Course: Special Electrical Machines (BEE061)

Unit 1
Induction machines

Electric Motors (A major power consumer in industries)

- Electromechanical device that converts electrical energy to mechanical energy.

- Motors in industry: 70% of electrical load.

General Classification of Motor

- Motors
  - DC
  - AC
    - Synchronous
    - Induction
      - Cage rotor
      - Wound rotor

Why Induction Motor ?

(Major Advantages)

- Rugged structure
- Low maintance
- Better reliability
- Ability to operate in dirty and explosive environment
- Higher efficiency
- Available in wide power range

Uses of Induction Motor

- Industrial Applications:
  - Steel and cement mills
  - Paper and textile mills etc.

- Domestic uses:
  - Pumps
  - Fans
  - Other home appliances

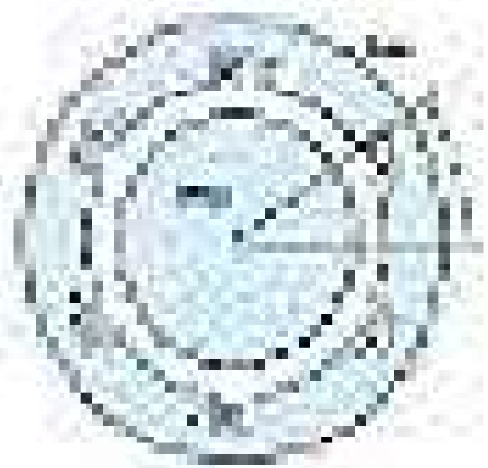
- Fixed and variable speed applications

Constructional Details

Major parts:

- Stator (stationary part)
  Three phase armature winding is embedded.

- Rotor (rotating part)
  Types: - Squirrel cage
  - Wound rotor



Cross sectional view of Induction motor

General view of stator and rotor

Complete view of Induction motor

Operating Principle of Induction Motor

- Rotating Magnetic Field

Input supply to stator

↓

Magnetic flux in each phase

↓ Resultant Flux

Rotating flux of constant magnitude ← Can be proved mathematically

Representation of constant rotating flux

- Speed of rotating flux $\xrightarrow{\text{known as}}$ *Synchronous* Speed

How rotating torque is produced ?

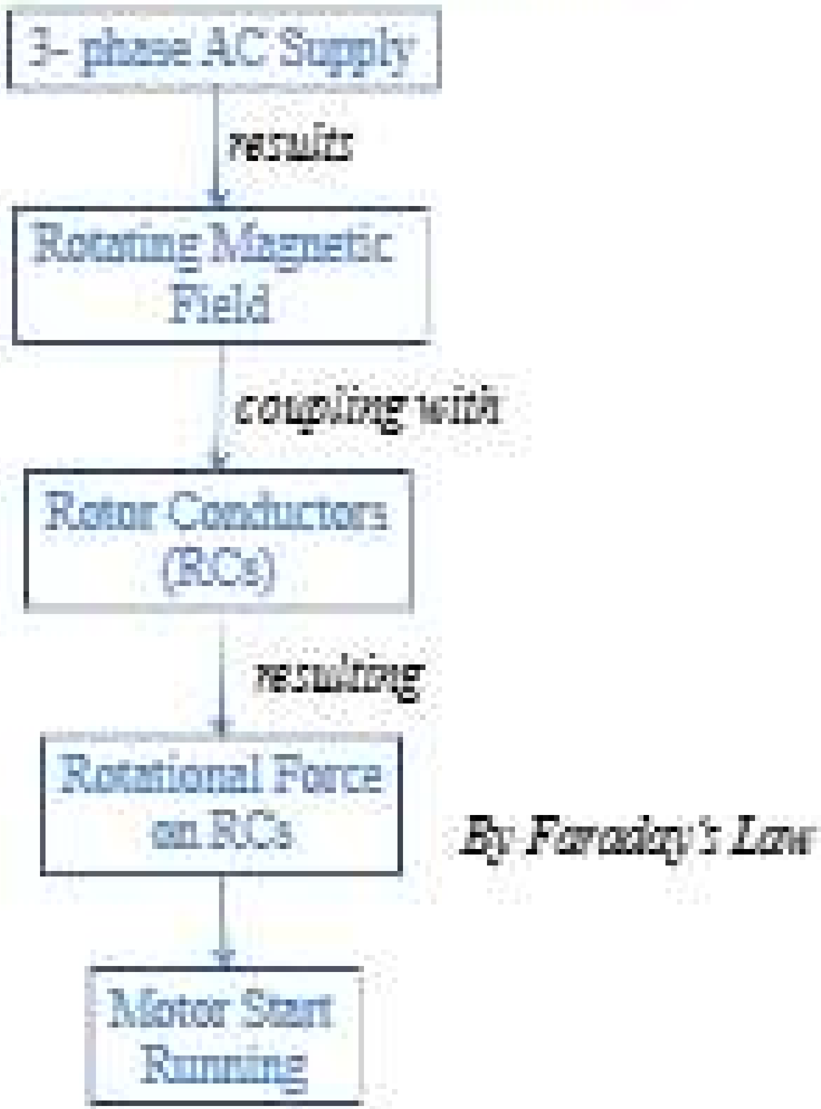
- Induced e.m.f. in rotor conductor (theory of electromagnetic induction).
- Flow of rotor current due to its closed circuit.
- Presence of current carrying rotor conductor in magnetic field produced force.

- Direction of force is governed by Faraday Left Hand Rule.

- Hence, induction motor is self starting.

- Speed of rotation is slightly less than synchronous speed.

Various Steps in motor operation



Review of Induction motor

Torque of induction motor

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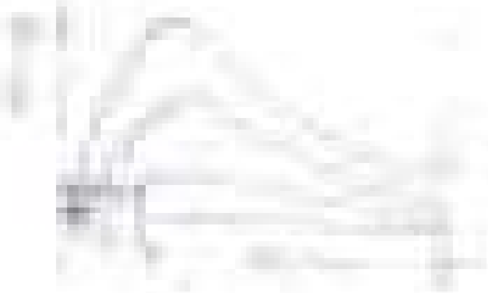
Stator Side

1. Stator voltage Control
2. Stator Frequency Control (V/f control)
3. Pole changing

Rotor Side

1. Rotor circuit resistance variation
2. EMF injection in rotor circuit
3. Cascade connection method

Speed Control by Stator voltage Control

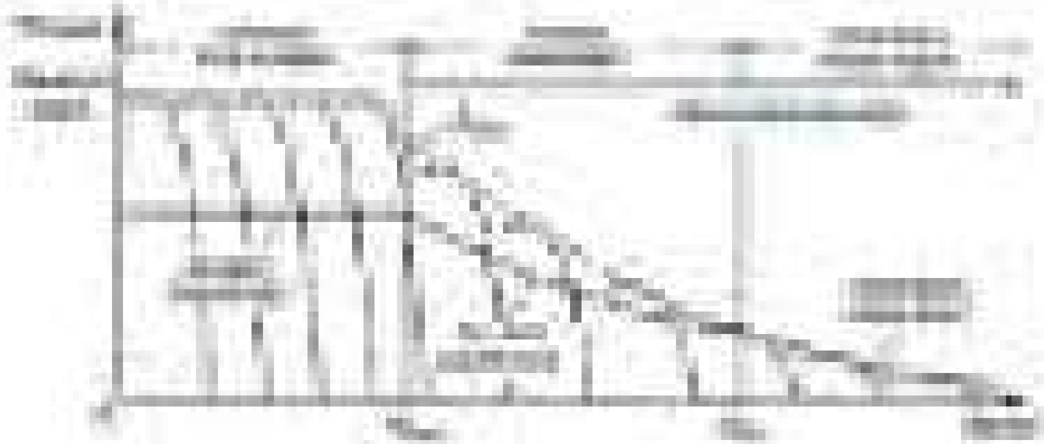


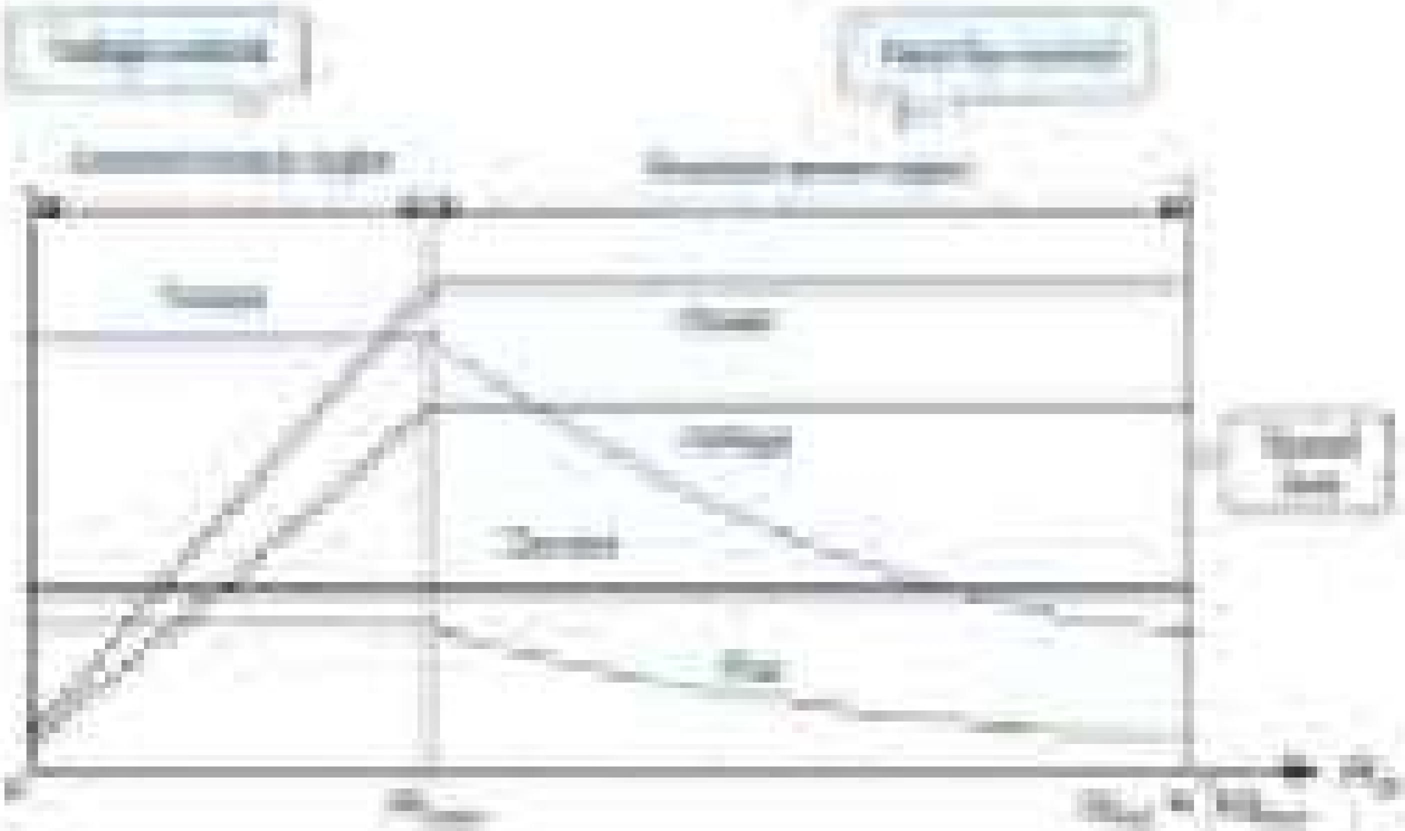
Speed Control by Stator Frequency Control
(i.e. V/f control)

f3<f2<f1

Operating region of Induction Motor

Constant torque region | Constant power region | Breakdown torque region



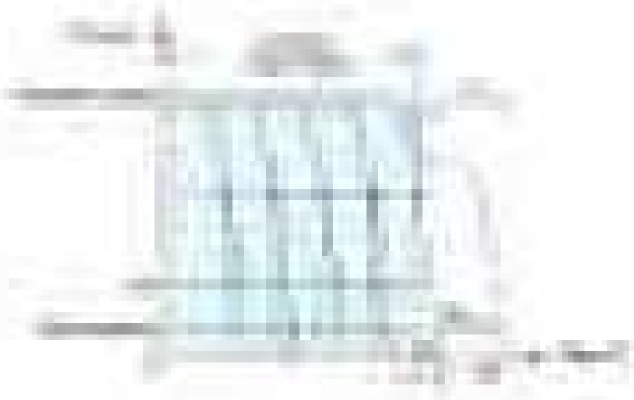


$$P = T\,\omega$$

A) Constant torque region

- Motor speed is increased by increasing the stator frequency maintaining constant flux (according to the linear V/f relationship)

- In this control method, since the output torque is proportional to the slip frequency, the output torque can be produced equally at any speed for the same slip frequency. How?



B) Constant power region

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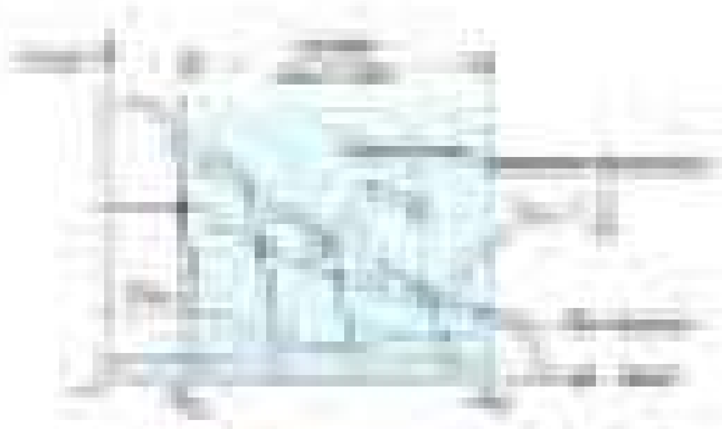


Linear Induction Motor (LIM)

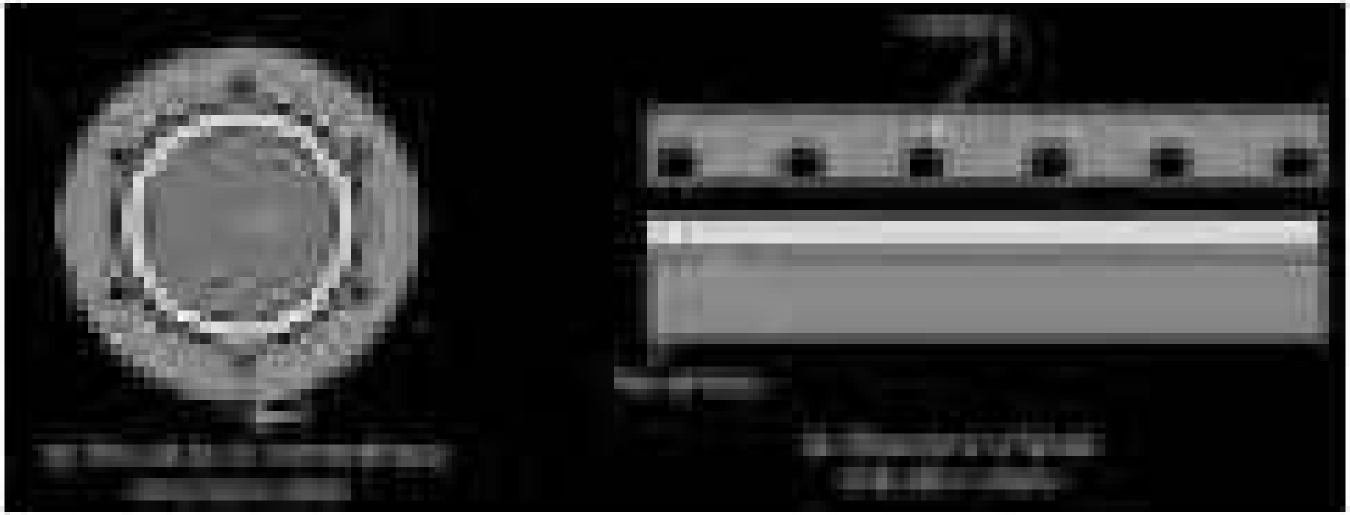
Linear induction motor (LIM)

is a motor which gives

a linear or translational motion

How and Why?

Construction of LIM



Constructional features of Linear induction motor

Operation of LIM

Three-phase AC supply

↓

Resultant travelling flux is produced

↓

Flux linkage to rotor conductor (secondary)

↓

Current will flow in secondary

↓

Linear Force or thrust (F) will be produced

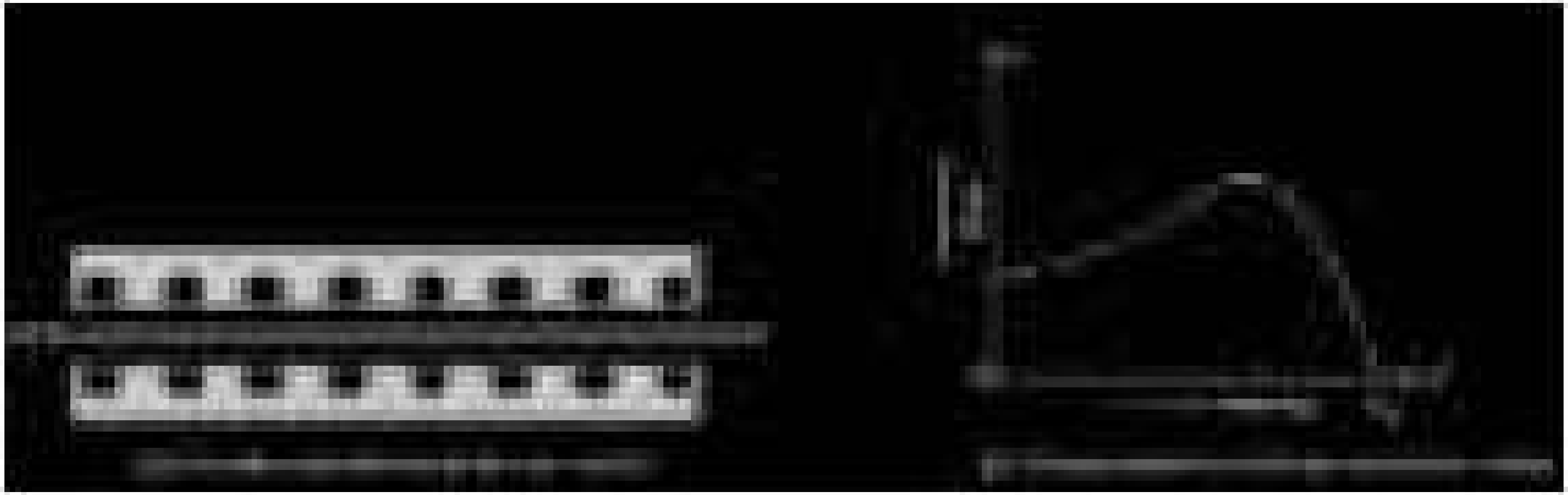
- For fixed secondary, primary will move in the direction of travelling wave

Types of LIM

Single-sided linear induction motor (SLIM)

Double-sided linear induction motor (DLIM)

primary is placed on both the sides of the secondary



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Two Phase AC SERVOMOTORS

- To control the machine it is operated with fixed voltage for the reference phase and variable voltage for the control phase.

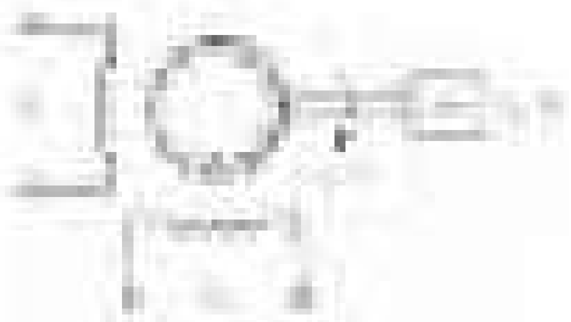
- The torque–speed characteristics are essentially linear (high rotor resistance assumed) for various control phase voltages.

- In low-power control applications (below a few watts), a special rotor construction is used to reduce the inertia of the rotor. A thin cup of nonmagnetic conducting material is used as the rotor (*drag-cup rotor*).

Drag-cup rotor construction

- A stationary iron core at the middle of the conducting cup completes the magnetic circuit

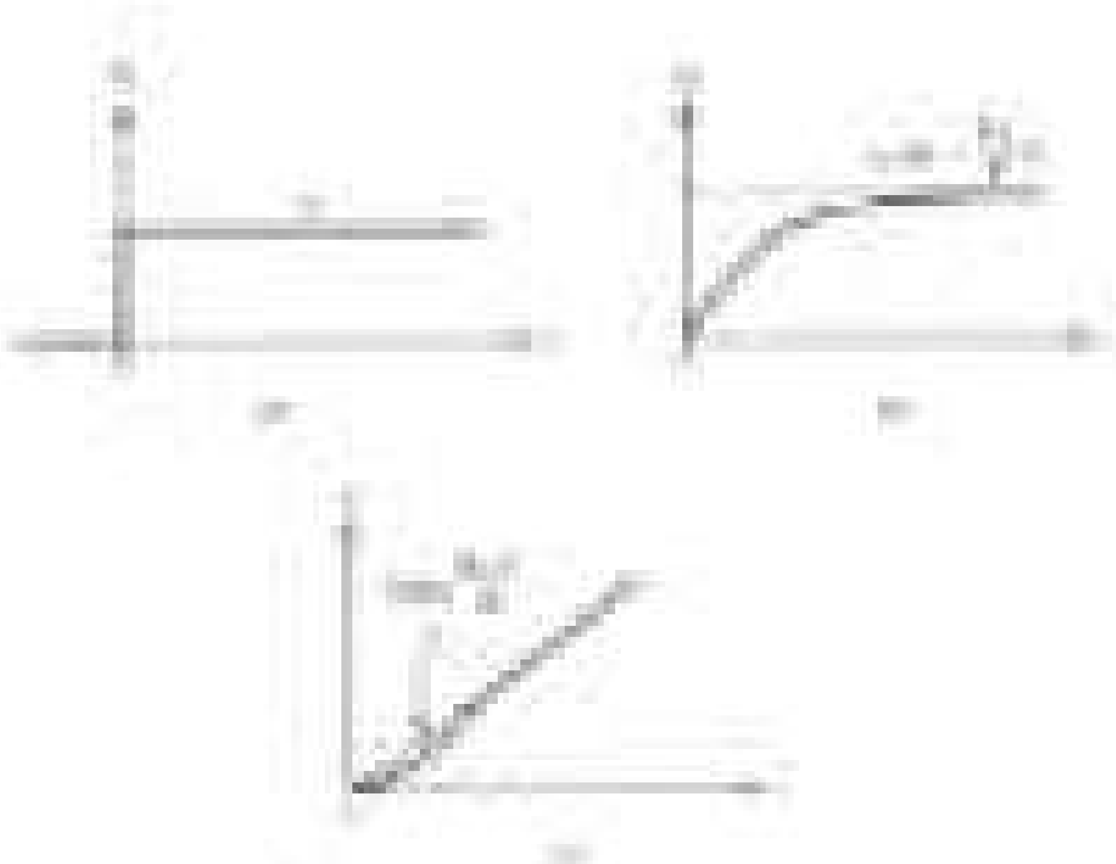
ANALYSIS: TRANSFER FUNCTION AND BLOCK DIAGRAM



Transfer functions.

