CHAPTER – 1

INTRODUCTION
1.1 INTRODUCTION

The adjustable speed driving systems have sprouted in several large-medium scale applications like industrial, domestic, irrigation and others. Utilization of eco-friendly and green semiconductor devices has greatly matured to conserve and squander energy of several devices [1]. Moreover, major issues are experienced in recent motors for adjustable speed functioning over decades of continuously developing technologies in micro-processing devices, power electronic components and control objectives. The non-permanent magnetic machines have been combined to accredit the reliable operation with low cost solution for an extensive range of applications.

Irrigation and domestic applications are believed to be the fastest growing end-product market for electric motor driven objectives in the coming decades. The vital applications are the air conditioners, washer’s room, irrigation applications, water pumping systems, freezers and others. Irrigation and domestic applications have to rely on classic historic electric motor drive technologies such as AC induction motors, DC motors and Universal motor. These motor drives are distinctly operated at constant-speed range directly from AC main source. Users may demand for very low energy cost, good performance, minimum acoustic noise and more comfort features. These formal implementations never provide the optimal solutions.

The contemporary vast proliferation of electric motor drives in domestic-irrigation applications, with advanced schemes, has conferred the very high demand for efficient adjustable speed operations. The precise demand for control of drive speed, with good transient stability, attains good efficiency and acquires the high stability factors. The drive usage has been distinct from trifle kilo watt range to high megawatt power ranges for several domestic utilities. Broad power-speed-torque
ranges are attuned to each operating mode with the working of generating/braking states [1]-[4]. The prime features of electric drive scheme are: good efficiency, definite speed range despite load changes, low maintenance and superb tracking.

**Fig. 1.1 Block Diagram of Electric Drive System**

The vital electric drive components are power sources, power electronic converter and effective control scheme for gate drive assembly and electric motor. The block diagram of electric drive scheme is shown in Fig.1.1. The essential requirement of power semiconductor topologies in electric drive system may perform the following activities:

- The power flow is carried from the source to load, when the motor drive is derived to suitable torque-speed characteristics required by mechanical load.
- Restriction of source currents within the tolerance limits and regulation of high ratio of current drawn from the source may not support the voltage dips during starting/braking transient state.
- The drive performance in operating conditions like starting, motoring, braking depends on the suitable selection of converter.

- The various advantages of electric drives are specified below;
- Flexible controlled characteristics, where the steady state and transient behavior of drive can be transformed to acquire basic load requirements. The
required speed can be attained within the regulated values of speed through very simple electric braking.

- Availability of broad torque-speed-power ranges with low no-load loss and maintaining incredible efficiency.
- Having short period of overload capability with more life at low noise, requirement of low maintenance and neat performance.
- They are adoptable at any operating conditions like explosive devices, radio-active elements and applications submersible with liquids.
- No pollution with no effect an environment.

1.2 SEGMENTS OF ELECTRIC DRIVES

Electrical motor drive comprises of eminent sources, power semiconductor devices, effective control objectives and motor based on definite load requirements. The basic discussions on these segments are explored with respect to irrigation and domestic applications.

1.2.1 SELECTION OF ELECTRIC MOTOR DRIVE

The selection of electric motor drive mostly depends on the type of application, in that, DC series, DC shunt motors play a vital role in many industrial and domestic applications but have more maintenance and high inertia problems [5]. Squirrel cage and wound rotor induction motor drives also are used in many irrigation and domestic applications but have cogging effects. That is why; the author selects the special motors which have favorable advantages that depend on type of machine like stepper motor, switched reluctance motor, brush-less DC motor drive and permanent magnet synchronous motor, which plays a vital role in domestic, irrigation, industrial and automotive applications.
In the past, induction and synchronous motor drives were deployed mostly for constant speed applications. Variable speed drives are expensive and give less efficient performance. Consequently AC and DC motors play a dominant role in adjustable speed applications by employing the power semiconductor devices [6]. Several advantages of AC motor drives replaced the DC motor drives in an adjustable speed drive applications. Out of the AC and DC motor drives, the special motor drives play a key role in several applications, in that, switched reluctance motor and stepper motor drives have become very popular for adjustable speed control and position control applications.

