**Chapter 1**

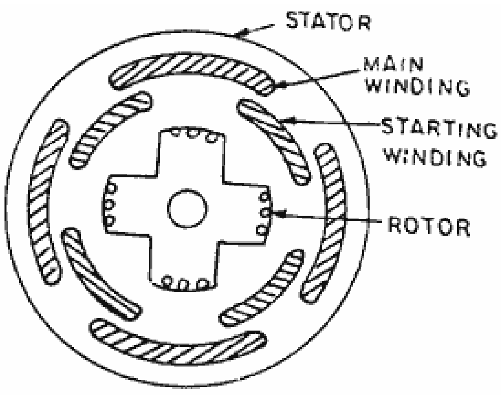
# INTRODUCTION

First time reluctance motors is mostly used by Davidson as a traction drive for an electric locomotive in 1838. But the “Re-Invention” has been possibly due to the region of inexpensive and by the help of high-power switching devices used in the motor. The term became popular from the 1980s onwards, through the efforts of the first commercial exploiters of the technology.

Reluctance motors are the special type of motor, where the output mechanical power and the overall performance is quite good as compared to the maintenance and operating cost. In fact, there are many timing devices where small motors having constant speed characteristic are very advantageous. These motors operate from a single phase ac supply.

They do not require dc source of power supply for excitation nor they do they use permanent magnets. The most commonly used types of single phase synchronous motors are reluctance motor and hysteresis motor. The output of reluctance motors lies within a few kilowatts and they are used in several applications, especially in various industries. The theory of reluctance motor is slightly different from the conventional motoring theory. That is why they are treated as special motor. In this chapter we are going to discuss about the construction and working principle of the reluctance motor.

## 1.1 Construction of Reluctance Motor




**Reluctance Motor**

Fig.1

Reluctance motor is actually a split phase induction motor with salient poles. The motor essentially consists of a stator and a rotor. In general stator of a single phase reluctance motor is similar to that of any one of the single-phase induction motors. Except for the permanent split capacitor (PSC) motor, all motors (1phase IM) are provided with a starting switch. The stator have two different windings – the main (having more number of turns) and auxiliary winding. This helps in developing a synchronously rotating magnetic field. The starting switch mentioned earlier is connected in series with the auxiliary winding. The rotor of a reluctance motor is made up with soft magnetic material and is almost similar to that of a squirrel cage motor except some rotor teeth are removed at appropriate places to produce salient poles. If we remove teeth from four locations then we produce a 4 pole salient pole structure. Each slot of rotor is provided with rotor bar conductors made of aluminum or copper which are short circuited by a pair of end rings as in case of squirrel cage induction motor. This type arrangement shown in the Fig.1.

## 1.2 Operating Principle of Reluctance Motor

Let us discuss that how a reluctance motor works. When the stator of the reluctance motor is supplied with a single phase ac supply the motor starts as an induction motor (single phase). The starting / centrifugal switch disconnects the axillary winding of the motor at a speed of about 75% of synchronous speed. Now the motor operates with its main winding in operation. Gradually it accelerates and attains speed very close to synchronous speed. When the reluctance motor starts to run at a speed close to synchronous speed, a reluctance torque is produced. The rotor aligns itself in minimum reluctance position. The rotor pulls into synchronism. After pulling into synchronism, the induction torque disappears but the rotor remains in synchronism due to synchronous reluctance torque alone. The motor adjusts its torque angle for change in load as in 3-ph synchronous motor. If load is excessive motor may not pull into synchronism and if already running it may pull out of synchronism.

## 1.3 Speed Torque Characteristics of Reluctance Motor

The starting torque of the reluctance motor is dependent upon position of rotor because the rotor is a salient pole one. The value of starting torque lies between 300 to 400 percent of its full load torque. The motor operates at a constant speed upto a little over 200% of its full load torque. We have already discussed that at about 75 percent of the synchronous speed, a centrifugal switch disconnects the auxiliary winding and motor runs with main winding only. So when it attains speed close to synchronous speed, the reluctance torque is produced that pulls rotor into synchronism and rotor rotates at synchronous speed. The motor may face some problem in proper synchronism when loading is increased beyond the value of pull out torque.