Time Response for a Step Change in Control Phase Voltage: Open Loop Operation

Consider a step change in the control phase voltage Va



Step response in a two-phase servo system.
(a) Step change in Va.
(b) Response in speed.
(c) Response in position.

Q1

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Induction machine as generator

Grid connected

Self-exited

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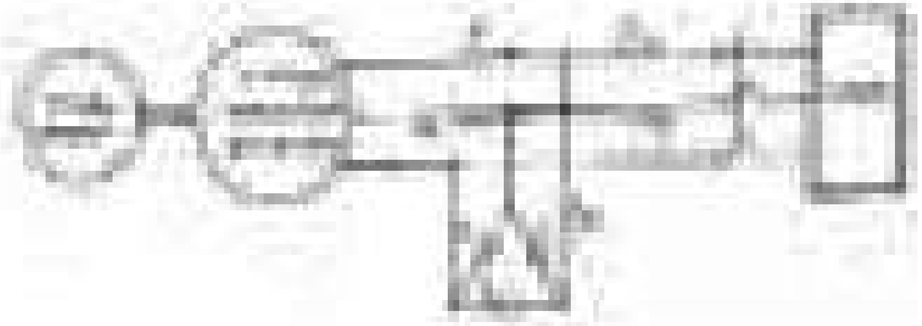
Self exited induction generator



- Capacitive reactive power, Q = Q1, reactive power needed by 3-phase induction generator + Q2, reactive power needed by the load.

- The reactive current of a capacitor depends upon the voltage across its terminals, *i.e.*, capacitor voltage [illegible]

Voltage Build-up in self-exited induction generator

Self exited induction generator

- The delta- connected capacitors across the generator terminals provide the magnetizing current necessary to excite the isolated generator

- Operating frequency depends primarily upon rotor speed but is affected by the load, while the voltage is mainly decided by capacitor reactance (XC) at the operating frequency.

Voltage Buildup in SEIG

Unit 2

Stepper motor

- *Def. A motor in which the rotor turns in discrete movements is called a* ***stepper motor.***

- [illegible]

- The angle through which the motor shaft rotates for each command pulse is called *the step angle β*.

- It is observed, the smaller the step angle, the greater the number of steps per revolution and higher the resolution or accuracy of positioning obtained.

[illegible]

- The resolution is given by the number of steps needed to complete one revolution of the rotor shaft. The higher the resolution, the greater the accuracy of positioning of objects by the motor.

Resolution = No. of steps/revolution = 360°/β

- When the pulse rate is high the shift rotation seems continuous and operation at a high rate is called slewing.

- [illegible]

[illegible]

Q1

[illegible]

Q2

[illegible]

[illegible]

[illegible]

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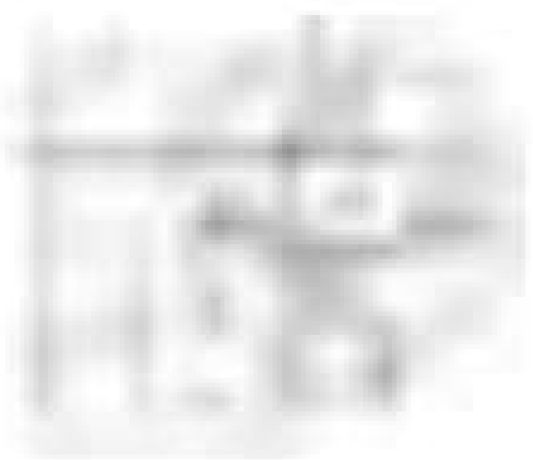
VARIABLE-RELUCTANCE STEPPER MOTOR

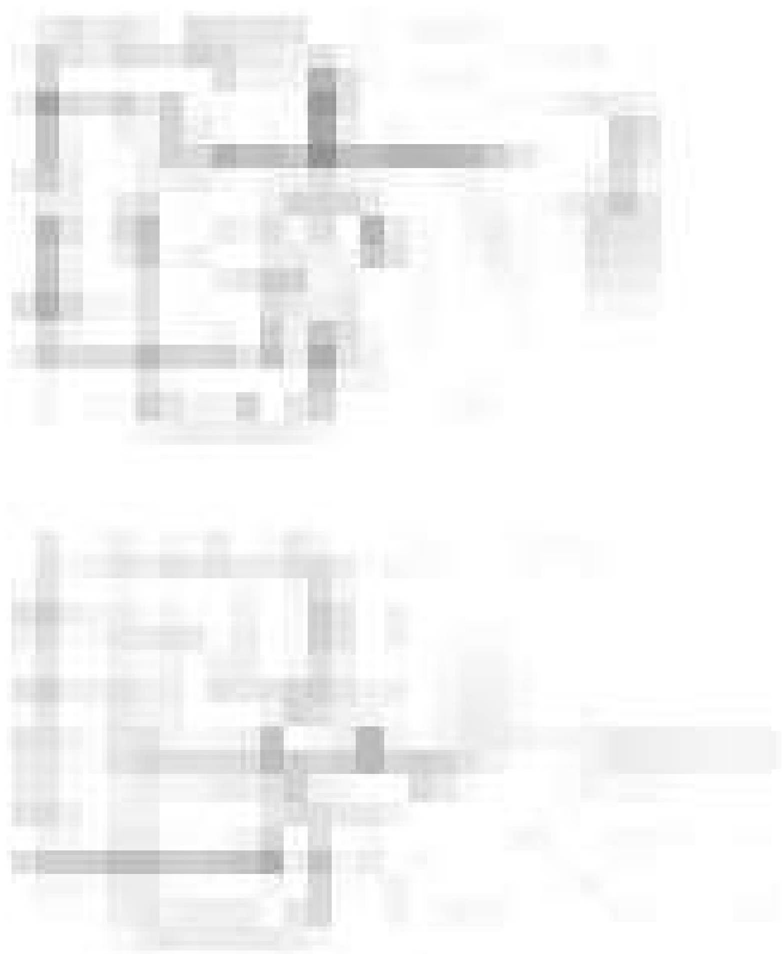
A. Single-Stack Stepper Motor



Basic circuit for a four-phase, 4/2 pole stepper motor.

- Reluctance torque is generated because of the tendency of the ferromagnetic rotor to align itself along the direction of the resultant magnetic field.

- Sequence: A, B, C, D etc. for 90 degree rotation in clockwise direction.



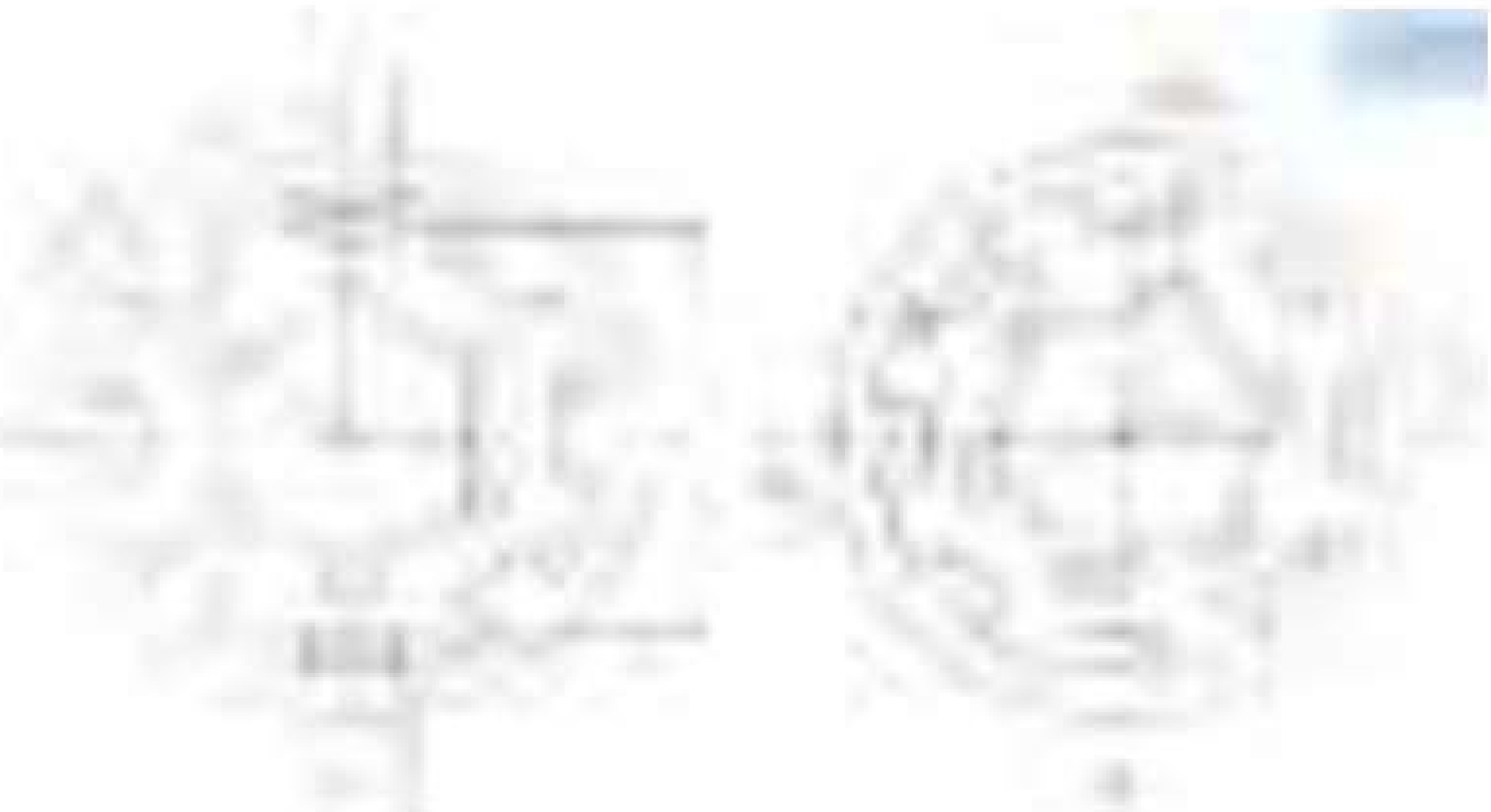
Operating modes of stepper motor for 90 step.

Sequence: A, A + B, B, B + C, and so forth

Operating modes of stepper motor for 45 step.

- Microstepping: The method of gradually shifting of excitation from one phase to another (e.g. From A to B with an intermediate step A+B) is known as microstepping.

- Lower values of step angle can be obtained by using a stepping motor with more number of poles on stator and teeth on rotor.



Multistack Stepper Motor

- A Multi Stack or m stack variable reluctance stepper motor is made up of m identical single stack variable reluctance motor. The rotor is mounted on the single shaft. The stator and rotor of the **Multi Stack Variable motor** have the same number of poles and hence, the same pole pitch.

- All the stator poles are aligned in a Multi-Stack motor. But the rotor poles are displaced by 1/m of the pole pitch angle from each other. The stator windings of each stack forms one phase as the stator pole windings are excited simultaneously. Thus, the number of phases and the number of stacks are same.

Cross section of a three-stack, variable-reluctance stepper motor parallel to the shaft.

- There are 12 stator and rotor poles in each stack. The pole pitch for the 12 pole rotor is 30, and the step angle or the rotor pole teeth are displaced by 10 degrees from each other.

Let Nr be the number of rotor teeth and m be the number of stacks or phases.

Hence, Tooth pitch is represented by the equation shown below.

[illegible]

As there are 12 poles in the stator and rotor, thus the value of Nr = 12. Now, putting the value of Nr in the equation (1) we get

[illegible]

The value of m= 3. Therefore, the step angle will be calculated by putting the value of m in the equation (2).

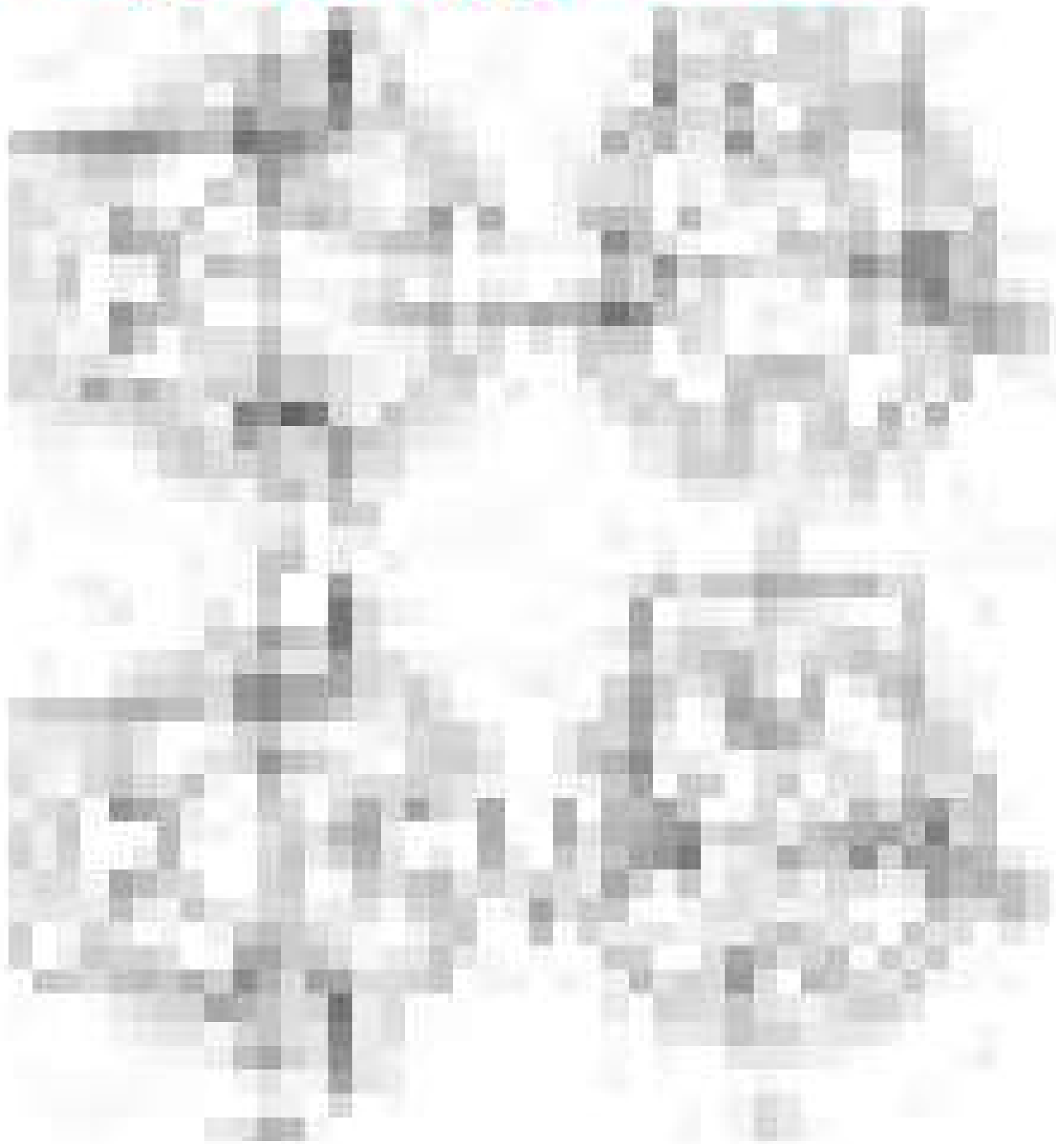
- When the phase winding A is excited the rotor teeth of stack A are aligned with the stator teeth as shown in the figure below.

- When phase A is de-energized, and phase B is excited, rotor teeth of the stack B are aligned with the stator teeth. The rotor movement is about 10 degrees in the anticlockwise direction.

- Similarly, now phase B is de-energized, and phase C is excited. The rotor moves another step of 1/3 of the pole pitch in the anticlockwise direction.

- However, during this whole process (A – B – C – A) the rotor has moved one rotor tooth pitch.

Permanent magnet stepper motor



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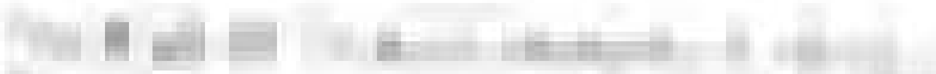
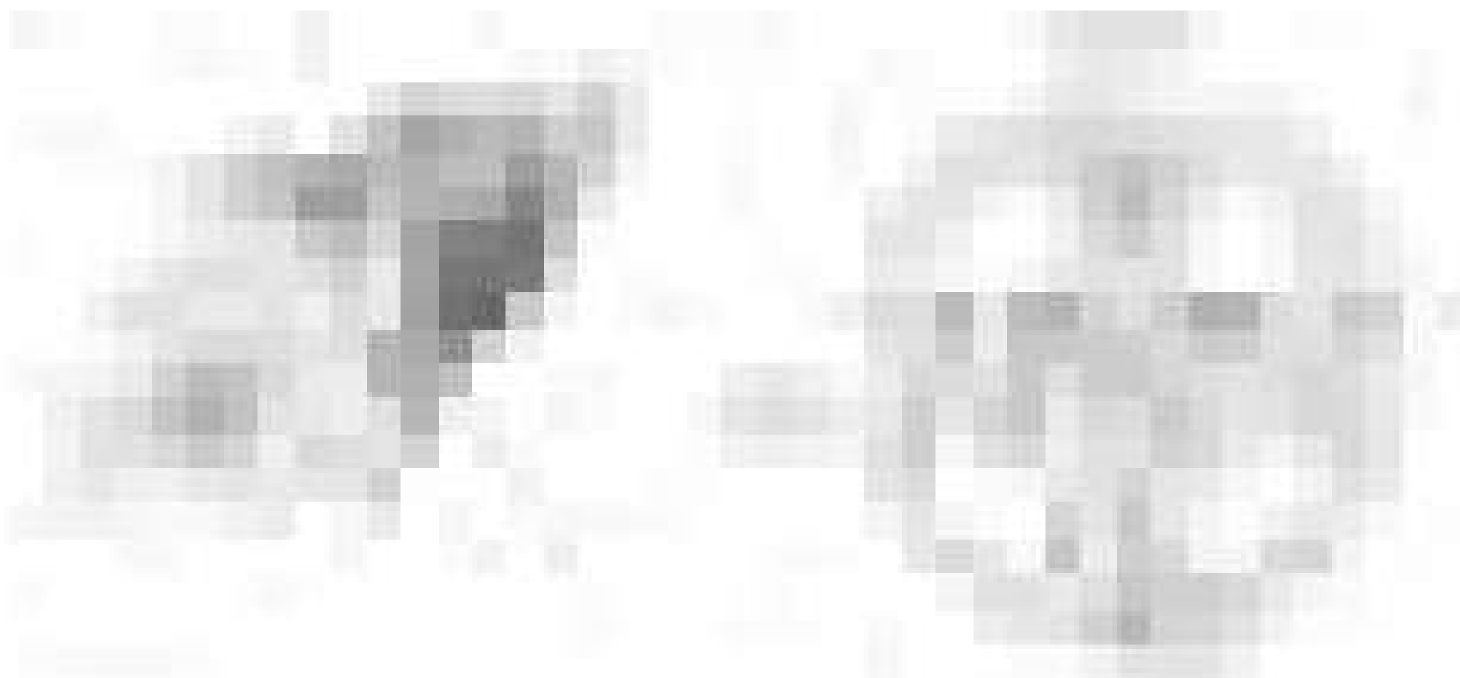
Half Step mode excitation



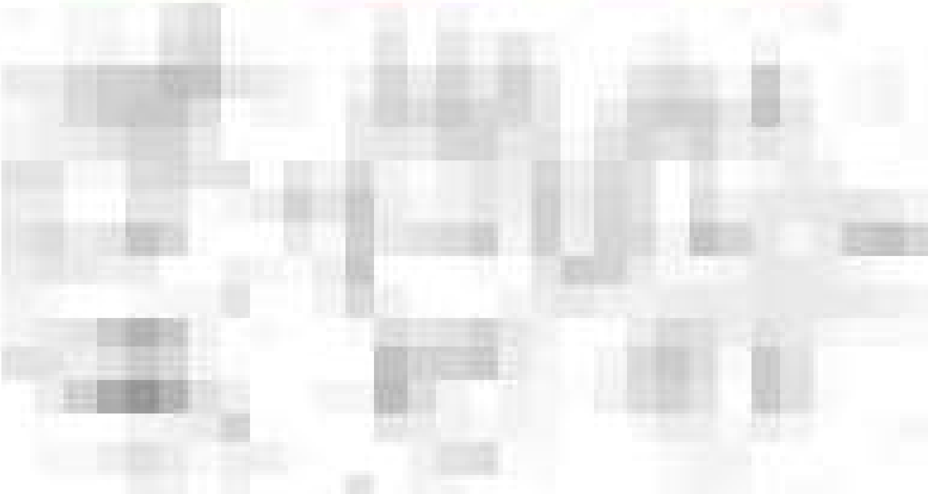
Rotor rotation through 45° with both windings excited together in PMSM

Hybrid Stepper Motor



Characteristics of Stepper Motor

A) Torque-Displacement Characteristic



B) Torque pulse rate characteristic

- With increase in stepping rate, the rotor gets less time in driving the load from one position to the next, the driving torque is therefore decreased

- **Pull-in torque**: It shows the maximum stepping rate for the various values of the load torque at which the motor can start, synchronize, stop or reverse.

- **Pull-out torque characteristics**: It shows the maximum stepping rate of the motor where it can run for the various values of load torque. But it cannot start, stop or reverse at this rate.

- The area between curves 1 and 2 represents the various torque values, the range of stepping rate, which the motors follow without losing the synchronism when it has already been started and synchronized. This is known as **Slew Range**.

DRIVE CIRCUITS

A) Unipolar Drive Circuit

- A phase winding is excited by applying a control signal to the base of the transistor (a sufficiently high base current is passed through the base of the transistor)
- The dc supply voltage Vs is chosen so that it produces the rated current I in the winding.

