COMPARATIVE STUDY OF VARIOUS CONVERTER TOPOLOGIES OF SWITCHED RELUCTANCE MOTOR DRIVE USING P-SPICE

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CERTIFICATE

I hereby certify that the work which is being presented in the thesis entitled, **" Comparative study of various converter topologies of switched reluctance motor drive using P-SPICE"**, in partial fulfillment of the requirements for the award of degree of **Master of Engineering in Power System & Electric 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 (Asst.Prof.)** and refers other researcher's works which are duly listed in the 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.

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

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ABSTRACT

Switched reluctance motor (SRM) has become a competitive selection for many applications of electric machine drive systems recently due to its relative simple construction and robustness. The advantages of those motors are high reliability, easy maintenance and good performance. The absence of permanent magnets and windings in rotor gives possibility to achieve very high speeds (over 10000 rpm) and turned SRM into perfect solution for operation in hard conditions like presence of vibrations or impacts. Such simple mechanical structure greatly reduces its price. Due to these features, SRM drives are used more and more into aerospace, automotive and home applications. The switched reluctance motor drive consists of converter and rotor position sensor.

The aim of this research is to study the various converter topologies of the switched reluctance motor drive using P-SPICE.

To accomplish this aim, the following objectives have to be conducted:

1. A study of the fundamental background of the SRM design, applications, and theory of operation is done.
2. All converter topologies which have been used as an SRM drive circuits in the literature are to be studied.
3. A comparison has to be done between the various converter topologies used for the switch reluctance motors drive system on the basis of phase current waveform, fourier analysis and total harmonic distortion.

The simulation of various converter topologies of switched reluctance motor drive is done using P-SPICE. Using P-SPICE the harmonic and fourier analysis of various converter is done and it is found that asymmetric bridge converter is most suitable for high speed applications because it has less fall times of current as compared to other converter topologies and less shoot through faults in this topology also. The comparative merits and demerits of the various converter is also discussed.

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NOMENCLATURE

ABBREVATION	MEANING
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
PWM	Pulse Width Modulation
SRM	Switched Reluctance Motor
EMI	Electro-magnetic interference
ZVT	Zero Voltage Transition
ZVS	Zero Voltage Switching
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
TDF	Torque distribution Function
FEA	Finite Element Analysis
SR	Switched Reluctance
SRMD	Switched Reluctance Motor Drive

CHAPTER 1

INTRODUCTION TO SWITCHED RELUCTANCE MOTOR

1.1 Introduction

This chapter deals with the introduction to switched reluctance motor, their principle of operation , torque production, various advantages ,disadvantages, applications and features of the switched reluctance motor drives is discussed.

A switched reluctance or variable reluctance motor does not contain any permanent magnets. The stator is similar to a brushless dc motor. However, the rotor consists only of iron laminates. The iron rotor is attracted to the energized stator pole. The polarity of the stator pole does not matter. Torque is produced as a result of the attraction between the electromagnet and the iron rotor. Switched reluctance motor control is simple to implement but this type of motors are not commonly available.

The switched reluctance motor (SRM) represents one of the earliest electric machines which was introduces 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 is 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 late in the sixties of the last century (1969), led to the re- invention of this motor and redirected the researchers to pay attention to its attractive features and advantages which help with 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 kinds. 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 this chapter could be eliminated or minimized using the high speed and high power semiconductor switches.

In industry, there is a very wide variety of designs of the switched reluctance machines which are used as motors or generators, these designs vary in number of phases, number of poles for both stator and rotor, number of teeth per pole, the shape of poles and whether a permanent magnet is included or not.

These previous options together with the converter topology used to drive the machine lead to an enormous number of designs and types of switched reluctance machine systems, which means both the switched reluctance machine with its drive circuit to suit different applications with different requirements. It is to be noted that it is well known to those who are interested in this kind of electrical machines that the drive circuit and the machine is one integrated system, one part of such a system can't be separately designed without considering the other part.

1.2 Switched Reluctance Motor

The switched reluctance motor (SRM) drives for industrial applications are of recent origin. Key to an understanding of any machine is its torque expression, which is derived from first principles. The implications of machine operation and its salient features are inferred from the torque expression [1]. The torque expression requires a relationship between machine flux linkages or inductance and the rotor position. The switched reluctance motor (SRM) is a synchronous machine. It has wound field coils as in a DC motor for the stator windings. The rotor however has no magnets or coils attached. The rotor of the motor becomes aligned as soon as the opposite poles of the stator become energized. In order to achieve a full rotation of the motor, the windings must be energized in the correct sequence.

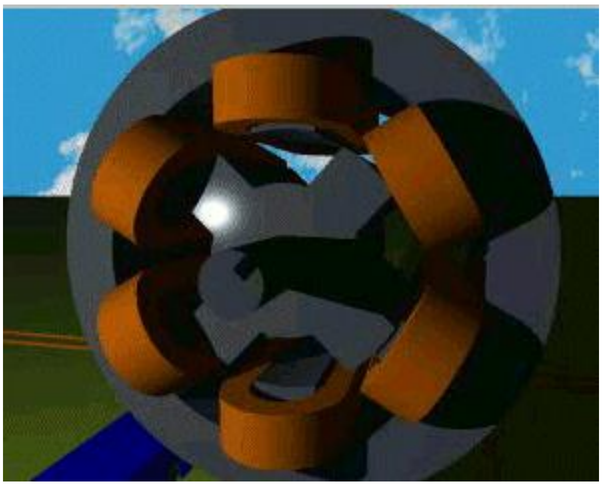


Figure 1 .1: Switched reluctance motor

Switched reluctance motor (SRM) is advantageous due to it's the simple construction, low manufacturing cost, and high torque density. Recently, its application has been widely spread from industrial to home appliance. However, SRM causes acoustic noise and vibration due to the torque ripples. The torque ripples can be reduced by means of the geometric motor shape design and the electric control. SRM needs a high input voltage, current, and phase inductance to get high torque [1, 2].

But, SRM uses a capacitor with low capacitance in the rectifier of a drive circuit because of the cost and its size. This causes ripples generated in the dc link voltage. Due to these ripples, the performance of the motor such as torque ripples and a radial force on the surface of the pole is degraded. Therefore, these kinds of conditions must be considered in analysis. When the switch turns off, the phase current flows through the freewheeling diodes or the capacitor of dc link. Generally, freewheeling diodes and dc link voltage ripples have not been considered when the motor is analysed . The time stepped voltage source finite element method (FEM) is used as the computational method to analyse the SRM, considering freewheeling diodes and dc link voltage ripples.

1.3 Operation of the Switched Reluctance Motor

How it works: The switched reluctance (SR) or variable reluctance motor contains no permanent magnets, has a rotor consisting of iron laminates, and a stator similar to the dc brushless motor. The iron rotor is attracted to the energized stator pole. Torque is produced as a result of this attraction between the electromagnet and the iron rotor. The simple, inexpensive construction of a switched reluctance motor requires a microcontroller for speed control and to reduce torque ripple and audible noise.

The rotor forms a magnetic circuit with the energized stator pole. The reluctance of a magnetic circuit is the magnetic equivalent to the resistance of a electric circuit. The reluctance of the magnetic circuit decreases as the rotor aligns with the stator pole. When the rotor is in line with the stator the gap between the rotor and stator is very small. At this point the reluctance is at a minimum. This is where the name “Switched Reluctance” comes from The inductance of the energized winding also varies as the rotor rotates. When the rotor is out of alignment, the inductance is very low, and the current will increase rapidly. When the rotor is aligned with the stator, the inductance will be very large and the slope decreases. This is one of the difficulties in driving a switched reluctance motor

The 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. Fig1.2 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 [3].

In a magnetic circuit, the rotating part prefers to come to the minimum reluctance position at the instance of excitation. While 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. 1.3. In the figure, consider that the rotor poles r_1 and r_1' and stator poles c and c′ are aligned.

Apply a current to phase a with the current direction as shown in Fig. 1.3a. 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.

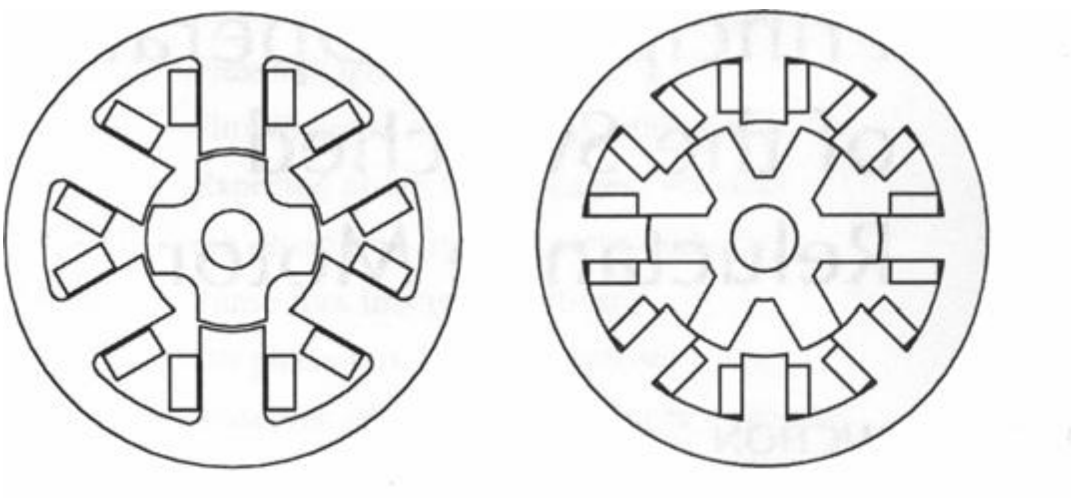


Figure 1 .2: SRM with 6/4 and 8/6 Poles

When they are aligned, the stator current of phase a is turned off and the corresponding situation is shown in Fig. 1.3b.

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 [3]. 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).

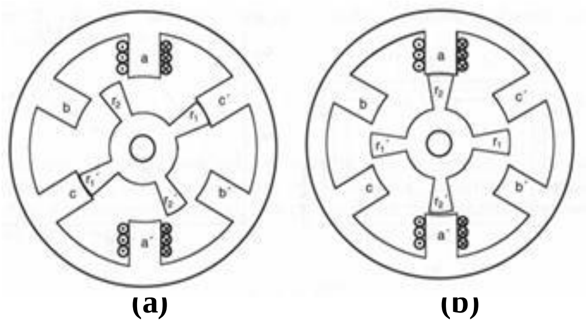


Figure 1.3: Operation of an SRM (a) Phase c aligned (b) Phase a aligned

1.4 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 [4].

When a phase is excited by applying a voltage across its concentrated coil, the currentt 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. 1.4. 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.

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

Because of the doubly salient geometry of an SR machine, the distance between the stator and rotor poles changes as the rotor rotates, and hence the reluctance of a flux path varies as shown in Fig. 1.5.

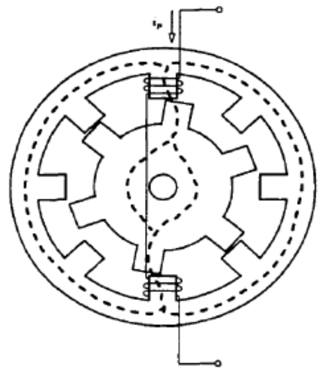


Figure 1.4: Magnetic circuit in a SR machine

A phase is in the unaligned position when the inter polar axis of the rotor Fig. 1.6 is aligned with the stator poles of the phase [4]. 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

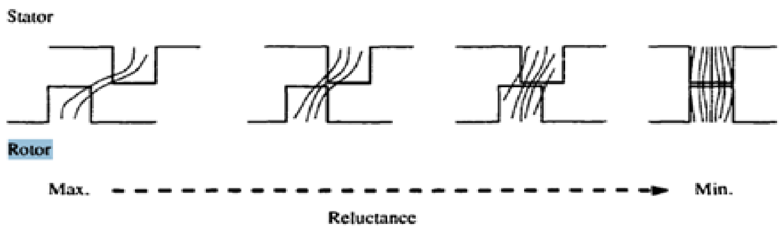


Figure 1.5: Variation of reluctance with respect to rotor position

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. Notice that the rotor poles of an SR machine do not require the existence of magnetic poles to produce torque. Interestingly enough, the radial magnetic attraction that operates an SR machine can become ten times larger than the circumference forces produced by an induction machine position.

In the aligned position shown in Fig. 1.6. 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 [4].

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.

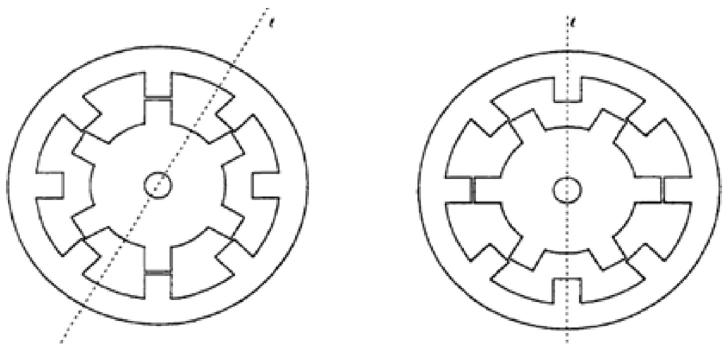


Figure 1.6: Aligned and unaligned positions

Also torque

$Te = dL(\theta, i).i^2/2\,d\theta$ ……………………………………………………… (1.1)

Where I is the instantaneous value of exciting current in the phase winding.

