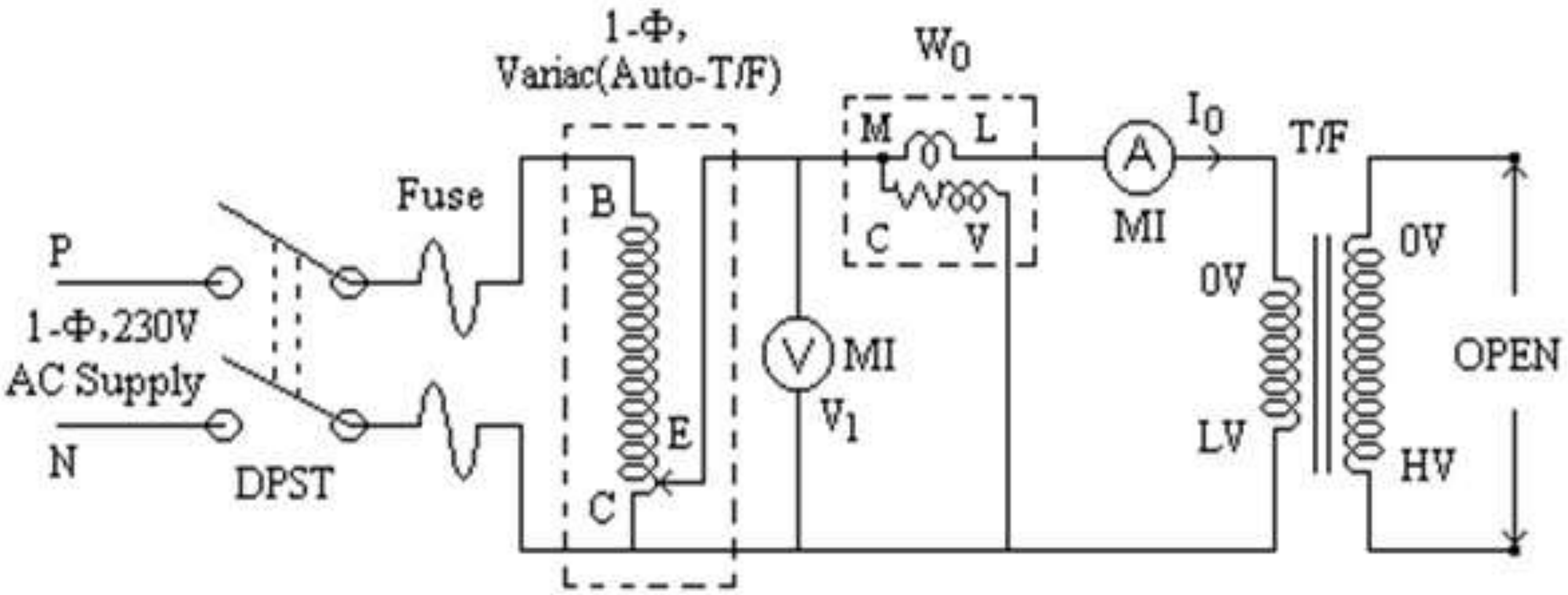
To Find

1. Equivalent Circuit Parameters
2. Losses
3. Efficiency
4. Regulation

Open Circuit Test

Purpose : To Find the Core Losses.

Circuit Diagram



Apparatus Required

1. 1-Φ Transformer
2. Voltmeter (MI)
3. Ammeter (MI)
4. Wattmeter (LPF)
5. 1-Φ Variac

Procedure for O.C test

- Connections are made as per the circuit diagram, and HV terminals are open for O.C test.
- Initially set the variac to zero output and switch ON the supply, by closing DPST.
- Increase the variac output voltage gradually till the rated voltage is reached. With rated voltage applied to the primary side, the readings of the voltmeter, wattmeter and ammeters are noted down in the tabular form as shown below.
- Calculate R_0 and X_0 from these readings.

Observations of O.C test

S.No	Voltage (V_1) Volts	Current (I_0) Amps	Power (W_0) Watts

Calculations of O.C test

$V_1 I_0 \cos\Phi_0 = W_0$

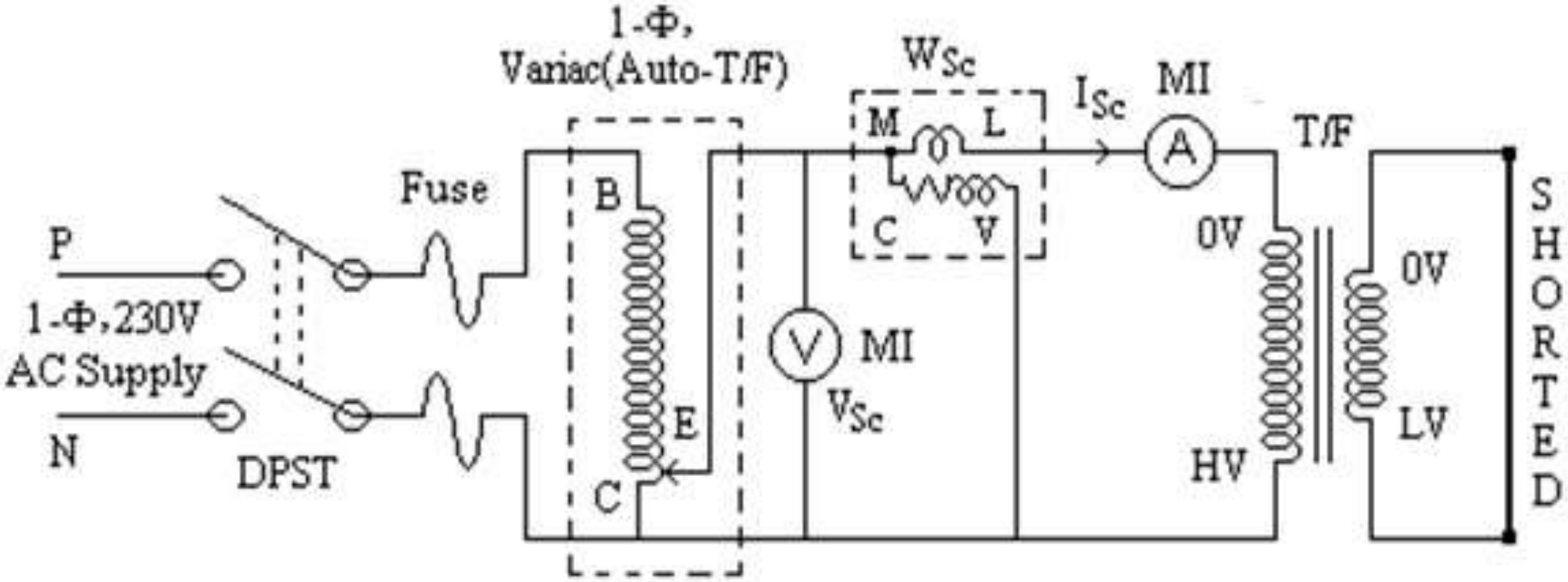
$I_w = I_0 \cos\Phi_0$ $I_\mu = I_0 \sin\Phi_0$ $X_0 = V_1/I_\mu$ & $R_0 = V_1/I_w$

.

Short Circuit Test

Purpose : To Find the Copper Losses.

Circuit Diagram



Apparatus Required

1. 1-Φ Transformer
2. Voltmeter (MI)
3. Ammeter (MI)
4. Wattmeter (UPF)
5. 1-Φ Variac

Procedure for S.C test

- Connections are made as per the above circuit diagram, and LV side terminals are shorted for S.C test.
- Initially set the variac to zero output and switch ON the supply by closing DPST.
- Slowly apply a low voltage with the help of the variac which circulates the rated current in the circuit, which is read by the ammeter.
- The readings of the voltmeter, wattmeter and the ammeters are noted down in the tabular form as shown below.
- Calculate the total resistance (R_{02}) and reactance (X_{02}) from these readings.

