Syllabus

AC Servomotors – construction – operation - DC servomotors – Stepper motor – operation – types-modes of excitation – AC series motor – Universal motor – Hysteresis motor – Reluctance motor – Switched reluctance motor – Permanent magnet DC motor – Brushless DC motor – Linear motors – Linear induction motors.

Expected outcome.

- The students will gain knowledge in the construction and principle of operation of certain special electrical machines having various applications.

Text Book:

E. G. Janardhanan, '*Special Electrical Machines*' PHI Learning Private Limited.

References:

1. Irving L. Kosow.'*Electrical Machinery and Transformers*', Oxford Science Publications.
2. T. J. E. Miller, '*Brushless PM and Reluctance Motor Drives*'.C.Larendon Press, Oxford.
3. Theodore Wildi, '*Electric Machines, Drives and Power Systems*', Prentice Hall India Ltd.
4. Veinott & Martin,'*Fractional & Subfractional hp Electric Motors*'.McGraw Hill International Edn.

Course Plan

Module	Contents	Hours	Sem. Exam Marks
I	AC Servomotors- Construction-principle of operation – performance characteristics – damped AC servomotors – Drag cup servomotor – applications. DC servomotors – field and armature controlled DC servomotors – permanent magnet armature controlled – series split field DC servomotor.	7	15%
II	Stepper motors – Basic principle – different types – variable reluctance- permanent magnet – hybrid type – comparison – theory of operation – monofilar and bifilar windings – modes of excitation – drive circuits – static and dynamic characteristics – applications	7	15%
FIRST INTERNAL EXAMINATION			
III	Single phase special electrical machines – AC series motor-construction – principle of working – phasor diagram – universal motor Hysteresis motor- constructional details- principle of operation – torque-slip characteristics – applications.	7	15%
IV	Reluctance motors – principle of operation – torque equation – torque slip characteristics-applications. Switched reluctance motors – principle of operation – power converter circuits – torque equation – different types – comparison – applications.	7	15%
SECOND INTERNAL EXAMINATION			
V	Permanent Magnet DC Motors – construction – principle of working. Brushless dc motor – construction – trapezoidal type-sinusoidal type – comparison – applications.	7	20%
VI	Linear motors – different types – linear reluctance motor – linear synchronous motors – construction – comparison. Linear induction motors – Expression for linear force – equivalent circuit – applications.	7	20%

Module 4

Reluctance Motor

A single phase synchronous Reluctance motor is same as the single cage type induction motor.

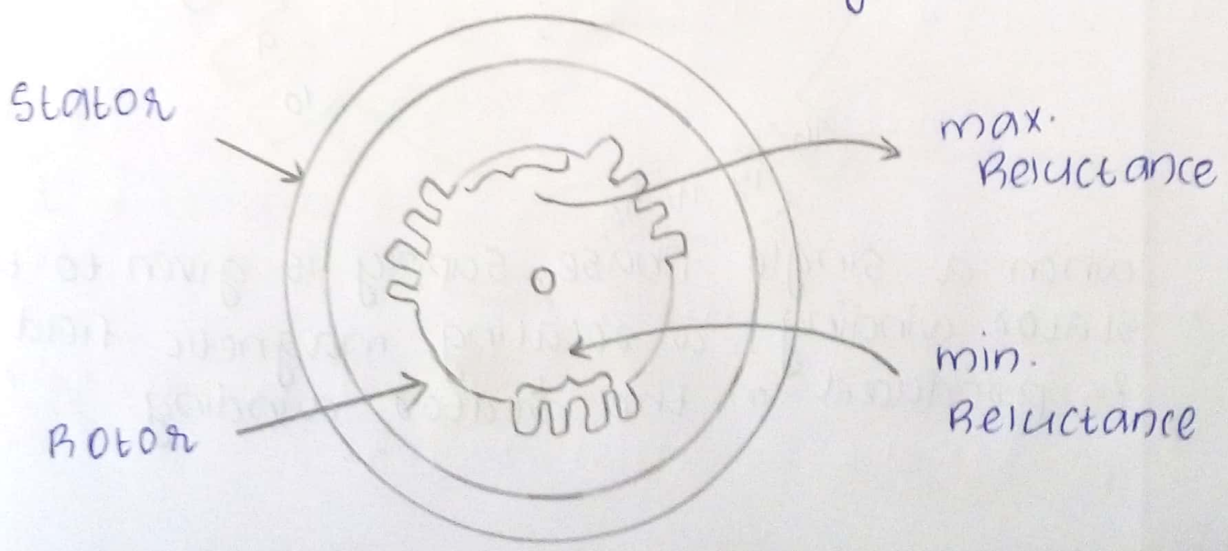
The stator of the motor has the main winding and auxiliary winding.

The stator of the single phase reluctance and induction motor are same.

The rotor of a reluctance motor is a squirrel cage with some rotor teeth removed in the certain places to provide the desired number of salient rotor poles.

There are various types of reluctance motors

- Synchronous reluctance
- Variable reluctance
- Switched Reluctance
- Variable Reluctance stepping

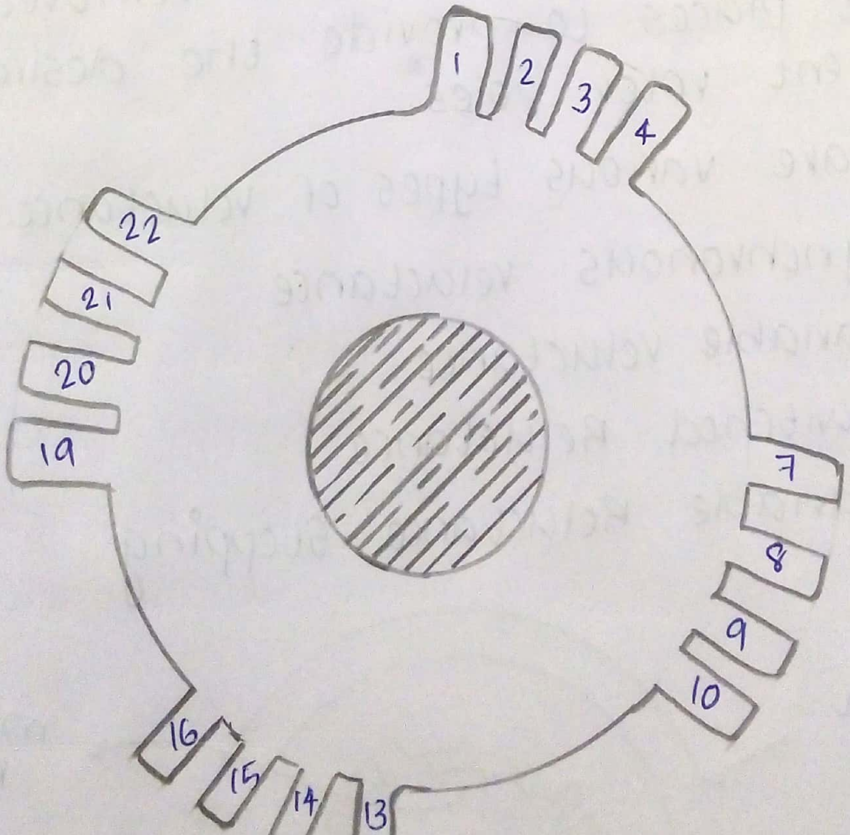


Principle of operation

The stator has three phase symmetrical winding, which creates sinusoidal rotating magnetic field in the air gap.