- The maximum voltage across the transistor occurs at the instant of switch off, and is

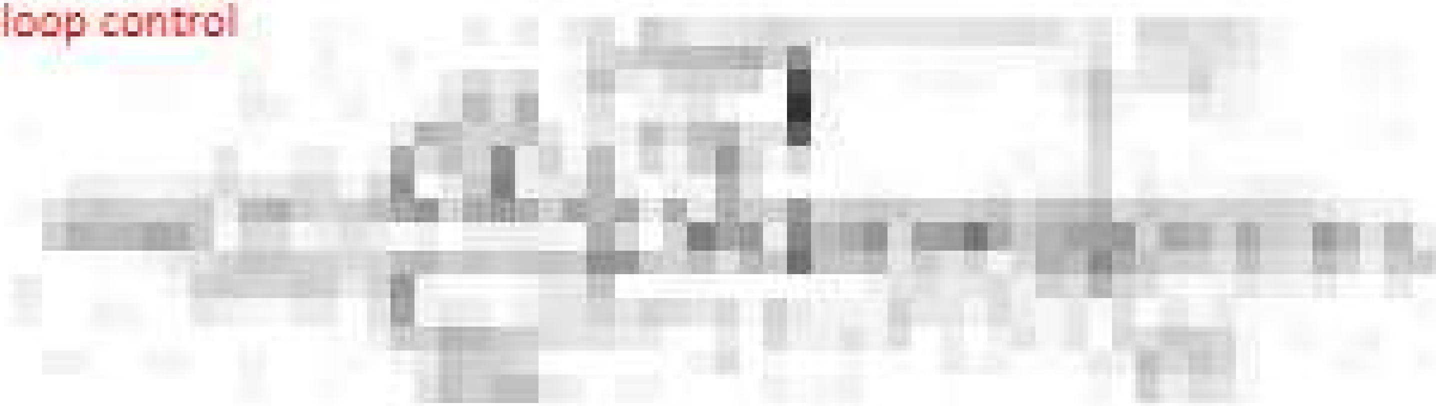
B) Bipolar Drive Circuit

One phase of a bipolar drive circuit

- Bipolar drive circuit suitable for a permanent magnet or hybrid-type stepper motor.
- The transistors are switched in pairs according to the current polarity required for the phase winding
- The four diodes D1 to D4 connected in antiparallel with the switching transistors provide the paths for the freewheeling currents
- Note that when current flows through D3 and D4 to the dc supply, some of the energy stored in the phase winding inductance at turnoff (of the transistors) is returned to the supply. This **improves the overall system efficiency**, and is a significant advantage of the bipolar drive circuit over the unipolar drive circuit.
- Bipolar drive circuits require more switching devices and are therefore more expensive than unipolar drive circuits.
- Note that the freewheeling currents in the bipolar drive circuit decay more rapidly than in the unipolar drive circuit, because the dc supply opposes them. Consequently, no additional freewheeling resistance is necessary in the bipolar drive circuit.

Control of Step Motors

A) Open-loop control



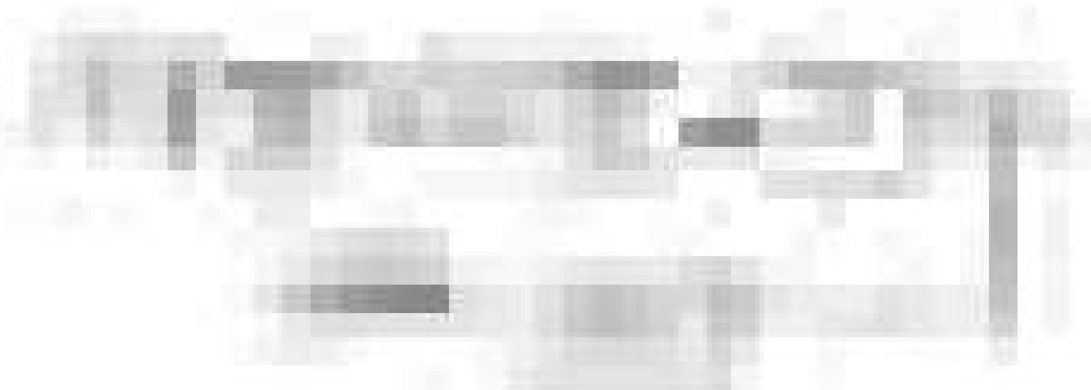
Open-loop control of a step motor

- The command to the pulse generator sets the number of steps for rotation and direction of rotation
- The Translator is a simple logical device and distributes the position pulse train to the different phases
- The amplifier block amplifies this signal and drives current in the corresponding winding.

- The direction of rotation can also be reversed by sending a direction pulse train to the translator. After receiving a directional pulse the step motor reverses the direction of rotation.

- The **major disadvantage** of the open loop scheme is that in case of a missed pulse, there is no way to detect it and correct the switching sequence. A missed pulse may be due to malfunctioning of the driver circuit or the pulse generator. This may give rise to erratic behaviour of the rotor.

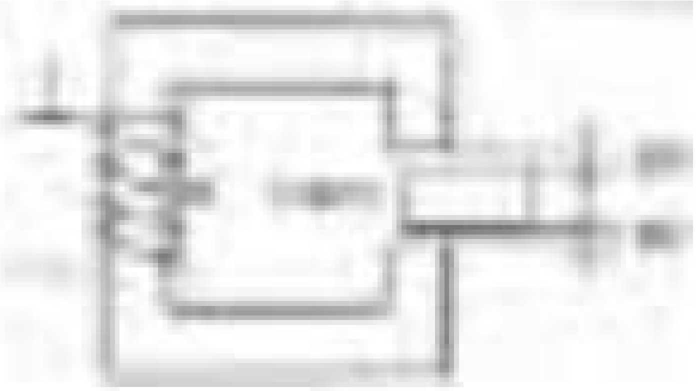
B) Closed-loop control



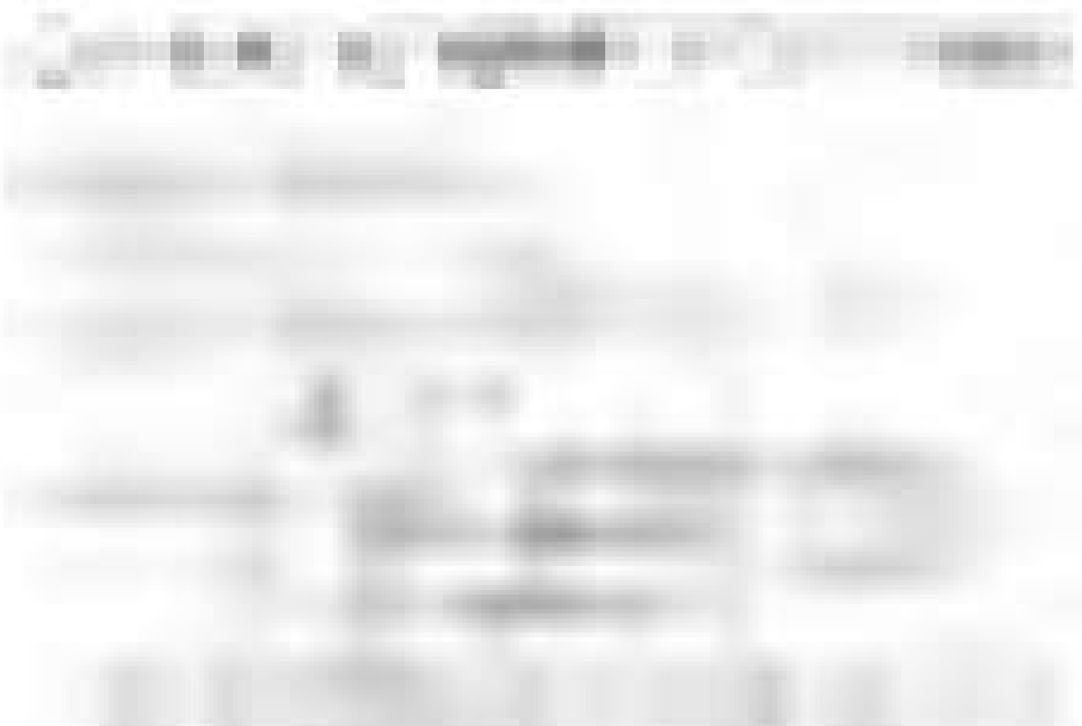
Feedback control of a step motor

The closed loop arrangement has the advantage over open loop control, since it does not allow any pulse to be missed and a pulse is send to the driving circuit after making sure that the motor has rotated in the proper direction by the earlier pulse sent. In order to implement this, we need a **feedback mechanism that will detect the rotation in every step and send the information back to the controller**. The incremental encoder here is a digital transducer used for measuring the angular displacement.

Torque/Force equation of Stepper Motor



Case I: Core permeability is Infinite



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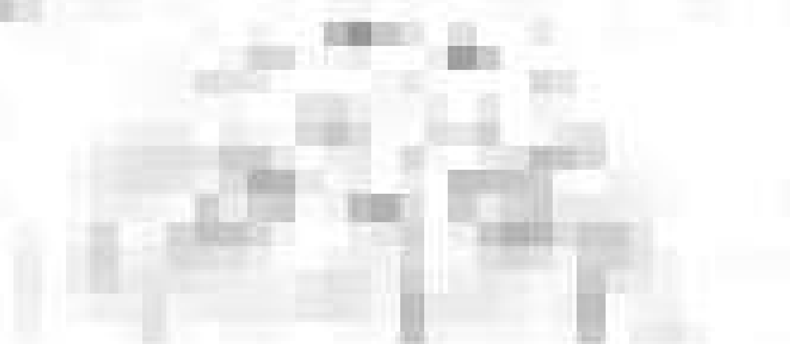
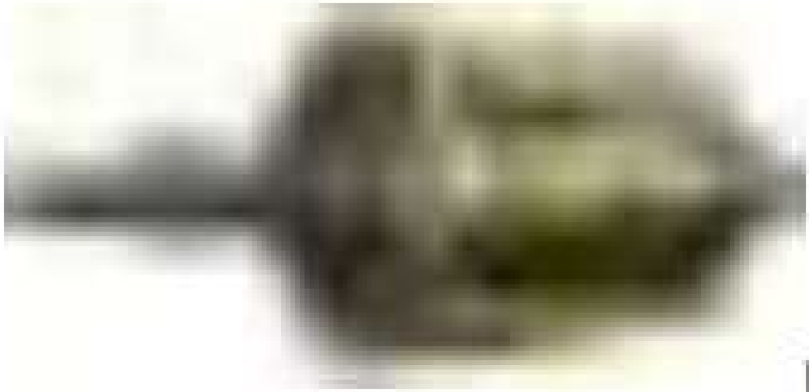


Unit 3

Switched Reluctance Motors



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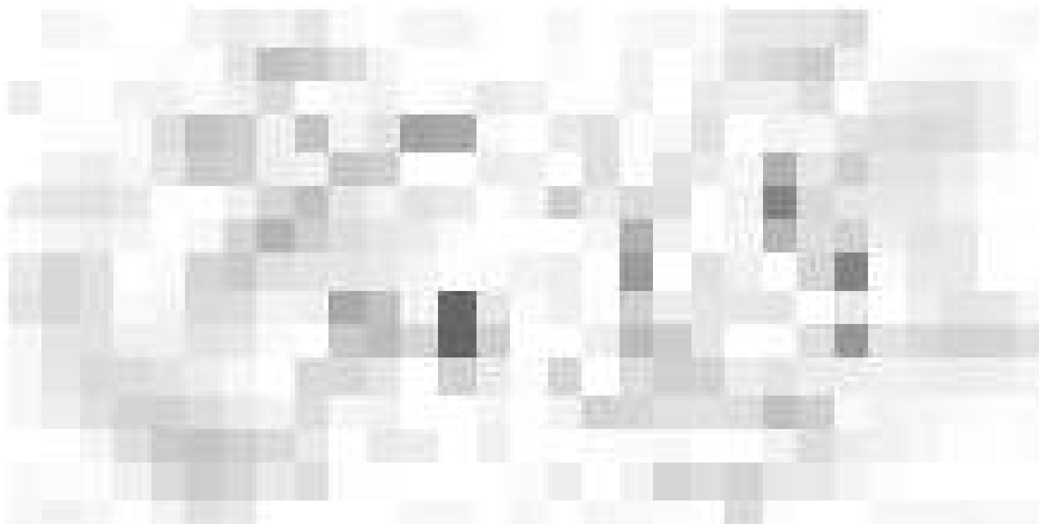

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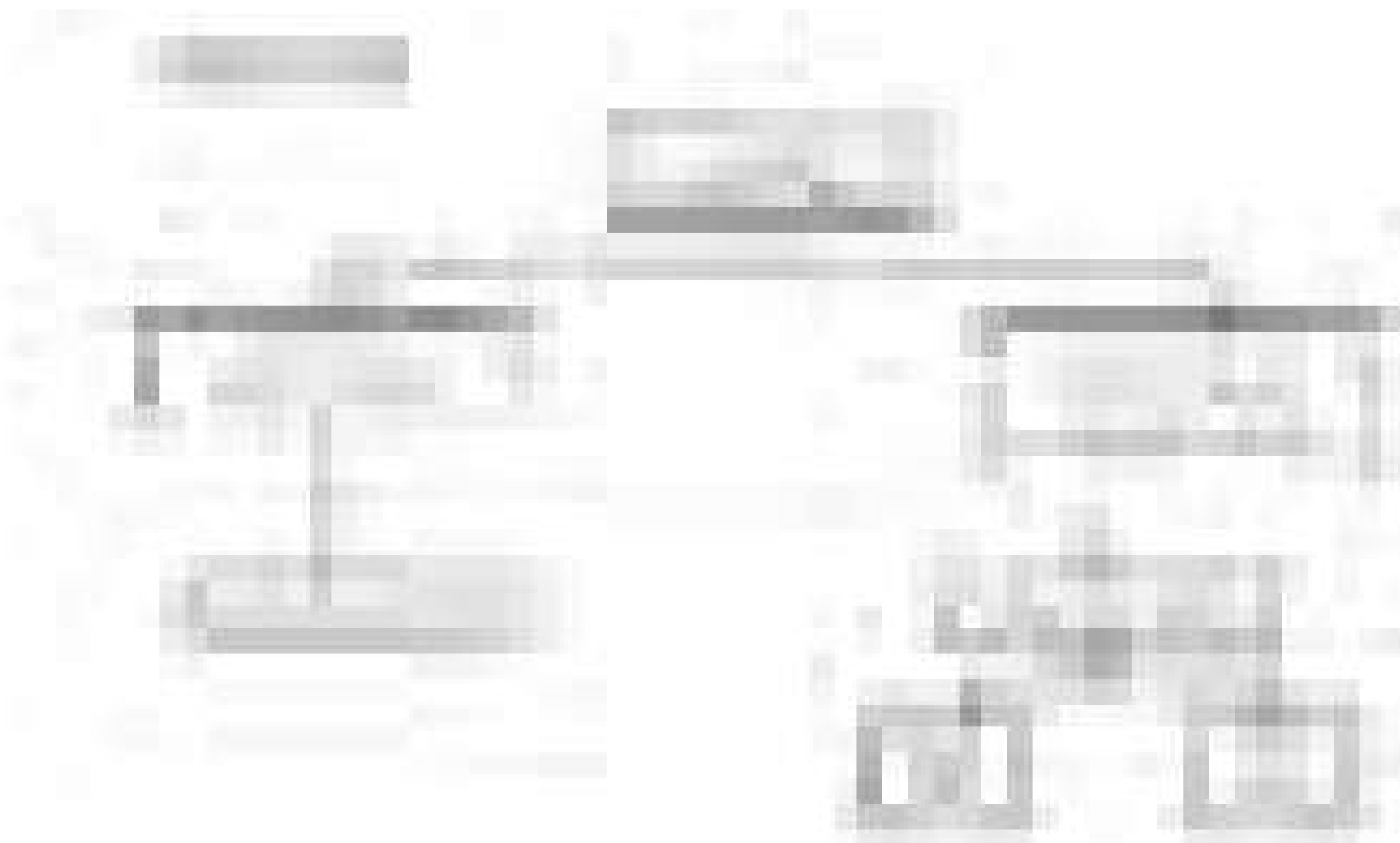
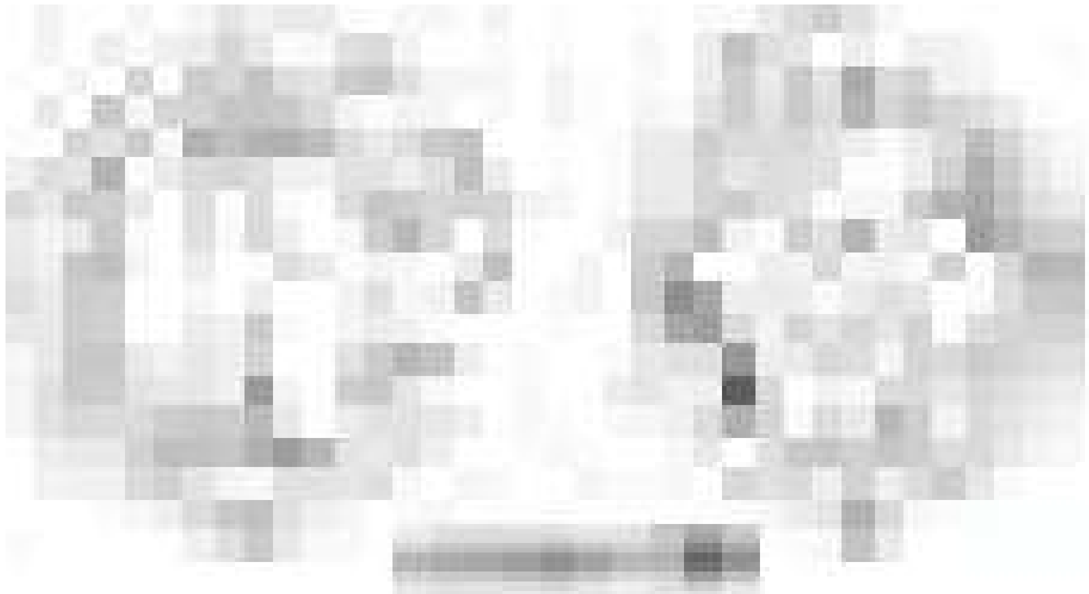


Principle of operation



For CCW rotation sequence of excitation is ABC.

Torque Developed Expression

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Energy stored in the magnetic field,

$$W_m = \frac{1}{2} L I^2$$

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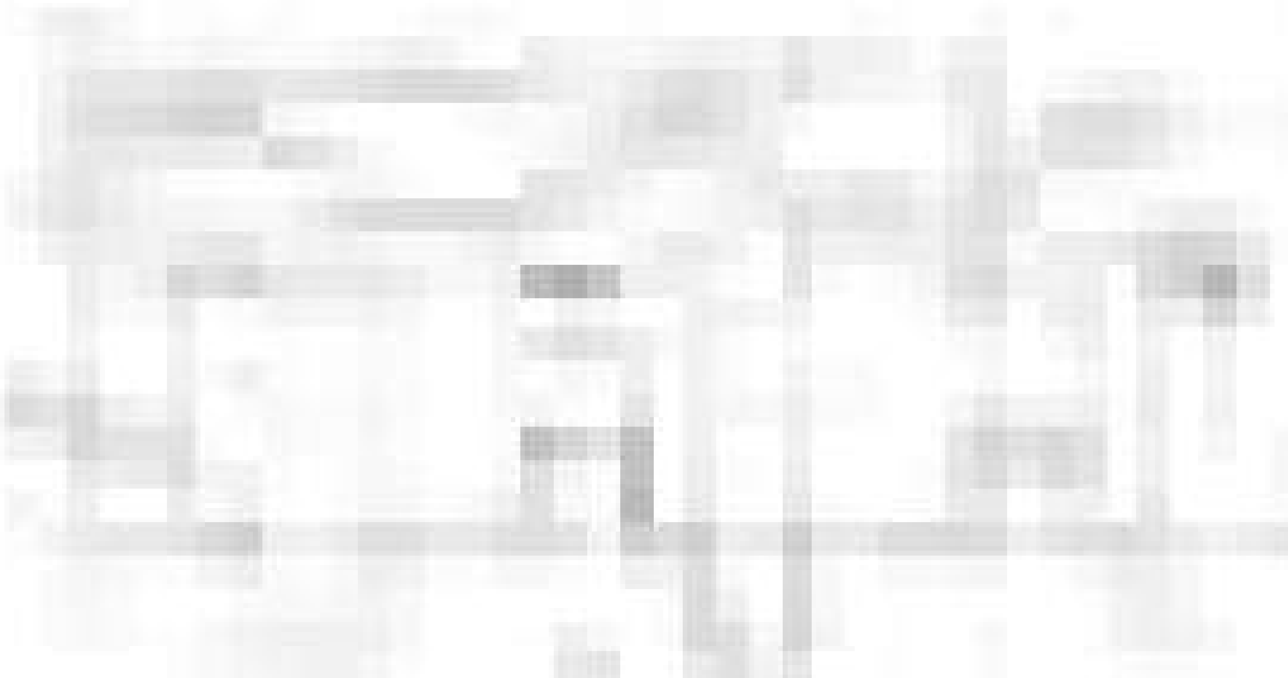

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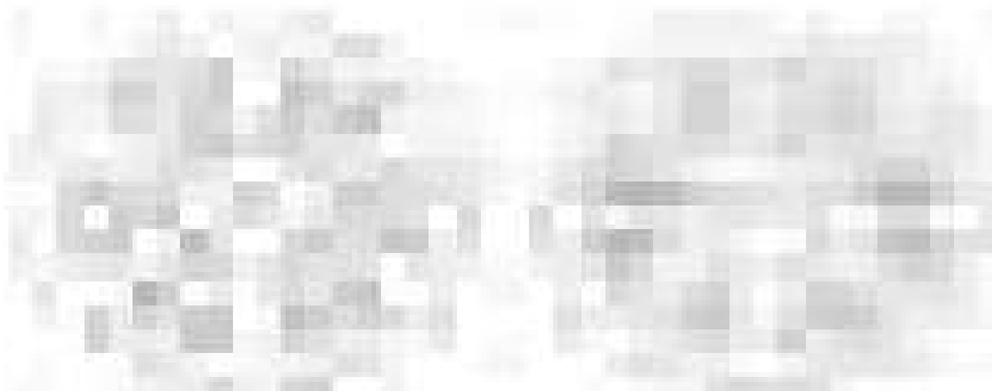

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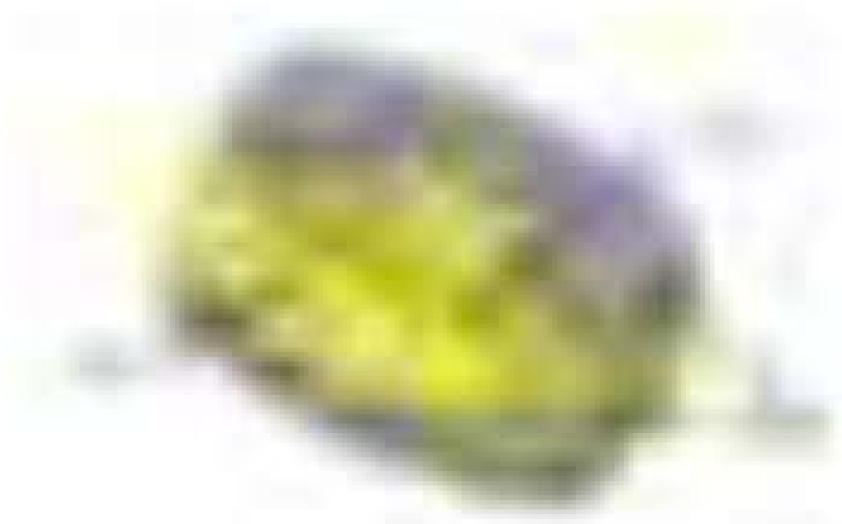
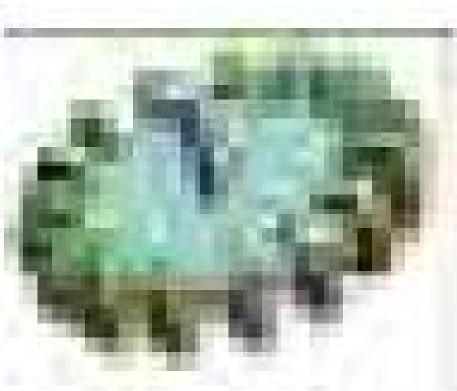
Axial-flux switched reluctance motors

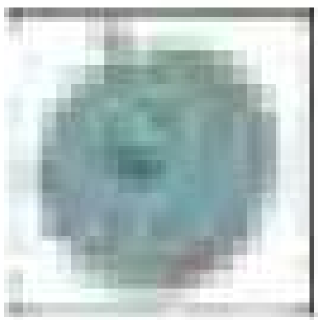
In these motors, the flux path is aligned with the motor axis, and they are used for cases where the motor length is of high importance and the motors with a small length and high torque are preferred for applications such as air conditioning fans and electric vehicles



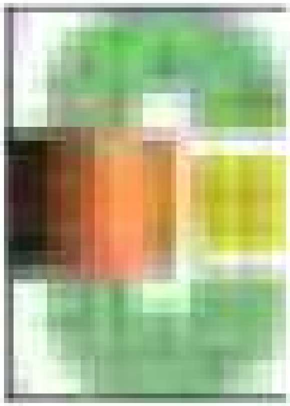
Axial field SRM: The magnetic field path is along the axial direction.