Observations of S.C test

S.No	Voltage (V_1) Volts	Current (I_{sc}) Amps	Power (Wsc) Watts

Calculations of O.C test

$$W_{Sc} = V_{Sc} I_{Sc} \cos\Phi_{Sc} \qquad \therefore \cos\Phi_{Sc} = \frac{W_{Sc}}{V_{Sc} I_{Sc}}$$

$$Z_{02} = \frac{V_{Sc}}{I_{Sc}} \quad ; \qquad Z_{01} = \frac{Z_{02}}{K^2}$$

•

$$W_{Sc}^2 = I_{Sc}^2 R_{02} \quad \therefore R_{02} = \frac{W_{Sc}}{I_{Sc}^2} \quad ; \qquad R_{01} = \frac{R_{02}}{K^2} \qquad \text{Where} \quad K = \frac{H.V}{L.V}$$

$$\therefore X_{02} = \sqrt{Z_{02}^2 - R_{02}^2} \qquad X_{01} = \sqrt{Z_{01}^2 - R_{01}^2}$$

Drawbacks of OC & SC Test

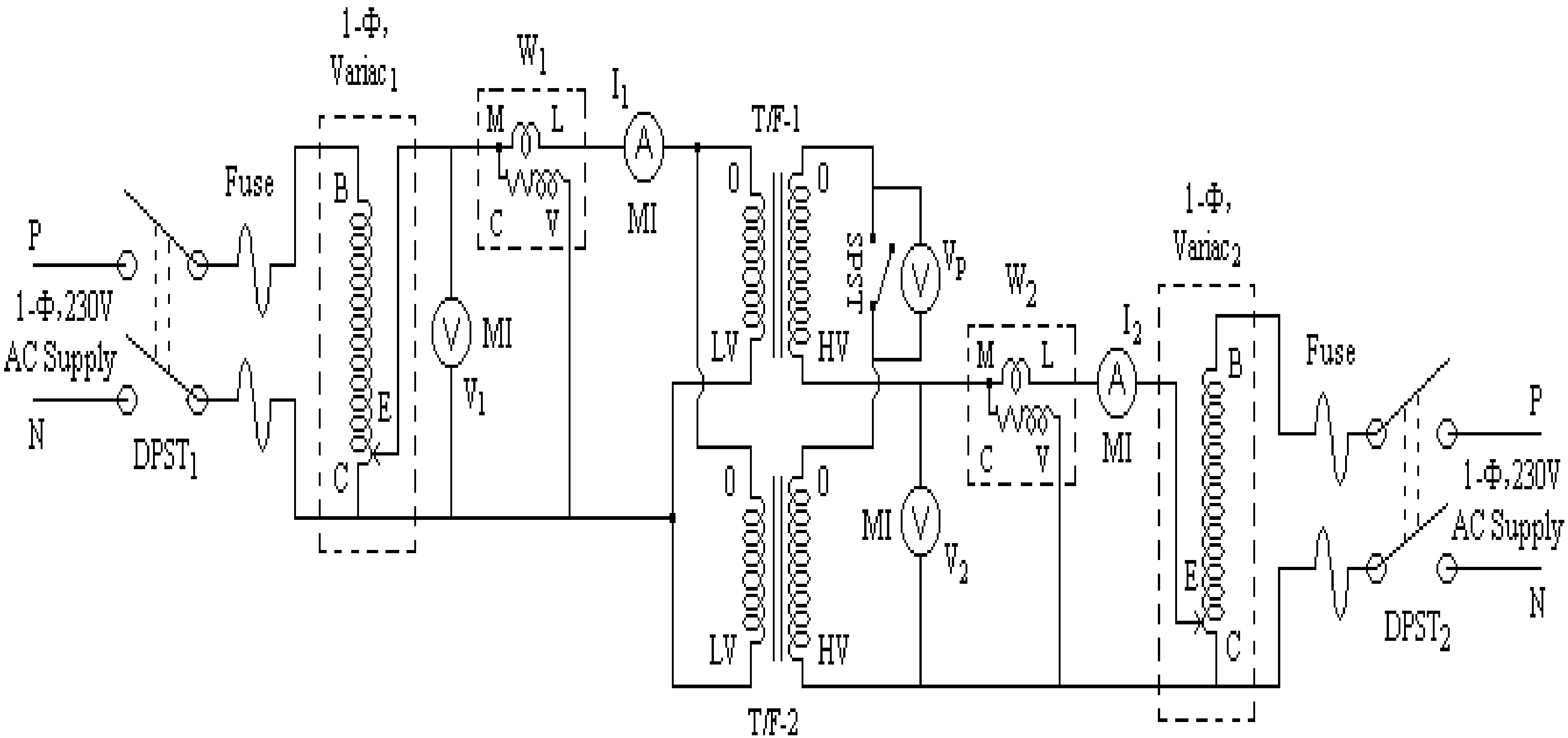
- In O.C. test, there is no load on the transformer while in S.C. circuit test only fractional load gets applied. In all O.C. and S.C. tests, the loading conditions are absent. Hence the results are inaccurate.
- In open and short circuit test iron losses and copper losses are determined separately but in actual use both losses occurs simultaneously.
- The temperature rise in the transformer is due to total loss that occurs simultaneously during actual use, it cant be determined by
  O.C and S.C tests.

Sumpner's Test

- The Sumpner's test (back to back test) is the very practical, convenient, efficient and minimum power consumption test which is done without actual loading to find regulation and efficiency of large power transformer.

- The Sumpner's test (back to back test) is the very practical, convenient, efficient and minimum power consumption test which is done without actual loading to find regulation and efficiency of large power transformer.

Circuit diagram of Sampner's test :



Procedure:

1. Connections are made as shown in fig (1).Initially open $DPST_2$ & SPST, keep both I-ϕ variacs at zero volts o/p position and close $DPST_1$.Increase the o/p voltage of $variac_1$ so that rated voltage is applied across LV windings of both transformers.
2. Check for the polarity of the Transformer secondary i.e. V_p must read zero volts . If the paralleling voltmeter V_p in the secondary is not showing zero reading, the terminals of either primary or secondary must be interchanged after opening $DPST_1$. Then V_1, I_1 & W_1 are noted.
3. Now close SPST & $DPST_2$.Slowly increase the o/p of $variac_2$ such that rated current I_2 flows through HV winding. Then I_2 & W_2 are noted.

Thus the following readings of all meters are noted:

$W_1 = 2P_i$ where P_i = Iron losses of each transformer

$W_2 = 2P_{SC}$ where P_{SC} = Copper losses of each transformer

8. Total losses of each Transformer

$$= \frac{W_1 + W_2}{2} \text{ at full load}$$

Let x be the fraction of full load, Then total losses at x times full load $= P_i + x^2 P_{Sc}$

Output at x times full load $= x \times$ full load output $= x \times$ F.L.O/P

9. Then η is calculated using the formula. $$\% \eta = \frac{O/p}{O/p + Total Losses} \times 100$$

Tabular form

Sl No	V_1 Volts	V_2 Volts	I_1 Amps	I_2 Amps	W_1 Watts	W_2 Watts	$P_i = \frac{W_1}{2}$ Watts	$P_{Sc} = \frac{W_2}{2}$ Watts	Total Losses $P_i + x^2 P_{Sc}$ Watts	O/P = $x \times$ F.L.O/P Watts	I/P = o/p + Total losses Watts	% η
1.												
2.												