The reluctance torque is developed because the induced magnetic field in the rotor, has a tendency to cause the rotor to align with the stator field at a minimum reluctance position.

Let us consider that the rotor of the squirrel cage induction motor consist of 24 cu bars. If the rotor bar 5, 6, 11, 12, 17, 18, 23, 24 are cut, it is similar to 4 salient poles.



when a single phase supply is given to the stator winding, a rotating magnetic field is produced in the stator winding when a salient pole rotor cut this magnetic field, rotor aligns in the minimum reluctance path due to reluctance torque.

The reluctance depends upon air gap between stator and rotor.

Fig. A shows 4 Pole salient pole rotor in which direction of 4 high permeance and 4 low permeance is shown.

High permeance means higher magnetic conductivity and higher inductance.
Similarly, low Permeance means lower magnetic conductivity and lower inductance.
The reluctance is inverse of permeance.
Low reluctance means higher inductance and vice versa

$$L \propto \frac{N^2}{S}$$

L : Inductance
S : Reluctance of magnetic path.

Low air gap means low reluctance and Vice versa.

$$S = \frac{L}{\mu_0 \mu_r a}$$

L = Length of air gap
$\mu_0 = 4\pi \times 10^{-7}$
μ_r = Relative permiability
a = Area

There is low reluctance path between stator and salient poles due to small air gap whereas high reluctance path between stator and inner polar axis due to large air gap.

The reluctance motor starts as an induction motor.

When the rotor rotates at its maximum speed, it aligns with the stator synchronous magnetic field due to reluctance torque.

The angle between stator poles and rotor poles of opposite polarity is called as torque angle.

As the torque angle increases, the reluctance torque also increases.

The max. reluctance torque attains at torque angle of 45°.

Advantages :

- Low maintanance
- DC supply not necessary
- simple construction
- constant speed characteristics.

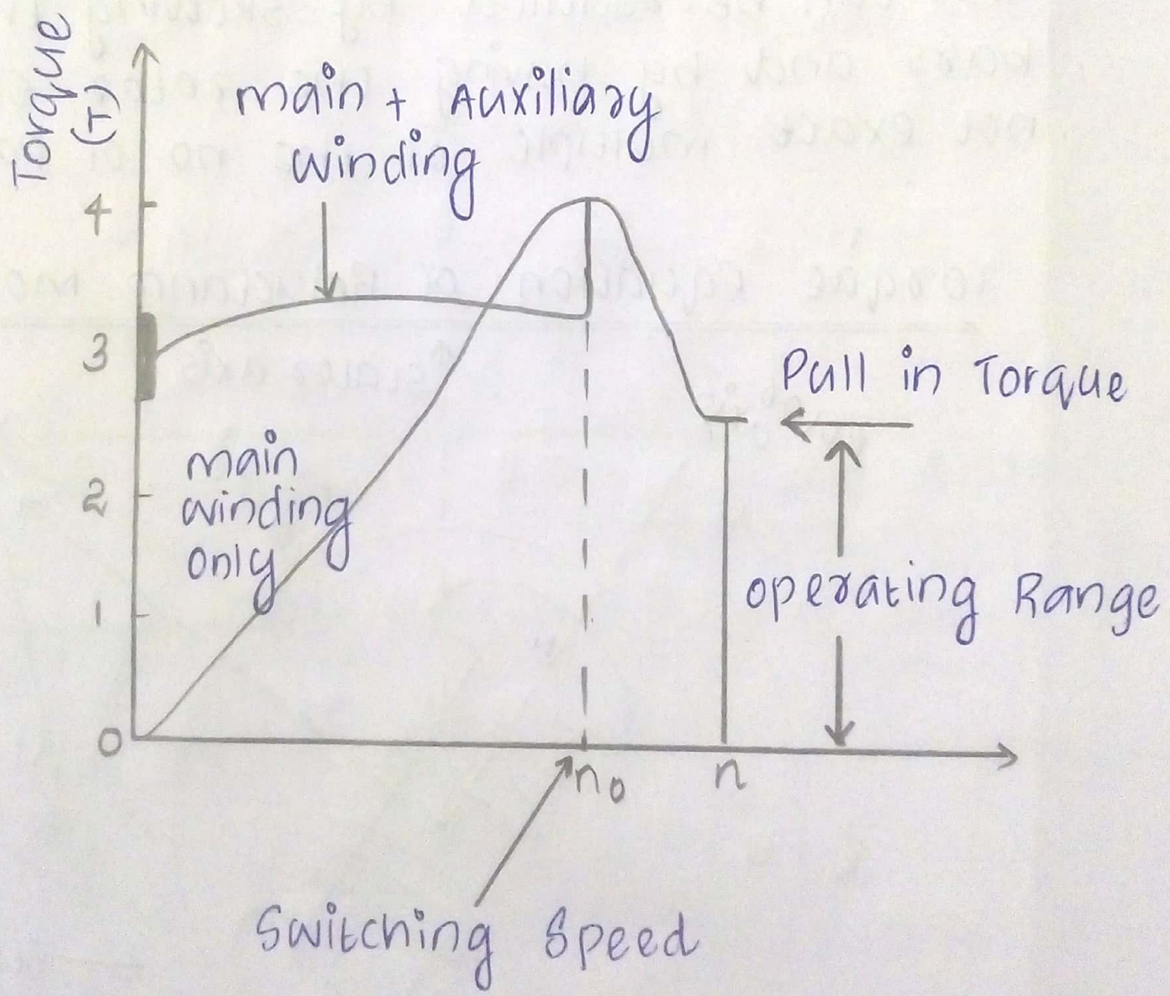
Disadvantages

- Low efficiency
- Low power factor
- only fraction of load taken as compared to 3 phase induction motor.