L is the self inductance of the phase winding.

The torque is proportional to the square of the current; hence the current can be unipolar to produce 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 [5].

Since the torque is proportional to the square of the current, this machine resembles 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 application this motor drive is expensive in comparison to

induction and synchronous motors. Because of its dependence on a power converter for its functioning, this motor drive 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 [5]. This is a feature unique to this machine only.

1.5 Advantages of Switched Reluctance Motor

There are several advantages of the switched reluctance machine that gives it preference over other types of electrical motors in many applications, these advantages are

1. Simple design and robust structure.
2. Unwind rotor
3. Lower 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 Disadvantages of the Switched reluctance motor

1. Necessity of electronic commutation.
2. Complicated analysis due to non – linear characteristics.
3. Difficulty of control.
4. Need to shaft position sensor.
5. Torque ripples.
6. Acoustic noise.

1.7 Applications of the Switched reluctance motor

1. Low power drives .
2. Medium power drives.
3. High power drives.

4. Linear drive applications.

5. High speed drives.

6. Emerging applications.

7. High volume applications.

8. Underwater applications.

9. Generator.

10. Pumps.

11. Actuation for aircraft flaps.

12. Power steering.

1.8 Features of the switch reluctance motor [6-7].

1. The torque in a SRM is independent of the polarity of the phase excitation current, which means only one switch per phase winding is required to energize or de-energize.

2. There is always one switch connected in series with a phase winding which makes the SRM self protected against shoot – through fault.

3. The phases of the SRM are electrically and magnetically independent which allows separate control of current and torque for each phase.

4. This also allows possible operation of the machine in case of one phase winding failure, although with reduced output power.

5. The mutual coupling between phases in a SRM can be neglected , this also gives an advance for independent phase current and torque control.

6. The phase inductance of the SRM varies with the rotor position in the either a linear or a nonlinear profile.

1.9 Objective of the Thesis

The aim of this research is to compare various converter topologies. Compare their rise time and the fall time for the phase current which in turn leads to results, first, is to meet the condition of better performance at higher speeds and less shoot through faults. For this purpose P-SPICE simulation of various converter topology is done.

The P-SPICE simulation of various converter topology is done for finding pahse current , fourier transform and the frequency analysis. And comparing them in aspects of harmonic distortion, phase current, frequency and fourier analysis of various converter topology. And various other factor like number of switches per phase, diodes per phase, reduction of shoot through faults are also taken into account.

By comparing various converter topologies it is found that asymmetric converter topology is suitable for high speed operation due to the fast fall and rise time of current and also provide negligible shoot through fault.

1.10 Organization of Thesis-

The work carried out has been summarized in five chapters.

The Chapter 1 highlights the brief introduction, principle of operation, the of switched reluctance motors.

The Chapter 2 highlights the brief introduction summary of work carried out by various researchers. The objective of the work is also identified and the outline of the thesis is also given in this chapter.

The Chapter 3 explains the various converter topology used for the switched reluctance motor, there operation, advantages, disadvantages and applications are also presented

The Chapter 4 discusses the results and discussions pertaining to various converter. The conclusions and the scope of further work are also presented in chapter 4.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

As per the literature available till date we classify the switched reluctance motor drives converters as follows:

- The single stage converter
- Multi stage converter
- Resonant converter

Among the single stage converters the most significant converters which are taken up in this study includes:

- Asymmetric bridge converter
- R-dump converter
- Split dc supply converter
- C-Dump converter
- Variable dc link converter
- Bifilar winding converter

Two stage converter and the resonant converter have also been analyzed in this work. Few literatures based on the SPICE simulations have also been reviewed in this chapter.

2.2 Literature Review

In this section different research paper corresponding to switched reluctance motor drive , converter configurations and P-SPICE simulation of converter is reviewed.

R. Krishnan, et al. proposed an energy efficient switched reluctance motor drive (SRMD) converter configuration. Which eliminates the need for a regenerative brake. The configuration involves the advantage that the energy stored in a winding is directly recycled to the succeeding phase instead of regenerating to the dc link or dumping it in a resistor. The design of the switched reluctance motor has to be coordinated with the converter in order to minimize the aligned inductance. This allows the fast decay of current in the phase winding when the succeeding phase is energized [1].

Peter N. Materu et al. described the main considerations in the design of a single-switch-per-phase converter for a switched reluctance motor (SRM) drive with particular attention to the choice of converter topology, the type of switching devices, the normalized rating of the power devices, and input filter design. The converter uses MOSFET switches [2].

A. Hava, et al. proposed a new type of converter topology for variable reluctance motor drives. The novelty of this converter has in the fact that the energy extracted from an off going phase is stored and is consequently utilized to either quickly turn on the next ongoing phase or energize the conducting phase frequently during the conduction interval instead of being returning back to the supply as for a conventional C-Dump circuit[3-4].

T.A. Lipo, et al. described new zero current switching converter topologies for variable reluctance machine drives. Which enables high frequency operation while maintaining low switching loss and reduced levels of electro-magnetic interference (EMI). The increase in frequency translates directly into improved current regulation in the machine phases, resulting in a high performance drive [5].

Sayeed Mir, et al. proposed energy- efficient converter topologies in conventional C – Dump converter. The topologies used in the paper overcome the limitations of the conventional C-Dump converter. Resulting in improved performance, lower cost and simpler control [6].

T.W Ching , et al. developed a zero-voltage soft- switching converter for switched reluctance motor drives. Which possesses the advantage that all switches and diodes can achieve ZVS when voltage and current stresses are kept at unity. It is especially suitable for SRM drives demanding efficient regenerative braking [7].

A. Consoli, et al. presented a C-dump converter topology for switched reluctance motor drives 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 SR motor drives aimed to equip home appliances, a very cost-sensitive market field [8].

A. Siadatan, et al. described a new drive circuit from the bridge family which uses resonant circuit during discharge. Which provides faster rate of current discharge . In the circuit, a capacitor is connected in series with the motor windings. This capacitor is charged resonantly by the use of motor phase windings during the phase turn off periods. In addition, an energy recovery circuit causes the trapped energy on resonant capacitor to be recovered by a single quadrant chopper comprising of a transistor, a capacitor and a diode. This converters provides faster rate of fall for the phase current, which permits the motor to operate at higher speeds [9-10].

S.S. Park, et al. presented a new resonant type converter for a variable reluctance motor drive is proposed to perform zero current switching of all solid state devices. The resonant circuit is partially resonant rather than fully resonant from the view point of the capacitor. The power circuit of the converter can be realized with unidirectional naturally commutated switches. The converter has many advantages such as low voltage stress or improved voltage utilization, low loss and no stress in the switching instant [11].

Ehab Elwakil design a new drive circuit topology of the SRM to meet the requirement of high-speed and or high-starting torque applications. The new topology is a modification of the conventional asymmetric converter topology. The modification is achieved by inserting a switched capacitance circuit in series with the motor phase .The novelty of introducing the switched capacitance circuit to the field of SRM drives is a main feature of this drive. [12].

K.L .Tseng, et al. presented an experimentally verified single-pulse-operation in a switched reluctance motor converter topology based on the basic buck-fronted topology and modified C-dump topology. Using only (n + 1) power switches, this topology is able to achieve full single-pulse operation, thereby reducing switching losses and acoustic noise. It also achieves a greater demagnetizing voltage compared to the basic buck-fronted topology, without having to increase the dc-source voltage. The converter is more robust as its dump capacitor stops being charged if the chopper switch fails [13].

P. Vijayragbvan , et al. presented the design and control of the buck converter based SRM drive . Which possesses the advantage of low number of switches and diodes that results in reduction of logic power supplies and gating circuits, compactness, lower overall cost, and higher reliability of the drive [14].

Sayeed Mir, et al. proposed topologies of SRM drives overcoming the limitations of the conventional C-dump converter, that could reduce the overall cost of the drive. The voltage ratings of the dump capacitor and the switching devices in the proposed converters are reduced to the supply voltage level compared to being twice the supply voltage (2Vdc) in the conventional C-dump converter. Also, the size of the dump inductor is considerably reduced. The converters have simple control that allows the motor phase current to freewheel during chopping mode [15].

Hong-Je Ryoo, et al. described a split source type converter topology for switched reluctance motor drives. The converter topology consists of 2 DC link capacitors, 6 switches and 6 diodes with 2switches and 2 diodes adding to a conventional split source converter to drive an 8/6 pole SRM. The main advantage of this converter is fast suppression of the tail current in the phase-winding, resulting in minimization of negative torque using doubly boosted voltage in the demagnetizing mode [16].

H. Chen , et al. presented the four different configurations of the power converter for the three-phase 12/8 switched reluctance motor drive, such as the asymmetric bridge circuit, the bifilar winding circuit, the resistance commutation circuit and the common switch circuit. The comparison of the four topologies are made with regard to the rated voltage of the switches, the rated voltage of the flywheel diodes, the average supplied voltage of phase winding, the average commutated voltage of phase winding, the numbers of the switches and the independence of the circuit [17].

R. Krishnan, et al. described the analysis and design of a low-cost, one switch per phase converter topology suitable for low- performance applications. Which has the advantage of a minimum possible number of semiconductor devices in the power circuit without the need for a bifilar winding [18].

Do-Hyun Jang proposed the new converter topology using half bridge inverter for the switched reluctance motor drives. Which maintains high efficiency though switches are reduced and energy is returned to the source after the turn-off. But this converter applies only to even number of stator slots [19].

J .Corda, et al. described a procedure for computing the losses in the switching circuit of power electronic converter of the switched reluctance drive, using the magnetization characteristics of SR motor and the characteristics of the power semiconductor devices[20].

R. Krishnan and S .Lee considered the analysis and design of a converter with minimum switches which is known as C-dump converter for use in non-bifilar wound SRM drive. The analysis of this topology includes the evaluation of the switching losses of the power switching devices and diodes, their current and voltage stresses, relationship between the energy storage capacitor, inductor and the duty cycle of the energy recovery circuit and the efficiency of the overall system for a given switching frequency [21].

Geun-Hie Rim, et al. paper proposed a new converter for switched reluctance motors. Compared to the conventional converter topologies which have switching losses due to voltage chopping to control phase currents, the proposed converter eliminates the switching losses by introducing buck-converter in the front end[22].

G. Rim, et al. presented a variable speed constant frequency power converter with a switched reluctance machine [23].

J D Wale and C Pollock presented a description and experimental results of a drive which employs a novel two phase switched reluctance motor with two fully pitched windings, based on a principle originally proposed for three phase machines. This form of winding gives rise to some unusual drive requirements, in particular continuous direct current in one winding, which offer potential benefits in the component count and ratings of the drive electronics[24].

H. Chen, et al. presented the dynamic simulation models of the switched reluctance motor drives. Using the simulink model the behaviour of the SRM motor is described [25].

Do-Hyun Jang presented a new converter topology using half bridge inverter for the switched reluctance motor drives is proposed. The proposed SRM drives are supplied by the ac pulse voltage source, while the conventional drives are supplied by dc voltage source. The SRM using proposed converter maintain high efficiency though the power switches are reduced. The full dc link voltage is applied to suppress the tail current quickly. Further It enables to extend the dwell angle to get more positive torque [26].

Kyu-Dong Kim, et al. presented a modified C-dump converter for SRM drives has full current pulse programming capability and better efficiency as well as involves lower cost. This SRM drive is most appropriate in applications such as in automobiles where low phase voltage drop, efficiency, simplicity, and compactness are important [27].

A. Consol, 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 European standards on power quality, thus reducing the cost and the complexity of switched reluctance motor drives aimed to equip home appliances [28].

K. N. Srinivas, et al. presented the circuit simulation of the dynamic performances of the Switched reluctance motor [29].

Tilak Gopalarathnam , et al. proposed a new converter topology with a SEPIC front-end for SR motors. The proposed scheme has the following advantages: It uses only four controlled switches, all of which are referenced to ground. This considerably simplifies their gate drive circuitry and results in low cost and compact packaging. 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 a high power factor can be obtained [30].

Tilak Gopalarathnam , et al. proposed a high power factor converter topology with SEPIC front-end for switched reluctance motor drives with unipolar currents. The converter is designed to operate in the discontinuous conduction mode**.** The front-end converter performs the tasks of power factor correction as well as phase-defluxing [31].

Chen Hao, et al. Introduced a combined control strategy where the turn-on angle and the turn-off angle in the power converter at the different range of the rotor speed are presented. The output and the rotor speed of the drive are controlled over the low rotor speed range by regulating the duty ratio of the pulse width modulation signal. The converter has the advantages of high systematic efficiency and the low current rating need of the main switches in the power converter [32].

M. Hiller, et al. presented a new converter concept for SRM drives with multiple energy sources. An additional switched capacitor per motor phase resulted in an extended control flexibility. This results in significant improvements of maximum torque, efficiency or torque ripple up to maximum speed. Further more a second energy source can easily be integrated in the drive system [33].