Whole motor



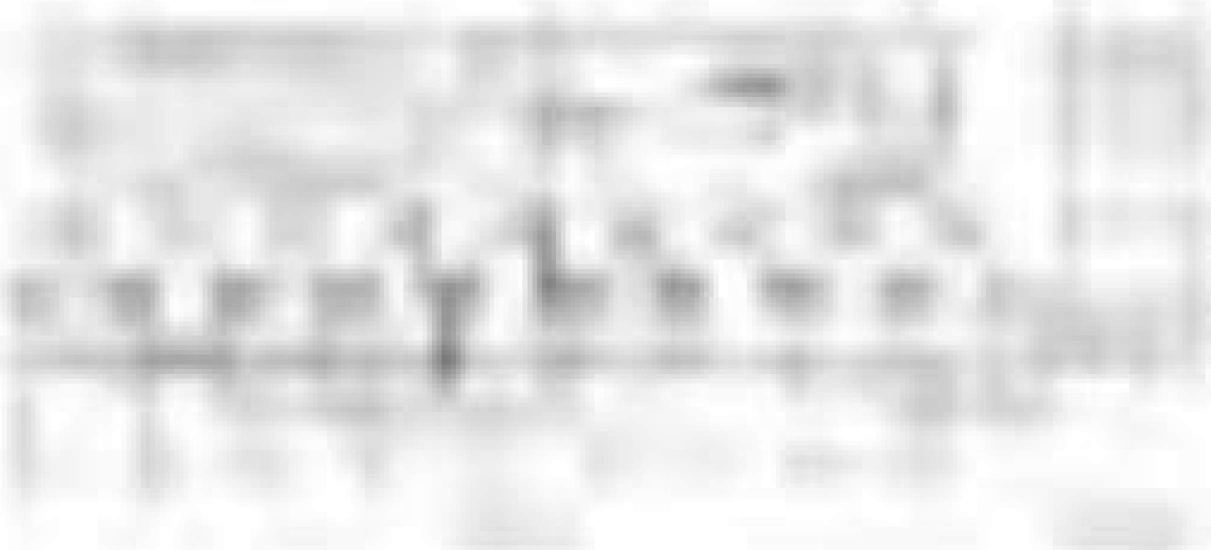
Rotor



The short magnetic flux path

Linear-switched reluctance motors

- Linear-switched reluctance motors (LSRMs) are similar to conventional SRMs in their structure except that their rotor and stator are cut open taking a linear form
- One of the applications of these motors is in electric trains and subways



One side LSRM

Two sided LSRM with winding on the translator

Operating modes

A) Single pulse mode $\xrightarrow{\text{also known as}}$ High speed mode

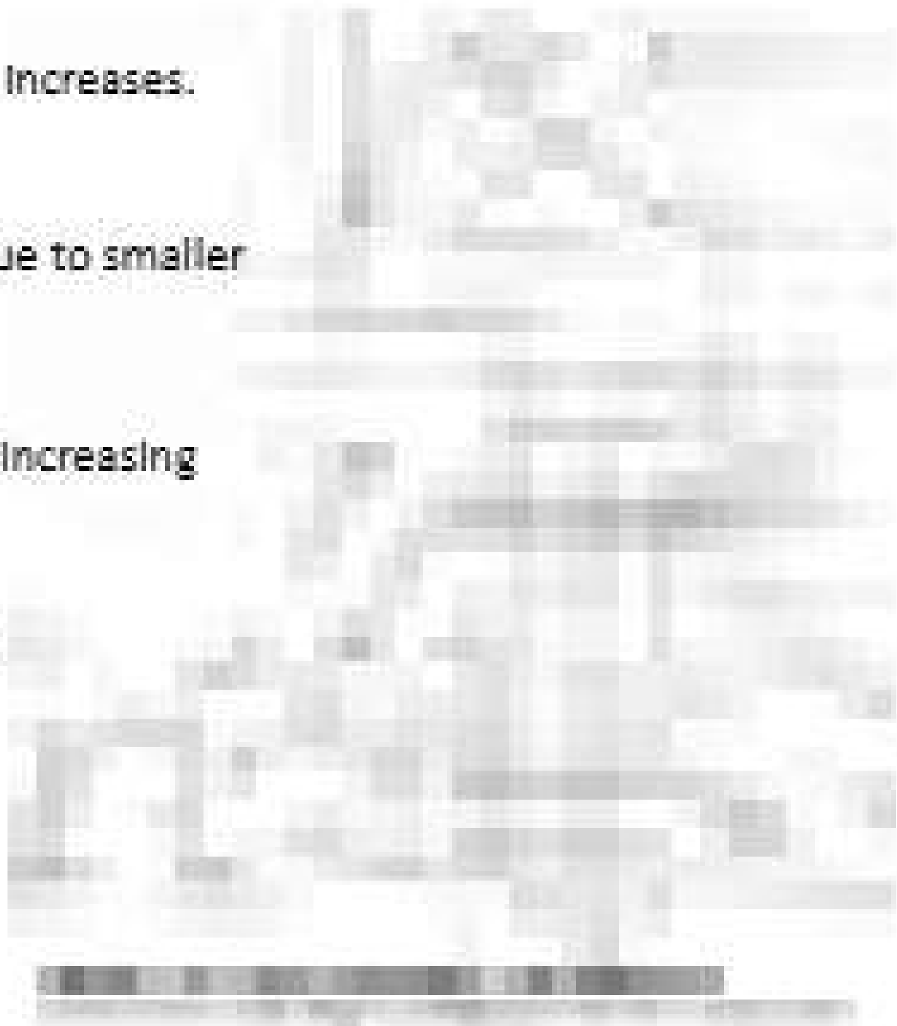
Current rise is within limits during the small time interval of each phase excitation.
It depends winding inductance and motional counter emf generated in stator winding

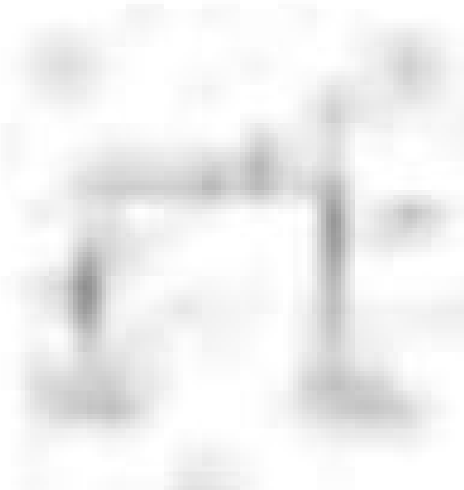
1. Input voltage Vs is applied before L increases.

2. Current is buildup to larger value due to smaller Inductance L, up to θ1.

3. After θ1, current decreases due to increasing L and back emf.

4. At θ2, negative voltage is applied And current falls to 0 at θ3.





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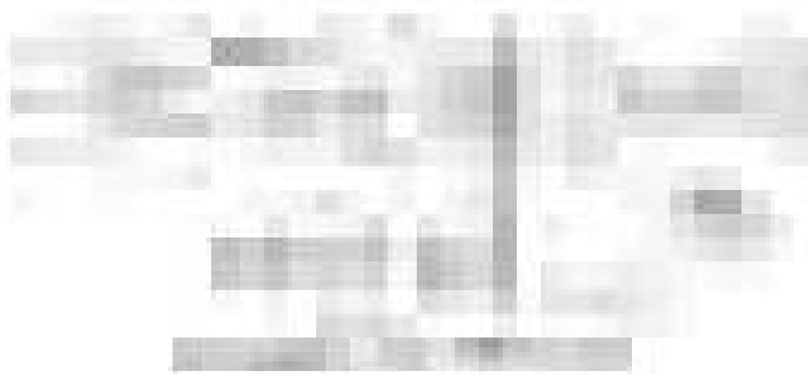
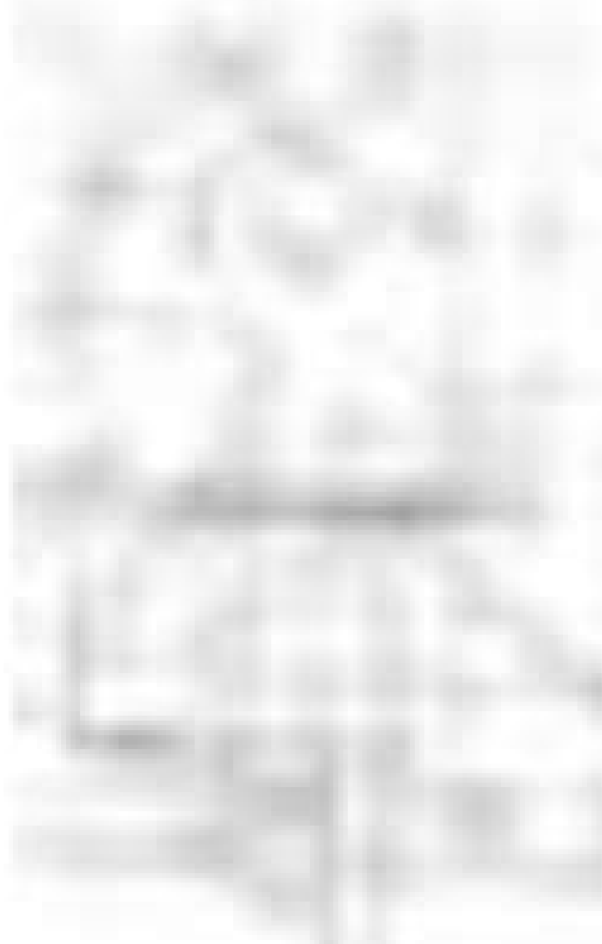
B) PWM (or chopping) pulse mode $\xrightarrow{\text{also known as}}$ Low speed mode

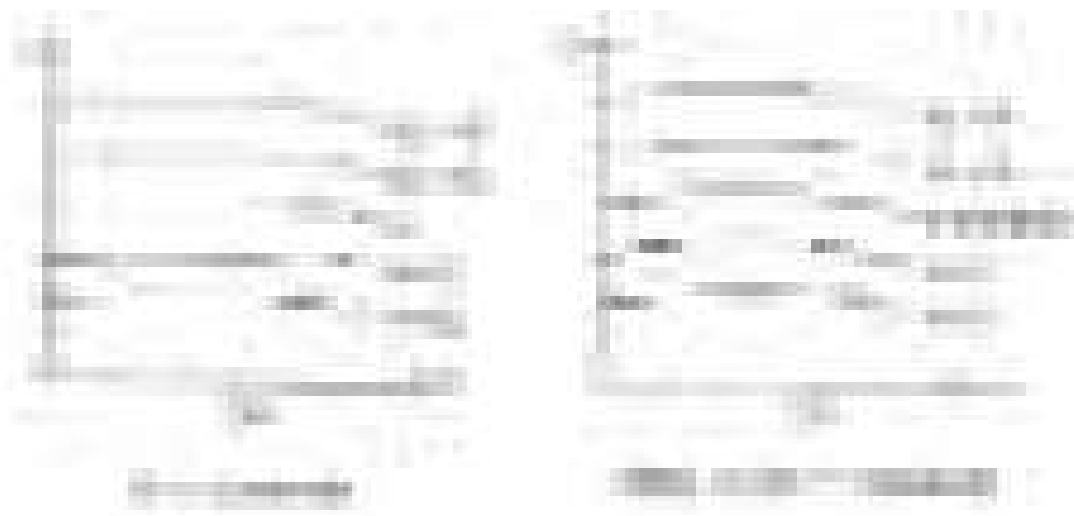
1. Initially, current in each phase is buildup during long period to higher value.

2. Current rise is kept within acceptable rating of motor and inverter components. Hence, current limiting device is used.





TORQUE-SPEED CHARACTERISTICS



Torque developed (i.e.) average torque developed but SRM depends upon the current wave form of SRM phase winding. Current waveform depends upon the conduction period and chopping details. It also depends upon the speed.

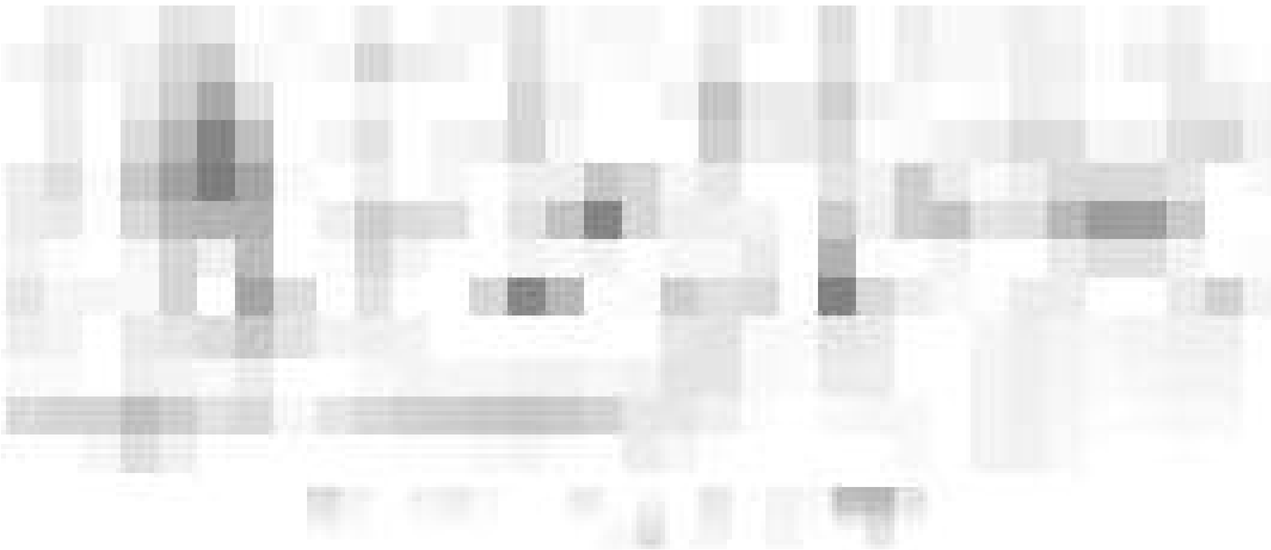
- The first region is known as the constant torque region, where the supply of voltage and commutation angles is fixed and is located below the rated speed, ωb

- The second region identified as the constant power region, starts from the rated speed ωb. In this region applied voltage remains at its rated value and as the rated speed is increased, the maximum torque is sustained by advancing the turn on angle with a fixed commutation angle. In this region, the torque falls inversely to the motor speed, 1/ω.

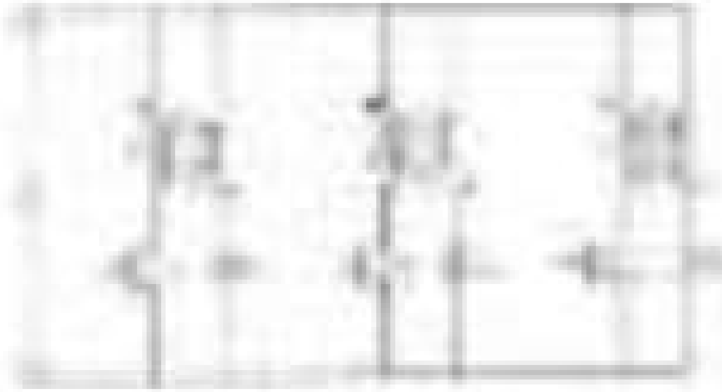
- Finally, there is a practical limitation to advancing the turn on angle, which, lets say, begins at some speed called ωp. At this point, the third region starts and the torque decreases as 1/ ω2. This mode is known as the natural mode and is usually neglected for most motor technology.

Torque Speed Capability Curve

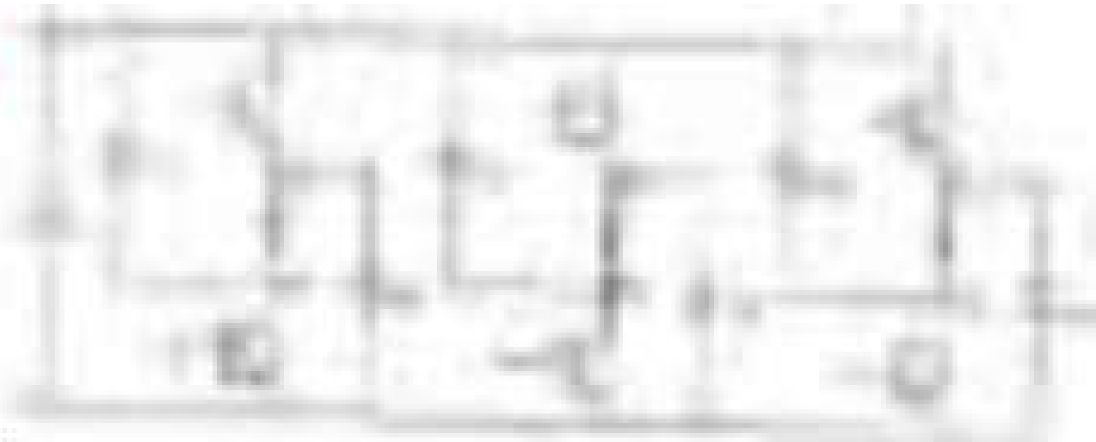
Inverter drive circuits



Phase winding using bifilar wires

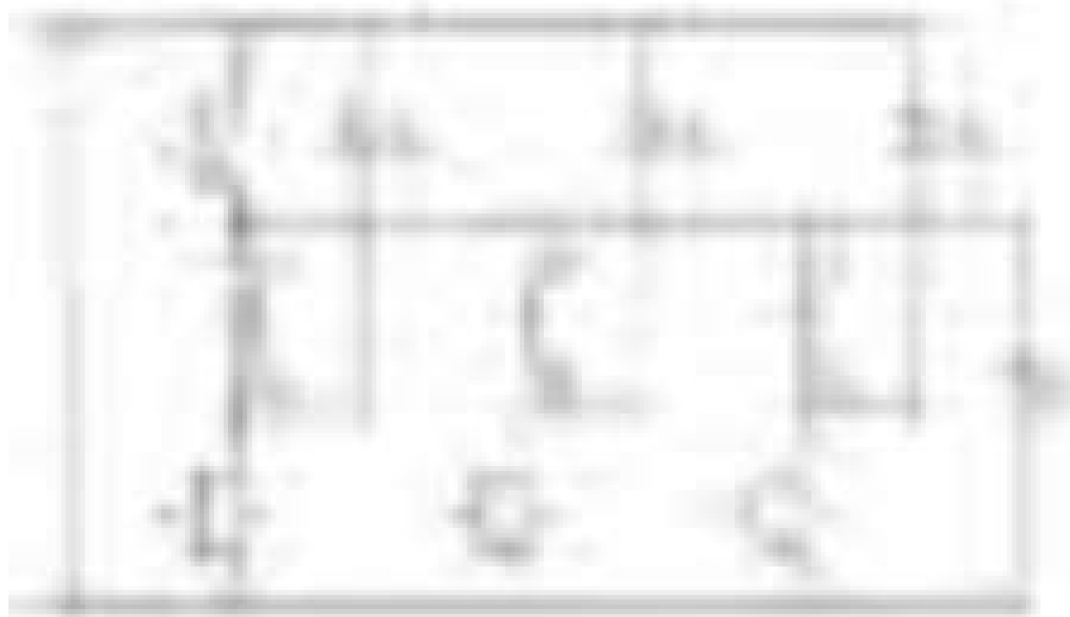


Two Power Semiconductor Switching Devices and two diodes per phase



Split – link circuit used with even phase number

(n+1) power switching devices and (n+1) diodes



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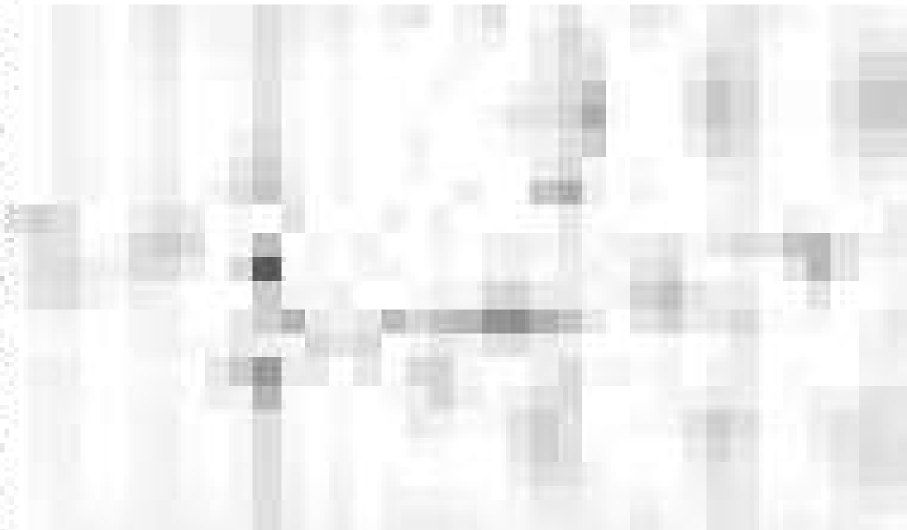
C-Damp Circuit

In that converter, assume that $T1$ is turned on to energize the phase *a*. When the phase current i_a exceeds the reference value, $T1$ is turned off, this enables the diode $D1$ to be forward biased, and the current path is closed through the dump capacitor C_d which increases the voltage across it in order to achieve fast demagnetization as asymmetric converter. Then the excess energy from the dump capacitor is transferred into the dc source via L_r by turning on the dump switch T_r. The voltage of the capacitor is regulated to be maintained at twice the supply voltage ($2U$) in order to apply ($-U$) across the outgoing phase for yielding faster demagnetization. The dump switch T_r is operated at a higher frequency than the phase switches

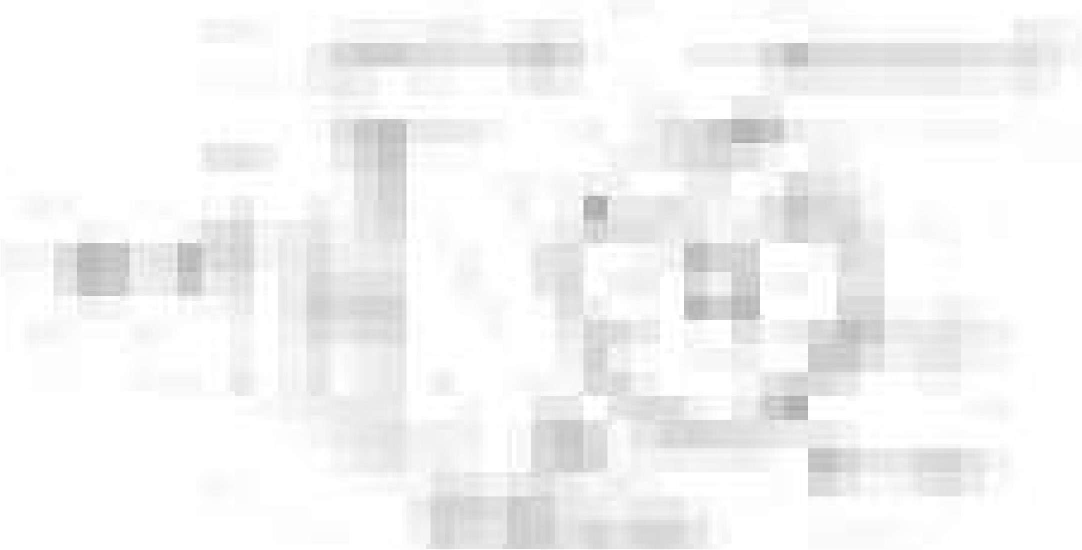


Control Circuits for SRM

(Current control techniques)

Rotor Position Sensors

Phototransistor Sensors



- Consist of revolving shutter with 120 degree gap.
- When the gap is aligned with the phototransistor PT1, the phototransistor will generate a current due to the light, while phototransistor PT2 and PT3 have only a very small leakage currents because the light is blocked by the revolving shutter.