Applications

- Automatic Regulator
- Signaling Devices
- Recording Instruments
- Tele printer
- Timer circuits
- Gramophone

Slip- Torque characteristics of Reluctance Motor



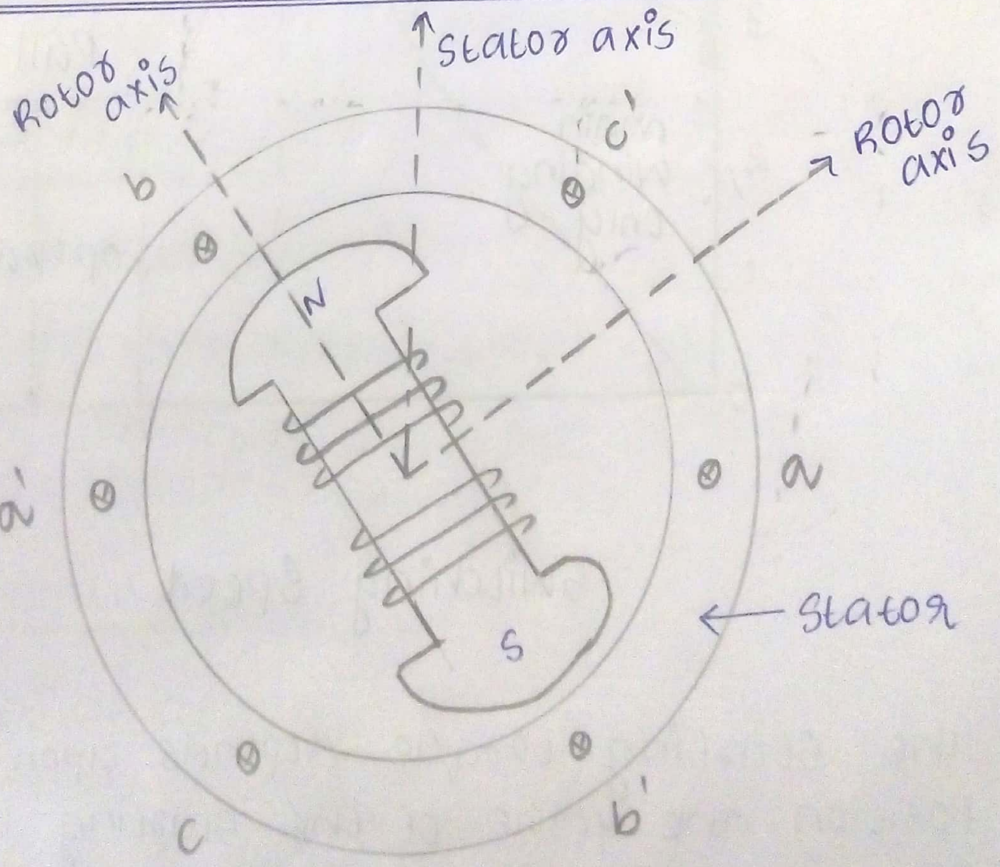
The starting torque depends upon the rotor position. The value of the starting torque varies between 300 to 400% of its Full load torque.

The motor operates at a constant speed up to a little over than 200 % of its full load torque.

If the loading of the motor is increased above the value of the pull out torque, the motor loose synchronism but continues to run as a single phase induction motor up to over 500 % of its rated torque.

At the starting the motor is subjected to cogging.
This can be reduced by skewing the rotor bars and by having the rotor slots not exact multiple of the no. of poles.

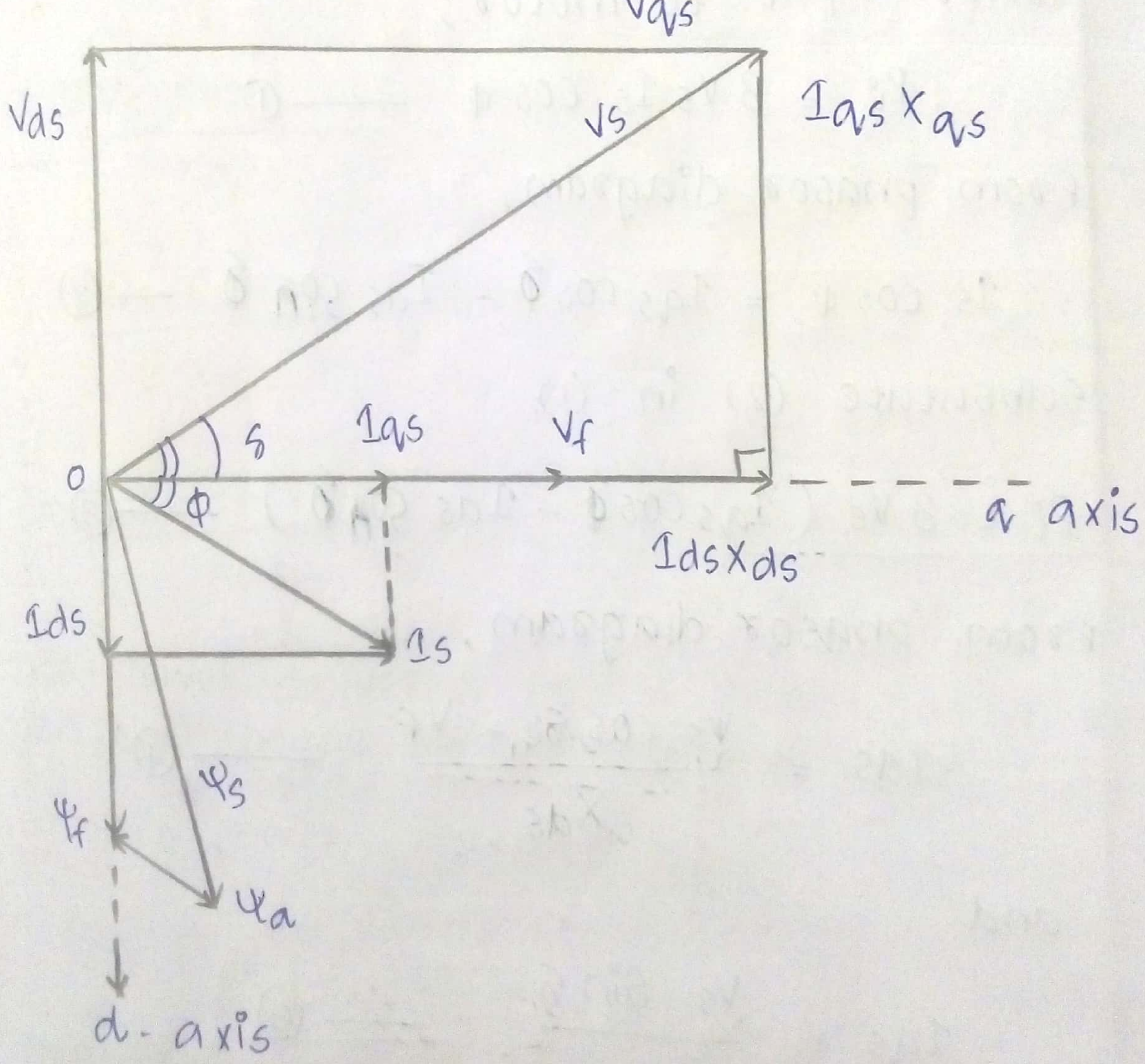
Torque Equation of Reluctance Motor



Reluctance torque is experienced by a ferromagnetic object placed in an external magnetic field, which causes the object to line up with the external magnetic field.

An external magnetic field induces an internal magnetic field in the object and because of this torque is produced.