Y.P.B. Yeung , et al. presented a 2(n+l) switch converter circuit for switched reluctance motor drive . Soft-switching condition is provided for chopping transistors. Resonant voltage of the transistors is clamped actively. This circuit can be controlled by single pulse operation, pulse width modulation, and constant current mode control methods [34].

S. Saravanan , et al. presented the novel converter topology for the switched reluctance motor drive which is composed of the minimum switch per phase and is supplied by ac voltage source while the conventional SRM converters are supplied by dc voltage source. The single phase voltage source inverter is used to obtain the ac voltage source. This proposed converter could return the energy stored in the phase coils after turning off the phase switch. A buck boost converter is added to the topology for controlling the amount of energy recycling to the source [35].

Yong- HO Yoon, et al. presented a paper in order to improve the weakness of the conventional SRM converter asymmetric bridge converter within limited internal environment of automobiles[36].

Sang –Hoon Song, et al. discussed the analysis of the different drive circuit topologies of switched reluctance motor drives for use in vehicles. Switched reluctance motor is famous for its fault tolerance and good dynamic response. Taking into account the requirement for effective operation and simplicity structure of converter in the limited internal environment of automobiles, the author inclines toward selecting the modified C-dump converter as well as the energy efficient C-dump converter discussed earlier such that more economical and efficient converter topology in automobile industries can be utilized [37].

P. Bazzaz, et al. developed and demonstrated a hybrid converter for high speed operation of switched reluctance motor drives. A capacitor is charged through the resonant circuit and discharged during next working stroke. This converter provides faster rate of rise and fall for the phase current, which permits the motor to operate at high speeds [38].

R. Jeyabharatlil, et al. introduced a new converter topology for switched reluctance motor drives .A sensor less circuit with SEPIC working as power factor pre-regulator (PFP) is used which acts as both a power factor correction as well as phase-de fluxing component, reducing the device count thus providing better current regulation[39].

Yuen-Chung Kim, et al. proposed a new type of four-switch converter for switched reluctance motor to provide a possibility for realization of low cost three-phase switched reluctance motor drive system. The new converter and its control scheme is explained and the current control algorithm is designed and the validity of the proposed converter is verified by simulation to get the desired dynamic performance[40].

Huijun Wang, et al. presented a modified multi-level converter for low cost high speed switched reluctance (SR) drive . The proposed multi-level converter has reduced number of power switches and diodes than that of a conventional asymmetric converter and a lower voltage rating of the dump capacitor comparing with the energy efficient C-dump converter. It has five operating modes, boosted, DC-link, zero, negative DC-ink and negative boosted voltage. The proposed multi-level converter has fast excitation and demagnetization modes of phase current, so dynamic response can be achieved as well as a high speed drive [41].

Tao Sun , et al. presented the comparisons on characteristics of CSRM and SSRM. Specially, the SSRM is analysed in two drive strategy, asymmetric converter and full-bridge inverter. The main reason of using an inverter is to reduce the drive cost. In this analysis process, the feasibility of novel drive method is proved first. Then, FEA is employed to calculate the inductance. The generated inductance profile is used in the couple field circuit analysis to calculate the current and torque. Finally, by means of the results of the dynamic simulation, the characteristics of three analysis models are obtained [42].

Zhang Zhu, et al. presented five converter topologies for LSRM their operation merits and drawbacks are also discussed. Comparisons are then made based on the overall performance. Each topology finds its most suitable application after comparison [43].

Minh Cao Ta et al. presented the modelling, simulation, and control of switched reluctance motor (SRM) for high-speed applications. The model of SRM is built with help of three dimensional relationship between excitation currents, rotor position and flux linkage. The relationship makes electromagnetic torque depend not only on the excitation currents but also on the rotor position. Therefore, it is not difficult to control a SRM to achieve high performance operations. In order to reduce torque ripple of the drive, they have used the torque distribution function (TDF) approach and proposed a novel TDF for high-speed applications [44].

O. Ichinokura, et al. presented a new calculation model of the switched reluctance motor (SRM) for use on SPICE which is a general-purpose circuit simulation program. In the calculation model, the electric circuit and magnetic circuit of SRM are separated and are coupled by proper controlled sources. Using the SPICE model, we can calculate readily and accurately the dynamic characteristics of the SRM [45].

H. Bagherian , et al. presented a bifilar drive circuit which uses dump capacitor during discharge period is presented. This topology utilizes the bifilar winding in conjunction with the dump capacitor to produce resonance in order to provide faster rate of current discharge. This technique permits the motor to operate at higher speeds [46].

J.Mahdavi, et al. described a comprehensive non linear dynamic model for a switched reluctance motor drive using P-spice is presented. The SRM is represented by its non linear dynamic equations and the magnetic model of SRM includes the representation of inductance-current-position characteristics which closely match those obtained experimentally. The variation of the phase inductance with rotor position is expressed by a limited number of fourier series terms [47].

Xiaoqun Wu, et al. provided a systematic approach to rationalizing the behaviour of the SPICE simulator, its practical significance being in the identification of the ranges of simulation parameters for which flawed solutions can be produced [48].

In the next chapter various converter topology used to drive the switched reluctance motor discussed. The brief principle of operation of converter, their advantages, disadvantages, features and application are discussed in detail.

CHAPTER-3

Converter Topologies

3.1 Introduction

In this chapter we are going to discuss the features of power converter circuits in switched reluctance motor drive, and the various converter topologies used along with the merits, demerits and application of each topology.

3.2 Features of the Power Switching Circuits

The essential features of the power switching circuit for each phase of reluctance motor are comprised of two parts.

1. A controlled switch to connect the voltage source to the coil windings to build up the current.

2. An alternative path for the current to flow when the switch is turned off, since the trapped energy in the phase winding can be used in the other strokes. In addition, this protects the switch from the high current produced by the energy trapped in the phase winding. Figure 3.1 shows a simple form of switching circuit for a switched reluctance motor.

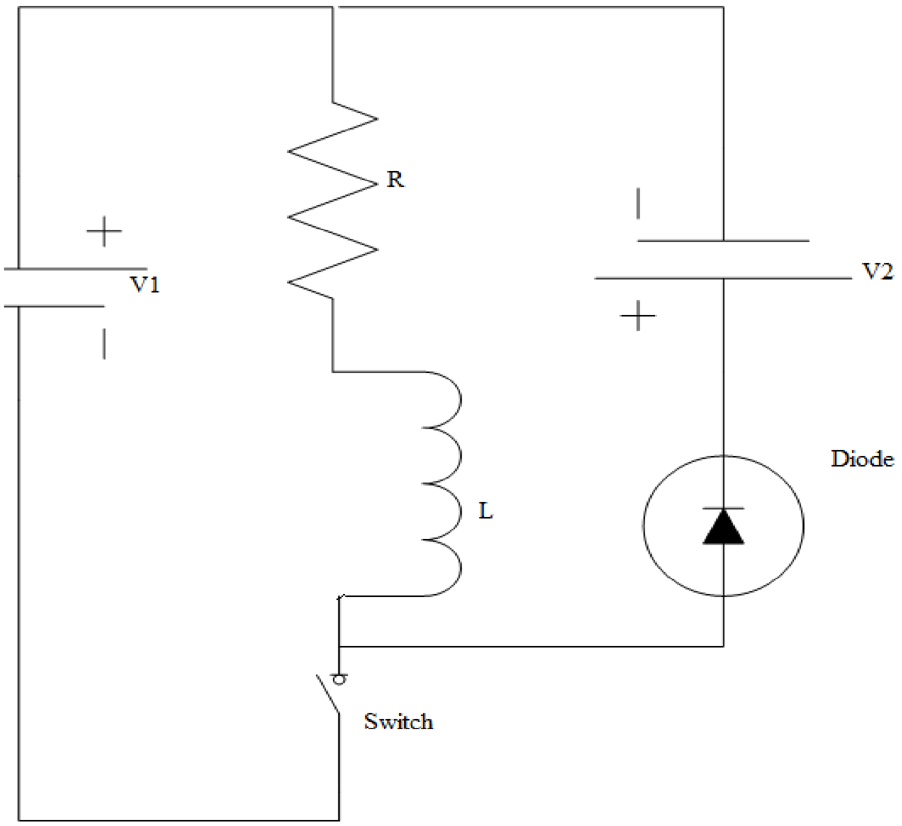


Figure 3.1 A General Drive Circuit

3.3 Various Converter Topologies for Switched Reluctance Motor

It is essential before considering the different topologies of switched reluctance motor drive circuits to introduce the following features of the motor which give it an attractive advance over other types of AC machines; and affects the design of the drive circuit, these features are:

1. The torque in a SRM is independent of the polarity of the phase excitation current, which means only one switch per phase winding is required to energize or de-energize this phase.
2. There is always one switch connected in series with a phase winding, which makes the SRM self protected against shoot-through fault.
3. The phases of the SRM are electrically and magnetically independent, which allows separate control of current and torque for each phase, and also allows possible operation of the machine in case of one phase winding failure, although with reduced output power.
4. The mutual coupling between phases in a SRM can be neglected; this also gives an advance for independent phase current and torque control.

5 The phase inductance of the SRM varies with the rotor position in either a linear or a non linear profile.

The previous facts about the SRM explain the expected function of the drive circuit for this type of AC machines, which could be concluded in three tasks; first, is to divert current into the phase only in the positive gradient period of its inductance profile. Second, is to shape the energizing current of each phase, including its amount and its rise and fall times, of course less rise and fall times are desired to maximize the torque productivity during motoring operation. Third task is to provide a path for the stored magnetic energy in the phase winding during the commutation period, otherwise it will result in excessive voltage stress across the phase winding, hence across the semiconductor switching element leading to its failure, this energy could be freewheeled, or returned to the DC source either by electronic or electromagnetic means .

There are several topologies suggested to achieve the above function of the drive circuit. These topologies are well classified in based on the number of switches used to energize and commutate each phase [8].

3.3.1 An Introduction to Converter Topology

Since the torque in SRM drives is independent of the excitation current polarity, the SRM drives require only one switch per phase winding. This is contrary to the ac motor drives where at least two switches per phase are required for current control. Moreover, the windings are not in series with the switches in ac motor drives, leading to irreparable damage in shoot-through faults. The SRM drives always have a phase winding in series with a switch. In case of a shoot-through fault, the inductance of the winding limits the rate of rise in current and provides time to initiate protective relaying to isolate the faults. The phases of the SRM are independent and, in case of one winding failure, uninterrupted operation of the motor drive operation is possible, although with reduced power output. Some configurations of converters used in SRM drives are presented and discussed in this thesis the comparisons of these converter topologies. While many of these configurations have been known for some time, the rest are emerging from research laboratories.

3.4 Converter Configurations

The mutual coupling between phases is negligible in SRM. This gives complete independence to each phase winding for control and torque generation. While this feature is advantageous, a lack of mutual coupling requires a careful handling of the stored magnetic field energy. The magnetic field energy has to be provided with a path during commutation of a phase; otherwise, it will result in excessive voltage across the windings and hence on the power semiconductor switches leading to their failure. The manner in which this energy is handled gives way to unique but numerous converter topologies for SRM drives. The energy could be freewheeled, partially converting it to mechanical/electrical energy and partially dissipating it in the machine windings. Another option is to return it to the dc source either by electronic or electromagnetic means. All of these options have given way to power converter topologies with q, (q+1), 1.5q, and 2q switch topologies, where q is the number of machine phases. A two-stage power converter configuration which does not fit categorization based on the number of machine phases is also included. They are considered in detail in the following.

All the converter topologies except the two-stage power converter assume that a dc voltage source is available for their inputs. This dc source may be from batteries or most usually a rectified ac supply with a filter to provide a dc input source to the SRM converter.

3.5 Power Converter for Switched Reluctance Motors

Since the torque in SRM drives is independent of the excitation current polarity, the SRM drives require only one switch per phase winding. Moreover, unlike the ac motor drives, the SRM drives always have a phase winding in series with a switch. Thus, in case of a shoot-through fault, the inductance of the winding limits the rate of rise in current and provides time to initiate the protection. Furthermore, the phases of SRM are independent and, in case of one winding failure, uninterrupted operation is possible. Following are some configurations of converter used in SRM drive.

3.6 Classification of Power Converter for Switched Reluctance Machines

3.6.1 Asymmetric Bridge Converter

Figure 3.2 shows the asymmetric bridge converter considering only one phase of the SRM. The rest of the phases are similarly connected. Turning on transistor T1and T2 will circulate a current in phase A of the SRM. If the current rises above the commanded value T1and T2 are turned off. The energy stored in the motor winding of phase A will keep the current in the same direction until it is depleted. Hence, diode D1and D2 will become forward biased leading to recharging of the source. That will decrease the current, rapidly bringing it below the commanded value. Assuming that a current of magnitude Ip is desired during the positive inductance slope for motoring action, the A-phase current command is generated with a linear inductance profile. Here, phase advancing both at the beginning and during commutation are neglected [9].