Advantages

- The power required to carry out the test is small.
- The transformers are tested at full-load conditions.
- As the test results gives the value of core and copper losses occurring simultaneously so heat run test can be conducted on two transformers.
- The secondary current(i.e I2) can be varied to any value using regulating transformer. Hence we can determine the copper losses at full load condition or at any load.

Drawbacks

- Only limitation is that two identical transformers are required. In practice exact identical transformers cannot be obtained and as two transformers are required, the test is not economical.

Conclusion

- In many electrical machines its seen that sumpner's test or back to back test is done in one or other way. As it is important to test every electrical machines at its rated capacity and its inconvenient for machines of large rating to actually fully load the equipment's and test. So for all electrical machines some form of back to back test becomes important.

Parallel Operation of a Transformer

Reasons/Advantages of Parallel Operation

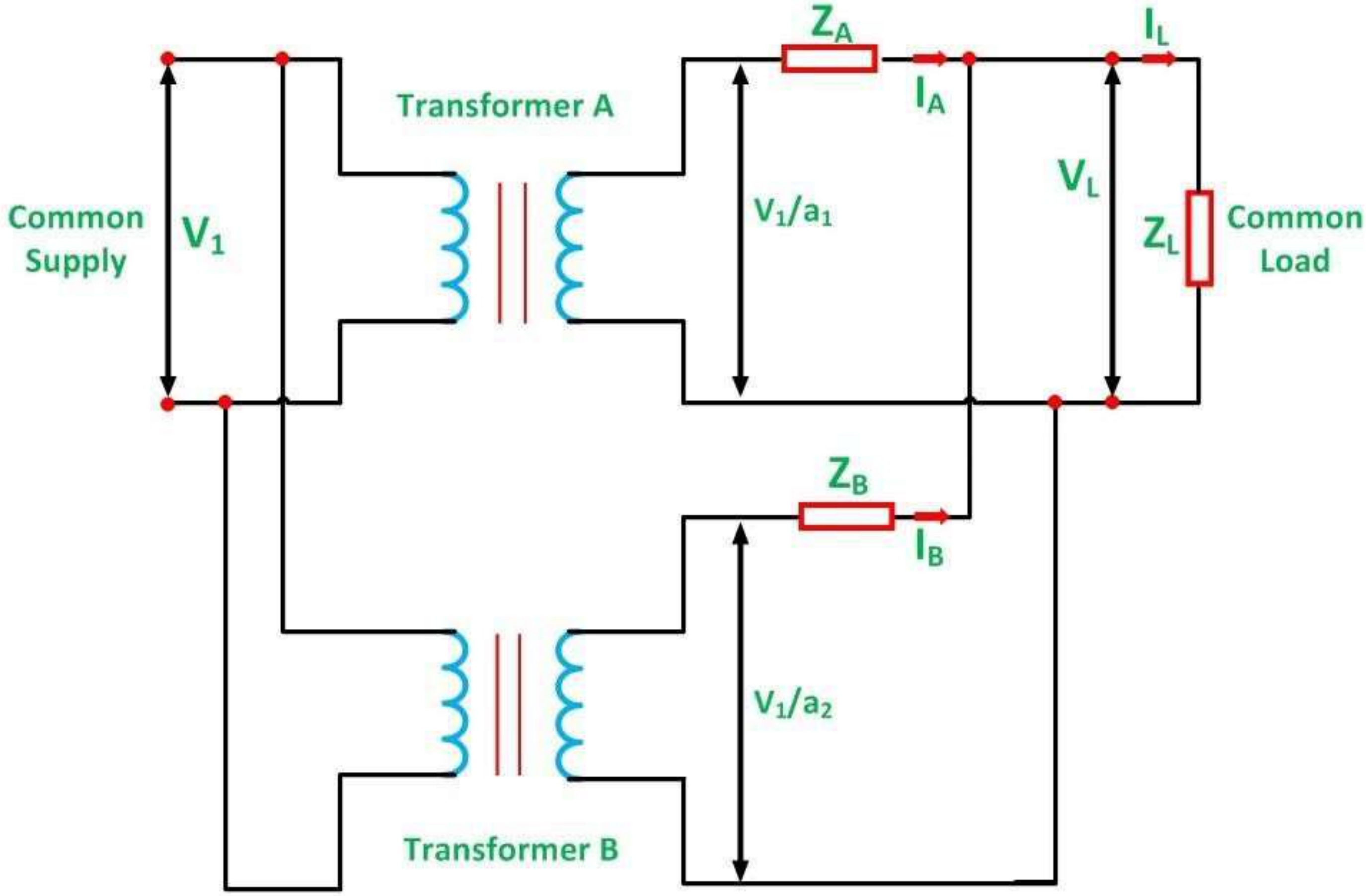
- It is impractical and uneconomical to have a single large transformer for heavy and large loads. Hence, it will be a wise decision to connect a number of transformers in parallel.
- In substations, the total load required may be supplied by an appropriate number of the transformer of standard size. As a result, this reduces the spare capacity of the substation.
- If the transformers are connected in parallel, so there will be scope in future, for expansion of a substation to supply a load beyond the capacity of the transformer already installed.
- If there will be any breakdown of a transformer in a system of transformers connected in parallel, there will be no interruption of power supply, for essential services.
- If any of the transformer from the system is taken out of service for its maintenance and inspection, the continuity of the supply will not get disturbed.

Necessary Conditions For Parallel Operation

- For the satisfactory parallel operation of the transformer, the two main conditions are necessary. One is that the **Polarities** of the transformers must be same. Another condition is that the **Turn Ratio** of the transformer should be equal.

The other two desirable conditions are as follows

- The voltage at full load across the transformer internal impedance should be equal.
- The ratio of their winding resistances to reactances should be equal for both the transformers. This condition ensures that both transformers operate at the same power factor, thus sharing their active power and reactive volt-amperes according to their ratings.



Transformer A
Common
Supply
V1
V1/a1
ZA
IA
IL
VL
ZL
Common
Load
ZB
IB
V1/a2
Transformer B

Let,

- a_1 is the turn ratio of the transformer A
  a_2 is the turn ratio of the transformer B
  Z_A is the equivalent impedance of the transformer A referred to secondary
  Z_B is the equivalent impedance of the transformer B referred to secondary
  Z_L is the load impedance across the secondary
  I_A is the current supplied to the load by the secondary of the transformer A
  I_B is the current supplied to the load by the secondary of the transformer B
  V_L is the secondary load voltage
  I_L is the load current

Applying Kirchhoff's Current Law

$$I_A + I_B = I_L \dots \dots \dots . (1)$$

By Kirchhoff's Voltage Law

$$V_L = \frac{V_1}{a_1} - I_A Z_A \dots \dots \dots . (2) \text{ and}$$

$$V_L = \frac{V_1}{a_2} - I_B Z_B \dots \dots \dots . (3)$$

Now putting the value of I_B from the equation (1) in equation (3) we will get

$$V_L = \frac{V_1}{a_2} - (I_L - I_A)\ Z_B \dots\dots\dots.(4)$$

Solving equations (2) and (4) we will get

$$I_A = \frac{Z_B I_L}{Z_A + Z_B} + \frac{V_1 (a_2 - a_1)}{a_1 a_2 (Z_A + Z_B)} \quad \dots\dots\dots (5)$$

$$I_B = \frac{Z_A I_L}{Z_A + Z_B} + \frac{V_1 (a_2 - a_1)}{a_1 a_2 (Z_A + Z_B)} \quad \dots\dots\dots (6)$$

- The current I_A and I_B has two components. The first component represents the transformers share of the load currents and the second component is a circulating current in the secondary windings of the single phase transformer.
- **The undesirable effects of the circulating currents are as follows**
- They increase the copper loss.
- The circulating current overload the one transformer and reduce the permissible load kVA.