Phasor diagram:



V_f - Excitation emf

ψ_f - Flux linkage induced by I_f

δ - Torque angle btwn V_s and V_f

ϕ - power factor angle btwn V_s and I_s

V_s, I_s - phase supply voltage and phase supply current resolved into corresponding d and q components

ψ_s - Stator flux linkage when armature flux linkage ψ_a aids field flux linkage ψ_f.

Power input to motor,

$$P_i = 3 V_s I_s \cos\phi \quad \text{——— (1)}$$

From phasor diagram,

$$I_s \cos\phi = I_{qs} \cos\delta - I_{ds} \sin\delta \quad \text{——— (2)}$$

Substitute (2) in (1)

$$P_i = 3 V_s \cdot (I_{qs} \cos\delta - I_{ds} \sin\delta) \quad \text{——— (3)}$$

From phasor diagram,

$$I_{ds} = \frac{V_s \cos\delta - V_f}{X_{ds}} \quad \text{——— (4)}$$

and

$$I_{qs} = \frac{V_s \sin\delta}{X_{qs}} \quad \text{——— (5)}$$

∴ Substitute (4) and (5) in (3)

$$P_i = 3V_s \left[\frac{V_s \sin\delta}{X_{qs}} \cos\delta - \frac{(V_s \cos\delta - V_f)}{X_{ds}} \cdot \sin\delta \right]$$

$$= 3V_s \left[\frac{V_s \sin\delta \cos\delta}{X_{qs}} - \frac{(V_s \cos\delta \sin\delta - V_f \sin\delta)}{X_{ds}} \right]$$

$$= 3V_s \left[\frac{V_s \sin\delta \cos\delta}{X_{qs}} - \frac{V_s . \sin 2\delta}{2X_{ds}} + \frac{V_f \sin\delta}{X_{ds}} \right]$$

$$= \frac{3V_s^2 \sin\delta \cos\delta}{X_{qs}} - \frac{3V_s^2 \sin 2\delta}{2X_{ds}} + \frac{3V_s V_f \sin\delta}{X_{ds}}$$

$$= \frac{3V_s^2 \sin 2\delta}{2X_{qs}} - \frac{3V_s^2 \sin 2\delta}{2X_{ds}} + \frac{3V_s V_f \sin\delta}{X_{ds}}$$

$$P_i = \frac{3V_s V_f \sin\delta}{X_{ds}} + \frac{3V_s^2 (X_{ds} - X_{qs})}{2X_{ds} X_{qs}} . \sin 2\delta \quad \text{—— (6)}$$

The power delivered to the shaft can be related with the torque developed in the motor

∴ shaft power, $P_s = \left(\frac{2}{P}\right) \omega_e T_e$

$\therefore P_s = P_i = \left(\frac{2}{P}\right) \omega_e T_e$

From this equation,

$$T_e = \left(\frac{P}{2}\right) \times \frac{1}{\omega_e} \times P_i \quad \text{—— (7)}$$

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substitute (7) in (6)

$$T_e = \left(\frac{P}{2}\right) \times \frac{1}{\omega_e} \times \left[\frac{3 V_s V_f}{X_{ds}} \sin\delta + \frac{3 V_s^2 (X_{ds} - X_{qs})}{2 X_{ds} X_{qs}} \sin 2\delta \right] \quad (8)$$

we can consider only magnitude,

$$\varphi_s = \left| \frac{V_s}{\omega_e} \right|$$

where,

$$V_s = \varphi_s \cdot \omega_e$$

similarly,

$$V_f = \varphi_f \cdot \omega_e$$

$$\because X_s = \omega_e L_s$$

$$X_{ds} = \omega_e L_{ds}$$

$$X_{qs} = \omega_e L_{qs}$$

substitute these in equation (8)

$$T_e = 3 \times \left(\frac{P}{2}\right)\left(\frac{1}{\omega_e}\right) \left[\frac{\varphi_s \omega_e \cdot \varphi_f \omega_e}{\omega_e L_{ds}} \sin\delta + \varphi_s^2 \omega_e^2 \cdot \frac{(\omega_e L_{ds} - \omega_e L_{qs})}{2 \omega_e^2 L_{ds} \cdot L_{qs}} \cdot \sin 2\delta \right]$$

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$$= 3 \times \left(\frac{P}{2}\right)\left[\frac{\varphi_s \omega_f}{L_{ds}} \cdot \sin\delta + \frac{\varphi_s^2 (L_{ds} - L_{qs})}{2 L_{ds} \cdot L_{qs}} \sin 2\delta\right]$$

where,

$$X_{ds} \neq X_{qs}$$

So, the torque developed by synchronous reluctance motor is :

$$T_e = 3 \times \left(\frac{P}{2}\right) \times \left[\frac{\varphi_s^2 (L_{ds} - L_{qs})}{2 L_{ds} \cdot L_{qs}} \sin 2\delta\right]$$

T_e = Reluctance Torque

δ = Torque Angle.

Switched Reluctance Motors

Switched Reluctance motor is also known as variable Reluctance motor.

This motor works on the principle of variable reluctance.

This means, the rotor always tries to align along the lowest reluctance path.

As the name suggests, a switching inverter is required for the operation of switched reluctance motor.

It has two different construction

- Singly Salient construction
- Doubly Salient construction

Stator and rotor magnetic circuits are laminated to reduce the core lossess in both type of switched Reluctance motor.