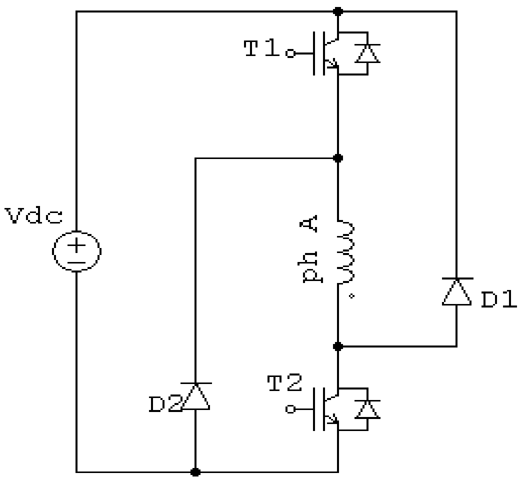


Figure 3.2 Asymmetric bridge converter

The current command, ia*, is enforced with a current feedback loop where it is compared with the phase current, ia. The current error is presumed to be processed through a hysteresis controller with a current window of Δi When the current error exceeds−Δi, the switches T1and T2 are turned off simultaneously. Hysteresis current controller is considered here due to its simplicity in concept and implementation. At that time , diodes, D1and D2 take over the current and complete the path through the dc source [9].

The most common configuration of SRM drive circuit is the asymmetric type with freewheeling and regeneration capability. The performance of this converter depends on the switching strategy, which varies between simultaneous switching of T_1 and T_2, or switching one switch ON and OFF while the other is ON all time. Selecting the proper switching strategy, dwell angle and control technique (usually hysteresis current control) will define the efficiency and application of this converter.

The asymmetric converter is the most common for voltage source operation for low power levels.

The switches and diode used per phase in asymmetric bridge are described here. The number of switches used per phase in asymmetric bridge converter is two. The number of diodes used per phase in asymmetric bridge converter is two.

The advantages of asymmetric bridge converter are as follows

1. Ideal for high performance current and torque control.
2. Allows greater flexibility in controlling machine current.
3. Capable of Positive, Negative, and zero voltage output.
4. Voltage stress across the switching element is restricted to Vdc .

The followings are the major disadvantages of the asymmetric bridge converter configurations of a switched reluctance motors

1. There are high switching losses occur in asymmetric bridge converter.
2. Presence of larger heat sinks.
3. Asymmetric bridge converter not suitable for high power applications.

The major application of asymmetric bridge converter is in low power levels inverters fed from a voltage source.

3.6.2 Asymmetric Converter Variation

Utilization of the power devices is poor in the asymmetrical converter. Their duty cycles can be increased while minimizing the number of self-commutating devices by introducing phase control devices (i.e., silicon-controlled rectifiers, or SCRs). An even number of phases is required to take advantage of this configuration. The SCRs serve mainly to steer currents into selective phases but are not used for control, as they require auxiliary commutation circuit, which increases the component count, cost, and packaging size. The number of diodes is reduced to one per phase which results in considerable savings compared to the two diodes per phase required in the asymmetrical converter discussed earlier. Note that alternate machine phases and not adjacent phases are grouped together under one set of self-commutating device pairs. This allows time for one phase current commutation up to one phase cycle and hence permits independent on and off control of each phase with overlapping currents not exceeding one phase cycle.

The advantages of this power topology are summarized as follows.

1. It has one self-commutating device, one SCR, and one diode per phase; this drive costs less compared to the two switches per phase asymmetrical converter.

2. Higher utilization of the self-commutating devices in this topology (i.e., once in two-phase cycles instead of once in four-phase cycles) decreases cost for high-power SRM drives.

3. The converter is capable of positive (+Vdc), negative (−Vdc), and zero voltage output capability and so it allows greater flexibility in controlling the machine current.

4. Phase current control is independent with a minimum number of self commutating devices.

The disadvantages of this converter are discussed below

1. An SCR is always in the current conduction path, thus increasing the losses in the converter and requiring a larger heat sink for cooling. This would further reduce the system efficiency much more noticeably in low power SRM drives than in high-power SRM drives.

2. Parts count is higher due to SCR gate drive amplifiers with their own isolation requirements.

3.6.3 (n+1) Switches and diode Configuration

Utilization of the power devices is poor in the asymmetric bridge converter. A more efficient converter topology is shown in Fig.3.3, which is called (n+1) switch and diode configuration.

When T1 and T2 are turned on, phase A is energized by applying the source voltage across the phase winding. The current can be limited to the set level by controlling either T1 or T2, or both. Similarly, phase B can be energized by T2 and T3

The merit of this converter is higher utilization of power devices due to the shared switch operation. Nevertheless, the circuit provides restricted current control during overlapping phase currents.

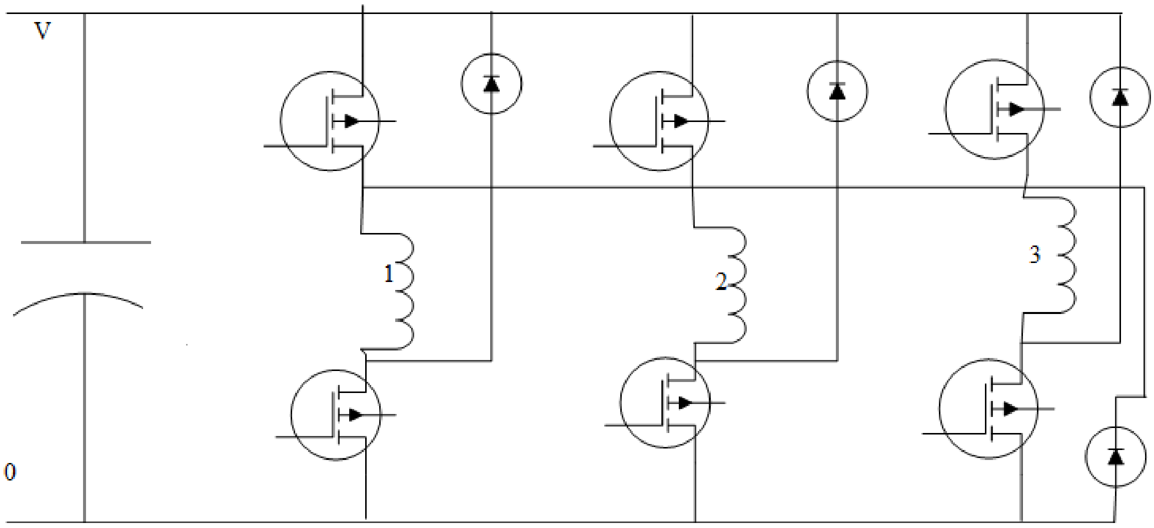


Fig 3.3 (n+1) Switches converter topology

3.6.4 Resonant Converter Circuits

The power converter topologies discussed up to are known as hard-switched topologies because during turn-on and turn-off the power switch and diode voltages and currents are nonzero, thus causing significant power loss in these devices. During the switching instant, if the current or voltage is zero, then the device loss is zero and topologies enabling such a condition are known as resonant circuits. Many variations of these topologies are available. Because the switching losses are theoretically zero in the resonant circuits, the circuit efficiency and hence the overall system efficiency is increased in the motor drive.

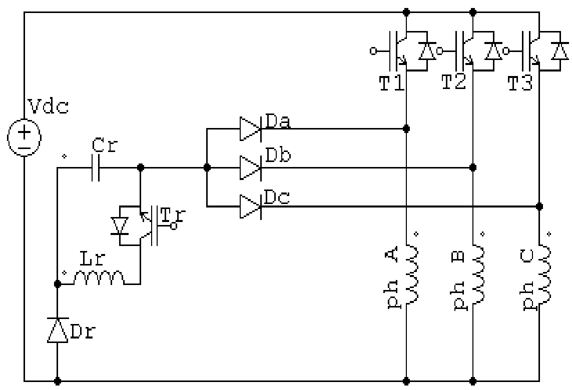


Figure 3.4 Resonant converter .

Further claims are being made as to the electromagnetic interference (EMI) reduction in these circuits compared to the hard-switched topologies that must be taken cautiously in the absence of good experimental correlation. Their main disadvantage is that the device voltage ratings have to be multiple times that of the source voltage due to the action of the resonant circuit. This increases the volt–ampere rating of the converter to multiple times that of the conventional hard-switched topologies, restricting its industrial use in switched reluctance motor drive systems. Its advantage is that the quality of the current waveform can be made very superior as the circuit can be operated at a higher frequency as the device switching losses are very small. Note that the switching losses can become a significant fraction of the conduction losses in the devices at very high frequencies, but at nominal frequencies of 20 kHz and lower that may not be true, hence the need for resonant circuits decreases and it has minimal impact on the motor drive [10].

For the sake of completeness, only one resonant topology is considered in this section a variant of the C-dump circuit topology with resonant commutation of the phase current. Its working is described below.

The resonant circuit consists of the inductor Lr , capacitor Cr, power switch Tr , and diode Dr The machine windings are connected in series with power devices T1, T2, and T3, and diodes D1, D2, and D3 steer the current of the machine phases during commutation and the excess current from the resonant circuit to the dc source, Vdc. Assume that the voltage across the resonant capacitor Vr , is positive and as indicated for positive polarity. The distinct modes of operation are outlined separately [11].

In mode 1,energization of the phase winding is achieved by switching the phase switch (say, T1). When the machine current exceeds the desired level, we wish to turn off the phase switch and reduce the energy transfer from the source to the machine.

In mode 2, turn-off of the phase switch results in the machine current being diverted via Dr , Cr , Da, and the phase-A winding. This charges the resonant capacitor Cr, thus reducing the current in the machine winding. When the current nears the acceptable lower limit, the phase switch T1 is turned on to keep the winding current fairly a constant.

Mode 3 is the resonant mode. With turn-on of the resonant switch, the resonant capacitor and inductor are connected in series, resulting in resonant oscillation. The energy in the capacitor is transferred to the inductor, resulting in the forward biasing of diodes Da and Dr and the current flows from the inductor to the load as well as to the dc source via the diode D1, inductor, device Tr, and Da. The current fed to the source current is the excess current that is over and above that of the load current.

During the resonant oscillation, the voltage across the capacitor has reversed and is negative which is conducive for the takeover of current from the phase switch when it is being turned off. Note that turn-off of the main switches is achieved with zero voltage because its anti parallel diode D1 is conducting during the energy recovery period, thus eliminating the turn-off switching loss in the phase switch.

Because the voltage across the capacitor Cr is two to three times that of the source voltage, its application across the machine winding rapidly commutates the current. This in turn gives a much higher conduction angle for the SRM drive without any concern for regeneration when the desired operation is in the motoring region. Note that this is one of the circuit topologies where the antiparallel diode of the switching device is utilized, whereas in conventional hard-switched topologies they are seldom used.

The switches and diode used per phase in resonant converter are described here. The number of switches used per phase in resonant converter is one. The number of diodes used per phase in resonant converter is one.

The advantages of resonant converter are summarized as follows

1. The switching losses in the resonant converter are very low.
2. The quality of current waveform is superior in resonant converter
3. The switching frequency of resonant converter is high.

The disadvantages of resonant converter are summarized as follows

1. Lower power density.
2. Emi influence problem arises in the resonant converter is very serious problem.
3. Higher rating of switching elements requirement.

The main application of resonant converter is suitable for high frequency applications
(f>20 Khz).

3.6.5Two Stage Power Converter

A scheme capable of transferring electrical power from the machine directly to the ac supply mains is shown in Figure 3.4 with two-stage power conversion. The first stage consists of a controllable converter with six switches and six diodes, and it interfaces input of a three-phase, 60-Hz ac supply to a single-phase, variable frequency ac output. This stage is a controlled rectifier /inverter but without the drawbacks of a low power factor and high input line harmonics. The other power stage is the commutating stage through which each phase winding is energized. Most of the SRM drives (the rectifier–capacitor source), except battery-source cases, cannot directly return the energy from the machine to the source due to the diode bridge and the current limitation of the electrolytic power capacitor, thus only a limited amount of returned energy is stored in the capacitors and reused. As a result, an extra circuit, such as a dump resistor across the capacitor, may be required to limit the voltage rise in the dc link, resulting in a low efficiency. In such cases, the current reversal affects the lifetime of the capacitor due to the frequent charging and discharging actions. However, this converter can return the power from the machine to the source directly without any limitations and eliminates the dc link capacitor. The elimination of dc link capacitor results in cost savings and in the enhancement of the reliability of the scheme and an increase in the power density of the scheme .

A disadvantage of this two-stage converter is its requirement for a higher number of power devices which results in higher costs. It is not economical if the regenerative power is not substantial.

An application that may be suitable for this converter topology is in variable-speed, constant-frequency generation using wind energy.

3.6.5.1 Front-End Converter

The converter configuration is shown in Figure 3.5. It is realized by cascading one switch with a diode for a switching block. It is composed of six MOSFET switches (T1 to T6) and six diodes (D1 to D6). The three-phase ac is connected to the midpoint of each leg and the output is applied across the phase winding. The MOSFETs withstand the positive voltage, and the diodes block the negative voltage excursion.

