

INVESTIGATION ON THE POWER FACTOR CORRECTION CIRCUITS FOR SWITCHED RELUCTANCE MOTOR DRIVES

**A Thesis Report Submitted in partial fulfillment of the
Requirement for the award of degree of
MASTER OF ENGINEERING**

In

**POWER SYSTEMS & ELECTRIC DRIVES
(PSED)**

Submitted by

MANOJ KUMAR

(Roll No. 800941018)

Under guidance of

Mr. SOUVIK GANGULI

Assistant professor, EIED

Thapar University, Patiala



**DEPARTMENT OF ELECTRICAL AND INSTRUMENTATION
ENGINEERING**

THAPAR UNIVERSITY, PATIALA (PUNJAB) -147004

JULY 2011

CERTIFICATE

I hereby certify that the work which is being presented in this thesis entitled, "Investigation on the Power Factor Correction Circuits for Switched Reluctance Motor Drives", in partial fulfillment of the requirements for the award of degree **Master of Engineering in Power System & Electrical Drives** submitted in **Electrical & Instrumentation Engineering Department of Thapar University, Patiala**, is an authentic record of my own work carried out under the supervision of **Mr. Souvik Ganguli (Assistant Professor)** and refers other researcher's work which are duly listed in reference section. The matter presented in this thesis has not been submitted for the award of any other degree of this or any other university.

Date: 13-07-11

Manoj Kumar
MANOJ KUMAR

Reg. No. 800941018

This is certify that the above statement made by the candidate is correct and true to the best of my knowledge

Souvik Ganguli
13-07-11
(Mr. SOUVIK GANGULI)

Assistant Professor (EIED)

Thapar University, Patiala

Countersigned by

S. Ghosh
14/7/11
(Dr. SMARAJIT GHOSH)

Professor & Head, (EIED)

Thapar University, (Patiala)

S.K. Mohapatra
(Dr. S.K. MOHAPATRA)

Dean (Academic Affairs)

Thapar University, (Patiala)

ACKNOWLEDGEMENT

I take this opportunity to express my profound sense of gratitude and respect to all those who helped me through the duration of this project work. First of all, I thank the Almighty, who gave me the opportunity and strength to carry out this work. My greatest thanks are to my parents who bestowed ability and strength in me to complete this work.

I would like to express my gratitude to Mr. Souvik Ganguli, Asstt. Prof. EIED, Thapar University, Patiala , for guidance and support throughout this project work . He has been a constant source of inspiration to me throughout the period of this work. I consider myself extremely fortunate for having the opportunity to learn and work under his supervision over the entire period.

I would also take this opportunity to express my gratitude and sincere thanks to Dr. Smarajit Ghosh, Prof. & Head, EIED, Thapar University, Patiala for his valuable support. I am also thankful to the entire faculty and staff of EIED, Thapar University, Patiala for their help, inspiration and moral support.

I thank all my classmates for their encouragement and help.

MANOJ KUMAR

(800941018)

ABSTRACT

Among the various electric drives available, switched reluctance motor (SRM) has become a popular choice for the domestic and industrial applications due to its simple and robust construction. Moreover, this motor does not have winding in the rotor; hence it is suitable for high speed applications (usually above 10000 rpm). These motor are extensively used in aerospace, automotive and other home appliances. The motor have winding in the stator which is excited from a separate source. The control of these motor drives is obtained using converter circuits that control the excitation of the phase by switching converter switches. The conventional converter circuit suffers from low power factor and high harmonic content which in turn affects the performance of the motor drive.

The aim of the work is to develop a suitable converter circuit that could give an improved power factor and low current harmonic. Various converter topologies are studied and simulation of asymmetric bridge converter was carried out using MATLAB/SIMULINK to study its performance on the various parameters of the switched reluctance motor (SRM) drive. Further the simulations of Diode Bridge Rectifier circuit (DBR) and the Switching Power Converter with Power Factor Correction (SPC-PFC) are carried out. The performance of SPC-PFC is compared with the DBR circuit and it found that the SPC-PFC circuit proves to be a superior configuration for improving the power factor and mitigating the harmonic content in these drives.

TABLE OF CONTENTS

TITLE	PAGE NO.
Certificates	I
Acknowledgement	II
Abstract	III
Table of contents	IV
List of figures	VII
Nomenclature	X
CHAPTER 1: SWITCHED RELUCTANCE MOTOR AND THEIR OPERATION	1-17
1.1 Introduction	1
1.2 Operation	3
1.3 Principle of Torque Production	4
1.4 Electrical Hardware	7
1.5 Relationship between Inductance & Rotor Position	9
1.6 SRM Configurations	11
1.6.1 Rotary SRM	11
1.6.2 Axial Field SRM	12
1.6.3 Single-Phase SRM	13
1.6.4 Linear SRMs	15
1.6.4.1 Machine Topology and Elementary Operations of LSRMS	15
1.7 Objective of the Thesis	17
1.8 Organization of Thesis	17
CHAPTER 2: LITERATURE REVIEW	18-22
2.1 Introduction	18
2.2 Literature Review	18

**CHAPTER 3: POWER FACTOR CORRECTION CIRCUITS FOR
SWITCHED RELUCTANCE MOTOR DRIVES**

23-45

3.1	Introduction	23
3.2	Modified Single-Phase Rectifier	23
3.2.1	Modes of Operation	24
3.3	Switching Power Converter with Power Factor Correction	26
3.3.1	Modes of Operation	27
3.4	Single-Ended Primary Inductance Converter (SEPIC) as Front-End Converter	30
3.4.1	Converter Topology	31
3.5	Unipolar Converter for Switched Reluctance Motor	32
3.5.1	Conventional C-dump Converter	32
3.5.2	Modified C-dump converter	33
3.5.3	Operating Stage of the Converter	34
3.6	Modified Asymmetric Bridge Converter	35
3.6.1	Asymmetric Converter for single phase SRM	36
3.6.2	Modified Bridge Converter	36
3.6.3	Operating Mode Analysis of Converter	37
3.7	Single Stage Converter	41
3.7.1	Configuration of Converter	41
3.7.2	Modes of Operation	43
3.8	Conclusion	45

CHAPTER 4: RESULTS AND DISCUSSIONS

46-56

4.1	Introduction	46
4.2	Converter Model for SRM Drives	46
4.3	Switching Power Converter with Power Factor Correction Model	53

4.4	Conclusion	56
4.5	Future scope of work	56
REFERENCES		57-60

LIST OF FIGURES

FIGURE NO.	TITLE	PAGE NO.
Figure 1.1:	SRM with 6/4 and 8/6 poles	3
Figure 1.2:	Operation of an SRM	
	(a) Phase c aligned	4
	(b) Phase a aligned	4
Figure 1.3:	Magnetic circuit in a SR machine	5
Figure 1.4:	Variation of reluctance with respect to rotor position	5
Figure 1.5:	Aligned and unaligned positions	6
Figure 1.6:	Typical configuration of power converter	7
Figure 1.7:	Current dynamics in a switching circuit	8
Figure 1.8:	Derivation of inductance vs. rotor position from rotor And stator pole arcs for an unsaturated SRM	
	(a) Basic rotor position definition in a two pole SRM.	10
	(b) Inductance profile	10
Figure 1.9:	Configuration of SRM	11
Figure 1.10:	Rotary machine SRM	12
Figure 1.11:	Axial field switched reluctance motor	12
Figure 1.12:	Single-phase SRM with permanent magnet to enable starting	14
Figure 1.13:	Single-phase machine with shifted pole pair and parking magnet	14
Figure 1.14:	Three-phase linear SRMs with longitudinal and transverse flux paths	
	(a) Three-phase longitudinal linear SRM	15
	(b) Three-phase transverse linear SRM	16
Figure 3.1:	Conventional Boost Type Converter	23
Figure 3.2:	Modified Rectifier Topology	24
Figure 3.3:	Modes of Operation of Modified Single Phase Rectifier	25
Figure 3.4:	AC/DC converter (a) DBR (b) SPC-PFC	27

Figure 3.5:	Mode 1	27
Figure 3.6:	Mode 2	28
Figure 3.7:	Mode 3	29
Figure 3.8:	Mode 4	29
Figure 3.9:	Converter Topology with SEPIC Front-End	31
Figure 3.10:	Capacitive Energy Recovery Converter (C-Dump)	32
Figure 3.11:	Modified C-Dump Converter	33
Figure 3.12:	Phase Switch State Sequence	34
Figure 3.13:	Dump Switch State Sequence	34
Figure 3.14:	Asymmetric Drive Circuit	36
Figure 3.15:	Modified Bridge Circuit	37
Figure 3.16:	Mode 1	38
Figure 3.17:	Mode 2	39
Figure 3.18:	Mode 3	40
Figure 3.19:	Mode 4	41
Figure 3.20:	(a) Asymmetric Converter without PFC	42
	(b) Single Stage Converter with PFC	42
Figure 3.21:	Mode 1	43
Figure 3.22:	Mode 2	44
Figure 3.23:	Mode 3	44
Figure 4.1:	Matlab/Simulink Model of Switched Reluctance Motor with Power Converter	47
Figure 4.2:	Output Waveforms of Switched Reluctance Motor Drive	50
Figure 4.3:	Stator Voltage Waveform of Switched Reluctance Motor Drive	50
Figure 4.4:	Flux Linkage Variation of Switched Reluctance Motor Drive	51
Figure 4.5:	Stator Current Variation of Switched Reluctance Motor Drive	51
Figure 4.6:	Electromagnetic Torque of Switched Reluctance Motor Drive	52

Figure 4.7:	Rotor Speed Profile of Switched Reluctance Motor Drive	52
Figure 4.8:	Rotor Position Variation of Switched Reluctance Motor Drive	53
Figure 4.9:	AC/DC converter (a) DBR (b) SPC-PFC	54
Figure 4.10:	Simulation Results of DBR	
	(a) Input voltage	55
	(b) Input current variation with time	55
Figure 4.11:	Simulation Results of SPC-PFC	
	(a) Input voltage	55
	(b) Input current variation with time	55

NOMENCLATURE

ABBREVIATION

MEANING

SRM	Switched Reluctance Motor
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
GTO	Gate Turn-off transistor
IGBT	Insulated Gate Bipolar Transistor
DSP	Digital Signal Processor
PWM	Pulse Width Modulation
PFC	Power Factor Correction
DCM	Discontinuous Conduction Mode
CCM	Continuous Conduction Mode
SSRM	Segmental Switched Reluctance Motor
CSRM	Conventional Switched Reluctance Motor
LSRM	Linear Switched Reluctance Motor
SR	Switched Reluctance
SRMD	Switched Reluctance Motor Drive
DBR	Diode Bridge Rectifier
SPC-PFC	Switching Power Converter with Power Factor Correction
SEPIC	Single Ended Primary Inductance Converter
PFP	Power Factor Pre regulator

SWITCHED RELUCTANCE MOTOR AND THEIR OPERATION

1.1 INTRODUCTION

In this chapter, we are going to discuss about the principle of operation of a switched reluctance motor, the principle of torque production, the basic characteristics of electrical hardware and finally the various configurations of switched reluctance motor.

The switched reluctance motor (SRM) represents one of the earliest electric machines which was introduced two centuries back in the history. It was not widely spread in industrial applications such as the induction and dc motors due to the fact that at the time when this machine was invented, there was no simultaneous progress in the field of power electronics and semiconductor switches which are necessary to drive this kind of electrical machines properly. The problems associated with the induction and dc machines together with the revolution of power electronics and semiconductors in the late sixties of the last century led to the reinvention of this motor and redirected the researchers to pay attention to its attractive features and advantages which helped in overcoming a lot of problems associated with other kinds of electrical machines such as brushes and commutators in dc machines and slip rings in wound rotor induction machines besides the speed limitation in both these motors. The simple design and robustness of the switched reluctance machine made it an attractive alternative for these kinds of electrical machines for many applications recently specially that most of its disadvantages which are mentioned in the following chapter could be eliminated or minimized by use of high speed and high power semiconductor switches such as the power thyristors, power GTOs, power transistors, power IGBTs and the power MOSFETs. The availability and the inexpensive cost of these power switches nowadays besides the presence of microprocessors and microcontrollers, PIC controllers and DSP chips makes it a strong opponent to other types of electrical machines. In industry, there is a very wide variety of design of the switched reluctance machines which are used as motors or generators, these designs vary with number of phases, number of poles for both stator and rotor, number of teeth per pole, the shape of poles or whether a permanent magnet is included or not.

These options together with the converter topology used to drive the machine led to an enormous number of designs and types of switched reluctance machine systems, which mean both the switched reluctance machine with its drive circuit, can suit varied applications with different requirements. It is well known to those who are interested in this kind of electrical machines that the drive circuit and the machine is an integrated system, one part of such a system cannot be separately designed without considering the other part. A switched reluctance machine is a rotating electric machine where both stator and rotor have salient poles. The stator winding is comprised of a set of coils, each of which is wound on one pole. Switched reluctance motors differ in the number of phases wound on the stator. Each of them has a certain number of suitable combinations of stator and rotor poles. When operated as a motor, the machine is excited by a sequence of current pulses applied to each phase. The individual phases are consequently excited, forcing the motor to rotate. The current pulses need to be applied to the respective phase at the exact rotor position relative to the excited phase. The inductance profile of switched reluctance motors is triangular shaped, with maximum inductance when it is in an aligned position and minimum inductance when unaligned. When the voltage is applied to the stator phase, the motor creates torque in the direction of increasing inductance. When the phase is energized in its minimum inductance position the rotor moves to the forthcoming position of maximum inductance. The profile of the phase current together with the magnetization characteristics defines the generated torque and thus the speed of the motor. There are several advantages of the switched reluctance machines that give it preference over other the types of electrical motors in many applications, these advantages are enumerated below as follows:

1. Simple design and robust structure.
2. Unwind rotor.
3. Low cost.
4. High starting torque without the problem of inrush currents compared with induction motor.
5. Suitable for high speed applications.
6. High reliability due to the electric and magnetic independency of the machine phases.
7. Suitable for high temperature applications compared to other machines of similar ratings.
8. Motor torque is independent of the phase current polarity.
9. Four quadrant operations.

- 10. A wide constant torque or power region in the torque speed characteristics.
- 11. High efficiency throughout every part of torque speed range [1-6].

1.2 OPERATION

The switched reluctance motor is an electric motor in which torque is produced by the tendency of its moveable part to move to a position where the inductance of the excited winding is maximized. The origin of the reluctance motor can be traced back to 1842, but the “reinvention” has been possibly due to the advent of inexpensive, high-power switching devices.

The reluctance motor is a type of synchronous machine. It has wound field coils of a dc motor for its stator windings and has no coils or magnets on its rotor. Fig.1.1 shows its typical structure of 6/4 and 8/6 poles. It can be seen that both the stator and rotor have salient poles; hence, the machine is a doubly salient machine. The rotor is aligned whenever the diametrically opposite stator poles are excited.

In the magnetic circuit, the rotating part prefers to come to the minimum reluctance position at the instance of excitation. While the two rotor poles are aligned to the two stator poles, another set of rotor poles is out of alignment with respect to a different set of stator poles. Then this set of stator poles is excited to bring the rotor poles into alignment. This elementary operation can be explained by Fig. 1.1. In the figure, consider that the rotor poles r_1 and r_1' and stator poles c and c' are aligned. A current is applied to phase “a” with the current direction as shown in Fig. 1.2a. A flux is established through stator poles a and a' and rotor poles r_2 and r_2' which tends to pull the rotor poles r_2 and r_2' toward the stator poles a and a' respectively.

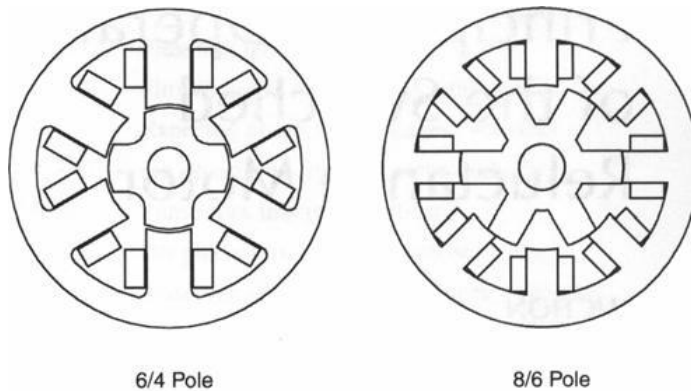


Fig. 1.1: SRM with 6/4 and 8/6 Poles

When they are aligned, the stator current of phase “a” is turned off and the corresponding situation is shown in Fig. 1.2 (b).

Now the stator winding b is excited, pulling r_1 and r_1' toward b and b' , respectively, in a clockwise direction. Likewise, energizing phase c winding results in the alignment of r_2 and r_2' with c and c' , respectively. Accordingly, by switching the stator currents in such a sequence, the rotor is rotated. Similarly, the switching of current in the sequence of acb will result in the reversal of rotor rotation. Since the movement of the rotor, hence the production of torque and power, involves a switching of currents into stator windings when there is a variation of reluctance, this variable speed motor is referred to as a switched reluctance motor (SRM) [4].

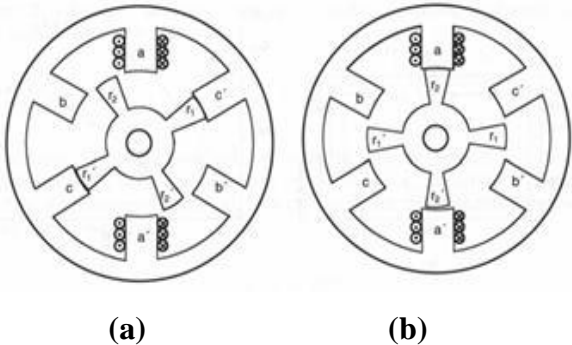


Fig. 1.2: Operation of an SRM (a) Phase c Aligned (b) Phase a Aligned

1.3 PRINCIPLE OF TORQUE PRODUCTION

Like many other electrical machines, an SR machine is an energy converter that takes electrical energy and produces mechanical energy in motoring operation, and vice versa in generating operation. The energy is stored in the magnetic field created by the phase windings and is exchanged between the electrical and the mechanical subsystems. In the following, the process of torque production in an SR machine is described [3].

When a phase is excited by applying a voltage across its concentrated coil, the current in the coil creates a magnetic flux through its stator poles. The magnetic flux flows through the pair of nearest rotor poles, travels in the rotor and stator steel, and closes a magnetic circuit, as shown in Fig. 1.3. In a magnetic circuit, there exists magnetic reluctance.

It is analogous to resistance in an electrical circuit and depends on the magnetic permeability of the material that the flux flows through. In the case of an SR machine, the

reluctance in the air gap between the stator and rotor poles is very large compared to that in steel.

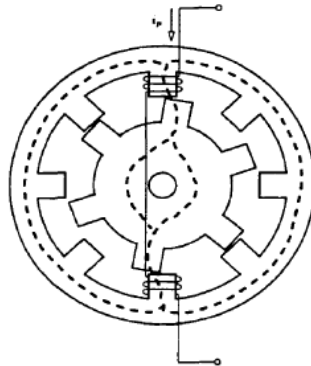


Fig. 1.3: Magnetic Circuit in a Switched Reluctance Machine

The total reluctance of the magnetic circuit can be well approximated by the reluctance of the air gap.