Reluctance motors are subjected to cogging at the time of starting. Cogging is the locking tendency of the rotor which can be minimized by skewing the rotor bars and not making the number of rotor slots equal to an exact multiple of the number of poles.

### 1.4 Types of Reluctance Motors

There are following type of motors are present,

- Switched reluctance motor.
- Variable reluctance stepper motor.
- Synchronous Reluctance Motor

**Chapter 2**

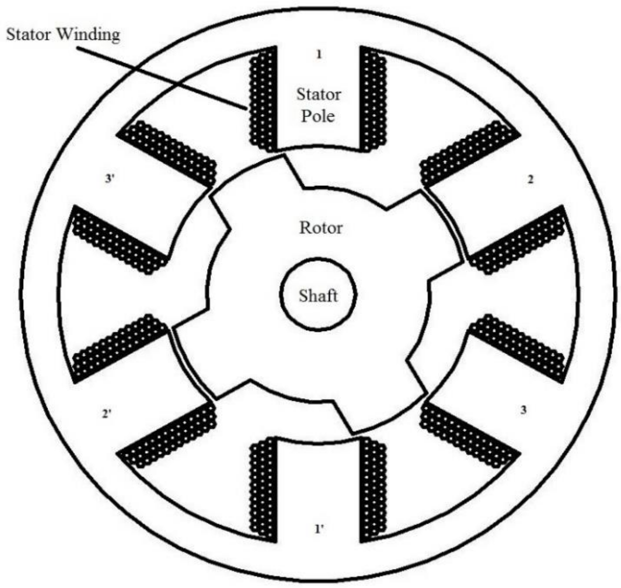
# SWITCHED RELUCTANCE MOTOR

## 2.1 Construction

The stator and rotor of a Switched Reluctance motor have salient poles. This doubly-salient arrangement is very effective for electromagnetic energy conversion.

In the stator part carries coils on each pole, the coils on opposite poles being connected in series. The rotor does not have magnets or coils attached with the rotor slots. It is a solid salient-pole rotor made of soft magnetic material with a laminated-steel.

The six stator coils shown in Figure are grouped to form three phases which are independently energized from a three-phase converter. Therefore cheap to manufacture and extremely robust. The motor shown in Fig.1 has six stator poles and four rotor poles.



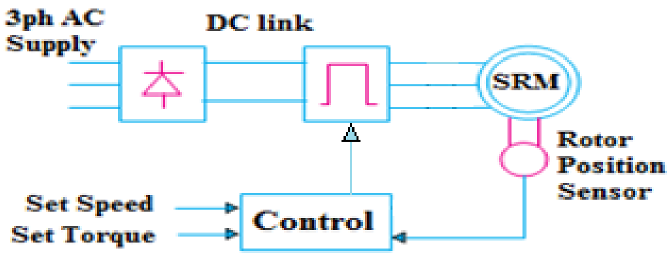

**Reluctance Motor**

Fig.1

## 2.2 Working

Usual arrangement is to energize stator coils sequentially with a single pulse of current at high speed. However, at starting and low speed, a current-chopper type control is used to limit the coil current.

The motor rotates in the anticlockwise direction when the stator phases are energized in the sequence 1, 2, 3 and in clockwise direction when energized in the sequence 1, 3, 2. When the stator coils are energized, the nearest pair of rotor poles is pulled into alignment with the appropriate stator poles by reluctance torque.