ROTARY ENCODER

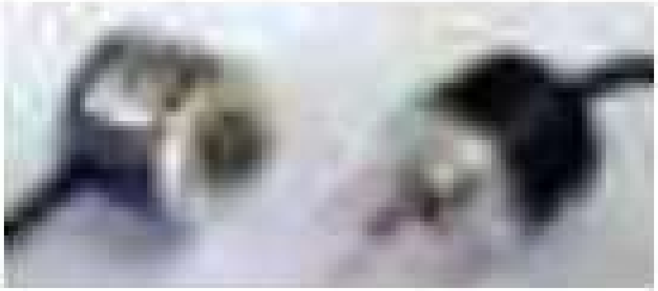
Absolute encoder, which can provide the absolute value of the rotation angle (complicated and expensive).

Incremental encoder, provides only
the incremental value of the rotation (most widely used).

- There are two sensor types used in encoders to generate digital signals such as magnetic and optical. The latter is more commonly used.
- The resolution of an incremental encoder is frequently described in terms of pulse per revolution (PPR), which is the total number of output pulses per complete revolution of the encoder shaft.

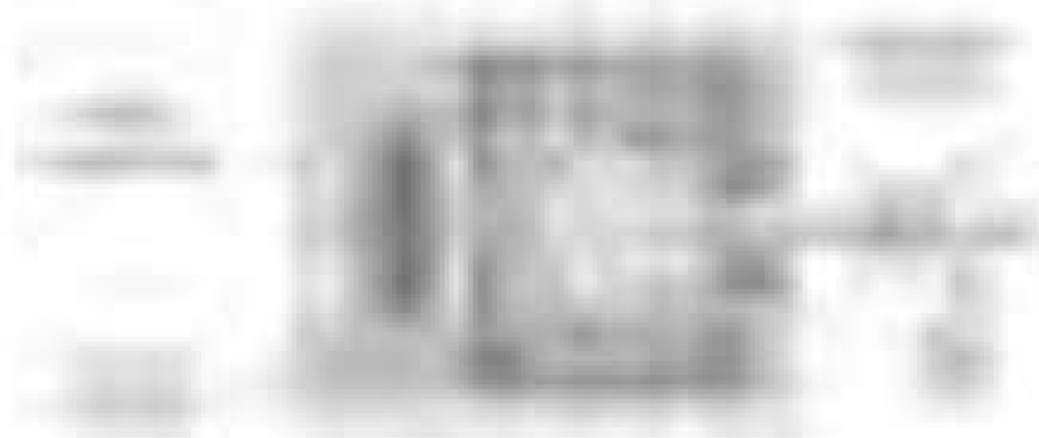
Two configurations:

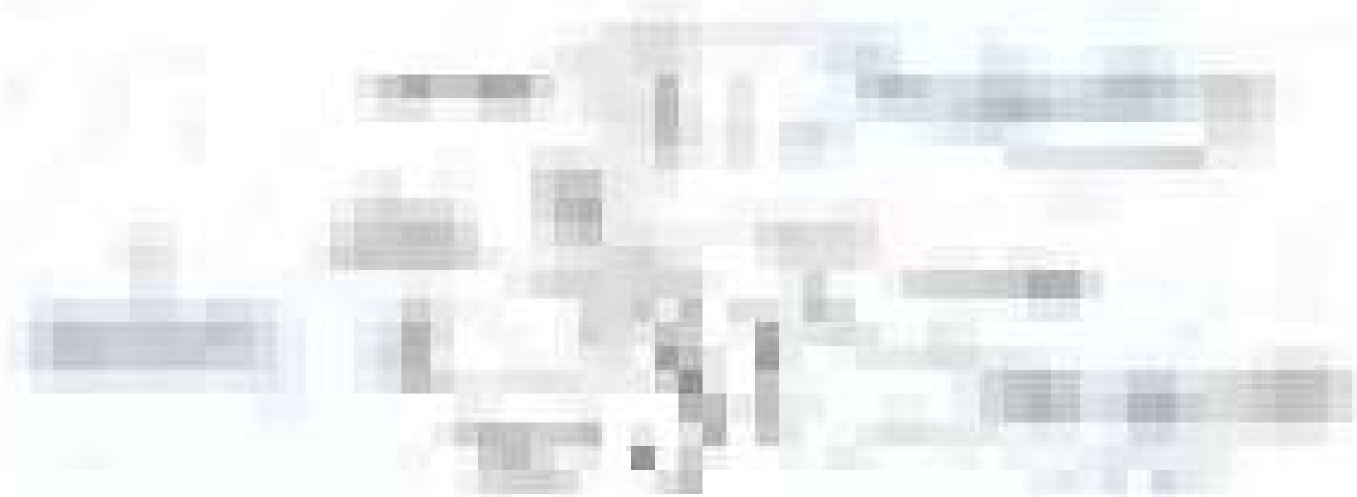
Shaft type that connects the shaft of a rotor with a coupling.
Hollow type, in which the shaft of a rotor is inserted into.



- It consists of a moving disc mounted to the rotating shaft, light sources (LEDs), and light receivers (phototransistors). The moving disc has the same number of slits as PPR. The light of LEDs passing through the slits on the disc is transmitted to phototransistors, and in turn, is converted to square wave shaped electric signals

- Commonly, the encoder has three outputs called A, B, and Z. The total number of A and B pulses per revolution is equal to PPR, with which the angular position and speed can be calculated. The A and B pulses are 90 out of phase, which allows the identification of the direction of rotation. For example, when rotating in the forward direction, pulse A is ahead of pulse B. There is another pulse Z known as the index or reference pulse besides pulses A and B. Pulse Z is generated once per revolution and can be used to set the reference position.





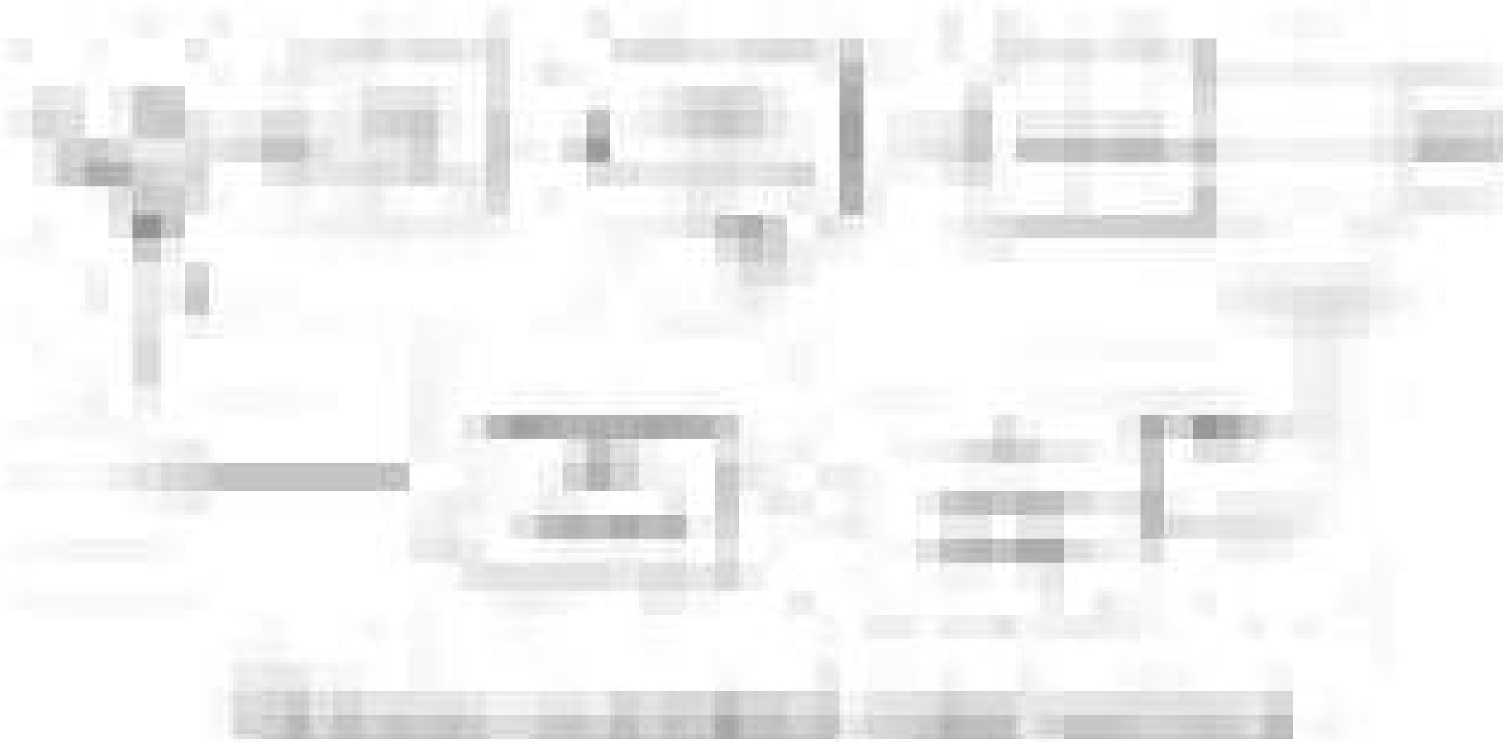
- The primary winding of a resolver, called reference winding, is located in the rotor and is excited through a rotary transformer. The two secondary windings, called SIN and COS Windings, are located in the stator and mechanically displaced by 90 degree from each other. In the resolver operation, a shaft angle θ can be measured from signals induced in the secondary windings after injecting AC voltage signal into the primary winding.
- When the primary winding is excited by an AC voltage Vr through a rotary transformer, voltages in the secondary windings are induced differently depending on the angle θ of the rotor shaft. The induced voltages vary as sine or cosine of the rotor angle, respectively. From an arctangent function of these signals, we can know the absolute angle θ of the rotor connected to the shaft as

[illegible]

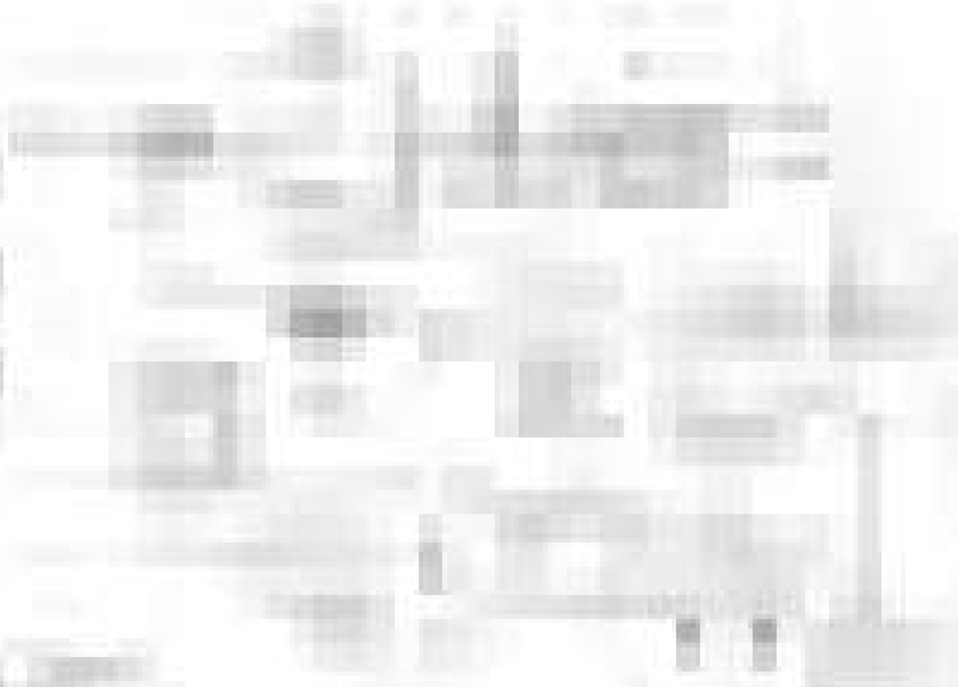
Sensorless operation

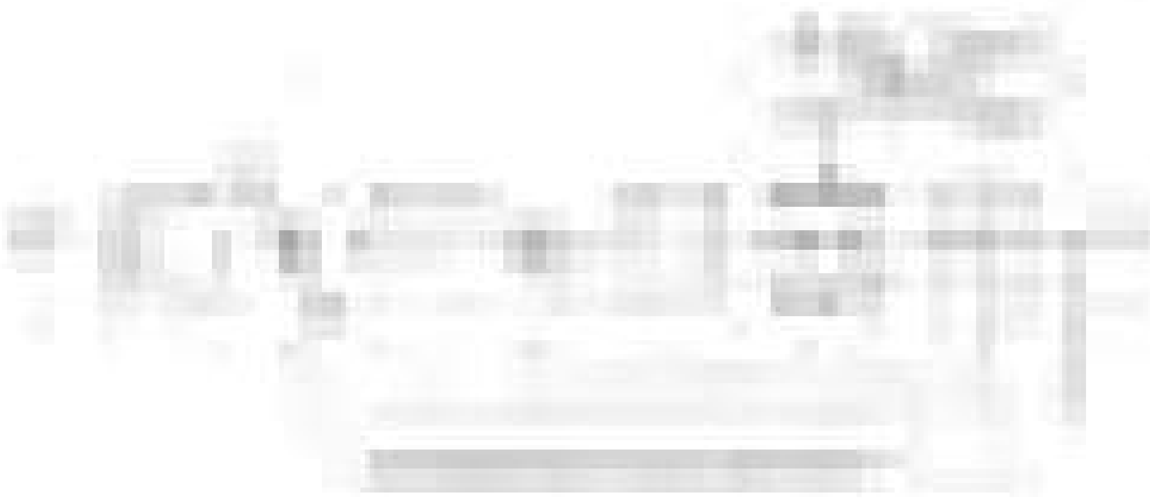
Problem with sensor

- Position sensors are discrete in nature.
- Adds complexity to the system.
- More costly.
- Installation of sensor is time taking and tedious job.
- Tends to reduce the reliability of the drive system.



CLOSED-LOOP, SPEED-CONTROLLED SRM DRIVE

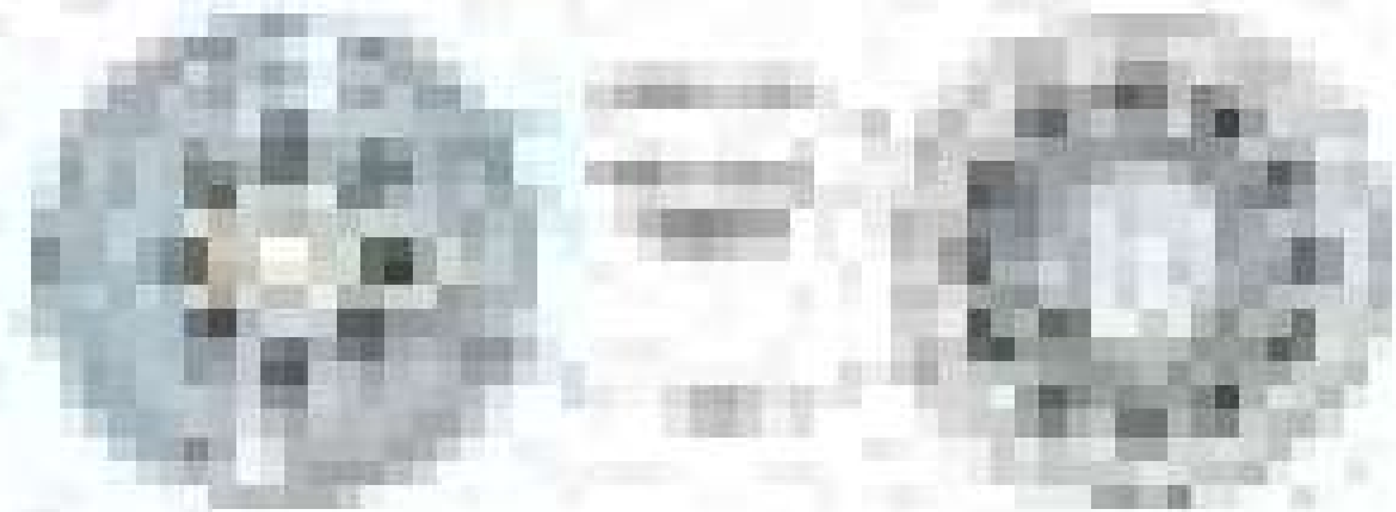




ROTOR POSITION MEASUREMENT AND ESTIMATION METHODS

Unit 4

Brushless DC Motor



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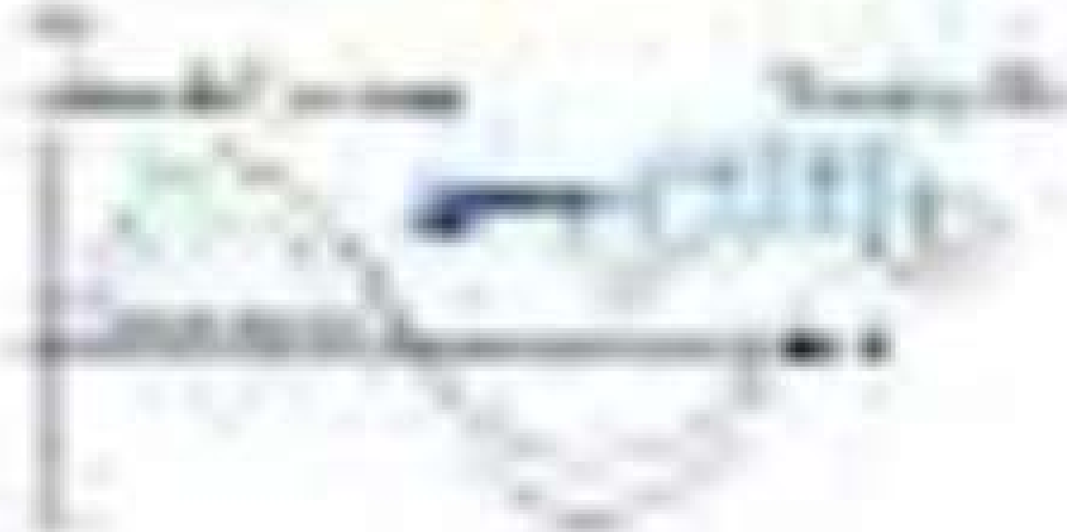

Construction of PMBLDC motor

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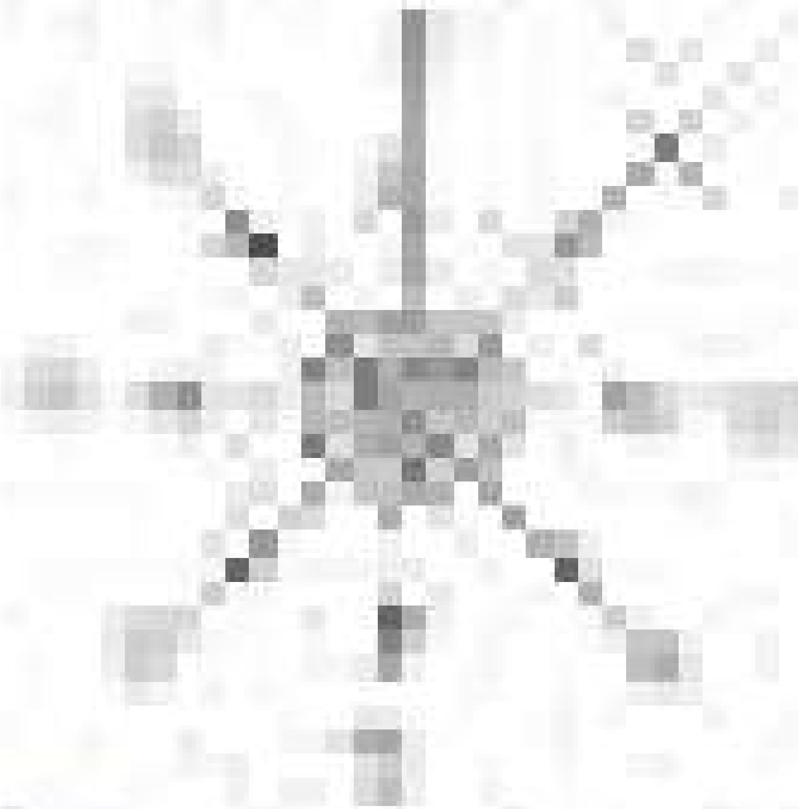
Advantages

