LECTURE NOTES
ON
ENERGY CONVERSION

SUDIPTA KUMR DAS

D.C Generator

An electrical Generator is a machine which converts mechanical energy (or power) into electrical energy (or power). The generator operates on the principle of the production of dynamically induced emf i.e., whenever flux is cut by the conductor, dynamically induced emf is produced in it according to the laws of electromagnetic induction, which will cause a flow of current in the conductor if the circuit is closed.

Hence, the basic essential parts of an electric generator are:

- A magnetic field and
- A conductor or conductors which can so move as to cut the flux

In dc generators the field is produced by the field magnets which are stationary. Permanent magnets are used for very small capacity machines and electromagnets are used for large machines to create magnetic flux. The conductors are situated on the periphery of the armature being rotated by the prime-mover.

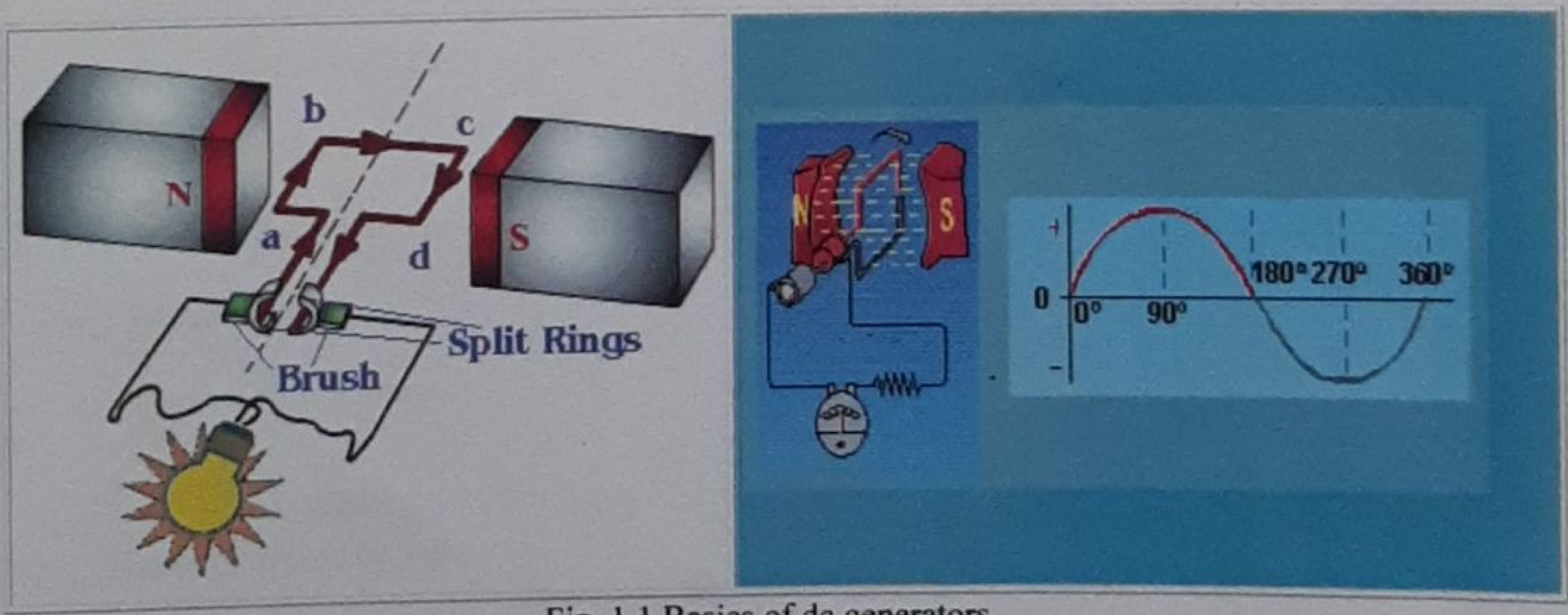


Fig. 1.1 Basics of dc generators

1.1 Practical DC generator construction

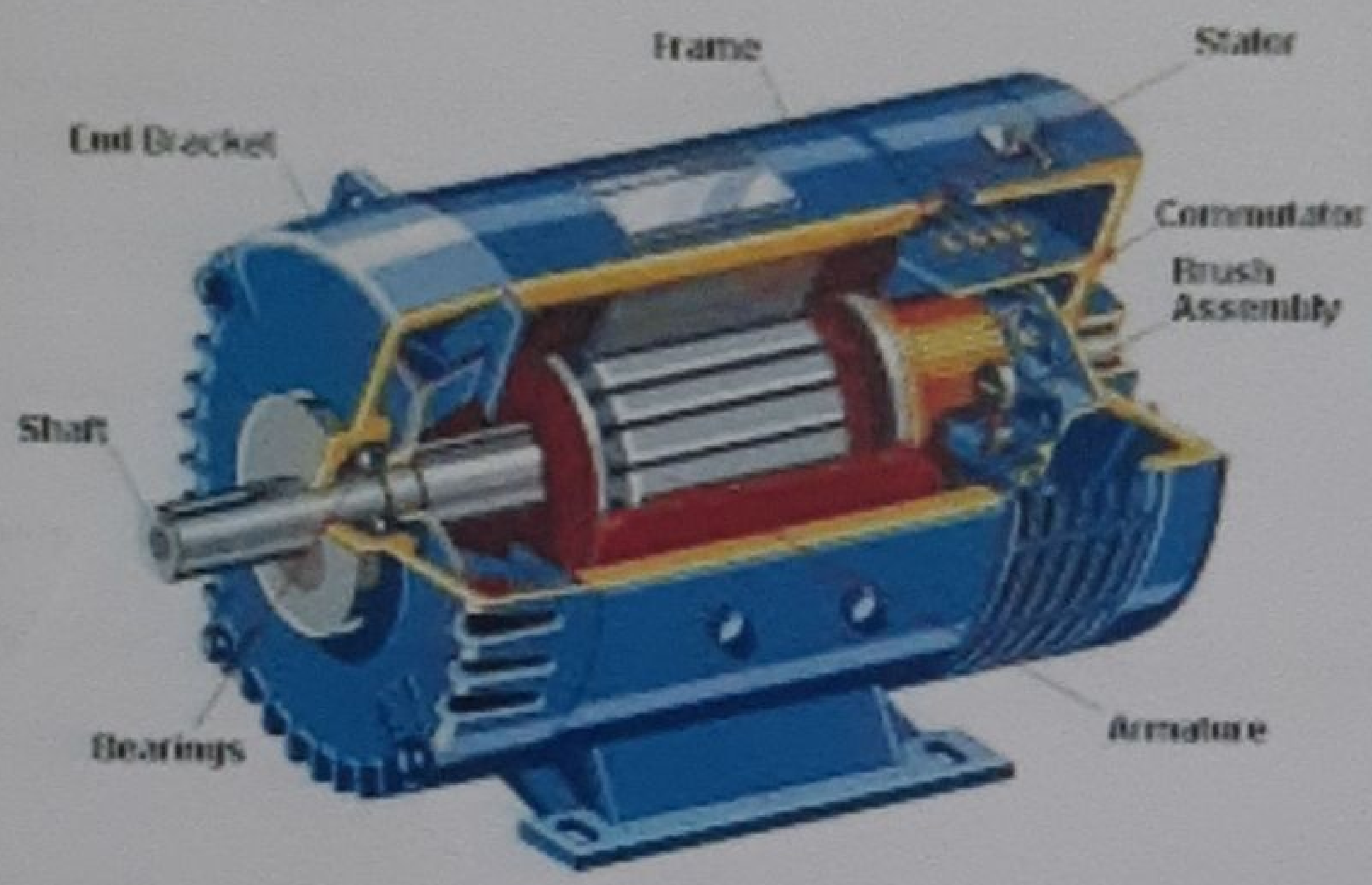


Fig. 1.2 Cut-away view of dc practical generators

The actual DC generator consists of the following essential parts:

- Magnetic frame or Yoke
- Pole Cores and Pole Shoes
- Pole Coils or Field Coils
- Armature Core
- Armature Windings or Conductors
- Commutator
- Brushes and Bearings

a) Magnetic frame or Yoke

Purpose of Yoke is

1. It act as a protecting cover for whole machine

2. It provides mechanical support for poles

3. It carries the magnetic flux produced by poles

b) Pole Cores and Pole Shoes

The field magnets consist of pole cores and pole shoes. The Pole shoes serve two purposes:

1. They spread out the flux in the air gap

2. They support the exciting coils

c) Armature

When current is passed through field coils, they electro-magnetize the poles which produce the necessary flux.

The Armature serves two purposes:

1. Armature houses the armature conductors or coils
2. It provides low reluctance path for flux

It is drum shaped and is built up of laminations made sheet steel to reduce eddy current loss. Slots are punched on the outer periphery of the disc. The Armature windings or conductors are wound in the form of flat rectangular coils and are placed in the slots of the Armature. The Armature windings are insulated from the armature body by insulating materials.

d) Commutator and brushes

The function of Commutator is to facilitate collection of current from the armature conductors and converts the alternating current induced in the armature conductors into unidirectional current in the external load circuit. The commutator is made up of insulated copper segments. Two brushes are pressed to the commutator to permit current flow. The Brushes are made of carbon or Graphite. Bearings are used for smooth running of the machine.

1.2 E.M.F. equation

Let, ϕ = flux per pole in weber

z = total number of armature conductors=no. of slots $\times$ no. of conductors/slot

P = no. of generator poles

A = no. of parallel paths in armature

N = armature rotation in revolutions per minute (rpm)

E = emf induced in any parallel path in armature

Generated emf, E_g = emf generated in any one of the parallel path i.e. E

Average emf generated/conductor $= \frac{d\phi}{dt}$ volts, $\because n = 1$

Now, flux cut per conductor in one revolution,

$d\phi = \phi P$ weber

No. of revolutions per second $= \frac{N}{60}$

Time for one revolution, $dt = \frac{60}{N}$ second

Hence, according to Faradays laws of Electromagnetic induction,

EMF generated/conductor $= \frac{d\phi}{dt} = \frac{\phi PN}{60}$ volts

For a simplex lap-wound generator:

No. of parallel paths $= P$

No. of conductors in one path $= \frac{z}{P}$

Hence, EMF generated/path $= \frac{\phi PN}{60} \times \frac{z}{P} = \frac{\phi zN}{60}$ volts

For a simplex wave-wound generator:

No. of parallel paths $= 2$

No. of conductors in one path $= \frac{z}{2}$

Hence, EMF generated/path $= \frac{\phi PN}{60} \times \frac{z}{2} = \frac{\phi zNP}{120}$ volts

In general generated EMF, $E_g = \frac{\phi zN}{60} \times \frac{P}{A}$

1.3 Types of generator

DC generators are usually classified according to the way in which their fields are excited. DC generators may be divided into, (a) separately excited dc generators, and (b) self excited dc generators.

a) separately excited dc generators

Separately excited generators are those whose field magnets are energized from an independent external source of dc current.

b) self excited dc generators

Self excited generators are those whose field magnets are energized by the current produced by the generators themselves. Due to residual magnetism, there is always present some flux in the poles. When the armature is rotated, some emf and hence some current flows which is partly or fully passed through the field coils thereby strengthening the residual pole flux.

There are three types of self excited dc generators named according to the manner in which their field coils (or windings) are connected to the armature. In shunt the two windings, field and armature are in parallel while in series type the two windings are in series. In compound type the part of the field winding is in parallel while other part in series with the armature winding.

D.C. Motor

An electric motor is a machine which converts electrical energy into mechanical energy.