1.2.2 POWER CONVERTER TOPOLOGY

General utilization of AC/DC motors requires AC-DC/DC-AC converters, but here the author selects a special motor drive. The main focus of several innovations on special motor drive is on different converter topologies and cost. So many converter topologies have emerged with quick commutated time during continuous action, fewer switches, low cost and greater efficiency [7]. The optimum selection of high grade converter for a specific application is very crucial concept for medium/high speed range motor drives. But, here the author prefers PV source based converter fed SRM drive for irrigation and domestic applications.

1.2.3 SUPPLY SYSTEM

The low capacity motor drive systems are integrated via single phase supply system and high capacity motor drive systems are integrated via poly phase supply system; exclusively for traction applications. In some applications, a low capacity DC source is taken from the renewable energy systems like PV powered drive system through power conditioning apparatus for water pumping irrigation applications.
Moreover, the selection of supply system should be done by the type of the motor and the application.

1.2.4 CONTROL STRATEGIES

The main intention of these strategies by providing different control objectives based on the nature of control units, drive position, will be decided by the specific drive and type of sources. The control scheme mostly employs the gate pulse firing units, which comprise of micro-processors, digital and linear integrated circuits and transistors [8]. Requirement of switching states is done to attain any one of the following operations:

(a) Drift the quadrant operations performed by Inter-changing the motor connections.

(b) Changing the power circuit parameters in discrete steps for quick start and stop in all the four quadrant operations.

(c) The solid state relays are preferred when control objective is more complex.

1.3 GRADING OF ELECTRICAL MACHINES

The categorization of electric machines can be done based on the generation of torque, controllability and weight ratio. With this background the machines can be classified into two: 1. Electro-magnetic Machines 2. Switched Reluctance Machines. In the electromagnetic machines, the torque is generated by the interaction of stator and rotor magnetic fields. These fields are coupled mutually for generating electromagnetic torque and make proper alignment of fields. The same principle that opposite magnetic poles attract and like poles repel can explain the electromagnetic torque generation. [9]. In commercial application, many of the machines are operated based on this principle. This type of motors are induction as well as DC motors and
more distributed based on the production of magnetic fields and geometric constructions.

Adjusted speed drives are used in several applications like agriculture water pumping. They invoke the high performance of control objective of the machine to attain the perfect industrial requirement by using high capacity power electronic apparatus. Earlier, DC machines were preferred, they offer advantages in several industrial sector. But they have several demerits, such as high running cost, high inertia rate, wear and tear of brushes and commutation problems, less efficient performance. To get over these problems classic squirrel cage type induction motors are used for irrigation applications in many fields. So, it is used but the major problem is it may require high range of inverter structure and effective control objective, and may lead to cogging effects.

Coming to second class of machines, the torque is produced by the variation of reluctance in air gap between the rotor and stator poles, these rotor poles are energized by reluctance torque. The principle is to rotate into low reluctance position. When the metal/magnet comes into direct contact, the reluctance gets minimized. This chapter presents the basic introduction to variable reluctance motor, their principle of operation, torque production, speed-torque characteristics and disadvantages.

The Switched Reluctance Motor (SRM), drive is an adjustable speed motor drive with specific characteristics. In this drive both the rotor and stator slots have the poles of saliency and consist of stackable iron laminations without windings on rotor. This motor is treated as a doubly salient type machine. The windings are connected diametrically opposite to form as a phase [1]-[10]. An effective power semi-conductor device is required to energize the suitable phase with respect to the rotor position. The
phase excitation may create the magnetic field path that may attract the closest rotor pole to the excited stator pole, in an effort to reduce the reluctance of the magnetic field path. Excitation is applied sequentially with phase windings to provoke the continuous rotation.

The SRM construction is very simple but the design parameters are difficult to obtain. The inductance of the stator windings is a function of both current and rotor position, hence makes the machine a non-linear one.

The outstanding features of SRM are;

- Rugged and Simple Construction
- Fault Tolerance
- Low Initial Cost
- Huge power-to-weight ratio.