- **Equal Voltage Ratio**
- In order to eliminate circulating currents, the voltage ratios must be identical. That is $a_1 = a_2$
- Under this condition,

$$I_A = \frac{Z_B I_L}{Z_A + Z_B} \quad \dots \dots \dots (7)$$

$$I_B = \frac{Z_A I_L}{Z_A + Z_B} \quad \dots \dots \dots (8)$$

Equating equation (7) and (8) we will get

$$\frac{I_A}{I_B} = \frac{Z_B}{Z_A} \quad \dots \dots \dots . (9)$$

$$I_A Z_A = I_B Z_B \dots \dots \dots (10)$$

Therefore, we know that

The total load in volt-ampere (VA) is

$$S_L = V_L I_L$$

The volt-ampere of transformer A is

$$S_A = V_L I_A$$

Similarly, the volt-ampere of transformer B is

$$S_B = V_L I_B$$

Hence, the various equations will be written as shown below

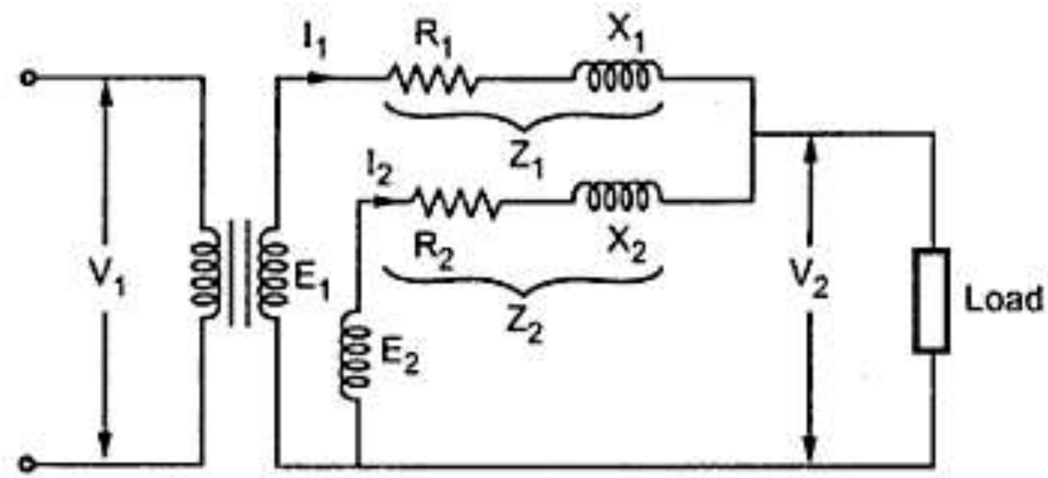
$$S_A = \frac{Z_B}{Z_A + Z_B} S_L \quad \ldots\ldots\ldots(11)$$

$$S_B = \frac{Z_A}{Z_A + Z_B} S_L \quad \ldots\ldots\ldots(12)$$

Equating the equation (11) and (12) we will get

$$\frac{S_A}{S_B} = \frac{Z_B}{Z_A} \quad \ldots\ldots\ldots(13)$$

Parallel Operation of Transformers with Unequal Voltage Ratios



Let us consider voltage ratio of transformer 1 is slightly more than 2. So that induced e.m.f.. E_1 is greater than E_2. Thus the resultant terminal voltage will be $E_1 - E_2$ which will cause a circulating current under no load condition.

$$I_c = (E_1 - E_2)/(Z_1 + Z_2)$$

From the circuit diagram we have,

$$E_1 = V_2 + I_1 Z_1$$

$$E_2 = V_2 + I_2 Z_2$$

Also, $I_L = I_1 + I_2$

$$V_2 = I_L Z_L = (I_I + I_2) Z_L$$

$$E_1 =(I_1 + I_2) Z_L + I_I Z_1 \quad ....(a)$$

$$E_2 =(I_1 + I_2) Z_L + I_2 Z_2 \quad ....(b)$$

Subtracting equations (a) and (b) we have,

$$E_1 - E_2 = I_1 Z_1 - I_2 Z_2$$

$$I_1 = \mathbf{(}(E_1 - E_2) + I_2 Z_2\mathbf{)} /Z_1$$

Subtracting this value in equation (b),

$$E_2 = I_2 Z_2 + \left[\left\{\frac{(E_1 - E_2) + I_2 Z_2}{Z_1}\right\} + I_2\right] Z_L$$

$I_2 = \mathbf{(}E_2 Z_1 - (E_1 - E_2)Z_L\mathbf{)} / \mathbf{(}Z_1 Z_2 + Z_L (Z_1 + Z_2)\mathbf{)}$

Similarly,

$I_1 = \mathbf{(}E_1 Z_2 + (E_1 - E_2)Z_L\mathbf{)} / \mathbf{(}Z_1 Z_2 + Z_L (Z_1 + Z_2)\mathbf{)}$

Adding the above equations,

$I_1 + I_2 = \mathbf{(}E_1 Z_2 + E_2 Z_1\mathbf{)} / \mathbf{(}Z_1 Z_2 + Z_L (Z_1 + Z_2)\mathbf{)}$ ....(c)

But $I_L = I_1 + I_2$

Load voltage, $V_2 = I_L Z_L$

Dividing both numerator and denominator of equation (c) by $Z_1 Z_2$,

$$I_L = \frac{\frac{E_1}{Z_1} + \frac{E_2}{Z_2}}{1 + \frac{Z_L (Z_1 + Z_2)}{Z_1 Z_2}}$$

$$I_L = \frac{\frac{E_1}{Z_1} + \frac{E_2}{Z_2}}{1 + \frac{Z_L}{Z_2} + \frac{Z_L}{Z_1}}$$

$$V_2 = I_L Z_L = \left[\frac{E_1/Z_1 + E_2/Z_2}{1 + \frac{Z_L}{Z_2} + \frac{Z_L}{Z_1}} \right] Z_L$$

$$= \frac{E_1/Z_1 + E_2/Z_2}{\frac{1}{Z_L} + \frac{1}{Z_2} + \frac{1}{Z_1}}$$

If impedances Z_1 and Z_2 are small in comparision with load impedance Z_L then product Z_1 Z_2may be neglected so we get,

$$I_1 = \frac{E_1 Z_2}{Z_L (Z_1 + Z_2)} + \frac{E_1 - E_2}{Z_1 + Z_2}$$

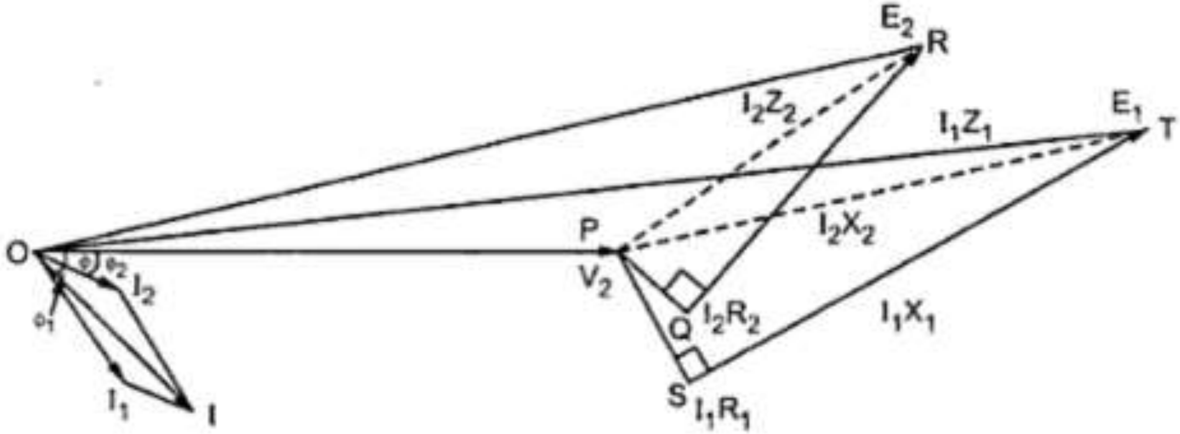
$$I_2 = \frac{E_2 Z_1}{Z_L (Z_1 + Z_2)} - \frac{E_1 - E_2}{Z_1 + Z_2}$$

But we know that

$$(E_1 - E_2) / (Z_1 + Z_2) = I_c$$

Key Point : This circulating current I_c adds to I_1 but subtracts from I_2. Hence transformer 1 gets overloaded. The transformers will not share the load according to their ratings.