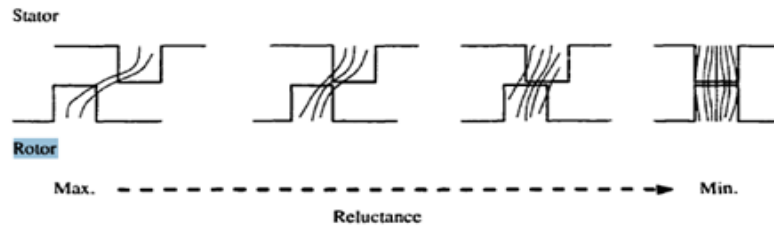


Fig. 1.4: Variation of Reluctance with Respect to Rotor Position

A phase is in the unaligned position when the inter-polar axis of the rotor Fig. 1.5 is aligned with the stator poles of the phase. The reluctance of the flux path is at its minimum in the aligned position and is at its maximum in the unaligned position. The variable reluctance principle is the tendency of the rotor to align itself to the minimum reluctance position. When a phase is excited, the pair of nearest rotor poles (part of the magnetic circuit) is attracted to align themselves to the excited stator poles. Thus, torque is produced. This principle is different from the magnetic interaction occurring in other electrical machines, such as permanent magnet motors and induction motors. The torque production in these other types of motor is based on the attraction between the North and South magnetic poles of permanent or electrically induced magnets. It is to be noted that the rotor poles of a SR machine do not require the existence of magnetic poles to produce torque.

In the aligned position shown in Fig. 1.5. There is no torque produced, even when the phase is energized, because the reluctance of the flux path is at its minimum. Hence, it is a stable equilibrium position. There is also no torque produced in the unaligned position because the stator pole is exactly in the middle of two adjacent rotor poles. However, as soon as the rotor is displaced to either side of the unaligned position, there appears a torque that displaces it even further and attracts it towards the next aligned position [3].

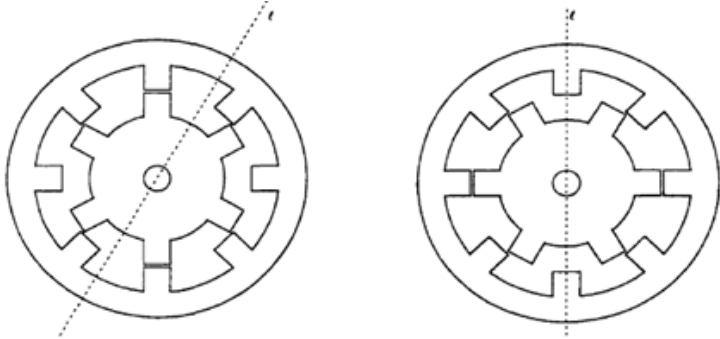


Fig. 1.5: Aligned and Unaligned Positions for Switched Reluctance Machine

Hence, the unaligned position is an unstable equilibrium position. Consequently, torque is produced in the direction from any unaligned position to the next aligned position. Since the rotor poles are identical around the rotor, the torque production is periodic.

Also torque,

$$T_e = \frac{dl(\theta,i)}{d\theta} \cdot \frac{i^2}{2} \tag{1.1}$$

The torque is proportional to the square of the current; hence the current can be unipolar so as to produce a unidirectional torque. Note that this is quite contrary to the case for ac machines. This unipolar current requirement has a distinct advantage in that only one power switch is required for control of current in a phase winding. Such a feature greatly reduces the number of power switches in the converter and thereby makes the drive economical. Since the torque is proportional to the square of the current, this machine resembles a dc series motor; hence, it has a good starting torque. The direction of rotation can be reversed by changing the sequence of stator excitation, which is a simple operation Torque and speed control is achieved with converter control. This machine requires a controllable converter for its operation and cannot be operated directly from three-phase line supply. Hence, for constant speed applications, this motor drive is expensive in comparison to induction and synchronous motors.

Due to its dependence on a power converter for its functioning, this motor drive is an inherently variable-speed motor drive system. There is very little mutual inductance between machine phase windings in SRM, and for all practical purposes it is considered to be negligible. Since mutual coupling is absent, each phase is electrically independent of other phases. This is a feature unique to this machine only. Due to this feature, note that a short-circuit fault in one phase winding has no effect on other phases. For one thing, it makes possible operation of other healthy phases of the machine and their operation will not be de-rated, as the voltage requirement is the same before and after the fault. Such independence of machine phases has tremendous consequence in aircraft actuators and generators, actuators used in defence applications, motors used in coolant pumps in nuclear power plants, traction and electric vehicles [10].

1.4 ELECTRICAL HARDWARE

SR machines utilize power converter switching circuits for the commutation and phase excitation. The most common configuration of a switching circuit is shown in Fig. 1.6. In general, a switching circuit for an SR machine is simple because of its unipolar characteristic of flux-linkage and phase current [3].

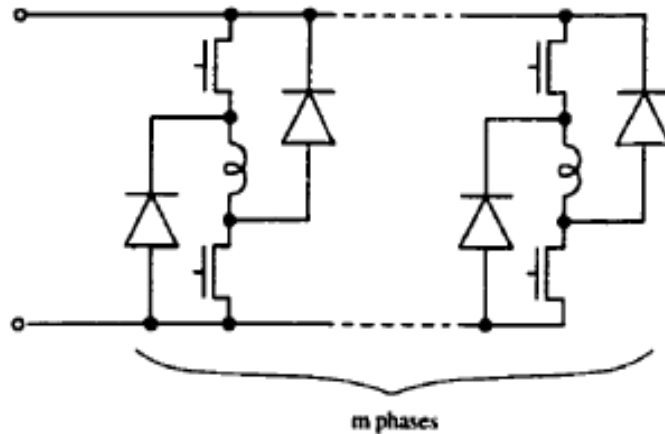


Fig. 1.6: Typical Configuration of Power Converter for Switched Reluctance Motor Drive

Since the direction of rotation does not depend on the signs of flux-linkage and phase current, a switching circuit of SR machine is designed so that the current in the excitation coil

flows only in one direction. In the following, we illustrate the main requirements that a switching circuit for an SR machine must satisfy. SR machines cannot operate directly from an AC or DC mains voltage supply because inputs to their phase windings must be current pulses. A power converter must supply unipolar current pulses from a DC voltage source, precisely at desired rotor positions. It must also regulate the magnitude and even waveform of the current in order to satisfy the requirements of torque and speed control and ensure safe operation of the motor and the power transistors. Finally, it must be able to supply pulses of reverse voltage for de-fluxing, i.e., forcing the phase current to zero in order to avoid reverse torque at certain rotor positions.

The desirable type of power converter has separate switches for each phase so that all phases are virtually independent of each other. The switching circuit considered in this research has the configuration in Fig. 1.7. The excitation coil in each phase is connected to one common DC voltage source (or a rectified AC supply) through a transistor switch on each end. The circuit has two freewheeling diodes to provide the unipolar characteristic of phase current. Fig. 1.7 shows the current flow in the switching circuit for one phase under different switching conditions.

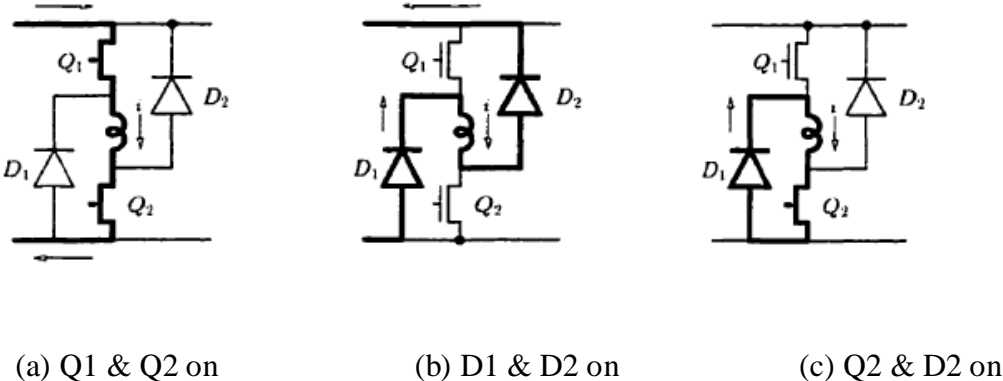


Fig. 1.7: Current Dynamics in a Switching Circuit

When both switches Q₁ and Q₂ are turned on Fig. 1.7a, a constant voltage is applied to the excitation coil, and the current starts to increase. The energy is stored in the magnetic field and converted to mechanical energy [3]. When both switches are turned off, as shown in Fig. 1.7b, the freewheeling diodes D₁ and D₂ allow the existing current in the coil to keep flowing in

the same direction. However, the reverse voltage applied to the excitation coil forces the current to decrease. The unused energy in the magnetic field is sent back to the voltage supply as seen in the direction of the current. When only one switch i.e., Q_2 is turned on Fig. 1.7c, the stored energy is dissipated by the phase resistance and the back emf developed in the coil, and thus, the phase current slowly decreases. If the initial current is zero in Fig. 1.7c, then the current will remain zero because there is no voltage applied across the coil. The switches are turned on and off to control a desired current level for each phase.

1.5 RELATIONSHIP BETWEEN INDUCTANCE AND ROTOR POSITION

The torque characteristics are dependent on the relationship between flux linkages and rotor position as a function of current [10]. The inductance corresponds to that of a stator-phase coil of the switched reluctance motor neglecting the fringe effect and saturation. From Fig. 1.9a and b, the various angles are derived as:

$$\theta_1 = \frac{1}{2} \left[\frac{2\pi}{p_r} (\beta_s + \beta_r) \right] \quad \dots 1.2$$

$$\theta_2 = \theta_1 + \beta_s \quad \dots 1.3$$

$$\theta_3 = \theta_2 + (\beta_r - \beta_s) \quad \dots 1.4$$

$$\theta_4 = (\theta_3 + \beta_s) \quad \dots 1.5$$

$$\theta_5 = (\theta_4 + \theta_1) = \frac{2\pi}{p_r} \quad \dots 1.6$$

Where β_s are β_r stator and rotor pole arcs, respectively, and P_r is the number of rotor poles. Four distinct inductance regions emerge:

- **0 – θ_1 and θ_4 - θ_5 :** The stator and rotor poles are not overlapping in this region and the flux is predominantly determined by the air path, thus making the inductance minimum and almost a constant. Hence, these regions do not contribute to torque production. The inductance in this region is known as unaligned inductance, L_u .
- **θ_1 - θ_2 :** poles overlap, so the flux path is mainly through stator and rotor laminations. This increases the inductance with rotor position, giving the positive slope. A current impressed in

the winding during this region produces a positive (i.e., motoring) torque. This region comes to an end when the overlap of poles is complete [10].

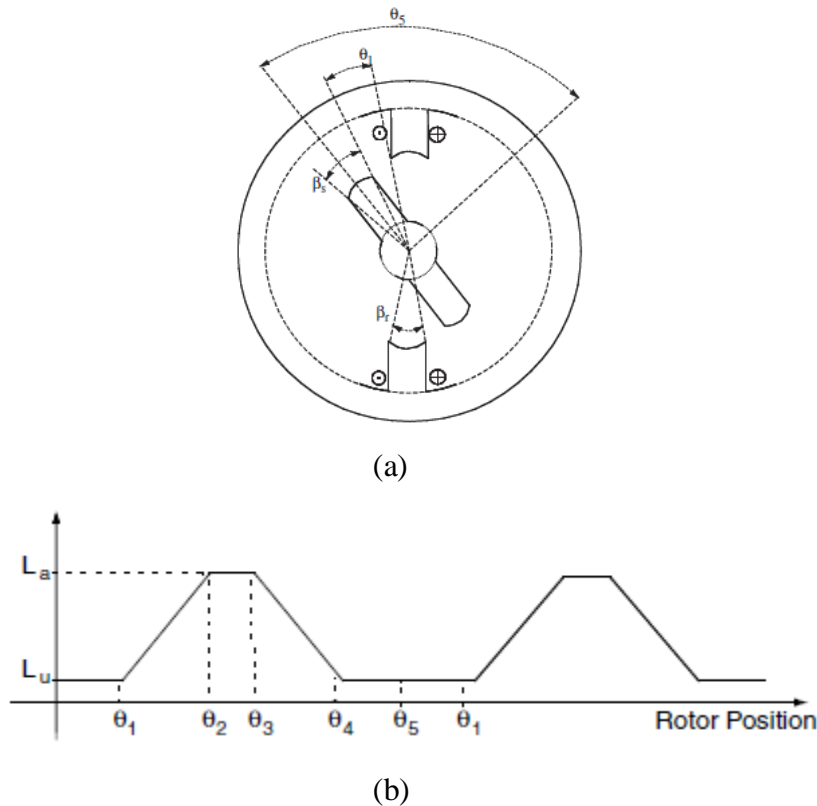


Fig. 1.8: Derivation of Inductance vs. Rotor Position from Rotor and Stator Pole Arcs for an unsaturated Switched Reluctance Machine

(a) Basic Rotor Position Definition in a Two Pole SRM. (b) Inductance Profile

- **θ_2 – θ_3 :** During this period, movement of rotor pole does not alter the complete overlap of the stator pole and does not change the dominant flux path. This has the effect of keeping the inductance maximum and constant, and this inductance is known as aligned inductance, L_a . As there is no change in the inductance in this region, torque generation is zero even when a current is present in this interval. 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 for part of the time if the current has been decaying in the negative slope region of the inductance.
- **θ_3 – θ_4 :** The rotor pole is moving away from overlapping the stator pole in this region. This is very much similar to θ_1 – θ_2 region, but it has decreasing inductance and increasing

rotor position contributing to a negative slope of the inductance region [10]. The operation of the machine in this region results in negative torque (i.e., generation of electrical energy from mechanical input to the switched reluctance machine).

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. The torque ripples are 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.

1.6 SRM CONFIGURATIONS

Switched reluctance motors can be classified as shown in Fig.1.9. The initial classification is made on the basis of the nature of the motion (i.e. rotating or linear).

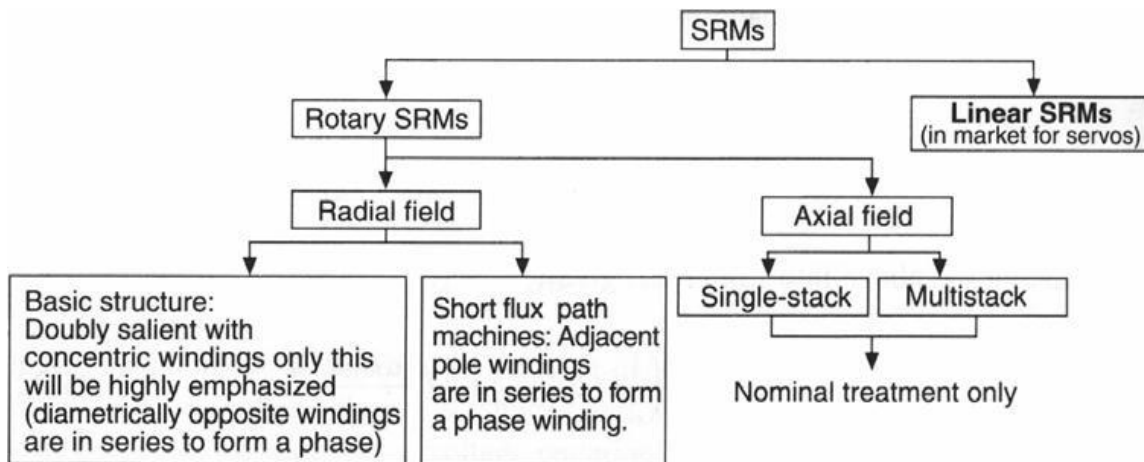


Fig. 1.9: Configuration of SRM

1.6.1 ROTARY SRM

The rotary machine-based SRMs 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 SRM is classified as radial field. When the flux path is along the axial direction, the machine is called an axial field SRM [10].

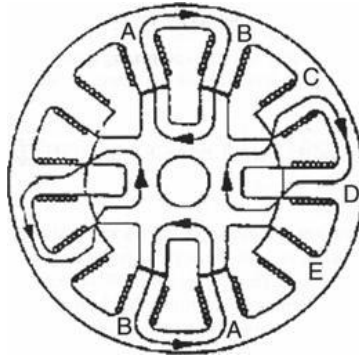


Figure 1.10: Rotary Machine SRM

Radial fields SRMs 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 SRMs, in which the phase coil is placed in the diametrically opposite slots. In the shorter flux path SRMs, the phase coil is placed in the slots adjacent to each other, as shown in Fig. 1.10. Short flux path SRMs 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.

1.6.2 AXIAL FIELD SRM

The axial configuration of a SRM is shown in Fig. 1.11. This type of SRMs is ideal for Applications where the total length may be constrained, such as in a ceiling fan or in a Propulsion application [5].

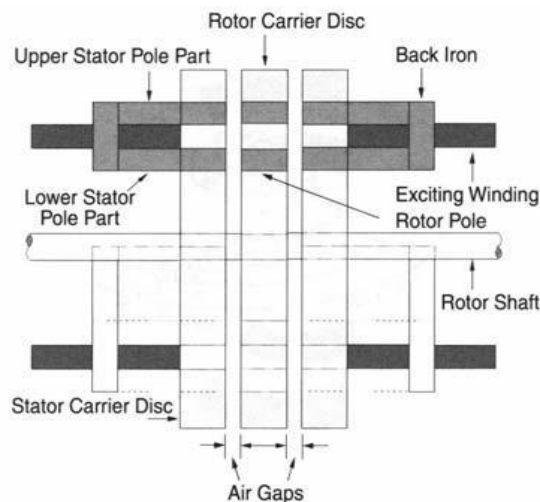


Fig. 1.11: Axial Field Switched Reluctance Motor

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. The advantage of lower core losses due to the fact that flux reversals do not occur in stator back iron in addition to having short flux paths. They have the disadvantages of having a slightly higher mutual inductance compared to conventional radial field SRMs and a possible higher uneven magnetic pull on the rotor. Conventional radial field SRMs with longer flux paths have been established for many applications due to overwhelming research and development data available on these machines. A recent variation of this type has full pitch coils [5]. A hybridized version of radial field SRMs with permanent magnets placed either in the back iron or on the stator poles, similar to pole shoes in configuration, has been studied and is known as a flux reversal machine. By bringing the permanent magnets onto the stator, the machines can have the high-speed and high-response operational advantages unique to the SRMs.

1.6.3 SINGLE-PHASE SRM

Single-phase SRMs are of interest as they bear a strong resemblance to single phase induction and universal machines and share their low-cost manufacture as well. High-speed applications are particularly appealing for single-phase SRMs. When the stator and rotor poles are aligned, the current is turned off and the rotor keeps moving due to the stored kinetic energy. As the poles become unaligned, the stator winding again is energized, producing an electromagnetic torque. A problem with single-phase SRM operation arises only when the stator and rotor poles are in alignment at standstill or the rotor is at a position where the torque produced may be lower than the load torque at starting. This can be overcome by having a permanent magnet on the stator to pull the rotor away from the alignment, or to an appropriate position, to enable the generation of maximum electromagnetic torque, as shown in Fig. 1.12. The single-phase SRMs operate with a maximum duty cycle of 0.5, and therefore, they have a torque discontinuity that results in torque ripple and noise. Applications, which are insensitive to this drawback, such as hand tools and home appliances, are ideal for this machine [6].

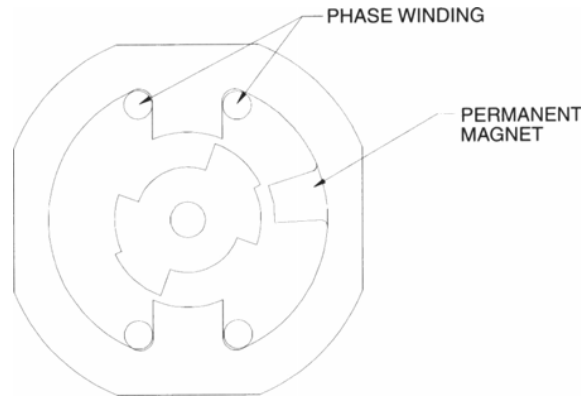


Fig. 1.12: Single-Phase SRM with Permanent Magnet to enable Starting

Starting from any rotor can also be achieved by shifting one pole from its normal position by as much as $20^\circ/P_s$, where P_s is the number of stator poles, by having two different gaps (steps) in the rotor poles for each half of the pole arc as shown in Fig. 1.13.