The outstanding features of SRM drive makes an alternative for the existing DC/AC motors for variable speed drives, with outstanding features. But it has a few disadvantages:

- It may demand the virtual power controller for successful operation.
- Generation of high torque ripples in comparison to classical motor drives.
- Need for high switching voltage at windings, the power factor of the drive is very low and presence of uneven harmonic components at input currents are also very high.
- Acoustic noise and vibration

Several SRM geometric designs can be obtained by varying number of poles on stator and rotor as depicted in Fig1.2. When a stator pole pair is to be energized, the most adjacent rotor pole pair is attracted by reducing the reluctance of magnetic
path. Therefore by energizing the stator side pole pairs in a successive manner, the torque is developed.

Switched Reluctance (SRM) drives can eliminate the permanent magnets and brushes. The stator side comprising of steel laminations with salient poles, and rotor too is formed as salient nature. Due to its simplicity, the proposed SRM offers the reliable operation. In near feature it will replace many other drives.

\[\text{Fig. 1.2 SRM Geometries by Stator-Rotor Poles}\]
1.4 MAIN PRINCIPLE OF OPERATION

The Switched Reluctance drive consists of field coils on stator poles and no windings on rotor poles. The rotor is constructed of soft magnetic material, when supply is given, the stator gets excited. The sectional representation of SRM is shown in Fig.1.3. In novel motor drives, a high power range unique switched electronic system is needed. It offers better control and power shaping. Energizing more than one stator poles may affect the rotor to move in forward path to a reduced reluctance state. The rotor regulates the magnetic circuit with respect to energized stator pole paths. The reluctance and resistance are major equivalents in magnetic and electric circuit systems, when the rotor aligns with the stator poles the reluctance is at its minimum.

![Fig. 1.3 Sectional Representation of SRM](image)

![Fig. 1.4 Inductance vs. Rotor Position](image)
Energized stator winding inductance may change as per the rotor position; with maximum air-gap leading to low inductance. Stator pole is aligned when the air-gap is to be low, giving high inductance. The proposed SRM drive is also named as variable reluctance drive by several researchers. The variation of inductance with rotor position is shown in Fig.1.4.

1.4.1 THE SIMPLE SWITCHING SEQUENCE METHODOLOGY

Fig. 1.5 Simple Switching Sequence Methodology of SRM Drive

At a given moment a pair of poles on the stator is excited by a phase with opposite polarities; say A, A' - B, B'; C, C'. In Fig. 1.5, if the A- and A poles are energized then the rotor will align with respect to these poles. Once this occurs then the B- and B are energized and A- and A are de-energized. Then the rotor will be aligned to B- and B poles, the switching continues to C- and C poles before arriving back to starting condition. The sequence can also be reversed to rotate the motor in reverse direction. The motoring operation sequence can be proved to be unstable as depicted in Fig.1.5.

1.4.2 ENHANCED SWITCHING SEQUENCE

For acquiring a better stable system, the following, “quadrature” sequence is used as shown in Fig.1.6. The stator poles A- and A then poles B- and B are
energized, at first when the rotor poles are in between A and B, then de-energizing the A-stator pole. The rotor tries to move and align with the pole of B, BC, C and CA, before a full motion is attained. This enhanced sequence can be taken to rotate the motor in reverse direction.

Fig. 1.6 Enhanced Switching Sequence of SRM

The generation of torque by the rotor pole has the tendency to reduce the reluctance, when the current is directed through the stator pole pairs. The torque generation is independent of current direction of stator pole paths. The torque is a function of rotor position. Torque can be continuously generated by synchronizing intelligent excitation of every phase with respect to rotor position.

1.5 SPEED - TORQUE CHARACTERISTICS OF SRM

Several control objectives of motor drive systems are mostly dependent on the motor speed-torque characteristics. The proposed SRM drive speed-torque characteristics are depicted in Fig.1.7. When the rotor rotates in magnetized direction, the torque is motoring torque. The instantaneous torque developed obviously depends on the instantaneous rotor position and phase current. Fig.1.7 represents the Torque-Speed characteristics of SRM drive, where different regions are evaluated with
respect to rotor position such as constant torque region, constant power region and falling power region.

![Torque-Speed Characteristics of SRM Drive](image)

**Fig. 1.7 Torque-Speed Characteristics of SRM Drive**

1.5.1 **REGION 1- CONSTANT TORQUE-REGION**

The torque-current is always kept constant, when switching states are given constant, at low speeds the current immediately raises due to very low back EMF. Advancement of phase turn ON/OFF is highly necessary for medium speed applications; it is required to minimize the current to nearly zero before flowing via alignment because of non-presentation of breaking torque.