The phasor diagram is shown in the Fig. 2.



The two transformers will operate at different power factor Φ_1 and Φ_2 are the power factor angles of these two transformers whereas Φ is the combined p.f. angle.

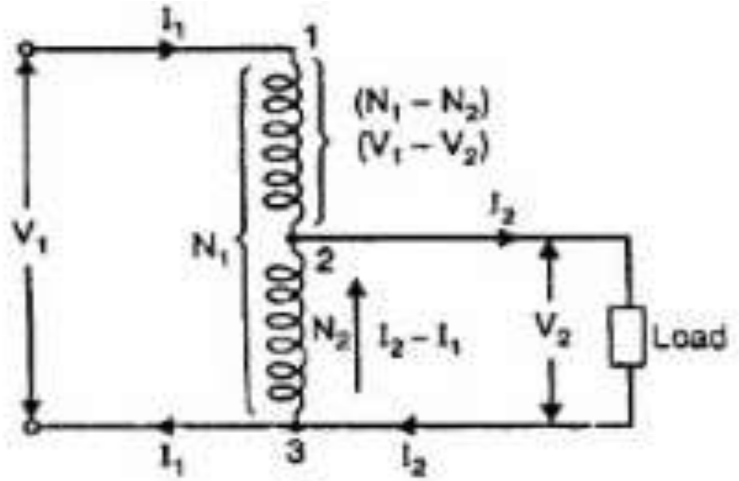
Here E_A and E_B have the same phase but there may be some phase difference between the two due to some difference of internal connection as for the connection in parallel of a Star/Star and a Star/Delta 3 phase transformers.

Key Point : While solving the problems on parallel operation of transformers it is convenient to work with numerical values of impedances instead of percentage values.

AutoTransformer

- An **autotransformer** (sometimes called ***auto step d*** An **autotransformer** (sometimes called ***auto step down transformer***)is an electrical **transformer** with only one winding. The "auto" (Greek for "self") prefix refers to the single coil acting on itself and not to any kind of automatic mechanism. ***own transformer***)is an electrical **transformer** with only one winding. The "auto" (Greek for "self") prefix refers to the single coil acting on itself and not to any kind of automatic mechanism.

Theory of Autotransformer



(i)

N1=primary turn(1-3)

N2=secondary turn(2-3)

I1=primary current

I2=secondary current

V1=primary voltage

V2=secondary votage

From the above fig.

We get

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

$$V_2(N_1 - N_2) = N_2(V_1 - V_2)$$

$$V_2N_1 - V_2N_2 = N_2V_1 - N_2V_2$$

$$V_2N_1 = N_2V_1$$

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

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

$$V_1 I_1 = V_2 I_2$$

OUT PUT

The primary and secondary windings of an autotransformer are

Connected magnetically as well as electrically. So the power transferred primary to secondary inductively as well as conductively.

$$\text{Output apparent power} = V_2 I_2$$

$$\text{Apparent power transferred inductively} = V_2(I_2 - I_1) = V_2(I_2 - K\,I_2)$$

$$= V_2 I_2(1 - K) = V_1 I_1(1 - K)$$

$$\text{Power transferred inductively} = \text{Input} \times (1 - K)$$

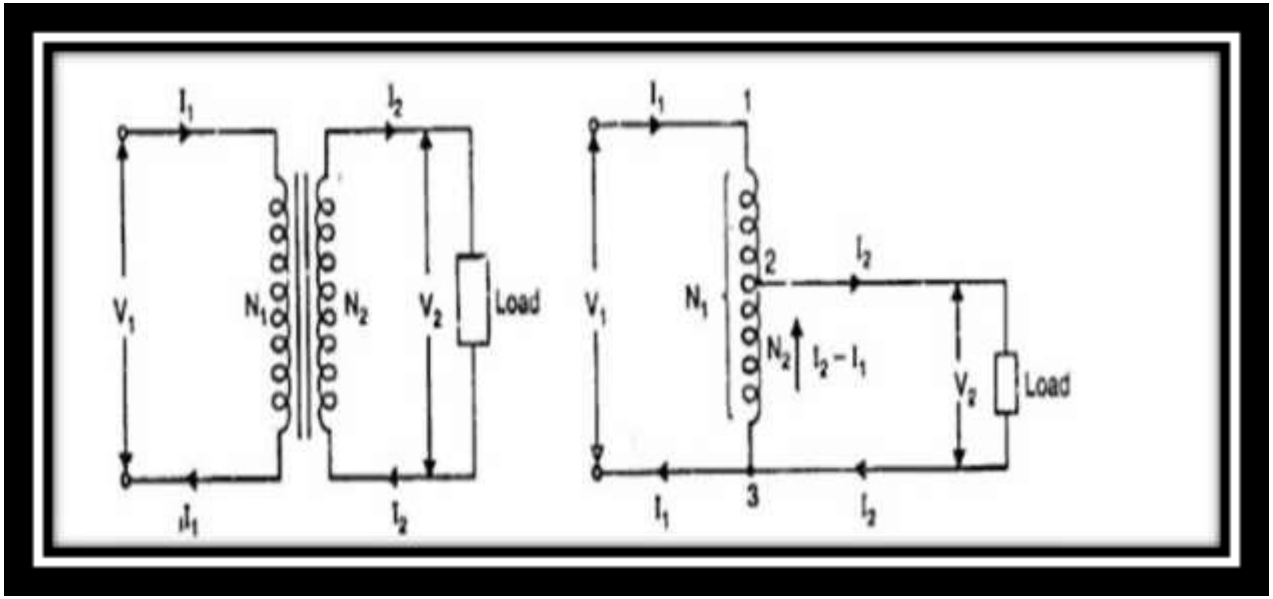
$$\text{Power transferred conductively} = \text{Input} - \text{Input}\,(1 - K)$$

$$= \text{Input}\,[1 - (1 - K)]$$

$$= K \times \text{Input}$$

Copper Saving in Auto transformer

- The same output and voltage transformation ratio an autotransformer requires less copper than the 2-winding transformer



Weight of Cu required in a winding ∝ current × turns

Winding transformer

$$\text{Weight of Cu required} \propto (I_1N_1 + I_2N_2)$$

Autotransformer

$$\text{Weight of Cu required in section 1-2} \propto I_1(N_1 - N_2)$$

$$\text{Weight of Cu required in section 2-3} \propto (I_2 - I_1)N_2$$

$$\therefore \quad \text{Total weight of Cu required} \propto I_1(N_1 - N_2) + (I_2 - I_1)N_2$$

$$\frac{\text{Weight of Cu in autotransformer}}{\text{Weight of Cu in ordinary transformer}} = \frac{I_1(N_1 - N_2) + (I_2 - I_1)N_2}{I_1N_1 + I_2N_2}$$

$$= \frac{N_1I_1 - N_2I_1 + N_2I_2 - N_2I_1}{N_1I_1 + N_2I_2}$$

$$= \frac{N_1I_1 + N_2I_2 - 2N_2I_1}{N_1I_1 + N_2I_2}$$

$$= 1 - \frac{2N_2I_1}{N_1I_1 + N_2I_2}$$

$$= 1 - \frac{2N_2I_1}{2N_1I_1} \qquad (\because \; N_2I_2 = N_1I_1)$$

$$= 1 - \frac{N_2}{N_1} = 1 - K$$

$\therefore$ Wt. of Cu in autotransformer (W_a)