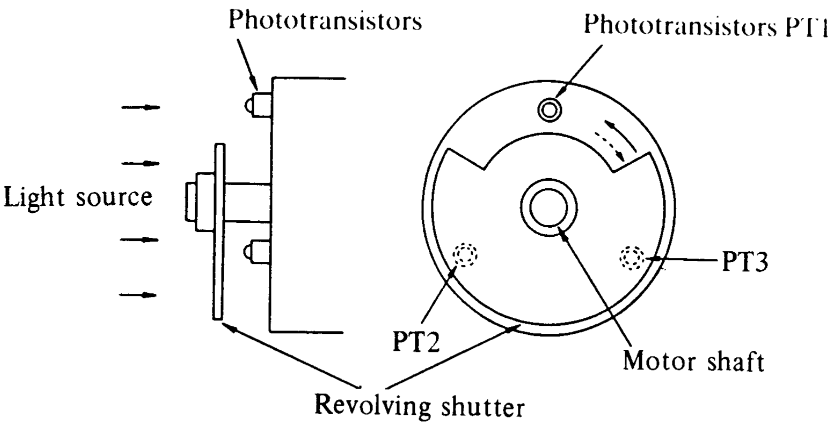



**Closed Loop Control of a Switched Reluctance Motor**

Fig.2

Closed-loop control is essential to optimize the switching angles of the applied coil voltages. The stator phases are switched by signals derived from a shaft-mounted rotor position detectors such as Phototransistor sensors. This causes the behavior of the Switched Reluctance motor to resemble that of a dc motor. The closed loop control of a switched reluctance motor shown the Fig-2.

Phototransistor sensors is based on the photoelectric principle. Fig.3 shows the basic structure of the phototransistor sensor.




**Phototransistor Sensors**

Fig.3

As shown in the figure, a revolving shutter with a 120° electric angle gap is installed on the rotor shaft, rotating with the rotor of the Switched Reluctance Motor. Phototransistors of the same number as the motor three phase are fixed on the stator. 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. In this case, the stator phase associate with PT1 should be turned on. Similar situation will occur when the gap of revolving shutter is aligned with PT2 or PT3

### 2.3 Principle of Operation

The torque production in the switched reluctance motor can be explained using the Elementary principle of electromechanical energy conversion. In the case of a rotating machine, the incremental mechanical energy in terms of the electromagnetic torque and change in rotor position can be written as:

$$\Delta W_m = T_e \Delta\theta \qquad (1)$$

Where $T_e$ is the electromagnetic torque and $\Delta\theta$ the incremental rotor angle. Therefore, The electromagnetic torque can be obtained by:

$$Te = \Delta Wm/\Delta\theta \qquad (2)$$

For the case of constant excitation (i.e., when the mmf is constant), the incremental Mechanical energy is equal to the change of magnetic co-energy, $W_f$

$$\Delta W_m = \Delta W_f \qquad (3)$$

By the theory of electromagnetic field, if no magnetic saturation exists, the co-energy at any position in the motor can be expressed by,

$$W_f = \frac{1}{2} L\,(\theta, i)\, i^2 \qquad (4)$$

Where $L(\theta, i)$ is the stator inductance at a particular position, and $i$ the stator phase Current. Hence, the electromagnetic torque is,

$$Te = \Delta Wm/\Delta\theta = \Delta W_f/\Delta\theta = \partial W_f/\partial\theta$$

$$Te = \frac{\partial L\,(\theta,\ i)}{\partial\theta}\left(\frac{i^2}{2}\right) \qquad (5)$$

Equation (5) has the following implications:

1. The torque is proportional to the square of the current and hence, the current can be unipolar to produce unidirectional torque. This is a distinct advantage in that only one power switch is required for the control of current in a phase winding and thereby makes the drive economical.

2. Since the torque is proportional to the square of the current, it has a good starting torque.
3. Because the stator inductance of a stator winding is a function of both the rotor position and stator current, thus making it nonlinear, a simple equivalent circuit development for Switch Reluctance Motor is not possible.
4. A generation action is made possible with unipolar current due to its operation on the negative slope of the inductance profile. As a result, this machine is suitable for four-quadrant operation with a converter.
5. Because of its dependence on a power converter for its operation, this motor is an inherently variable-speed motor drive system.