1.5.2 **REGION-2 CONSTANT POWER-REGION**

The current over-lap starts when the back EMF is forced to reduce and no more possibility of chopping control. Conducting angle and speed are proportional to each other; to regulate maximum current, high torque is to be injected. Windage and core losses should be minimized rapidly up to 3 times of those at base speed and maintain the constant power region as depicted in above Fig. 1.7.

1.5.3 **REGION-3 FALLING POWER REGION**
The falling power region or natural falling characteristics is to be maintained when the rotor pole pitch is half and equals to the conduction angle. The conduction angle should be fixed, but forwarded in the direction of switching states. The torque falls inversely as square of the speed. The Co-Energy trajectory is followed with energy conversion mechanism as depicted in Fig.1.8.

![Co-Energy Trajectory](image)

**Fig. 1.8 Co-Energy Trajectory**

The supply energy (W\textsubscript{ret}) is converted in to mechanical energy (W\textsubscript{con}) based on the co-energy trajectory. The feature of SRM drive with better magnetic design is to reduce the energy returning by advanced phase energization control.

### 1.6 PROPOSED SRM DRIVE SCHEME

The proposed Switched Reluctance motor drive is excited by an imperative sequence of DC active pulses provided to every phase and then the rotor is forced to rotate. At the specific position of rotor side, current pulses are acquired and applied with respect to a phase. That’s why specific position of rotor is required; this can be attained by rotor position sensor. The controller transfers the information with respect to desired speed and suitable ON/OFF of the respective power semi-conductor elements by the switching circuit, then the desired phase winding is integrated to DC.
supply. The current signal is again fed back to controller to restrain the motor currents within the tolerance limits.

![Block Diagram of Proposed SRM Drive System](image)

**Fig. 1.9 Block Diagram of Proposed SRM Drive System**

### 1.7 EQUIVALENT CIRCUIT OF PROPOSED SRM DRIVE

The equivalent circuit of proposed Switched Reluctance motor drive is depicted in Fig. 1.10, with \( L \) inductance and \( R_s \) resistance with initial conditions. There are no limitations of mutual coupling between the magnetic saturation, leakage flux, fringing flux, phase current. The analytical representation of SRM drive can be followed in three ways:

- Motion Equation
- Electromagnetic Torque Equation
- Voltage Equation

![Equivalent Circuit of a Proposed SRM Drive](image)

**Fig. 1.10 Equivalent Circuit of a Proposed SRM Drive (per phase model)**
1.8 DYNAMIC MATHEMATICAL MODEL OF PROPOSED SRM DRIVE

SRM drive comprises of stator-rotor salient poles, only stator supports the coils.

The Frame of the phases getting directly by interfacing diametrically by opposite pole pairs, as rotor rotates provided by excitation through sequentially switching. The reluctance torque in SRM drive is produced by reluctance of the magnetic field path and with help of rotor position. Stator and rotor poles try to align due to generation of reluctance torque by energizing a phase of SRM drive [11]. The dynamic mathematical model of proposed SRM drive comprises of many electrical equations for each phase, as follows;

The voltage equation is

\[ V = R_s i + \frac{d\lambda(\theta, i)}{dt} \]  \hspace{1cm} (1.1)

Where the, \( R_s \) and \( \lambda \) are values of per phase resistance and flux linkages respectively.

\[ \lambda = L(\theta, i)i \]  \hspace{1cm} (1.2)

Where the, \( L \) is per phase value of inductance by substituting the equation (1.2) in Equation (1.1), the voltage equation to be

\[ V = R_s i + L(\theta, i) \frac{di}{dt} + \frac{dL(\theta, i)}{d\theta} i\omega_m \]  \hspace{1cm} (1.3)

Where \( \omega_m \) is angular velocity

The induced emf is

\[ e = \frac{dL(\theta, i)}{d\theta} i\omega_m = i\omega_m K_b \]  \hspace{1cm} (1.4)

Where the, \( K_b \) is emf constant

\[ K_b = \frac{dL(\theta, i)}{d\theta} \]  \hspace{1cm} (1.5)

