CHAPTER 4

LITERATURE REVIEW

4.1 Proposed Motor Drive for Energy efficient operation

Federal regulations (India, China, Brazil and Russia) (sanjoy Dube et al 2010) in some appliances with regard to mandates on higher efficiency of the system to start with have come into force, and it is expected that they spread to other categories of appliances too. One way efficiency can be increased by introducing variable speed operation of the motor. Variable speed operation increases the part load efficiency as well as delivers higher efficiency over the entire speed range, and hence the interest in variable speed motor drives for applications that have traditionally remained constant speed or with a few set speeds in home appliances. While a variable speed universal motor drive may become acceptable in some appliances, the industry wants to move away from brush and commutator-based machines for reasons of reliability, safety, longevity of operation, acoustic noise and overload capability for longer duration. Hence, the search for low costing and simple method of four quadrant brushless motor drive has intensified with the prospective on variable speed applications in home appliances with high efficiency.

The common features of low cost motor drives required for high volume applications are:

- High Brushless motor (can be ac or permanent magnet brushless dc or SRM).
- Speed operational capability.
- High efficiency operability over a wide speed range.
- Four quadrant operational capability.
- Minimum number of controllable switches.
- Rotor position sensor-free operation.
- Smallest foot print for controller and converter layout to reduce the volume, weight and cost of the power electronics and controller.

4.2 Machine and Power Converter

4.2.1 Machine

The machine selection was based on the factors such as

- Free of brush and commutator.
• Easier manufacturability.
• Preferably no permanent magnets on the rotor or stator to reduce manufacturing complexity.
• Operability at speeds up to 40,000rpm.
• The lowest cost and operational capability with unidirectional current.

Above these factors, the choice narrows down to switched reluctance machine. The machine is a two-phase SRM with one phase forming the main phase and the other forming the auxiliary phase. The torque is mainly extracted from the operation of the main phase. The auxiliary phase is intended for commutation of current in main phase winding system. The auxiliary winding also lends itself to sense the rotor position by monitoring its current and flux linkages or by other variables and means. The number of turns in the main and auxiliary winding need not be equal to each other and their wire sizes also may not be equal. The only requirement of the machine is that the phase windings must be spatially shifted from each other.

4.2.2 Self-Starting

The single switch converter creates a challenge in starting the SRM. As the dc link is energized, the current flow in the main winding attracts the rotor poles to alignment with main stator poles. At this position, there is no torque production capability for the main winding even if the current is built into the main phase winding. As for the auxiliary winding, it requires a current to produce a torque. This current can come from the auxiliary capacitor when the main current decays and the auxiliary capacitor has enough charge to initiate a current closing the current path through the dc link capacitor. If the auxiliary current is insufficient to produce a significant torque to move the rotor from its aligned position with the main stator poles, then other options are built in for self-starting.

In order to start reliably, a starting scheme is proposed. When the rotor poles are aligned to main stator poles, a start gate pulse signal of certain duration is applied to the controllable switch. At this time, the rotor is at standstill. This results in turn-on of the switch for a desirable duration until the current is equal to nominal or reset value and then the switch is turned off. That provides a charge to the auxiliary capacitor, and also forcing a current in the auxiliary winding. Thereby, the energy in
the main winding is transferred to the auxiliary winding or auxiliary capacitor due to the flow of current from the main winding to the auxiliary winding and to the capacitor depending upon the charge state of the capacitor. This results in the auxiliary winding producing a torque. That torque may be enough to move the rotor poles away from their aligned position with main stator poles. When the main winding current decays, the auxiliary capacitor supplies the auxiliary winding with the current resulting in some positive torque production by auxiliary phase winding.

However, the starting problem will persist if the rotor poles align with the stator main poles exactly and the starting torque produced by the auxiliary winding is insufficient to turn the rotor poles away from the aligned position with the main poles. In that case, multiple turn-on and turn-off of the controllable switch builds a large current in the main winding and also the auxiliary winding resulting in starting of the machine. The number of multiple turn-on and turn-off signals are determined by many factors including that of the thermal capability of the machine as well as by the way the two machine phases are arranged spatially with respect to each other or how the rotor is constructed so that there is an overlap of torque characteristics of phase windings over the rotor position. It is critical to ensure that the desired direction of rotation is enforced quickly when single-pulse or multiple-pulse starting is applied, so that the rotor does not traverse noticeably over a significant angular distance in the unintended direction.