Applications



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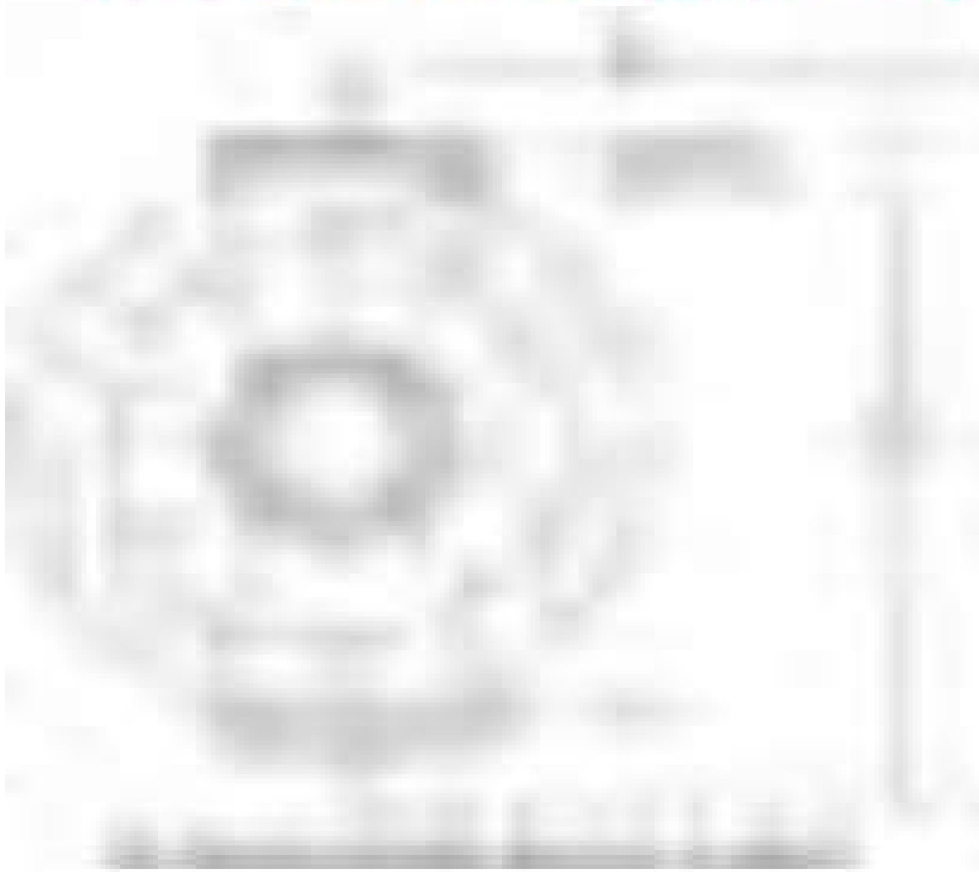
Commutator

Mechanical commutator



Electronics commutator

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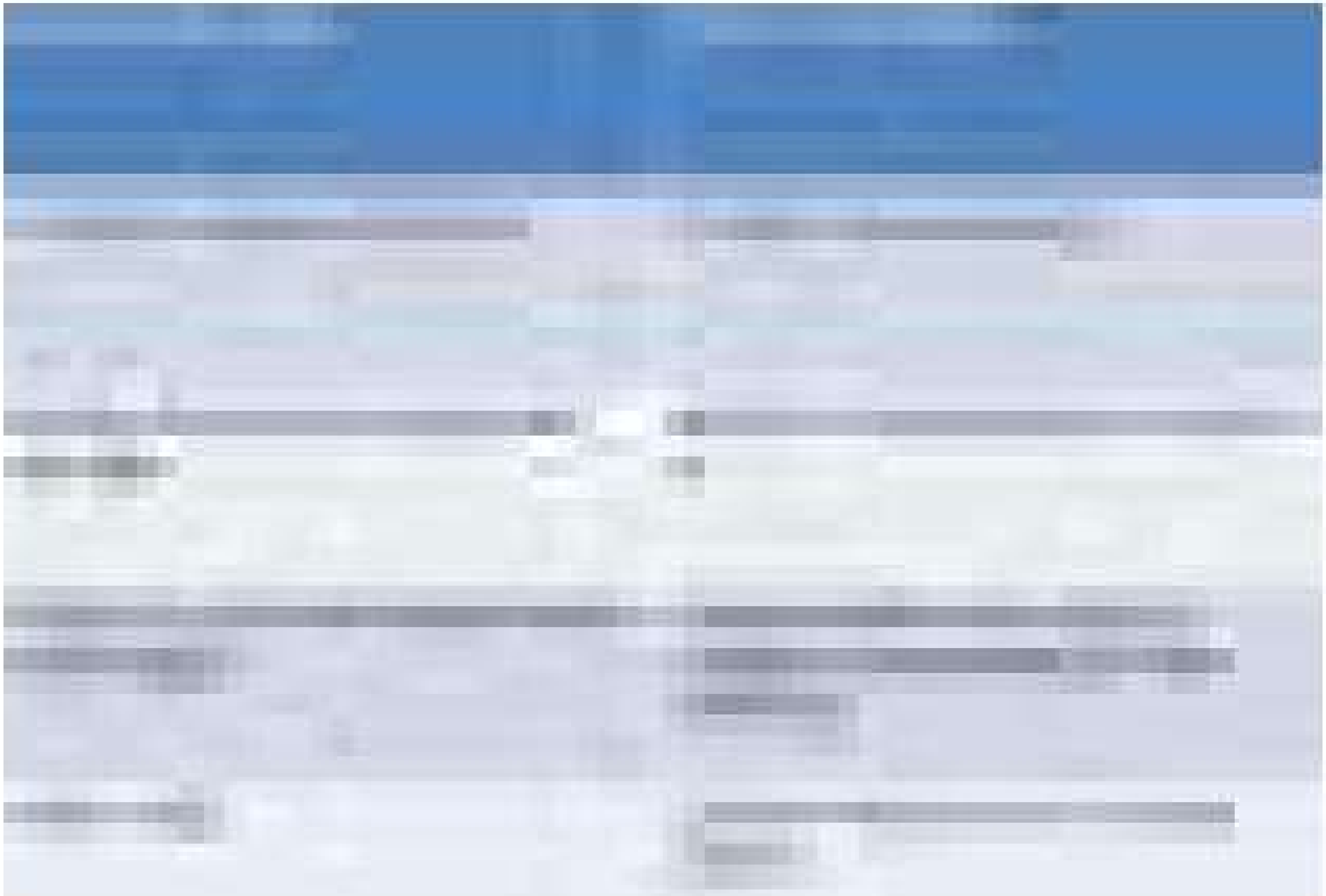
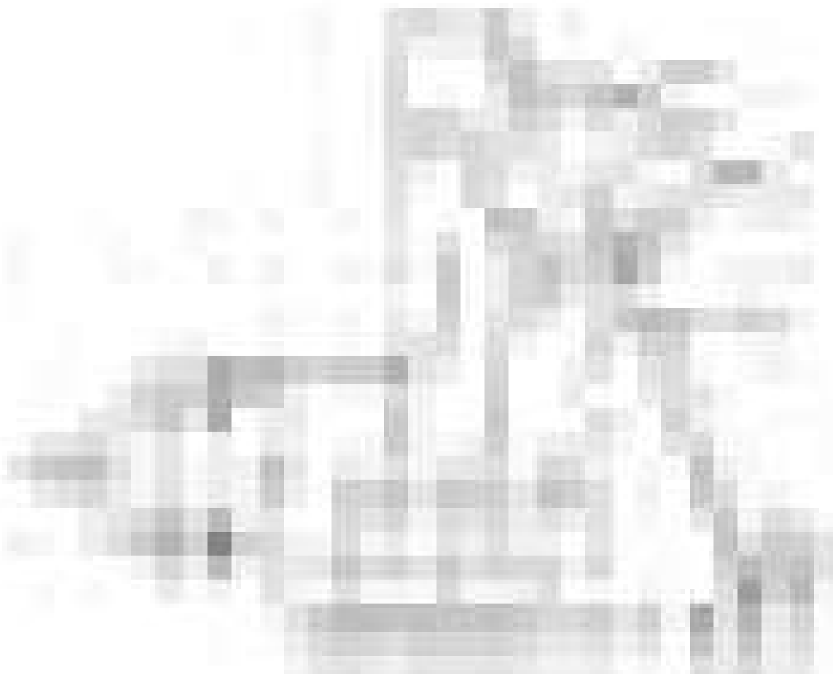
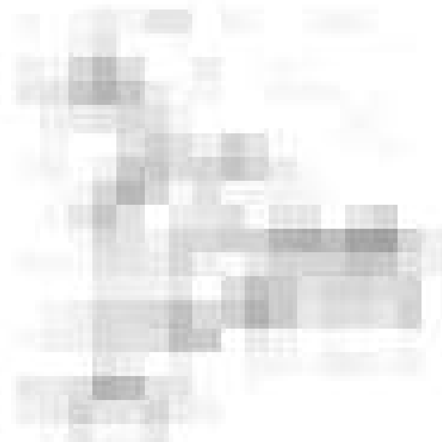
Comparison between mechanical and electronic commutator

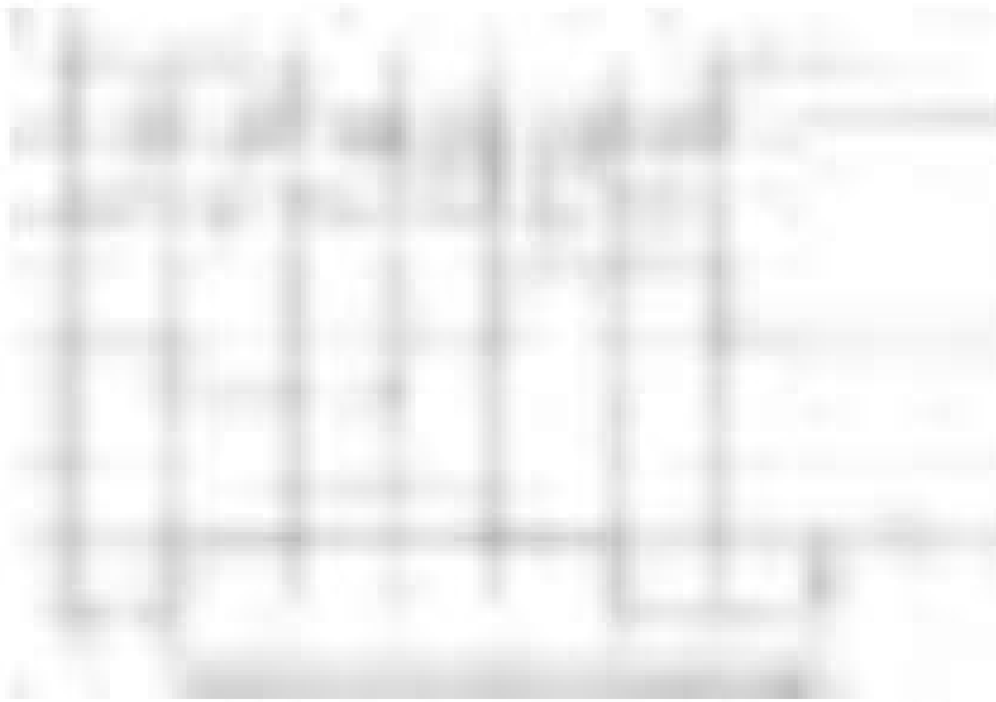


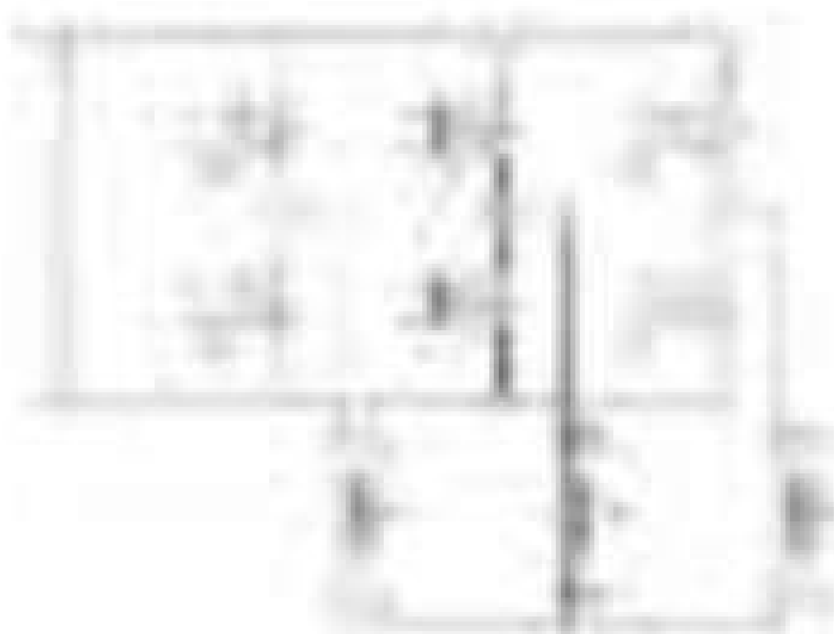
Operating principle of BLDC motor

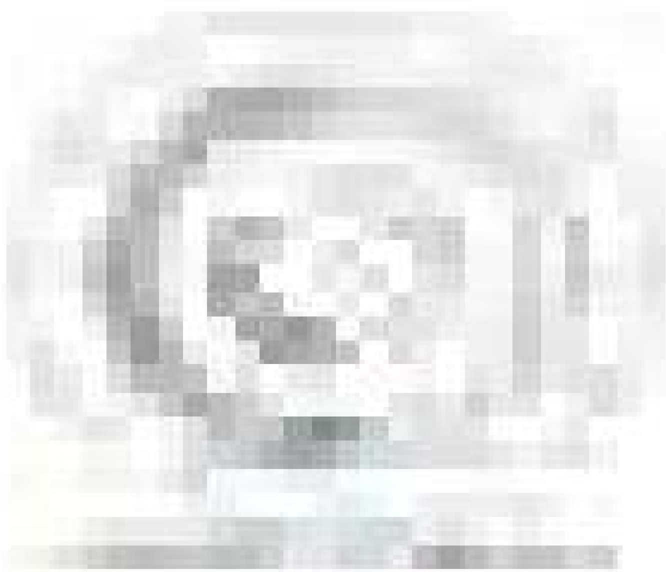


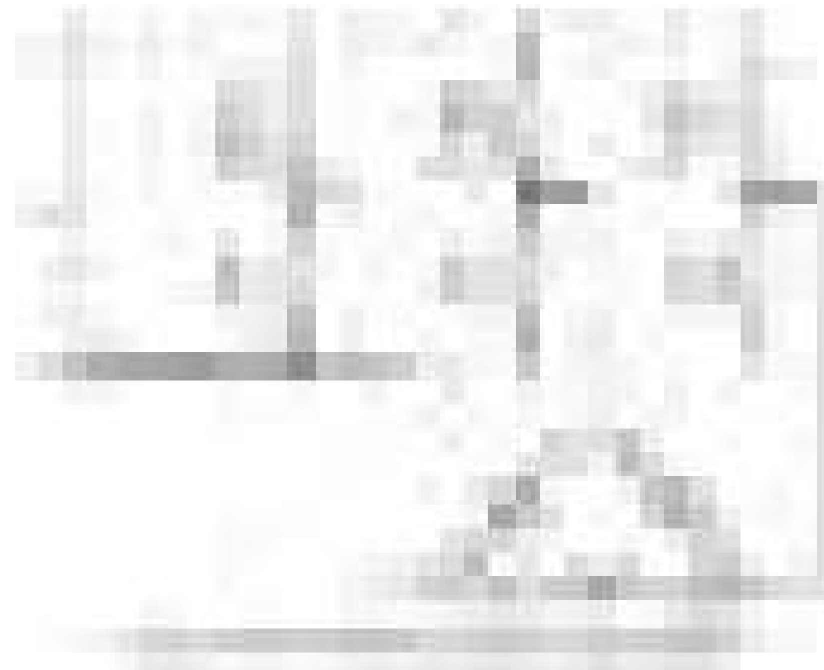


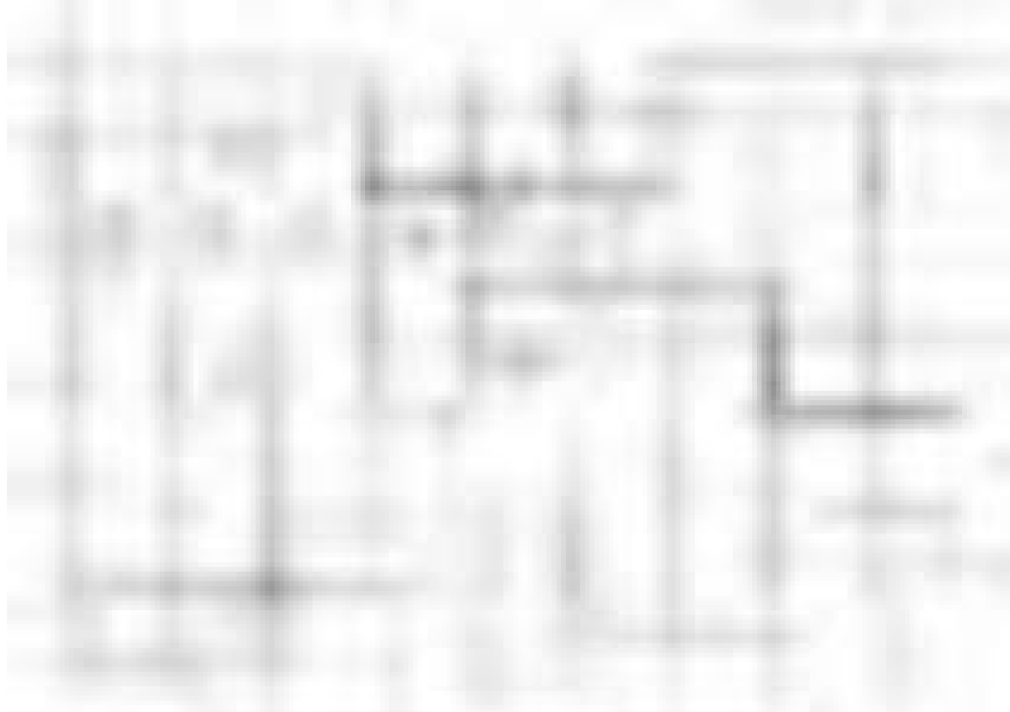
In the BLDC motor drive, only two of the three-phase windings are excited, while the other winding is left unexcited.











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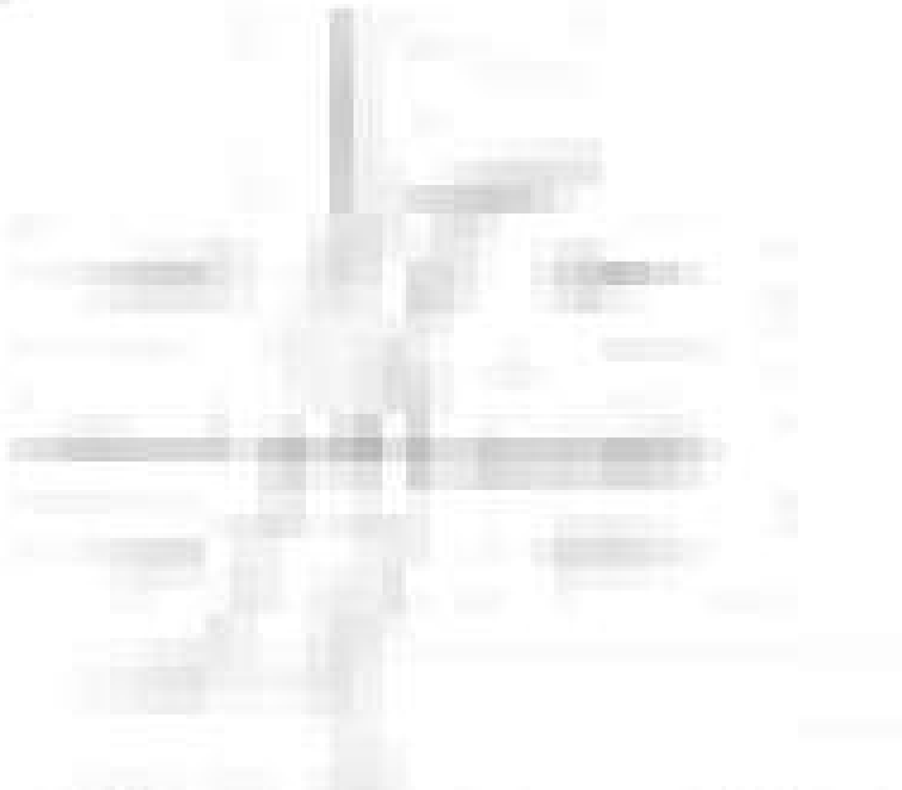

$$B = \mu_0 H + B_i$$

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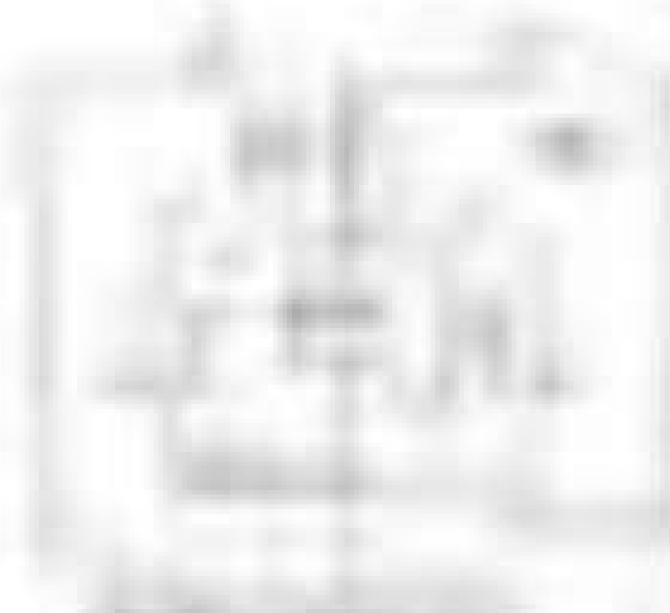
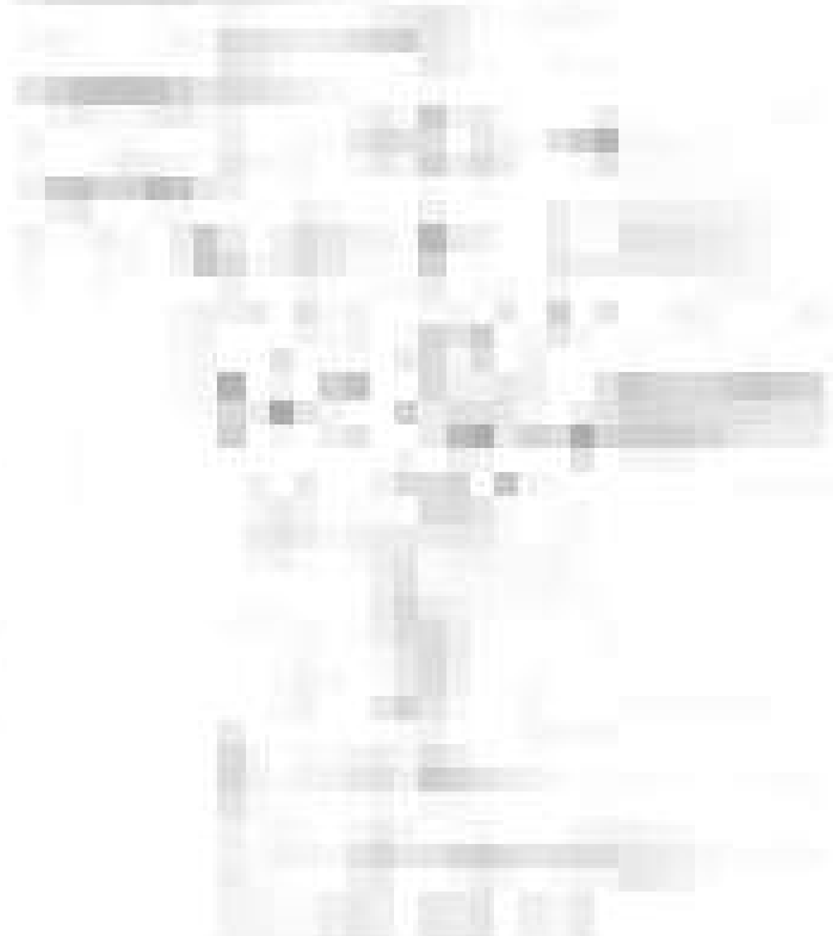