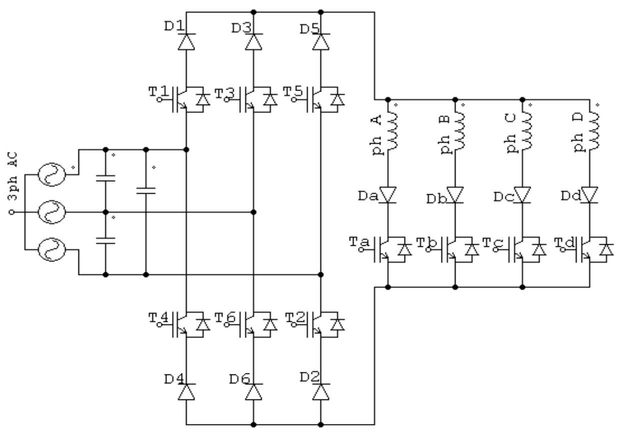


Figure 3.5 Two stage power converter.

Each MOSFET is provided with a turn-off snubber circuitry to reduce the turn-off switching stress. The capacitors on the ac side provide current path when both a top and bottom switch are turned off. It is a two-quadrant converter. Note that the switching block eliminates shoot-through faults; that is, any number of switches can be activated simultaneously without a detrimental outcome. This feature is greatly advantageous in controlling the converter and will be discussed in detail in the section on converter control. The output voltage and switching signal in the PWM mode are very similar to a conventional three-phase diode bridge output with chopping. Peak currents through devices are determined primarily by the machine phase current. The voltage ratings are dependent on the peak voltage of the three-phase ac source [12].

3.6.5.2 Machine-side converter

Each phase winding of the SRM is connected in series with a self-commutating device and a diode. The diodes prevent the phase current reversal, which may happen through the anti parallel diodes of the MOSFETs when the polarity of the applied voltage is changed by the front-end converter for generation. Compared to the frontend converter, the switching frequency of this converter is very low, because it is used only for phase commutation. At the point of commutation, there is no current flowing in the phase winding, which greatly reduces turn-off stresses of the MOSFET switches. Peak currents through the devices are determined primarily by the machine. The peak current and voltage ratings of the devices are the same as those of the front end converter.

3.6.5.3 Operation of the Scheme

Basic operational waveforms are considered to look at the operation of the two-stage converter with an SRM. The front-end converter is basically phase controllable; therefore, the current can flow at any phase of the source voltage. The phase relationship between the phase voltage and current is set at , similar to a thyristor -based, phase-controlled rectifier. Dc link voltage is maximized at the activation angle. The humps in the voltage can be removed by using a low-pass filter on the supply side. The bipolarity current indicates that only one current path is provided for the winding energization and regeneration. In other words, only two phases out of the three phases of the supply are used as the current path at a given time.

The switches and diode used per phase in two stage power converter are described here. The number of switches used per phase in two stage power converter is 1(+6). The number of diodes used per phase in two stage power converter is 1(+6).

The advantages of two stage power converter are summarized as follows

1. The cost of the two stage power converter is very low.
2. The reliability of the two stage power converter is higher than the other converter topology.
3. Higher power density is the another advantage of the this converter topology.

The disadvantages of two stage power converter are summarized as follows

1. Requirement of higher number of switches.
2. Not economical if regenerative operation is not substantial.

The major application of this converter is suitable for variable speed, constant frequency generation using wind energy.

3.6.6 Variable dc Link Converter Topology

An alternate variable dc link voltage converter circuit with four switches and diodes is shown in Figure input voltage to the machine windings. Further, this stage provides the isolation required for faster commutation of the current with the constant source voltage Vdc. The energization mode is initiated by turning on the phase switch (say, T1) and thereby applying the voltage Vi to machine phase A. To regulate the winding, switch T1 is turned off which initiates the routing of the current through the freewheeling diode D1, the dc source voltage Vdc, and phase A winding, regardless of the on or off condition of the chopper switch Tc. That would apply a fixed negative dc source voltage Vdc across the machine phase winding.

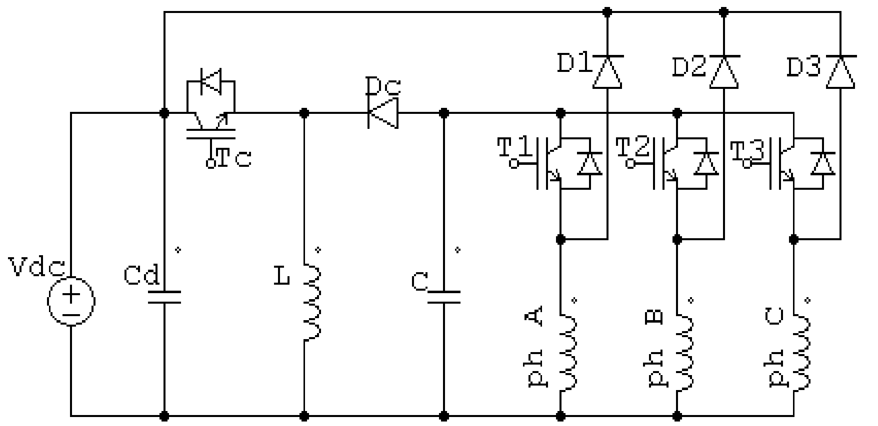


Figure 3.6 Variable dc link converter .

The energy in the output capacitor C will be able to cater to the oncoming phase (say, B) during the time that the switch Tc is turned off. In this manner, the independence between various machine phases is maintained in this converter topology. There is only one switch per machine phase, and it is connected in series with the phase winding which prevents a shoot-through fault. The switch Tc, diode Dc, inductor L, and output capacitor C form the buck-boost, front end power stage. The machine dc link voltage Vi can be varied from zero to greater than (say, two times) the dc source voltage Vdc to obtain the desirable [1].

The distinct advantage of this power converter compared to the converter with a buck converter front end is that the input voltage to the machine phases could be increased over and above the dc source voltage to accelerate the build up of the current in the machine phases.

But a much greater advantage is found in the generation mode of the machine because the phase energization instance coincides near the rotor and stator pole alignment where the inductance is many times greater than the unaligned inductance encountered initially in the motoring mode of operation. These advantages come with a penalty in the voltage rating of the switches. All the machine phase switches have to be rated at least to the maximum output voltage of the chopper. The chopper switch voltage rating is equal to the sum of the dc source and machine input voltages.

For example, assuming that the machine input voltage (i.e., the output voltage of the chopper circuit) is equal to, say, twice the source voltage, then the voltage rating of the chopper rises to three times that of the source voltage. In the buck mode of operation, when the machine input voltage is less than that of the source voltage, the switch ratings are still higher than that of the buck front-end converter while retaining the advantages of the buck front-end converter topology [12, 14].

The switches and diode used per phase in variable dc link converter are described here. The number of switches used per phase in variable dc link converter is one. The number of diodes used per phase in variable dc link converter is one.

The advantages of variable dc link converter are summarized as follows

1. Higher DC source can be adopted in variable dc link converter.
2. Existence of lower core losses in this converter topology.
3. Lower switching losses.
4. Reduced acoustic noise is the main advantage of this converter topology.

The disadvantages of variable dc link converter are summarized as follows

1. Lower commutation voltage.
2. Lower overall system efficiency.
3. Unsuitable for continuous generative operation.

The application of variable DC link converter is that suitable for four quadrant sensor-less applications. And preferred in generation mode of operation.

3.6.7 C-Dump Converter

The C-dump converter is shown in Figure 3.7 with an energy recovery circuit. The stored magnetic energy is partially diverted to the capacitor Cd and recovered from it by the single quadrant chopper comprising of Tr, Lr, and Dr and sent to the dc source. Assume that T1 is turned on to energize phase A and when the A-phase current exceeds the reference,T1 is turned off.

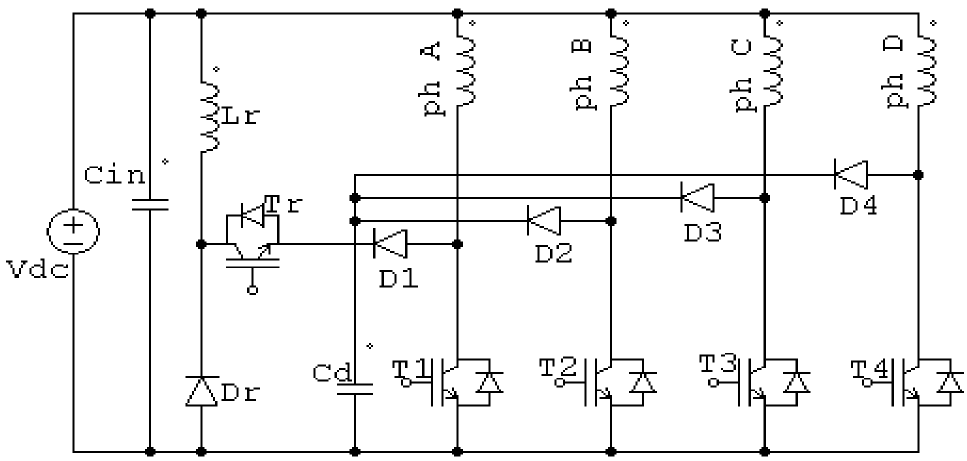


Figure 3.7 C–Dump converter

This enables the diode D1 to be forward biased, and the current path is closed through Cd which increases the voltage across it. This has the effect of reducing the A-phase current, and, when the current falls below the reference by Δi (i.e., current window), T1 is turned on to maintain the current close to its reference. When current has to be turned off completely in phase A, T1 is turned off, and partially stored magnetic energy in phase A is transferred to energy dump capacitor, Cd . The remaining magnetic energy in the machine phase has been converted to mechanical energy [3,4].

This converter has the advantage of minimum switches allowing independent phase current control. The main disadvantage of this circuit is that the current commutation is limited by the difference between voltage across Cd, vo, and the dc link voltage. Speedy commutation of currents requires larger vo, which results in increasing the voltage rating of the power devices. Further, the energy circulating between Cd and the dc link results in additional losses in the machine, Tr, Lr, and Dr, thereby decreasing the efficiency of the motor drive.

The energy recovery circuit is activated only whenT1, T2, T3, orT4 switches are conducting to avoid freewheeling of the phase currents. The control pulses to Tr end with the turn-off of the phase switches. The control pulse is generated based on the reference and actual value of E with a window of hysteresis to minimize the switching of Tr. This circuit has gained in popularity since its introduction in the early stages of SRM drive research and development; therefore, a detailed analysis of this circuit is presented here. Analysis in the following sections considers computation of switching losses of the power devices, maximum voltage, and current ratings of the power devices for an SRM drive of known power rating; ratings of the energy recovery capacitor, Cd, inductor, Lo, and its duty cycle; and the efficiency of the overall circuit [15].

The switches and diode used per phase in C-Dump converter are described here. The number of switches used per phase in C-Dump converter is one. The number of diodes used per phase in C-Dump converter is one.

The advantages of C-Dump converter are summarized as follows

1. Requirement of minimum number of switches.
2. Independent phase current control is possible in C-Dump converter.

The disadvantages of C-Dump converter are summarized as follows

1. Current commutation is limited by the difference between the voltage across Cd and the link.
2. C-Dump converter is not suitable for high speeds.
3. Efficiency of the C-Dump converter is lower .
4. C-Dump converter is unable to provide zero voltage .

The application of the C-Dump converter in the low speed applications .

3.6.8 Split Dc Supply Converter

A split dc supply for each phase allows freewheeling and regeneration, as shown in Figure 3.8. This topology preserves one switch per phase; its operation is as follows. Phase A is energized by turning on T1. The current circulates through T1, phase A, and capacitor C1. When T1 is turned off, the current will continue to flow through phase A, capacitor C2, and diode D2. In that process, C2 is being charged up and hence the stored energy in phase A is depleted quickly. Similar operation follows for phase B. A hysteresis current controller with a window of Δi is assumed. The phase voltage is Vdc /2 when T1 is on, and when it is turned off with a current established in phase A, the phase voltage is –Vdc/2. The voltage across the transistor T1 during the on time is negligible, and it is Vdc when the current is turned off. That makes the switch voltage rating at least equal to the dc link voltage. As the stator current reference, goes to zero, the switch T1 is turned off regardless of the magnitude of ia. When the winding current becomes zero, the voltage across T1 drops to 0.5 Vdc and so also does the voltage across D2. Note that this converter configuration has the disadvantage of derating the supply dc voltage, Vdc, by utilizing only half its value at any time. Moreover, care has to be exercised in balancing the charge of C1 and C2 by proper design measures [16].

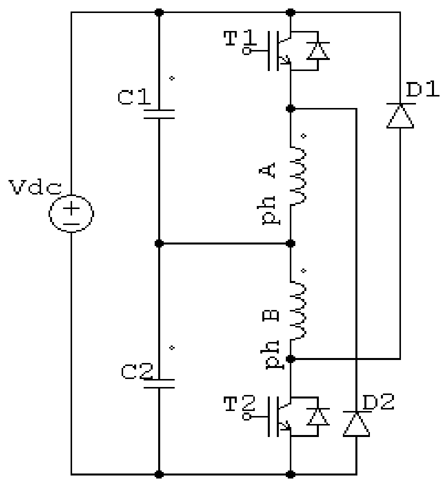


Figure 3.8 Split dc supply converter

For balancing the charge across the dc link capacitors, the number of machine phases has to be even and not odd. In order to improve the cost-competitive edge of the SRM drive, this converter was chosen in earlier integral horse power (hp) product developments, but its use in fractional hp SRM drives supplied by a single phase 120-V ac supply is much more justifiable; the neutral of the ac supply is tied to the midpoint of the dc link and so capacitors can be rated to 200 V dc, thus minimizing the cost of the converter.