4.3 Four Quadrant Control and Operation of SRM Drive

A large literature exists on four quadrant control of conventional SRM drives with high degree of freedom in the machine converter and none exists for SRM drives with single controllable switch power converter. This is due to the absence of the converter itself, because of the peculiarities of the operational modes of this converter such as limited direct current control of main phase and its heavy dependence on the auxiliary phase winding and auxiliary capacitor state. Likewise, the auxiliary winding current control is dependent on the duty cycle of the controllable switch, motor speed and load and state of auxiliary capacitor state. These constraints have to be managed very tightly in order to implement a four quadrant variable speed operation in this motor drive.
4.3.1 Clockwise Motoring (CW) and Regeneration

In order to achieve motoring in the forward direction, say, clockwise direction, the stator winding should be excited when the motor is moving from unaligned to the aligned position. Assuming that the rotor poles reach unaligned position of the main phase winding and such a position is detected, the main winding is energized. When the rotor poles have reached near the aligned position with the main poles, the current in the main phase is turned off. The machine spins in the clockwise direction and during this time, the main winding is energized as the rotor poles move from the auxiliary stator poles to main stator poles. The regenerative braking, on the contrary, is achieved by excitation of the stator windings when the rotor moves from the aligned position towards the unaligned position. During this time, the kinetic energy in the machine is transferred to the dc link source via the auxiliary winding. The machine is still in the CW direction of rotation but its speed rapidly decreases towards standstill.

4.3.2 Counter Clockwise (CCW) Direction Motoring and Regeneration

When the speed reversal command is obtained, the control goes into the CW regeneration mode as explained above. That brings the rotor to a standstill position. Instead of waiting for the absolute standstill position, continuous energisation of the main phase is attempted during the time rotor poles move from aligned to unaligned rotor positions. This not only slows the rotor to standstill rapidly but also provides an opportunity for reversal if the rotor poles come to a stop between the main auxiliary poles. Therefore, there is the necessity for determining the instant when the rotor of the machine is ideally positioned for reversal. Hall Effect sensors are used to ascertain the rotor position and speed and they are located at the main and auxiliary winding. From the sensor output, it is determined whether the machine has reversed its direction. Crucial to this is finding the aligned rotor position of the rotor poles with the auxiliary poles. This is the ideal moment for energizing the main stator phase so that the machine can start motoring in the CCW direction.

4.3.3 Delay time

After sensing the unaligned position, PWM signal is cleared and a reversal start pulse can be implemented. Sufficient time for the reversal start pulse, which may be named delay time, is required due to the fact that the rotor does not
move from its aligned position with the stator main poles as it does not produce any
torque at this position. Best position to insert the start pulse for reverse rotation is
when the rotor poles are in between the main stator poles and the auxiliary stator
poles. The way to get the rotor into such a position is achieved by the following
procedure.

The start pulse for reverse rotation consists of one turn-on switch signal and
one turn-off switch signal. When turn-on signal is given to the controllable switch,
current flows into the main winding. During turn-off of the controllable switch,
current in the main winding flows into the auxiliary winding after charging the
capacitor to a value equal to dc link voltage. When the controllable switch is again
turned on, the current in the auxiliary winding goes to the dc link source resulting in
its prolongation. With the increase of auxiliary current by this process of charm im and
discharging from the main winding, the rotor starts moving from its aligned position.
The energy in the capacitor will increase the current through the auxiliary windings,
thus producing the torque moving the rotor poles toward the stator auxiliary pole pair
and eventually aligning the rotor with the auxiliary poles and enabling the rotation in CCW direction of rotation.

4.4 Sensorless Operation of the Switched Reluctance Machine

The Switched Reluctance Machine (SRM) is an attractive choice for many
industrial applications due to the simplicity of its design and robustness. One of the
main disadvantages of the SRM is that the rotor position must be known for the
control of the machine. The position must be either measured or determined
sensorless.

If the position information is determined from sensors, absolute encoders or
Hall Effect sensors are used. The position sensor can have negative influence on the
reliability and increases the size of the system, which is the most important
disadvantage for small drives. To omit the sensor for the control, several methods for
the sensorless rotor position estimation have been proposed. A classification of
existing sensorless techniques was summarized as
1. Flux-current detection technique

2. Model-based methods such as
   a) State observer method
   b) Inductance model-based technique
   c) Neural networks
   d) Fuzzy logic
   e) Signal injection

Some methods are good for low and medium speed, and some are good for medium and high speed. To achieve operation of the SRM in the whole speed range often the combination of two methods is necessary, one for low speed and another one for high speed.