$= (1 - K) \times$ Wt. in ordinary transformer (W_o)

or $\quad W_a = (1 - K) \times W_o$

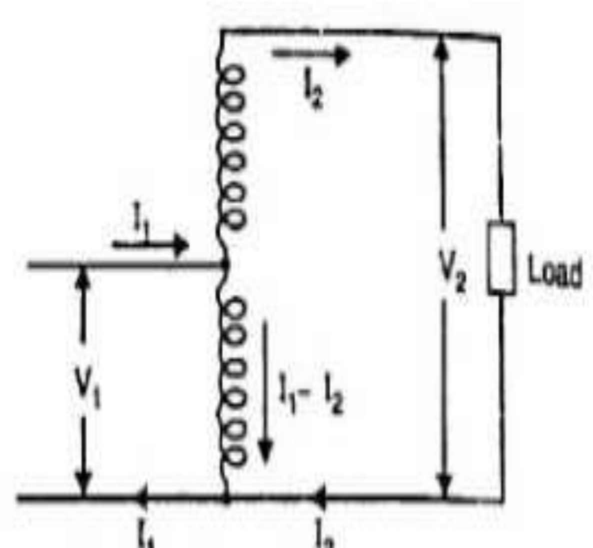
$\therefore \quad$ Saving in Cu $= W_o - W_a = W_a - (1 - K)W_o = K\,W_o$

or $\quad$ Saving in Cu $= K \times$ Wt. ofCu in ordinary transformer

Types of AUTOTransformer

Step UP Transformer :

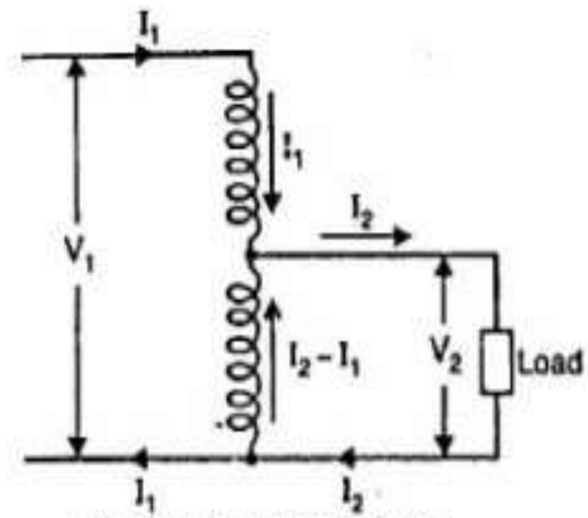
A transformer in which Ns>Np is called a step up transformer. A step up transformer is a transformer which converts low alternatic voltage to high alternatic voltage.



Step-up autotransformer

StepDOWNTransformer :

A transformer in which Np>Ns is called a step down transformer. A step down transformer is a transformer which converts high alternating voltage to low alternating voltage.



Step-down autotransformer

Conversion of 2-winding transformer *into* autotransformer

ADDITIVE POLARITY (SEP-UP)

SUBSTRACTIVE POLARITY (STEP DOWN)

ADDITIVE POLARITY

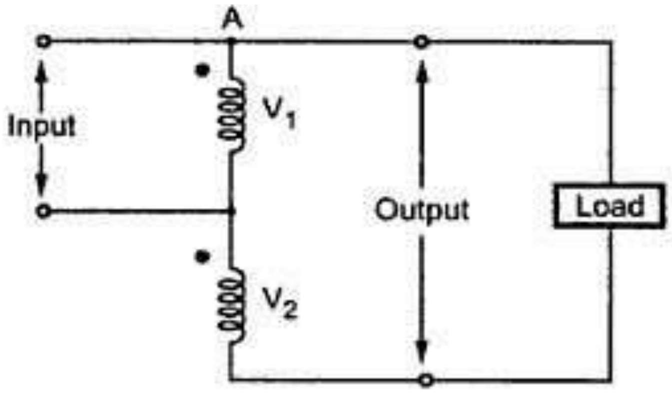


Fig. 9.9 Autotransformer

The common point A which is common to input and output can be taken as the top of autotransformer. The corresponding autotransformer is shown in the Fig. 9.9.

Thus if input is V_1 then the output is $V_1 + V_2$ due to additive polarities.

Key Point : *The autotransformer with additive polarity is a step-up autotransformer.*

With common point A at the bottom autotransformer can be shown as in the Fig. 9.10.

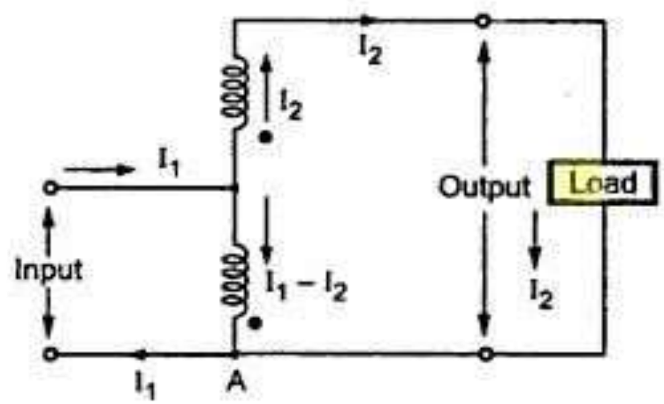


Fig. 9.10 Step-up autotransformer

In this case common current flow towards the common terminal

SUBSTRACTIVE POLARITY

The primary and secondary windings can be connected in series opposition as shown in the Fig. 9.11 which is called subtractive polarity.

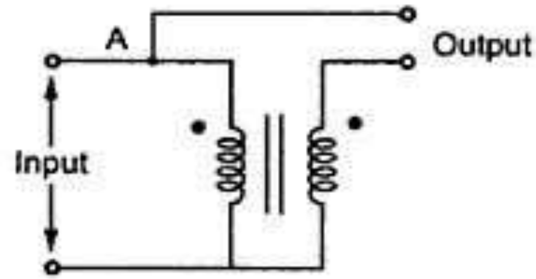


Fig. 9.11 Subtractive polarity connection

The common point A which is common to input and output can be taken as the top of the autotransformer as shown in the Fig. 9.12.

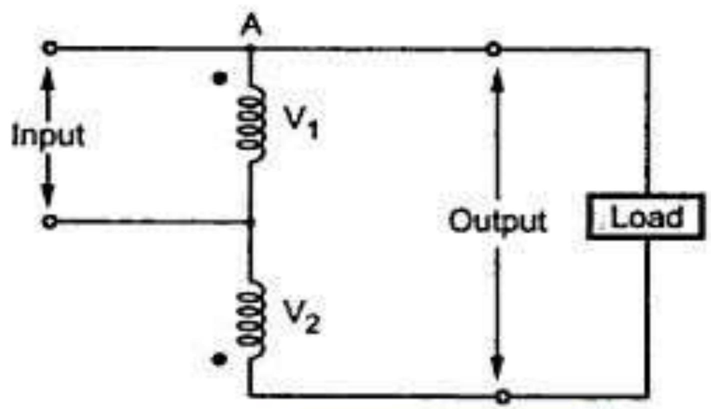


Fig. 9.12 Autotransformer

Thus if input is V_1 then the output voltage is $V_1 - V_2$ due to subtractive polarities.