**2.4 Stator Inductance**

The torque characteristics of switched reluctance motor are dependent on the relationship between the stator flux linkages and the rotor position as a function of the stator current. A typical phase inductance v/s rotor position is shown in the below figure

Four distinct inductance regions emerge:

In that,

βs – Stator Pole Arc

βr – Rotor Pole Arc

Pr – No. of Rotor Poles

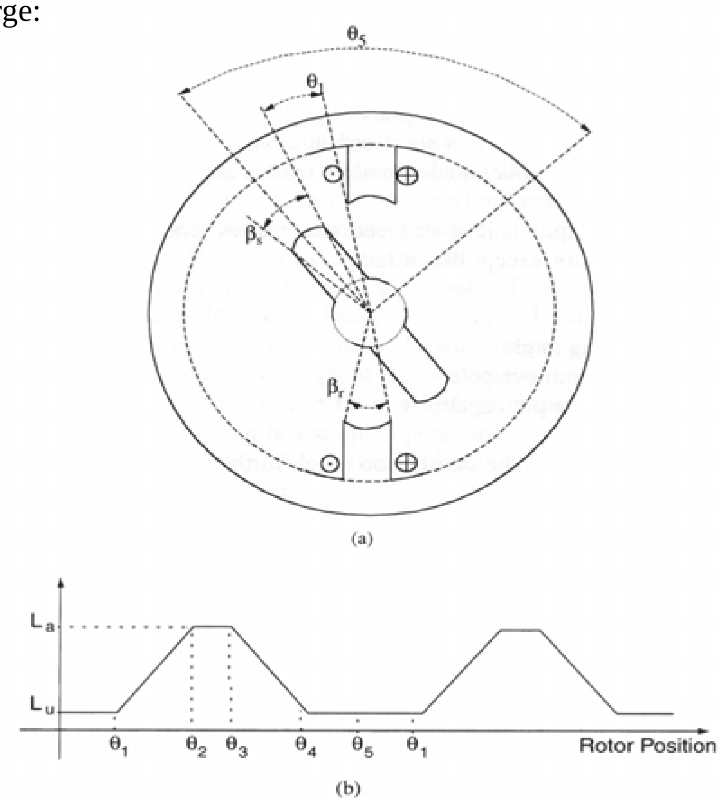
$\theta_1 = \frac{1}{2}\left(\frac{2\pi}{Pr} - (\beta s + \beta r)\right)$

$\theta_2 = \theta_1 + \beta s$

$\theta_3 = \theta_2 + (\beta r - \beta s)$

$\theta_4 = \theta_3 + \beta s$

$\theta_5 = \theta_1 + \theta_4 = \frac{2\pi}{Pr}$




**A typical phase inductance v/s rotor position wave form**

Fig.1

1. $0 \sim \theta_1$ and $\theta_4 \sim \theta_5$: The stator and rotor poles are not overlap, and the inductance is minimum and almost a constant. Hence, these regions do not contribute to torque production.
2. $\theta_1 \sim \theta_2$: Poles overlap, so that the flux path is mainly through the stator and rotor laminations. This increases the inductance with the rotor position and gives it a positive slope. A current impressed in the winding during this region produces a positive torque. This region comes to an end when the overlap of poles is complete.
3. $\theta_2 \sim \theta_3$: During this period, movement of rotor pole does not alter the complete overlap of the stator pole. This has the effect of keeping the inductance maximum and constant. Therefore, torque generation is zero. In spite of this fact, it serves a useful function by providing time for the stator current to come to zero or lower levels when it is commutated, thus preventing negative torque generation in the negative slope region of the inductance.
4. $\theta_3 \sim \theta_4$: the rotor pole is moving away from overlapping the stator pole in this region and the inductance decreases, making a negative slope of the inductance region. The operation of the machine in this region results in negative torque.

