Salahaddin University – Erbil

College of Engineering

Electrical engineering Department

Forth year power

Special Machine

Part Two

TWO PHASE CONTROL MOTOR (SERVO MOTOR)

A schematic diagram of a 2- phase control motor is shown in Fig (1.38)

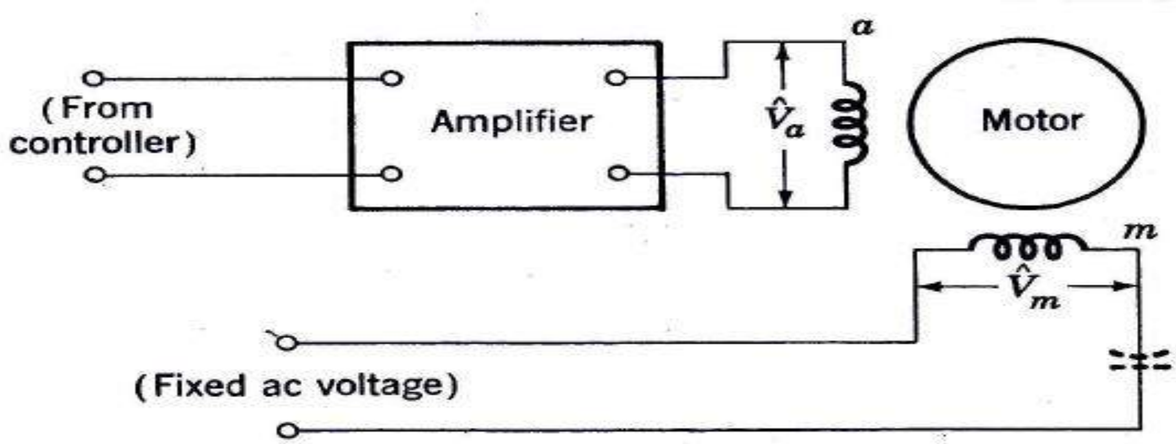


Fig (1.38) Two phase control motor (servo motor)

Vm: phase m of the motor is fixed, or reference phase **Vm,** is applied from a(Constant – voltage), (Constant-frequency) source.

Va : the auxiliary control phase, is supplied from magnetic –amplifier or soiled-state construction .

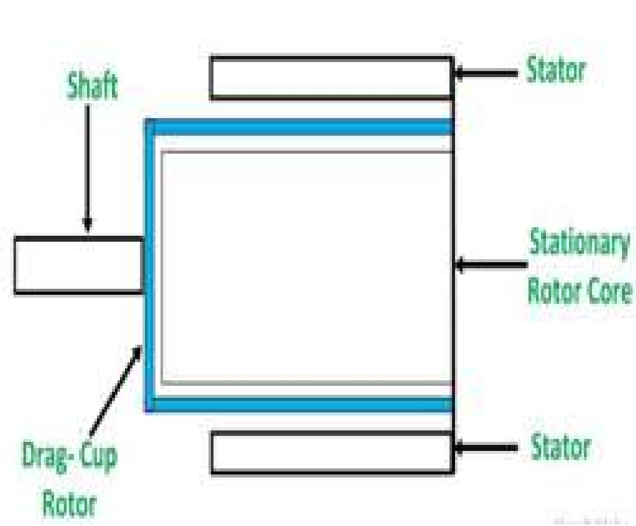
The **Va** amplitude is proportional to the input control signal:

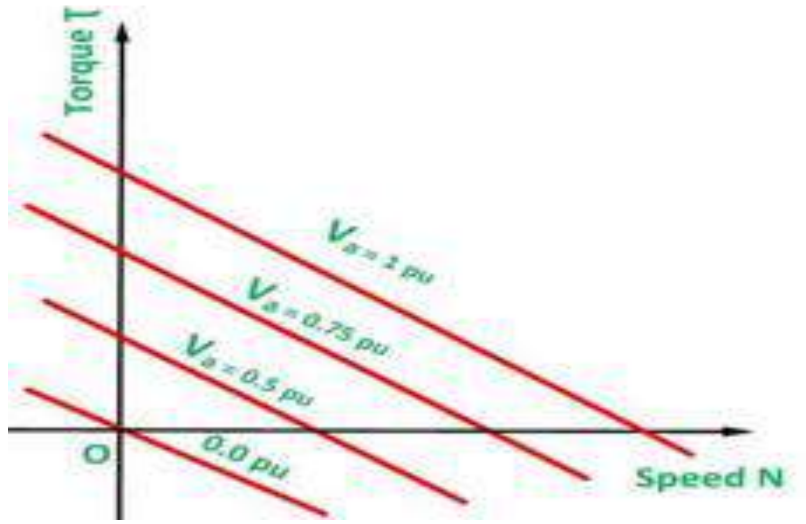
Va α input signal to amplifier

The Drag Cup Servo Motor

The motor response to a light control signal is improved by reducing the weight and inertia of the motor in a design known as the Drag Cup Servo motor which is shown in the Fig (1.39).

The rotor of Drag cup servo motor is made of a thin cup of nonmagnetic conducting material. A stationary iron core is placed in the middle of conducting cup. This arrangement completes the magnetic circuit. As rotor of the motor is made of thin material, its resistance will be high, which results high starting torque.





Fig(1.39)Drag Cup Servo Motor Fig (1.40) torque-speed curves of a servo-motor

Method of operation

Motor Operation, is like an unbalanced 2-phase induction Motor, and is suitable for control system up to a few hundred watts. The two voltages, reference voltage (**Vm**) and control voltage (**Va**) must be in synchronism, which means both of them must be drawn from the same source.

They(**Vm &Va**),must also made to be approximately in time quadrature(i.e 90 Phase shift), The control phase voltage is shifted in phase by 90° from the reference phase voltage by using two methods:-

1- By introducing phase 90° shift in the amplifier circuit.

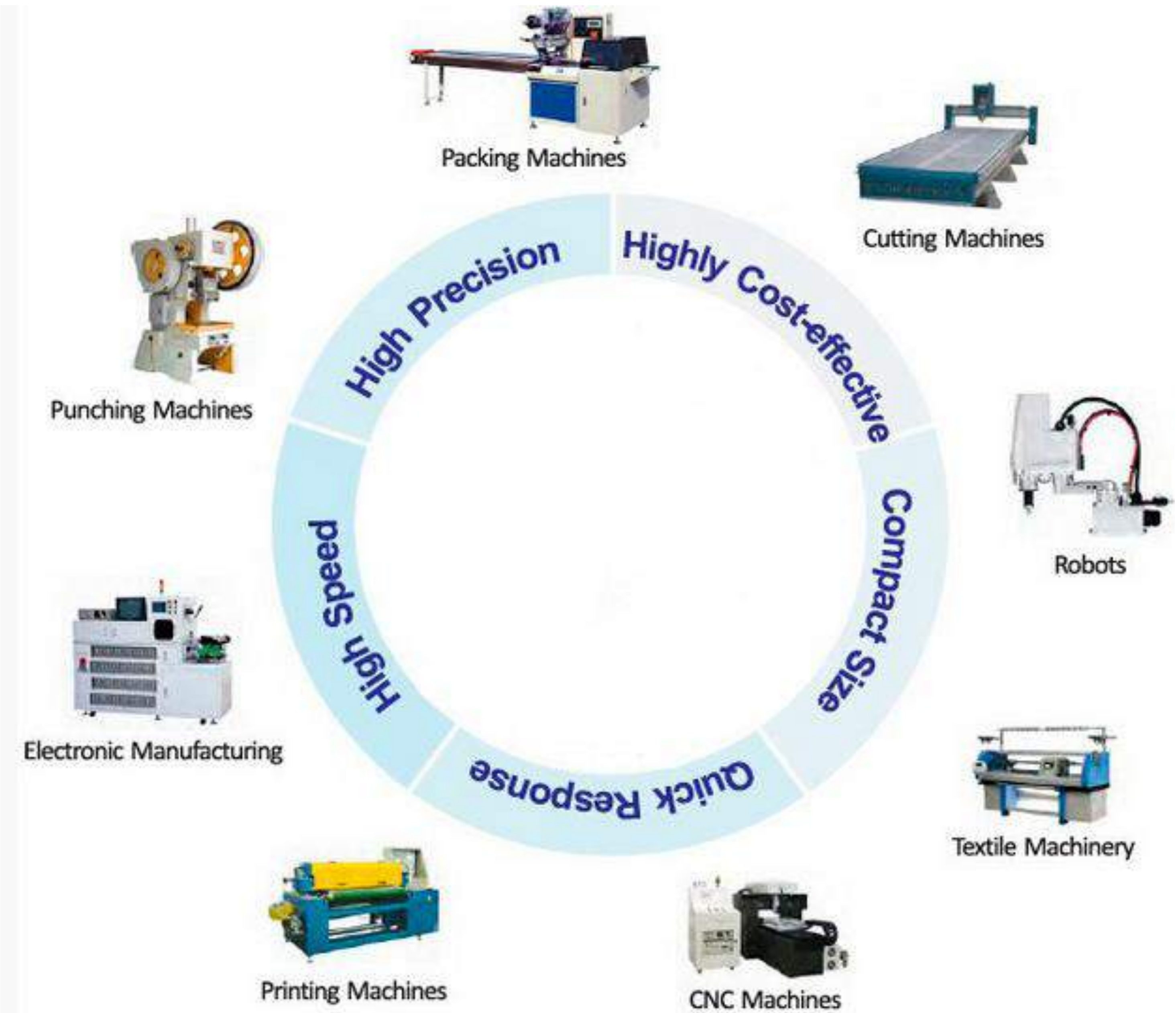
2- Connecting a suitable capacitor in series with reference phase (**M**).

When **Va** leads **Vm** by approximately 90° rotation in one direction is obtained, but if **Va** lags **Vm**, rotation in the other direction result.

The Torque Slip Characteristic

For 2-Phase motor. The torque can be easily controlled by varying magnitude of ac voltage applied to control phase (**Va**), with unity reference voltage (**Vm** =1p.u). For stable operation, torque-speed of a Servo-Motor, shown in Fig (1.40), be linear with negative slope (torque reducing within creasing speed).This indeed is the useful region of operation employed in position control systems. Desired linear characteristic of servo motor is obtained by designing a high resistance rotor so that max. Torque occurs at a slip of – 0.5 or so. High resistance also imparts another important feature, it does not develop a single-phasing torque which disturb control characteristic of the motor.

Applications of Servo Motor



HYSTERSIS MOTOR

The phenomenon of hysteresis can be used to produce mechanical Torque in Hysteresis motor which is defined as**;** a single phase synchronous motor having cylindrical rotor, and works on hysteresis losses induced in the rotor of hardened steel. Hysteresis motors are special A.C. motors (single or 3- phase) stator, can operate at synchronous speed without Rotor field winding.

Construction

A hysteresis motor is constructed of 4 - main components, Fig (1.41):

1. Stator (Single phase stator winding)
2. Rotor
3. Shaft.
4. Shading coil, (if the stator have shaded pole).

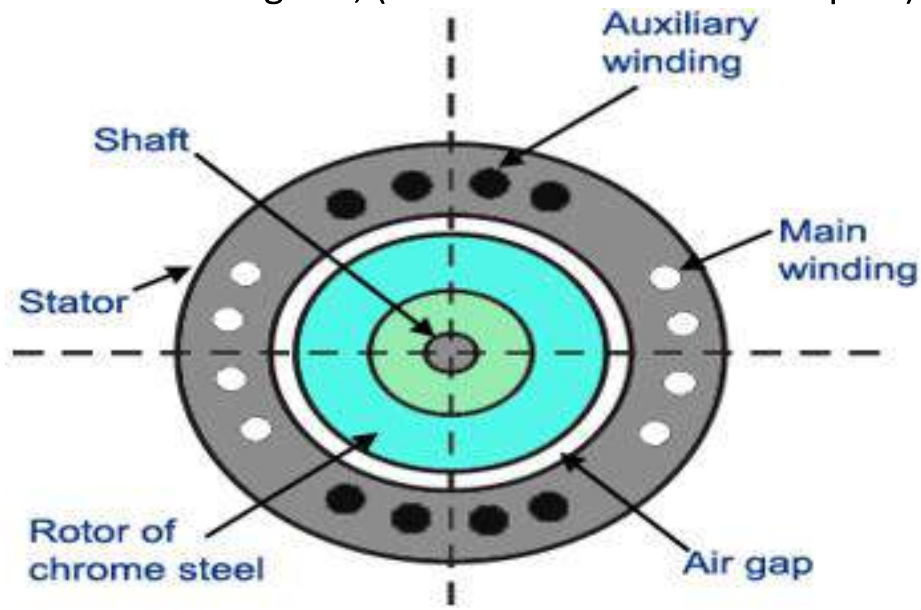


Fig (1.41) cross – section of Hysteresis motor

The Stator is designed in a particular manner to produce synchronous revolving field from single phase supply. It is slotted carrying distribution winding designed to produce as nearly as possible sinusoidal space distribution of flux m.m.f **F1**, Fig (1.42). In 1–phase motors, Stator carries two windings, (a) main winding (b) auxiliary winding. And stator winding usually are a permanent- split capacitor type

Motor Fig (1.43). In another type of hysteresis motor design the stator holds poles of shaded type.

The Rotor of hysteresis motor is made of magnetic material with high hysteresis loss property, like chrome, cobalt steel. Hysteresis loss becomes high due to large area of hysteresis loop .The magnetic cylindrical portion of the rotor does not carry any winding or teeth, is assembled over shaft through arbor of nonmagnetic material like brass. Also the Rotor is provided with high resistance to reduce eddy current loss.