The per phase torque is given by

\[ T_e(\theta, i) = \frac{1}{2} i^2 \frac{dL(\theta, i)}{d\theta} \]  \hspace{1cm} (1.6)
The total torque equation is

\[ T_{\text{total}}(\theta, i) = \sum_{\text{phases}} \frac{1}{2} i^2 \frac{dL(\theta, i)}{d\theta} \]  

(1.7)

By substituting in the mechanical equation, we get

\[ T_{\text{total}} - T_l = J_m \frac{d\omega_m}{dt} + B_m \omega_m \]  

(1.8)

Where

\[ J_m = \text{moment of inertia} \]

\[ T_l = \text{load torque and} \]

\[ B_m = \text{friction coefficient.} \]

The followed inferences can be arrived at from the equations (1.1) to (1.8).

1. The torque is directly proportional to the square of current, and then the torque is uni-directional, and requires low number of switches.

2. The inductance of stator winding is non-linear; hence representation of this by a simple mathematical equivalent circuit is not possible.

3. The torque is directly proportional to the square of current, due to which the machine attains a good starting torque.

4. The positive slope region gives motoring operation; the negative slope region gives generating operation from the inductance vs. rotor position characteristics.

5. If the stator excitation is changed sequentially then the direction of rotation can be changed.

6. The SRM is suitable for four quadrant operation. By the selection of suitable converter, it is possible to control the speed and torque of the drive.

7. For a constant speed operation, this drive is more costly compared to other motor drive systems.
8. This motor drive system is inherently applicable to variable speed motor drives.

1.9 ADVANTAGES OF PROPOSED SRM DRIVE

The advantages of proposed SRM drive are:

1. Very Simple structure and Robust design.
2. No windings on rotor.
3. Low cost.
4. No in-rush currents while the starting torque is very high.
5. Application to very high speed ranges.
6. Independence of phases due to the electric and magnetic reliability.
7. Operated at very high temperature ranges, in the range of 700°c to 2100°c.
8. Has good efficiency.
9. Broad constant torque and power region.

1.10 DISADVANTAGES OF PROPOSED SRM DRIVE

1. Torque ripples are large.
2. Requirement of electronic commutation device.
3. Control strategy is too complex.
4. Due to non-linear characteristics, analysis is too difficult.
5. Acoustic noise.
6. Need of rotor position sensor.

1.11 APPLICATIONS OF PROPOSED SRM DRIVE

1. High/low/medium power drives applications.
2. Linear drive systems
3. High speed drives applications.
4. Emerged applications.
5. High volume applications.
6. Under/over -water applications.
7. Actuation for aircraft lifts.
9. Electric Vehicles/Hybrid Electric Vehicles

1.12 MAJOR OBJECTIVES

The major driving force for the implementation of optimal motor drive system for irrigated water pumping system and domestic applications is dictated by several economic and environmental concerns. The selection of right electric motor drive is on primary agenda to domestic and irrigation applications. Different types of electric motors such as DC motor, Induction motor, SRM Drive and permanent magnet motor drive are utilized for intended schemes. Of all these, SRM drive is widely used in many applications due to increased demand for variable speed drive system, low cost, high performance and acoustic noise performance.

The SRM drive is key attraction for intended applications due to its simple design, low cost, greater fault diagnosis and tolerance to high temperature ranges. The primary aspect of several innovations taking part on SRM drive depends on many converter strategies; cost and performance of the drive. Basic requirement of unipolar current and phase independence have been generated by a variety of many converter strategies for SRM drive. Many topologies have emerged with minimized switch count and fast commutated time with continuous process.

The selection of converter strategies for a particular application is the key concept for high speed range drive scheme. The performance, size and cost of the SRM drive are mainly dependent on the better selection of converter topology with
advanced control objectives. With this, the main intension is to develop a good converter strategy with effective speed-torque characteristics of different converter strategies and basic requirement of converters along with their advantages/dis-advantages based on intended applications, that is, water pump sets in irrigation applications and domestic air-conditioning devices.