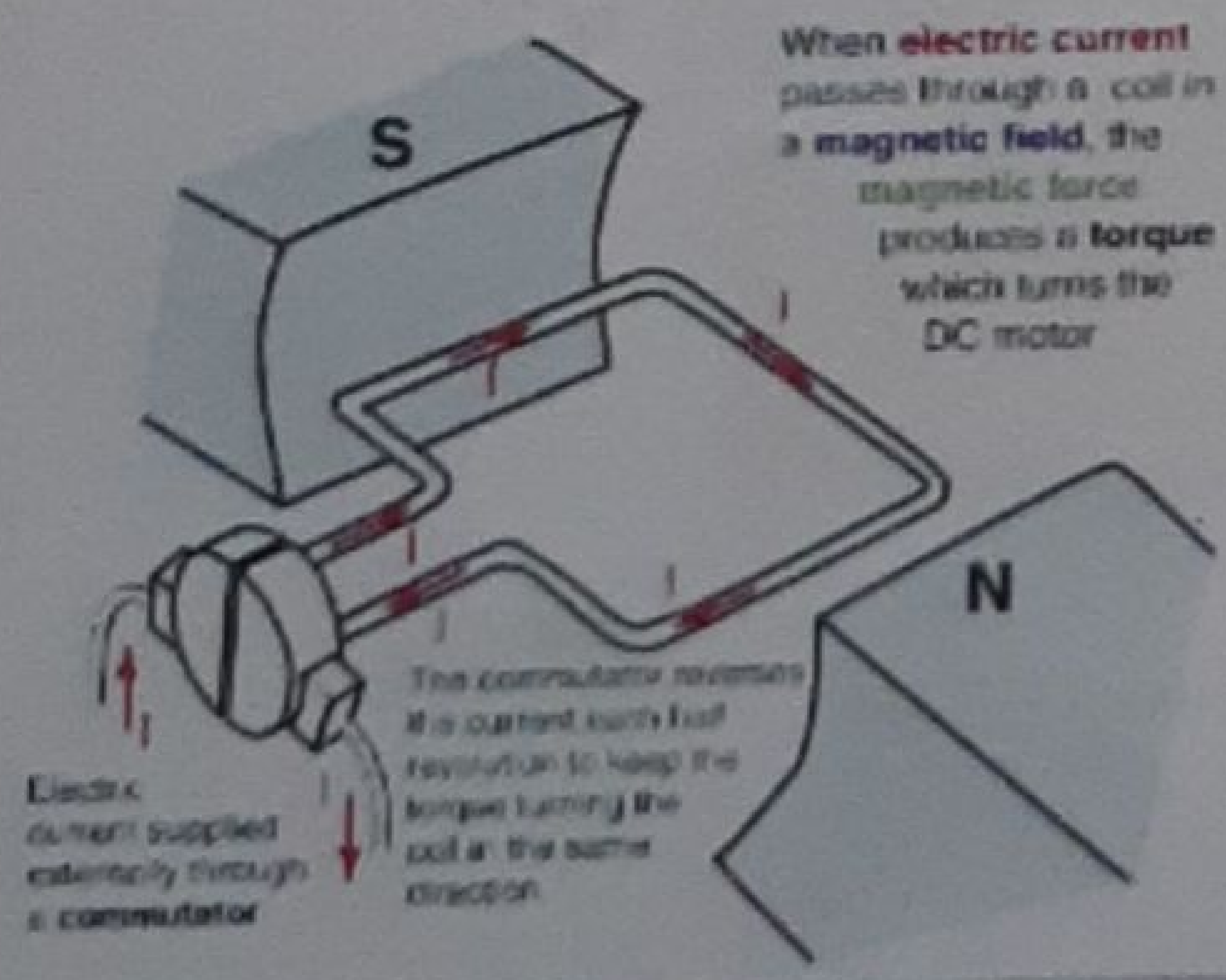
2.1 Principle of operation

It is based on the principle that when a current-carrying conductor is placed in a magnetic field, it experiences a mechanical force whose direction is given by Fleming's Left-hand rule and whose magnitude is given by

Force, $\mathbf{F = B\ I\ l}$ newton

Where B is the magnetic field in weber/m^2. I is the current in amperes and l is the length of the coil in meter.

Fleming's left hand rule says that if we extend the index finger, middle finger and thumb of our left hand in such a way that the current carrying conductor is placed in a magnetic field (represented by the index finger) is perpendicular to the direction of current (represented by the middle finger), then the conductor experiences a force in the direction (represented by the thumb) mutually perpendicular to both the direction of field and the current in the conductor.



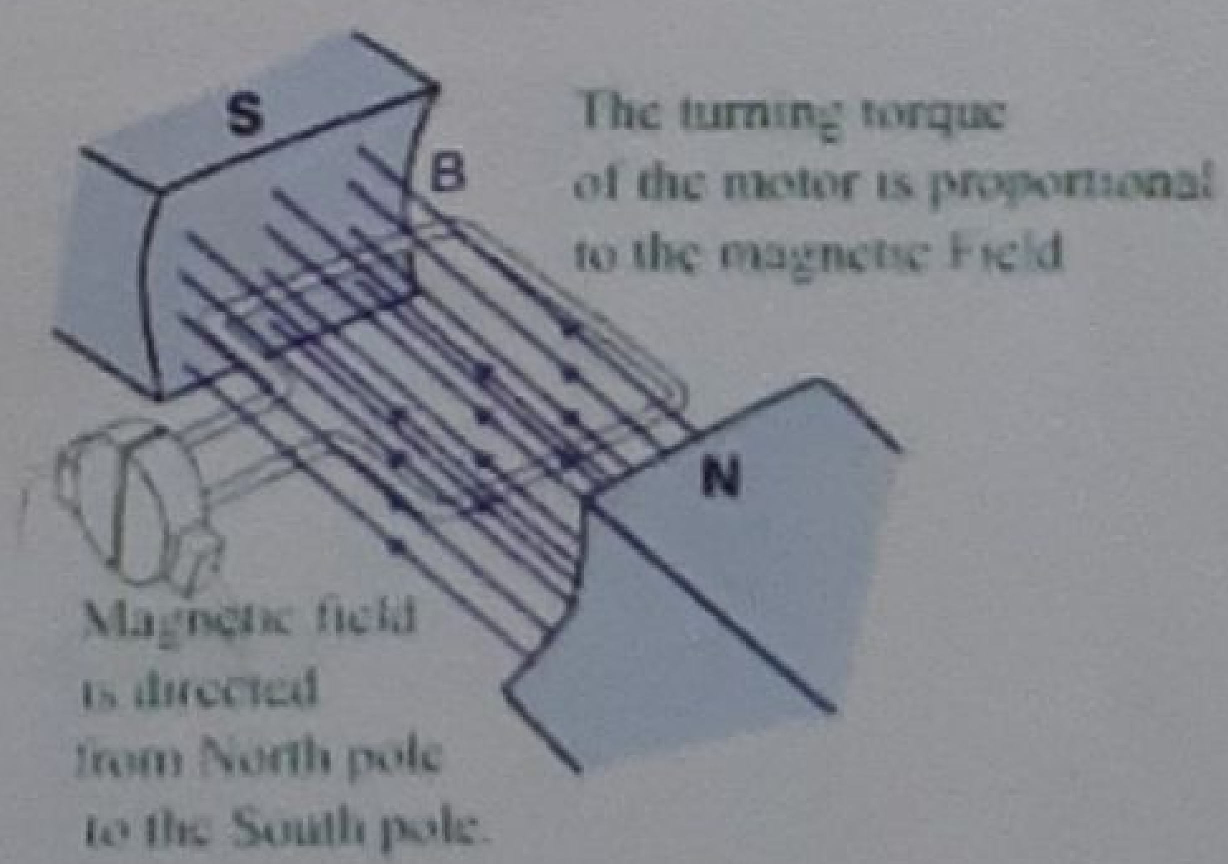


Figure 2.1: Force in DC Motor **Figure 2.2 : Magnetic Field in DC Motor**

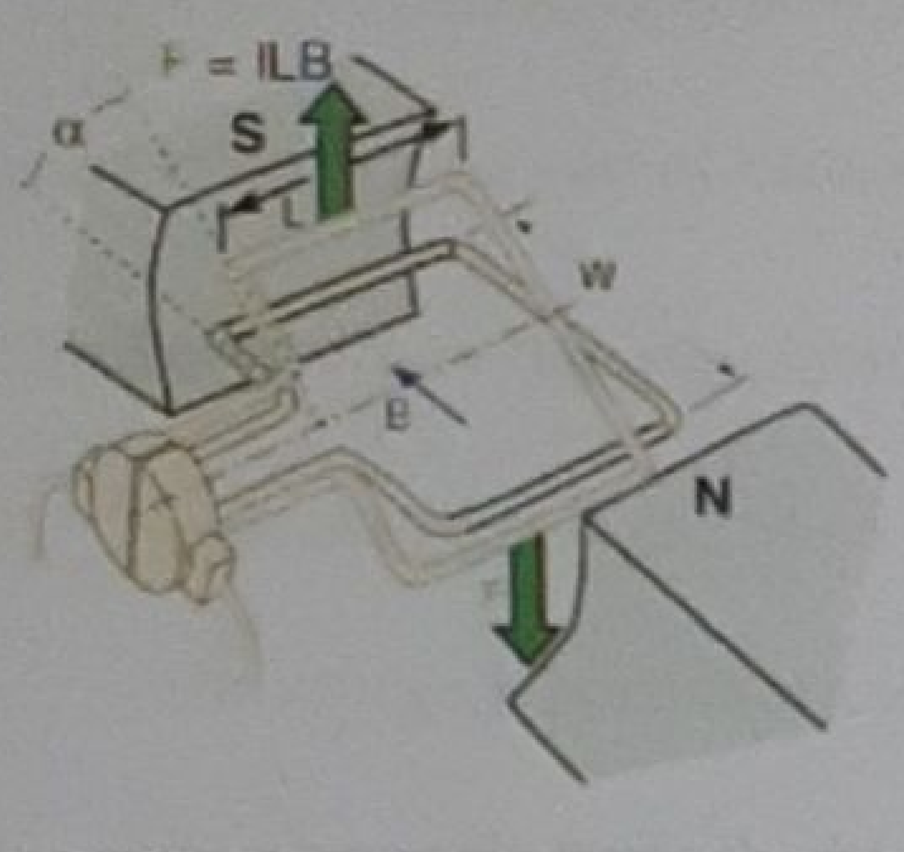


Figure 2.3 : Torque in DC Motor

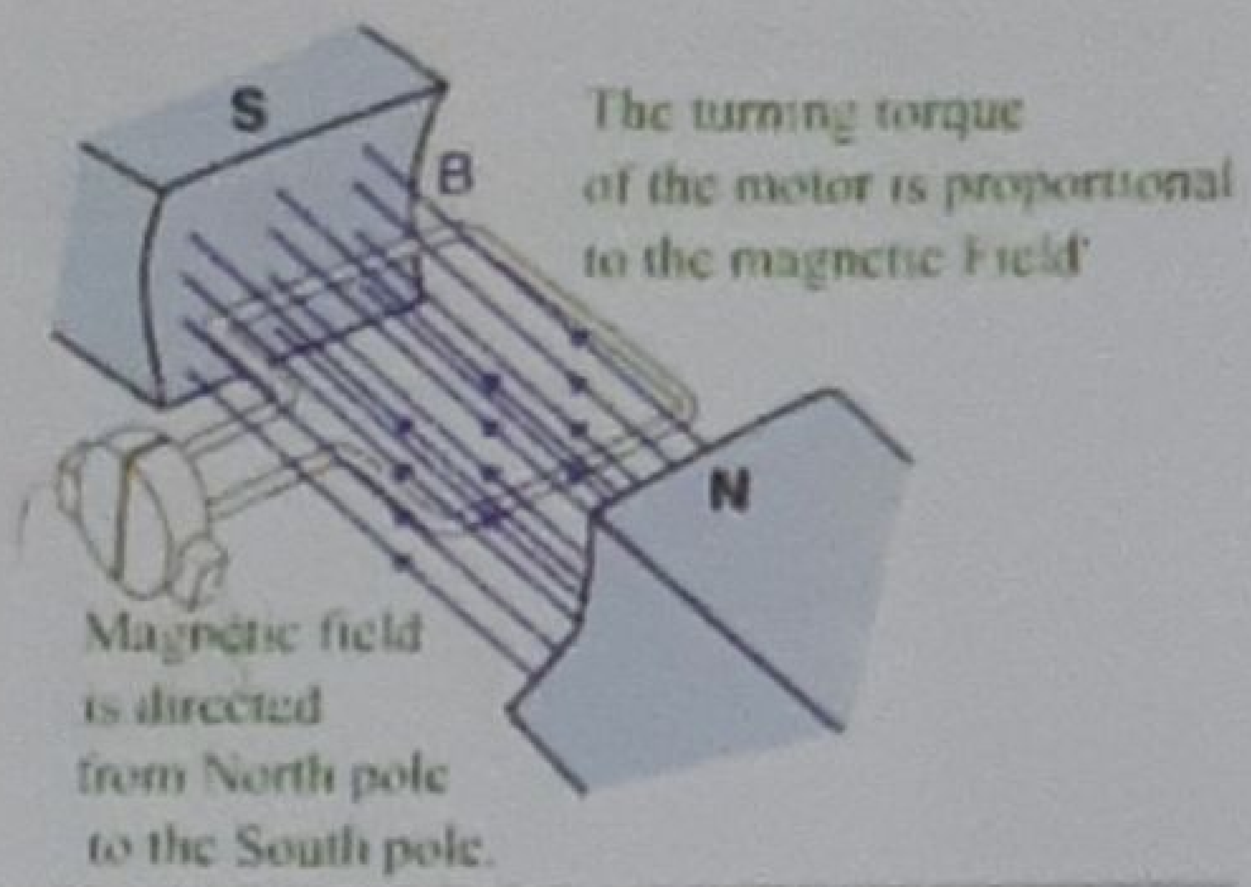


Figure 2.4 : Current Flow in DC Motor

Constructionally, there is no basic difference between a dc generator and motor. In fact, the same dc machine can be used interchangeably as a generator or as a motor. The basic construction of a dc motor contains a current carrying armature which is connected to the supply end through commutator segments and brushes and placed within the north south poles of a permanent or an electro-magnet.