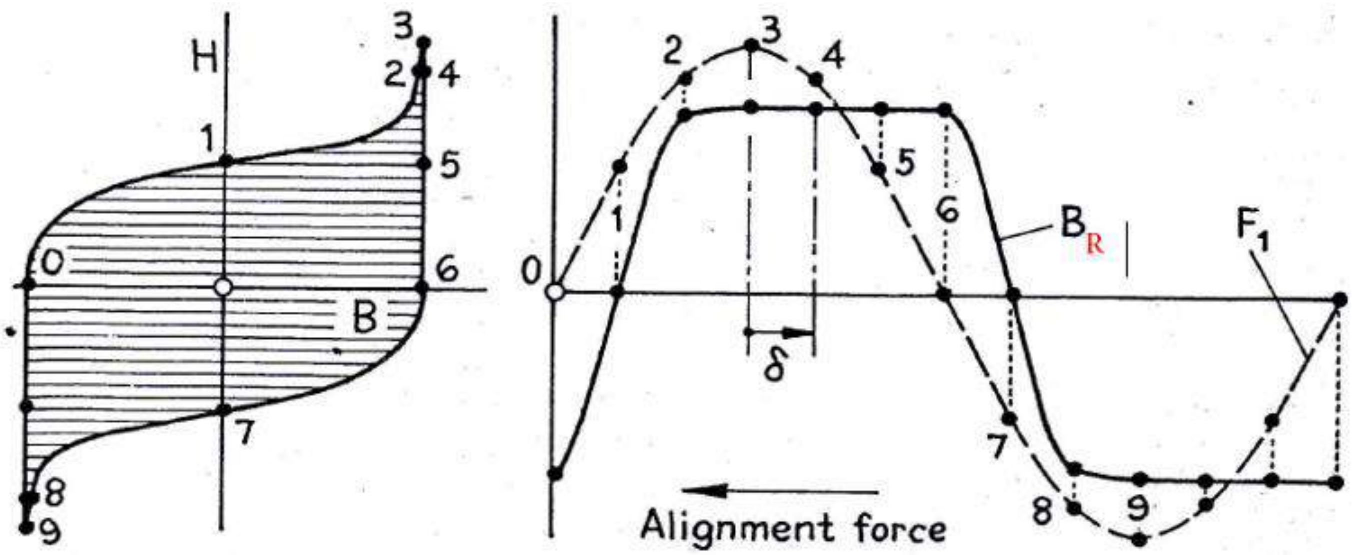


Fig (1.42) Flux distribution

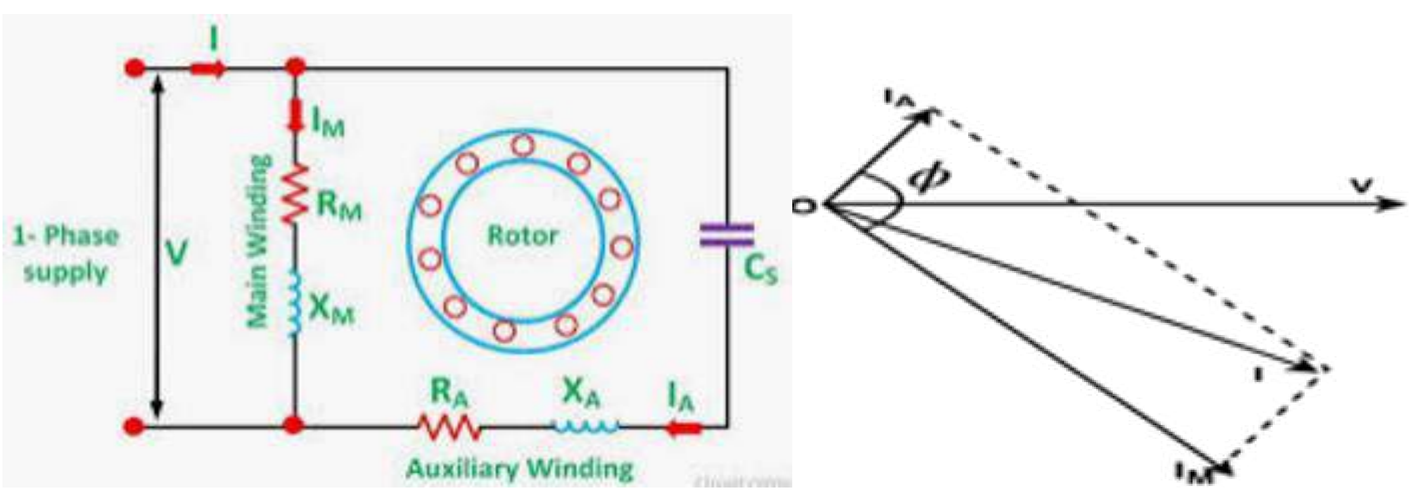


Fig (1.43) Permanent split – capacitor motor

Method of operation

The stator produces a rotating magnetic field approximately constant in space wave form and revolving at synchronous speed .For a 2-pole stator, the instantaneous magnetic condition in air Gap and rotor are indicated in Fig (1.44a).

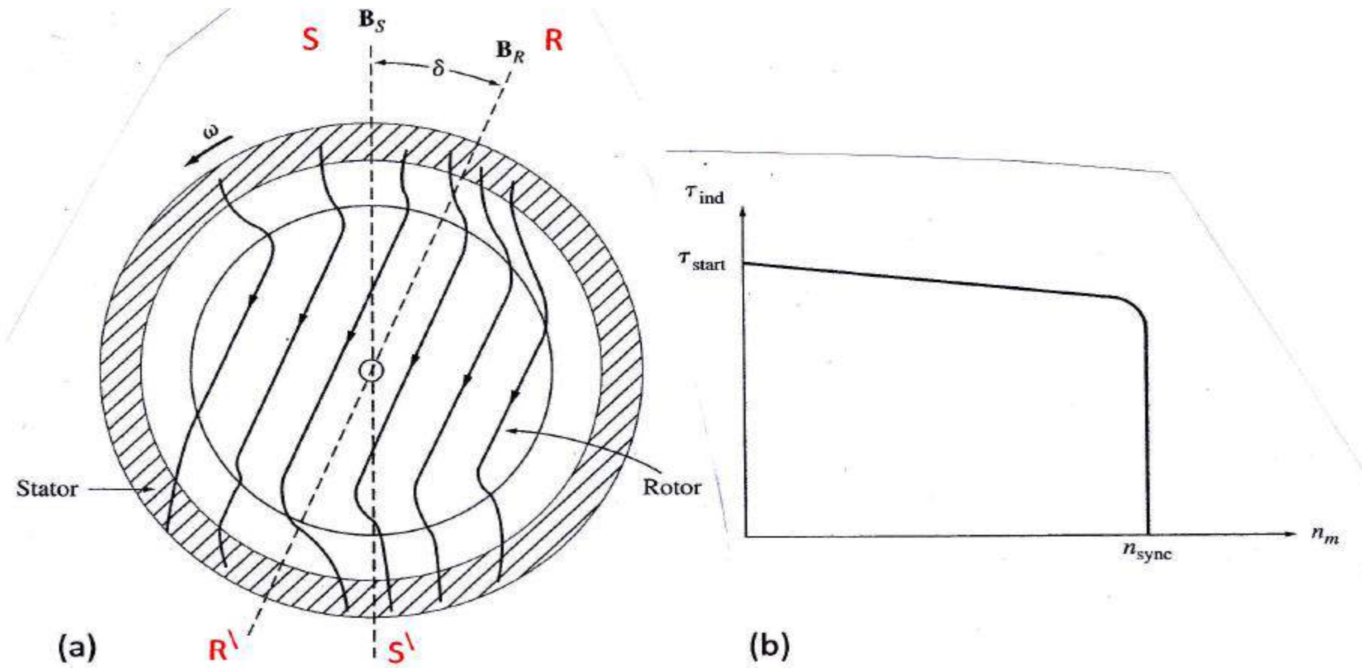


Fig (1.44) : a) construction of hysteresis motor ; b) Torque speed characteristic

SS- (m.m.f F1): stator m.m.f. Axis wave revolves at synchronous speed.

RR- rotor flux wave axis.

Because hysteresis ,the rotor magnetization lags behind **F1**,and therefore axis **RR** lags behind axis of stator m.m.f (**F1**) wave by the hysteretic lag angle(**δ**).If the rotor is stationary, the produced starting torque is proportional to (**δ**) :-

$$\tau_{ind} \propto \delta$$

τind - Induced Torque **δ-** Torque angle

The rotor will accelerate if torque of the load is less than developed Torque of the motor .While the Rotor accelerates , the lag angle (**δ**) remains constant , since the angle (**δ**) Depends merely on rotor hysteresis loop, therefore, the motor develops constant Torque right up to synchronous speed.

Flux density Distribution (**Br**) and stator travelling wave m.m.f.(**F1**) are shown in Fig (1.42).

The hysteresis effects cause the rotor flux density (**Br**) to be displaced in angular position from (**F1**) by an angle (**δ**).

The sequence of excitation through the values **0, 1, 2,** produces corresponding changes of (**Br**).

The developing Torque depends on a displacement angle (**δ**) between **F1 & Br**, and it is independent of speed, i.e cyclic Hysteresis loop is not affected by slip(**S**).

The Equation of Hystersis Torque

Hysteresis power loss in the rotor of the hysteresis motor is given by

$$P_h = K_h \times f_r \times B^n_{max} \qquad ....(1.12\ )$$

Where,

f_r : is the frequency of flux reversal in the rotor (Hz).

B_{max} : is the maximum value of flux density in the air gap (T).

P_h : is the heat-power loss due to hysteresis (W).

k_h : is the hysteresis constant. Hysteresis Torque

The Hysteresis Torque equation can be derived as:

$$P_{mech} = P_h\,((1 - s) / s))$$

$$P_h = K_h \times f \times B^n_{max.}$$

$$(\,T_h \times n_r\,) / 5252 = K_h \times f \times B^n_{max.} \times ((1\text{-}s) / s)$$

$$n_r = n_s(1-s) \quad \rightarrow\rightarrow \quad f_r = s\, f_s$$

$$T_h = (5252 \times K_h \times B^n_{max} / n_s)$$

$$n_s = 120\, f_s / P$$

$$T_h = (5252\, K_h \times B^n_{max}) / (120/P) \qquad ....(1.13)$$

From hysteresis torque equation (1. 13), it is clear that hysteresis torque is independent of frequency and speed.

Torque slip characteristic

Starting behavior of a hysteresis motor is like a single phase induction motor and running behavior is same as a synchronous motor. When rotor speed reaches near the synchronous speed, the stator pulls the rotor into synchronism .Rotor poles are attracted towards the moving stator poles and runs at synchronous speed .Torque-Speed of hysteresis motor can be explained as, Fig (1.44b), the torque is almost constant for starting, running condition up to synchronous speed. Operates noiselessly with constant speed.

Types of Hysteresis Motors

According to construction there are various types of hysteresis motor:

1. Cylindrical hysteresis motors: It has cylindrical rotor.
2. Disk hysteresis motors: It has annular ring shaped rotor.
3. Circumferential-Field hysteresis motor: It has rotor supported by a ring of nonmagnetic material with zero magnetic permeability.
4. Axial-Field hysteresis motor: It has rotor supported by a ring of magnetic material with infinite magnetic permeability.

Advantages of Hysteresis Motor

*No teeth, no rotor winding, no mechanical vibrations during its operation.

*quiet operation is and noiseless as there is no vibration.

*It is suitable to accelerate inertia loads.

Multi-speed operation can be achieved by employing gear train.

Disadvantages of Hysteresis Motor

- Hysteresis motor has poor output that is one-quarter of output of an induction motor with same dimension.
- Low (efficiency, Torque, and power factor).
- This type of motor is available in very small size only.

Applications of Hysteresis Motor

Hysteresis motors have many applications, including:

1. Sound producing equipment's.
2. Sound recording instruments.
3. High quality record players
4. Timing devices, and Electric clocks.
5. Tele printers.

Example:-

A small 60 HZ hysteresis clock motor possesses 32 poles .In making one complete turn with respect to the revolving field , hysteresis loss in rotor=(0.8J).

Calculate:

A) The pull - in and pull – out torques.
B) The maximum power output before the motor stalls.
C) The rotor losses when the motor is stalled.
D) The rotor losses when the motor runs at synchronous speed.

Let us define:

The hysteresis loss per one revolution is (E_h) joules, and the field rotates at (n) revolution per minute.

The energy dissipated in the rotor per minute is:

W = revolution per minute × loss per one revolution

$= \mathbf{n \times E_h}$ .... (1)

The corresponding power (dissipated as heat) P_h is:

P_h = (energy dissipated) / Time = **W / t** .... (2)

P_h – Power (watt) : **W** – Energy done (J) : **t** – time (sec.)

$P_h = (n \times E_h) / 60^o$ (watt) .... (3)

However, power dissipated in rotor only come from mechanical power:

$P_{mech} = \omega \times t = (2\pi \times n \times T) / 60 = (n \times T) / 9.55$ ....(4)

P_{mech} –mechanical power (watt)

T – Torque (N.m) **n** – Speed of rotation (r / min)

9.55 – a constant to take care of units (Exact value = **30 /π**)

Because ($P_{mech} = P_h$) , we have

$(n \times T) / 9.55 = (n \times E_h) / 60^o$ .... (5)

Whence:

$T = E_h / 6.28$ = ... (6)

Where: **T** – Torque Exerted on the rotor (N.m)

E_h – hysteresis Energy dissipated in the rotor per turn (J / r)

6.28 – constant (exact value =2 π).

Solution:

A) The pull in &pull out Torque are about equal in a hysteresis motor : Eqn (6)

T = $\mathbf{E_h}$ / 6.28 →→ = 0.8 / 6.28 = 0.127 (N.m)

B) The max. power using Eqn (4)

P = (**n** × **T**) / 9.55

The synchronous speed ns:

n = **ns** = (120×**f**) / **P**

= (120 × 60) / 32 = 225 r / min

P = (225 × 0.127) / 9.55 = 3 watt →→ = 1 /250 h.p

C) When the motor stalls .The rotating field moves at 225 (r /min) with respect to the motor.

The energy loss per minute is therefore:

W = 225 × 08 = 180 J

The power dissipated in the rotor is:

P = **W** / **t** = 3 watt

D) There is no energy loss in the rotor when the motor runs at synchronous speed. Because the magnetic domains no longer reverse.

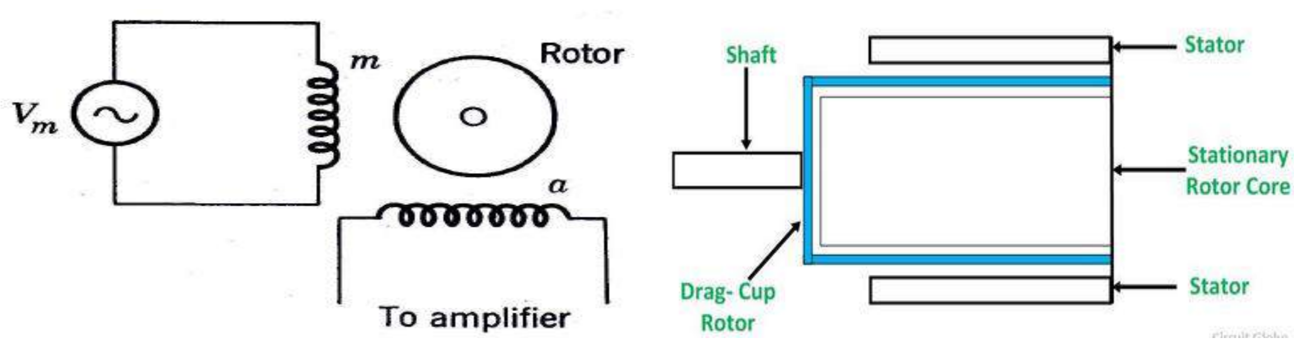
TACHOMERTERS

The tachometer use for measuring the rotational speed or angular velocity of the machine which is coupled to it. It works on the principle of relative motion between the magnetic field and shaft of the coupled device.

A.C TACHOMERTERS

A small 2 phase induction motor may be used for a feedback control system to measure shaft angular velocity, which is proportional to a feedback signal of carrier frequency amplitude, and it is often desirable that this measure be in the form of constant frequency. To achieve a low-inertia, a rotor drag-cup construction is commonly employed, Fig (1.45b).

The schematic diagram is shown in Fig (1.45 a)



(a) The schematic diagram (b) rotor drag-cup

Fig (1.45) 2 – phase A.C TACHOMERTER

m –Winding of reference field (fixed field).

a –auxiliary winding (control field winding), this phase (**a**) is left open-circuited.

The voltage across phase (**a**) is proportional to rotor speed

Method of operation

The winding (**m**) is energized from suitable alternating voltage with Constant magnitude & Constant frequency, then a voltage of the same frequency is Generated in the auxiliary winding (**a**).This generated voltage is applied to high impedance input circuit of an amplifier, therefore winding (**a**) considered as open – circuited.

The electrical requirements are, ideally that the magnitude of the signal voltage generated in winding (**a**) it should be linearly proportional to the speed:

$$V_a \; \alpha \; \omega \qquad (\omega - \text{speed})$$

Operation of A.C Tachometer , can be visualized in terms of double – Revolving field theory.

Equivalent circuit of A.C Tachometer is the same of a small single phase induction motor

The voltages Generated in winding (**m**), by the forward and backward flux waves, respectively, these flux waves also generate voltage in the auxiliary winding.

Let: **Na** = number of effective turns in windings (**a**)

Nm = number of effective turns in windings (m)

IF: **A = Na / Nm,** and

Va = The voltage generated in winding (**a**).

Vm = The voltage generated in winding (m).

$$V_a = (N_a / N_m) \times V_m = A \times V_m \quad ....(1.14)$$

A.C – Tachometer should be small, and its inertia also should be small when rapid speed variation are encountered. Depends on natures of the induced voltage, electrical tachometer is categorized into two types.