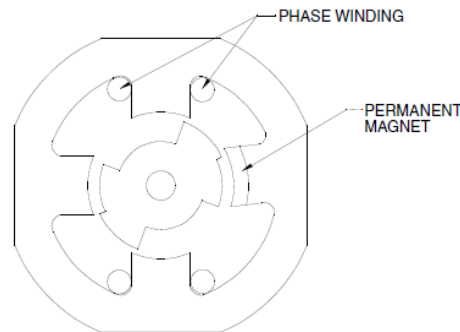


Fig. 1.13: Single-Phase Machine with Shifted Pole Pair and Parking Magnet

By shaping the stator poles with side shifts and pole horns, by shaping the stator and rotor pole, or by shaping the stator poles to provide graded air gaps. Single-phase motors have also been designed with a claw pole structure, with six poles on the stator and rotor having both radial and axial air gaps, offering higher efficiency than that of standard single-phase machines with only radial air gaps. The construction of this machine is a little more intricate than its counterpart and may not be attractive for large-scale production. All these methods provide asymmetric saturation in the stator and rotor, resulting in shifting of the flux axis and hence variation in the capability to provide electromagnetic torque at all positions [6].

1.6.4 LINEAR SRMs

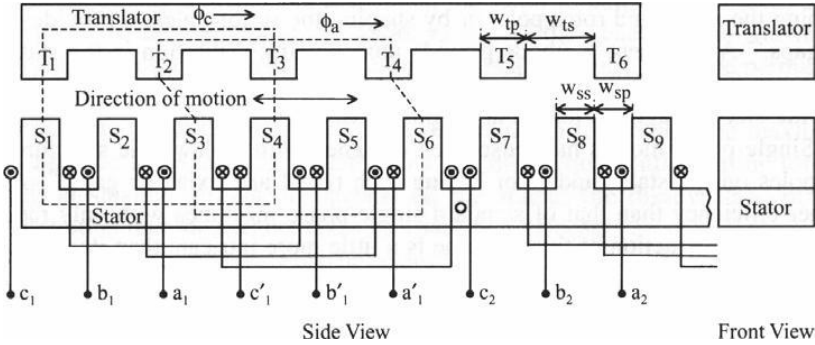
Linear motor drives are being increasingly considered for machine tool drives because they reduce the need for mechanical subsystems of gears and rotary-to-linear motion converters, such as lead screws. Positioning accuracy is improved by the absence of gears that contribute to the backlashes in the linear motor drives.

Linear machine drives combined with electromagnetic levitation are strong candidates for conveyor applications in semiconductor fabrication plants and possibly in low- and high speed transit applications because of their ability to produce propulsion force on the rotating part, known as the translator, without mechanical contact and friction.

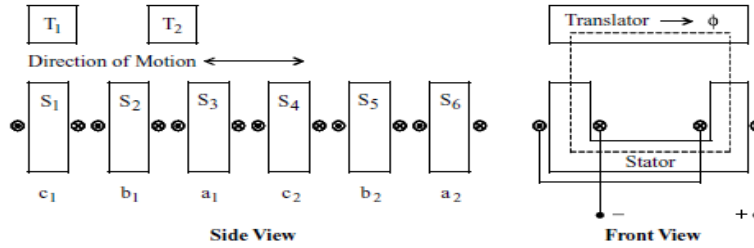
Linear switched reluctance machines (LSRMs) are the counterparts of the rotating switched reluctance machines. In fact, the linear switched reluctance machine is obtained from its rotary counterpart by cutting, along the shaft over its radius, both the stator and rotor and then rolling them out. In this section, various linear switched reluctance machine configurations are introduced. Further, the ideal inductance profile is related to the stator and translator lamination dimensions. A similar relationship for the rotary switched reluctance machine that has been derived earlier is worth noting [8].

1.6.4.1 MACHINE TOPOLOGY AND ELEMENTARY OPERATION OF LSRMs

A linear SRM may have windings either on the stator or translator (the moving part), whereas in the rotary switched reluctance machine the windings are always on the stator and the rotor contains no windings [7, 9]. Regardless of the location of phase windings, the fixed part is called either a stator or track and the moving part is called a translator.



(a)



(b)

Figure 1.14: Three-Phase Linear SRMs with Longitudinal and Transverse Flux Paths

(a) Three-Phase Longitudinal Linear SRM (b) Three-Phase Transverse Linear SRM

There are two distinct configurations of linear SRM in the literature: longitudinal flux and transverse flux. These two configurations can be obtained by unrolling both the stator and rotor of a rotary SRM with a radial magnetic flux path and axial magnetic flux path, respectively. Fig. 1.14 shows the longitudinal flux and transverse flux configurations for three-phase LSRM with an active (containing windings) stator and passive (with no windings) translator topology [9].

The longitudinal magnetic flux path configuration Fig. 1.14a is a linear counterpart of three-phase radial flux rotary SRM. The flux path in this machine is in the direction of the vehicle motion. This machine is simpler to manufacture, is mechanically robust, and has lower eddy current losses as the flux is in the same direction as the translator motion.

A transverse flux design Fig. 1.14b has the flux path perpendicular to the direction of vehicle motion. It allows a simple track consisting of individually mounted transverse bars. As the flux is perpendicular to the direction of motion, an emf is induced in the core, resulting in high eddy current losses. Longitudinal flux and transverse flux configurations for four-phase LSRM with an active translator and passive stator structure are shown in Fig. 1.15. The active stator and passive translator SRM configuration has the advantage of having the power supply and power converters being stationary, resulting in reduced weight of the vehicle.

This design, however, requires a large number of power converter sections along the track, resulting in high costs. On the other hand, a structure with an active translator and passive stator structure requires only one section of the power converter, but the power to the converter in the translator requires transfer by means of contact brushes which is not desirable for high-

speed applications or by inductive transfer with additional power-converter circuits, with consequent complexity and higher costs [8-9].

1.7 OBEJECTIVE OF THE THESIS

The aim of this thesis is to analyse the performance characteristics of the diode bridge rectifier (DBR) and switching power converter with power factor correction (SPC-PFC) in terms of harmonics, power factor and its effect on the performance of switched reluctance motor when these converters are being used with the motor drive circuit. The converter topology with SPC-PFC has been tried out to correct the input power factor of the motor which helps smooth operation, less acoustic noise, and reduced shaft vibration. The developed circuit SPC- PFC is connected with input side of SRM. The above analysis has been done in MATLAB Simulink environment, and based on the results obtained it has been concluded that the performance of SPC-PFC converter is superior to that of the conventional DBR.

1.8 ORGANIZATION OF THESIS

The thesis is organized as follows:

Chapter 1 highlights the brief introduction, principle of operation of the switched reluctance motor and various configurations of switched reluctance motor drives.

Chapter 2 highlights the brief introduction of the work carried out by various researchers.

Chapter 3 explains the various converter topologies used for power factor correction in switched reluctance motor drives. Their modes of operation are also presented in this chapter.

Chapter 4 discusses the results and discussions pertaining to SRM drive circuit with and without power factor correction topology. The conclusions and the future scope of work are also highlighted at the end of this chapter.

LITERATURE REVIEW

2.1 INTRODUCTION

As per literature available till date various topologies have been developed for power factor correction in switched reluctance motor drives. This chapter reviews the work done by various researchers in the field of different converter topologies and drive circuits for power factor correction in these drives. The literature study mainly deals with the following converter circuits:

- Modified single phase rectifier
- Switching power converter with power factor correction (SPC-PFC)
- Single-Ended primary inductance converter (SEPIC) as front-end converter
- Modified C-dump converter
- Modified asymmetric bridge converter
- Single stage converter

2.2 LITERATURE REVIEW

In this section different research papers corresponding to power factor correction circuit for switched reluctance motor drives, converter configuration and MATLAB simulation of converter are reviewed.

Geun-Hie et al. proposed a converter topology for power factor correction in switched reluctance motor which consists of a pair of buck-boost converter and a machine converter. The boost converter gives the system deliver the sinusoidal input current and enhances the dc source voltage. Moreover, it also provides voltage regulation. The buck converter is used to regulate the dc source voltage responding to motor speed variations. The wide pre-regulations by the two power conversion stages eliminate the high voltage-chopping to control the stator winding current. The use of nonlinear amplifier in the control circuit noticeably improved input current waveform; hence, unity power factor correction was achieved [13].

P.N. Enjeti et al. proposed a high performance single phase AC to DC rectifier with input power factor correction, by only having two semiconductors in the current path at any time; losses can be reduced over the conventional boost topology. Size and cost are also reduced by using fewer components and having the input inductor on the input ac side. The proposed topology, find it suitability for low and medium power application such as in power supplies and motor drives [14].

R. Jeyabharatlil et al. proposed a sensor less circuit with single-ended primary inductance converter (SEPIC) working as a power factor pre regulator (PFP) in order to improve the power factor. It gives better current regulation and high power factor with simplified gate circuit achieved at low cost. The converter is suitable for DC and AC low power and high power applications [15].

Young Ahn Kwon et al. presented the SRM drive system with the improved power factor and reduced harmonics. The system consists of the switching power converter with power factor correction (SPC-PFC), DC/DC converter and 3-phase inverter. AC/DC boost converter with SPC-PFC is operated as commented by the algorithm of power factor correction. DC/DC converter is operated to meet dc-link voltage determined by speed command. Inverter applies the voltage to the winding of SRM in response to the position and current-chopping signals. The SPC-PFC is designed to produce the pure sinusoidal input current, improve the power factor, and reduce harmonics [16].

R. Krishnan et al. developed a power factor correction circuit which consist a large input filter so that the harmonic pollution of the utility supply and the reduction of efficiency that could have been avoided. Input power factor correction for SRM drive system has been proposed for several appliances and experimentally verified on a laboratory prototype SRM drive system. Its performance has been compared without PFC regulator and found to be inferior in efficiency by 2% consistently even though superior in input power and less third order harmonics over the entire speed range of operation [17].

D.S.L. Simonetti et al. presented SEPIC and CUK converter working as a power factor pre regulator (PFP) in discontinuous conduction mode (DCM). And analyzed the desirable characteristics of (PFP), the converter works as a voltage follower, and the theoretical power factor is obtained unity [18].

A. Consoli et al. presented an innovative converter topology based on C-dump converter

configuration that is able to act as an active power factor controller. According to the features of the proposed circuit a conventional PFC stage is unnecessary to comply with the European standards on power quality, thus reducing the cost and the complexity of switched reluctance motor drives aimed to equip home appliances [19].

L. Caruso et al. presented a low power (750W) SR motor drive for home appliances featuring close to unity power factor and low cost. The proposed drive is simple speed control, minimum number of switch used in the inverter topology, and a compact high quality rectifier (HQR) input stage based on a quasi-resonant boost topology. Finally the performance of the proposed drive is evaluated in term of line current, harmonic spectrum, efficiency and dynamic performance [20].

Tilak Gopalarathnam et al. represented a new converter topology with a single ended primary inductance converter (SEPIC) front-end proposed for SR motor. It consist one switch in series with each motor phase. All the switches are ground-referenced, which simplifies their gate drive. In low voltage DC applications, it is capable of boosting the available input dc voltage to maximize the current regulated operation of the drive. For AC supply applications, it can be designed for operating either in DCM or in CCM depending on the power level, and high power factor can be obtained. The front-end converter performs the task of power factor correction as well as phase-de fluxing, thus keeping the component count low [21].

Jurgen Reinert et al. evaluated the need for power factor correction (PFC) in switched reluctance motor drives system supplied from single phase mains. A PFC circuit has to be implemented, but simpler technical solutions are often possible. It shows that if the PFC is needed, it was shown that the simplest solution would be a step-up converter drives in continuous conduction mode. Several measures to keep the system cost as low as possible were given [22].

Feel-Soon Kang et al. presented a single phase power factor corrected converter for switched reluctance motor drive to achieve sinusoidal, near unity power factor input current. It combines a power factor corrected converter and a conventional asymmetric SRM driver into one power stage, the configuration has a simple structure resulted in low cost. A prototype to drive 6/4 pole SRM employing a parking magnet is designed to evaluate the proposed topology [23].

D.H.Lee et al. presented a drive circuit add one switch and one diode, which can

separate the output of the ac/dc rectifier from the large capacitor and supply power to the SRM alternately. This allows the drive system to realize torque ripple reduction and power factor improvement through switching scheme [24].

A. Testa et al. presented an innovative converter topology that allows to improving the power factor of switched reluctance motor drives, aimed to equip home appliances. This topology is based on a modified C- dump converter configuration, where the energy recovery stage acts as an active power factor controller for off-line operation. This is made possible by the development of a new technique to manage the freewheeling energy, this is recovered back to the DC bus by mean of a suitable high frequency transformer. The proposed converter feature only low side configuration switches [25].

K. Thiyagarajah et al. in their paper introduced a boost topology with a high frequency inverter. The circuit consists of a boost converter in the front-end, a full-bridge inverter isolated by a high frequency transformer, and a secondary rectifier circuit. The front-end boost converter corrects the power factor, and the inverter in the second stage provides high frequency ac voltage which is converted into dc output voltage. This multistage power conversion topology lowers the overall converter efficiency, and the requirement of additional hardware decreases the reliability of the converter. This topology is useful for applications requiring isolation between input and output, such as chargers for electric vehicles [26].

Masayuki Morimoto et al. proposed the non-isolated drive system employs a non-isolated boost power factor correction converter as an input to the PWM inverter. It provides input PFC and high, stable, dc bus voltage, widening the field-weakening range in drive systems. The buck-boost cascaded converter based PWM inverter. The buck front end converter limits the input current to charge up the output capacitor smoothly and corrects the input power factor. The boost stage ensures inverter operation at low input voltages by a voltage step-up operation. The overall Efficiency of the variable speed drive system with one of these multi-stage converters is relatively low compared with the single stage converter based drive system. [27].

S.H. Lee et al. presented a new single-stage power-factor-corrected converter is proposed to improve input power factor for an efficient switched reluctance motor drive. The proposed converter uses the winding of SR motor as an input inductor for power-factor-correction. The converter switches play two important roles; one is to improve the input power factor and the other is to excite the motor phase. Consequently, ac-to-dc power converter and SR motor driver are

incorporated into one power stage, the so called single-stage approach. This drive circuit has a simple structure that results in cost saving [28].

M.R. Sahid et al. presented a new bridgeless power factor correction circuit based on Single-Ended Primary Inductance Converter (SEPIC). The small-signal and steady state analysis of the proposed converter has been derived using Current Injected Equivalent Circuit Approach (CIECA) method. It is found that these models are vital in knowing the dynamic characteristics and the appropriate parameters of the proposed converter operated in DCM. The simulation results show that the proposed converter is able to work as a simple PFC circuit with the capability to regulate the output voltage over a wide range of load values and with universal input voltage conditions [29].

S. H. Lee et.al. presented a new single-stage power-factor-corrected converter to improve input power factor for an efficient switched reluctance (SR) motor drive. The proposed converter uses the winding of SR motor as an input inductor for power-factor-correction. Converter switches play two important roles; one is to improve the input power factor and the other is to excite the motor phase. Consequently, ac-to-dc power converter and SR motor drive circuits are incorporated into one power stage, so called a single-stage approach is realized. This topology is desirable for high-performance and low cost SRM drive systems [30].

M. Barnes et.al. presented the passive and active filtering of current harmonics drawn from the single-phase ac supply to achieve power factor correction in switched reluctance drives. For some power ranges, the existing power electronics in a switched reluctance motor drive converter topology can be used to provide active power factor correction, so that with suitable filtering, near sinusoidal input current is drawn, in phase with the supply voltage. The power electronics component count is kept low and the operation of phases is not completely independent. This method of improving the power factor of the drive is suitable only for limited range of output power [31].

POWER FACTOR CORRECTION CIRCUITS FOR SWITCHED RELUCTANCE MOTOR DRIVES

3.1 INTRODUCTION

Earlier the switched reluctance motor employed a simple converter circuit which proved to be disadvantageous on the performance of motor, problems like high current harmonic and low power factor were faced as the excitation for the stator phase winding produced discontinuous pulses. The topologies which are able to solve the above problem have been discussed here in detail.

In this chapter we are going to discuss the various power converter circuits in switched reluctance motor drives and the various converter topologies used for power factor correction with their modes of operations.

3.2 MODIFIED SINGLE PHASE RECTIFIER

The conventional boost type converter consists of two diodes in series in every arm, but in the modified rectifier topology one diode and one switch are connected in series in every arm, also the series diode D_5 which is used in the boost topology has been eliminated. Another notable change is that the dc-side inductor is no longer necessary and instead the inductor has been shifted to the AC side. Fig 3.1 illustrates the conventional boost type converter and Fig. 3.2 illustrates the modified ac to dc rectifier topology.

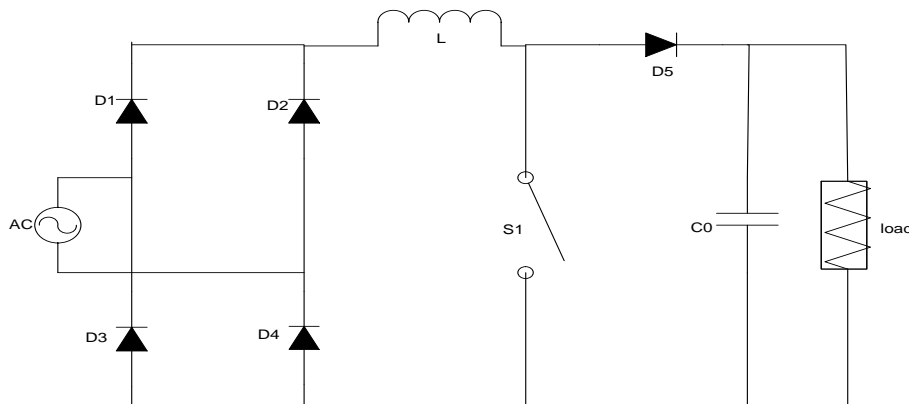


Fig. 3.1: Conventional Boost Type Converter

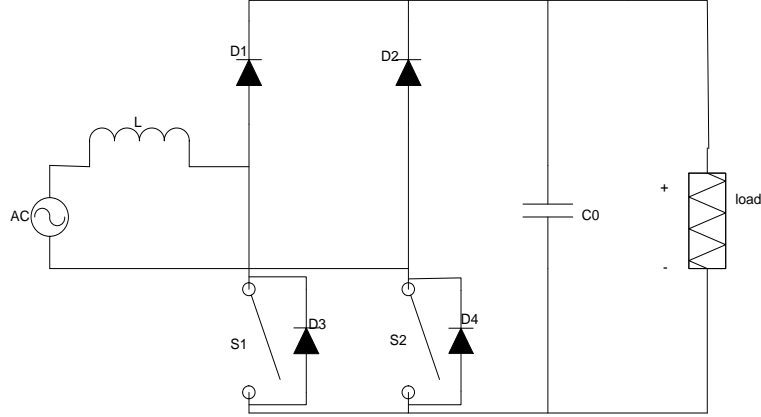


Fig. 3.2: Modified Rectifier Topology

The required advantages of the proposed approach are as follows:

1. Improved characteristics in term of high input power factor and sinusoidal shape of the input current.
2. At any given instant only two semiconductor device drops exist in the power flow path.
3. The RMS current ratings of the boost switch S_1 and S_2 are low.
4. The location of the boost inductor on the ac side contributes to reduction in electromagnetic interference.