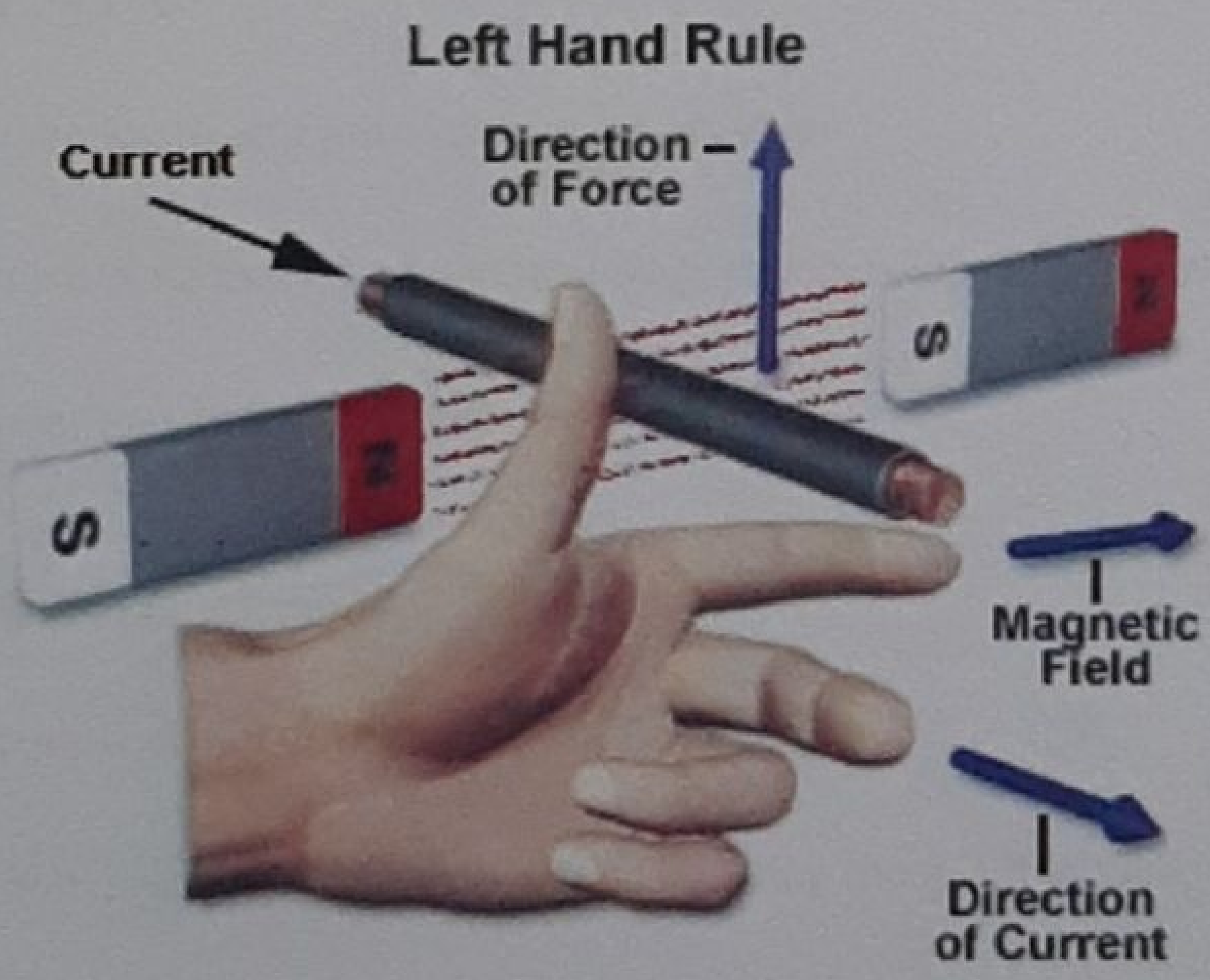


Fig. 2.5 Flemings Left hand rule

2.2 Back E.M.F

When the motor armature rotates, the conductors also rotate and hence cut the flux. In accordance with the laws of electromagnetic induction, emf is induced in them whose direction, as found by

Fleming's Right hand Rule, is in opposition to the applied voltage. Because of its opposing direction, it is referred to as counter emf of back emf E_b. V has to drive I_a against the opposition of E_b. The power required to overcome this opposition is $E_b I_a$.

2.3 Voltage Equation of a Motor

The voltage V applied across the motor armature has to,

(a) Overcome the back emf E_b, and

(b) Supply the armature ohmic drop $I_a R_a$

Hence, $V = E_b + I_a R_a$

This is known as voltage equation of a dc motor.

Now, multiplying both sides by I_a, we get

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

Where, VI_a = Electrical power input to the armature

$E_b I_a$ = Electrical equivalent of mechanical power developed in the armature

$I_a^2 R_a$ = copper loss in the armature

2.4 Condition for maximum efficiency

The gross mechanical power developed by motor is, $P_m = VI_a - I_a^2 R_a$

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

$$\frac{dP_m}{dI_a} = V - 2I_a R_a = 0$$

Hence, $I_a R_a = V/2$

As, $V = E_b + I_a R_a$ and $I_a R_a = V/2$

Hence, $E_b = V/2$

We also know that electrical power converted into mechanical power in the armature $= E_b I_a$ watt.

Comparing above equations, we get $T_a \times 2\pi N = E_b I_a$

After simplification, if N in rps, $T_a = \frac{E_b I_a}{2\pi N}$

If N is in rpm, then $T_a = 9.55\frac{E_b I_a}{N}$ N-m

Also, $T_a = 0.159\phi Z I_a \times (P/A)$ N-m

2.5.2 Shaft torque

The whole of the armature torque, as calculated above, is not available for doing useful work, because of iron and friction losses in the motor. The torque which is available for doing useful work is known as shaft torque T_{sh}. The motor output is given by

Output $= T_{sh} \times 2\pi N$ watt provided T_{sh} is in N-m and N in rps.

Hence, $T_{sh} = \frac{Output\_in\_watts}{2\pi N}$, if N is in rps

And, if N is in rpm, then $T_{sh} = \frac{Output\_in\_watts}{2\pi N/60} = 9.55\frac{Output}{N}$

2.6 Speed Control of DC Motor

Speed control means intentional change of the drive speed to a value required for performing the specific work process. Speed control is a different concept from speed regulation where there is natural change in speed due to change in load on the shaft. Speed control is either done manually by the operator or by means of some automatic control device.

One of the important features of dc motor is that its speed can be controlled with relative ease. We know that the expression of speed control dc motor is given as,

$$N = \frac{V - I_a R_a}{Z\phi} \cdot \left(\frac{A}{P}\right) = K\frac{V - I_a R_a}{\phi} \text{ rps}$$

Where, R_a armature circuit resistance.

Therefore speed (N) of 3 types of dc motor – SERIES, SHUNT AND COMPOUND can be controlled by changing the quantities on RHS of the expression. So speed can be varied by changing

(i) terminal voltage of the armature V ,

(ii) armature circuit resistance R and

(iii) flux per pole ϕ .

The first two cases involve change that affects armature circuit and the third one involves change in magnetic field. Therefore speed control of dc motor is classified as

1) armature control methods and

2) field control methods.

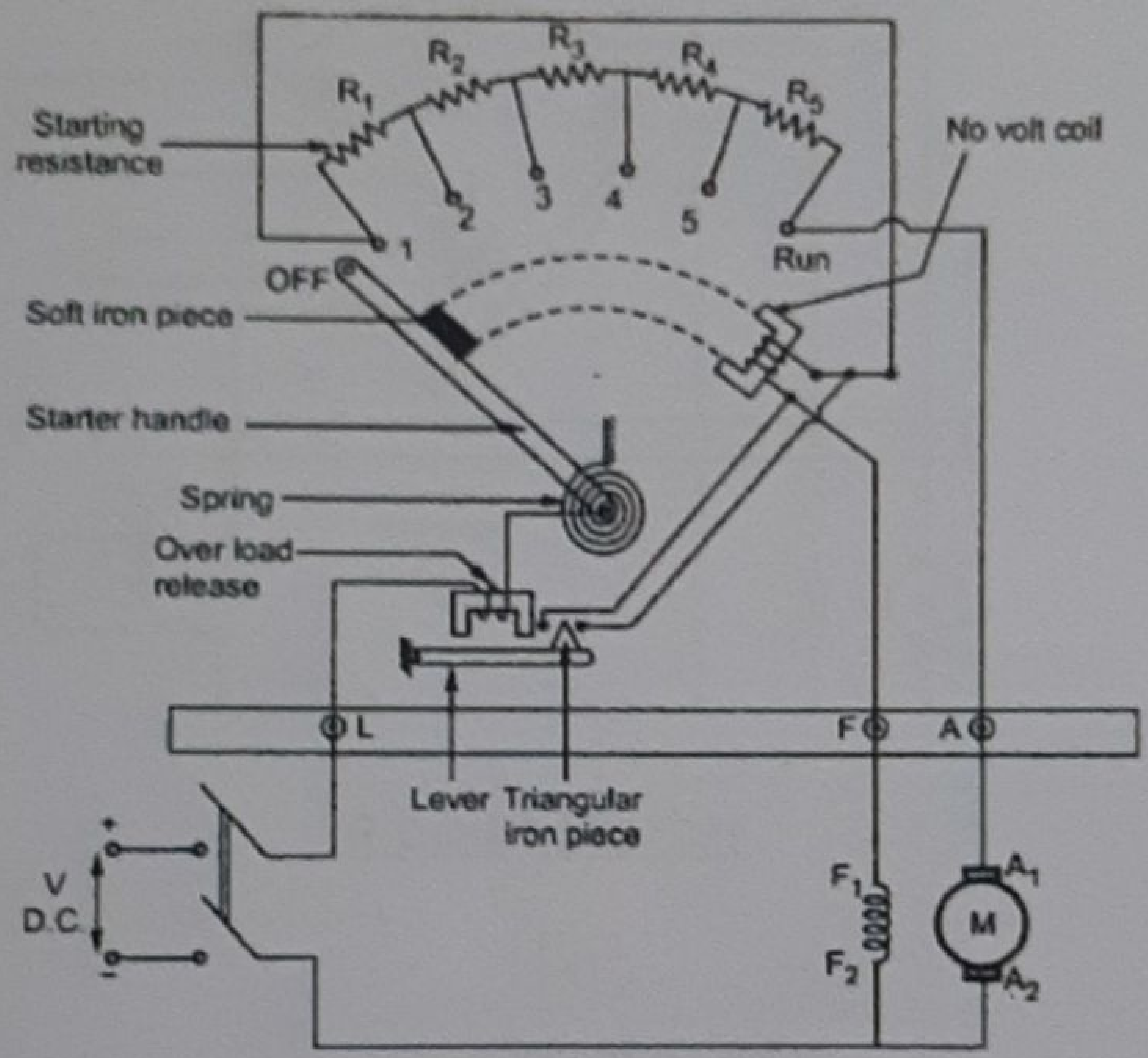
2.7 Motor starters

The starting of DC motor is somewhat different from the starting of all other types of electrical motors. This difference is credited to the fact that a dc motor unlike other types of motor has a very high starting current that has the potential of damaging the internal circuit of the armature winding of dc motor if not restricted to some limited value. This limitation to the starting current of dc motor is brought about by means of the starter. Thus the distinguishing fact about the starting methods of dc motor is that it is facilitated by means of a starter. Or rather a device containing a variable resistance connected in series to the armature winding so as to limit the starting current of dc motor to a desired optimum value taking into consideration the safety aspect of the motor.