Key Point : *The autotransformer with subtractive polarity is a step-down autotransformer.*

With common point A at the bottom, autotransformer can be shown as in the Fig. 9.13.

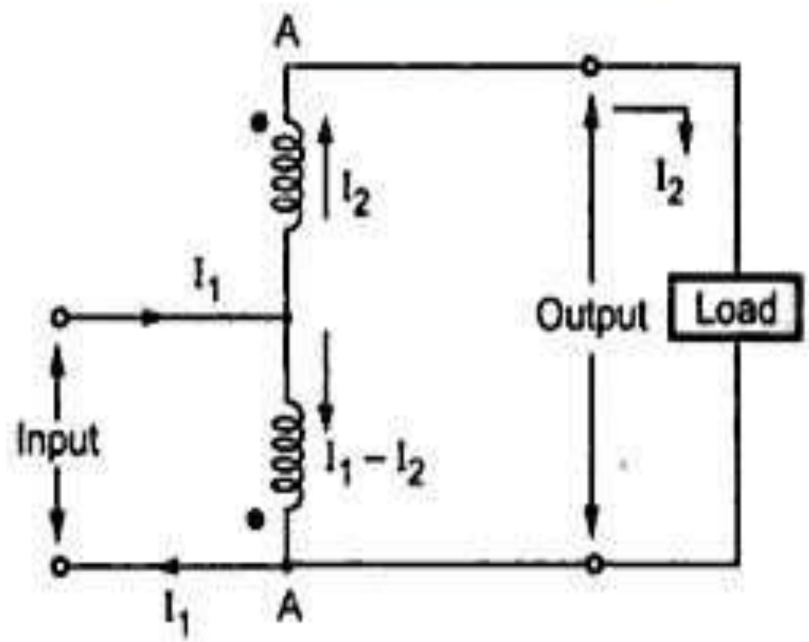


Fig. 9.13 Step-down autotransformer

In this case common current flow away from common terminal

Advantages

An autotransformer operates at a higher efficiency than a two-winding transformer of similar rating.

An autotransformer has better voltage regulation than a two-windingtransformer of the same rating.

An autotransformer has smaller size than a two-winding transformer of the same rating.

An autotransformer requires smaller exciting current than a two-windingtransformer of the same rating.

DISADVANTAGES

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

- An autotransformer is not safe for stepping down a high voltage to a low voltage. As an illustration.

If an open circuit develops in the common portion of the winding, then full-primary voltage will appear across the load. In such a case, any one coming in contact with the secondary is subjected to high voltage. This could be dangerous to both the persons and equipment. For this reason, autotransformers are prohibited for general use.

The short-circuit current is much larger than for the two-winding transformer of the same rating. So that a short-circuited secondary causes part of the primary also to be short-circuited. This reduces the effective resistance and reactance.

APPLICATION

Autotransformers are used to compensate for voltage drops in transmission and distribution lines. When used for this purpose, they are known as booster transformers.

- Autotransformers are used for reducing the voltage supplied to a.c.motors during the starting period.
- Autotransformers are used for continuously variable supply.

On long rural power distribution lines, special autotransformers with automatic tap-changing equipment are inserted as voltage regulators, so that customers at the far end of the line receive the same average voltage as those closer to the source. The variable ratio of the autotransformer compensates for the voltage drop along the line.

In control equipment for 1-phase and 3-phase electrical locomotives.

LIMITATION

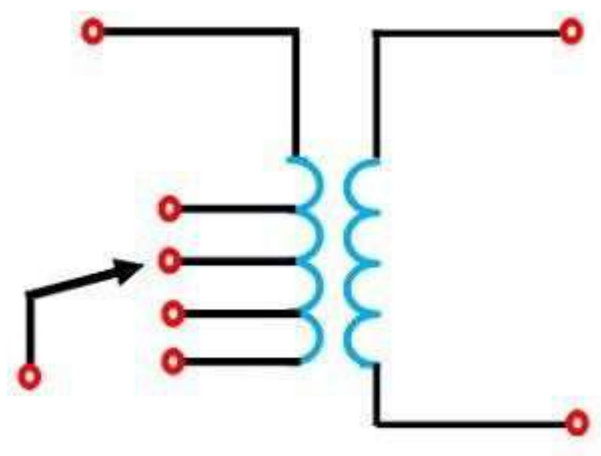
- Because it requires both fewer windings and a smaller core, an autotransformer for power applications is typically lighter and less costly than a two-winding transformer, up to a voltage ratio of about 3:1; beyond that range, a two-winding transformer is usually more economical.
- Like multiple-winding transformers, autotransformers operate on time-varying magnetic fields and so will not function with DC.
- A failure of the insulation of the windings of an autotransformer can result in full input voltage applied to the output. Also, a break in the part of the winding that is used as both primary and secondary will result in the transformer acting as an inductor in series with the load .

Tap-changing Transformers

- The change of voltage is affected by changing the numbers of turns of the transformer provided with taps. For sufficiently close control of voltage, taps are usually provided on the high voltage windings of the transformer. There are two types of tap-changing transformers
- Off-load tap changing transformer
- On-load tap changing transformer

Off-load tap changing transformer

In this method, the transformer is disconnected from the main supply when the tap setting is to be changed. The tap setting is usually done manually. The off load tap changing transformer is shown in the figure below



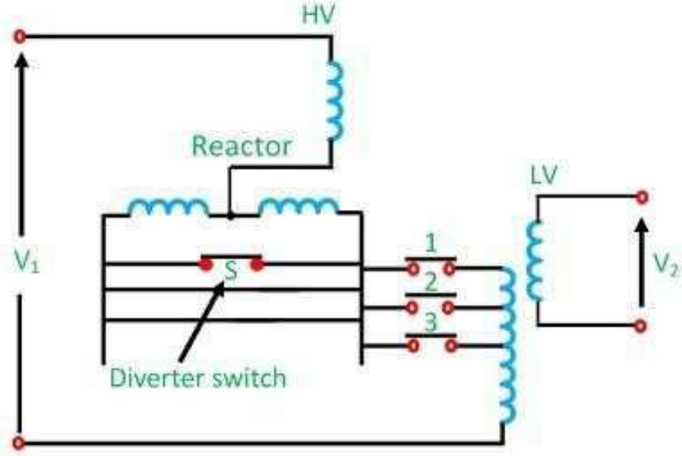
Off-load tap-changing transformer

On-load tap-changing transformer

In order that the supply may not be interrupted, on-load tap changing transformer are sued. Such a transformer is known as a tap-changing under load transformer. While tapping, two essential conditions are to be fulfilled.

The load circuit should not be broken to avoid arcing and prevent the damage of contacts.

No parts of the windings should be short–circuited while adjusting the tap.