3.2.1 MODES OF OPERATION

Fig. 3.3 illustrates the various modes of operation for the proposed approach. Mode 1 in fig 3.3a occurs when the input ac voltage is positive and the switches are open. The current flows through diode D_1 through the capacitor and the load, and back through the anti-parallel diode of S_2 . Fig. 3.3 (b) shows the operation of mode 2 which occurs when the input ac voltage is positive and the switches are closed. Input current flows through the switch S_1 and back through the anti-parallel diode of S_2 ; thus providing a path for the input current. At the same time, the bulk capacitor discharges and supplies current to the load.

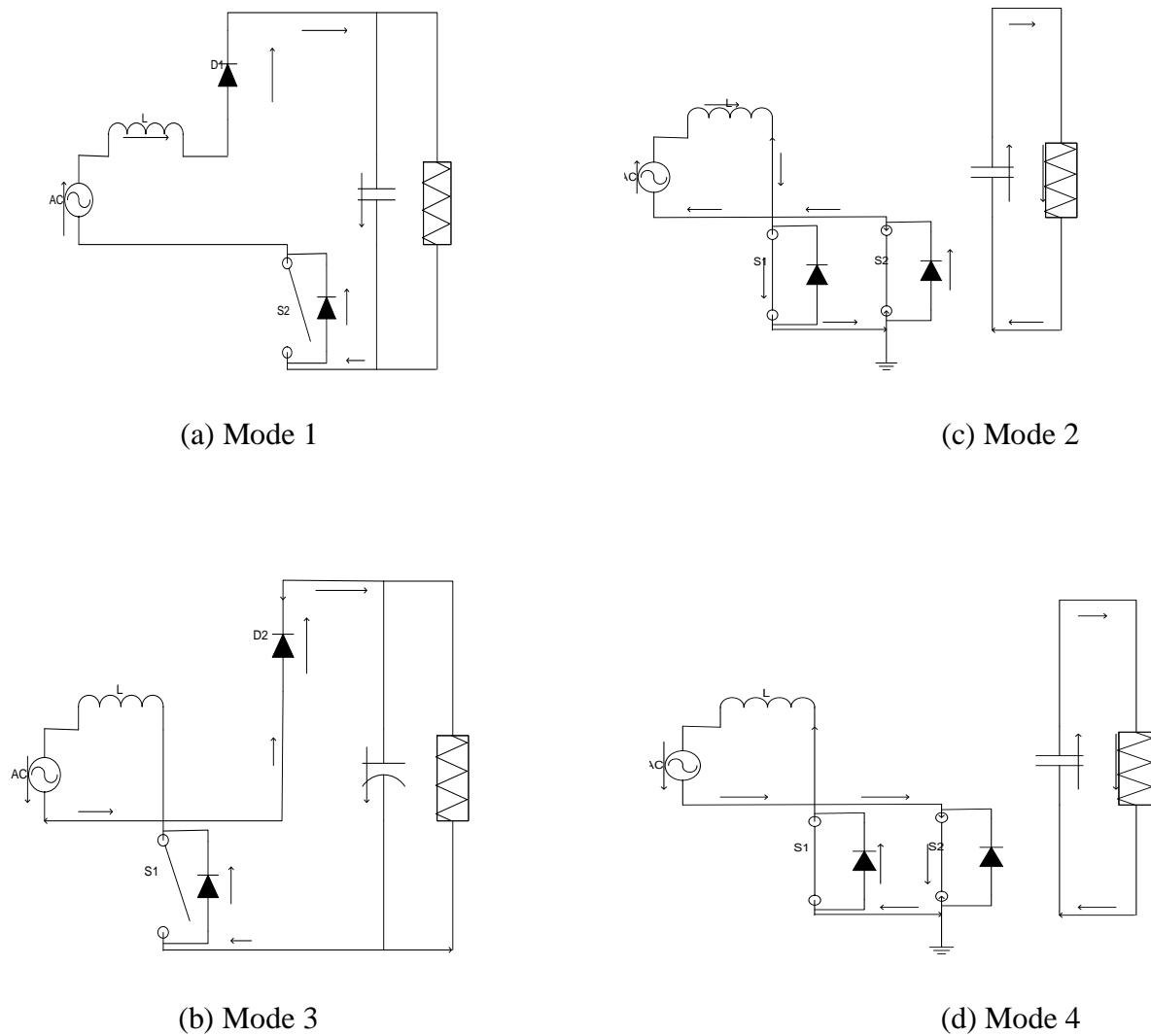
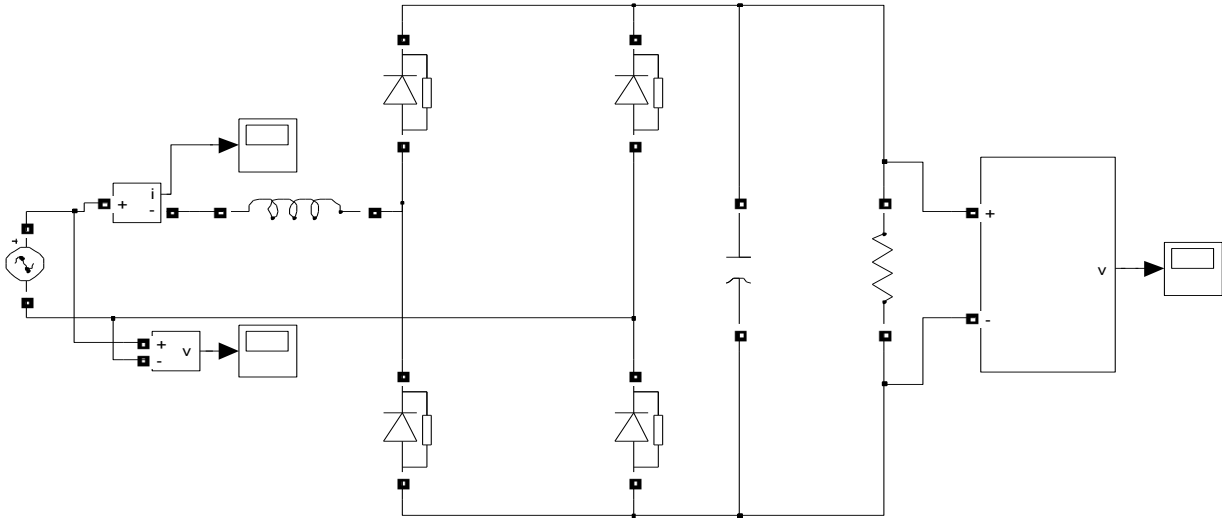


Fig. 3.3: Modes of Operation of Modified Single Phase Rectifier

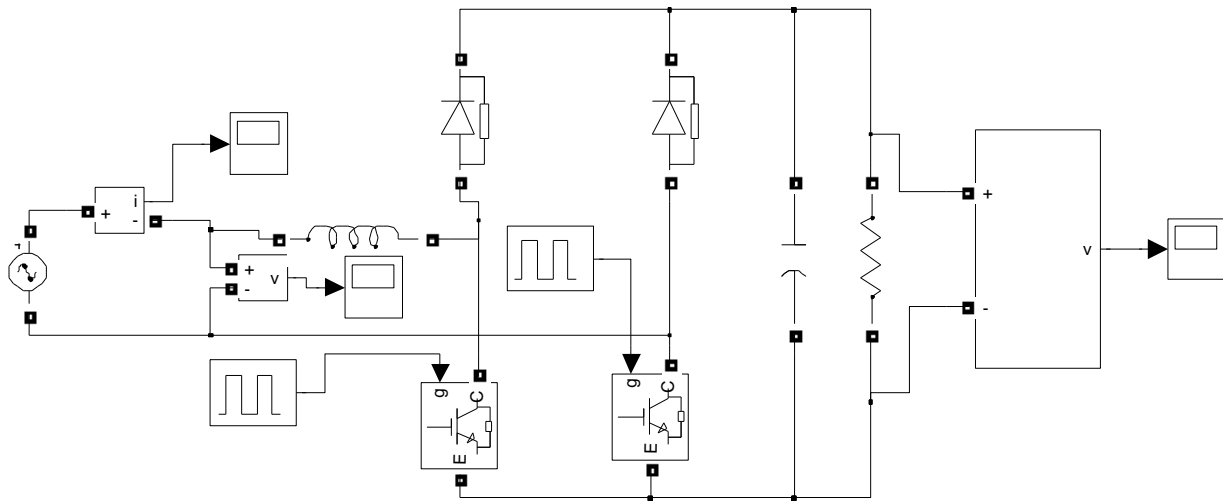
Mode 3 in Fig. 3.3 (c) occurs when the input ac voltage is negative and the switches are open. Current flows through diode D_2 , through the capacitor and load, and back through the anti-parallel diode of S_1 . Fig. 3.3 (d) shows mode 4 which occurs when the input ac voltage is negative and the switches are closed. Input current flows through the switch S_2 and back through the anti-parallel diode of S_1 ; thus providing a path for the input current. At the same time, the dc capacitor discharges and supplies current to the load [14].

3.3 SWITCHING POWER CONVERTER WITH POWER FACTOR CORRECTION (SPC-PFC)

The switching power converter with power factor correction (SPC-PFC) is designed to produce pure sinusoidal input current, which gives high power factor and reduced harmonics. The diode bridge rectifier (DBR) is extensively used for changing constant ac input voltage to controlled dc output voltage in a phase controlled rectifier, a power electronic device is turned off as ac supply voltage reverse biases and turned on as ac supply voltage is forward biased. The output voltage level of the circuit depends on the firing sequences of the power electronic device. A simple diode bridge rectifier circuit suffers from the problems viz. low power factor in the input supply side and considerable harmonic. A new convertor topology is introduced instead of simple diode bridge rectifier, known as Switching Power Converter with Power Factor Correction (SPC-PFC) which helps the improvement of power factor and reduced the harmonic content to a great extent. In SPC-PFC, a pair of diode and IGBT (insulated gate bipolar transistor) is used in every arm. The SPC-PFC is operated in four modes of operation. DBR does not meet the requirements of IEEE-519 and IEC-555 due to high harmonic and low power factor so SPC-PFC is used for reducing its harmonics and improving the power factor.



(a)



(b)

Fig. 3.4: AC/DC converter (a) DBR (b) SPC-PFC

Fig 3.4 shows the AC/DC converter (a) DBR (b) SPC-PFC. The four operation modes of SPC-PFC are discussed below.

3.3.1 MODES OF OPERATION

MODE 1:

When the input voltage is positive, S_1 is turned on and the inductor current increases through the body-diode of S_2 and the magnetic energy gets stored in the inductor. Since diode D_1 and D_2 are reverse biased, C_1 provides the power to the load.

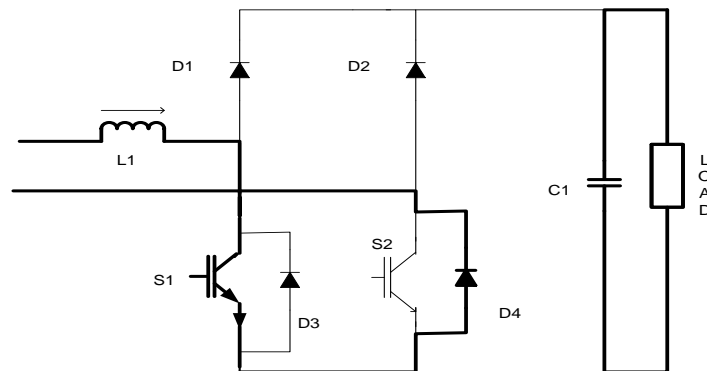


Fig. 3.5: Mode 1

Fig 3.5 shows the circuit used in case of mode 1, the dark line show the flow of current in the circuit. The voltage equation is given by.

$$v_{ac} - L_1 \frac{di_{l1}}{dt} = 0 \tag{3.1}$$

MODE 2:

In this case the diode D_1 is forward biased and provides a path to the flow of power. The power flows through D_1 to load and C_1 to body diode of S_2 . Stored energy in the inductor and the energy from the input source are transferred to C_1 and load. Then the capacitor C_1 gets charged and the power is transferred to the load.

The voltage equation in this case is given by.

$$v_{ac} - L_1 \frac{di_{l1}}{dt} - v_{dc} = 0 \tag{3.2}$$

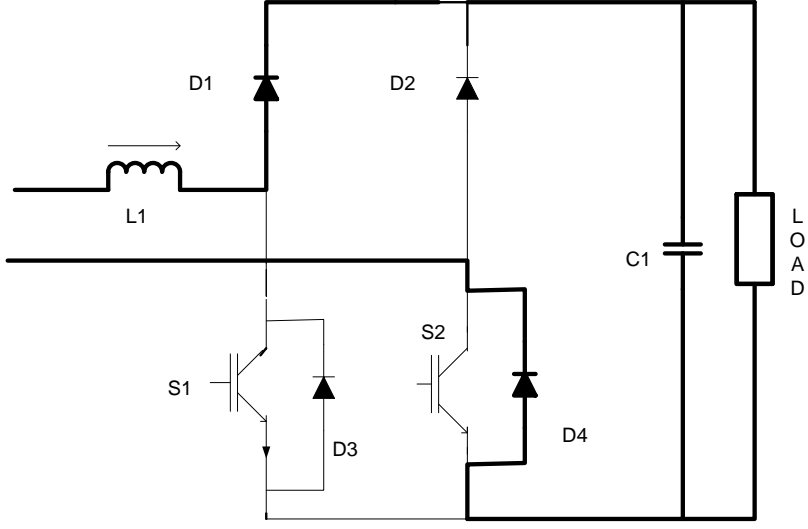


Fig. 3.6: Mode 2

Fig 3.6 shows the circuit in case of mode 2, the dark line shows the flow of current in the circuit.

MODE 3 AND 4:

Modes 3 and 4 are similar to the modes 1 and 2 respectively; excepting that the input voltage is negative. Fig 3.7 and Fig 3.8 shows the circuit diagram of mode 3 and mode 4 respectively.

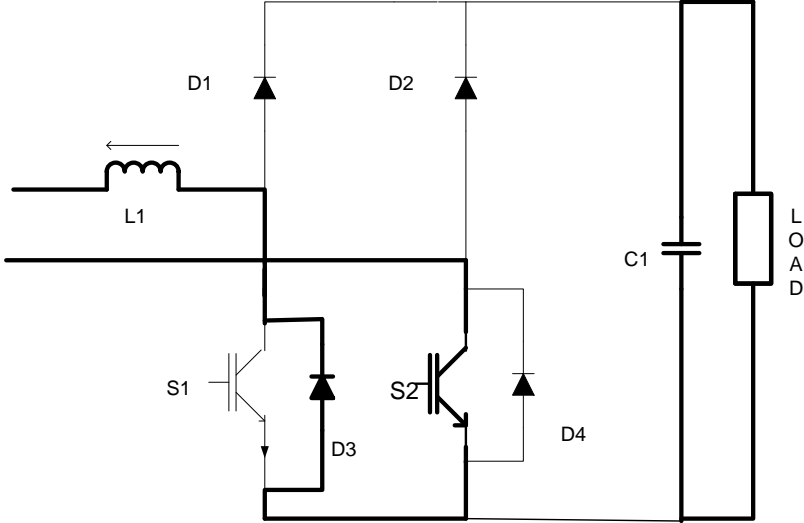


Fig. 3.7: Mode 3

In mode 3 the capacitor C_1 is supplying power to the load with negative polarity.

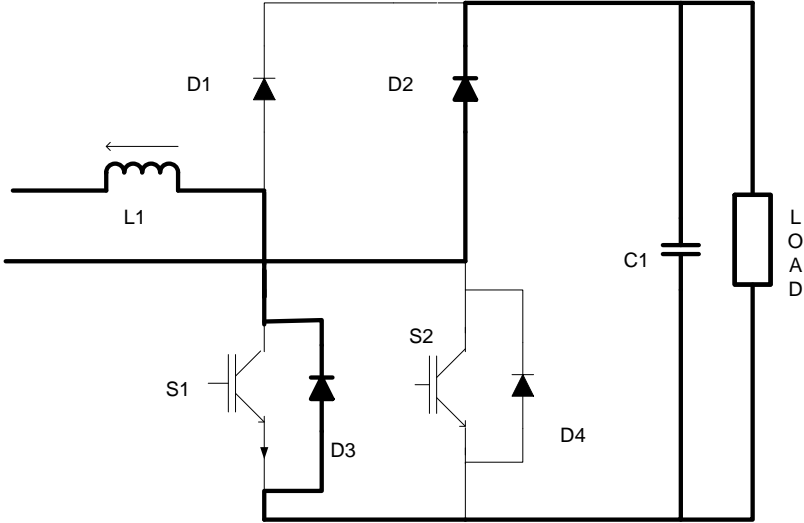


Fig. 3.8: Mode 4

In mode 4 D_2 is forward biased and power flows through the path D_2 to C_1 and load to the body diode of S_1 , then the path is complete.

The fundamental input current I_{ac1} may be written as.

$$I_{ac1} = \frac{V_{ac} - V_{c1}}{j\omega L_1} \quad \dots\dots 3.3$$

$$I_{ac1} \angle \phi = \frac{V_{ac} \angle 0^\circ - V_{c1} e^{-j\psi}}{j\omega L_1} \quad \dots\dots 3.4$$

$$I_{ac1} = \frac{\sqrt{(V_{ac} - V_{c1} \cos \psi)^2 + (V_{c1} \sin \psi)^2}}{(\omega L_1)^2} \quad \dots\dots 3.5$$

$$\phi = \tan^{-1} \frac{V_{c1} \sin \psi}{V_{ac} - V_{c1} \cos \psi} \quad \dots\dots 3.6$$

where V_{c1} is the fundamental component of the converter voltage, since I_{ac1} and ϕ are the functions of V_{c1} and ψ , the magnitude and phase of the fundamental input current may be variable according to V_{c1} [16].

3.4 SINGLE-ENDED PRIMARY INDUCTANCE CONVERTER (SEPIC) AS FRONT-END CONVERTER

This converter topology is proposed for driving a Switched Reluctance Motor with unipolar current. It consists of a front-end Single-Ended Primary Inductance Converter (SEPIC) and a switch in series with each motor phase. All the switches are ground-referenced, which simplifies their gate drives. The available input voltage can be boosted for better current regulation, which is an advantage for low voltage applications. The converter can be controlled to operate at a high power factor with an ac supply. For low power applications, the converter is designed to operate in the discontinuous conduction mode. In this operation mode, it approximates a voltage follower and the line current follows the line voltage waveform to a certain extent. The improved power factor is achieved without the use of any voltage or current sensors. For higher power levels, multiplier control is used with operation in the continuous conduction mode. The

simplicity and reduced parts count of this topology makes it an attractive low-cost choice for many variable speed drive applications.

3.4.1 CONVERTER TOPOLOGY

This converter consists of four controlled switches and diodes as shown in Fig.3.9. The front-end consists of a SEPIC DC/DC converter comprised of inductors L_1 and L_2 , switch S_1 , intermediate capacitor C_1 , diode D_1 and output capacitor C_2 .