The switches and diode used per phase in split dc supply converter are described here. The number of switches used per phase in split dc supply converter is one. The number of diodes used per phase in split dc supply converter is one.

The advantages of the split dc supply converter are as follows

1. Compactness of converter package.
2. Lower cost due to minimum number of switches and diodes.
3. Capability of regeneration of stored energy.

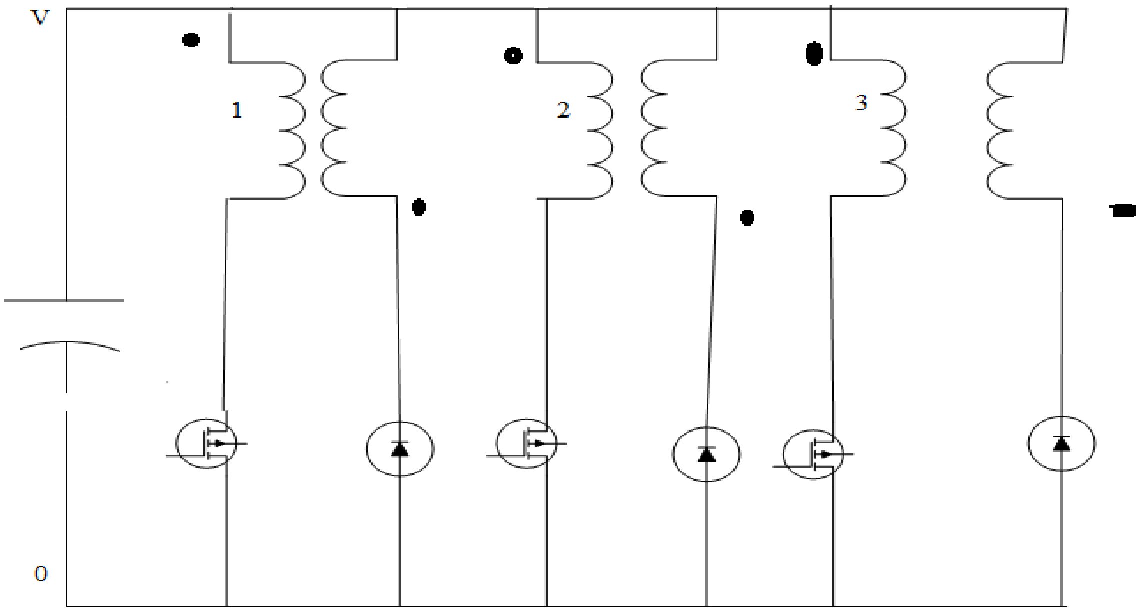
The disadvantages of the split dc supply converter are as follows

1. De –rating of the supply voltage.
2. Suitable only for motors with an even number of phases.

Application of split dc supply converter is in fractional hp motors with even number of phases.

3.6.9 Bifilar Type Converter

Fig.3.9 shows a converter configuration with one power switch and one diode per phase but regenerating the stored magnetic energy to the source. This is achieved by having a bifilar winding with the polarity as shown in the figure 3.9.



(a) 3.9 Bifilar type drive

It is shown that the voltage across the power switch can be very much higher than the source voltage. A disadvantage of this drive is that the SRM needs a bifilar winding, which increases the complexity of the motor. The Bifilar type converter , also has one switch and one diode per phase but with the capability of regenerating the stored magnetic energy to the supply by the bifilar winding. This converter is also utilizing one switch per phase. The bifilar converter has the drawbacks of reduced power density, and the high stress on the switching elements due to the bifilar windings inductance.

Figure 3.10 shows a converter configuration with one transistor and one diode per phase but regenerating the stored magnetic energy to the source. This is achieved by having a bifilar winding with the polarity as shown in the figure 3.10. When the phase-A current is turned off by removing the base drive signal to T1, the induced Emf in the winding is of such polarity that D1 is forward biased. This leads to the circulation of current through D1, the bifilar secondary winding, and the source, thus transferring energy from the machine winding to the source [17].

During current turn-off, the applied voltage across the bifilar secondary winding is equal to the dc link voltage. The voltage reflected into the main winding is dependent upon the turns ratio of the windings.

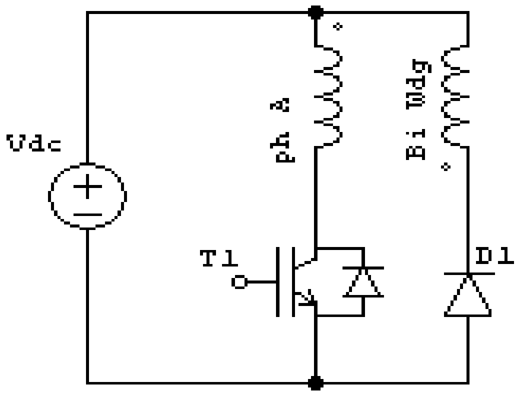


Figure 3.10 Bifilar type converter

Considering the turns ratio between the main winding in series with the power switch and the auxiliary winding in series with the diode as a, the voltage across the power switch is

$$V_{T1} = Vdc + aVdc = (1 + a)Vdc \quad (3.1)$$

This shows that the voltage across T1 can be very much greater than the source voltage. One switch per phase comes with a voltage penalty on the switch. The volt ampere (VA) capability of the switch will not be very different for one switch compared to two switches per phase circuit. The disadvantage of this drive is that the SRM needs a bifilar winding and such a form of winding is not economical for large motors. Also, the bifilar windings require additional slot volume, reducing the power density of the SRM [12].

The switches and diode used per phase in bifilar type converter are described here. The number of switches used per phase in bifilar type converter is one. The number of diodes used per phase in bifilar type converter is one.

The advantages of bifilar type converter are summarized as follows

1. Compactness of converter package.
2. Lower cost due to minimum number of switches and diodes.
3. Capability of regeneration of stored energy.

The disadvantages of bifilar type converter are summarized as follows

1. High stress on switching element.
2. Reduced power density.

One of the major application of bifilar type converter is not economical for large motors.

3.6.10 R-Dump Converter

Figure 3.11 shows a converter configuration with one transistor and one diode per phase of the SRM. When T1 is turned off, the current freewheels through D1, charging Cs, and later flows through the external resistor R. This resistor partially dissipates the energy stored in phase A. This has the disadvantage that the current in phase A will take longer to extinguish compared to recharging the source. The energy, in addition, is dissipated in a resistor, thus reducing the overall efficiency of the motor drive [18].

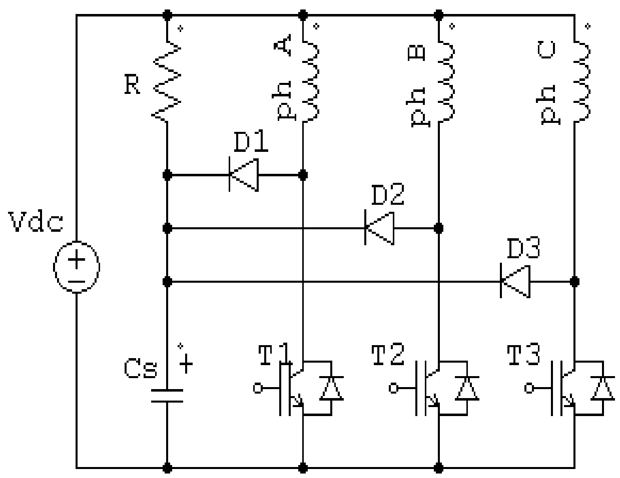


Figure 3.11 R-Dump converter.

The hysteresis current controller turns off T1 when the phase current exceeds the current command, by Δi. Turning off T1 will reduce the current, which in turn induces an emf in the winding to sustain ia in the same direction. This emf forward biases diode D1. The voltage across the resistor R is iaR. Note that the voltage across the resistor has a positive polarity with respect to the positive rail of the source voltage.

Design considerations such as the turn-off transient voltage have to be included in the rating of the switch T1. The selection of R not only determines the power dissipation but also the switch voltage. A lower value of R increases the fall time of the current. If the current comes under the negative slope region of the phase inductance, negative torque will be generated, decreasing the average motoring torque. A high value of R increases the voltage drop across the winding and hence across T1 [12].

The switches and diodes used per phase in R-Dump converter are described here. The number of switches used per phase in R-Dump converter is one. The number of diodes used per phase in R-Dump converter is one.

The advantages of R-Dump converter are summarized as follows

1. Compactness of converter package

2. Lower cost due to minimum number of switches and diodes.

The disadvantages of R-Dump converter are summarized as follows

1. Unable to apply zero voltage output during current conduction.

2. Reduced system efficiency.

3. Rate of change of phase voltage is doubled.

The application of R-Dump converter is in low speed and low switching frequencies applications.

3.7 Advantages of Introducing Capacitor

Because the voltage across the capacitor Cr is two to three times that of the source voltage, its application across the machine winding rapidly commutates the current. This in turn gives a much higher conduction angle for the SRM drive without any concern for regeneration when the desired operation is in the motoring region. Note that this is one of the circuit topologies where the anti parallel diode of the switching device is utilized, whereas in conventional hard-switched topologies they are seldom used.

The advantage of introducing capacitor in asymmetric bridge converter is discussed. In asymmetric bridge converter a capacitor is connected in series with the motor windings. This capacitor is charged resonantly by the use of motor phase windings during the phase turn off periods. In addition, an energy recovery circuit causes the trapped energy on resonant capacitor to be recovered by a single quadrant chopper comprising of a transistor, a capacitor and a diode. This topology provides faster rate of fall for the phase current, which permits the motor to operate at higher speeds. This is the advantage of introducing a capacitor in asymmetric bridge converter is that the motor operate at higher speeds and a less number of shoot through faults in the switched reluctance motor drive [12].

3.8 Selection of the Proper Converter Topology

However the selection of the proper converter for a certain application depends on many factors the designer has to compromise between them, such as;

1. The hp capability- For which hp capability the converter is suitable. This the main considerations taken into account foe choosing a particular converter topology for a particular requirement.

2. Size and volume requirement-The power converter having small size and less volume requirement is preferable in most of the applications.

3. Economic considerations-The cost of power converter is important factor taken into account while selecting a power converter. A low cost power converter is usually suitable.

4. Speed requirements-The power converter suitable for high speed range is generally preferable.

5. Switching frequency's range requirement.

6. Whether the machine is used for motoring or for generation [12].

The comparisons between the different converter topologies on the basis of switches per phase, diode per phase, advantages , disadvantages and application basis is done. From the literature review and the above comparison between different topologies of converters which are utilized as an SRM drive circuits, it has been shown that the asymmetric converter topology is the most common topology which is used for most of the applications of the switched reluctance machines in industry, therefore this converter will be used at very large scale in SRM drive circuits.

3.9 Conclusion

Thus we have discussed about the various converter topology used in SRM drives. From the discussion it follows that asymmetric bridge converter is the most common topology used for SRM drives. This topology provide much faster rate of fall for the phase current which permits the motor to operate at higher speeds in comparison to other types of converters. Faster rate of fall for the phase current also reduces the shoot through fault. The asymmetric bridge converter provides freewheeling, regeneration and phase independence capability The asymmetric bridge circuit is more suitable for the high power drive than the other types of the circuit. Because of absence of the resistance commutation circuit there is no high heat generation in the asymmetric bridge converter. Also the absence of any coil in the asymmetric bridge converter there is no presence of the copper losses. These reasons makes the asymmetric bridge converter most suitable for high power drive.

In other converters bifilar winding converter and split dc supply converter provide capability of regeneration of stored energy. C-Dump converter provides independent phase current control. The resonant converter provides high switching frequency capability and two stage power converter provides higher power density.