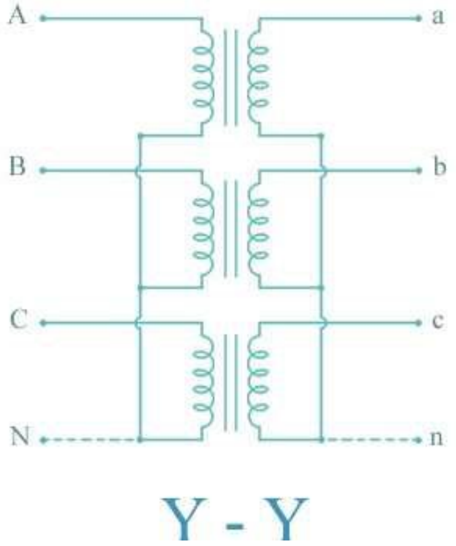
On-load tap changing using a reactor

Poly Phase Transformer Connections

- Star- Star (Y-Y)
- Delta-Delta (Δ-Δ)
- Star-Delta (Y- Δ)
- Delta-Star (Δ-Y)
- Open Delta (V-V)
- Scott Connection (T-T)

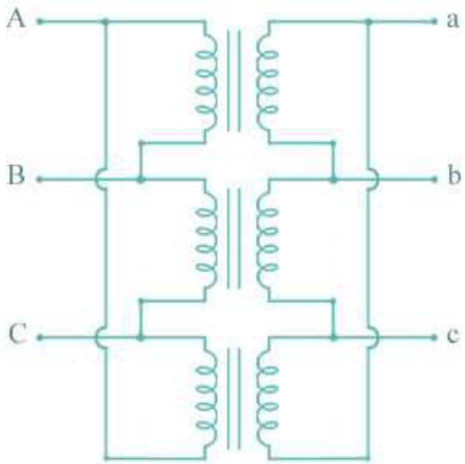
Star-Star (Y-Y)

- Star-star connection is generally used for small, high-voltage transformers. Because of star connection, number of required turns/phase is reduced (as phase voltage in star connection is $1/\sqrt{3}$ times of line voltage only). Thus, the amount of insulation required is also reduced.
- The ratio of line voltages on the primary side and the secondary side is equal to the transformation ratio of the transformers.
- Line voltages on both sides are in phase with each other.
- This connection can be used only if the connected load is balanced.



Delta-Delta (Δ-Δ)

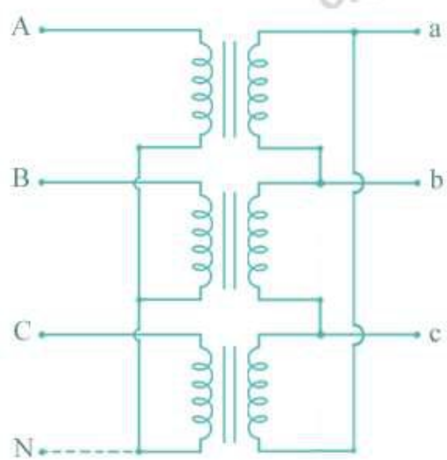
- This connection is generally used for large, low-voltage transformers. Number of required phase/turns is relatively greater than that for star-star connection.
- The ratio of line voltages on the primary and the secondary side is equal to the transformation ratio of the transformers.
- This connection can be used even for unbalanced loading.
- Another advantage of this type of connection is that even if one transformer is disabled, system can continue to operate in open delta connection but with reduced available capacity.



Δ - Δ

Star-Delta (Y- Δ)

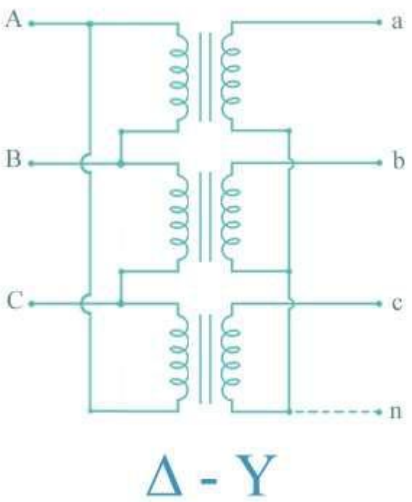
- The primary winding is star star (Y) connected with grounded neutral and the secondary winding is delta connected.
- This connection is mainly used in step down transformer at the substation end of the transmission line.
- The ratio of secondary to primary line voltage is $1/\sqrt{3}$ times the transformation ratio.
- There is 30° shift between the primary and secondary line voltages.



Y - Δ

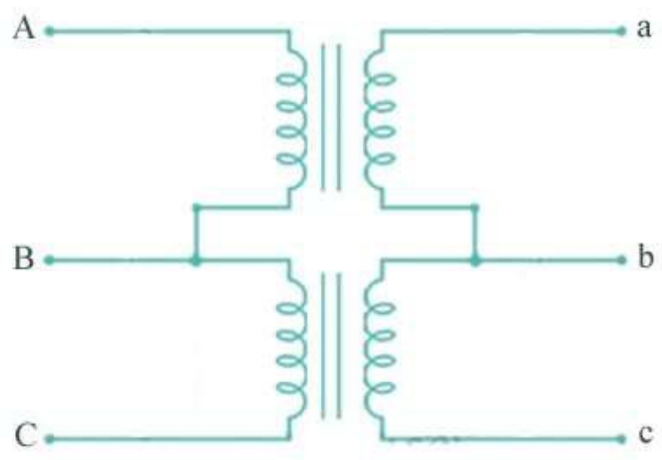
Delta-Star (Δ-Y)

- The primary winding is connected in delta and the secondary winding is connected in star with neutral grounded. Thus it can be used to provide 3-phase 4-wire service.
- This type of connection is mainly used in step-up transformer at the beginning of transmission line.
- The ratio of secodary to primary line voltage is √3 times the transformation ratio.
- There is 30° shift between the primary and secondary line voltages.



Open Delta (V-V)

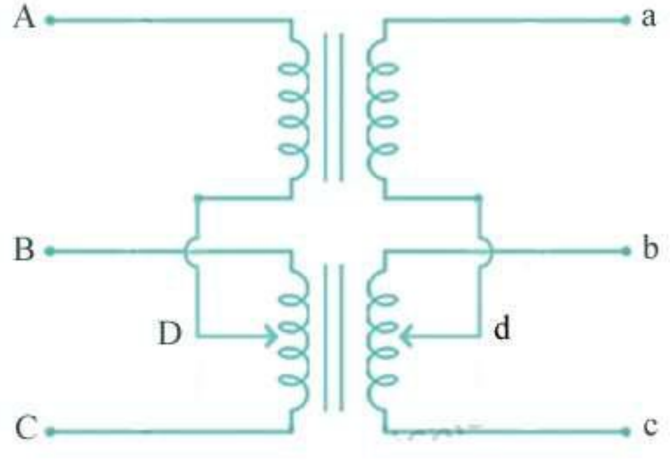
- Two transformers are used and primary and secondary connections are made as shown in the figure below. Open delta connection can be used when one of the transformers in Δ-Δ bank is disabled and the service is to be continued until the faulty transformer is repaired or replaced. It can also be used for small three phase loads where installation of full three transformer bank is un-necessary. The total load carrying capacity of open delta connection is 57.7% than that would be for delta-delta connection.



Open Delta (V-V) Connection

Scott Connection (T-T)

- Two transformers are used in this type of connection. One of the transformers has centre taps on both primary and secondary windings (which is called as main transformer). The other transormer is called as teaser transformer. Scott connection can also be used for three phase to two phase conversion. The connection is made as shown in the figure below.



Scott (T-T) Connection

Tertiary Winding of Transformer | Three Winding Transformer

- In some high rating transformer, one winding in addition to its primary and secondary winding is used. This additional winding, apart from primary and secondary windings, is known as **Tertiary winding of transformer**. Because of this third winding, the transformer is called **three winding transformer** or **3 winding transformer**.

Advantages of Using Tertiary Winding in Transformer

- It reduces the unbalancing in the primary due to unbalancing in three phase load.
- It redistributes the flow of fault current.
- Sometime it is required to supply an auxiliary load in different voltage level in addition to its main secondary load. This secondary load can be taken from tertiary winding of **three winding transformer**.
- As the **tertiary winding** is connected in delta formation in **3 winding transformer**, it assists in limitation of fault current in the event of a short circuit from line to neutral.