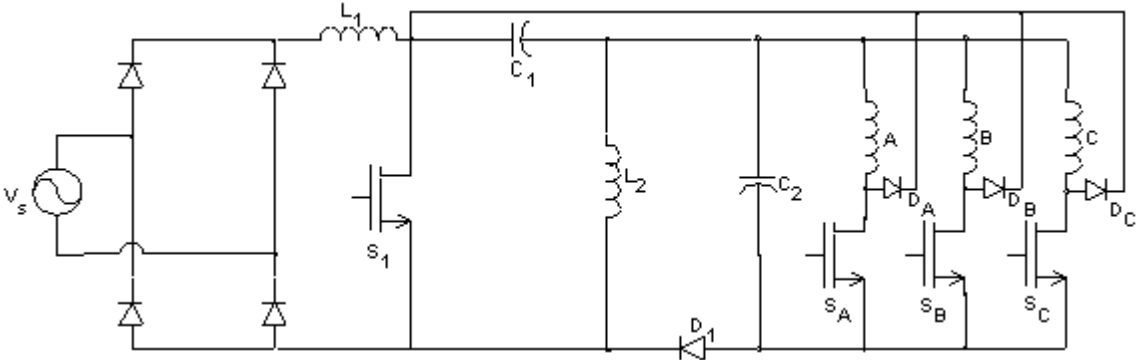


Fig. 3.9: Converter Topology with SEPIC Front-End

A, B and C are the three machine windings and the currents through them are controlled by turning-on and turning-off of the switches S_A , S_B and S_C respectively. The diodes D_A , D_B and D_C serve to freewheel the winding currents when the switches are turned off during current regulation and phase commutation. The output of the converter is used to energize the three phases of the motor, and the voltage of capacitor C_1 is used to demagnetize the phases during turn-off and for current control.

At low speeds, when the back-emf is low, the switching frequency of the phase switches increases in order to regulate the phase current. The switching frequency and hence the losses at low speeds are minimized by bucking the input voltage to lower levels at the output V_{DC} . At higher speeds, the current regulator loses its ability to force current into the phases especially during turn-on because of the high back- emf voltage. The ability of the SEPIC front-end to boost the available input voltage makes it possible to maintain current- regulated operation of the drive at higher speed. This feature makes the proposed topology particularly suitable for low voltage DC applications such as automotive circuits.

For applications requiring operation from an ac supply, it is desired to obtain improved power factor. The front-end converter could be designed to operate either in DCM or CCM. For low power levels, it is preferable to operate the SEPIC front-end in DCM, and the following desirable characteristics are obtained. The converter works as a voltage follower, meaning that the input current naturally follows the input voltage profile and theoretically its power factor is unity [21].

3.5 UNIPOLAR CONVERTER FOR SWITCHED RELUCTANCE MOTOR

This topology is based on a modified C-dump converter configuration, where the energy recovery stage acts as an active power factor controller for off-line operation. This is made possible by the development of a new technique to manage the freewheeling energy that is recovered back to the DC bus by means of a suitable HF transformer. The proposed approach omits the PFC stage, which is normally included in motor drives devoted to home appliances applications in order to comply with power quality requirements. Moreover, the proposed converter topology features only low side configuration switches, allowing easy integration of all the power semiconductors on a single chip exploiting smart power technologies.

3.5.1 CONVENTIONAL C-DUMP CONVERTER

The C-dump topology, shown in Fig. 10 is suitable either to provide a freewheeling path either to provide a voltage polarity inversion during the phase demagnetization.

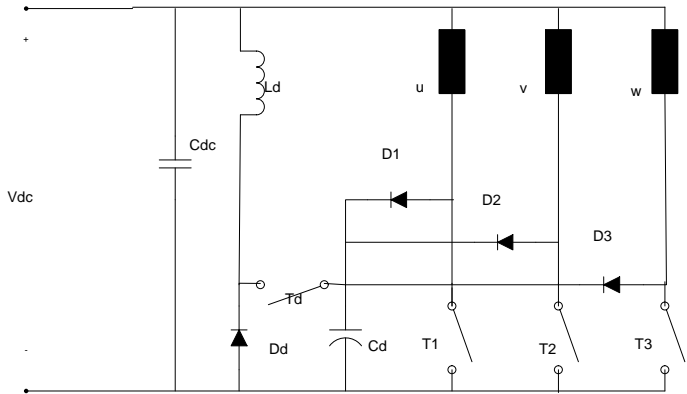


Fig. 3.10: Capacitive Energy Recovery Converter (C-Dump)

factor. Suitable choice of the primary and secondary inductances, as well as of the turn ratio is of concern to limit the current ripple and to shape the input current, improving the power factor.

3.5.3 OPERATING STAGE OF THE CONVERTER

In the conventional C-dump converter, the freewheeling energy is simply fed back to the DC bus with the purpose of saving energy, in the modified converter the energy transfer between the primary of the HF transformer, L_d and the secondary L_i , is twofold since it allows both to regulate the voltage across C_d and to improve the power factor. Such an energy transfer is performed by the switch T_d which is operated only across the time period T_{OFF} , forcing the power converter to draw current from the AC network, while controlling the voltage across the dump capacitor that is held around twice the dc bus voltage, in order to provide a fast phase winding demagnetization.

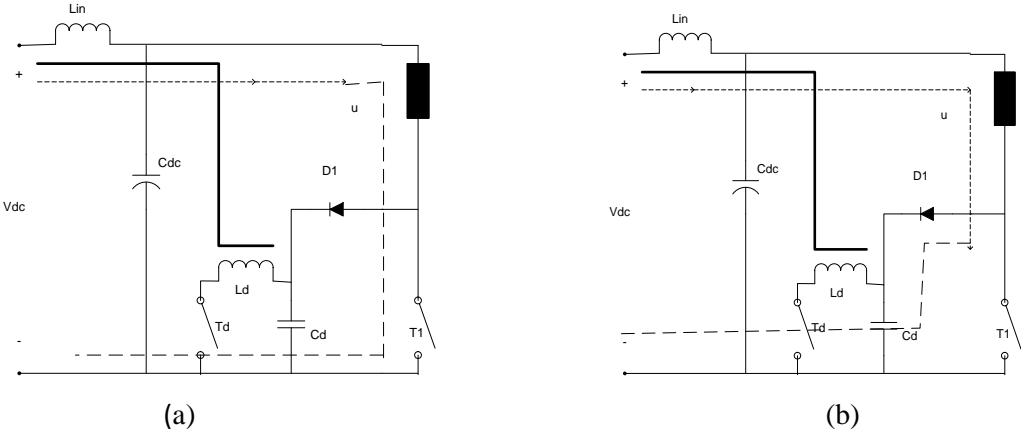


Fig. 3.12: Phase Switch State Sequence

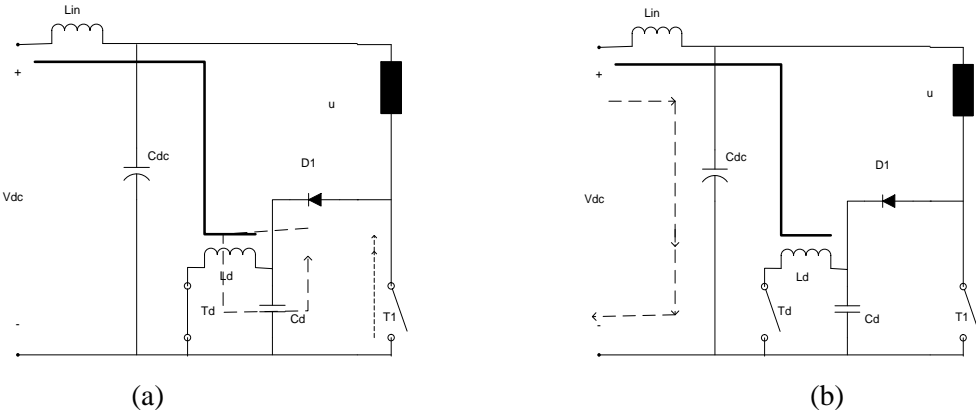


Fig. 3.13: Dump Switch State Sequence

Suitable voltage sensing devices, connected to a voltage comparator, allows detecting when the rectified AC voltage is lower than the DC bus voltage, thus allowing identifying T_{OFF} . During such a period the dump switch T_d is operated at constant duty cycle in order to control the voltage across C_d , while outside T_{OFF} the dump switch is turned off. Since the behavior of the whole drive can be qualitatively described by composition of the operations of the three phases the operations of the three phase windings of the SR machine separately have been considered separately. Looking at phase U the phase switch state sequence is drawn in Fig.3.12a. When the phase switch is turned on the current flows through the phase winding coming from the DC bus, as shown in Fig.3.12a. As the phase switch is turned off, the phase current circulates through the C-dump capacitor, whose voltage, being T_d off, freely increases as shown in Fig. 3.12b. During T_{OFF} the phase switch state sequence basically does not change, while the dump switch T_d is operated at a constant duty cycle, forcing the converter to follow the state sequence reported in Fig.13. If the dump switch T_d is turned on, C_d is discharged through the primary L_d of the transformer. Due to the selected transformer coupling mode and the presence of the diode bridge, no additional current flows on the secondary side of the transformer, this acts as a conventional inductive input filter, as shown in Fig.13a. As T_d is turned off, the current flowing through the primary side of the transformer is reflected to the secondary, forcing the diode bridge to conduct, even if the rectified AC voltage is lower than the DC bus voltage.

3.6 MODIFIED ASYMMETRIC BRIDGE CONVERTER

In a single-phase switched reluctance motor (SRM) drive, the dc voltage source is generally supplied by a circuit consisting of a bridge rectifier and a filter capacitor connected to an ac line. The charging time of the capacitor is shorter from the ac source as capacity increases. The bridge rectifier draws pulsating current from the ac source, which results in a degraded power factor (PF) and lower system efficiency. A single-phase SRM drive system is presented here, which includes the realization of a drive circuit for the reduction of torque ripple and PF improvement with a novel switching topology. The proposed drive circuit adds one switch and one diode, which can separate the output of the ac/dc rectifier from the large capacitor and supply power to the SRM alternately. This allows the drive system to realize torque ripple reduction and power factor improvement through the switching scheme.

3.6.1 ASYMMETRIC CONVERTER FOR SINGLE PHASE SRM

Fig. 3.14 shows a conventional asymmetric converter for a single-phase SR drive circuit. The drive circuit has a simple diode rectifier, a filter capacitor and an asymmetric bridge converter. The rectifier and the filter capacitor supply the dc source. The filter capacitor reduces dc voltage ripple and stores the recovered energy from the motor during demagnetization. This drive structure is very simple, but the capacitor charges and discharge which gives a pulsating ac line current and results in a low PF. The low PF of the motor increases the reactive power of the power line [19].

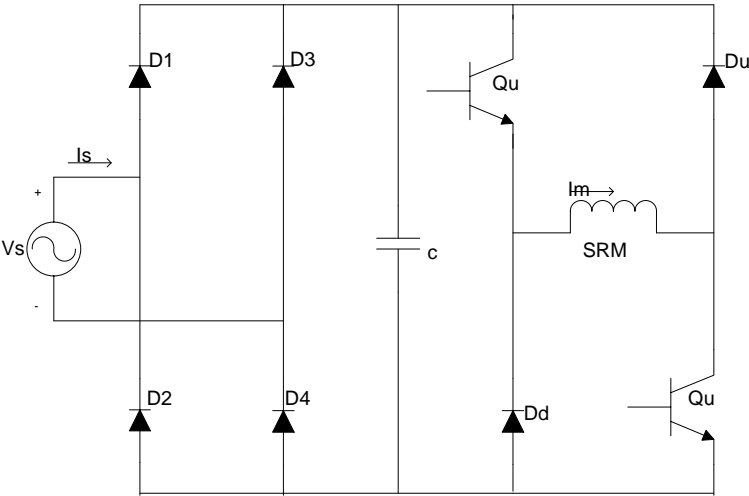


Fig. 3.14: Asymmetric Drive Circuit

3.6.2 MODIFIED BRIDGE CONVERTER

In contrast to the asymmetric drive circuit, the capacitor appears at the back-end of the proposed PFC circuit. The positive pulse output voltage of a full-wave bridge is applied to the SRM phase winding directly. On the other hand, the capacitor can supply to the SRM phase winding during magnetization, and store recovered energy during demagnetization. The circuit involves a discharge switch Q_F and a diode D_F in parallel with the discharge switch. Fig 3.15 shows the modified power factor correction circuit.

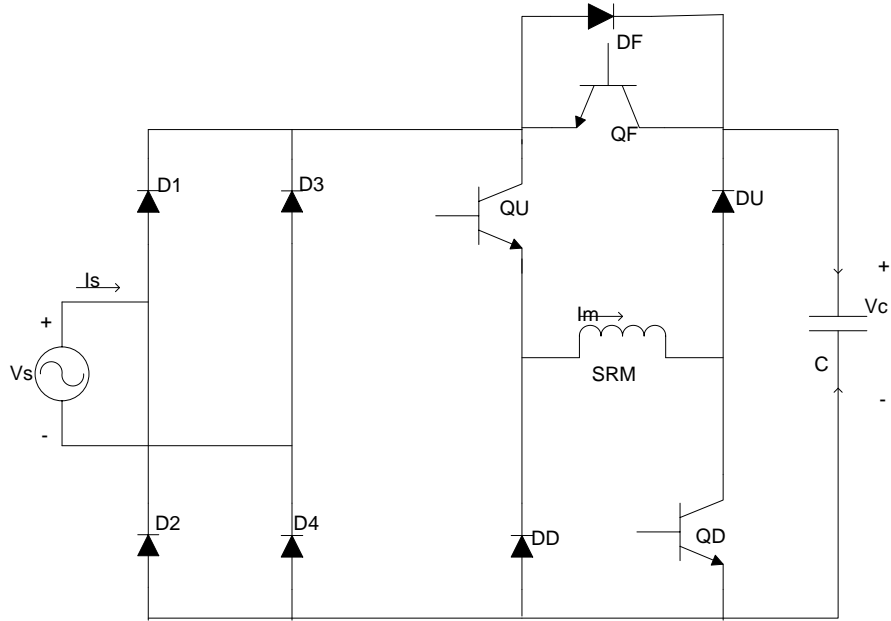


Fig. 3.15: Modified Bridge Circuit

3.6.3 OPERATING MODE ANALYSIS OF CONVERTER

To analyze the operation of the proposed PFC drive, the converter is divided into four modes from different states of switches, i.e., discharging current excitation mode, input current excitation mode, energy feedback mode and source charging mode, respectively. These modes are described in [24].

MODE 1: DISCHARGING CURRENT EXCITAION MODE

In this mode, two phase switch (Q_U , Q_D) and a discharge switch (Q_F) are switched on. The phase current flows through C_F , Q_F , Q_U , and Q_D . While this mode works on the exciting state, the high voltage of the discharge capacitor, which is recovered during energy feedback mode, is applied to the phase winding for a faster excitation current.

The phase voltage equation is obtained as

$$V_C = Ri_1 + L_{min} \frac{di_1}{dt} = -\frac{1}{C} \int i_1 dt \quad \dots\dots 3.7$$

where V_C is capacitor voltage, L_{min} is minimum phase inductance, i_1 is current in mode 1 and C is

capacitance of the capacitor.

Fig 3.16 shows the diagram of discharging current excitation mode.

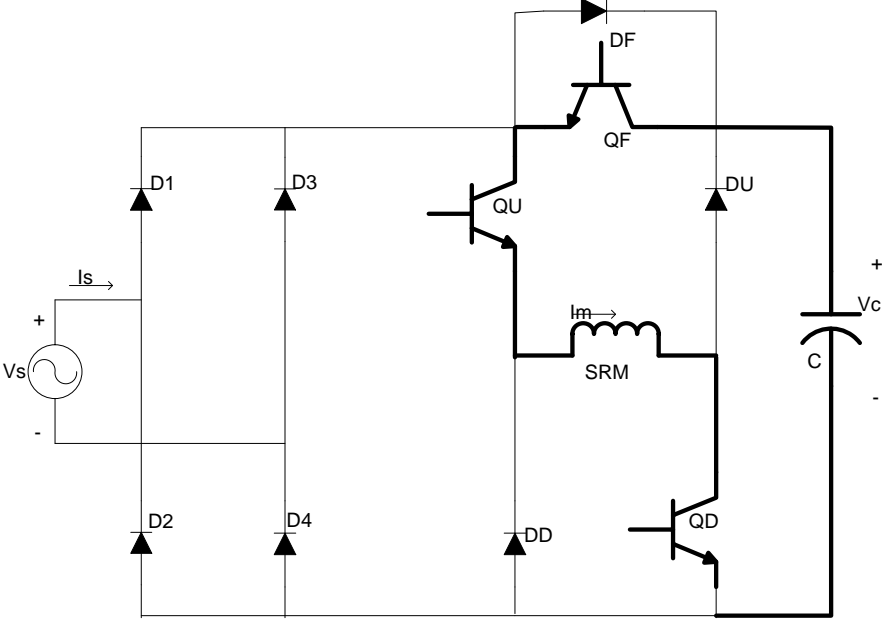


Fig. 3.16: Mode 1

While this mode works on the torque developing state, stored energy in the capacitor transform to the mechanical energy directly.

The phase voltage equation is obtained as

$$V_C = Ri_1 + L_{(\theta,i_1)} \frac{di_1}{dt} + i_1 \frac{\partial L(\theta,i_1)}{\partial \theta} \omega_{rm} = -\frac{1}{C} \int i_1 dt \quad \dots\dots 3.8$$

where $L(\theta, i_1)$ is phase inductance which depends on rotor position and phase current, and ω_{rm} is the rotational speed of SRM.

MODE 2: SOURCE CURRENT EXCITATION MODE

Fig 3.17 shows the source current excitation mode. In this mode, two phase switches (Q_U, Q_D) are switched on, and source voltage is applied to the phase winding.

The phase voltage equation for this mode is

$$|V_s| = Ri_2 + L_{min} \frac{di_2}{dt} \tag{3.9}$$

where V_s is the source voltage and i_2 is the current in mode 2.

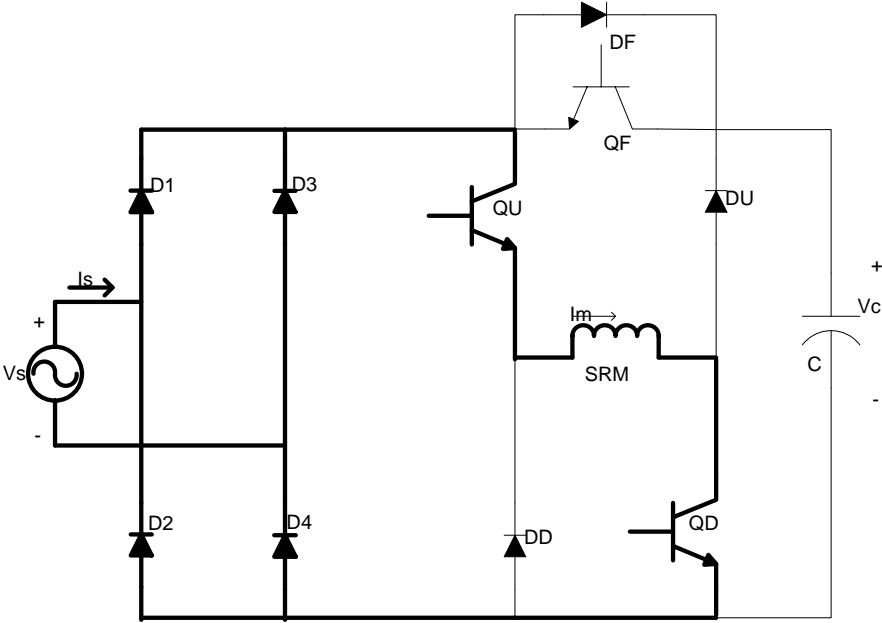


Fig. 3.17: Mode 2

In the torque developing period, the source power can flow into the motor directly, and can be converted into mechanical torque. It can contribute to improving the power factor of the power factor correction drive.

The phase voltage equation is given as

$$|V_s| = Ri_2 + L_{(\theta,i_2)} \frac{di_2}{dt} + i_2 \frac{\partial L(\theta,i_2)}{\partial \theta} \omega_{rm} \tag{3.10}$$

MODE 3: ENERGY FEEDBACK MODE

Fig 3.18 shows the energy feedback mode (mode 3). In this mode, the phase switches and discharge switch are turned off. The phase current flows through two diodes and reactive power is

returned to recharge the capacitor.