Starters can be of several types and requires a great deal of explanation and some intricate level understanding. But on a brief over-view the main types of starters used in the industry today can be illustrated as:-

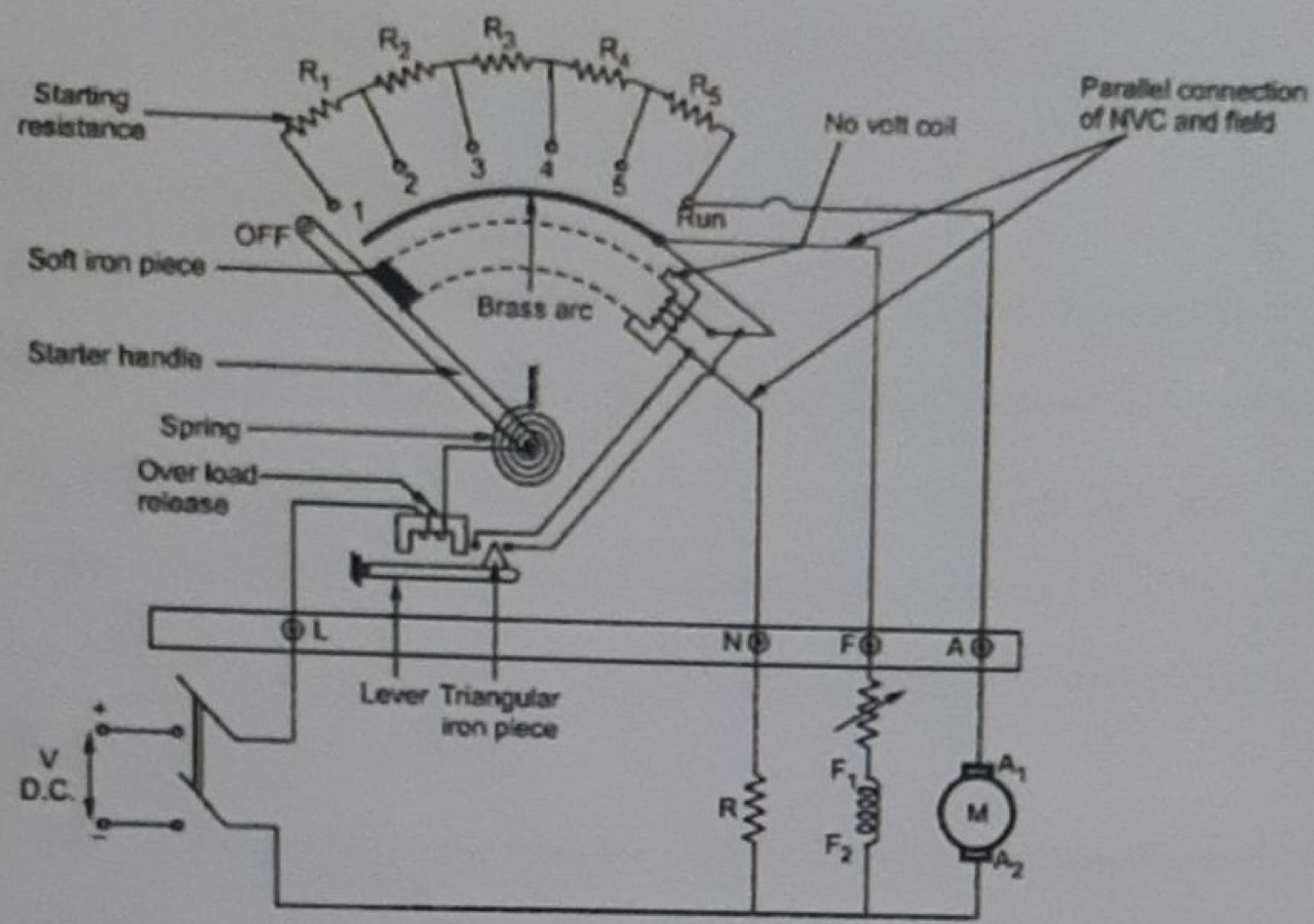
1. 3 point starter.

2. 4 point starter.



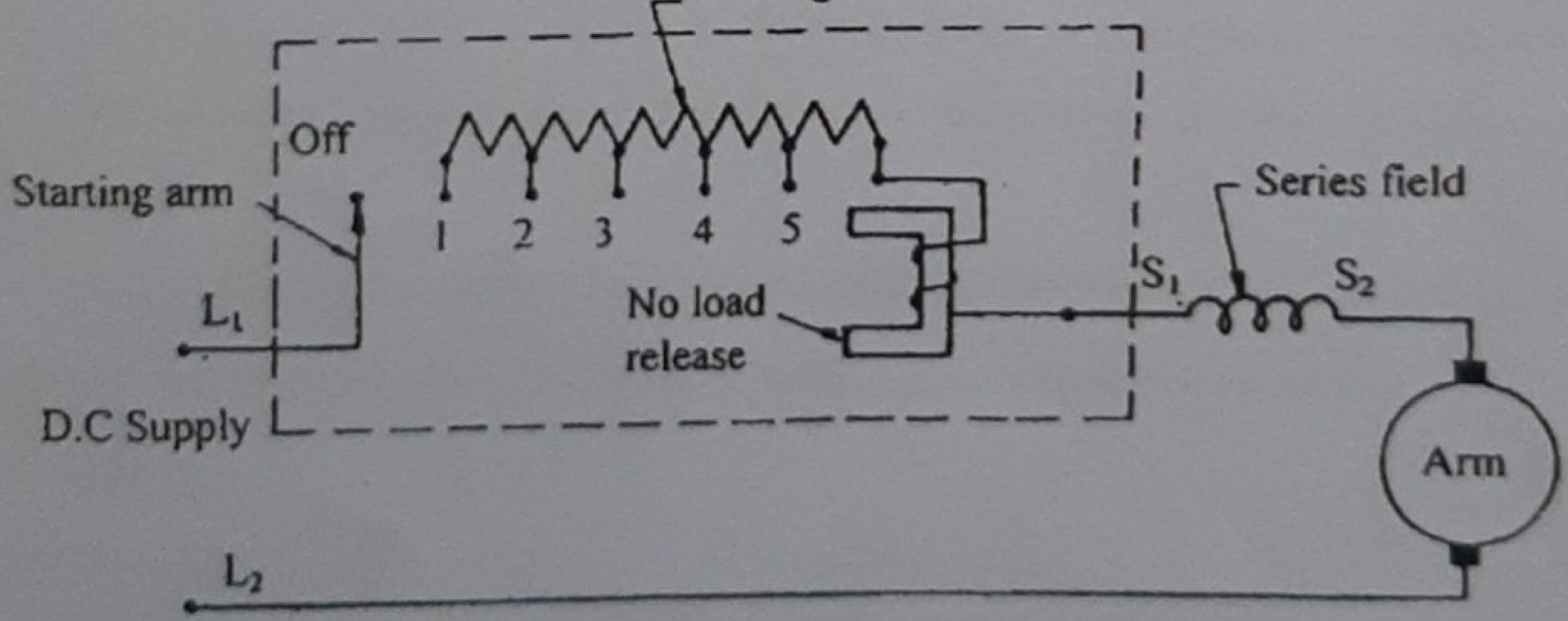
3 point Starter

Fig. 2.6



4 point Starter

Fig. 2.7



Series motor starter, no-load release.

Fig. 2.8

Single phase Transformer

3.1 Principle of operation and construction

A transformer is a static or stationary piece of apparatus by means of which electric power in one circuit is transformed into electric power of the same frequency in another circuit. Although transformers have no moving parts, they are essential to electromechanical energy conversion. They make it possible to increase or decrease the voltage so that power can be transmitted at a voltage level that results in low costs, and can be distributed and used safely. In addition, they can provide matching of impedances, and regulate the flow of power (real or reactive) in a network.

- The physical basis of a transformer is mutual induction between two circuits linked by a common magnetic field.
- In its simplest form, it consists of two inductive coils which are electrically separated but magnetically linked through a path of low reluctance. The two coils posses high mutual inductance.
- If one coil is connected to a source of alternating voltage, an alternating flux is set up in the laminated core, most of which is linked with the other coil in which it produces mutually induced emf.

Constructionally, the transformers are of two general types, distinguished from each other merely by the manner in which the primary and secondary coils are placed around the laminated core.

a) Core type
b) Shell type

In the so-called core type transformer, the windings surround a considerable part of the core whereas in shell-type transformer, the core surrounds considerable portions of the winding.

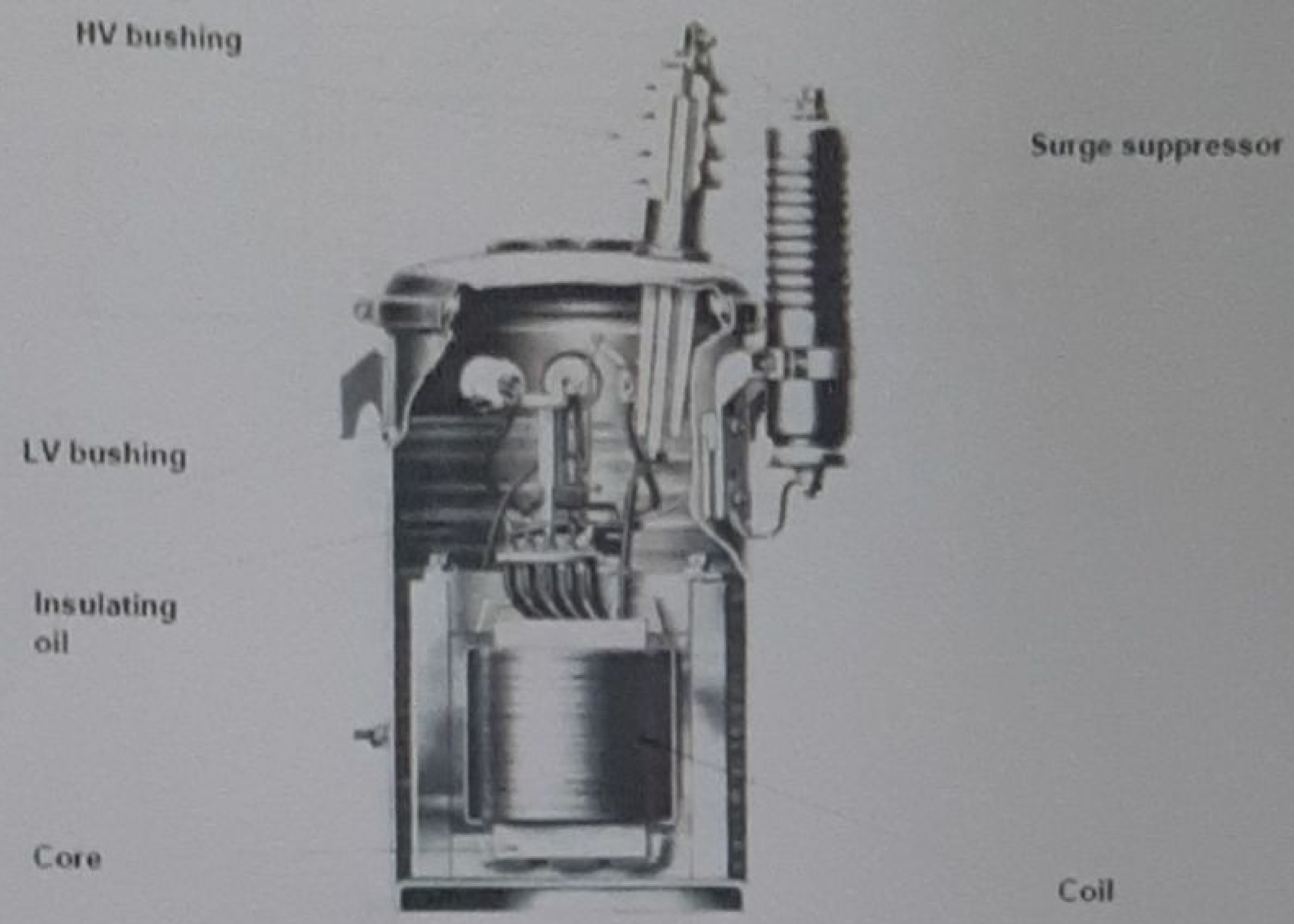


Fig.3.1 Physical diagram of a transformer

3.2 Elementary theory of an ideal transformer

An ideal transformer is one which has no losses i.e. its windings have no ohmic resistance, there is no magnetic leakage and hence which has no copper and core losses. An ideal transformer consists of two purely inductive coils wound on a loss free core.

In its simplest form it consist of, two inductive coils which are electrically separated but magnetically linked through a path of low reluctance. If one coil (primary) is connected to a source of alternating voltage, an alternating flux is set up in the laminated core, most of which is linked with the other coil in which it produces mutually-induced e.m.f. according to Faraday's Laws of Electromagnetic Induction. If the second coil (secondary circuit) is closed, a current flows in it and so electric energy is transferred (entirely magnetically) from the first coil to the second coil.