*AC Tachometer Generator * DC Tachometer Generator.

DC Tachometer Generator

The main parts of DC tachometer generator are, Permanent magnet, armature, commutator, brushes, variable resistor, and moving coil voltmeter. The machine whose speed is to be measured is coupled with the shaft of DC tachometer generator .Fig (1.46)

The DC tachometer works on the principle that when a closed conductor moves in the magnetic field, EMF induces in the conductor. The magnitude of induced emf depends on flux link with the conductor and the Shaft speed.

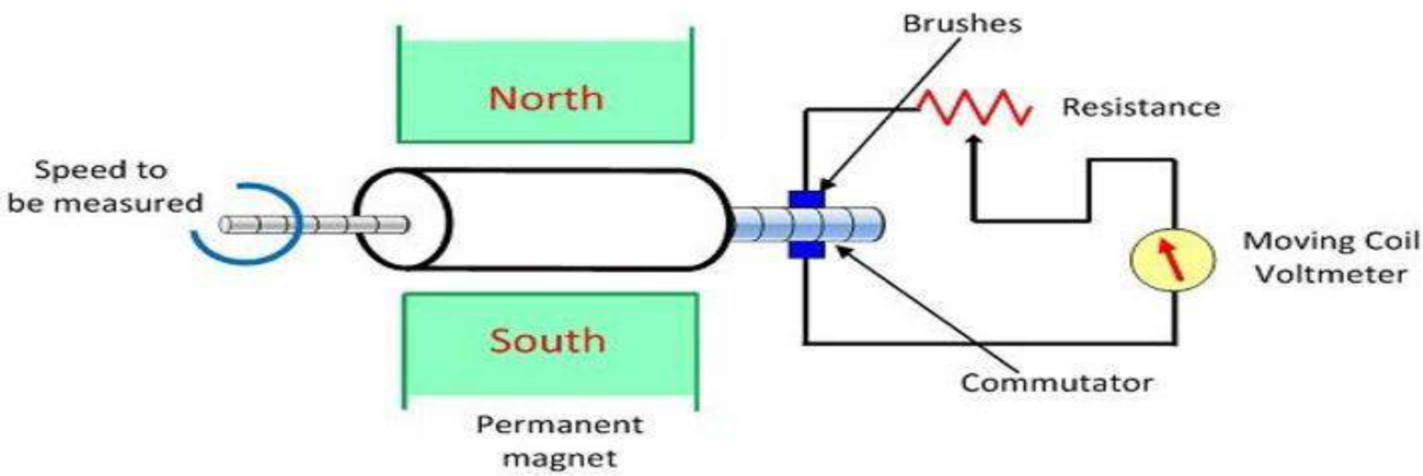


Fig (1.46) DC tachometer generator.

Armature of DC generator revolves between a constant field of permanent magnet. The rotation induces the emf in the coil. The magnitude of the induced emf is proportional to the shaft speed.

The commutator converts the alternating current of the armature coil to the direct current with the help of the brushes. The moving coil voltmeter measures the induced emf. The polarity of the induced voltage determines the direction of the shaft motion. The resistance is connected in series with the voltmeter for controlling the heavy current of the armature.

The emf induces in the dc tachometer generator is given as:

$$E_a = (\phi \times P \times N \times Z) / 60\,a \qquad \text{..............} \; (1.\ 15)$$

Where: **Ea** – generated voltage. : **ϕ** – flux per poles. : **P**- number of poles
N – speed in r.p.m. : **Z** –number of conductor in armature windings
a – number of the parallel path in the armature windings.

Ea α N →→ Ea = K × N

K = constant = **(ϕ × P × Z / (60 ×a)** .... (1. 16)

Advantages of the DC Generator:

*The polarity of induced voltages indicates the direction of shaft rotation.

*The conventional DC type voltmeter is used for measuring the induced voltage.

Disadvantages of DC Generator

*The commutator and brushes required periodic maintenance.

*output resistance is kept high as compared to input resistance. If a large current is induced in armature conductor, constant field of permanent magnet will be distorted.

AC Tachometer Generator

DC tacho. gen. uses commutator and brushes which have many disadvantages. AC tacho. gen. designs for reducing these problems. AC tacho. has stationary armature and rotating magnetic field. Thus, commutator and brushes are absent, as shown in Fig (1.47)

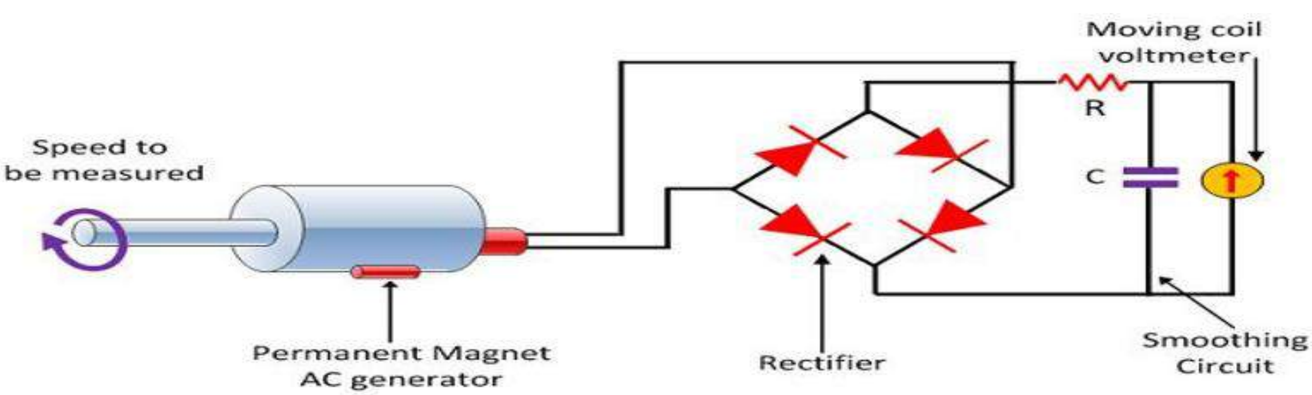


Fig (1.47) A.C tachometer generator

Rotating magnetic field induced EMF in stationary coil of stator. Amplitude and frequency of induced emf are proportional to the shaft speed. Thus, either amplitude or frequency are used for measuring the angular velocity.

The above circuit is used for measuring rotor speed by considering the amplitude of induced voltage. Induced voltages are rectified and then passes to capacitor filter for smoothening the ripples of rectified voltages.

Drag Cup Type A.C tachometer Generator

The drag cup type A.C tachometer is shown in the Fig (1.48) blew.

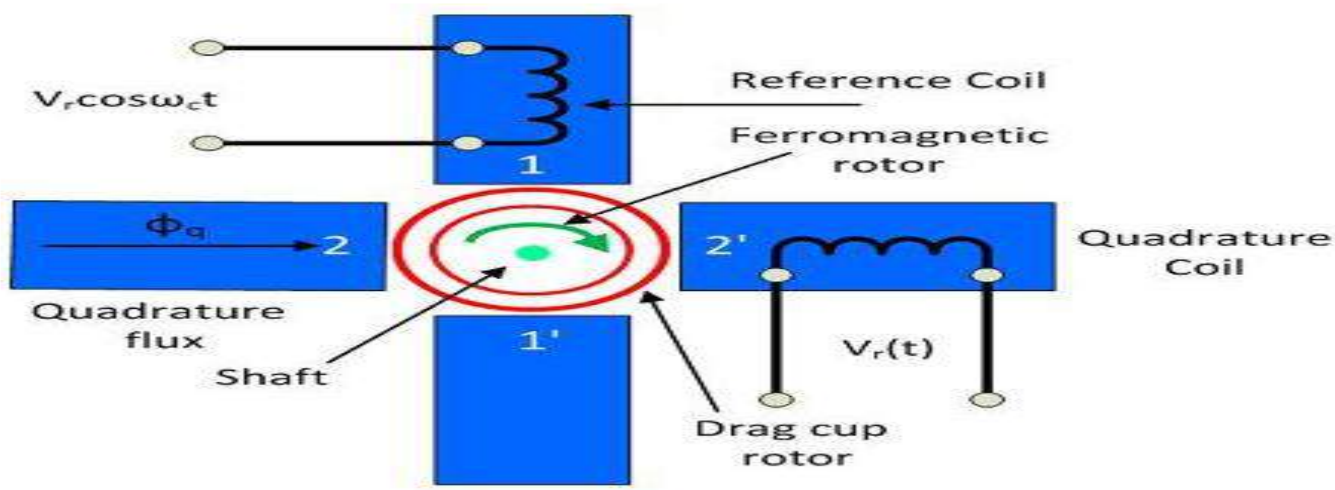


Fig (1.48) drag cup type A.C tachometer

The stator consists 2 windings, (reference and quadrature) winding. Both windings are mounted 90° apart from each other. The rotor of tachometer is made with thin aluminum cup, and placed between field structure.

The Rotor is made of highly inductive material which has low inertia. The input is provided to the reference winding, and the output is obtained from the quadrature winding. Rotation of rotor between the magnetic field induced voltage in sensing winding. Induced voltage is proportional to rotation speed.

Advantages:

- The drag cup Tacho generator generates the ripple free output voltage.
- The cost of the generator is also very less.

Disadvantage:

Nonlinear relationship obtains between output voltage and input speed when the rotor rotates at high speed.

Mechanical tachometer

Mechanical tachometers is an instrument measuring the rotation speed of a shaft or disk, as in a motor or other machine. The device usually displays the revolutions per minute (RPM) on a calibrated analogue dial, but digital displays are increasingly common .For example, mechanical hand-tachometer is designed to accurately measure RPM and surface speed on a wide range of application, Fig (1.49).

(a) Analogue tupe (b) digital display type

Fig (1.49) Mechanical tachometer

SYNCHRO DRIVE SYSTEM

Consider two conventional wound Rotor Induction motors whose 3 phase stators are connected in star connection(Y), with axes 120^o a part and parallel. Two phases of the respective rotors are also connected in parallel and energized from a (A.C) single phase source, i.e both rotors have a single winding connected to common (A.C) voltage source Fig (1.50)

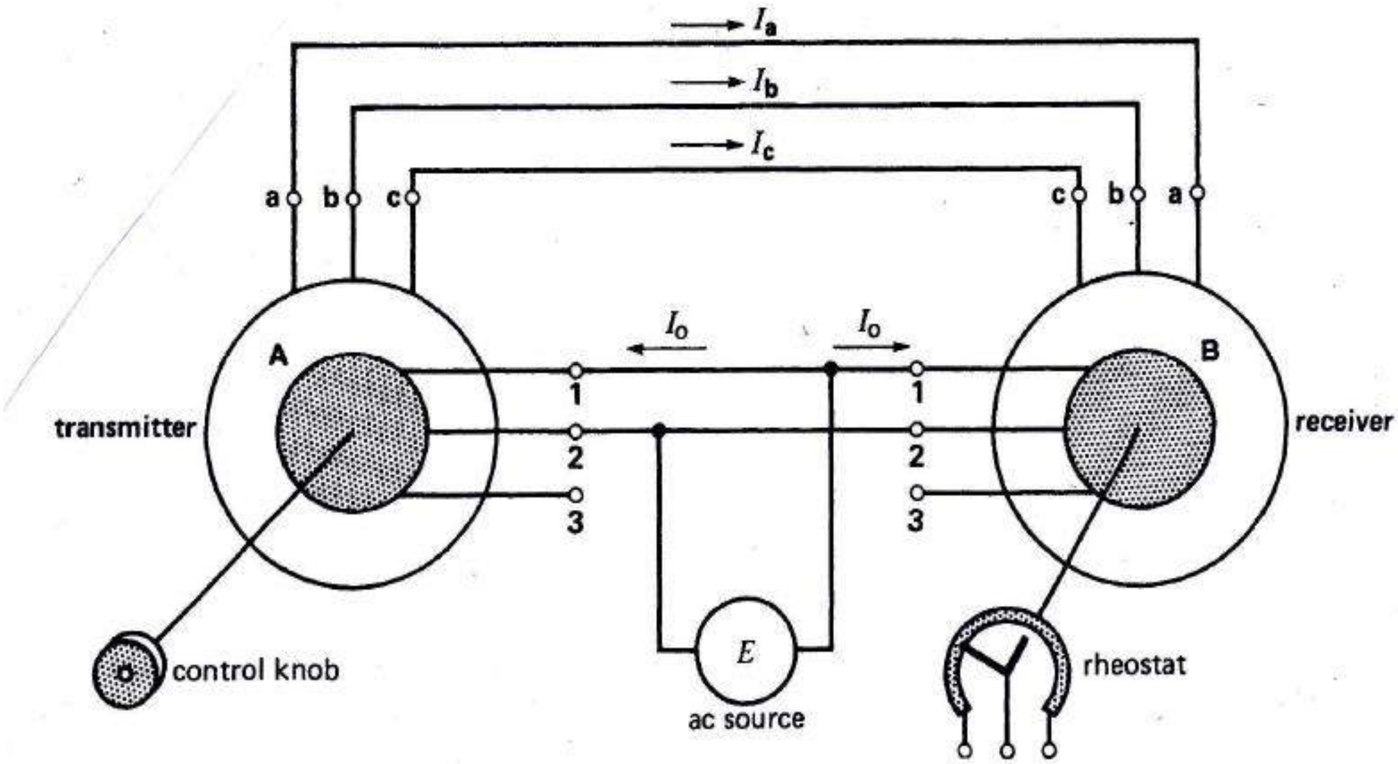


Fig (1.50) components and connection of a synchro system

The remarkable feature about this arrangement is that the rotor of one machine will automatically track with the other rotor. Thus, If we slowly turn rotor (A) clock wise through 17^o, rotor (B) will move clock wise 17^o, obviously; such a system enables us to control a rheostat from a remote location.

2-wound – Rotor motors are required, one (transmitter) is coupled to a control knob, and other (the receiver) is coupled to the rheostat. The five conductor cable **(a, b, c, 1 & 2)** linking the transmitter and receiver constitutes the flexible electrical shaft.

The behavior of this synchro system (SELSYN) is explained as follows:

When the single phase rotor winding are excited, voltages are induced by transformer action in the Y – connected stator windings.

The rotors behave like the primaries of two transformers.

The voltages induced in the 3 – phase stator windings of transmitter are unequal (because the windings are displaced by 120^0), and the same is true for the voltages induced in the stator of receiver.

The stator voltages of the transmitter and receiver Balance each other and, consequently, NO current flows in the lines connecting the stator, but rotors carry a small exciting current $\mathbf{I_0}$, Fig (1. 51) shows the equivalent circuit.

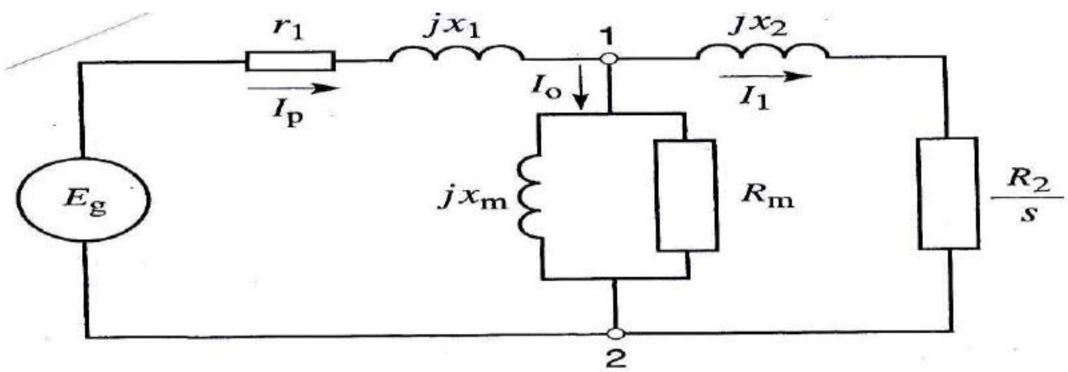


Fig (1.51) Equivalent CCT of 1 phase of a 3 phase motor referred to primary (stator).