4.5 Literature Review for SRM

Different types of converters are used for energy efficient operations of SRM. Mike et al 1998 analyzed a number of power electronic converter circuits exist for switched reluctance machines. They brought together the sum total of converter topologies for switched reluctance drives. The converters are compared using straightforward total semiconductor volt-ampere (VA) per phase sum, and the relative cost of the drive system elements. For low-power drives, the dissipative converter with lower VA rating is suitable. For low speeds, the triac converter is effective. The actual cost of the converters depends on the cost of passive components and transient voltages. The number of phases used in the drive is also a significant factor.

Sayeed Mir et al 1997 has worked in the area of basic converter design with control circuit. He introduced new C-dump converter. His new topologies overcome the limitations of the conventional C-dump converter. The work consists of two parts; i) improving the converter design for reducing the overall cost of the SRM drive, ii) simulation of the experimental results in order to demonstrate the performance of converters. This type of converters has simple control requirements, and allows the motor phase current to freewheel during the chopping mode. In this investigation two
energy-efficient **C-dump converters** have been employed. The converters are able to improve the limitations of the conventional **C-dump** converter, resulting in improved performance, lower cost and simpler control. Simulation and the experimental results demonstrate the good performance of the converters. The penalty for this elimination is the additional diode voltage drop in the forward conduction path, which could become significant in some low-voltage applications.

Slobodan Vukosavid et al 1991 prepared, analyzed and compared several **inverter** power circuits that are suitable for switched reluctance motor (SRM) drives with each other. The comparison is based on the peak voltage and current ratings of the power switches and on the size and peak ratings of the dc-link components. The work described two five inverter circuits. The inverter circuit gave a detailed design procedure. Of these five, only two circuits were found suitable for industrial SRM drives supplied from 380 or 460 V ac lines. The remaining three circuits use dual-rail topology. The dual-rail inverters may find applications in **low-power** low-voltage drives but are not suitable for industrial drives. The SRM starting torque very much influences the inverter rating.

A new converter topology for switched reluctance motor drives was proposed by Krishnan 1996. The new converter has the advantage of minimum of power switching devices at same voltage rating. The converter provides the four quadrant operation with the advantageous and important control features of independent energisation and commutation of each phase winding. It has the advantages of requiring a chopper section with its attendant passive filter for reducing the dc link voltage for motor winding application.

A new and cost effective converter was proposed by Zhang et al 2011 for energy efficient operation. The converter consists of “half-bridge” IGBT modules and SCRs, for switched reluctance motor drives. This method allows the sharing of the IGBT bridge to the switched reluctance motors winding and thus significantly reduce by half of the component cost. The requirements of switched reluctance motor drives on converters and the operation of the proposed converter were analyzed. In this work new converter is compared with conventional asymmetric bridge converter. The new converter with half-bridge switch modules is more compact and has higher utilization of power switches and lower cost.
The developed converter has three conventional operating modes that are charging, freewheeling and discharging modes. Hence, the single-pulse voltage control, the hysteresis current control and the PWM voltage control are implemented in the developed converter. As a result, this study provides the valuable converter for SRM drives in industrial applications. The proposed new arrangement allows the reduction in circuit components by nearly half and mainly the main performance of the motor drive.

This research is focused on minimizing the drawbacks of using a switched reluctance motor (SRM) in applications where servo control is required. In these applications, an SRM exhibits two main disadvantages namely, producing high torque ripple and requiring a rotor position sensor for its operation. The requirement of a rotor position sensor increases the cost and complexity of the drive system. It also tends to reduce the reliability of the drive systems. Despite these disadvantages, the SRM is an attractive option in drive system because of its simple construction, low cost, ability to operate at high speeds and the requirement of a simple power electronic converter. Literature reports both the methods of sensorless rotor position operation and torque ripple minimization of SRM as a separate solution to the two problems. The challenge is to achieve these together and this is the aim of this research.