In the next chapter we are going to highlight about the SPICE simulations of the various converter topologies. Finally a comparison is being made among the various topologies with regard to total harmonic distortion, fourier analysis and phase current

CHAPTER 4

Results and Discussions

4.1 Introduction

This chapter discusses the P-SPICE simulation of asymmetric bridge converter, bifilar winding converter, R-dump converter, two stage power converter, variable dc link converter, split dc supply converter, resonant converter, and C-dump converter used predominantly in SRM drives. The Total Harmonic Distortion(THD) , Fourier analysis, small signal bias solution and operating point information for the diodes and transistors are obtained and compared for each of the above mentioned converter configurations . Finally the phase current of the windings of the each of the converters are show

4.2 P-Spice Simulation for the Asymmetric Bridge converter

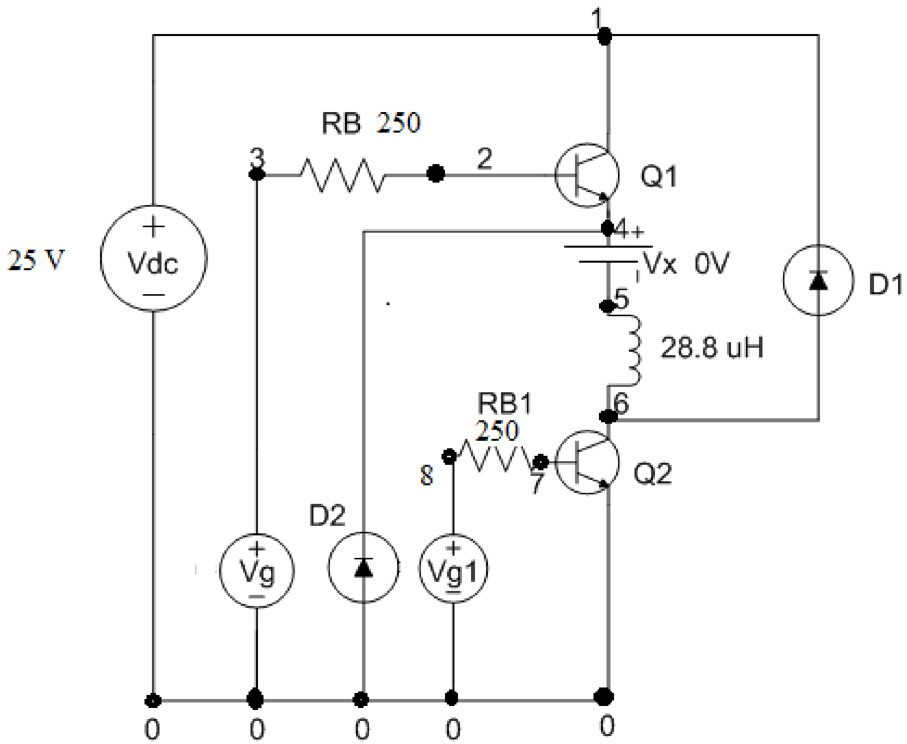


Fig.4.1 P-Spice circuit for the asymmetric bridge converter

4.2.1 Fourier Analysis

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	1.200E+02	4.947E-04	1.000E+00	7.928E+01	0.000E+00
2	2.400E+02	4.942E-04	9.991E-01	6.855E+01	-9.000E+01
3	3.600E+02	4.935E-04	9.976E-01	5.783E+01	-1.800E+02

4	4.800E+02	4.924E-04	9.954E-01	4.711E+01	-2.700E+02
5	6.000E+02	4.911E-04	9.927E-01	3.638E+01	-3.600E+02
6	7.200E+02	4.894E-04	9.893E-01	2.566E+01	-4.500E+02
7	8.400E+02	4.875E-04	9.854E-01	1.493E+01	-5.400E+02
8	9.600E+02	4.852E-04	9.808E-01	4.210E+00	-6.300E+02
9	1.080E+03	4.827E-04	9.757E-01	-6.513E+00	-7.200E+02

Table 4.1 Fourier analysis for the asymmetric bridge converter

TOTAL HARMONIC DISTORTION = 2.798788E+02 PERCENT

So the input current THD=27.98%=0.2798

TEMPERATURE = 27.000 DEG C

FOURIER COMPONENTS OF TRANSIENT RESPONSE I (VX)

DC COMPONENT = 2.474232E-04

4.2.2 Small Signal Bias Solution TEMPERATURE = 27.000 DEG C

NODE	VOLTAGE	NODE	VOLTAGE	NODE	VOLTAGE	NODE	VOLTAGE
(1)	2.459E-09	(2)	619.8E-15	(3)	0.0000	(4)	1.796E-09
(5)	1.796E-09	(6)	1.796E-09	(7)	58.88E-15	(8)	0.0000

Table 4.2 Small signal bias solution for the asymmetric bridge converter

4.2.3 Voltage Source Currents

NAME	CURRENT
Vx	4.400E-15
VG	2.479E-15
VG1	2.355E-16

Table 4.3 Voltage source currents analysis for the asymmetric bridge converter

4.2.4 Operating Point Information

Diodes

NAME	D1	D2
MODEL	DNAME	DNAME
ID	1.28E-14	3.47E-14
VD	6.63E-10	1.80E-09
REQ	5.17E+04	5.17E+04
CAP	0.00E+00	0.00E+00

Bipolar Junction Transistor

NAME	Q1	Q2
MODEL	MODQ1	MODQ1
IB	-4.52E-21	-3.07E-21
IC	5.04E-21	5.33E-21
VBE	-1.80E-09	5.89E-14
VBC	-2.46E-09	-1.80E-09
VCE	6.63E-10	1.80E-09
BETADC	-5.04E-01	-5.33E-01
GM	6.68E-21	1.81E-20
RPI	5.66E+12	5.66E+12
RX	0.00E+00	0.00E+00
RO	7.93E+11	7.93E+11
CBE	4.49E-12	4.49E-12
CBC	3.02E-19	3.02E-19
CJS	0.00E+00	0.00E+00
BETAAC	3.78E-08	1.02E-07
CBX/CBX2	0.00E+00	0.00E+00
FT/FT2	2.37E-10	6.40E-10

Table 4.4 Operating point information for the asymmetric bridge converter

4.2.5 Plot Results for the asymmetric bridge converter

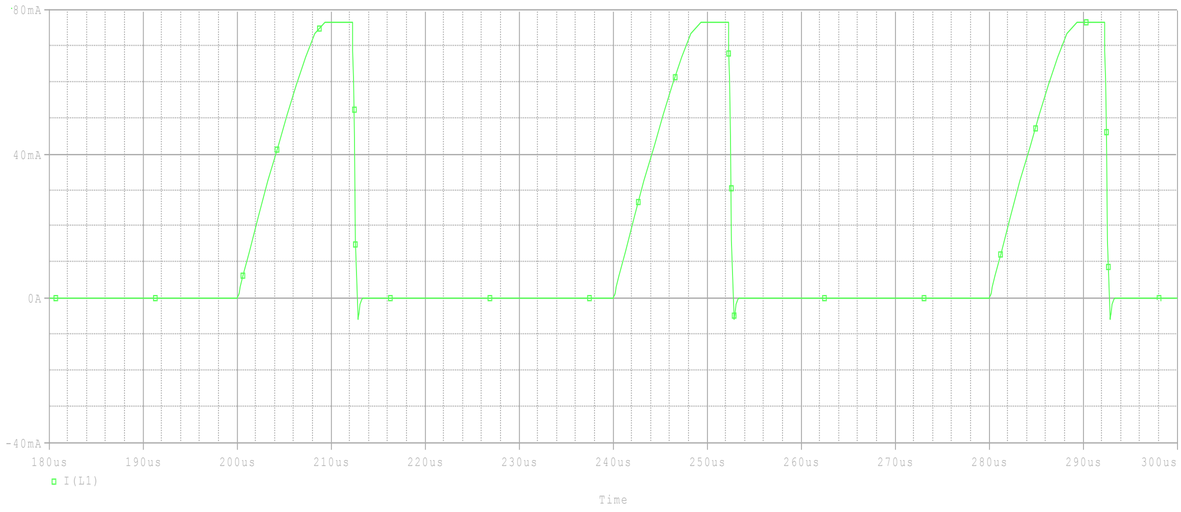


Fig.4.2 Variation of phase current with respect to time

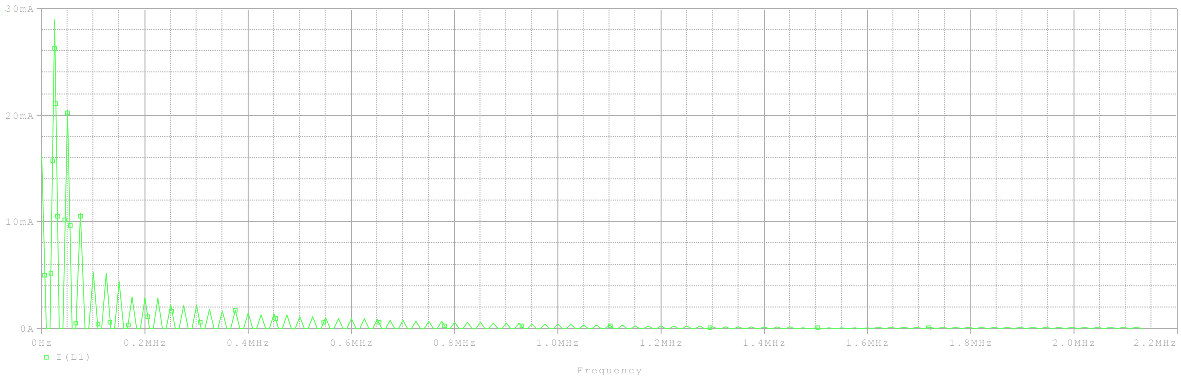


Fig.4.3 Fast fourier analysis for the phase winding of asymmetric bridge

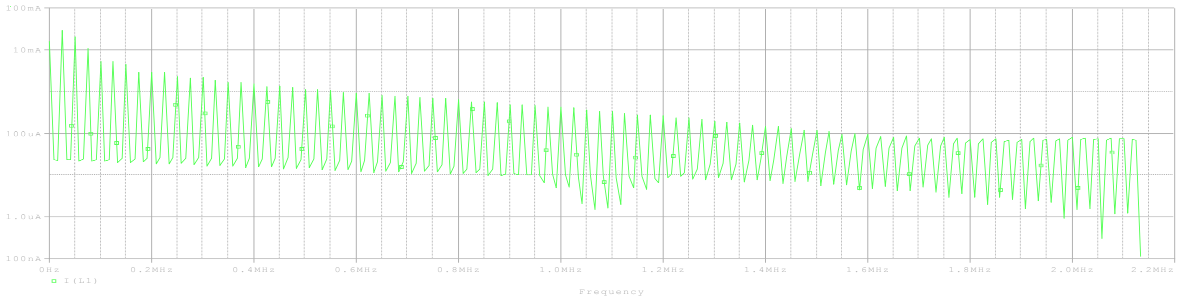


Fig.4.4 Variation of phase current with respect to frequency

4.2.6 Power factor calculation

Input current THD=27.77%=0.2777

Displacement angle Ø1=79.28

DF=cos(Ø1)=cos (79.28)=0.1860096

The input PF=1/ (1+THD^2)^1/2×Cos(Ø1)= 0.179(leading)

4.2.7 Conclusion

This topology provide much faster rate of fall for the phase current as shown in plot for phase current which permits the motor to operate at higher speeds in comparison to other types of converter. Faster rate of fall for the phase current also reduces the shoot through fault. Hence the asymmetric bridge converter also reduces the shoot through faults. It is important to achieve the fault tolerant control of the high power switched reluctance motor drive in order to enhance the reliability of the drive. The asymmetric bridge circuit, in which independent phase control is possible so fault tolerant control of drive is possible in asymmetric bridge converter.

The asymmetric bridge circuit is more suitable for the high power drive than the other types of the circuit. Because of absence of the resistance commutation circuit there is no high heat generation in the asymmetric bridge converter. Also the absence of any coil in the asymmetric bridge converter there is no presence of the copper losses. These reasons makes the asymmetric bridge converter most suitable for high power drive.

From the results it is concluded that asymmetric bridge converter have low harmonic distortion and used for leading power factor SRM drives.

4.3 P-spice Simulation for the Resonant Converter

4.3.1 Small Signal Bias Solution

NODE	VOLTAGE	NODE	VOLTAGE	NODE	VOLTAGE	NODE	VOLTAGE
(1)	-43.58E-06	(2)	2.849E-15	(3)	0.0000	(4)	0.0000
(5)	0.0000	(6)	2.849E-15	(7)	0.0000	(8)	0.0000
(9)	0.0000	(11)	2.849E-15	(12)	0.0000	(13)	0.0000
(14)	0.0000	(15)	.1868	(16)	.1781	(17)	.1781
(18)	47.18E-12	(19)	0.0000	(20)	.1781		

Table 4.5 Small signal bias solution for the resonant converter

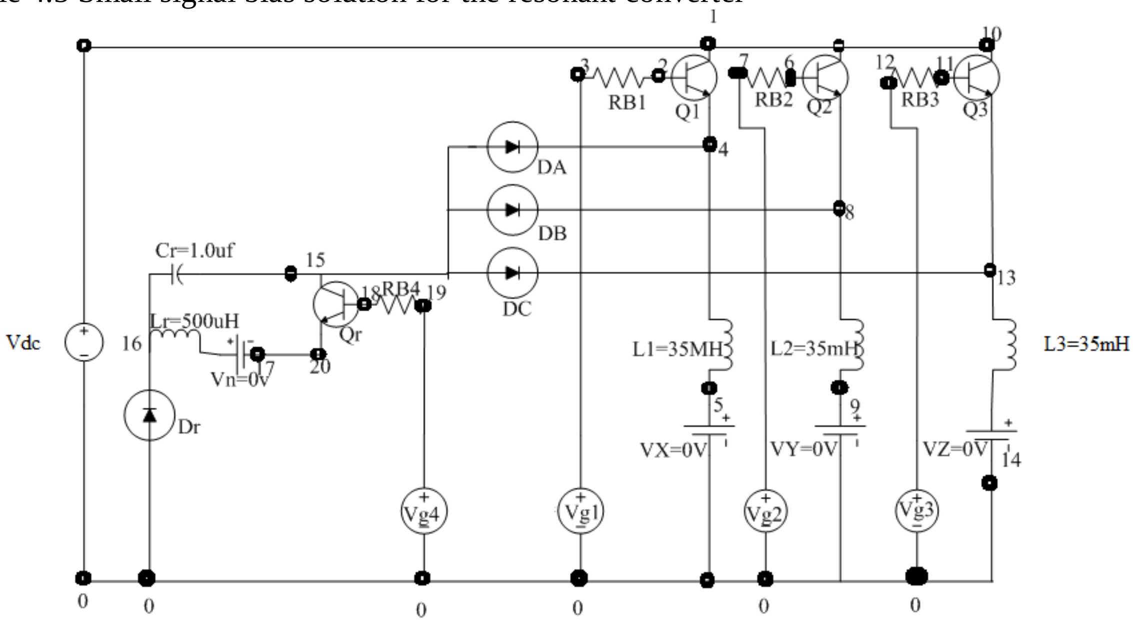


Fig.4.5 P-spice circuit for the resonant converter

4.3.2 Fourier Analysis

TEMPERATURE = 27.000 DEG C

FOURIER COMPONENTS OF TRANSIENT RESPONSE I (VX)