NOW:

If we turn the rotor of transmitter, the three stator voltages will change.

They will No longer Balance, consequently ,$\mathbf{I_a}$, $\mathbf{I_b}$,,$\mathbf{I_c}$, will flow in lines ,as shown in Fig (1.50).

These currents in conjunction with the air gap magnetic fields, produce Torque on the Rotors, tending to line them up ,since the rotor of receiver is free to rotate , it will line up with the transmitter .As soon as the Rotors are a legend , the stator voltages are ON Balance (phase by phase),and the Torque – producing current disappear .

Synchro Error Detector (Angular Position System)

The synchro transmitter and the control transformer together used for detecting the error, Fig (1.52), the voltage equation (1.17), is equal to the shaft position of the rotor of control transformer and transmitter.

$$E(t) = K' V_r \cos\phi \sin\omega_c t \qquad \ldots\ldots(1.17)$$

The total angular separation between the rotors is $\phi = (90^o - \theta_R + \theta_C)$

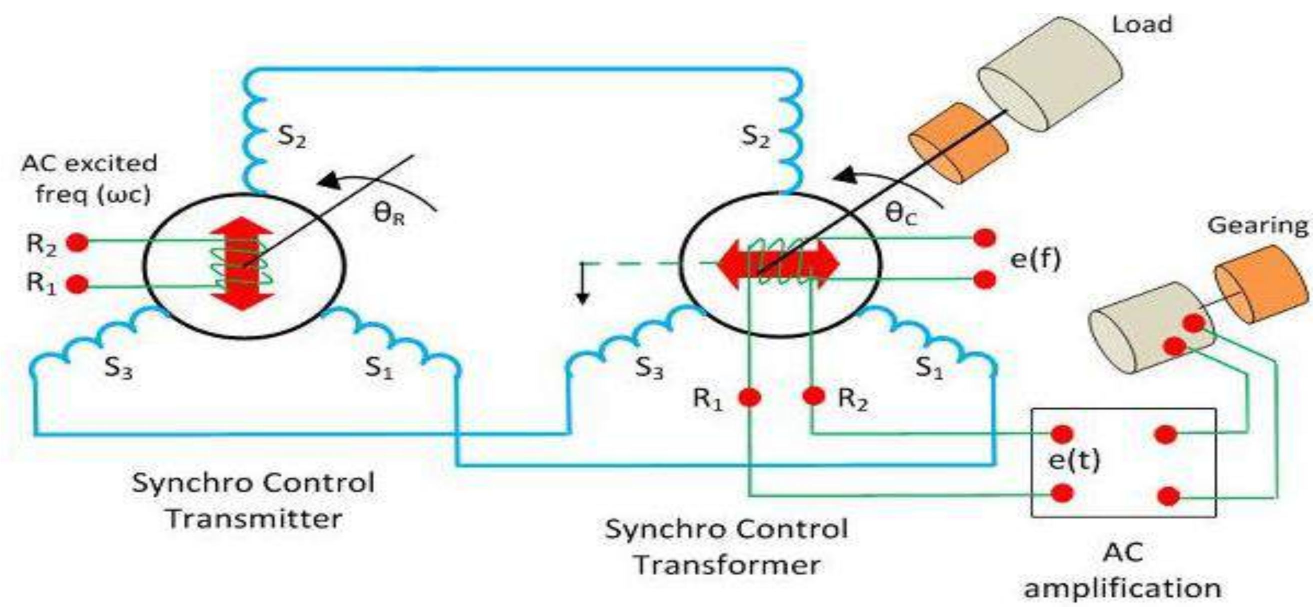


Fig (1.52) Positional Control System

Rotor of synchro transmitter is mechanically connected to the input shaft.

Rotor of control transformer is mechanically connected to the output shaft, electrically connected to the input of a servo amplifier. Mechanical power to turn the output shaft and its associated load is furnished by a 2 – phase control motor (servo motor), the input to control winding of motor is supplied by amplifier which includes Phase – splitting capacitor Motor on its circuitry.

When the output shaft is in the correct position (90^o from the input shaft), the voltage input to the amplifier, and hence the power input to the control winding of the motor is ZERO, and the motor not turned.

When an angular discrepancy exists, a definite error voltage appears at the amplifier input, its relative polarity is such that the motor is caused to turn in the direction to correct the angular discrepancy.

The error signal is applied to the differential amplifier which gives input to the servo motor. The gear of servo motor rotates the rotor of control Transformer.

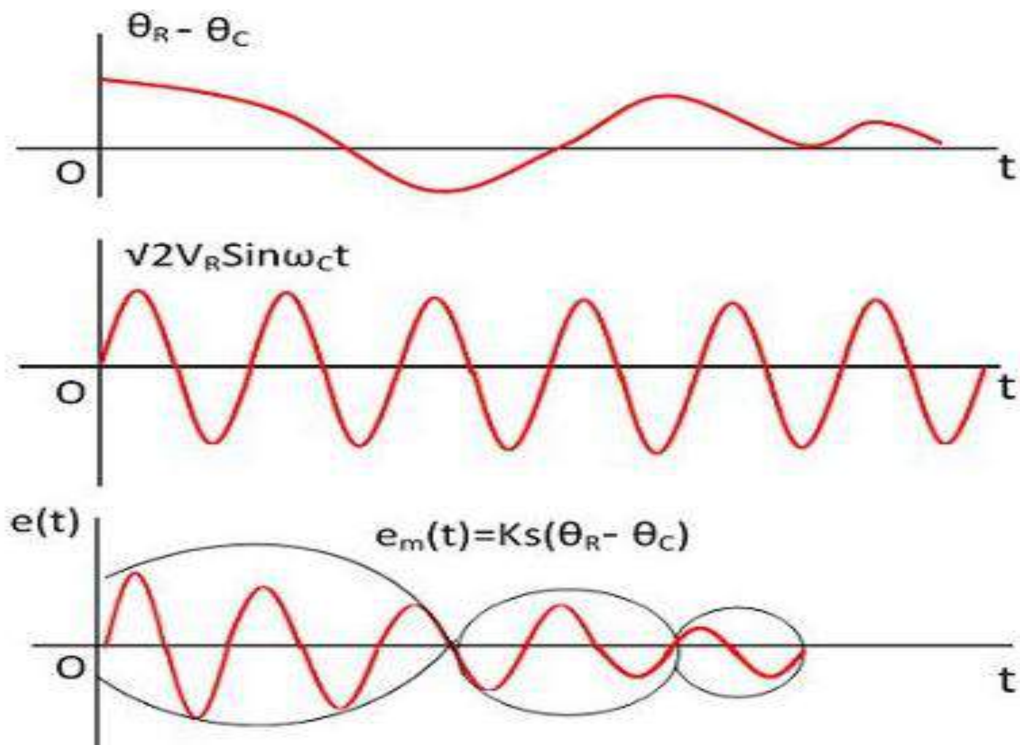


Fig (1. 53) Wave form of Synchro Error Detector

Fig (1.53) above shows the output of the synchro error detector which is a modulate signal. The modulating wave above shown the misalignment between the rotor position and the carrier wave.

$e(t) = (\theta_R - \theta_C)$ Where K_s is the error detector

Differential – Synchro

A modification of the Synchro drive System may be introduced by including a DIFFEREN TIAL – SYNCHRO ,thereby permitting the rotation of the shaft to be a function of two SUM or DIFFERENC of two other shafts ,the differential

Synchronous acts as a differential transmitter , Fig (1.54)

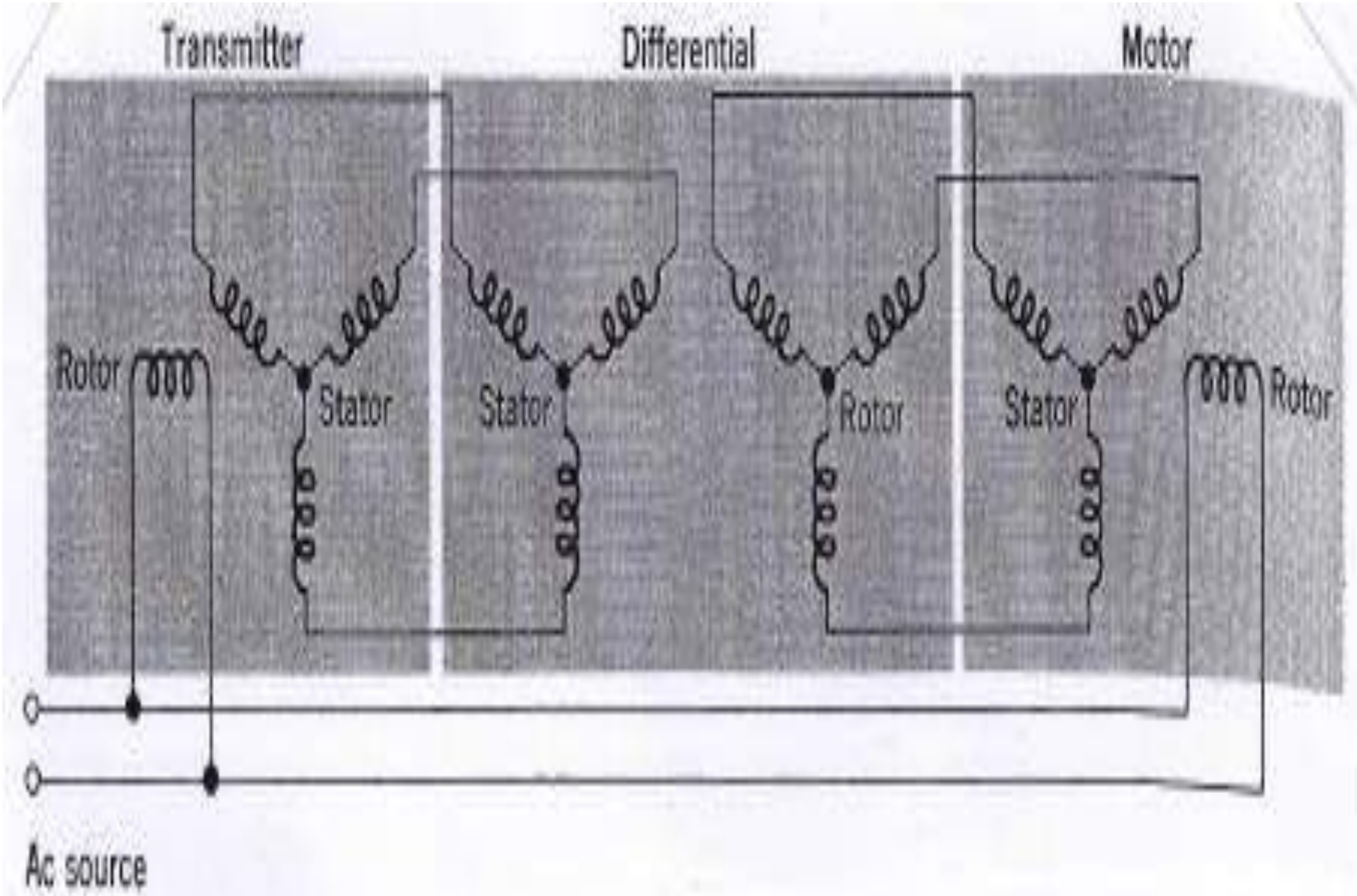


Fig (1. 54) Differential Synchro System

The voltages impressed on its stator windings induce corresponding voltages in the rotor winding .The differential transmitters usually have a Bank of 3 Capacitors connected across the primary (stator) terminals to improve power factor and hence minimize the overheating in the system.

To minimize dynamic errors, mechanical dampers (front and rear) are built into the motor rotors units as shown in Fig (1.55).

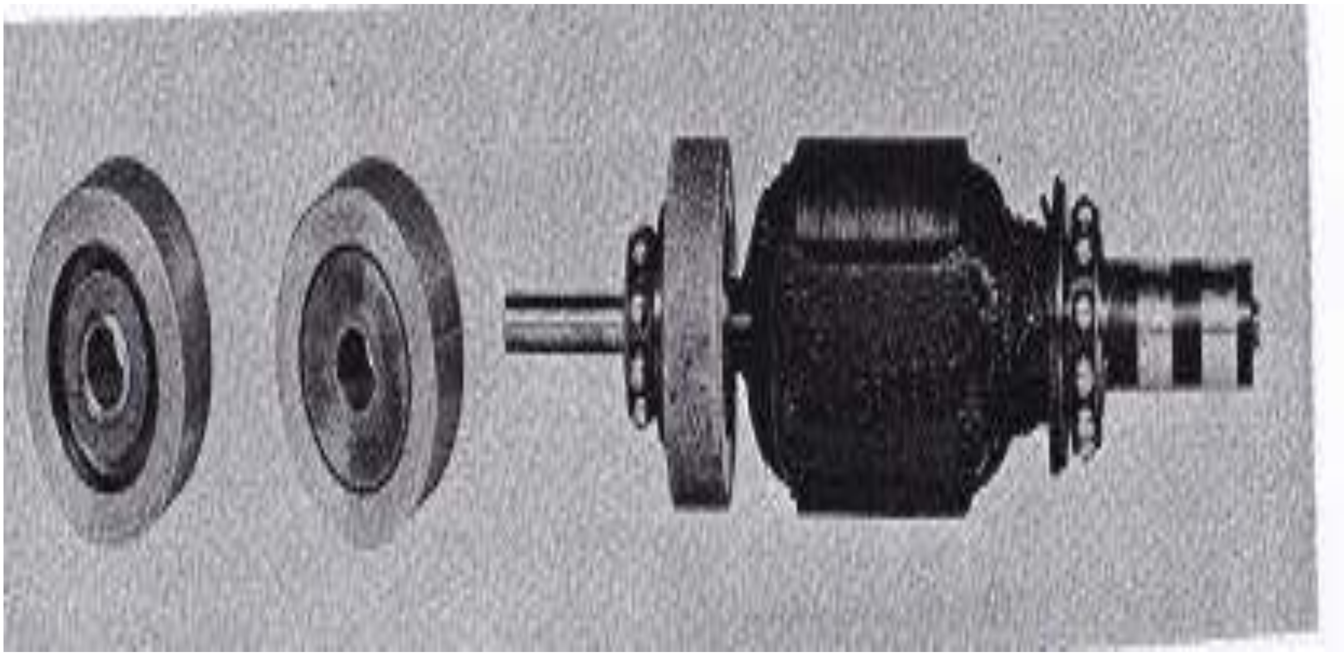


Fig (1.55) Two dampers, and wound rotor, of Synchro Motor

Applications

1 – Synchro are often employed to indicate of an antenna, a valve, and a gun turret .

2 – The transmitters and receivers are built with watch – like precision to ensure that they will track with as little error as possible, (i.e angular information)

3 - Synchro are used in control systems for transmitting shaft – position information for maintaining synchronism between two or more shafts, Fig (1.52).

REPULSION MOTOR

A Repulsion Motor is a type of single phase electric commutator motor which runs on alternating current (A.C) power supply.

Construction of Repulsion Motor

It is a single-phase AC motor , The construction is similar to split-phase (I.M) and D.C Series Motor, which consist of two main components , rotor and stator, they are inductively coupled ,Fig (1.56). Field winding (or a distributed type winding or the stator) is similar to the main winding of split-phase (I.M) motor. Hence distributed flux in the gap is decreased and reluctance is also decreased, which in turn improves power factor.