Iqbal Husain 2002 has worked in the area of Torque ripple. The torque pulsations in switched reluctance motors (SRMs) are relatively higher compared to sinusoidal machines due to the doubly salient structure of the motor. Both machine design and electronic control approaches have been used to minimize the torque ripple in SRMs. This work presents an extensive review of the origin of torque ripple and the approaches adopted over the past decade to minimize the torque ripple. A hybrid torque-ripple-minimizing controller that incorporates the attractive features of some of the techniques developed in the past decade is presented along with simulation and experimental results.

The torque ripple in an SRM is not necessarily detrimental, but depends on the application. The advent of powerful microprocessors and Digital, Signal Processing (DSP) with their prices gradually decreasing will alleviate both the cost and complexity issues. The extensive survey of the available torque-ripple-minimizing methods has shown that the ripple minimization should be handled from
both design and controls points of view. The relatively recent approaches of torque-ripple minimization attempt smooth torque over a wide speed range. Although the torque ripple will progressively increase with speed, these new approaches are highly desirable for applications where the speed range varies widely.

Another method is proposed by Sheth et al 2005 for reducing the torque ripple by changing the uniform air gap between stator and rotor pole effects of non uniform air gap produced by the relative eccentricity between the stator and rotor axes. Concentricity error in the rotor geometry on one half, and also the motor with an elliptical rotor are presented. It is observed that with the increase in relative eccentricity or positive concentricity error, the average torque increases along with an increase in the ripple content. In case of relative eccentricity, the static torque characteristics for the different phases will be different resulting in more noise and vibration of the system.

The non uniform air gap caused by the relative eccentricity between the stator and rotor axes will result in higher average torque. The rate of increase of average torque is more for relative eccentricity more than 25%. The variations in the flux densities in the stator and rotor poles, and the air gap lose its uniformity, which will cause more noise and vibration. With the increase in concentricity error in the positive direction also, the average torque and torque ripple increase.

A new closed loop system was proposed by Yong cheng et al for torque controlling. Analyzing direct instantaneous torque control method, sliding mode control (SMC) was introduced in control algorithm. Relative outgoing phase torque compensation algorithm was proposed.

Hak seung et al has worked in direct torque control method. Direct torque control (DTC) combined with sliding mode control (SMC) for a switched reluctance motor (SRM) was worked out. The conventional method to control the torque ripple utilizes torque sharing function (TSF). However the control method using TSF has the problem of unexpected torque ripple. To overcome this problem, DTC using SMC is derived. Torque ripple minimization of switched reluctance motor was achieved using direct torque control based on sliding mode. The stability of the system verified through lyapunov function.

Torque ripple minimization of switched reluctance motor drives is a major subject based on these drives’ extensive use in the industry. A nonlinear dynamic model is developed (Namazi et al 2010) and decomposed into separate slow and
fast passive subsystems that are interconnected by negative feedbacks. A high-performance passivity-based current controller is proposed for reducing torque ripple in switched reluctance motor.

Complete model of SRM possesses two-time-scale characteristics and decomposed as the feedback interconnection of the two electrical and mechanical passive linked subsystems. Hence, by using cascaded torque control structure, the proposed PBC algorithm is designed. Because of taking the machine physical structure characteristics into account, it can overcome the inherent nonlinear characteristics of the system.

Sliding mode current controller for the switched reluctance machine (SRM) is proposed by Xavier rain et al. 2010. This strategy is first analyzed theoretically, and then tested by simulation and on an experimental test bench. It is a second order sliding mode using the super twisting algorithm. It has good performances, high dynamics like the hysteresis controller and low current ripples with fixed switching frequency operation (PWM).

The torque pulsations in switched reluctance motors (SRMs) are relatively higher compared to sinusoidal machines due to the doubly salient structure of the motor. Research of Iqbal Husain et al is focused on minimizing the drawbacks of using a switched reluctance motor (SRM) in applications where servo control is required. In these applications, an SRM exhibits two main disadvantages namely, producing high torque ripple and a rotor position sensor for its operation. Both machine design and electronic control approaches have been used to minimize the torque ripple in SRMs. This investigation presents an extensive review of the origin of torque ripple and the approaches adopted over the past decade to minimize the torque ripple.

The relatively recent approaches of torque-ripple minimization attempt smooth torque over a wide speed range. Although the torque ripple will progressively increase with speed, these new approaches are highly desirable for applications where the speed range varies widely.

The disadvantage of the above technology is that the power rating of each component is high and it requires additional control circuit. The purpose of this work is to reduce the cost of the power drive and increase the efficiency of the system by reducing the switching losses and torque ripple.