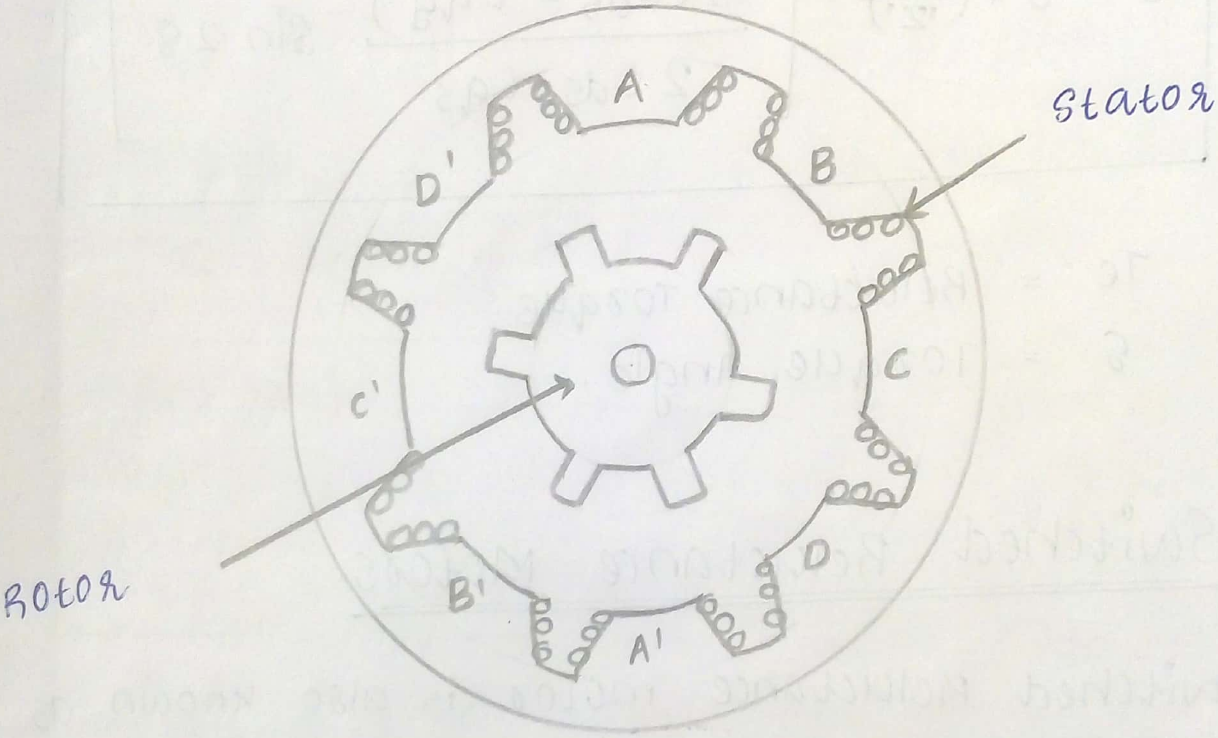
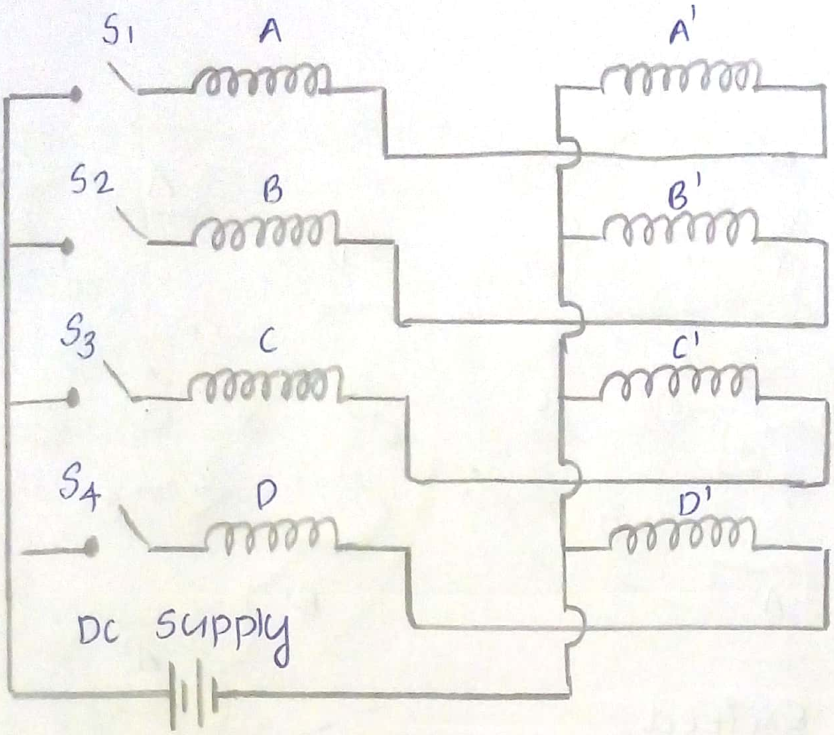


Fig (a): Four phase, Eight pole SRM

The stator of SRM is built by stacking suitably punched silicon laminations to the appropriate length.

The rotor contains no winding or permanent magnet.

It is built up of steel laminations.

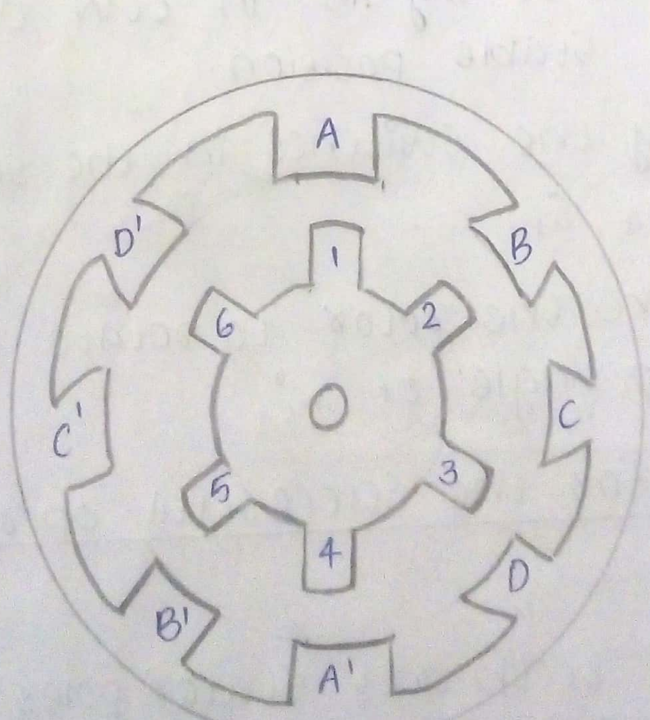


<u>principle of operation</u>

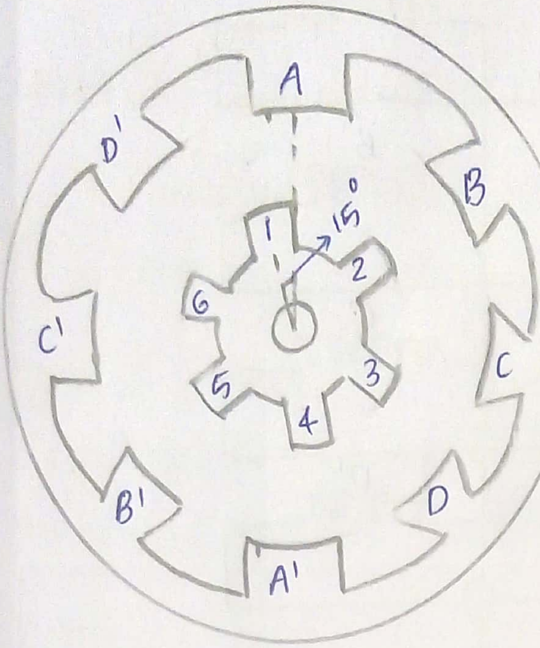
consider an SRM with 8 stator poles and 6 rotor teeth.