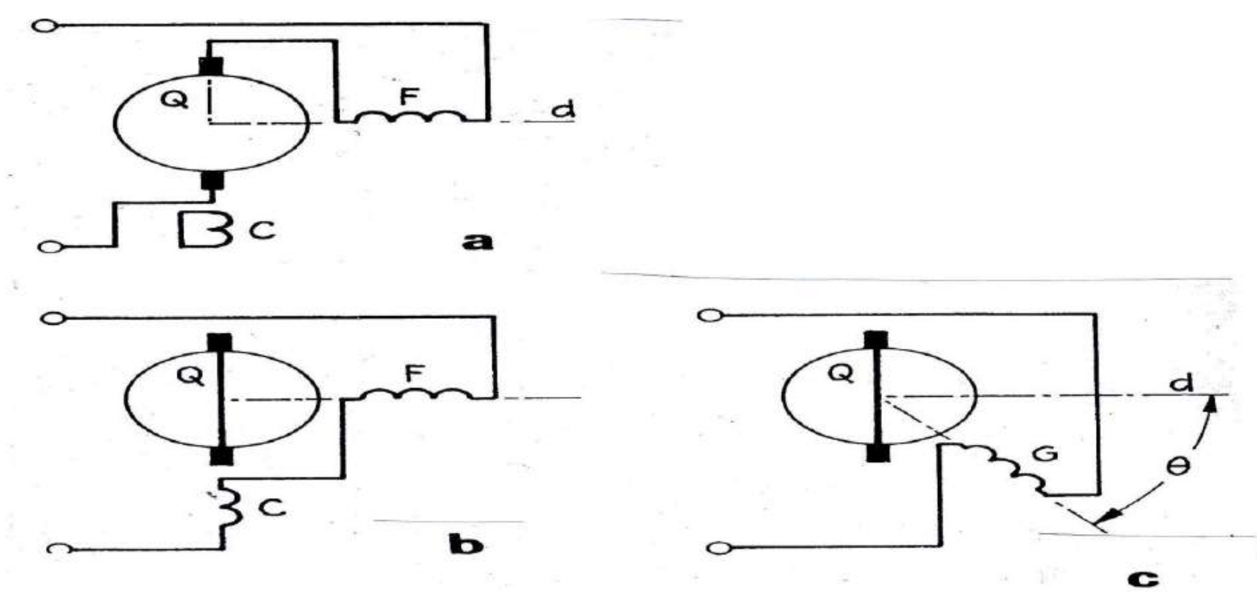


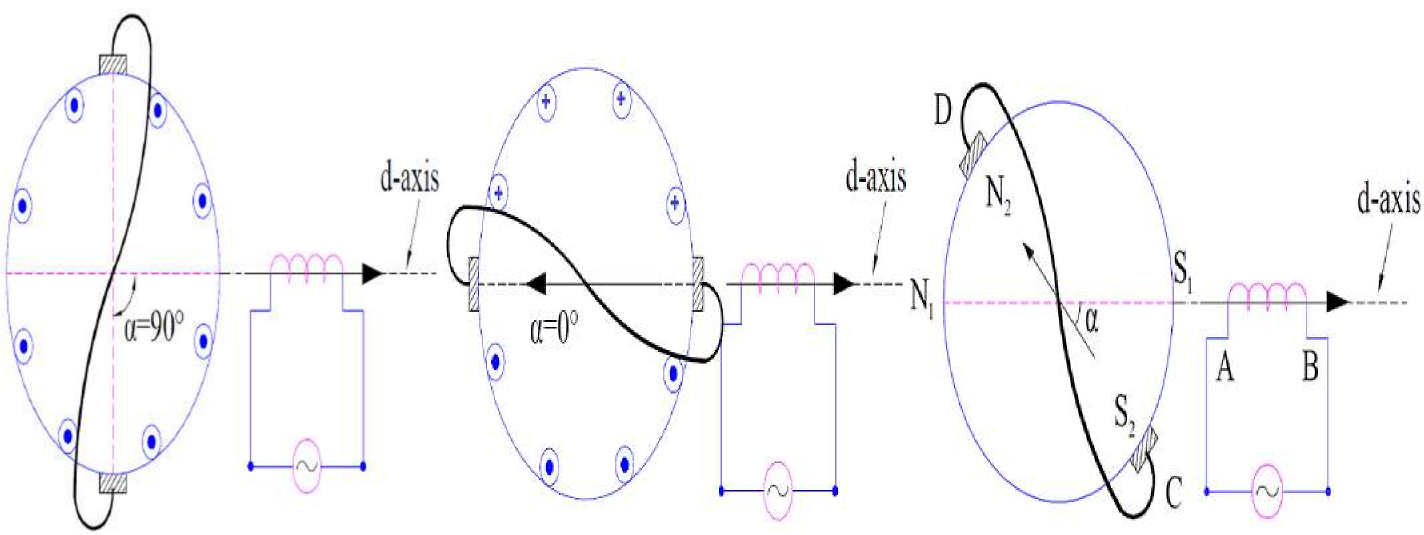
Fig (1.56) Repulsion Motor design

The rotor winding is designed for a law working voltage, it is similar to DC series motor which is provided with a drum-type winding connected to commutator, which is in-turn connected to short- circuited brushes to provide a closed current path. A brush holder mechanism provides variable crankshaft to change the direction or alignment of brushes along the axis. Hence the torque produced during this process helps to control the speed. The energy in repulsion motor is transferred through the transformer action or by the induction action (where the emf is transferred between stator to the rotor).

The stator winding has, either **d**-axes & **q**-axes Fig (1.56 b), or is displaced by an angle **θ** to the **d**-axes Fig (1.56c).

Working method of Repulsion Motor

When stator winding is supplied with single phase AC, it produces a magnetic flux along d -axis. This magnetic flux link with rotor winding, creates an emf, due to this emf, a rotor current is produced. This rotor current in turn produces a magnetic flux which is directed along the brush axis due to commutator assembly. Due to the interaction of stator and rotor produced fluxes, an electromagnetic torque is produced. Let us discuss this aspect in detail.



(a) **α** = 90°　　(b) **α** = 0°　　(c) 0° < **α** < 90°

Fig(1.57) position of brush axis with respect to d – axes

Let us rename (**θ** as **α**, i.e **θ = α**).In Fig (1.57a), the angle **α** between stator produced field and brush axis is 90°. This means, the brush axis is in quadrature with the **d axis,** under this condition, there will not be any mutual induction between the stator and rotor windings. Therefore, NO e.m.f and hence NO rotor current is produced. Thus NO electromagnetic torque is developed.

This means that motor will not run when $\alpha = 90°$**.** As the stator produced flux is unaffected by the zero rotor m.m.f, this condition is similar to the open circuit Transformer. This is the reason, the brush position of $\alpha = 90°$ is called open-circuit, no-load, high impedance or neutral position.

Let us now consider the case when $\alpha = 0°$ as shown in Fig (1.57 b). In this condition, a maximum e.m.f is induced across the brushes. This is because the rotor and stator magnetic flux coincides and hence there is a perfect mutual coupling between them:

No electromagnetic torque is developed as $\alpha = 0°$**.** Thus in repulsion motor, No electromagnetic torque is developed when the angle between the stator and rotor magnetic flux axis is either **0°** or **90**°.

But actually the brush axis occupies a position somewhere in between $\alpha = 0°$ and $\alpha = 90°$ as shown in Fig (1.57c).

(c) $0^o < \alpha < 90^o$

At an intermediate of (α). Typical value:

$$50^o < \alpha < 70^o$$

1) stator winding is equivalent to separate winding **C** & **F**, as shown in fig (1.56b).

2) There is a **q** – axes flux to induce Rotor current , and a **d** – axes flux for interaction Torque production .

NOW : Asume 2 – pole machine with a separat winding (**F** and **C**):

- Stator current I_s in **F** develops → ϕ_d (ϕ_d : d - axes flux in phase with I_s).

-the combination of m.mfs of(**C** and **Q** develops) → ϕ_q

-So that ϕ_q lags ϕ_d by 90^o.

- ω_r is the rotor angular speed .

ϕ_d induced → e.m. f. $E_r = k \times \omega_r \times \phi_d$

ϕ_q induced → e.m. f. $E_p = k \times \omega_1 \times \phi_q$

NOW:

E_r is in phase with ϕ_d & E_p is in quadrature with ϕ_q

They balance to give :

$$E_r = E_p$$

So that :-

$$\omega_r \times \phi_d = \omega_1 \times \phi_q \rightarrow\rightarrow \phi_q / \phi_d = \omega_r / \omega_1$$

If $\omega_r = \omega_1$ therefore $\phi_d = \phi_q$ are equal in magnitude ,and as they are in Both spase and time quadrature they produce a constant travelling wave field in the air gap.

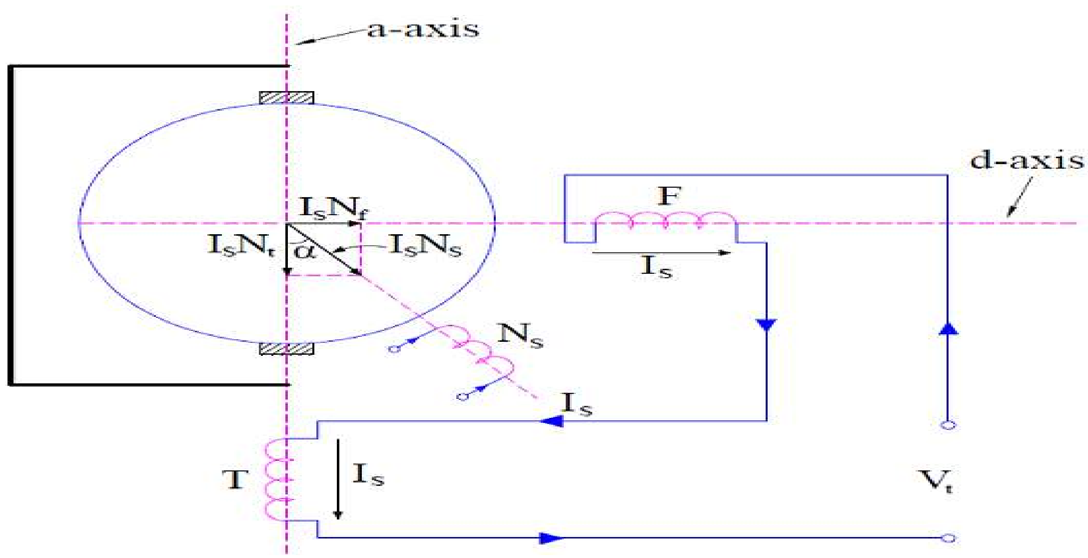
-Below synchronous speed :- →→ $\phi_d > \phi_q$

-Above synchronous speed :- →→ $\phi_d < \phi_q$

If the stator flux is assumed to be directed from A to B, then the produced rotor flux must also have a component in a direction opposite to stator flux. Therefore rotor flux will be directed from C to D. Since stator flux is toward A to B, South Pole (S1) is generated at A. Similarly South Pole (S2) is generated on rotor at C. Since similar poles repel each other, S1 will repel S2. Due to this repulsion between the like poles, motor will rotate in clockwise direction. This is the reason; this motor is called Repulsion Motor. It is clear from the above Fig (1. 57c), that the direction of rotation for repulsion motor can be reversed by simply changing the brush axis to the other side of filed winding (stator winding).

Torque and speed control

The starting torque is determined by the angle of brush shift from the main magnetic axis. The maximum torque is obtained from a brush shift of 45°. Brush shift can also be used to control the speed. It is quite clear that for production of electromagnetic torque in repulsion motor, brush position must not be along **d axis** or **q axis**. In general, the brush occupies some intermediate position. But for the sake of simplicity, we assume brush axis vertical to shift stator field axis as shown in Fig (1. 58) below, to reduce the calculation effort.



Fig(1,58) Repulsion Motor (brush and stator field axis)

In the above figure, field axis is making an angle of **α** with brush axis. If I_s and N_s are the stator filed current and effective number of stator turns then stator **mmf=** I_sN_s is directed along its axis as shown in Fig (1.58). Stator field is now replaced by two stator coils **F** and **T** such that stator **mmf= IsNs** remain unchanged in magnitude and direction.

The number of turns N_t of coil **T** can be found as below.

m.m.f of coil T = $I_s N_t$

Component of stator **mmf** along the brush axis = $I_s N_s \cos\alpha$

$I_s\ N_t = I_s\ N_s$ Cosα →→ **$N_t = N_s$ Cosα**

Similarly, number of turns of coil F is given as : **$N_f = N_s$ Sinα**

Since the magnetic axis of rotor winding and coil T coincides, all the flux produced by coil T will link with the rotor winding. This means that rotor mmf will be equal to the mmf of coil **T** as per lenz's law. Therefore,

Rotor **mmf = mmf of coil T**

$= I_s N_t$ → $= I_s N_s$ Cosα

Now, the electromagnetic torque

T_e = **k ×** (Stator **mmf**)× (Rotor **mmf**) Sinα → **k** is a constant

= k ($I_s N_s$) ($I_s N_s$ Cosα) Sinα → = (k/2) $(I_s N_s)^2$ (2CosαSinα)

= (k/2) $(I_s N_s)^2$ Sin2α → Sin2α = 2CosαSinα]

Therefore, the torque in repulsion motor is given as

T_e = (k/2) $(I_s N_s)^2$ Sin2α ……………………..(1. 18)

From torque equation, it is clear that max. Torque is achieved when stator and rotor magnetic axis are displaced from each other by 45°.

Variation of current and torque with respect to different positions of brush is shown in Fig (1.59) below.

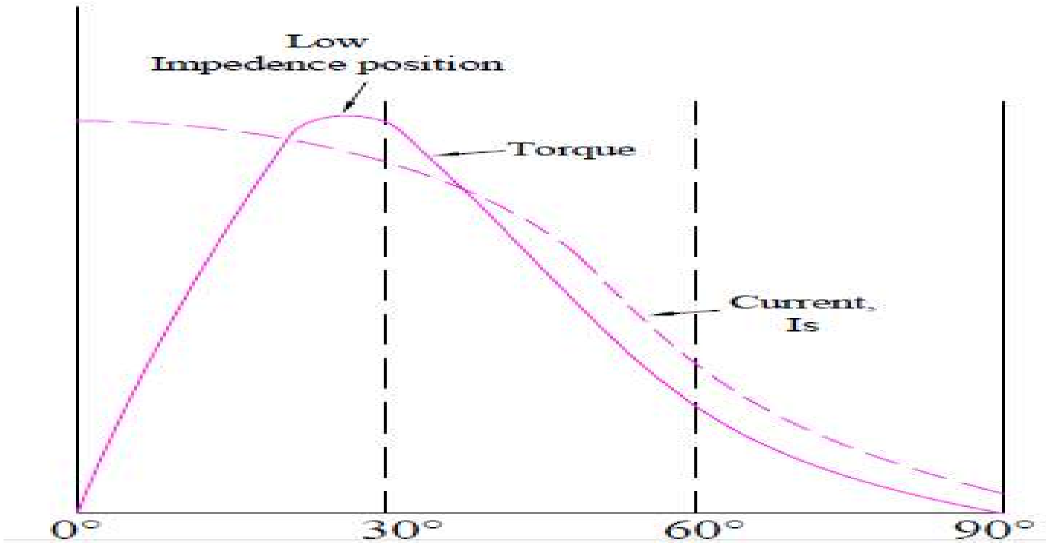


Fig (1.59) Torque and current variation Vs brush positions

Following points regarding must be noted from the above curve:

- Rotor current is maximum when the brush axis and d-axis coincides.
- Rotor current is zero when the brush occupies a position in quadrature with the direct axis.
- Maximum torque in repulsion motor is achieved when stator and rotor field axis are 45° apart.

Types of Repulsion Motor

There are three kinds of motors available.