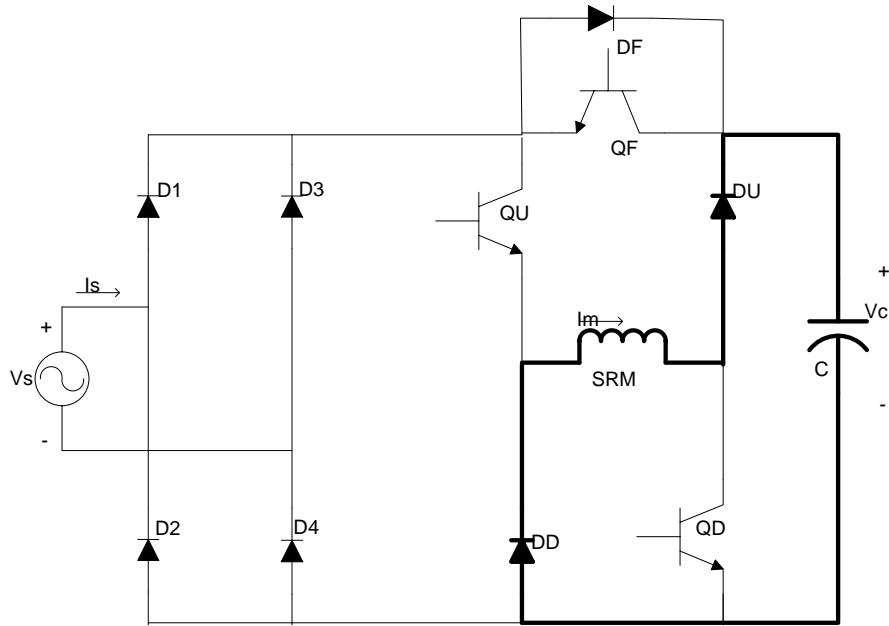


Fig. 3.18: Mode 3

The phase voltage equation for this operating mode is given as

$$-V_C = R i_3 + L_{(\theta, i_3)} \frac{d i_3}{d t} + i_3 \frac{\partial L(\theta, i_3)}{\partial \theta} \omega_{r m} = -\frac{1}{C} \int i_1 d t \quad \dots 3.10$$

where i_3 is the current in mode 3.

MODE 4: SOURCE CHARGING MODE

Fig 3.19 shows the source charging mode (mode 4). This mode is independent of switch state and is present when the source voltage is greater than the capacitor voltage.

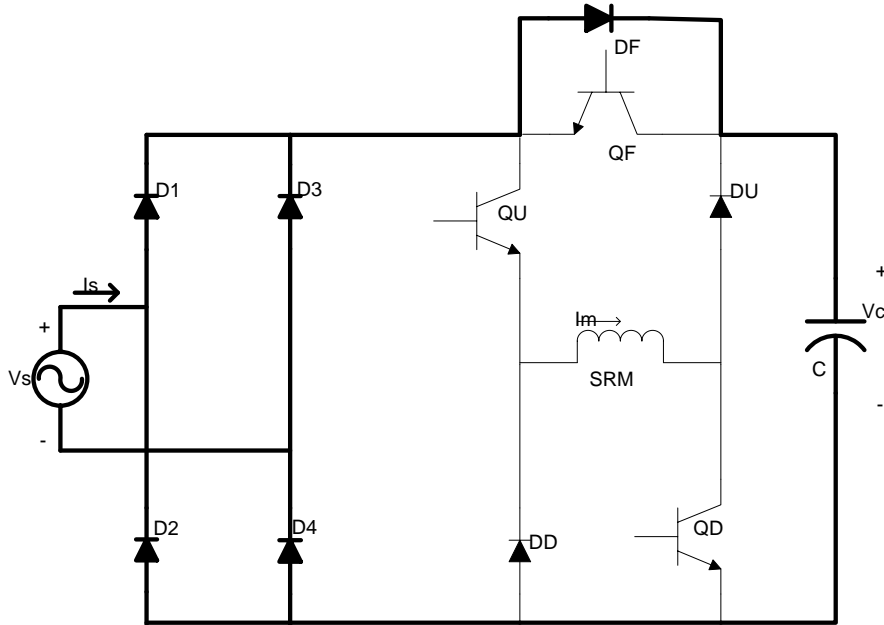


Fig. 3.19: Mode 4

The capacitor voltage equation is given as

$$|V_s| = V_c = \frac{1}{C} \int i_4 dt \quad \dots\dots 3.11$$

where i_4 is current in mode 4.

3.7 SINGLE STAGE CONVERTER

The single-stage power-factor-corrected converter also improves the input power factor of an efficient switched reluctance (SR) motor drive. This converter uses the winding of SR motor as an input inductor for power-factor-correction. Converter switches play two important roles; one is to improve the input power factor and the other is to excite the motor phase. Consequently, ac-to-dc power converter and SR motor driver are incorporated into one power stage [29].

3.7.1 CONFIGURATION OF CONVERTER

Fig 3.20 shows configurations of the classic converter and the power-factor-corrected (PFC) SRM drive respectively. The conventional converter illustrated in Fig 3.20 (a) employs a bulk capacitor in the end of the diode rectifier. Although it shows simple configuration, it draws a

pulsating ac line current resulted in low power factor and high harmonic line current. In the viewpoint of energy saving, to improve the power factor is very important in practical applications. To solve the problems, power-factor-correction circuitry is often added in front of the conventional converter. However, the two-stage approach has several disadvantages such as complexity of the circuit composition, additional control loop, high cost etc. One of the important factors in the selection of a driver for the SRM may be the cost; thus, a single-stage power-factor corrected converter is desirable for a practical and low cost SRM drive industry. Fig. 20b shows the proposed single-stage power factor- corrected converter for SRM drive. The most remarkable characteristic of the proposed converter is that there is no bulk capacitor in the end of the diode rectifier. Therefore, it can control the input current covering all ranges of the input power. When the phase switch is turned off, capacitor C_f is necessary to recover the energy stored in the motor winding, which is used for an input inductor. It separately works with the input part.

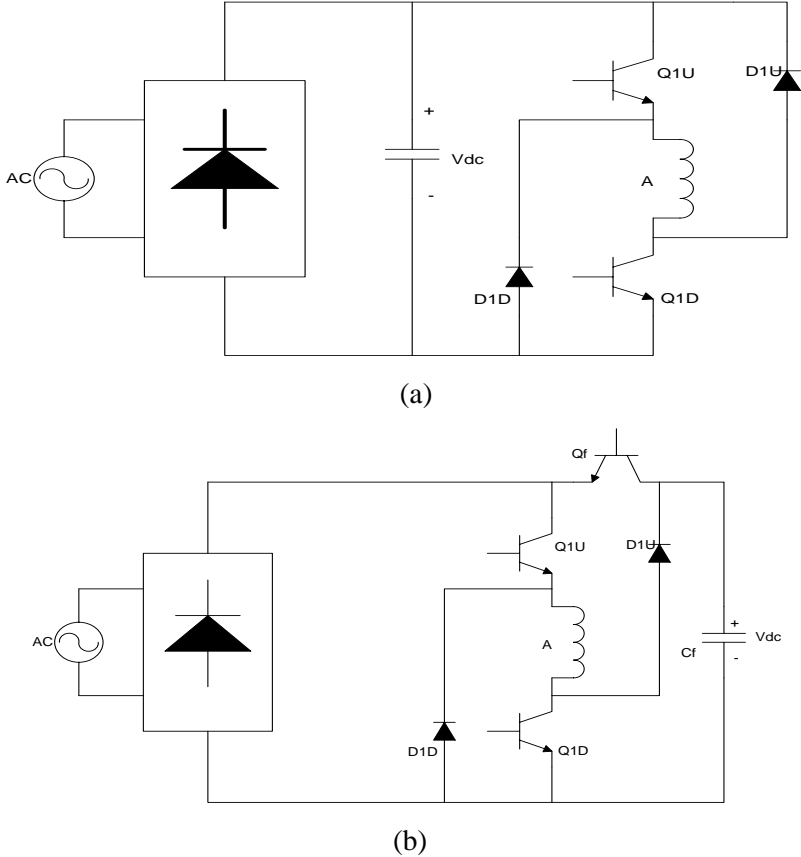


Fig. 3.20: (a) Asymmetric Converter without PFC (b) Single Stage Converter with PFC

Its operational modes are divided into three modes: a phase excitation by the external capacitor, a phase excitation by the input voltage source and demagnetizing mode which are described below.

3.7.2 MODES OF OPERATION

MODE 1:

With turning on the phase switches Q_1U and Q_1D , a phase current begins to flow from the external capacitor. Because the amplitude of the input voltage is lower than that of the external capacitor voltage, there is no input current from the ac line. The higher voltage that is recovered and stored at Mode 3, is more efficient for the faster settling of a flat-topped phase current. The phase current flows through C_f , Q_f , Q_1U and Q_1D . Fig. 3.21 shows the circuit in case of mode 1.

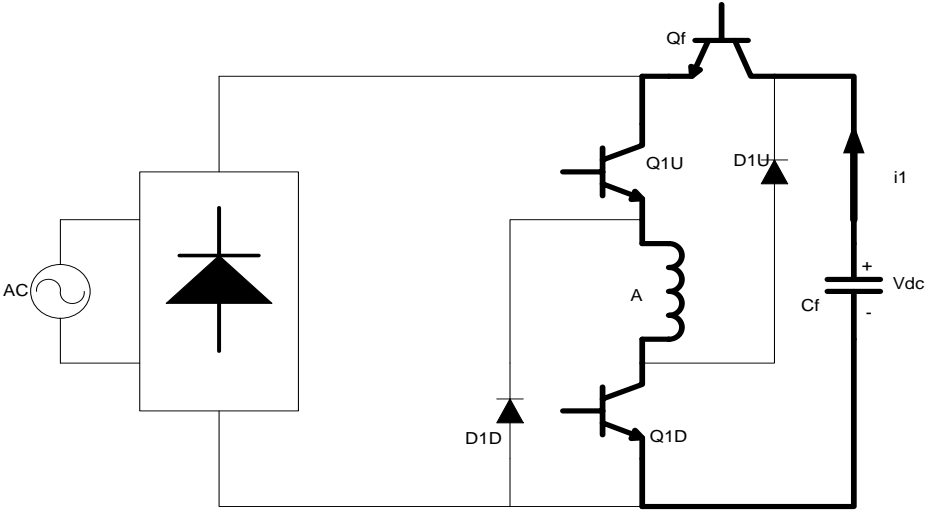


Fig. 3.21: Mode 1

MODE 2:

This mode starts when the amplitude of voltage across the external capacitor becomes equivalent to that of input voltage. The phase is continuously magnetized by input voltage source instead of the external capacitor. The phase current flows through Q_1U and Q_1D . During Mode 2, Q_f should be turned off to draw current from the input supply. The voltage across the capacitor C_f maintains a constant voltage level under a same motor speed. The voltage level is controlled by the duty ratio of the converter switches. To increase the motor speed, the capacitor voltage should be increased. To do so, the duty ratio of the switches should be increased. Internally, the relationship

between the capacitor voltage and the duty ratio is very similar to that of the general boost converter. Fig 3.22 shows the circuit in case of mode 2.

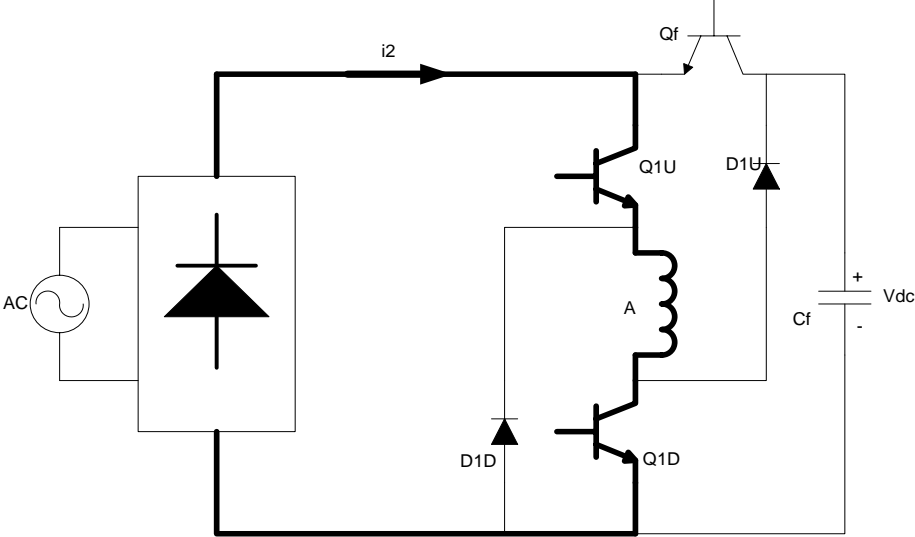


Fig. 3.22: Mode 2

Mode 3:

Fig 3.23 shows the circuit in case of mode 3. When the phase switches are turned off, a reactive power of the phase winding is transferred to the external capacitor through freewheeling diodes, D_1D and D_1U .

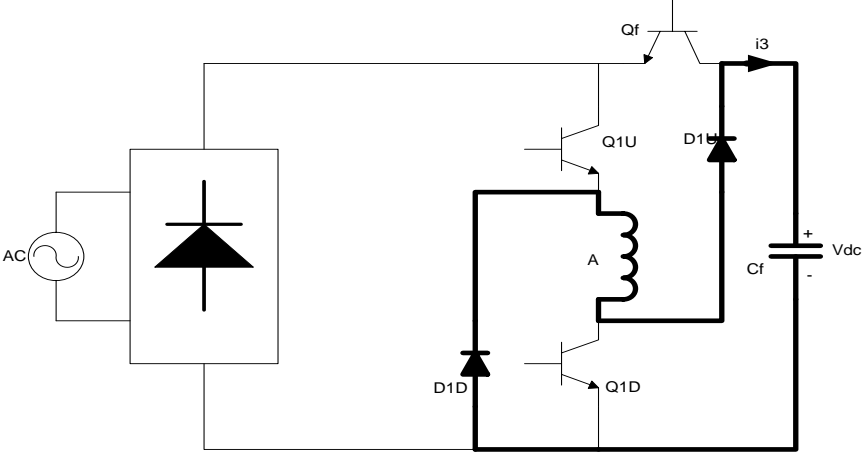


Fig. 3.23: Mode 3

3.8 CONCLUSION

Thus we have discussed about the various converter topologies used for power factor correction in switched reluctance motor drives. From the discussion, it follows that asymmetric bridge converter is the most common topology used for operating a switched reluctance motor drive. For power factor correction mostly the modified topologies are used instead of the conventional circuits such as a modified single phase rectifier is used in place of a conventional rectifier and a modified C-dump converter is used instead of a conventional C-dump converter. These circuits are however suitable for low and medium power application. In some circuits such as modified asymmetric converter and single stage power converter combination of a rectifier and a boost circuit is often preferred. Another topology that has been discussed is the single ended primary inductor circuit (SEPIC). The purpose of SEPIC converter is to boost up the DC voltage. This topology finds applications for high power applications.

RESULTS AND DISCUSSIONS

4.1 INTRODUCTION

In this chapter, we have shown the converter model of switched reluctance motor drive. It consists of a dc source, switched reluctance motor model, an asymmetric bridge converter i.e. used for converting dc into required ac, and a scope which shows the various output parameters of the motor like stator voltage, flux linkage, stator current, electromagnetic torque, rotor speed and rotor position. Another model shows two converters viz. diode bridge rectifier (DBR) and a switching power converter with power factor correction (SPC-PFC). The waveform basically shows the comparison between input current and voltage of both the converters. The simulated results are obtained in MATLAB/SIMULINK environment and they are discussed thoroughly in this section.

4.2 CONVERTER MODEL FOR SRM DRIVES

A converter model for switched reluctance motor is shown in Fig 4.1. The SRM is fed by a three-phase asymmetrical power converter having three legs, each of which consists of two IGBTs and two free-wheeling diodes. During conduction periods, the active IGBTs apply positive source voltage to the stator windings to drive positive currents into the phase windings. During free-wheeling periods, negative voltage is applied to the windings and the stored energy is returned to the power DC source through the diodes. The fall time of the currents in motor windings can thus be reduced. By using a position sensor attached to the rotor, the turn-on and turn-off angles of the motor phases can be accurately imposed. These switching angles can be used to control the developed torque waveforms. The phase currents are independently controlled by using three hysteresis controllers which generate the IGBTs drive signals by comparing the measured currents with the reference currents. The IGBTs' switching frequency is mainly determined by the hysteresis band.

A 6/4 three phase switched reluctance motor is used in this model which have six poles in stator and four poles on the rotor. The motor phase winding is excited by the three phase supply which is provided by the motor converter.

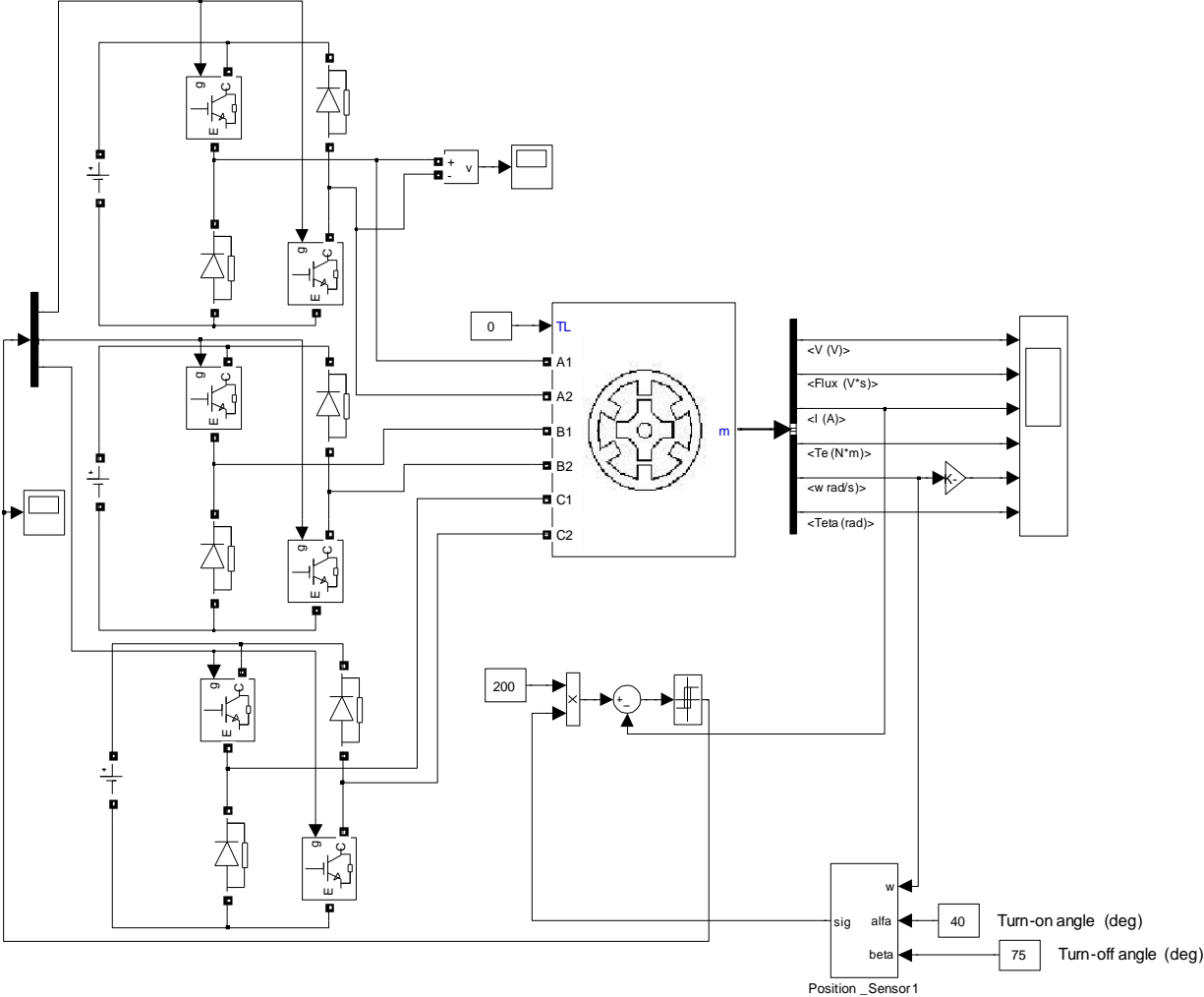


Fig. 4.1: Matlab/Simulink Model of Switched Reluctance Motor with Power Converter

The switching circuit uses 6 IGBTs .These IGBTs act as switches to provide a series of DC pulses to the switched reluctance motor. Since the SRM frequency controls are for 3-phase motors, there are six IGBTs, two for each phase. One IGBT connects each motor terminal to the positive side of the DC supply (240 V) while the other connects each motor terminal to the negative side of the DC supply. In this way, each terminal to terminal or line to line voltage can be either positive or negative. By controlling the switching sequence of the IGBTs, the control provides a simulated 3-phase sine voltage with frequency and voltage control. The waveform is

composed of DC pulses and does not look too much like a sine wave, but the effective value is a reasonably good simulation of a sine wave.