It has 4 phases, A-A', B-B', C-C', D-D'

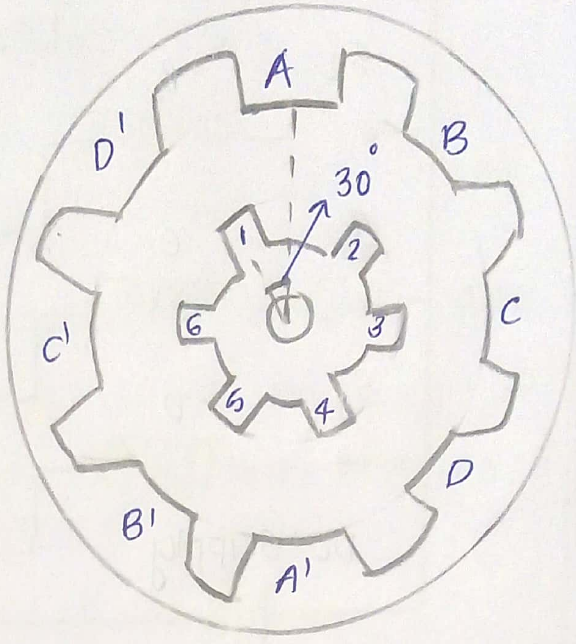
These phases can be excited by DC supply through switches S1, S2, S3 and S4.



Phase A Excited



Phase B Excited



Phase C Excited

Let, A-A' be energized for a significant time so that the rotor rests in the equilibrium position.

Phase A-A' is de-energized by turning switch S1 OFF and excited B-B' by turning switch S2 ON.

The rotor moves by 15° in CCW direction and attains stable position.

By operating the switches in the sequence S_1, S_2, S_3, S_4, S_1 . . .

we can make the rotor to rotate in CCW with a step angle of 15°.

Conditions for the successful operation of SRM

1. No of rotor teeth and stator poles must be even and not equal.

2. stator phase is energized when the inductance of that phase is low or increasing.

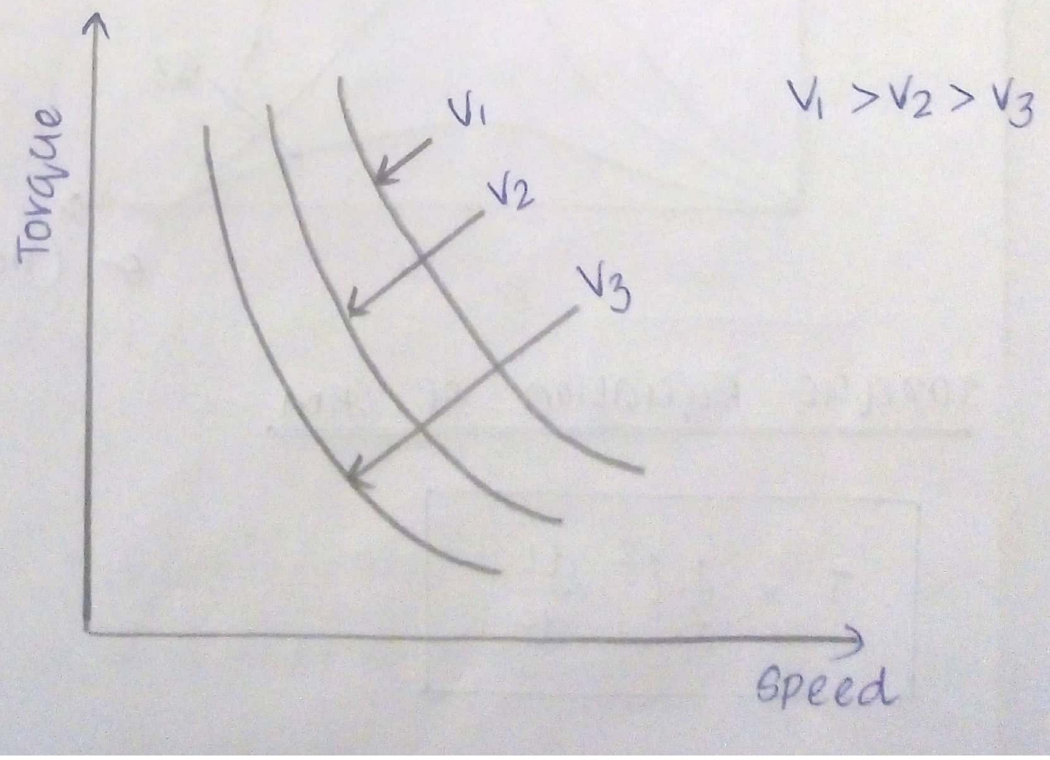
3. The rotor position sensing is essential for switching operations at correct instants.

4. To reduce iron loss, laminated rotor and stator structures should be used.

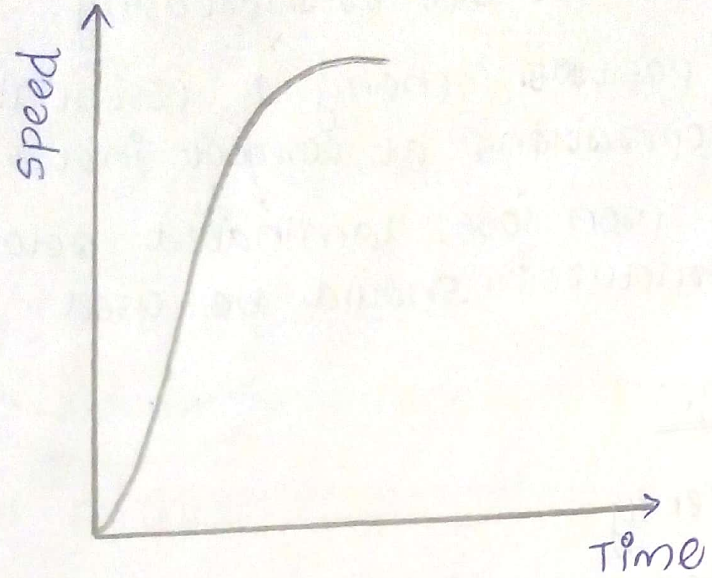
Advantages

- High efficiency
- Good performance in terms of torque to inertia ratio
- maximum operating speed
- simple construction
- Available in various size, power, speed ranges.