* Compensated Repulsion Motor * Repulsion Start Induction Motor

* Repulsion Induction Motor

1- Compensated Repulsion Motor

This motor includes an extra winding namely compensating winding. The set of two brushes are placed in between the normal short circuit brush set. Both the compensating winding as well as brush sets are connected in series to deactivate the effect of cross magnetizing of armature response. The windings that are connected in series will generate a magnetic field, which changes directly through armature current.

2- Repulsion Start Induction Motor

This motor type work like a repulsion motor, although they run like an induction motor with stable speed characteristics. It includes a stator, a rotor, a commutator, and a centrifugal device. Here rotor is similar to the wire-wound dc armature. A centrifugal device is used to short circuited commutator bars.

3-Repulsion Induction Motor

This kind of motor mainly works on principle of both inductions and repulsion. It consists of a stator winding, 2-rotor windings and a set of 2 brushes which is (S.C) short-circuited. Two rotor windings are normal DC winding and one squirrel cage connected to the commutator

Advantages

1*Starting torque is high 2* Good speed regulation 3*Starting current will be reduced

4* For sudden heavy loads, the torque can be developed.

Disadvantages

1*Sparks will occur at brushes 2 * power factor is very poor at low speed

3* The speed at no-load condition is extremely high & unsafe

*Brushes & commutator exhaust quickly due to heat generation & arcing at of the brush.

Applications

1*High speed lifts 2* Fans and pumps 3 * Air compressors 4* Petrol pumps

5*Printing presses 6* Textile machines

7*Film winding machines (smooth manual speed and direction adjustment could be achieved without complicated circuitry.

PERMANENT MAGNENT MACHINE

A small electric machines have the benefit of pre-excitation from the magnets, the permanent magnet machine solved the cost minimization function, with advantage of a compact design that eliminates field winding.

In a permanent magnet generator, the rotor magnetic field produced by permanent magnets. Other types of generator use electromagnets to produce a magnetic field in a rotor winding. The direct current in the rotor field winding is fed through a slip-ring assembly or provided by a brushless exciter on the same shaft. Permanent magnet generators (PMGs) or alternators (PMAs) do not require a DC supply for the excitation circuit,

The construction

The magnetic – circuit design is a somewhat complicated process, some forms of permanent magnet motor (PM) are shown in Fig (1.60).

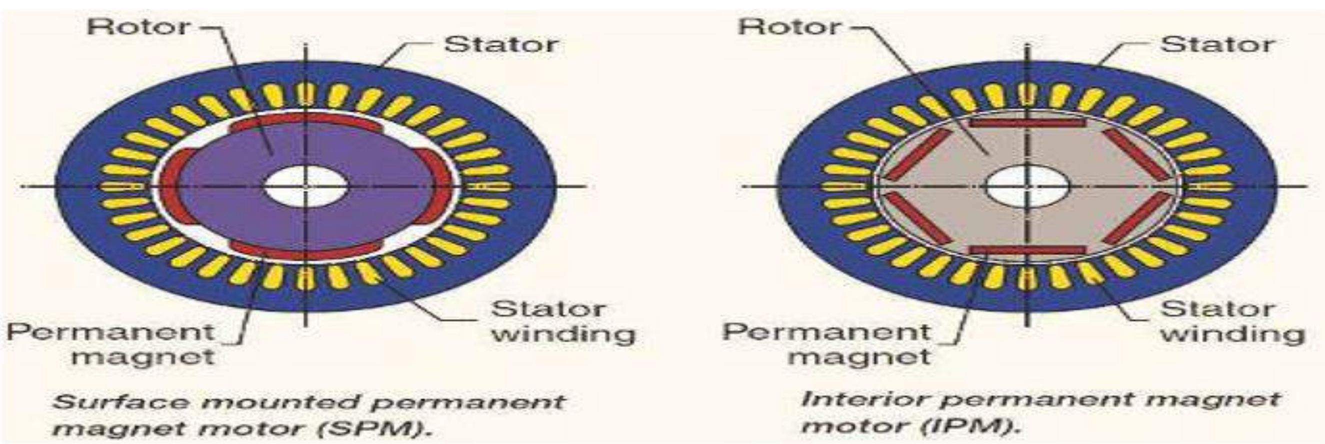


Fig (1.60) **Permanent magnet Motor**

The permanent magnets are generally contained in the Rotor of (PMG) machine, which can be classified into three type:

1 - **Radial flux machine** **2-Axial flux** **3- Transverse flux**

Radial flux and axial flux machines are the most common PMG type.

Radial flux machines

In radial flux machine magnetic field is at right angles to rotation axis, in radial direction, and stator coils are aligned with axis of rotation. Field Generation occurs when the rotor magnets move around the stator. This is conventional configuration used for all types of generator. Fig (1.61) shows a typical radial flux PMG. Radial flux PMGs are characterized by a small number of poles and operate at high rotational speeds.

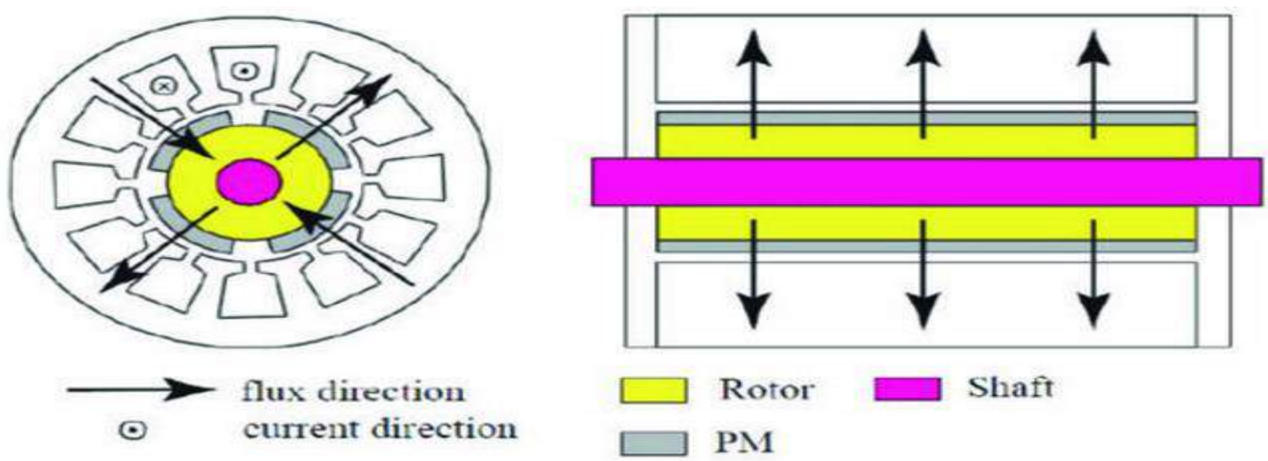


Fig.(1.61): Radial flux PMG .

Axial flux machines

In an axial flux machine the magnetic field is aligned with the axis of rotation, and flows in across the airgap in an axial direction. The stator coils are arranged in a radial pattern at right angles to the axis of rotation. A typical axial flux machine is shown in Fig. (1.62). Low speed generators require a large number of poles and hence a large diameter rotor and stator. For these applications the axial flux configuration has proved to be more suitable. The axial flux configuration also finds application in vertical axis generators, such as vertical axis wind turbines and hydropower plant.

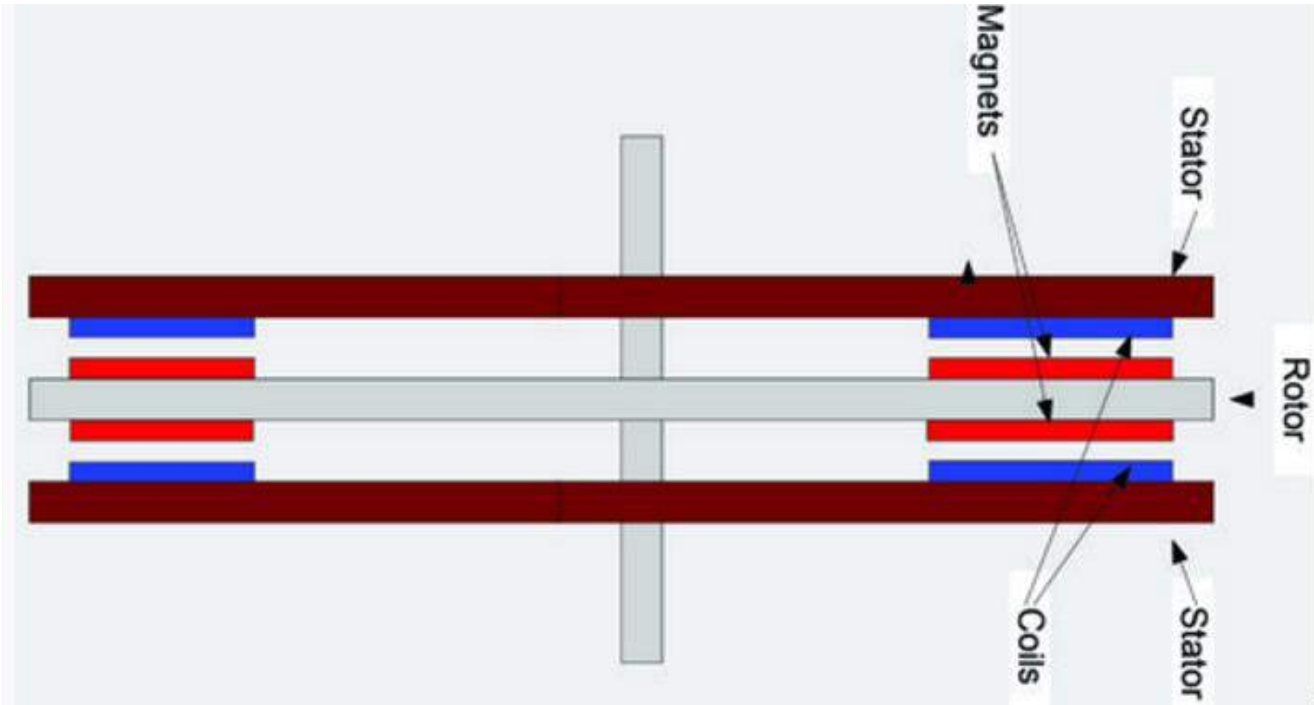


Fig (1.62): Axial flux PMG.

Transverse flux PMGs

The transverse flux principle combines elements of both radial and axial flux machines. In the transverse flux machine, the magnets are located on the rotor, and the flux flows in a transverse direction around the stator yoke. The stator coil is located inside the stator yoke. The TFPM configuration allows multiple layers of rotor magnet and stator coil. Fig (1.63) shows the basic configuration of the TFPM.

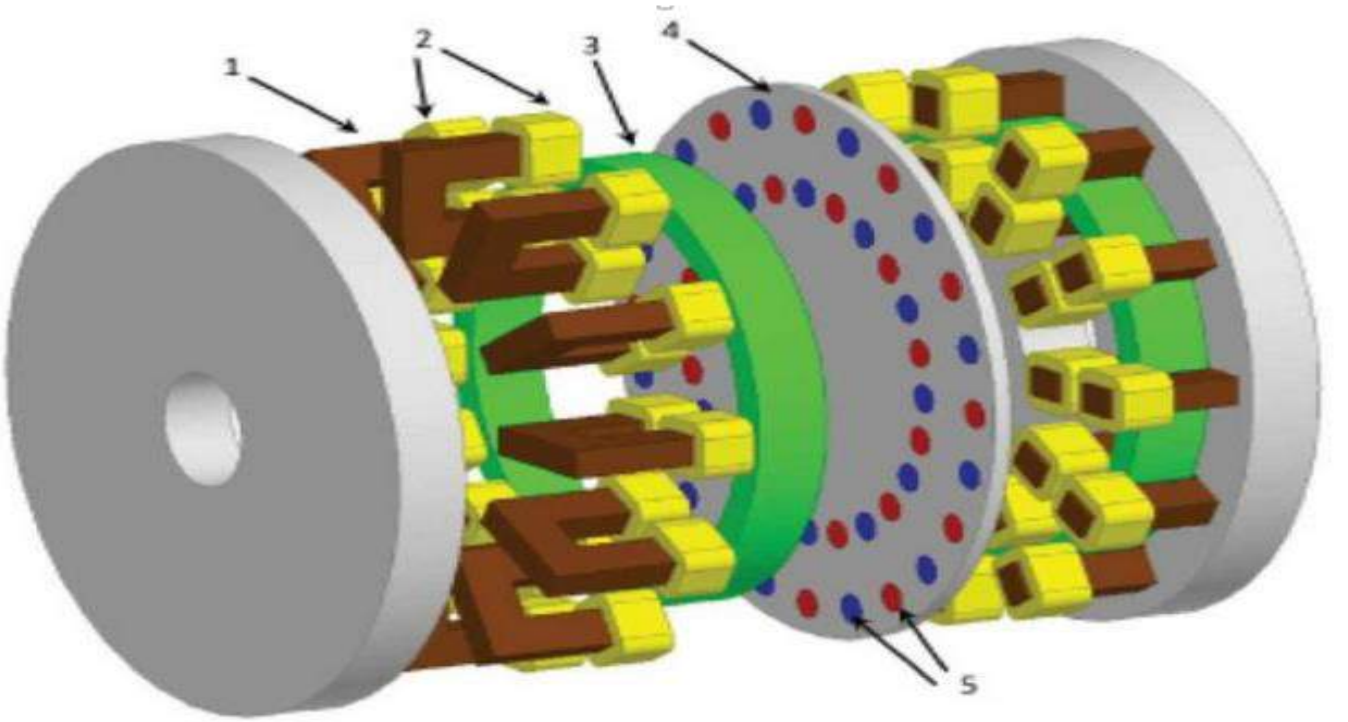


Fig (1.63): Structure of hybrid-excited TFPM generator (1) Stator U-type core (2) Excitation windings (3) Phase winding (4) Rotor disk (5) Permanent magnets

Application

Generator:

- The (PM) Generator, which needs no starting cage, is efficient and robust.
- It has been adopted for the role of pilot exciter for the field of large generators.
- In the (alternative), Energy source such as wind drive.

Motor machine:

Rating from 5 watt TO 50 Kw have been used in process in dusters (e.g synthetic Fibers) where a precise speed is required for up wards of 200 r.p.m., with overall speed control by a variable – frequency inverter.

For speed above 1500 r.p.m. it is necessary to abandon the usual laminar Rotor for a solid form.

SCHRAGE MOTOR

This Motor, Fig (1 .64), is essentially a combination of wound rotor induction motor and frequency convertor. Schrage motor can be treated as an inverted poly phase induction motor. The primary winding is on rotor. Three phase supply is given to the primary (Rotor) via 3 slip rings. The secondary winding is on the stator. Apart from primary and secondary there is a third type of winding called as tertiary winding which is connected to the commutator. The primary and tertiary are housed in the same rotor slots and are mutually coupled. The stator winding terminals are connected to commutator via 3 sets of movable brushes **A_1A_2, B_1B_2 and C_1C_2**. Each phase terminated on a pair of commutator brush gear comprises 2 movable rockers geared together and filled with 3 brushes per pole pair.

The rockers can be shifted in opposite direction by means of a hand wheel or pilot Motor. Angular displacement between the brushes determines the injected emf into the secondary winding which is required for speed and power factor control.