The IGBT turns on when the collector-emitter voltage is positive and greater than V_f and a positive signal is applied at the gate input ($g > 0$). It turns off when the collector-emitter voltage is positive and a 0 signal is applied at the gate input ($g = 0$).

The IGBT device is in the off state when the collector-emitter voltage is negative. Note that many commercial IGBTs do not have the reverse blocking capability. Therefore, they are usually used with an anti-parallel diode. The IGBT block contains a series R_s - C_s snubber circuit, which is connected in parallel with the IGBT device (between terminals C and E). Each IGBT has a diode in parallel but positioned to conduct current in the opposite direction. The "anti-parallel" diodes conduct the portion of the motor current waveform that lags the voltage.

A current is passed through one of the stator windings; torque is generated by the tendency of the rotor to align with the excited stator pole. , if the poles a1 and a2 are energized then the rotor will align itself with these poles. Once this has occurred it is possible for the stator poles to be de-energized before the stator poles of b1 and b2 are energized. The rotor is now positioned at the stator poles b. This sequence continues through c before arriving back at the start. This sequence can also be reversed to achieve motion in the opposite direction. This sequence can be found to be unstable while in operation.

The direction of the torque generated is a function of the rotor position with respect to the energized phase, and is independent of the direction of current flowing through the phase winding. Continuous torque can be produced by intelligently synchronizing each phase's excitation with the rotor position. The amount of current flowing through the SRM winding is controlled by switching on and off power electronic devices, IGBTs here, which can connect each SRM phase to the DC bus.

While designing the switching circuit we need to keep the following points in mind.

- For the purpose of the phase current control, it is necessary to modulate the phase voltage. This is especially important at low speed, when the motor back-emf is low.
- The voltage gain of the converter should be maximum possible in order to extend the constant power operation mode and increase the maximum speed of the motor drive.
- Large fall time of phase current results in negative torque and this time can be reduced if demagnetizing voltage is kept as high as possible.

- It is necessary, at the same time, to control current in one phase and force demagnetizing of some other phase of the motor. This is crucial for reduction of the torque ripple.
- Converter has to be single rail in order to reduce the voltage stress across the semiconductor switches.
- The power converter must not require bipolar windings or rely upon the motor construction.
- A low number of semiconductor switches is desirable.

Phase current in IGBT based power converter is controlled by selecting from the three possible states as per the sequence given below:

- Both switches in a phase leg are on. Each phase is energized from the power supply viz. 240 V (magnetizing stage).
- Both switches in a phase leg are off. Phase current commutates to the diodes and decays rapidly (demagnetizing stage).
- Only one of the switches is off. The voltage across winding is near zero and phase current decays slowly (freewheeling).

Experimental investigation based on a DC supply voltage of 240 V is used. The converter turn-on and turn-off angles are kept constant at 45 deg and 75 deg, respectively over the speed range. The reference current is 200 A and the hysteresis band is chosen as ± 10 A. The SRM is started by applying the step reference to the regulator input. The acceleration rate depends on the load characteristics.

The output characteristics for the following are obtained from the simulations using MATLAB/Simulink model.

- V-stator voltage
- Flux –flux linkage
- I-stator current
- T_e – electromagnetic torque
- W-rotor speed
- Theta –rotor position

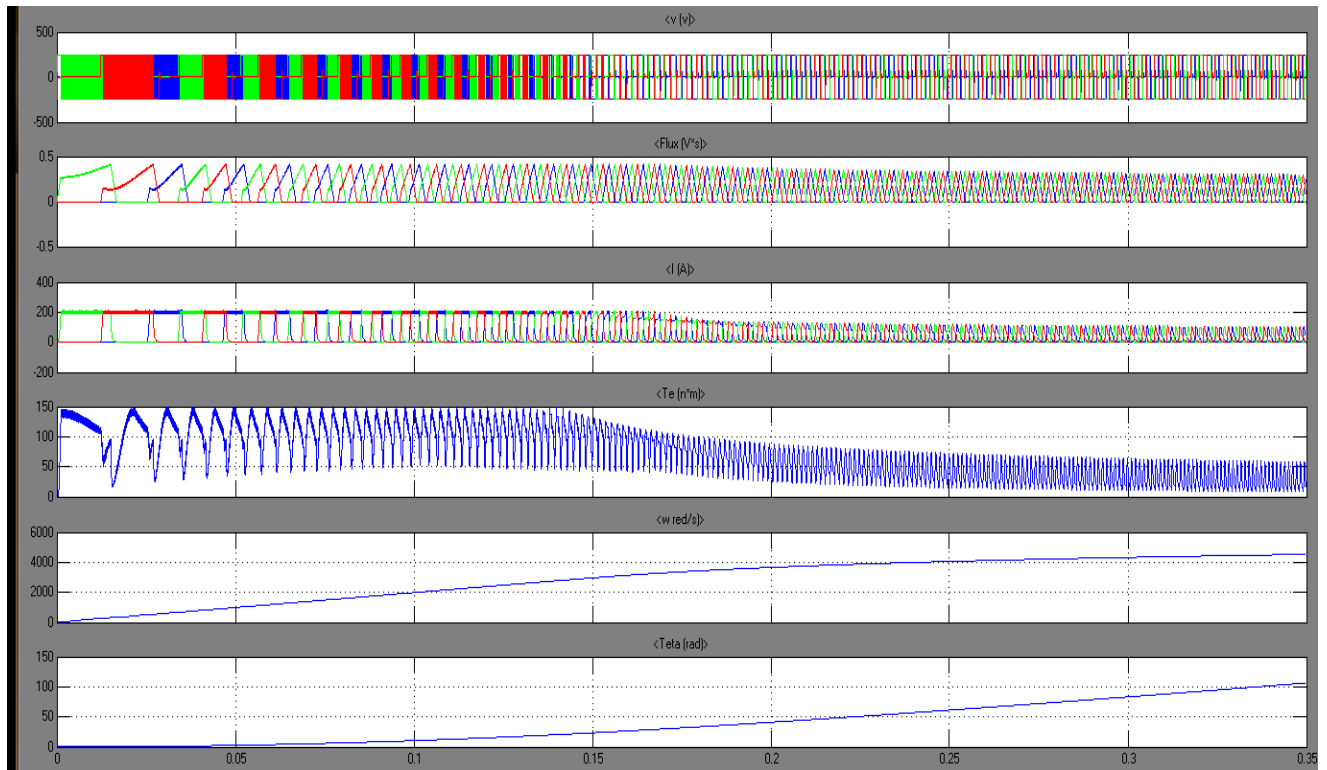


Fig. 4.2: Output Waveforms of Switched Reluctance Motor Drive

Fig 4.2 shows the various output characteristics of the switched reluctance motor drive. These characteristics are simulated output of SRM converter model which is shown in Fig. 4.1.

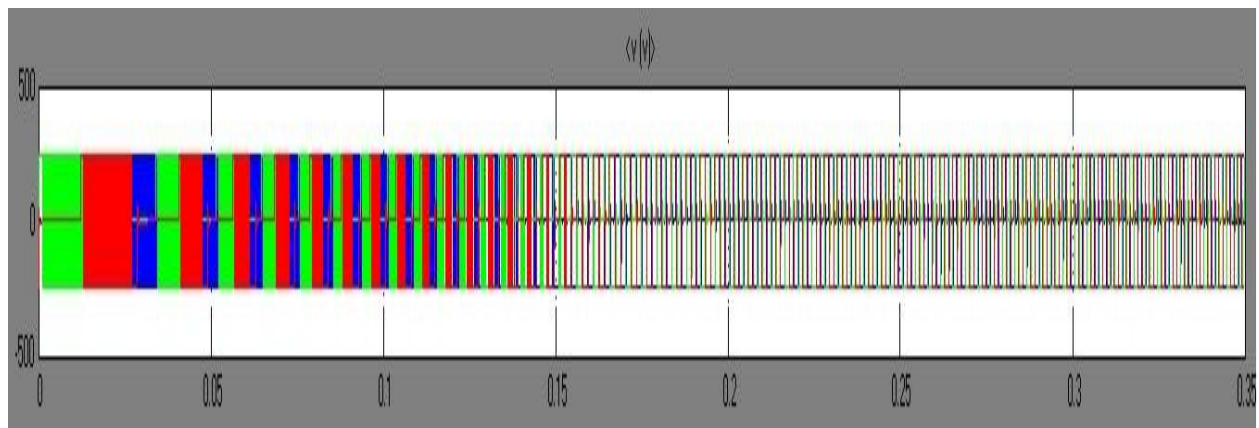


Fig 4.3 Stator Voltage Waveform of Switched Reluctance Motor Drive

Fig 4.3 shows the stator voltage of SRM which is the voltage versus time graph, voltage varies on y-axis and time is shown on x-axis the three color of graph shows the output of three different dc voltage source shown in Fig 4.1. There is a small delay in triggering ON of the power switch, hence the wave form starts from near to the zero point and no other delay period is observed in the whole graph of the voltage. The magnitude of the voltage is approximately 240V.

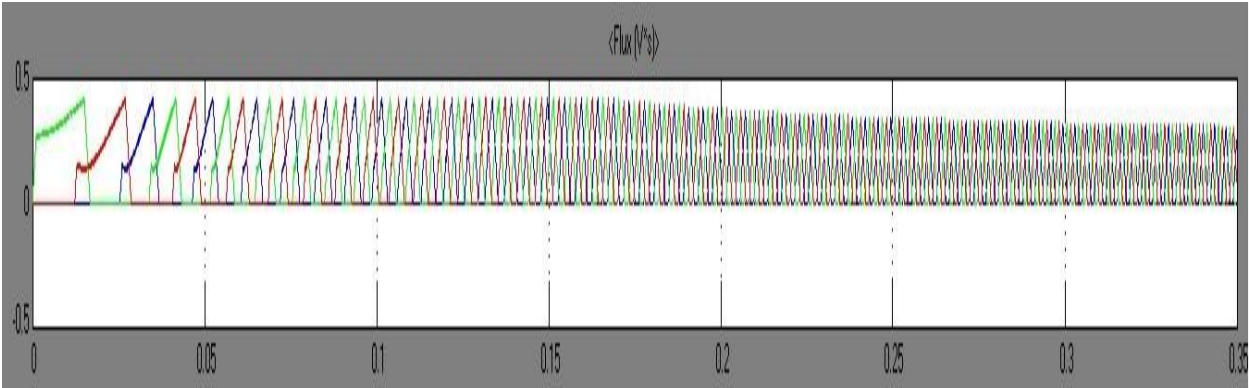


Fig. 4.4: Flux Linkage Variation of Switched Reluctance Motor Drive

Fig 4.4 shows the flux linkage of SRM, where the variation of flux linkage in the stator winding is plotted with respect to time. There are three colors of waveform that shows the flux linkage in three phases, in between stator and rotor pole of SRM. The flux linkage depends on the alignment of the rotor and stator pole. In the graph shown there is no initial delay and output is stable initially. However, there is no delay when the next phase is triggered.

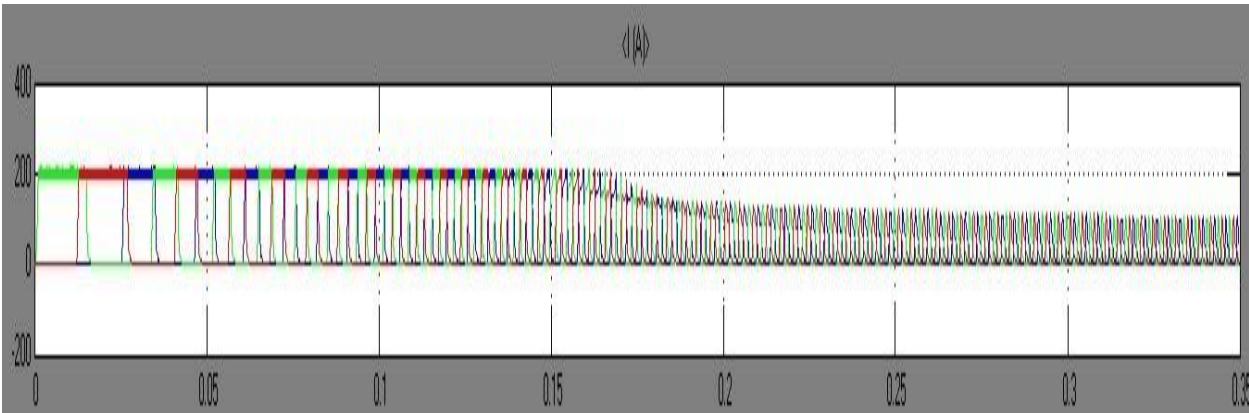


Fig. 4.5: Stator Current Variation of Switched Reluctance Motor Drive

Fig 4.5 shows the stator current of switched reluctance motor drive. The maximum value is

200 A. The graph shows the variation of stator current with respect to time. The graph signifies that during the initial stage the starting current is high and it finally comes to a lower and steady value after 0.18Sec. Three different colors signify different phase currents. No delay of switching of the devices is implemented which is observed from the graph.

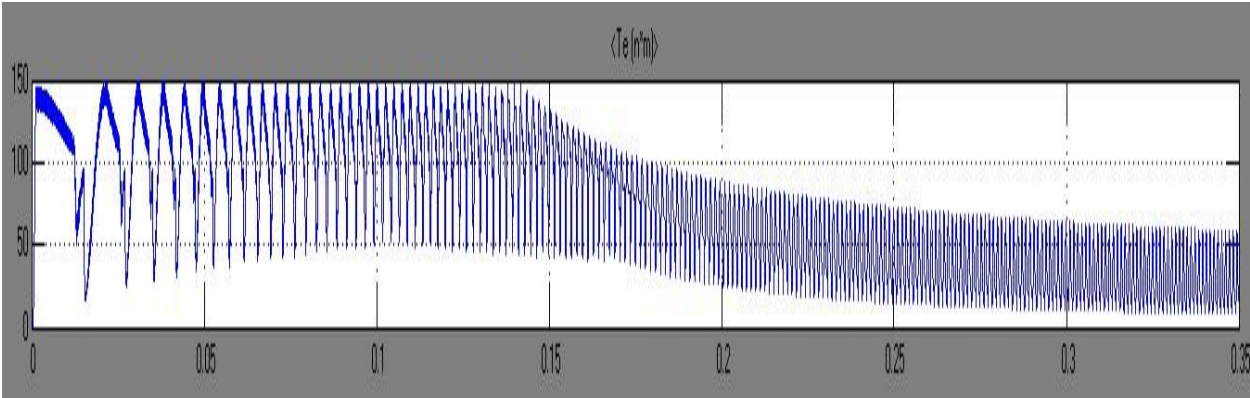


Fig 4.6 Electromagnetic Torque Characteristics of Switched Reluctance Motor Drive

Fig 4.6 shows the developed torque of SRM which shows the plot of torque in N-m with respect to time. Torque characteristics depend on the relationship between flux linkages and rotor position as a function of time. We have observed from the waveform that the torque at starting period is high but after 0.15 seconds it gradually reduces and becomes constant. The maximum torque achieved is 150 N-m at starting and after 0.15 it is approximately 80 N-m. This means the starting torque of this motor drive is very high.

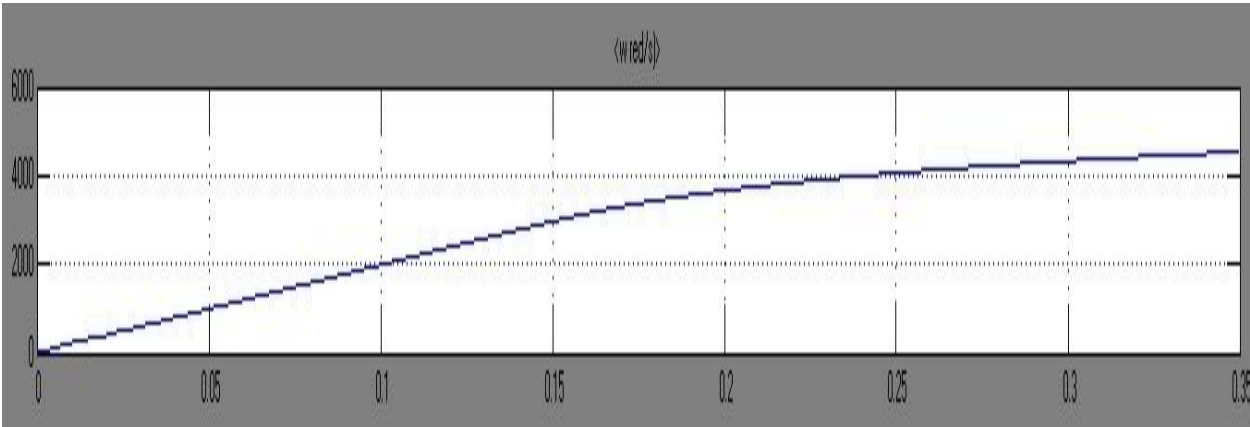


Fig. 4.7: Rotor Speed Profile of Switched Reluctance Motor Drive

Fig 4.7 shows the rotor speed of the switched reluctance motor and its variation is plotted

with respect to time .We have observed that the speed varies initially but becomes constant after a certain point. The maximum speed obtained is approximately 5000 rad/s.