1.13 MAIN CONTRIBUTION OF THE THESIS

This work deals with different applications and the author proposes new high grade converters for SRM drive with PI and advanced intelligent controller with respect to intended water pumping based irrigated applications and enhancement of power factor using proposed SRM drive based air-conditioning applications. The major contributions are listed in detail:

Contribution 1: Water Pumping System in Irrigation Applications

Irrigation system is a well-developed process on many farms and is practised at several levels around the world. It allows the diverse crops which in turn increase size of fields. Moreover, several irrigation schemes constitute a greater range of classical energy via the use of electric motor drive system powered by fuels. Earlier, so many farmers used diesel engines based pumps for irrigation applications; the mounted pressures of oil crisis forced to use electric drive systems. The automated solar powered irrigation systems support a sustainable solution to improve the efficiency.

In irrigation fields, use of renewable energy system is required primarily for flooding irrigated areas. The main utilization of this PV-irrigated system will be able to contribute to socio-economic development. Mainly, it is a perfect solution for energy crisis to farmers and this system preserves electric energy by minimizing the use of grid power and providing a solution to environment friendly irrigated fields. A
proper selection, operation and maintenance of Electric motors for pumps can provide trouble free service for several years.

Since different electric motors are used for water pumping applications, proposed SRM drive is quite popular in this sector. In this contribution, application of SRM Drive for agricultural fields with closed loop operation is discussed. The maximum power can be extracted by using maximum power point tracking (MPPT) algorithm. MPPT, with perturb and observe method, which obtains effective results for irrigation applications is discussed. To verify the proposed scheme, simulation studies have been carried out for agricultural and Air-Conditioning Applications using Matlab/Simulink software.

**Contribution 2: Enhancement of Power Factor for Proposed SRM Drive in Air-Conditioning Applications**

In recent days, several areas using heavy loads like air-conditioners, cause many disturbances to main source resulting in current and voltage distortions to unexpecting levels. Owing to non-controlled charging of capacitor, the motor drive in ACs draws pulsed current from AC mains. Hence, it attains several power quality (PQ) concerns at source side, which highly affect the loads near the PCC level. The major concern is the power factor.

Several power factor correction (PFC) units are being designed to regulate the quality power with respect to IEEE and IEC standards. PFC scheme is a good solution for AC-DC power conversion to minimize the harmonics in line current, to get good efficiency and to enhance the capacity of motor drive systems. Several basic types of PFC units are active and passive units. Active PFC units are mostly used over passive with effective feedback controllers in order to secure high PF.
This contribution deals with a power factor correction (PFC)-based Cuk converter-fed SRM drive which is a cost-effective solution for low-power applications. The speed of the SRM is controlled by varying the dc-bus voltage of VSI converter which uses a low frequency switching (electronic commutation of the SRM) for low switching losses. A diode bridge rectifier and subsequently a Cuk converter working in a discontinuous conduction mode (DCM) are used for control of dc-link voltage with unity power factor at ac mains. Performance of the PFC Cuk converter is evaluated under four different operating conditions of discontinuous and continuous conduction modes (CCM) and a comparison is made to select the best suited mode of operation. The performance of the proposed system is evaluated in MATLAB/Simulink software and its performance is observed over a wide range of speeds with unity power factor at ac mains.

1.14 ORGANIZATION OF THESIS REPORT

The thesis comprises of the followed eight chapters may include;

- **Chapter 1**, evaluates the basic classification of drive system and their parts, classification of electric machines, operating principle of SRM drive, torque-speed characteristics of proposed SRM drive, equivalent circuit of proposed SRM drive, dynamic mathematical model of proposed SRM drive, advantages, disadvantages, applications, major objectives, major contributions.

- **Chapter 2**, explores the Literature Survey of several objectives based on intended applications.

- **Chapter 3**, presents the design procedure of SRM based on 6/4 pole structures and magnetic circuit analysis.

- **Chapter 4**, describes the mathematical modeling of 6/4 SRM drive, matlab/simulink evaluations for 6/4 SRM drive system and simulation results.
- **Chapter 5**, describes different converter topologies and principle of operation, converter features and control strategy for SRM drive.

- **Chapter 6**, describes the enhancement of PFC by using proposed SRM drive in air-conditioning applications, working principle, proposed control objective, matlab/simulink results.

- **Chapter 7**, describes the water pumping system using proposed SRM drive in irrigation applications, working principle, proposed control objective, matlab/simulink results.

- The final conclusions of the thesis and few recommendations for future work are summarized in **Chapter 8**.