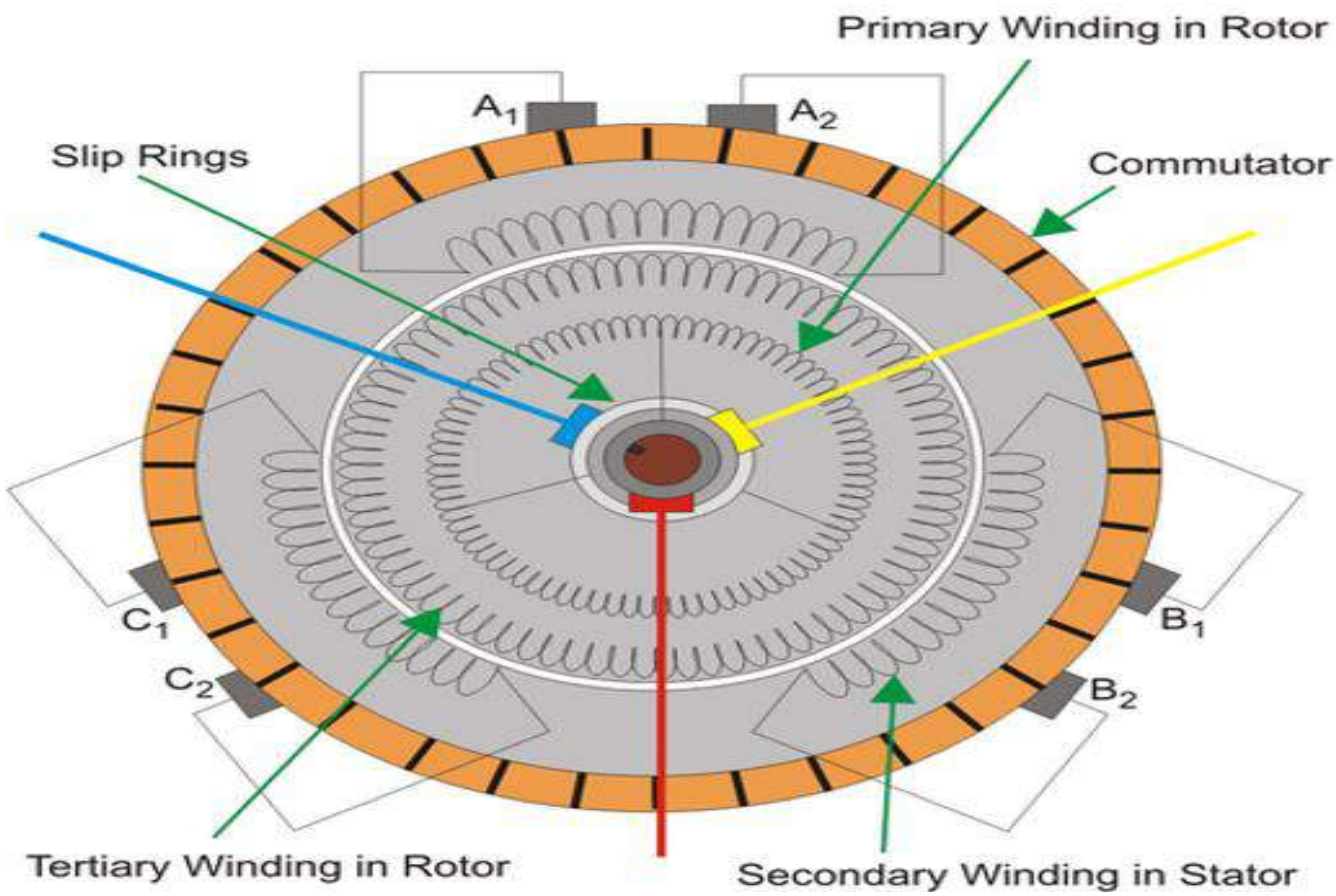


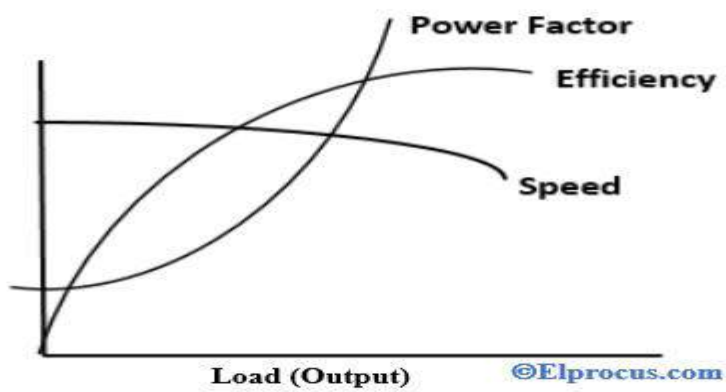
Fig (1.64) Schrage Motor

Method of operation

At standstill conditions due to three phase currents flowing in the primary winding a rotating field is produced. This rotating field cuts the secondary with a synchronous speed **n_S**.

Therefore according to Lenz's law the rotor will rotate in a direction so as to oppose the cause i.e. to induce slip frequency **emfs** into secondary. Therefore the rotor rotates opposite to the direction of synchronous rotating field. Now air gap field is rotating at slip speed **$n_s - n_r$** with respect to secondary. Therefore the **emf** collected by the stationary brushes is at slip frequency and hence suitable for injection into secondary.

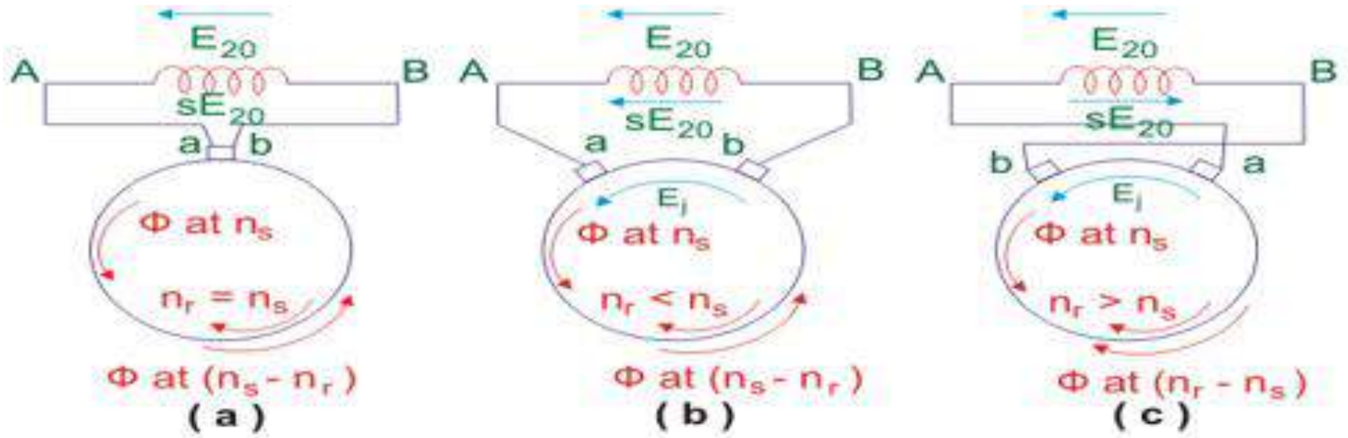
The regulating windings are induced by transformer action and the secondary windings are induced by dynamically induced EMF. Compare to a normal induction motor, rotor RMF is at SN_S with respect to the rotor and at N_S with respect to the stator. The **$N_s - N_r$** is air gap speed with respect to stator. As shown in Fig(1.65), we can observe that when the load increases, the power factor increases, speed decreases, and the efficiency increases.



Fig(1.65) output load Vs Power factor , speed, and Efficiency.

Speed control

Speed control of Schrage Motor is possible by varying the injected **emf** into the motor which can be controlled by changing the angular displacement between two brushes .Now based on the Fig (1.66), we shall take a look to speed control of schrage motor.



(IM) operation (sub – synchronous speed) (super – synchronous speed)

Fig (1.66) Speed control of Schrage Motor

In the above figure:

E_{20} = standstill **emf** induced in the secondary.
sE_{20} = induced **emf** at any slip **s**.
a, b = brush terminals.

In Fig (1.65a) both brushes are connected to the same commutator segment and hence are short circuited. Injected **emf** in this case is ZERO. Therefore rotor rotates with speed close to synchronous speed.

In Fig (1.65b) brushes (**a**&**b**) are separated by an angular displacement **θ** such that the tertiary winding axis between brushes (**a**&**b**) is coincident with secondary winding axis. We find that injected **emf** **E_j** is in phase opposition to **E_{20}**. Hence the motor operates at sub synchronous speeds i.e.:

$$\mathbf{n_r < n_s.}$$

In Fig (1.65c) the brush positions are interchanged. The injected **emf** is in phase with the standstill **emf** **E_{20}**. Hence the motor operates at super synchronous speed i.e.:

$$\mathbf{n_r > n_s.}$$

For any brush separation **θ**, the injected **emf** is given by:

$$E_j = E_{jmax} \times \sin(\theta / 2) \qquad \text{.....(1.19)}$$

From equation (1. 19), it can be seen that:

1 – At $\theta = 0^0$ → emf $E_j = 0$

(i.e when the brushes are S.C).

2 – At $\theta = 90^0$ → emf $E_j = E_{jmax}$

(i.e .when brushes are one pole pitch apart).

Torque speed characteristics

If we apply KVL to secondary circuit then we get:

$$sE_{20} \pm E_j = I_2 Z_2$$

Under no load conditions I_2 value is very small and hence the can be neglected. Therefore we have,

$$S_0 E_{20} \pm E_j = 0$$

$$S_0 = \frac{\pm Ej}{E20}$$

Where, S_0 is the no load slip

$$S_j \times E_{jmax} \times \sin\frac{\theta}{2}$$

$$E_{jmax} = \sqrt{2} \times \phi_m \times f_s (Z/A)$$

Where:

E_{jmax} is the transformer emf induced in the Tertiary winding.

ϕ_m = max flux linkage

f_s = supply frequency

Z = number of conductors in tertiary

A = number of parallel paths

Also:

$$E_{20} = \sqrt{2} \times \pi \times \phi_m \times f_s \times N'_2$$

Where:

E_{20} = the transformer **emf** induced in the secondary.
N_2' = effective number of turns in the secondary.

Now on substituting these values in the expression of no load slip we get:

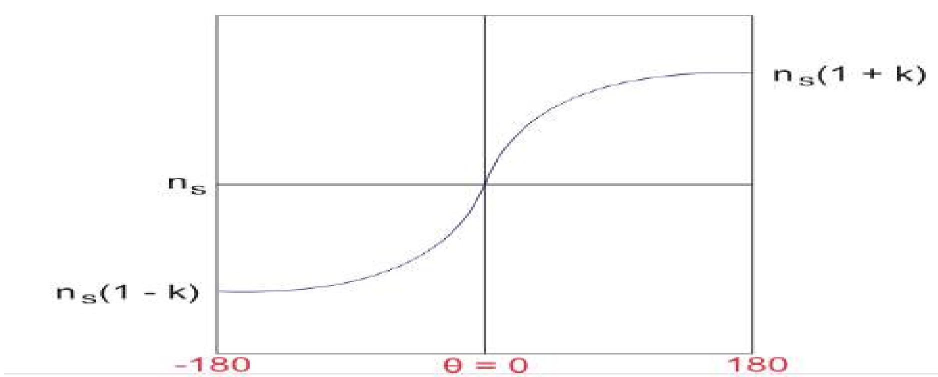
$$S_0 = \pm \frac{Z}{A\,\pi\,N2'} \text{ Sin } (\theta / 2) \quad \rightarrow \quad S_0 = \pm k \text{ Sin } (\theta / 2)$$

implies that slip values depend completely on machine constants and brush separation.

$$n_{ro} = (1 - S_0)\, n_s$$

$$n_{ro} = \{ 1 \pm k \text{ Sin } (\theta / 2)\} \times n_s$$

$$n_{ro\ min.} = \{ 1 - k \text{ Sin } (\theta / 2)\} \times n_s \qquad n_{ro\ max} = \{ 1 + k \text{ Sin } (\theta / 2)\} \times n_s$$



This shows that two different speeds are possible at no load depending on the phase of injected emf. The magnitude of these speeds can be controlled by adjusting the brush separation.

Under load conditions:

$$sE_{20} \pm E_j = I_2 \times Z_2 \quad \rightarrow \rightarrow \quad s = \pm(E_j / E_{20}) + (I_2 \times Z_2 / E_{20})$$

If $\quad I_2 = C \times T_e \quad \rightarrow \rightarrow \quad s = \pm(E_j / E_{20}) + (C \times T_e \times Z_2 / E_{20})$

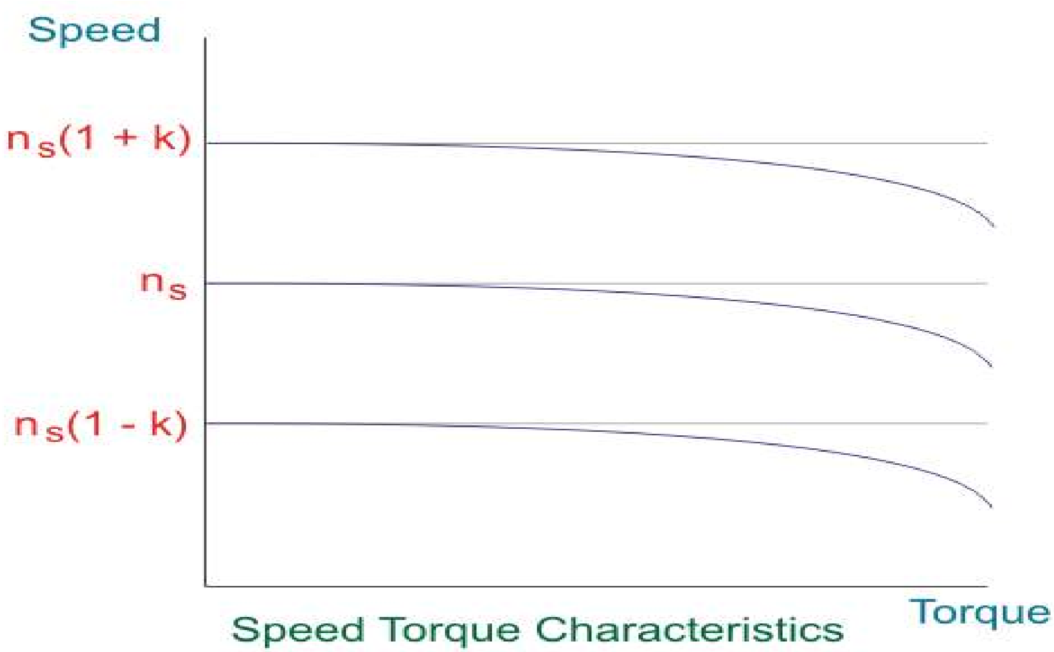


Fig (1.67) Speed Torque Characteristics

Applications

Used in drives requiring variable speed such as cranes, fan, centrifugal pumps, conveyors, Paper mills... etc.

Advantages

The advantages of the Schrage motor are

1 - High Speed. 2-Power factor (PF) is high for high speed. 3-Easy to control the speed.

Disadvantages

The disadvantages of the Schrage motor are

1 - High Losses. 2- Structure is complicated. 3- Low efficiency

LINEAR INDUCTION MOTOR (LIM)

We can drive the linear (m / c) directly from conventional machine by cutting and unrolling both the stator and the Rotor ,without affecting the shape or speed the magnetic field .Such a flat stator produces a afield that moves at a constant speed , in a straight line ,this flux travels at a linear synchronous speed given as:

$$V_s = 2 \times W \times f \qquad \text{.......} \; (1.\,20)$$

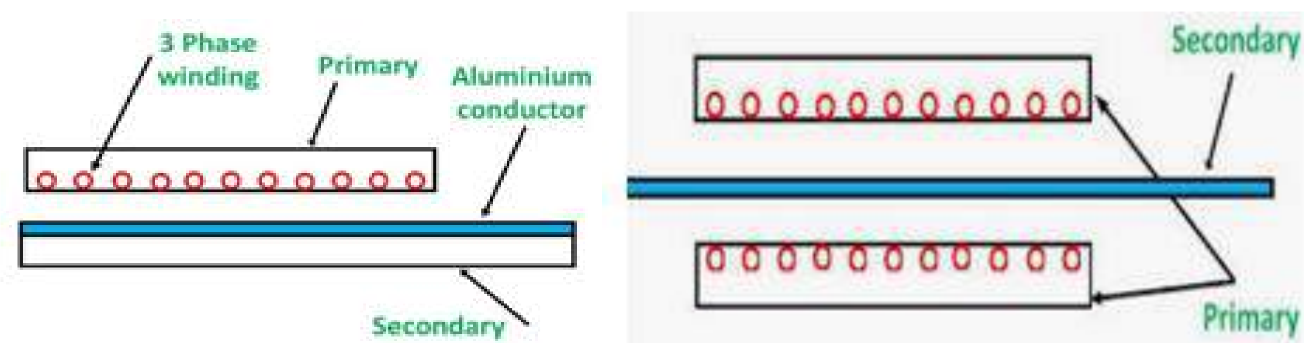
Where: V_s – linear synchronous speed (m/s).