It is not possible to achieve the ideal inductance profile shown in Fig.1 (b) in an actual motor due to saturation. Saturation causes the inductance profile to curve near the top and thus reduces the torque constant. For rectangular currents, it can be seen that the motoring torque is produced for a short duration in pulsed form, resulting in a large torque ripple. This can create problems of increased audible noise, fatigue of the shaft, and possible speed oscillations. However, the torque ripples can be minimized by designing the machine such that the inductance profiles of two succeeding phases overlap during the ending of one and the beginning of the other. In turn, this requires the correct choice of number of stator and rotor poles and their pole arcs. An alternative technique to reduce the torque ripples is to shape the current.

## Chapter 3

### TYPES OF SWITCHED RELUCTANCE MOTOR

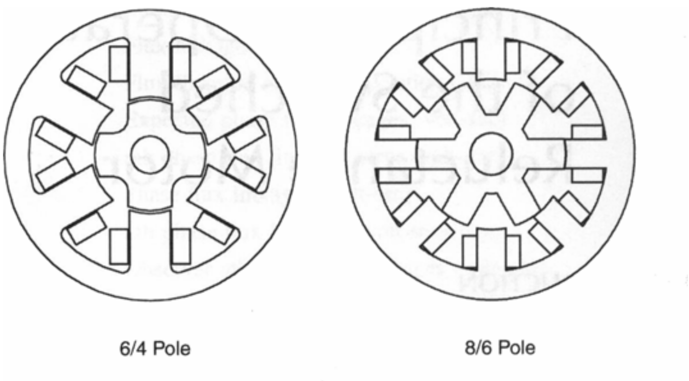
### 3.1 Classification of Switched Reluctance Motor

This switched reluctance motor are classified into two types based on the motion.

- Rotary Switched Reluctance Motor.
- Linear Switched Reluctance Motor.

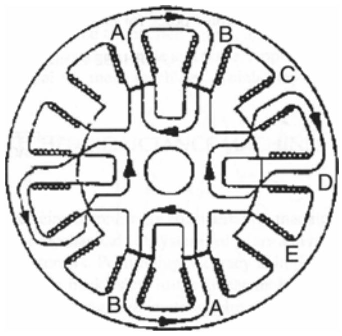
### 3.2 Rotary Switched Reluctance Motor

The rotary machine-based Switched Reluctance Motors are further differentiated by the nature of the magnetic field path as to its direction with respect to the axial length of the machine. If the magnetic field path is perpendicular to the shaft, which may also be seen as along the radius of the cylindrical stator and rotor, the Switched Reluctance Motor is classified as radial field. When the flux path is along the axial direction, the machine is called an axial field Switched Reluctance Motor.