Kc: carter's coefficient,

Ag- air gap area through which the flux passes as it crosses he gap

If we write the ratio of magnet pole area to air gap area as



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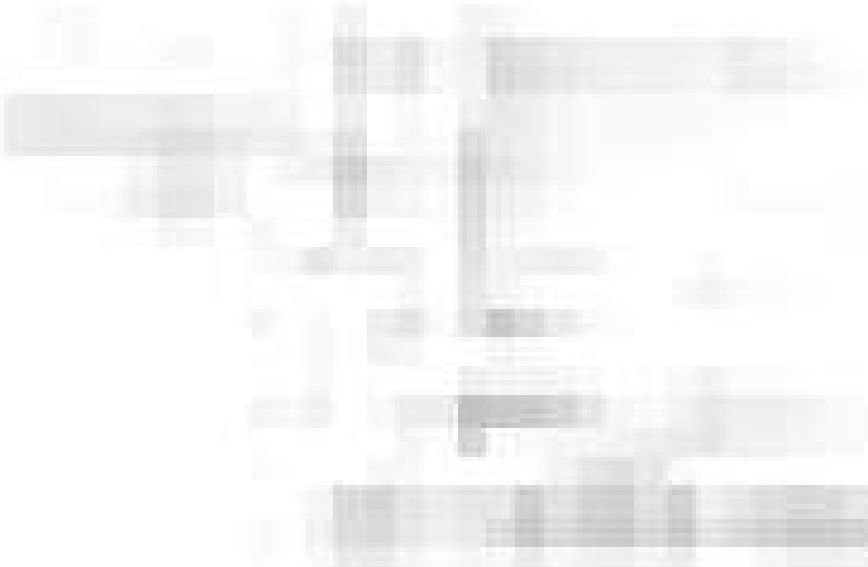

If the phase windings are star-connected, then at any time there are just two phases and two transistors conducting.

$$V = E + RI$$

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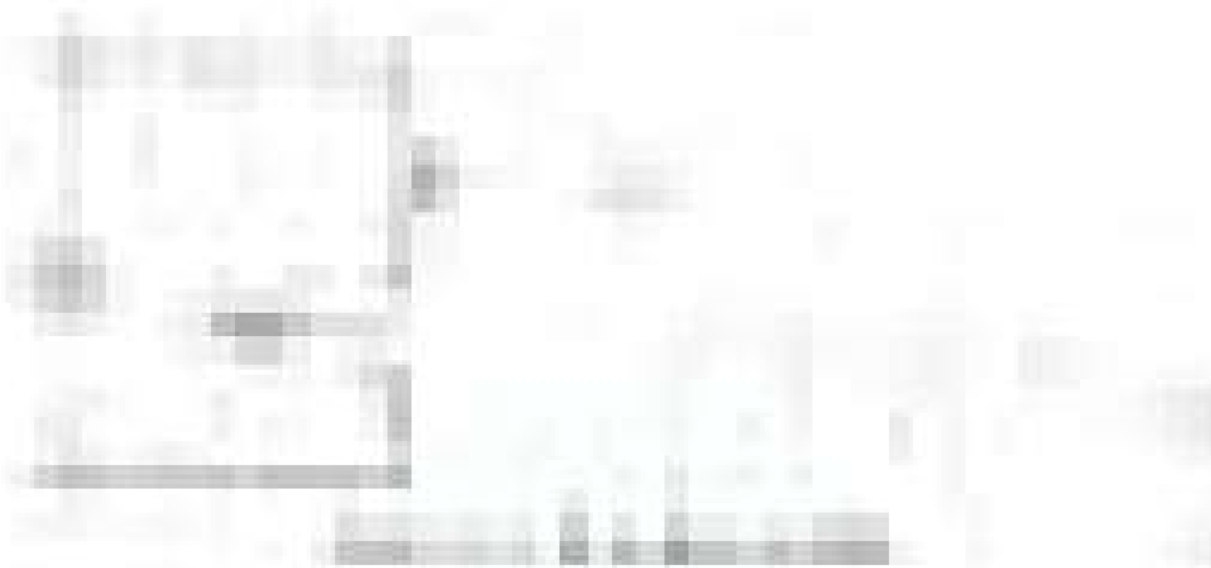

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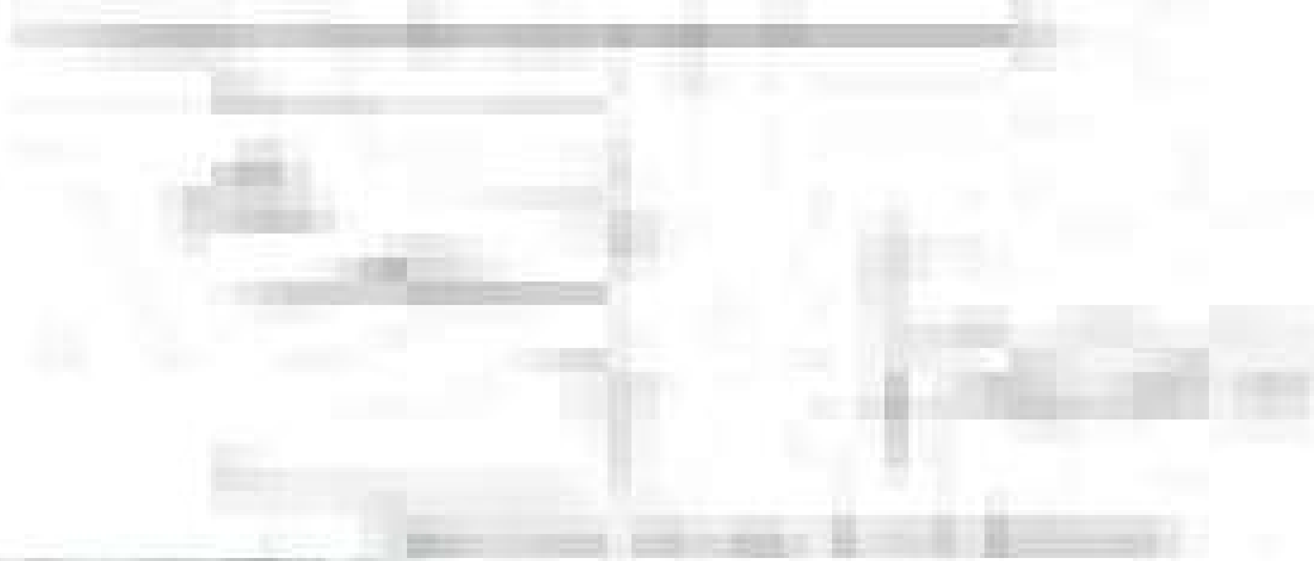

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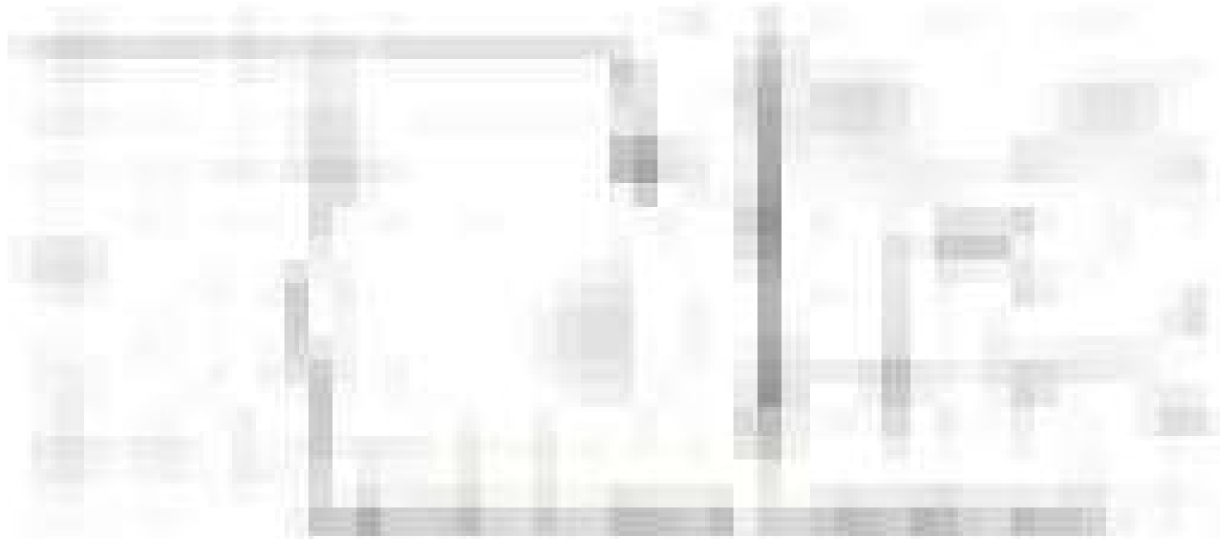

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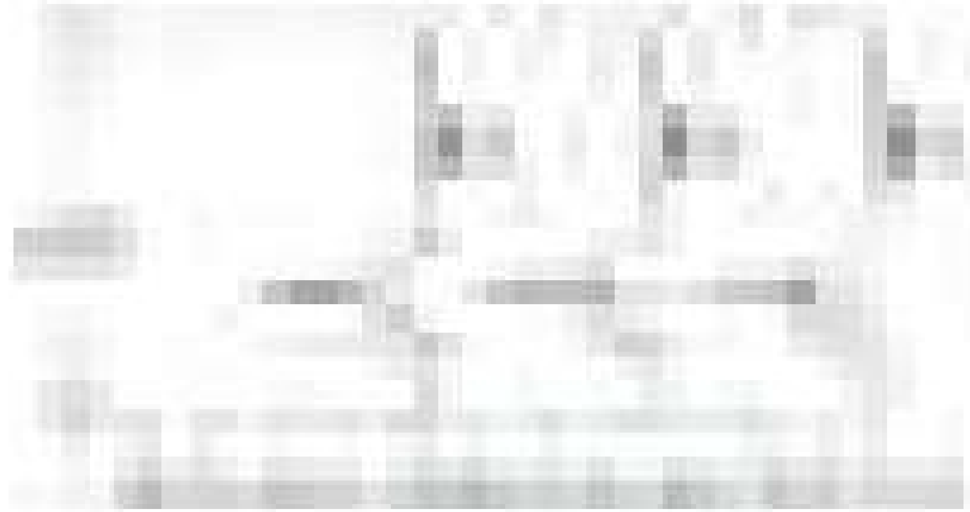

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Printed Circuit Board (PCB) Motor

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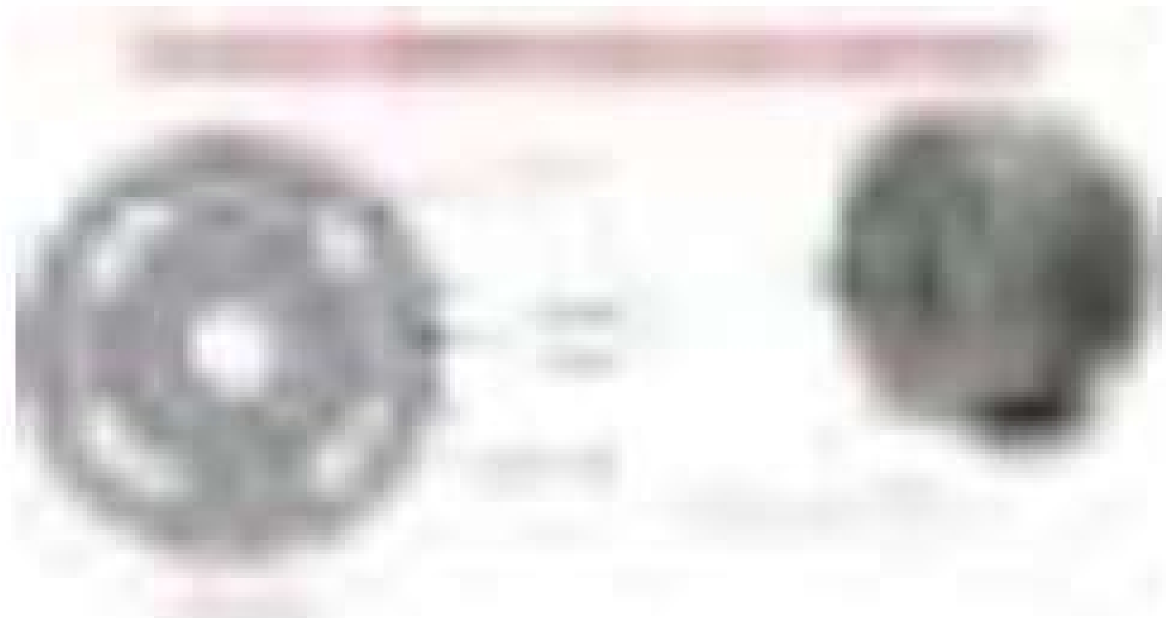
Permanent Magnet Synchronous Generator



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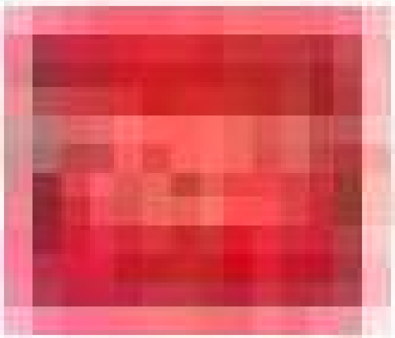
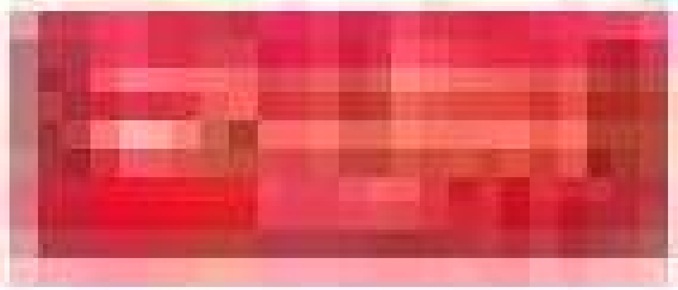
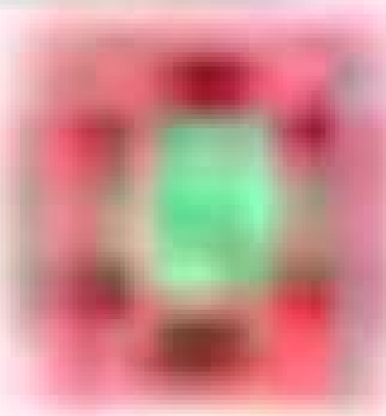
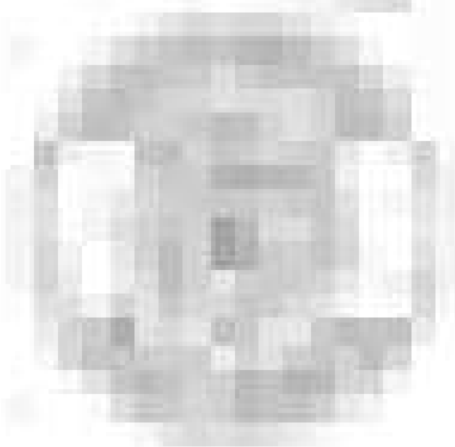
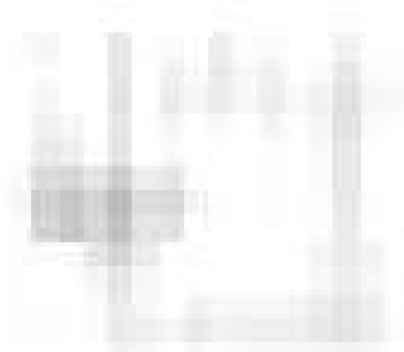




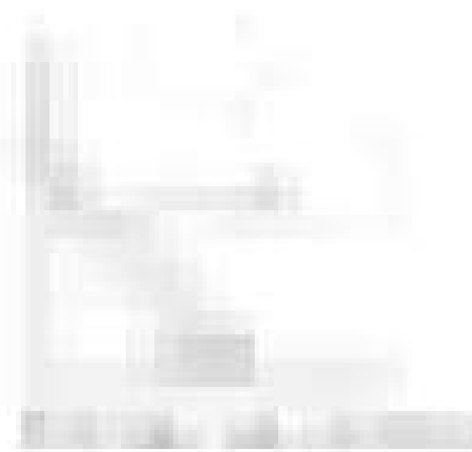






Schematic diagram

Speed-torque characteristics



By changing the supply voltage, the no-load speed N_0 of the motor is changed without affecting the slope of the characteristic

By change the effective resistance of the armature circuit (inserting some resistance in series with the armature), the slope of the speed-torque characteristic changes without affecting the no-load speed N_0 of the motor

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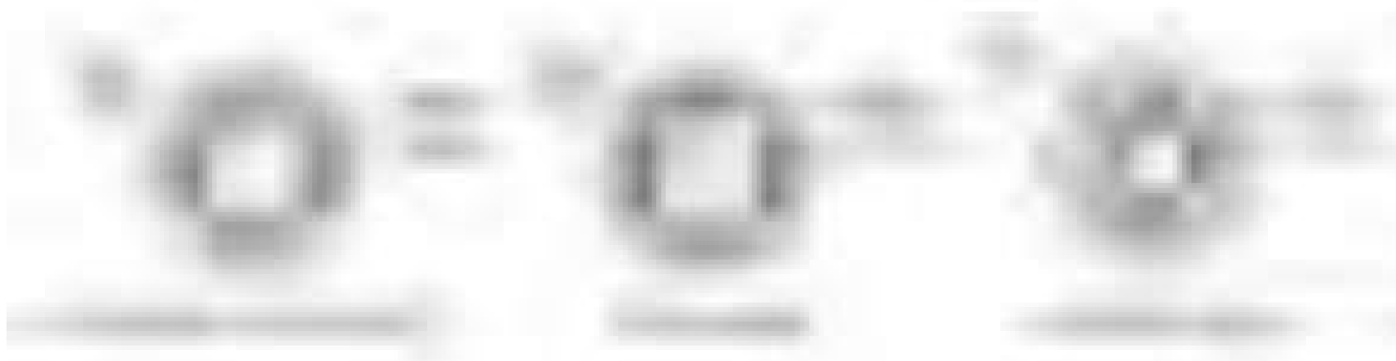
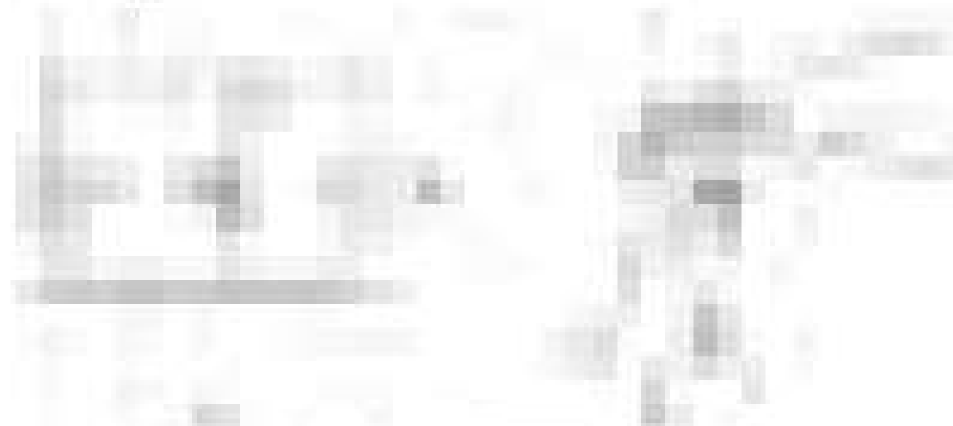
Permanent Magnet AC Motor

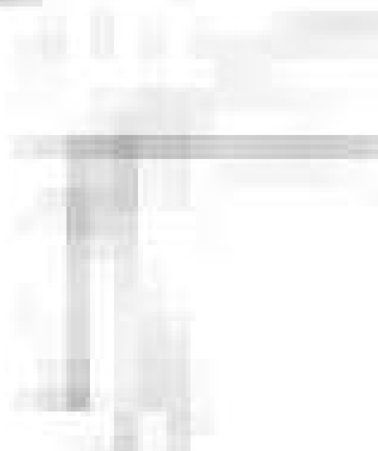
Permanent Magnet Synchronous Motors Types



- Since the voltages induced in the stator phases of a sinusoidal PMAC motor are sinusoidal, ideally, the three stator phases must be supplied with variable frequency sinusoidal voltages or currents with a phase difference of 120° between them. Let us now examine its behavior from a variable frequency current source.
- Norton's equivalent of the synchronous motor equivalent circuit



The mechanical power developed is



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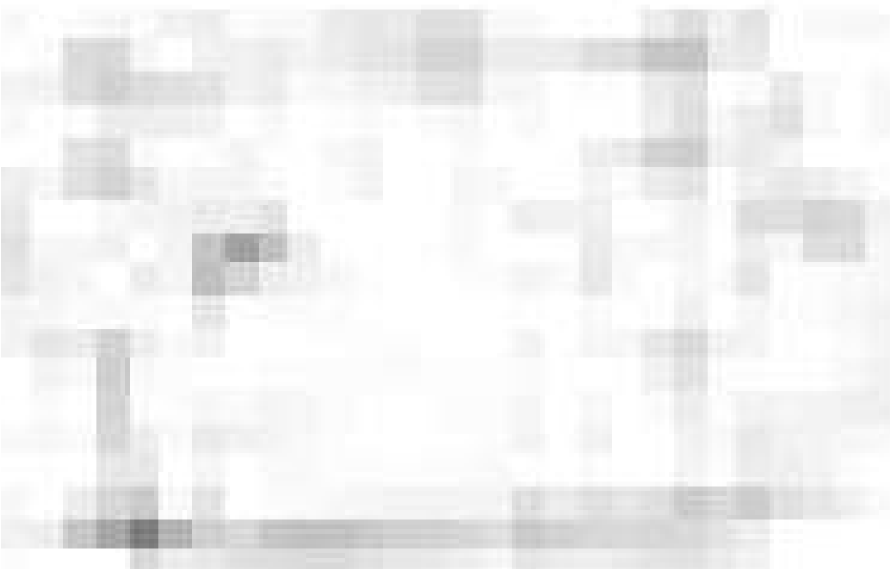
Unit 5

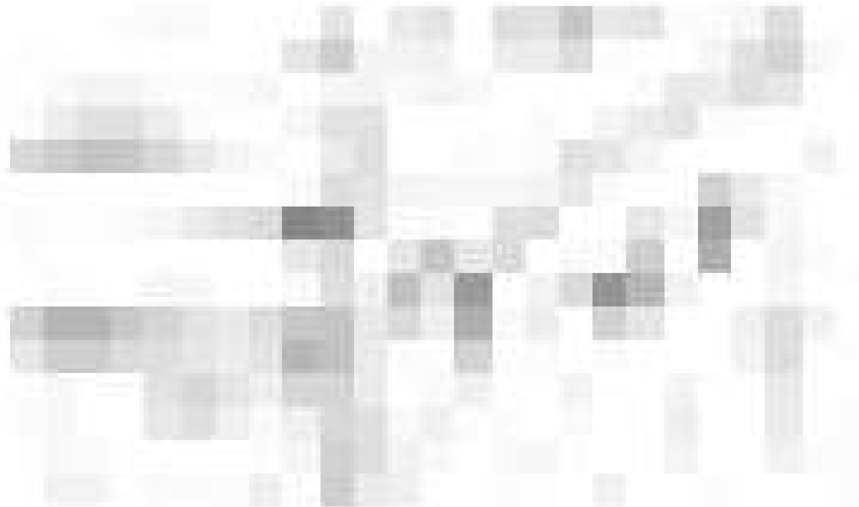
Single phase series motor (Universal Motor)

- Conductively compensated motor
- Inductively compensated universal-motor

If compensated winding connected in series with armature and field winding in such a case motor is called a **conductively compensated motor.**

If compensating winding short-circuited on itself in such a case motor is called **inductively compensated** and received excitation voltage by transformer action since it is inductively coupled.