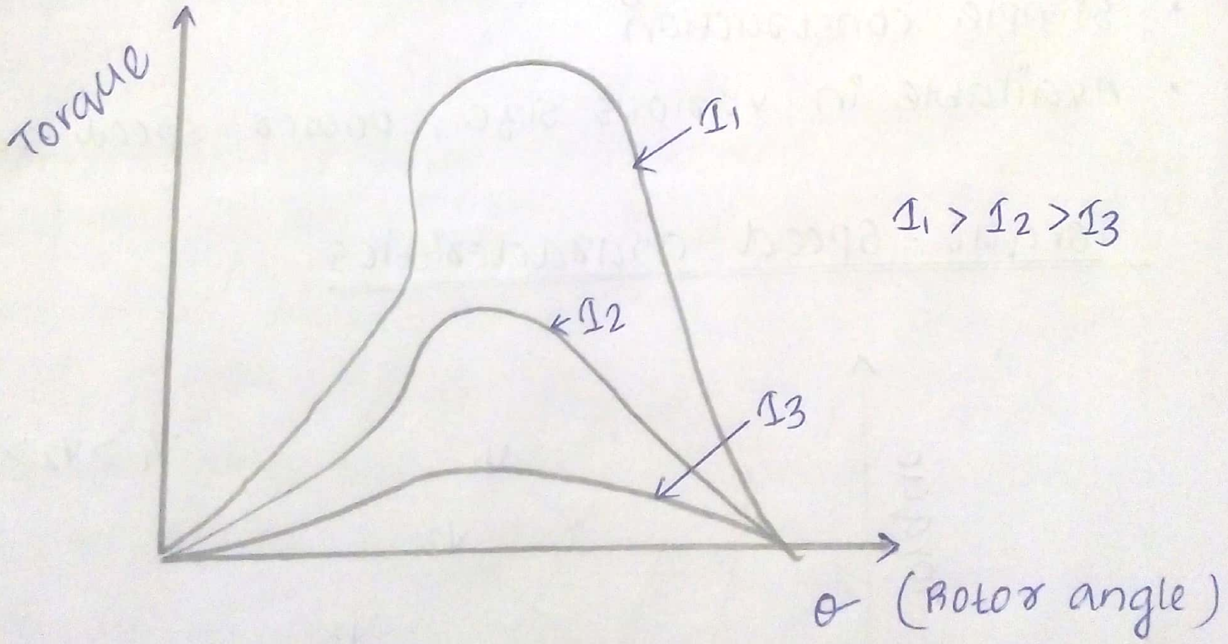
Torque - speed characteristics



Speed - Time curve



Torque - Angle characteristics



Torque Equation of SRM

$$T = \frac{1}{2} i^2 \frac{dL}{d\theta}$$

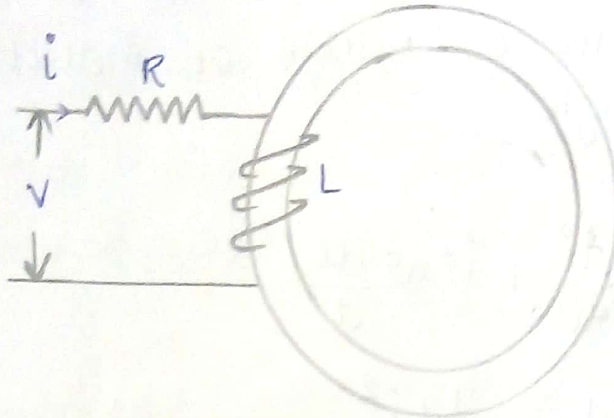


Fig: Basic R-L circuit of SRM

From the figure,

$$V = iR + \frac{d\lambda}{dt}$$

where,

λ is a function of θ and L

$$\frac{d\lambda}{dt} = \frac{di}{dt} + \frac{di}{dt}\theta$$

$$V = iR + \frac{d(Li)}{dt}$$

$$= iR + L\frac{di}{dt} + i\frac{dL}{dt}$$

$$= iR + L\frac{di}{dt} + i\frac{dL}{d} \times \frac{d}{dt}$$

$$\therefore V = iR + L\frac{di}{dt} + i\omega\frac{dL}{d}$$

where,

iR = ohmic drop

$L\frac{di}{dt}$ = emf due to incremental inductance

$i\omega\frac{dL}{d}$ = self emf

Self induced emf is proportional to current speed and rate of change of inductance with rotor angle.

$$Vi = i^2R + L\frac{di}{dt} + i^2\omega\frac{dL}{d}$$

Energy stored $= \frac{1}{2}Li^2$

Rate of change of energy stored $= \frac{d}{dt}\left[\frac{1}{2}Li^2\right]$

$$= \frac{1}{2}L \cdot 2i\frac{di}{dt} + \frac{1}{2}i^2\frac{dL}{dt}$$

$$= Li\frac{di}{dt} + \frac{1}{2}i^2\frac{dL}{d} \times \frac{d}{dt}$$

$$\frac{dW_{mag}}{dt} = Li\frac{di}{dt} + \frac{1}{2}i^2\omega\frac{dL}{d}$$

Mechanical Energy Transferred, P_m

$$P_m = Vi \cdot i^2R \cdot \frac{dW_{mag}}{dt}$$

$$= i^2R + L\frac{di}{dt} + i^2\omega\frac{dL}{d} \cdot i^2R \cdot Li\frac{di}{dt} + \frac{1}{2}i^2\omega\frac{dL}{dt}$$

$$= \frac{1}{2}i^2\omega\frac{dL}{d\theta}$$

$$\boxed{P_m = \omega T}$$

$\therefore$ Torque, $T = \frac{1}{2}i^2\frac{dL}{d\theta}$

Applications of SRM

- washing machine
- Vaccum cleaner
- Fans
- Future automobile application
- Robotic control applications.

Q comparison between switched Reluctance and Reluctance motor.

Switched Reluctance	Reluctance Motor
The conduction angle for phase current is controlled and synchronised with rotor position.	construction is simple, Robust, as there is no brush.
maximum operating speed	It is impossible to have very high speeds.
High Efficiency	low Efficiency
It is designed for efficient power conversion at high speeds	No permanent magnet, neither in the stator nor in the rotor

Power converter Circuits

A power converter is an electrical circuit that changes the electrical energy from one form into the desired form.

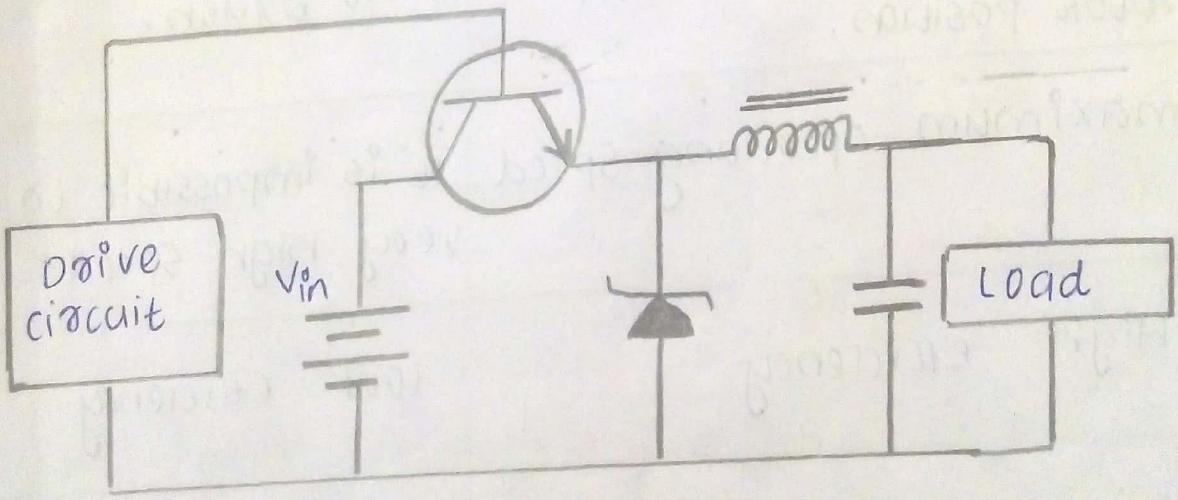
A converter do one or more functions and give an output that differs from the input.