**Long Flux Path Switched Reluctance Motor**

Fig.1

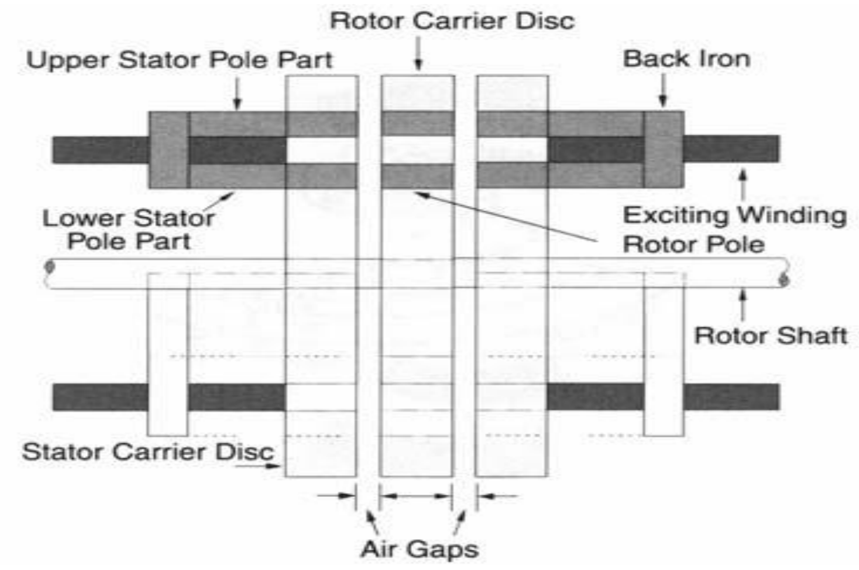



**Short Flux Path Switched Reluctance Motor**

Fig.2

Radial field Switched Reluctance Motors are most commonly used. They can be divided into shorter and longer flux paths based on how a phase coil is placed. The conventional one is the long flux path Switched Reluctance Motors, in which the phase coil is placed in the diametrically opposite slots, as shown in Fig.1. In the shorter flux path Switched Reluctance Motors, the phase coil is placed in the slots adjacent to each other, as shown in Fig.2. Short flux path Switched Reluctance Motors have the advantage of lower core losses due to the fact that the flux reversals do not occur in stator back iron in addition to having short flux paths.

However, they have disadvantage of having a slightly higher mutual inductance and a possible higher uneven magnetic pull on the rotor.




**Axial Configuration of a Switched Reluctance Motor**

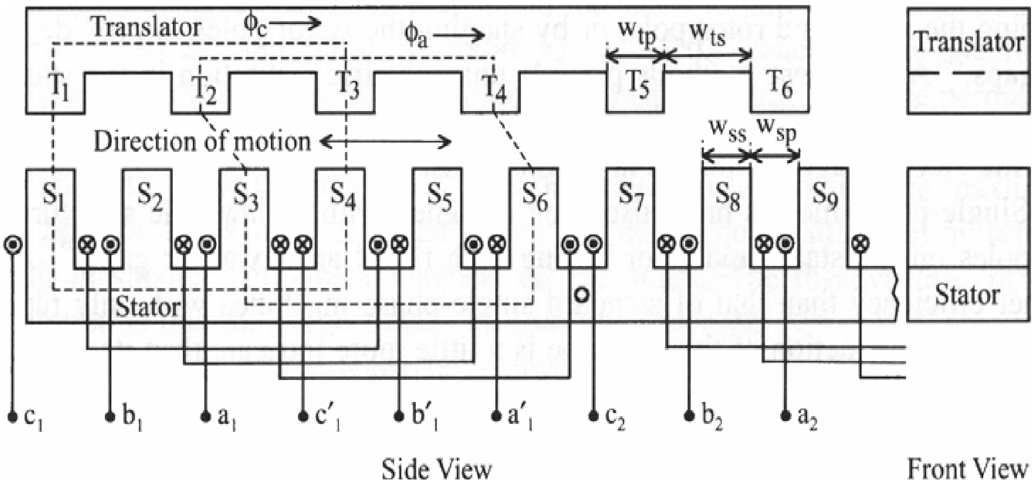
Fig.3

The axial configuration of a Switched Reluctance Motor is shown in Fig.3. This type of Switched Reluctance Motors is ideal for applications where the total length may be constrained, such as in a ceiling fan or in a propulsion application. The disadvantage of this configuration is that the stator laminations have to be folded one on top of the other, unlike the simple stacking of laminations in the radial field configuration.

### 3.3 Linear Switched Reluctance Motor

Linear electric motors are electromechanical devices that develop motion in a straight line, without the use of a mechanism to convert rotary motion to linear motion. Linear motors have nearly the same long history as rotary motors. The first linear electric motor was devised in 1883. But large air gaps and low efficiencies prevented linear electric motors from being widely used. Unlike rotary electric motors, the linear motor has a start and an end to its travel. Linear switched reluctance machines (LSRMs) are an attractive alternative to linear induction or synchronous machines due to lack of windings on either the stator or rotor structure and absence of mechanical gears.

Linear switched reluctance motors (LSRMs) are the counterparts of the rotating Switched Reluctance Motors. In fact, the linear switched reluctance motor is obtained from its rotary counterpart by cutting along the shaft over its radius and rolling them out. Fig.4 shows the configuration of a three phase Linear Switched Reluctance Motor.