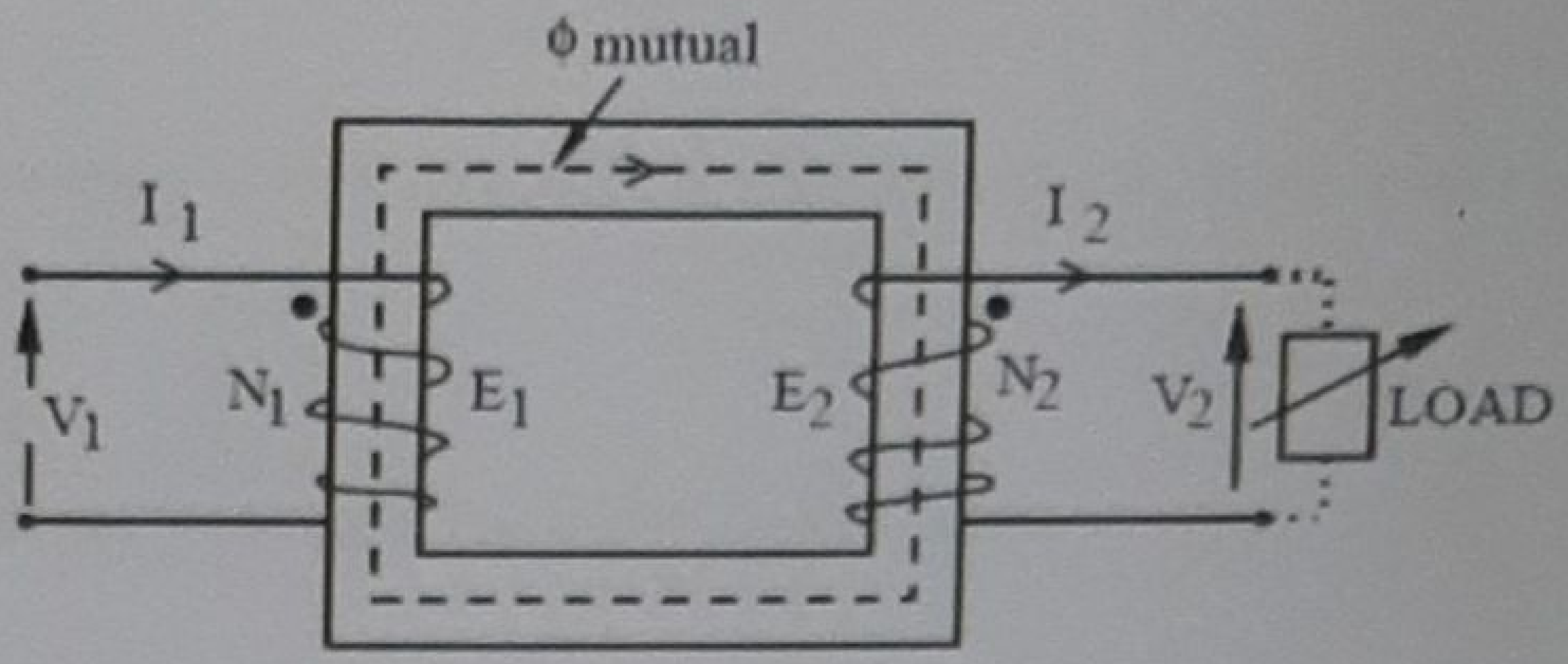


Fig.3.2 Elementary Transformer

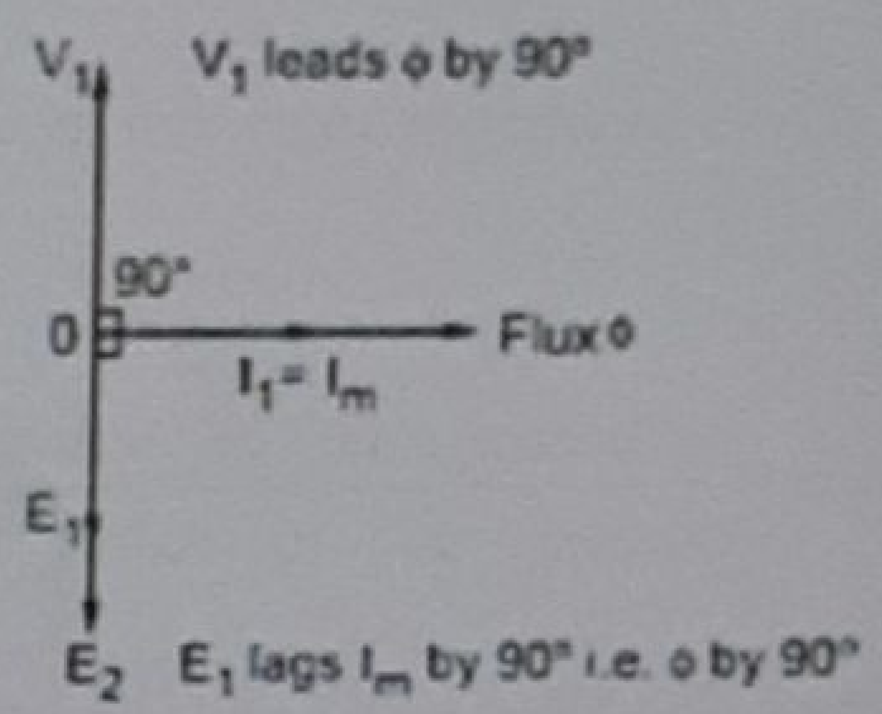


Fig.3.3 Vector representation of applied voltage, induced emf flux and magnetizing current of a single phase transformer

3.2 E.M.F. equation

Let, N_1 = No. of turns in primary

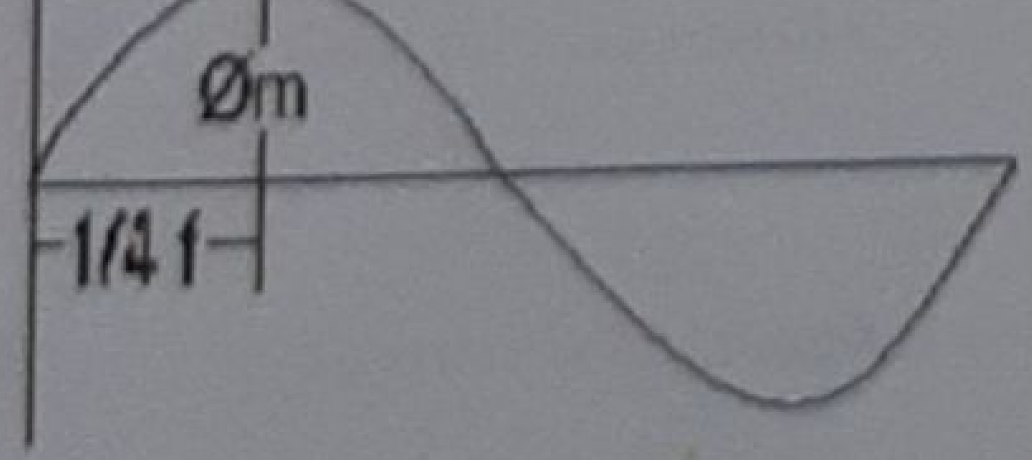
N_2 = No. of turns in secondary

ϕ_m = Maximum flux in core in webers = $B_m \times A$

B_m = Maximum flux density

A = Area

f = Frequency of ac input in Hz



The flux increases from its zero value to maximum value ϕ_m in one quarter of the cycle i.e. in $1/4f$ second.

The average rate of change of flux $= \frac{\phi_m}{1/4f} = 4f\phi_m$ wb/sec or volts

Now, rate of change of flux per turn means induced emf in volts.

Hence, average EMF/turn $= 4f\phi_m$ volts

If flux varies sinusoidally, then rms value of induced emf is obtained by multiplying the average value with form factor.

$$Form\_factor = \frac{rms\_value\_of\_ac\_quantity}{average\_value\_of\_ac\_quantity} = 1.11$$

Hence, rms value of EMF/turn $= 1.11 \times 4f\phi_m = 4.44f\phi_m$ volts

Now, r.m.s value of induced e.m.f in the whole of primary winding

= (induced e.m.f. / turn) x No. of primary winding

$E_1 = 4.44f\phi_m N_1$ ------------------- (i)

Similarly, r.m.s. value of e.m.f. induced in secondary is,

$E_2 = 4.44f\phi_m N_2$ ------------------- (ii)

Voltage transformation ratio

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

This constant K is known as voltage transformation ratio.

(i) If K>1, then the transformer is called step-up transformer.

(ii) If K<1, then the transformer is called step-down transformer.

3.3 Transformer with losses but no magnetic leakage

There are two cases, (i) when a transformer is on no load and (ii) when it is loaded.

3.4 Actual and approximate equivalent circuits

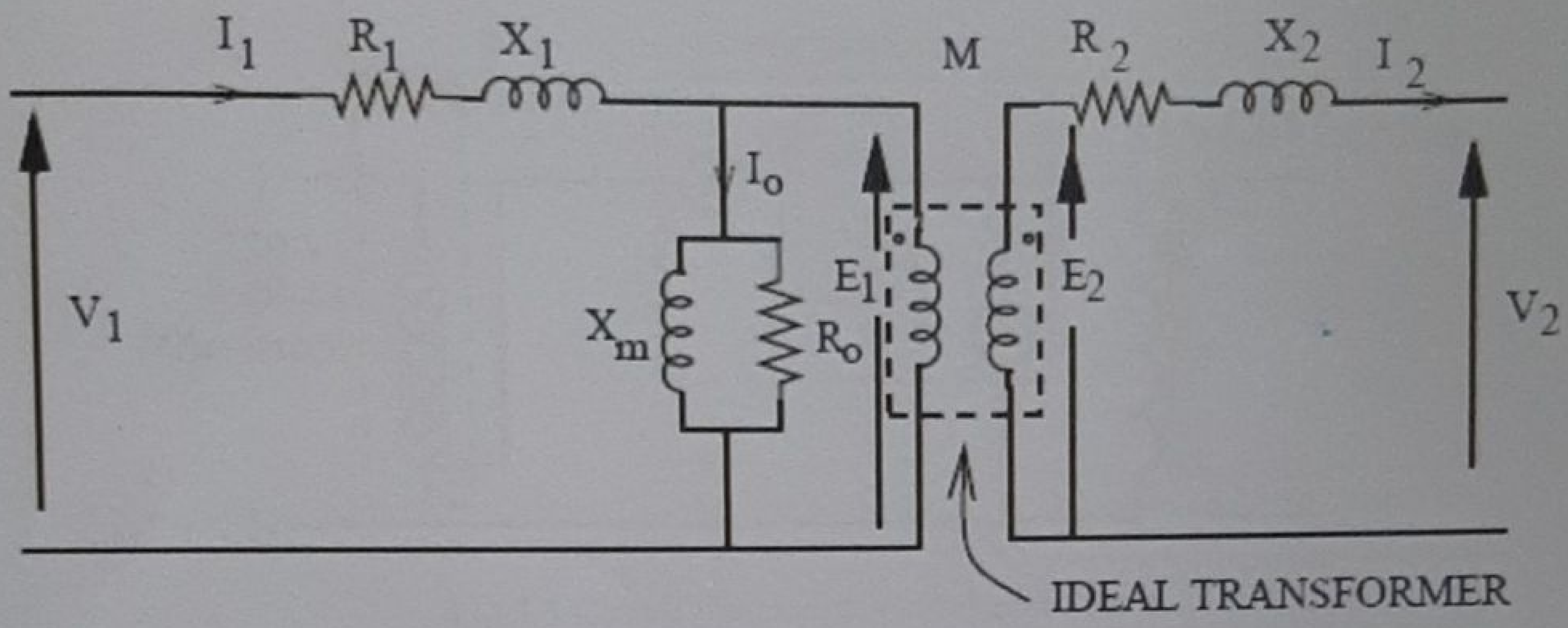


Fig. 3.3(a)