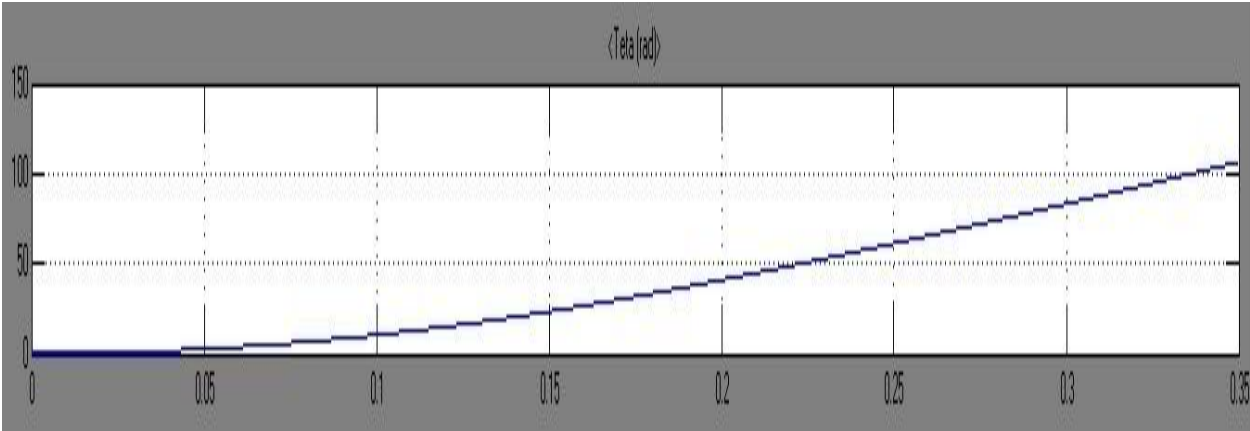


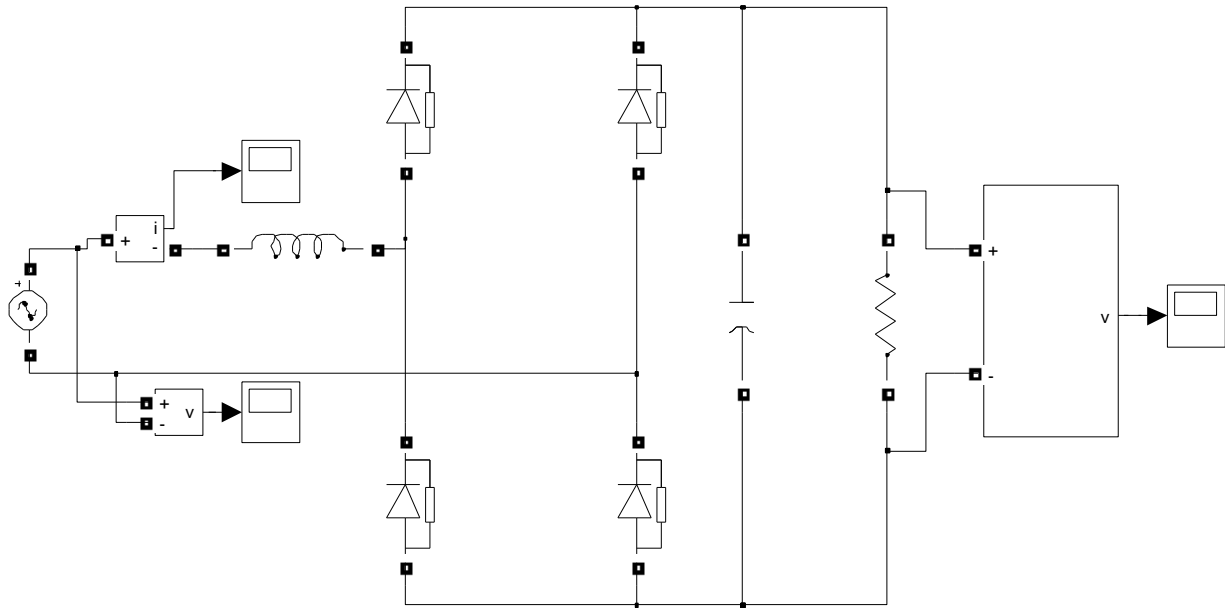
Fig. 4.8: Rotor Position Variation of Switched Reluctance Motor Drive

Fig 4.8 shows the variation of rotor position angle theta with respect to time. This angle is the position of rotor and stator pole. The developed torque depends on this angle theta. The maximum angle observed is approximately 100.

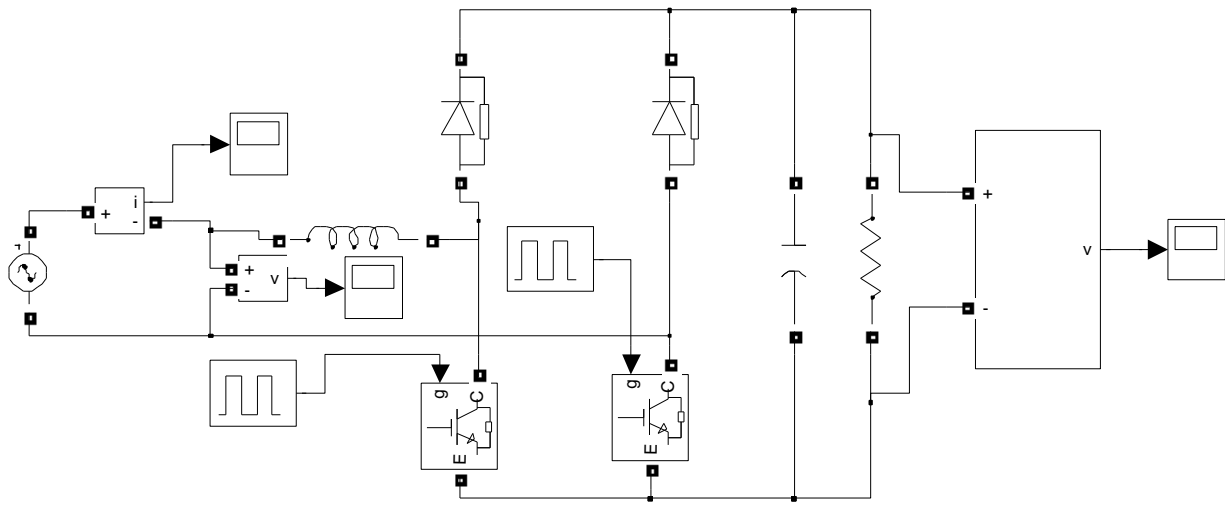
The above results reflect the performance of switched reluctance motor drive using a conventional asymmetric converter without any input power factor correction. In the subsequent section, we will discuss a power factor correction circuit for a switched reluctance motor drive and observe its output waveforms.

4.3 SWITCHING POWER CONVERTER WITH POWER FACTOR CORRECTION (SPC-PFC) MODEL

In this section, we have shown here the model of a novel switching power converter with power factor correction (SPC-PFC) and shown the simulation result of it. These results are compared with the simulation results obtained using a simple diode bridge rectifier (DBR). The simulated result shows the waveform of the input current and voltage. In SPC-PFC a pair of diode and IGBT (insulated gate bipolar transistor) is used in every arm. This circuit gives a better power factor and less harmonic content than the diode-bridge-rectifier (DBR). The SPC-PFC is operated in four modes which are already discussed in Chapter 3. Fig 4.9 (a) shows the model of a diode bridge rectifier (DBR) while Fig 4.9 (b) shows the model of switching power converter with power factor correction (SPC-PFC) using Matlab/Simulink.

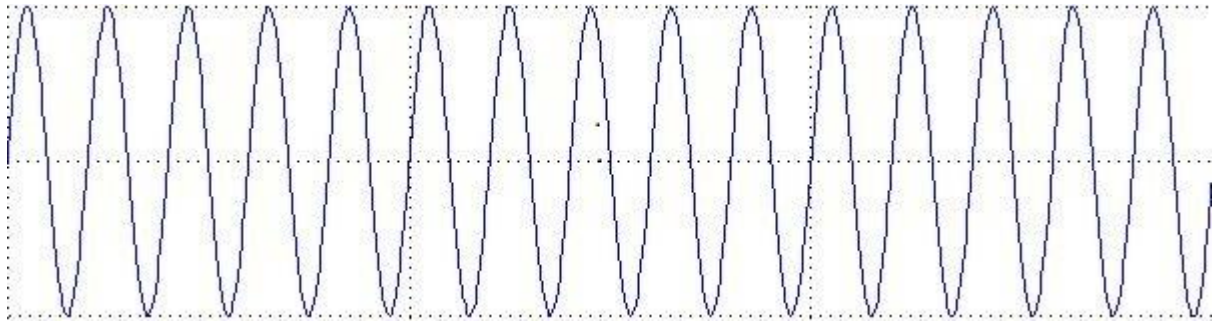


(a)

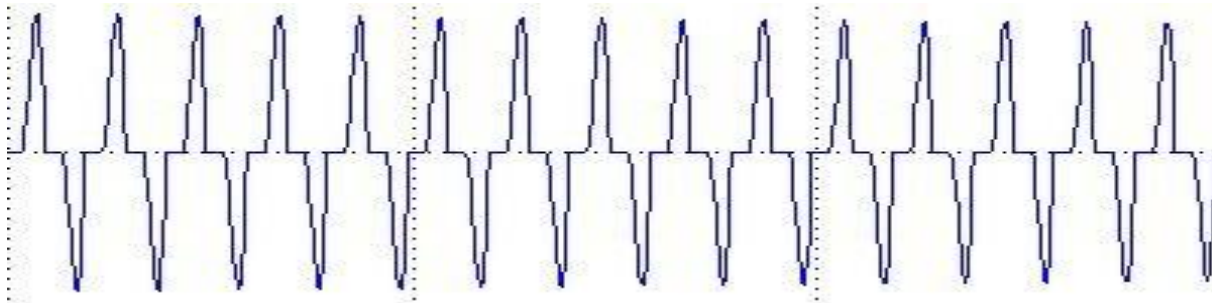


(b)

Fig. 4.9: AC/DC converter (a) DBR (b) SPC-PFC

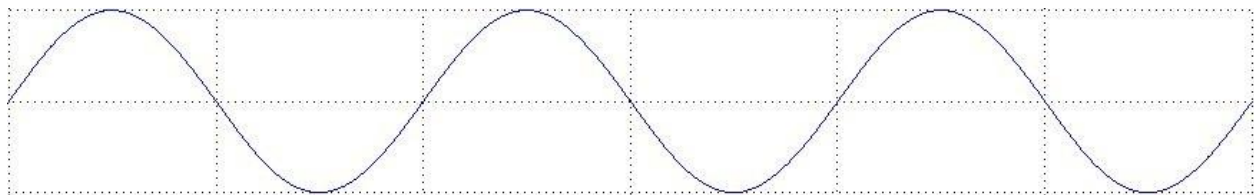


(a)

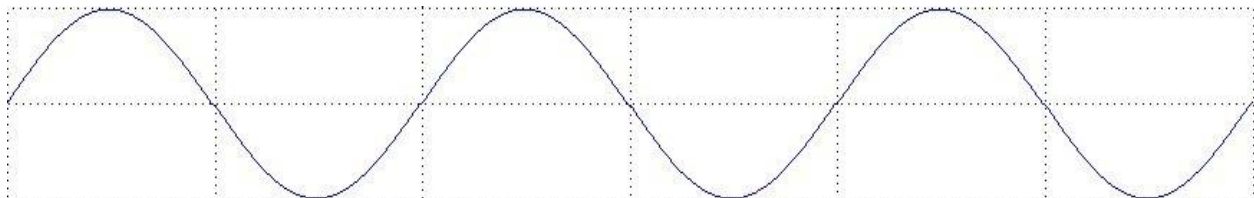


(b)

Fig. 4.10: Simulation Results of DBR (a) input voltage (b) input current variation with time



(a)



(b)

Fig. 4.11: Simulation Results of SPC-PFC (a) input voltage (b) input current variation with time

Fig 4.10 shows the simulated results of DBR. By observing the waveform of the input current and input voltage we have found out the current waveform is not in phase with the voltage

waveform. So we can conclude that the power factor that can be obtained is relatively poor. By observing Fig 4.11, which is the simulated result in case of SPC-PFC, we have seen that the input current is more in phase with the input voltage. So we can say that the power factor is high in comparison with the DBR.

4.4 CONCLUSIONS

Various converter topologies employed in switched reluctance motor drives have been discussed in Chapter 3. The main focus was to simulate a new converter topology which could give an improved power factor and less harmonic content based on the various topologies available. The performance of a switched reluctance motor drive is simulated in MATLAB/SIMULINK environment using asymmetric bridge converter where various drives parameter such as stator voltage, flux linkage, stator current, electromagnetic torque, rotor speed and position are being analyzed and discussed. Further the conventional diode bridge rectifier (DBR) and switching power converter with power factor correction (SPC-PFC) are simulated. Based on the waveforms obtained we have arrived at the conclusion that the input current is more in phase with the input voltage in case of SPC-PFC when compared to DBR. Hence SPC-PFC has improved power factor than DBR. If SPC-PFC is used with drive circuit of SR motor, than we can have a SRM drive with superior performance as compared to the other drive system.

4.5 FUTURE SCOPE OF WORK

For future study the power factor correction circuit can include a PWM converter or inverter for switched reluctance motor drive system to improve overall efficiency and reliability of the drive. The circuit developed may be used in various applications namely electric vehicles, aerospace, automotive and domestic appliances.

REFERENCES

- [1] R. Krishnan, "Switched Reluctance Motor Drives: Modeling Simulation, Analysis, Design, and Applications", Boca Raton, FL: CRC Press, pp. 398, 2001.
- [2] T. J. E. Miller, "Electronic Control of Switched Reluctance Machines", Oxford: Newnes, pp. 272, 2001.
- [3] T. J. E. Miller, "Optimal design of switched reluctance motors," IEEE Transactions on, Industrial Electronics, vol. 49, pp. 15-27, 2002.
- [4] K. Nakamura, T. Ono, H. Goto, T. Watanabe and O. Ichinokura, "A novel switched reluctance motor with wound-cores put on stator and rotor poles," IEEE Transactions on Magnetics, vol. 41, pp. 3919-3921, 2005.
- [5] S. Song, W. Liu and Y. Wang, "Modeling, dynamic simulation and control of a four-phase switched reluctance motor," IEEE International Conference on Control and Automation, pp. 1290-1295, 2008.
- [6] Michael T. Direnzo, "Switched Reluctance Motor Control-Basic Operation, Application Report", pp.3-20, Feb 2000.
- [7] Atsuhiko Sakurai, "Sliding Mode Control of Switched Reluctance Motor" , PhD Thesis, University of Toronto, 2001.
- [8] Krishnan, R., M. Abouzeid, and X. Mang, "A Design Procedure for Axial Field Switched Reluctance Motor", in Conference. Records IEEE IAS Annual Meeting, Vol. 1, pp. 241-246, 1990.

- [9] Chatratana, S. and H.R. Bolton, "Investigation Into Small, Single Phase Switched Reluctance Motor", in Preceding IEEE Conference on Small and Special Electrical Machine, pp. 99-102, 1981.
- [10] Lee, Byeong-Seok, Han-Kyung Bae, Praveen Vijayraghavan, and R. Krishnan, "Design Of A Linear Switched Reluctance Machine", IEEE IAS Annual Meeting, Phoenix, pp. 2267–2274, 1999.
- [11] Deshpande, U.S., J.J. Cathey, and E. Richter, "A High Force Density Linear Switched Reluctance Machine", IEEE IAS Annual Meeting., vol.1 Toronto, Canada, pp. 251-257, 1993.
- [12] Liu, C.T. and Y.N. Chen, "On the Feasible Polygon Classification of a Linear Switched Reluctance Machine" IEEE Electric Machines and Drives Conference. Record, Milwaukee, WI, pp. 11.1-11.3, 1997.
- [13] Geun-Hie Rim, Won-Ho Kim, Eun-Soo Kim, Ki-Chul Lee, "A Chopping less Converter for Switched Reluctance Motor with Unity Power Factor and Sinusoidal Input Current", the 25th Annual IEEE Power Electronics Specialists' Conference, Vol. 1, pp. 500-507, 1994.
- [14] P.N. Enjeti and R.Martines, "A High Power Performance Single Phase AC to DC Rectifier with Input Power Factor Correction" IEEE APEC Conference Record. Feb, Orlando, FL. pp 83-89, Feb 1994.
- [15] R. Jeyabharatlil, P. Veena and M. Rajaram, "A New Converter Topology for Switched Reluctance Motor Drive". IEEE Annual Conference of Power Electronics, pp.580-584, 2005.
- [16] Young Ahn Kwon, Kyoo Jae Shin, and G H Rim, "Switched Reluctance Motor Drives System with Improved Power Factor", IEEE/IECON Industrial. Electronics International Conference. Vol-2. pp. 541-545,1997.

- [17] R.Krishnan and S.Lee, "Effect of Power Factor Circuit on Switched Reluctance Motor Drives for Application", IEEE/APEC, pp.83-89, 1994.
- [18] D.S.L.Simonetti, j.Sebastian and j.Uceda, "The Discontinuous Conduction Mode SEPIC and cuk Power Factor Preregulators, Analysis and Design", IEEE Transaction on Industrial Electronics, vol. 44, pp. 630-637, oct.1997.
- [19] A. Consoli, A.Testa, N Aiello, F.Gennara and M. Lo Presti, "Unipolar Converter for Switched Reluctance Motor Drives with Power Factor Improvement," in Proceeding APEC, , vol.2, pp. 1103-1108, 2001.
- [20] L. Caruso, A. Consoli, G.Scarcella, and A.Testa, "A Switched Reluctance Motor Drive Operating at Unity Power Factor," in Conference. Record. IEEE IAS Annual Meeting, vol. 1, pp.410-417, 1996.
- [21] Tilak Gopalarathnam and Hamid A. Toliyat, "A High Power Factor Converter Topology for Switched Reluctance Motor Drives", 37th IAS Annual Industry Applications Conference, Vol. 3, pp. 1647-1652, 2002.
- [22] Jurgen Reinert and Stefan Schroder, "Power Factor Correction for Switched Reluctance Drives", IEEE Transaction on Industrial Electronics. 49: pp. 54-57, 2002.
- [23] Feel-Soon Kang, Jung-Han Lee, Cheul-U Kim and Sung-Jun Park, "Single Phase Power Factor Corrected Switched Reluctance Motor", 28th IEEE Annual Conference of Industrial Electronics Society, Vol. 2, pp. 1055-1059, 2002.
- [24] D.H. Lee, Z.G. Lee, J. Liang and J.Ahn, "Single Phase SRM Drives with Torque Ripple Reduction and Power Factor Correction", IEEE Transaction On Industry Application, vol. 43, No 6, pp. 1578-1587, Nov-Dec. 2007.

[25] A.Testa, N Aiello, F.Gennara and M. Lo Presti, “Unipolar Converter for Switched Reluctance Motor Drives with Power Factor Improvement,” in Proceeding APEC, vol.2, pp. 1103-1108, 2001.

[26] K. Thiyagarajah, "A High Switching Frequency IGBT PWM Rectifier/Inverter System for AC Motor Drives Operating from Single Phase Supply," IEEE PESC Conference Record , pp. 663-671, 1990.

[27] Masayuki Morimoto, "High Efficiency, Unity Power Factor VVVF Drive System of an Induction Motor," IEEE Transaction on Power electronics, Vol. 6, No. 3, July , pp. 498-502, july 1991.

[28] Shiyong Lee “Effect of Input Power Factor Correction on Variable Speed Drive System” PhD Thesis, Virginia Polytechnic Institute and State University, 1999.

[29] Mohd Rodhi Sahid, Abdul Halim Mohd Yatim, “Modeling and simulation of a new Bridgeless SEPIC power factor correction circuit” Simulation Modelling Practice and Theory vol.19, pp. 599–611, 2011.

[30] Sang-Hun Lee, Feel-soon Kang, Sung-Jun Park, Su Eog Cho and Man Hyung Lee, “Single-stage power-factor-corrected converter for switched reluctance motor drive” Electric Power Systems Research, vol 76, pp. 534–540, 2006.

[31] M.Barnes and C.Pollock, “Power Factor Correction in Switched Reluctance Motor Drives,” in Proceeding. Power Electronic and Variable Speed Drives, pp.17-25, 1998.

Website Links

[1] http://en.wikipedia.org/wiki/Switched_reluctance_motor.

[2] http://dr-ooi.com/Basic_of_SR_Motor.htm.

[3]http://en.wikipedia.org/wiki/Power_factor.