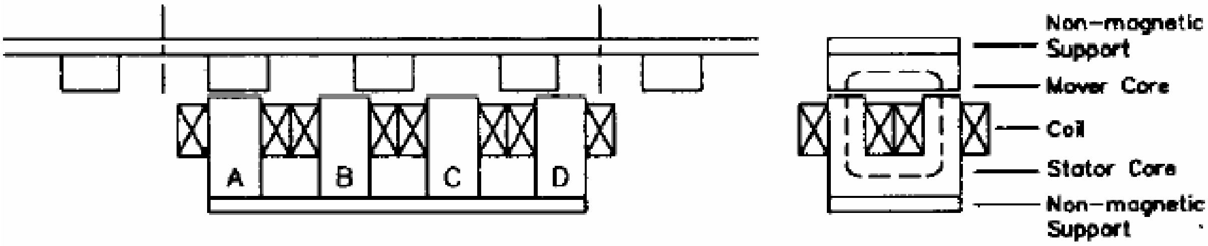

**Configuration of a three phase Linear Switched Reluctance Motor**

Fig.4

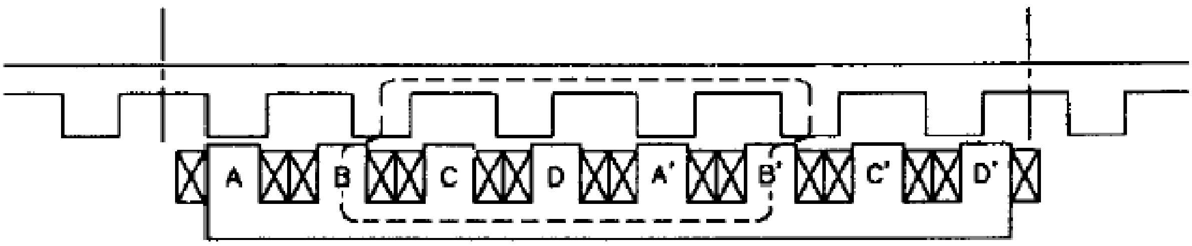
Based on the direction of the flux path with respect to the axial length of the machine the Linear Switched Reluctance Motors are further differentiated as,

- Transverse flux configuration of Linear Switched Reluctance Motor
- Longitudinal flux configuration of Linear Switched Reluctance Motor

Transverse flux configuration of Linear Switched Reluctance Motor




Longitudinal flux configuration of Linear Switched Reluctance Motor



**Chapter 4**

# ADVANTAGES, DISADVANTAGES & APPLICATIONS

## 4.1 Advantages of Switched Reluctance Motor

Reluctance motor offers following advantages. These are:

- Construction of the motor is simple.
- Brushes, commentator's , permanent magnets are absent
- Starting torque is quite good
- Accurate speed control is possible
- Cost effective and easy maintenance.
- Higher efficiency
- More power per unit weight and volume
- Has no windings or slip rings in the rotor
- Can run at very high speed (upto 30,000 rpm) in hazardous atmospheres.
- Four-quadrant operation is possible with appropriate drive circuitry.

## 4.2 Disadvantage of Switched Reluctance Motor

- Noisy in the operation
- This type of motor not well-suited for smooth torque production.
- Flux linkage and Non-linear function of stator currents as well as rotor position control of the motors a tough challenge.

## 4.3 Applications

- Washing Machines, Weaving Machinery.
- Centrifugal Pumps, Compressors, Door Openers
- Analog Electronic Meters.
- Control Rod Drive Mechanisms of Nuclear Reactors.
- Microcontroller Based Operation Control Circuits.

# CONCLUSION

Reluctance Motors double salient structure makes its magnetic characteristics highly nonlinear and the flux linkage is also a nonlinear function of stator currents as well as rotor position. All these make the control of the reluctance motors a tough challenging. But Reluctance motors can deliver very high power density at low cost, making them ideal for many applications.

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