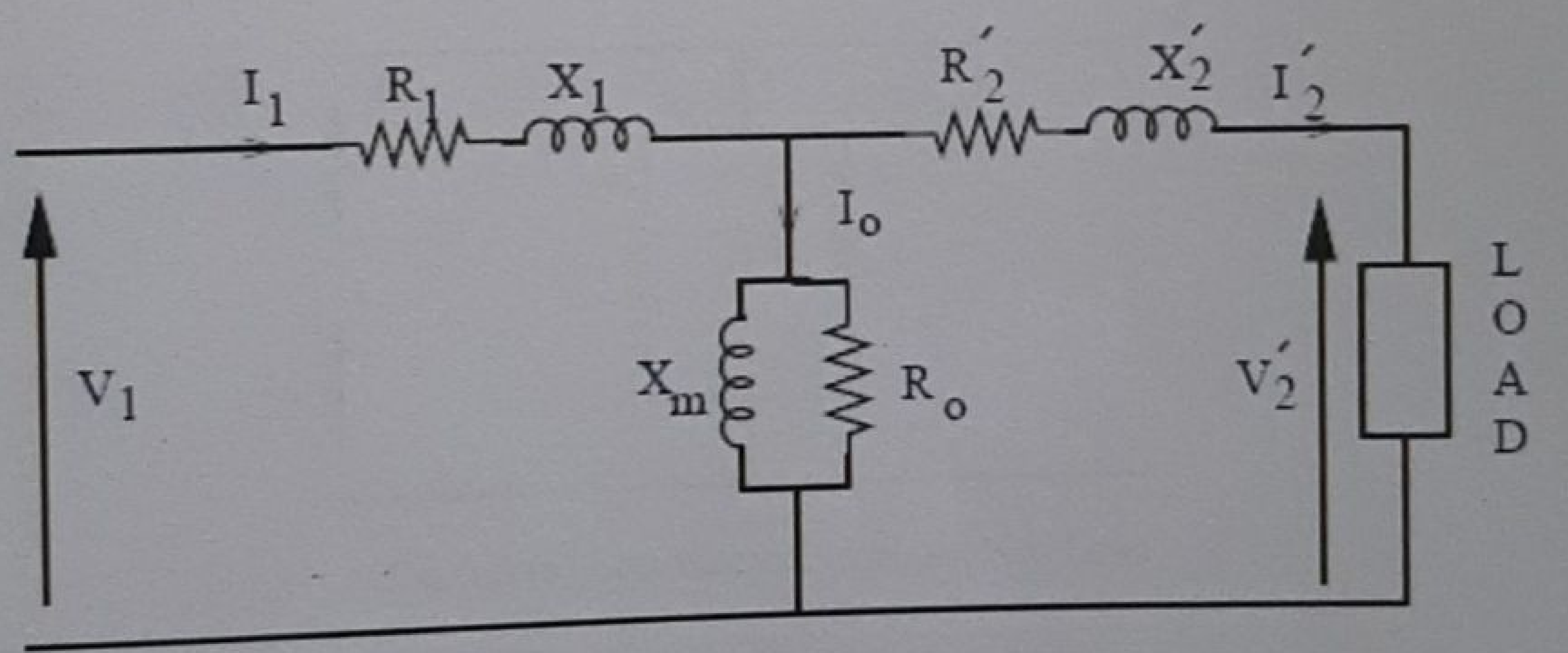
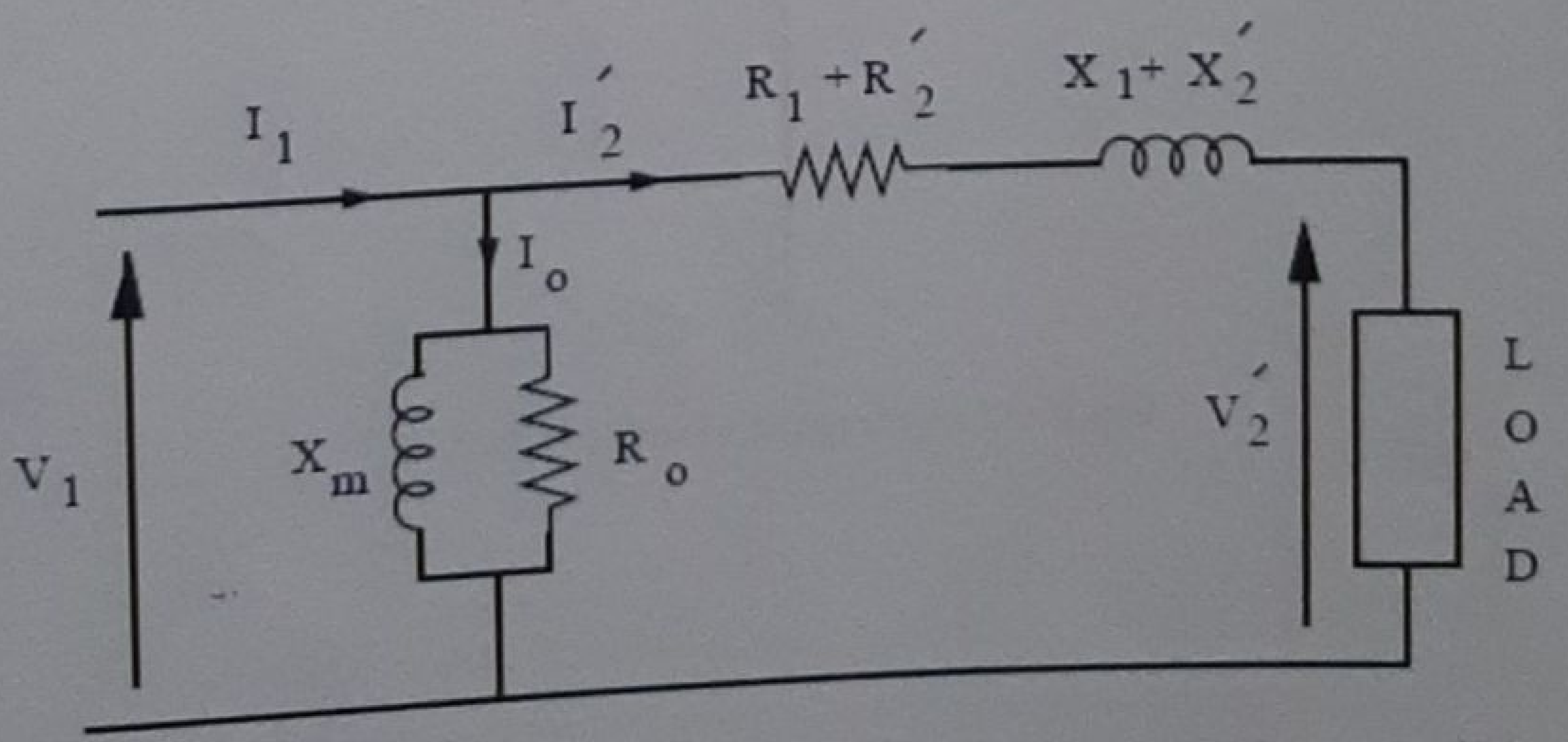


Fig. 3.3(b)



Scanned by TapScanner

Fig.3.4 Approximate equivalent circuit of transformer

3.5 Open and short circuit tests

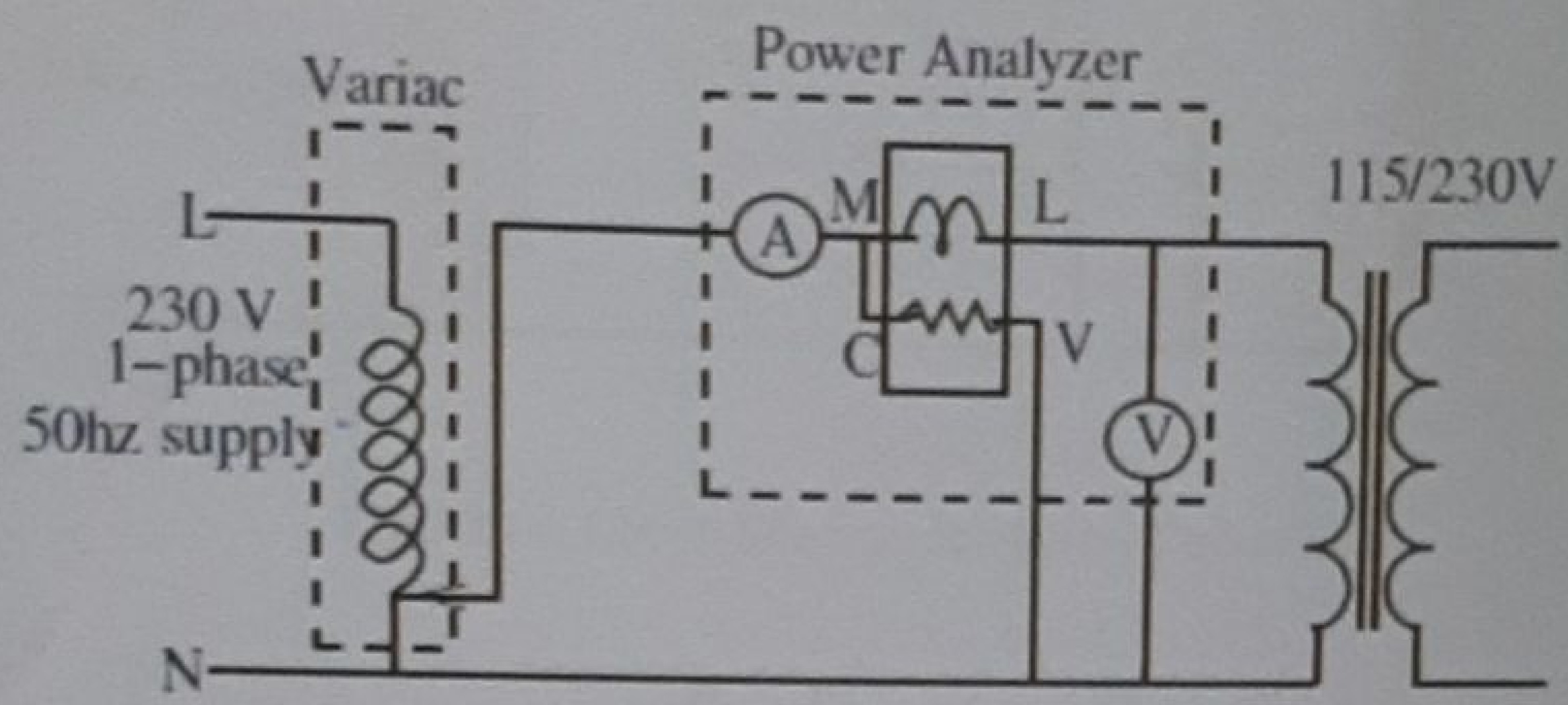


Fig.3.5 Circuit Diagram for No-Load Test

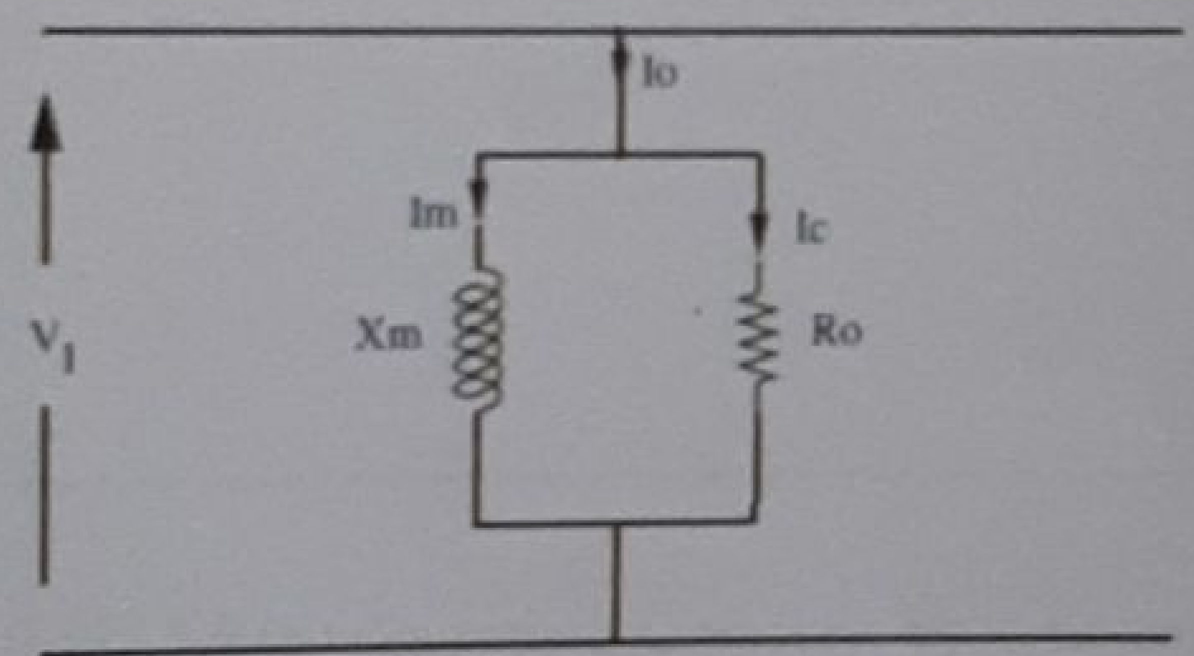


Fig.3.6 (a) Equivalent Circuit on No-Load

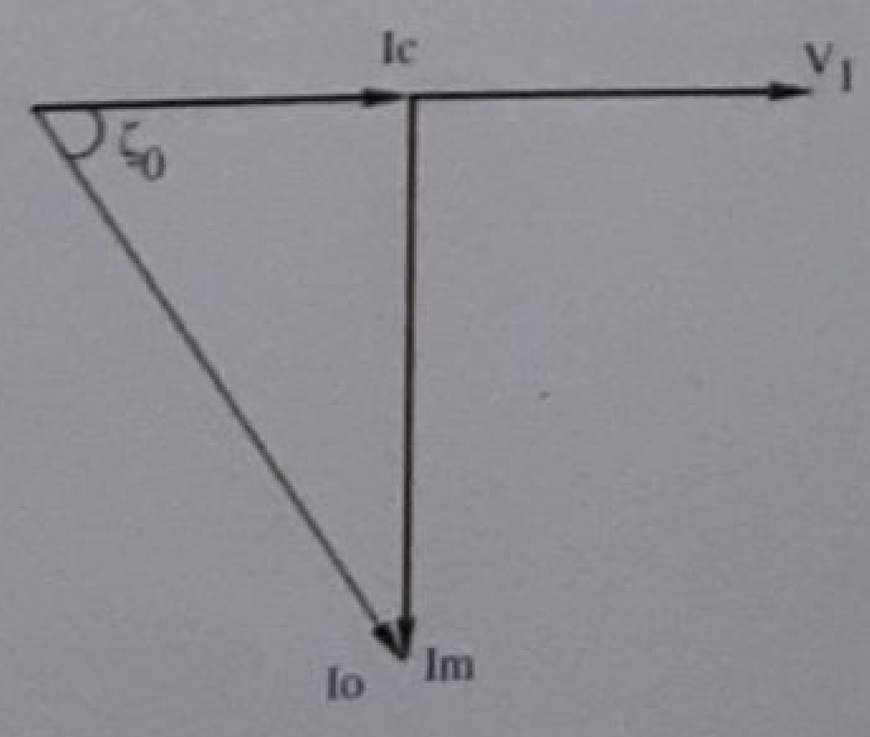


Fig.3.7 (b) Phasor Diagram on No-Load

Three Phase Transformer

In general, for transformation, transmission and utilization of electric energy, it is economical to use the three phase system rather than the single phase. For three phase transformation, two arrangements are possible. First is to use a bank of three single phase transformer and the second, a single three phase transformer with the primary and secondary of each phase wound on three lags of a common core. The advantages of a single unit of 3-phase transformer as compared to a bank of three single phase transformer are the cost is much less, occupies less floor space for equal rating and weighs less.