W – width of one pole – pitch (m): **f** – frequency (Hz)

The linear speed does not depend upon the number of poles but only on the width of pole pitch .Thus ,it is possible for a 2- pole linear stator to create a field moving at the same speed as that of a 6 – pole linear stator (say),provide they have the same pole – pitch .

If a flat squirrel – cage winding (Rotor) is brought near the flat stator, Fig (1.68a), the travelling field drags the Rotor. In practice, we generally use a simple aluminum or copper as the Rotor. To increase power and to reduce reluctance of the magnetic path, two flat stators are usually mounted face to face on opposite sides of aluminum plate Fig (1.68b).

The direction of movement can be reversed by inter changing any two stator leads.



(a) Single side LIM (b) double side LIM

Fig (1.68) components of 3 – phase LIM

In some practical application, the Rotor is stationary while the stator moves, for example (high – speed trans), the Rotor is composed of thick aluminum plate fixed to the ground and extending over the full length of track .The linear stator is bolted to the under carriage of train. Train speed is varied by changing the frequency applied to the stator.

Types and Applications

The **LIM** have three main operating duties which influence the design and construction, can be classified:

1) Power (Drive) machine:

This is concerned with transport of mass, as applied to conveyors, haulers, electromagnetic pumps, travelling Cranes and high speed rail way traction, with acceptable power efficiency.

2) Energy (Accelerator) machine:

The duty is to accelerate a mass from rest to a high speed within a specified time and distance, as for Car – Crash test, and the Launching of air craft.

The criterion is the energy efficiency, the ratio of useful energy to the total primary electrical energy input.

3) Force (Actuator) machine:

The develops Trust at rest, or a low speed over short stroke, as in the operation of stop – Valves, impact metal forming, Door – closers, the stirring of molten.

The criterion is the ratio of Force produced to input power.

Example:- A stator of a linear induction motor (LIM) is excited from a 75 Hz electronic source .If the distance between consecutive phase groups of phase A is 300 m.m . Calculate the linear speed of the magnetic field.

Solution: The pole – pitch is 300 m.m = 0.3 m.

$$\mathbf{V_s = 2 \times W \times f}$$

$$= 2 \times o.3 \times 75 \quad = 45 \quad m/s \quad \text{OR} \quad = 162\ km/hr$$

SATURABLE REACTOR

A saturable Reactor is a special form of inductor where the magnetic core can be saturated by a direct electric current in a control winding. Once saturated, the inductance of saturable reactor drops dramatically, this decreases inductive reactance and allows increased flow of the alternating current (AC), See Fig (1.69).

G – AC Source.

L – Lamp (load).

T – Saturable Reactor.

R – Variable Resistor.

B – D.C Source (Battery)

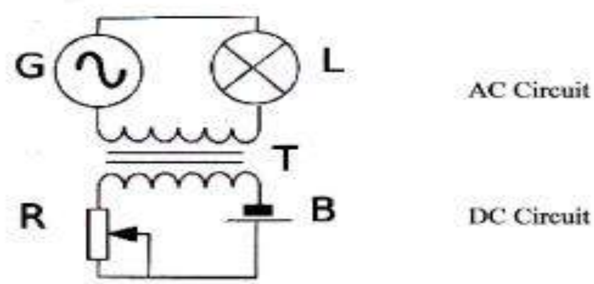


Fig (1.69) Equivalent CCT of saturable reactor

In concept, alternating current through the lamp (**L**) can be controlled by saturation of the iron core with the direct current, regulated by variable resistor (**R**).

Saturable reactors provide a very simple means to remotely and proportionally control the alternating current (A.C) through a load such as an incandescent Lamp; The (A.C) load current is roughly proportional to Direct current (D.C) in the control circuit.

A Saturable Reactor – Core

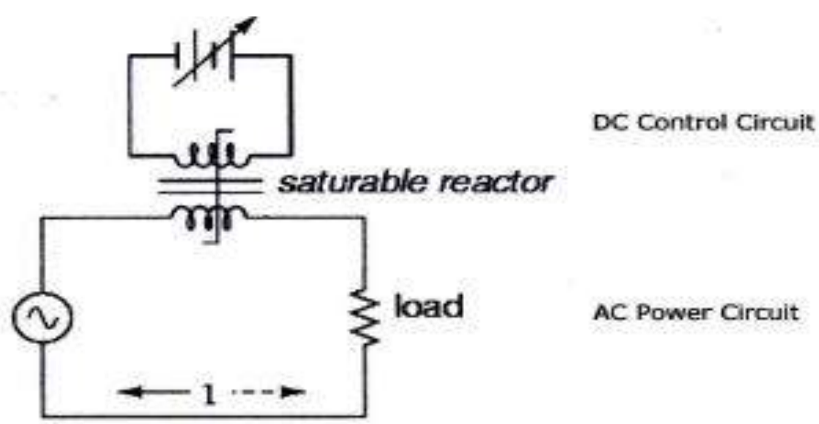
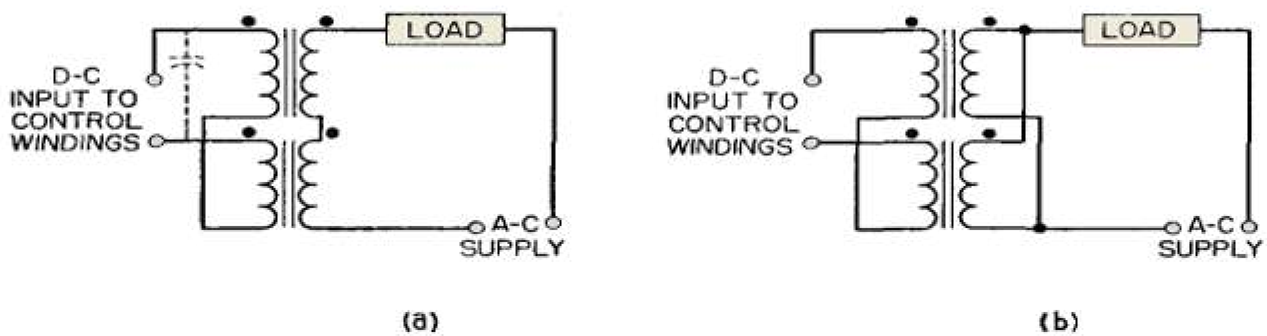


Fig (1.70) Schematic representation of Saturable Reactor

The above schematic representation, Fig (1.70), of single core Saturable reactor, the upper winding being (D.C) control winding and the lower being (A.C) power winding through which the controlled (A.C) current flow.

Increased (D.C) control current produces more magnetic flux in the reactor core, driving it closer to saturation condition, thus, decreasing the power winding's inductance, decreasing its impedance, and increasing current to the load. Therefore the (D.C) control current is able to exert control over the (A.C) current delivered to the load.



Magnetic Amplifier

Fig (1.71) Simple Magnetic Amplifiers

The reactor, with a battery-fed (D.C) source controlling one winding and (A.C) power fed through the other winding, would have (A.C) voltage induced in the (D.C) winding. If this (D.C) winding were closed only on the battery, it would effectively short-circuit the (A.C) voltage in the power winding. This difficulty might be overcome by using a high impedance in the d-c control circuit. A more common solution is to use two reactors, one of the (D.C) windings of which is reversed (i.e out of phase), while the (A.C) windings add normally (in phase). Connections of this sort are shown in Fig (1.71a), with the (AC) power windings in series; it is possible to connect them in parallel as in Fig (1.71b) in order to allow more load current to flow at lower voltage.

The placement of the phasing dots on the two reactors is shown in Fig (1.71).

If both reactors are identical ,any voltage induced in the control windings by load currnt through the power windings will cancel out to **zero** at the Battery terminals .Since the (D.C) control current through both reactors produces magnetic flux in different direction through the reactor cores ,one reactor will saturate more in one cycle of the (A.C) power while other reactor will saturate more in the other cycle ,thus equalizing the control action through each half – cycle so that the (A.C) power is "throttled" symmetrically .This phasing of control windings can be accomplished with two separate reactors as shown , or in a single reactor design with intelligent layout of the windings and core .

Saturable reactor technology has even been miniaturized to the circuit – board level in compact packages more generally known as **Magnetic Amplifiers.**

The Effect of Reactance Variation on Saturable Reactor

To study reactance variation effect on Saturable Reactor, using winding pattern of Fig(1.72).

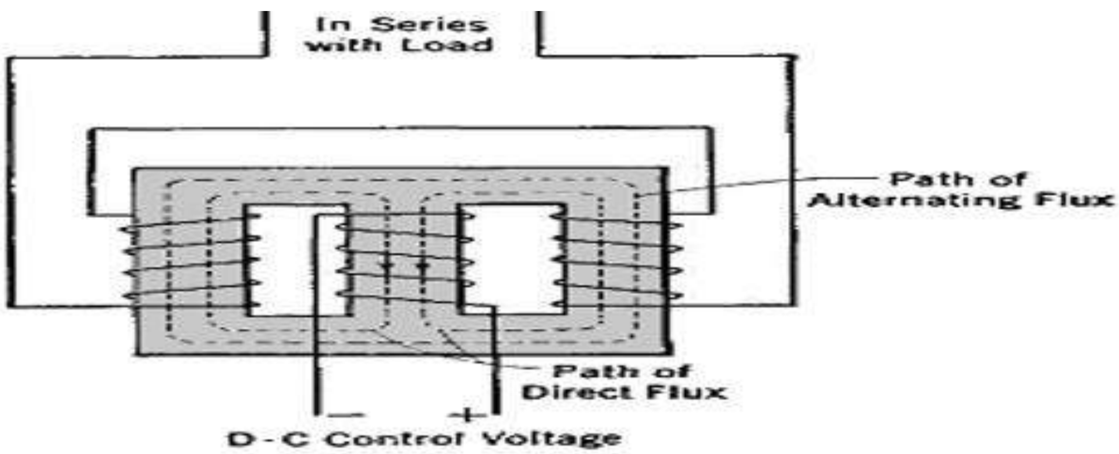


Fig (1.72) Saturable Reactor circuit

Because of the non- linear shape of iron saturation curve, the flux per ampere, and hence the inductance of an iron - core reactor, is a complex function of flux density in the core. As the flux density increases beyond the first approximately straight portion of magnetization curve, the reactance decreases rapidly. By superposing a uni-directional but variable **mmf** on the core, a variable reactor without moving parts may be obtained. Fig (1.72) shows one of the simpler methods of doing this. The a-c coils produce simultaneous **mmf's**, and hence flux, around the long outer magnetic circuit but none of appreciable magnitude in the middle leg. In this way, no (A.C) voltage is induced in (D.C) control coil on middle leg. Flux produced by (D.C) control coil divides between two outside legs and produces a variable "pre-saturation" in them. The core is said to be "biased" by (D.C) Ampere-Turns. The effect of bias on the coil reactance shown in Fig (1.73) . If the core is biased by 2 ampere-turns per inch and an alternating current producing NIm = 0.5 is passed through the(A.C) coil, the reactance of coil will swing from 27.5

Ω when the alternating current is negative to only 13 Ω when the current is positive. From graph the average reactance is about 20.2 Ω

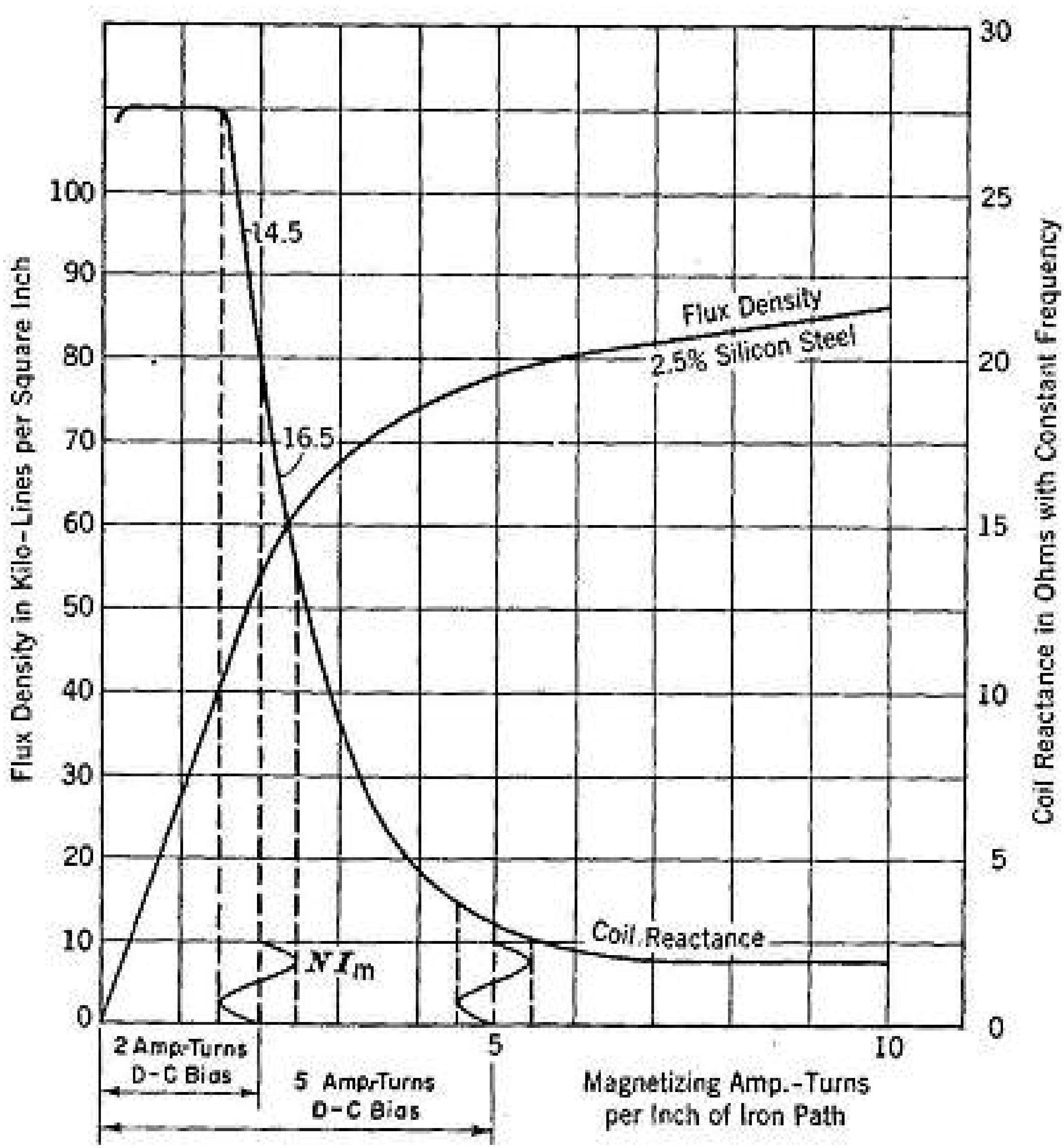


Fig (1.73) The Effect of Reactance Variation on Saturable Reactor