Types of power converter circuits:

1) Buck converter circuit

The figure shows the buck converter circuit.

It is a type of DC-DC "switching" power conversion circuit.



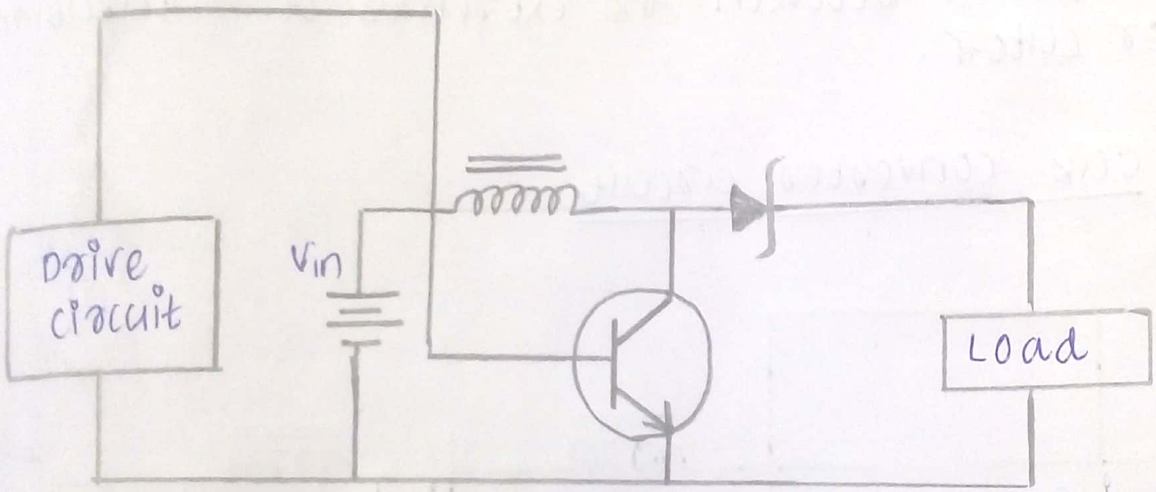
In this circuit, the transistor is either fully ON or fully OFF.

By avoiding the transistors "Active" mode, very low transistor power dissipations can be acheived.

with little power wasted in the form of heat, switching power conversion circuits are typically very efficient.

2) Boost converter circuit

The figure shows the boost converter circuit. It is a type of DC-DC switching power conversion circuit.

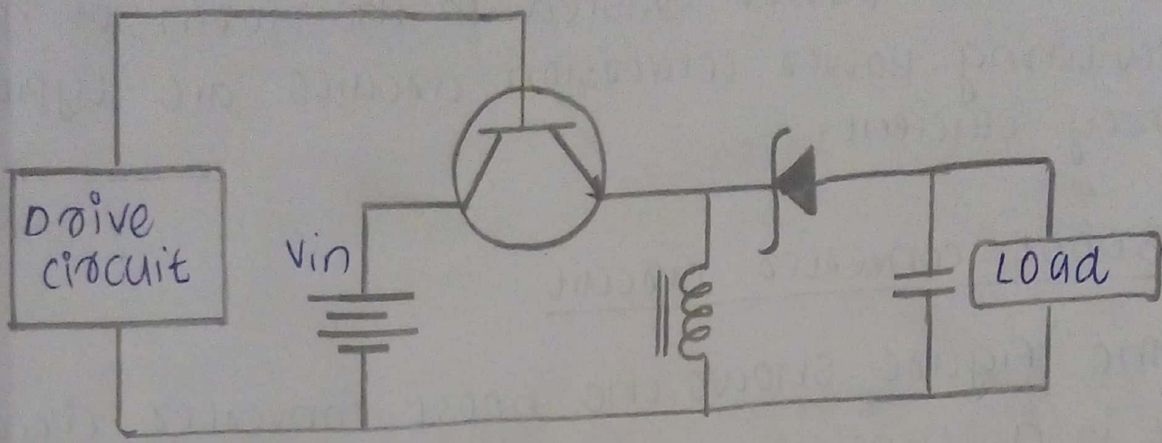


The circuit is driven between the extremes of saturation or cutoff.

By avoiding the transistors Active mode, very low transistor power dissipations can be acheived.

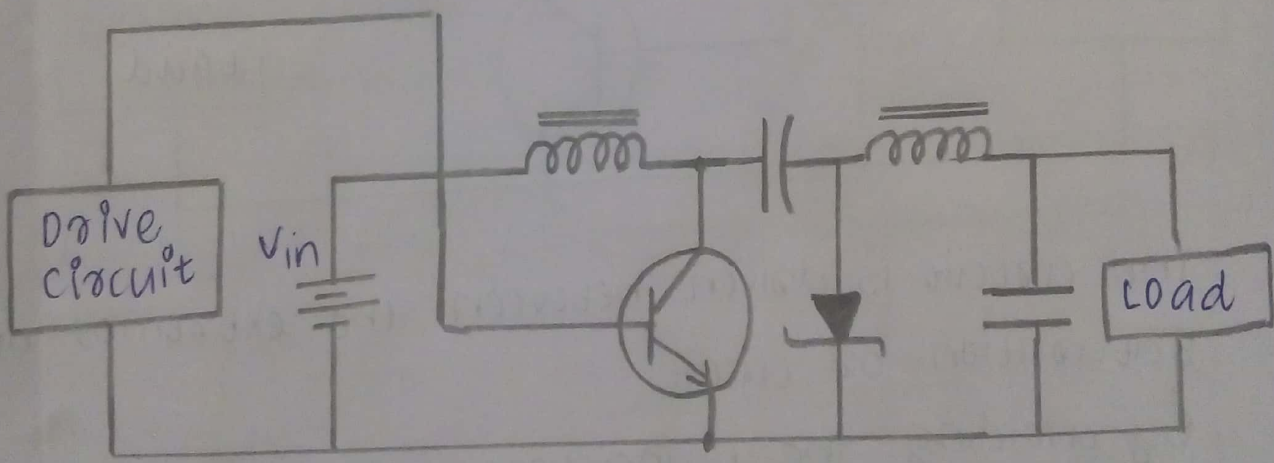
3) Inverting converter circuit

The figure shows the inverting converter circuit, It is a type of DC-DC switching power conversion circuit.



in this circuit, the transistor is either fully ON or fully off.
ie, driven between the extremes of saturation or cutoff.

4) Cuk converter circuit



The figure shows the cuk converter circuit.
It is a type of DC-DC switching power conversion circuit.
with little power wasted in the form of heat, switching power conversion circuits are typically very efficient.