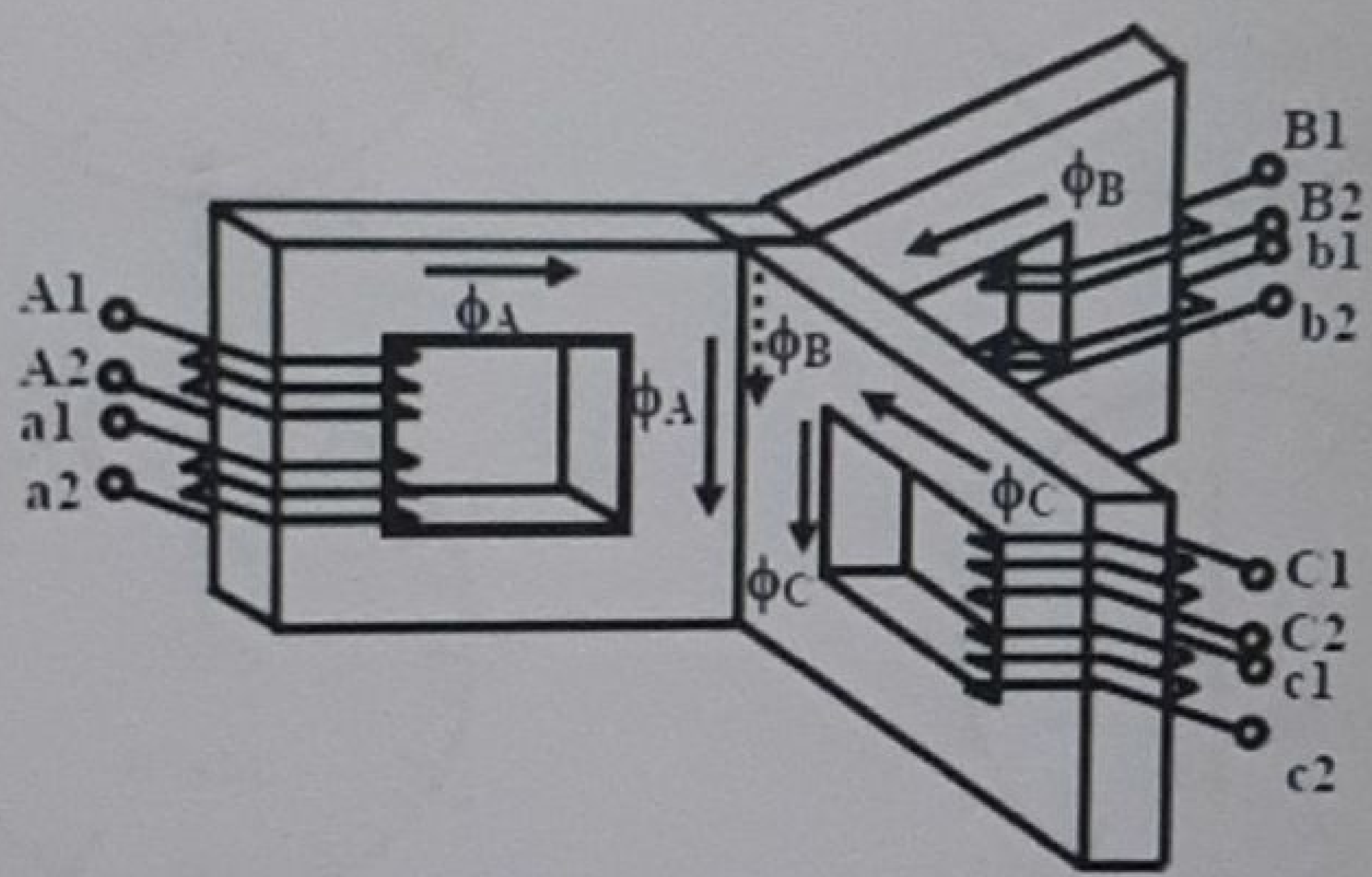


Fig.4.1 A conceptual three phase transformer

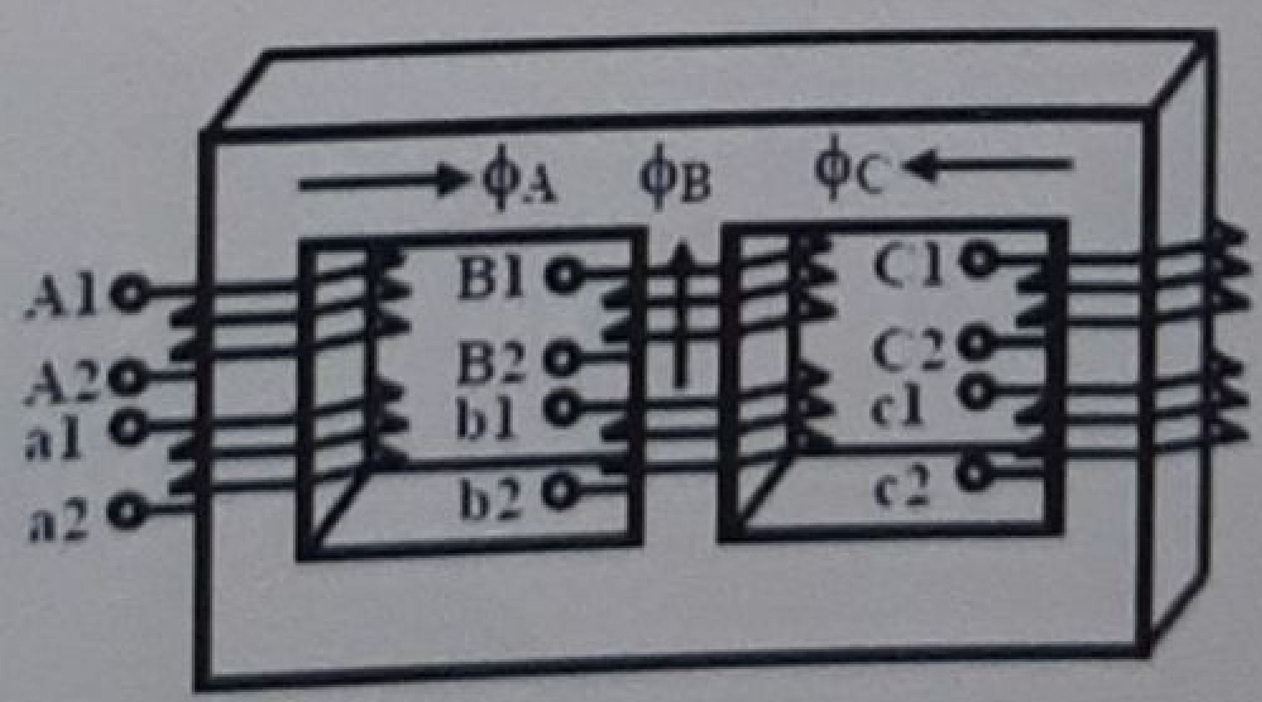


Fig.4.2 A practical three phase core type three phase transformers

4.1 Three phase transformer connections

A variety of connections are possible on each side of a 3-phase transformer. The three phases could be connected in star, delta, open delta or zig-zag star. Each of the three phases could have two windings or may have auto connection. Further, certain types of connections require a third winding known as tertiary.

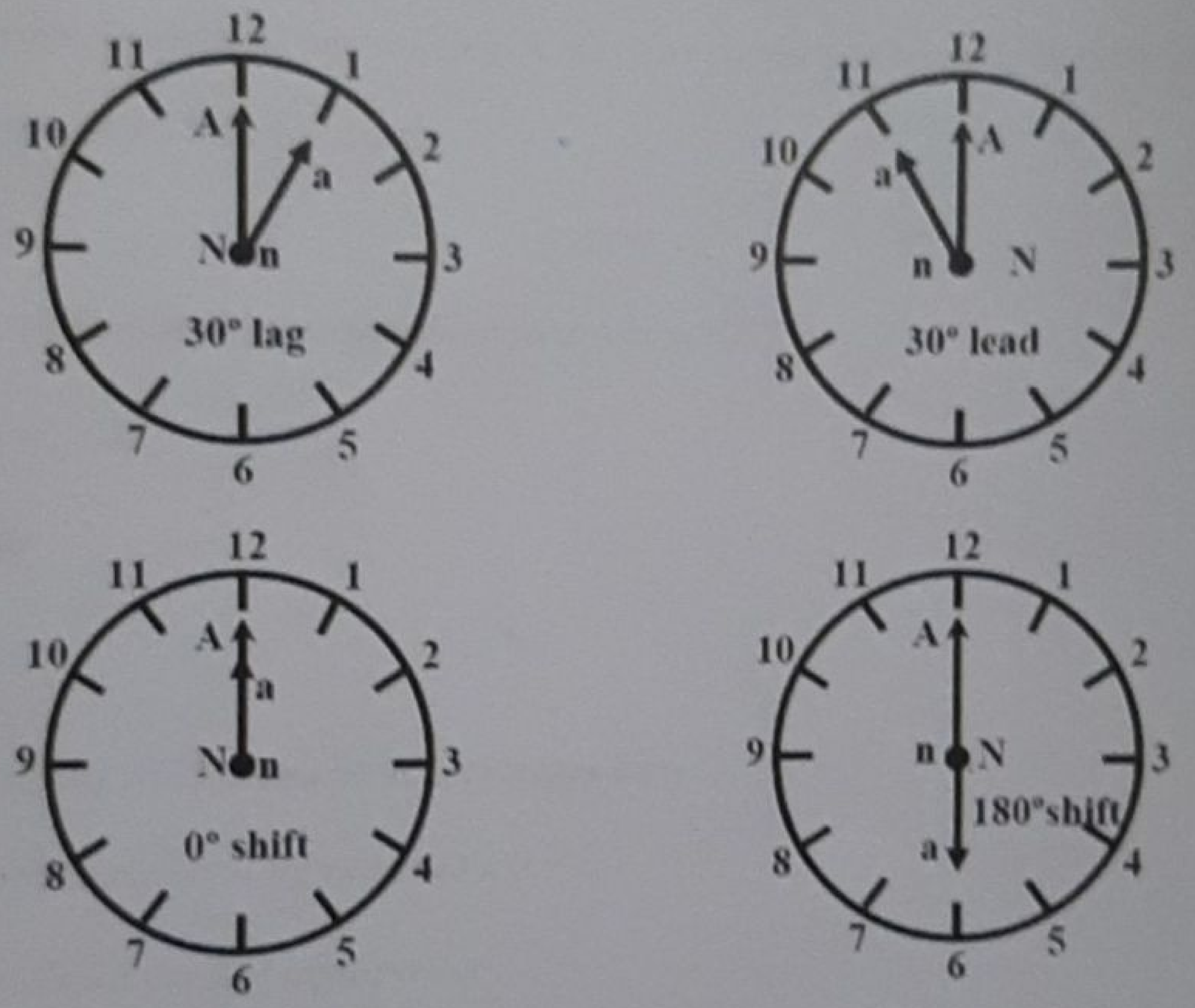


Fig.4.3 Clock convention representing vector groups

Any two winding transformer can be converted into an autotransformer either step-down or step-up. If we employ additive polarity between the high voltage and low voltage sides, we get a step-up transformer. If, however, we use the subtractive polarity, we get a step-down autotransformer. The connections are given in fig.2.