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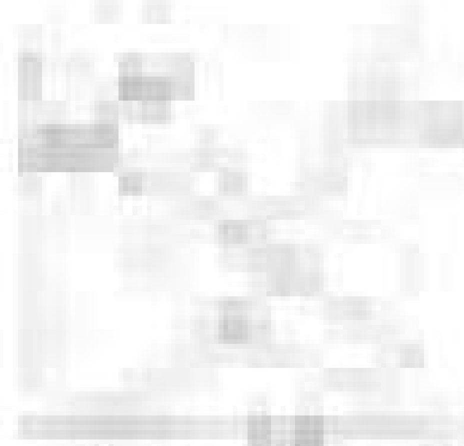

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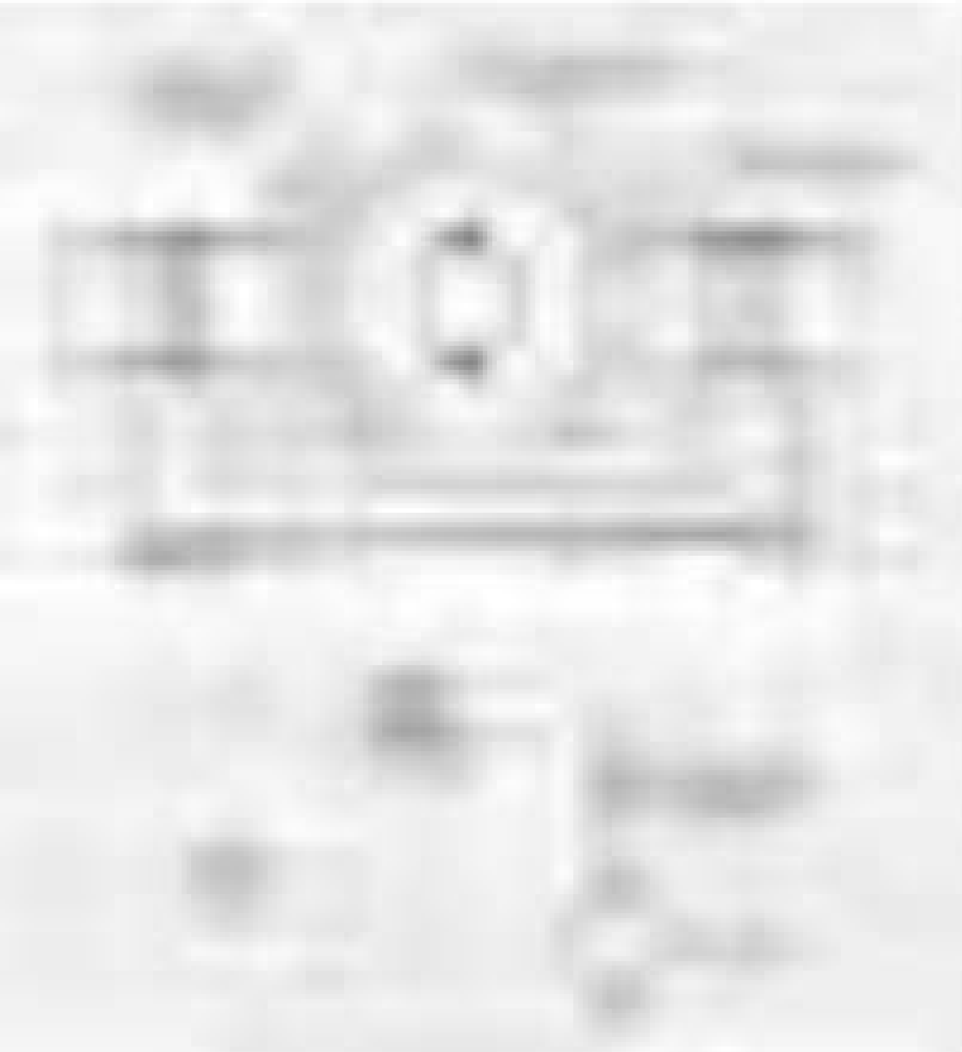

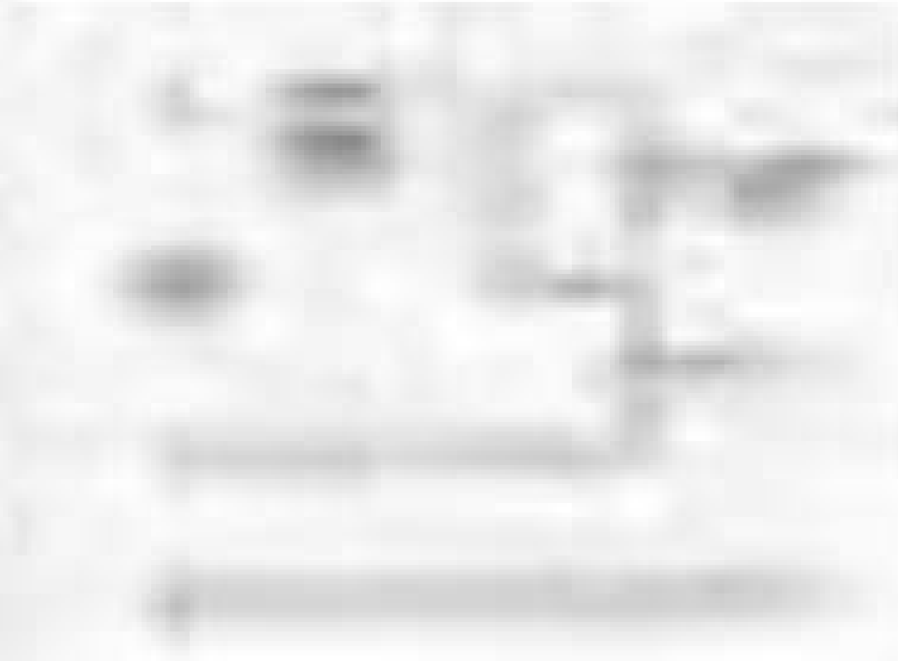

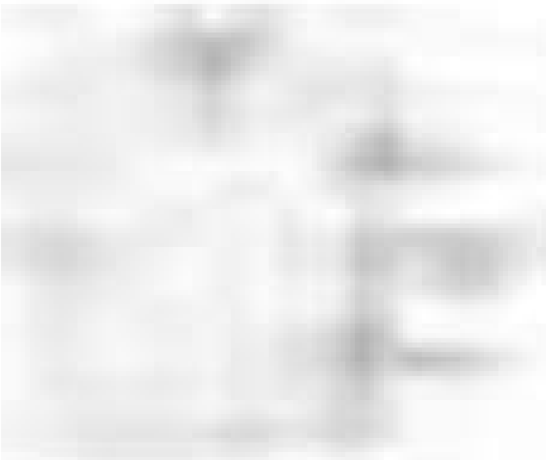

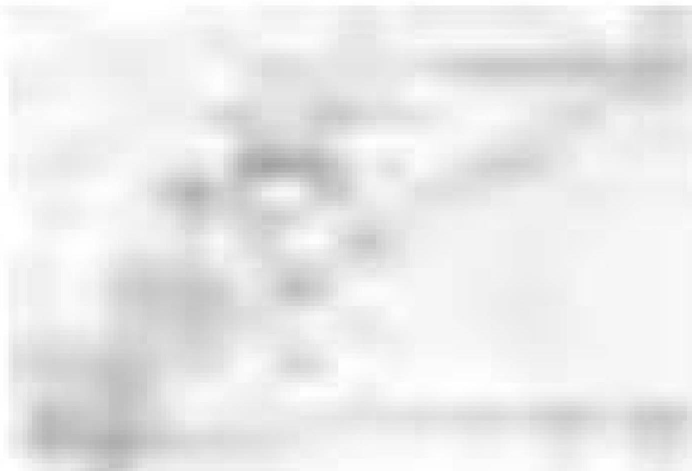

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Repulsion Motor

The main components of repulsion motor are stator, rotor and commutator brush assembly. The stator carries a single phase exciting winding similar to the main winding of single phase induction motor. The rotor has distributed DC winding connected to the commutator at one end just like in DC motor. The carbon brushes are short circuited on themselves.

- The basic principle behind the working of repulsion motor is that "similar poles repel each other." This means two North poles will repel each other. Similarly, two South poles will repel each other.

- When the stator winding of repulsion motor is supplied with single phase AC, it produces a magnetic flux along the direct axis as shown in figure above by arrow mark. This magnetic flux when link with the 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.

Under this condition, there will not be any mutual induction between the stator and rotor windings. Therefore, no emf and hence no rotor current is produced. Thus no electromagnetic torque is developed.

In this condition, a maximum emf 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. Large rotor currents produce rotor mmf opposite to stator mmf.

- No electromagnetic torque is developed as $\alpha = 0^\circ$. 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°.

- Electromagnetic torque T is given as

T_e = k (Stator Field Strength) (Rotor Field Strength) Sinα
where is k is a constant.

- 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.***

Torque Equation of Repulsion Motor

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

Mmf of coil T = $I_t N_t$

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

$I_t N_t = I_s N_s Cos\alpha$

$N_t = N_s Cos\alpha$

Similarly, the number of turns of coil F is given as

$N_f = N_s Sin\alpha$

Now, the electromagnetic torque

T_e = k (Stator Field Strength) (Rotor Field Strength) Sinα

where is k is a constant.

$= k (I_s N_s)(I_s N_s Cos\alpha) Sin\alpha$

$= (k/2)(I_s N_s)^2 (2 Cos\alpha Sin\alpha)$

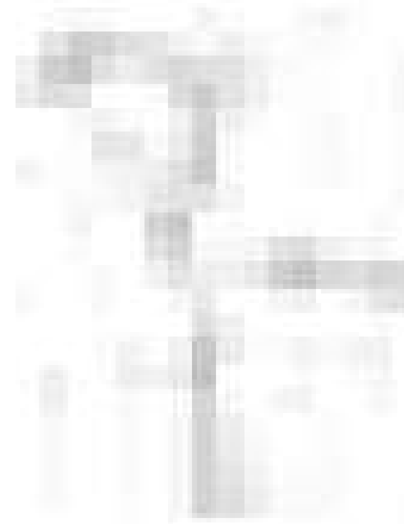
$= (k/2)(I_s N_s)^2 Sin2\alpha$ ..... $[Sin2\alpha = 2 Cos\alpha Sin\alpha]$

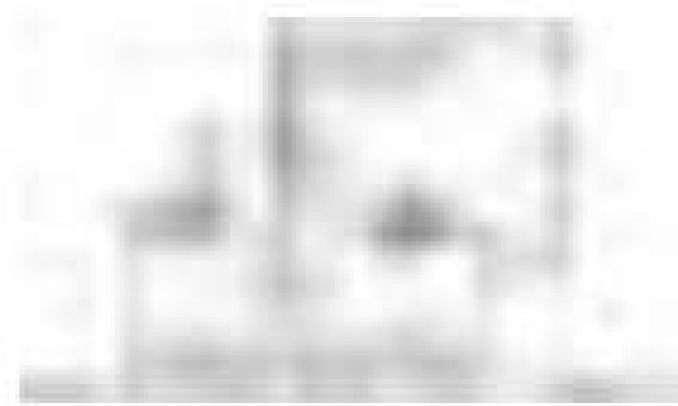
Therefore, the torque in repulsion motor is given as

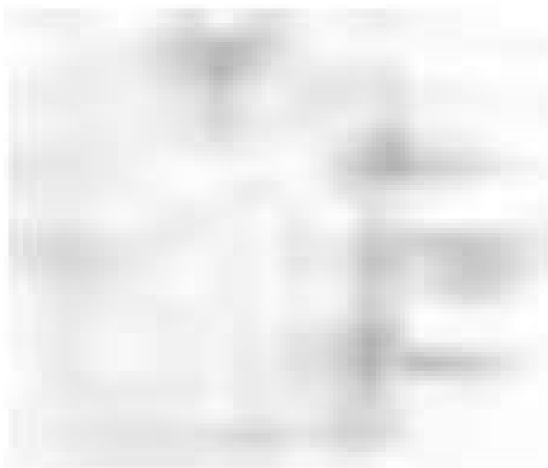
$T_e = (k/2)(I_s N_s)^2 Sin2\alpha$

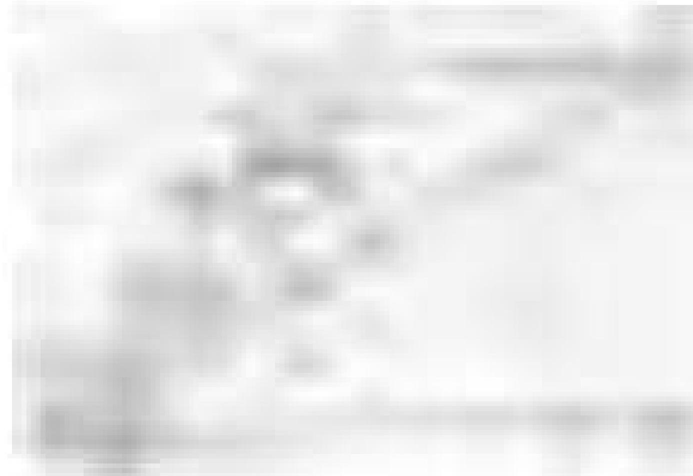
Maximum torque is achieved when stator and rotor magnetic axis are displaced from each other by 45°

The variation of current and torque with respect to different positions of brush is shown









Reluctance Motor

[illegible]

1. [illegible]

2. [illegible]

3. [illegible]

4. [illegible]

Supply is given applied to the stator

↓

A rotating magnetic field is produced

↓

Magnetises the rotor ring and induces pole

↓

Induced rotor flux lags behind the rotating stator flux

↓

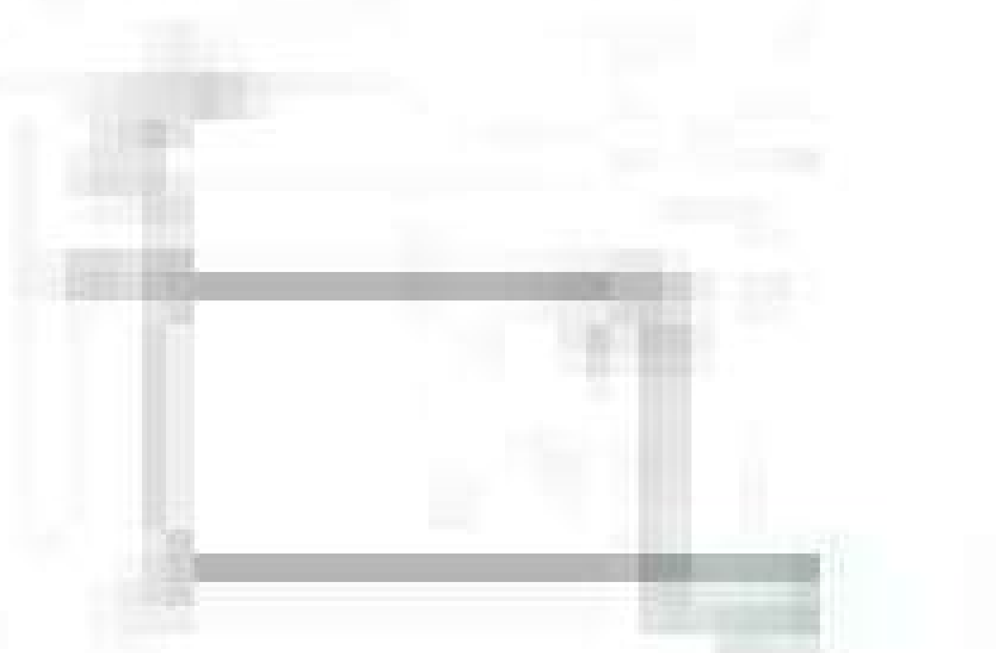
Production of the torque

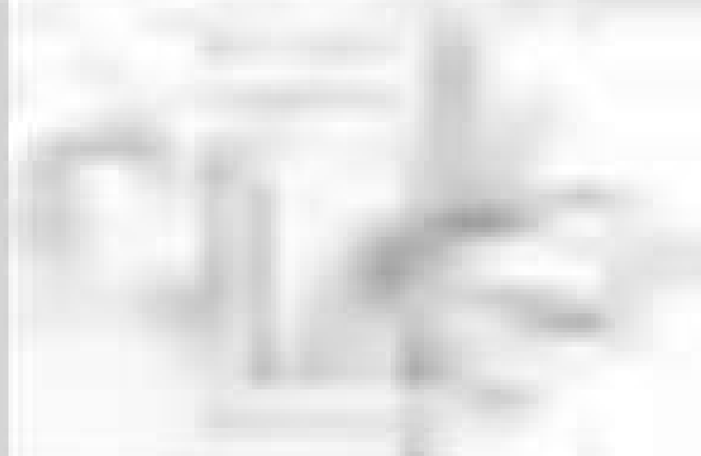
[illegible]

[illegible]

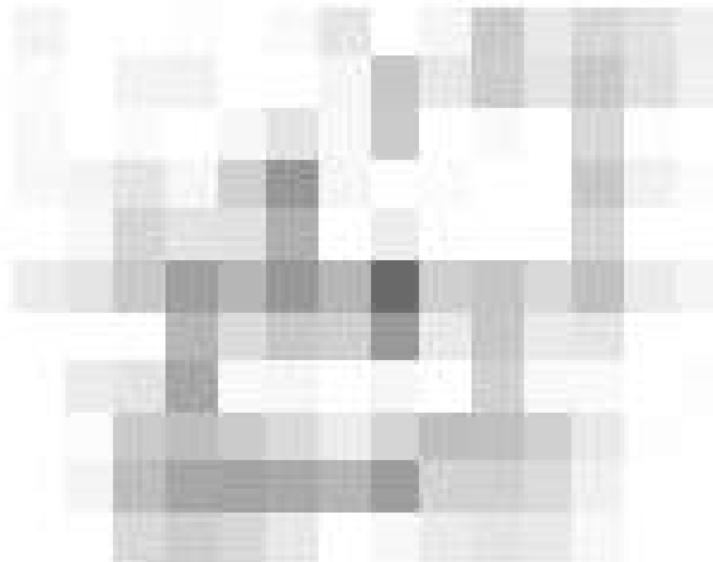
[illegible]

[illegible]





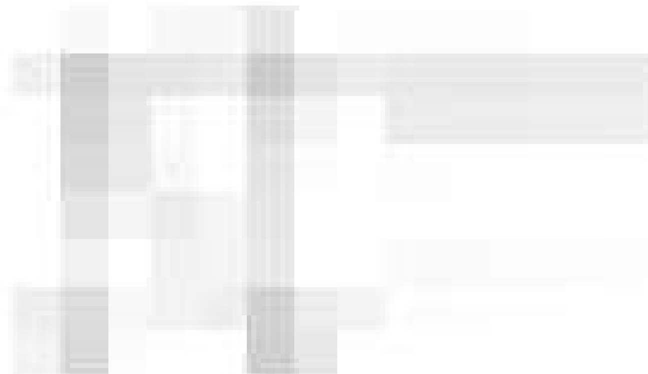
Commutation In AC motor



$$e_1 = L_0 \frac{\varepsilon_i}{L_c}$$

Rotational emf E_2.

$$E_2 = \sqrt{2}\,\pi f_2 N_c \phi_c$$



[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

SUB-SYNCHRONOUS MOTOR

Manual rotor rotation at synchronous speed

↓

Input supply to stator

↓

Alternating field in airgap

↓

Stator and rotor poles interlocking

↓

Rotor poles go ahead due to inertia

↓

Magnetic flux goes to zero & increases in Reverse direction

↓

Stator poles attract rotor poles again