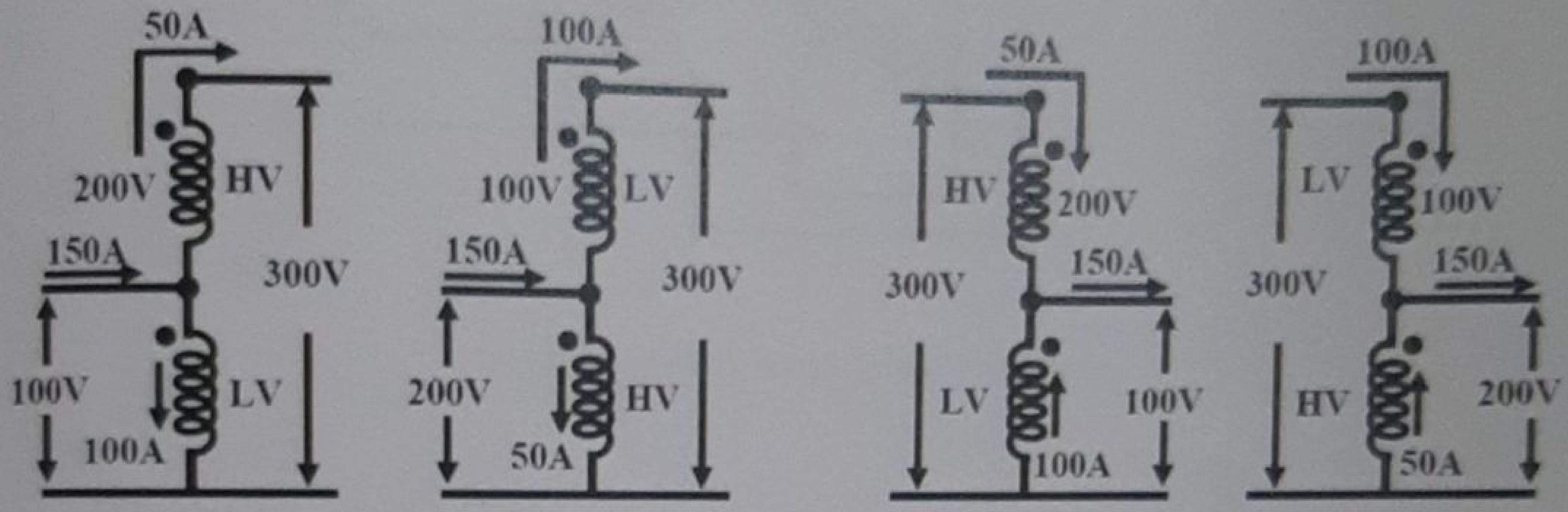


Fig.5.2 A two winding transformer connected as an autotransformer in various ways

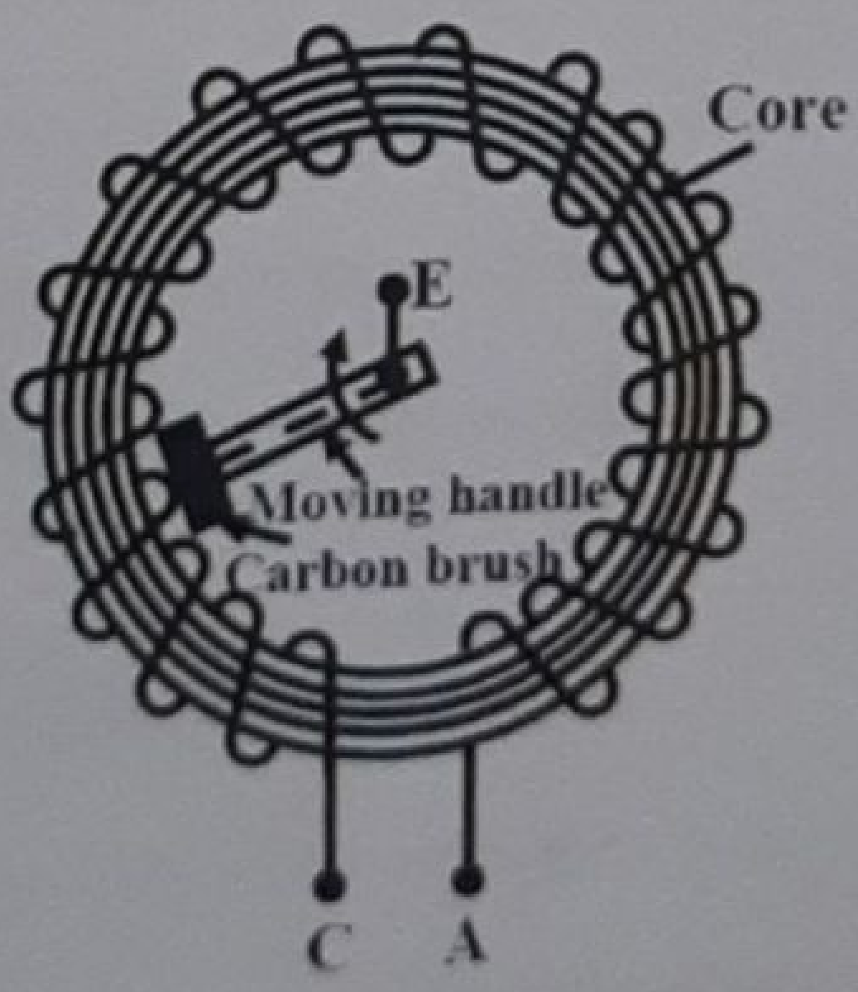


Fig.5.3 Autotransformer or Variac

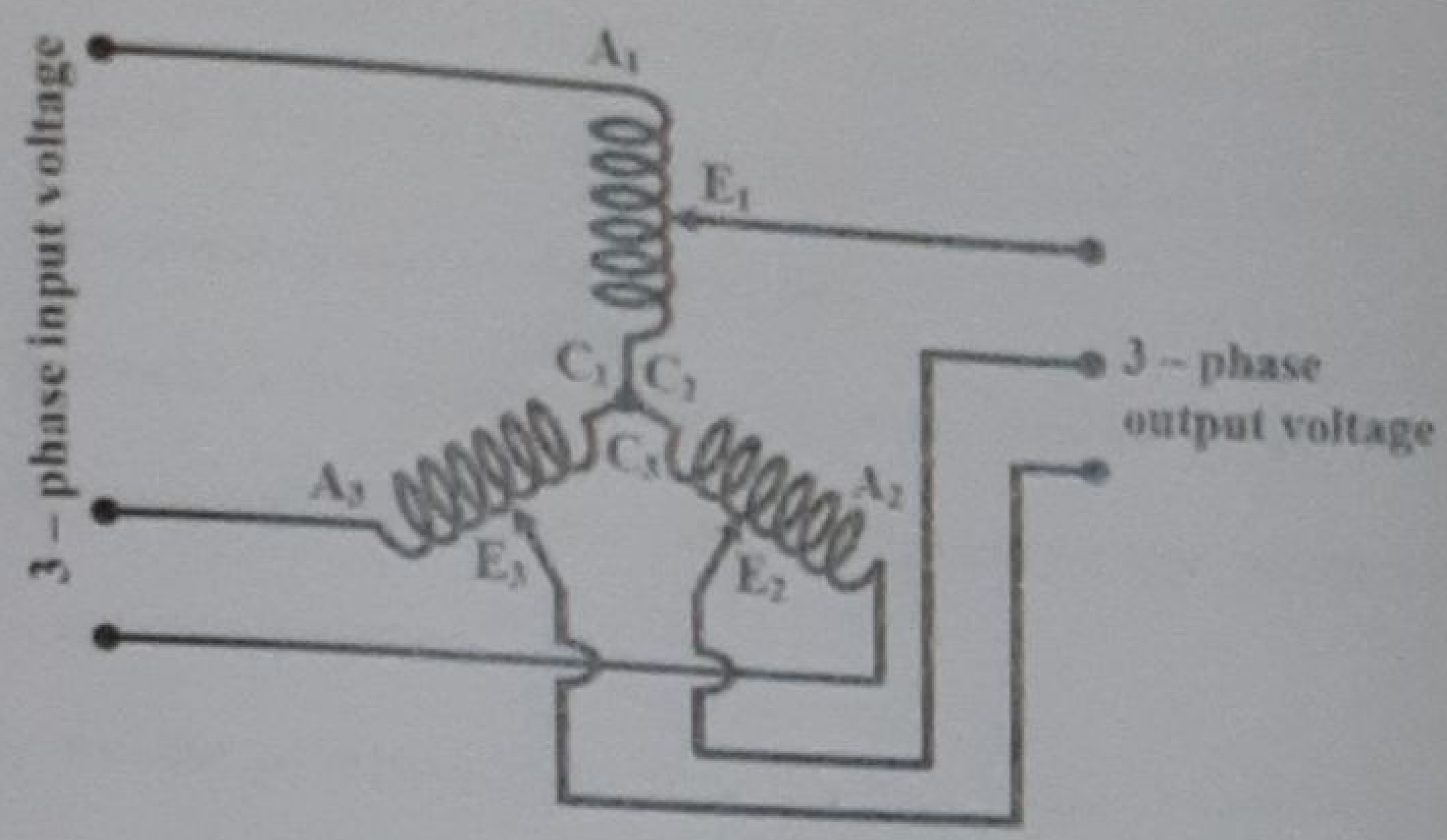


Fig.5.4 3 – Phase autotransformer connection

Synchronous Machines

A synchronous machine operates at constant speed in the steady state. Under steady state conditions, the rotating air gap field and the rotor in a synchronous machine rotate at the same speed, called the synchronous speed which depends on the frequency of the armature current and the number of field poles. Synchronous machines are used primarily as gemerators of electric power. In this case they are called alternators. Synchronous generators are the primary energy conversion devices of the worlds electric power systems today.

6.1 Construction of three phase synchronous machines

A synchronous machine consists of two main parts namely, an armature winding and a magnetic field, similar to a dc machine. The following are the main advantages of rotating field type synchronous machines.

(a) Two slip rings are required for the supply of direct current to the rotor while in stationary field type 3 to 4 slip rings would be needed.

(b) The power used in exciting the field system may be only about two percent of the ac output of the machine and that too is supplied at low voltage, thus it is easier and economical to design slip rings to carry this smaller power for the rotating field.

(c) The voltage generated in the armature is much higher and therefore greater insulation is required for the armature winding. Thus it is much easier to insulate the high voltage winding when it is mounted on a stationary structure.

(d) Note that by the use of stationary armature this high voltage insulation is not subjected to mechanical stress due to centrifugal forces. The end conductors of the armature winding can be braced securely in position thereby making it fit to withstand the large forces by sudden short circuit.

(e) The main connecting cables can be connected directly with the armature winding. With rotating armature, the current would have to be calculated by means of slip rings and with high voltage and large power, such collection, would pose serious problems.

(f) Rotating field is comparatively light and can be constructed for high speed operation.

(g) Cooling systems are comparatively easier.

6.1.1 Stator

The stator of a three phase synchronous machine consists of a stator frame, a slotted stator, which provides a low reluctance path for the magnetic flux. It has a distributed winding embedded in the slots similar to that of three phase induction machine.

6.1.2 Rotor

The rotor has a winding called the field winding, which carries direct current. The field winding on the rotating frame is normally fed from an external dc source through slip rings and bruses. Two types of rotors are used in synchronous machines, the cylindrical rotor and a salient pole rotor. Depending on the type of rotor used synchronous machines are broadly divided into two groups as follows:

- High speed machines with cylindrical (non- salient pole) rotors

- Low speed machines with salient pole rotors

The cylindrical rotor has one distributed winding and an essentially uniform air gap. These rotors are used in large generators with two or sometimes four poles and are usually driven by steam turbines. The rotors are long and have a small diameter. The features are,

- They have small diameters and very long axial length.
- Dynamic balancing is better.
- Operation is quieter and windage losses are less.
- The speed is 1000 to 3000 rpm.
- Used with steam turbines and steam engines.

The rotors of salient pole machines have concentrated winding on the poles and a non-uniform air gap. Salient pole generators have a large number of poles, sometimes as many as 50, and operate at lower speed. The alternators in hydroelectric power stations are of the salient pole type and are driven by water turbines. The rotors are shorter in length but have a large diameter. The speed is 120 to 400 rpm.

6.2 Equation of induced E.M.F.

Let, $\phi =$ flux per pole in weber

$z =$ total number of armature conductors or coil sides in series/phase $= 2T$

$T =$ no. of turns or coils per phase

$P =$ no. of generator poles

$f =$ frequence of induced emf in Hz

$N =$ rotor speed in revolutions per minute (rpm)

$K_d =$ distribution factor $= \dfrac{\sin(m\beta/2)}{m\sin(\beta/2)}$

K_c or $K_P =$ pitch or coil span factor $= \cos\dfrac{\alpha}{2}$

$K_f =$ form factor