DC COMPONENT = 9.142905E-04

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE(DEG)
1	1.200E+02	1.825E-03	1.000E+00	8.453E+01	0.000E+00
2	2.400E+02	1.812E-03	9.934E-01	7.906E+01	-8.999E+01
3	3.600E+02	1.792E-03	9.823E-01	7.360E+01	-1.800E+02
4	4.800E+02	1.764E-03	9.670E-01	6.816E+01	-2.699E+02
5	6.000E+02	1.729E-03	9.476E-01	6.275E+01	-3.599E+02

6	7.200E+02	1.686E-03	9.241E-01	5.738E+01	-4.498E+02
7	8.400E+02	1.636E-03	8.969E-01	5.204E+01	-5.396E+02
8	9.600E+02	1.580E-03	8.661E-01	4.676E+01	-6.294E+02
9	1.080E+03	1.518E-03	8.320E-01	4.155E+01	-7.192E+02

Table 4.6 Fourier analysis for the resonant converter

TOTAL HARMONIC DISTORTION = 2.624040E+02 PERCENT

So the input current THD=26.24 %=0.2624

4.3.3 Voltage Source Currents

NAME	CURRENT
VG1	1.140E-17
VX	-6.523E-14
VG4	1.887E-13
VL	-6.934E-15
VG2	1.140E-17
VY	-6.523E-14
VG3	1.140E-17
V2	-6.523E-14

Table 4.7 Voltage source currents for the resonant converter

4.3.4 Operating Point Information

Diodes

NAME	DA	DB	DC	DR
MODEL	DMOD	DMOD	DMOD	DMOD
ID	1.37E-10	1.37E-10	1.37E-10	9.79E-11
VD	1.87E-01	1.87E-01	1.87E-01	1.78E-01
REQ	1.89E+08	1.89E+08	1.89E+08	2.64E+08
CAP	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Bipolar Junction Transistor

NAME	Q1	QR	Q2	Q3
MODEL	QM	QM	QM	QM
IB	4.38E-17	-1.89E-13	4.38E-17	4.38E-17
IC	-8.75E-17	1.96E-13	-8.75E-17	-8.75E-17
VBE	2.85E-15	-1.78E-01	2.85E-15	2.85E-15
VBC	4.36E-05	-1.87E-01	4.36E-05	4.36E-05
VCE	-4.36E-05	8.73E-03	-4.36E-05	-4.36E-05
BETADC	-2.00E+00	-1.04E+00	-2.00E+00	-2.00E+00
GM	-6.08E-18	-8.61E-17	-6.08E-18	-6.08E-18
RPI	9.96E+13	1.00E+14	9.96E+13	9.96E+13
RX	5.00E+00	5.00E+00	5.00E+00	5.00E+00

RO	9.96E+11	9.98E+11	9.96E+11	9.96E+11
CBE	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CBC	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CJS	0.00E+00	0.00E+00	0.00E+00	0.00E+00
BETAAC	-6.06E-04	-8.61E-03	-6.06E-04	-6.06E-04
CBX/CBX2	0.00E+00	0.00E+00	0.00E+00	0.00E+00
FT/FT2	-9.68E+01	-1.37E+03	-9.68E+01	-9.68E+01

Table 4.8 Operating point information for the resonant converter

4.3.5 Plot results for the resonant converter

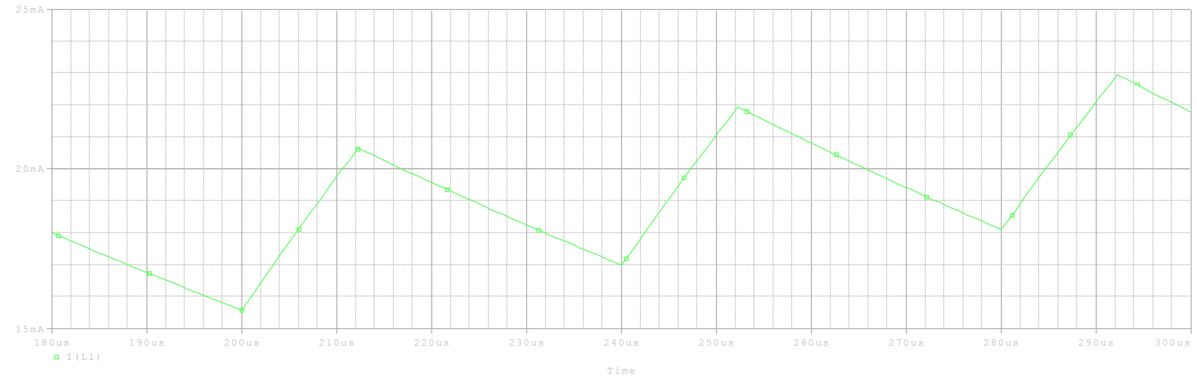


Fig.4.6Variation of phase current with respect to time

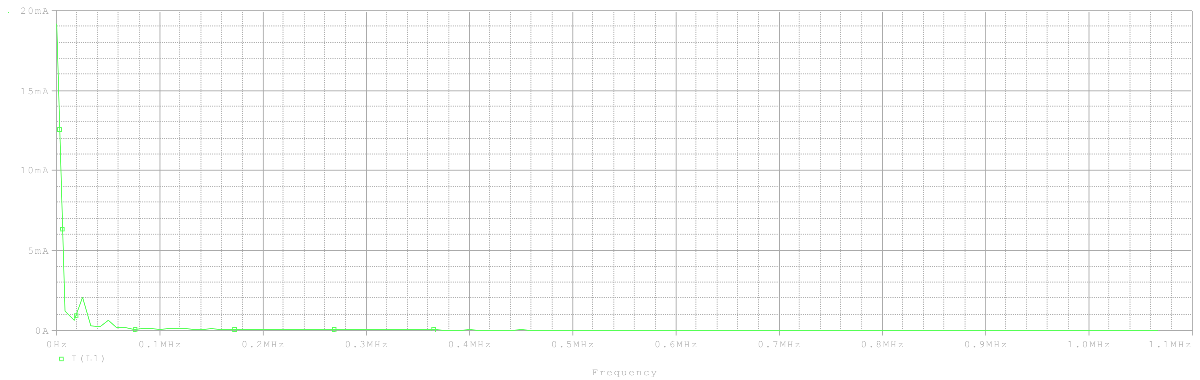


Fig.4.7 Fast fourier analysis for the phase winding of resonant converter

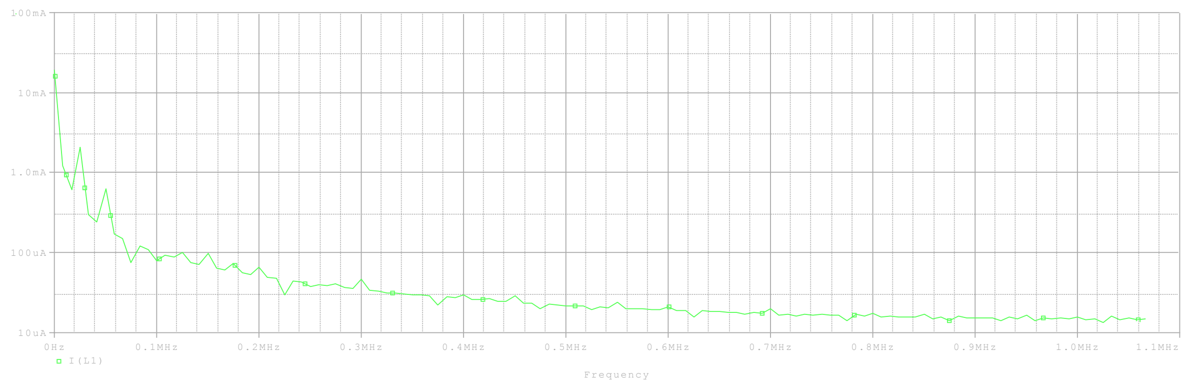


Fig.4.8 Variation of the phase current with respect to frequency

4.3.6 Conclusions

The drive circuit with resonant circuit shows much faster decay time than the bifilar winding configuration. It provide faster rate of fall for the phase current, which permits the motor to operate at higher speeds. The plot results for the resonant converter shows that it provides the linear rise and fall for the phase current. The total harmonic distortion for the resonant converter is very low so it provides superior current waveforms.

The resonant converter has many advantages such as a simple configuration, low voltage stress, improved utilization of supply voltage and in particular no stresses or losses in the switching interval. The fourier analysis and analysis of phase current with frequency is done.

4.4 P-spice Simulation for the Two Stage Power Converter

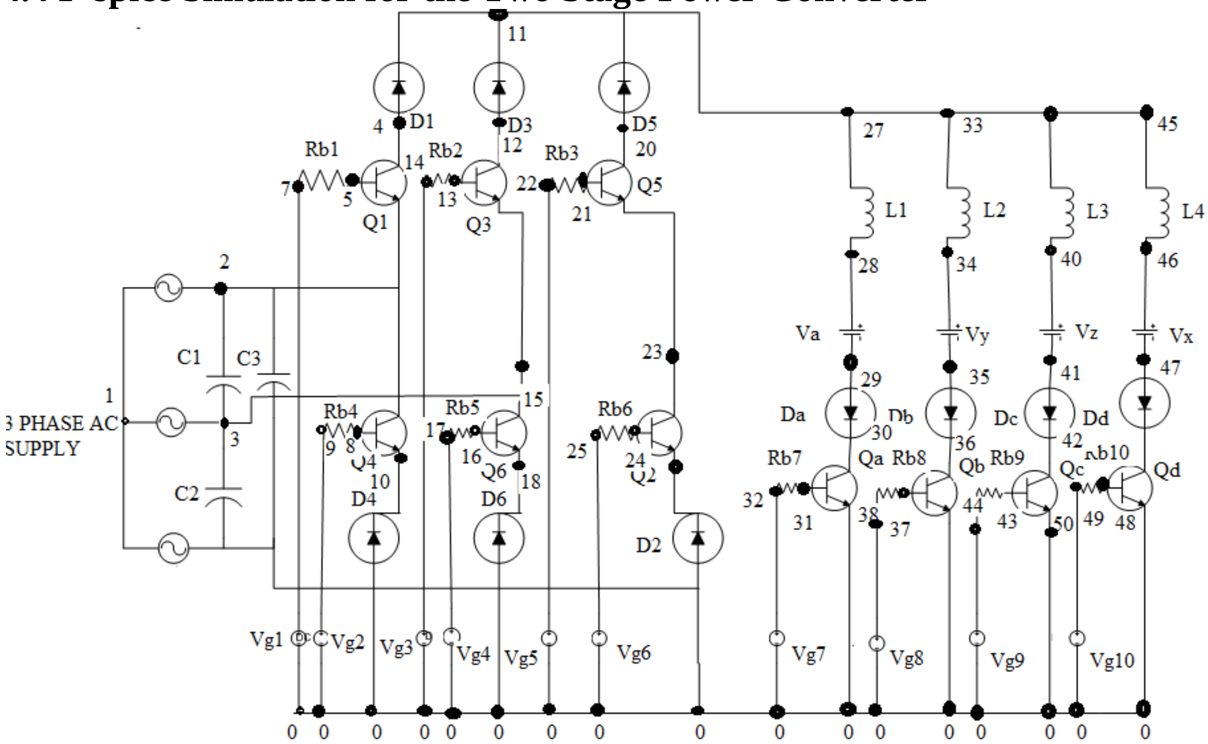


Fig.4.9 P-spice circuit for the two stage power converter

4.4.1 Fourier Analysis

TEMPERATURE = 27.000 DEG C

FOURIER COMPONENTS OF TRANSIENT RESPONSE I (VX)

DC COMPONENT = 2.336725E-17

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE(DEG)
1	1.200E+02	4.671E-17	1.000E+00	8.742E+01	0.000E+00
2	2.400E+02	4.663E-17	9.984E-01	8.484E+01	-9.000E+01
3	3.600E+02	4.651E-17	9.957E-01	8.227E+01	-1.800E+02

4	4.800E+02	4.634E-17	9.920E-01	7.970E+01	-2.700E+02
5	6.000E+02	4.611E-17	9.873E-01	7.713E+01	-3.600E+02
6	7.200E+02	4.584E-17	9.815E-01	7.457E+01	-4.500E+02
7	8.400E+02	4.553E-17	9.747E-01	7.202E+01	-5.399E+02
8	9.600E+02	4.516E-17	9.669E-01	6.948E+01	6.299E+02
9	1.080E+03	4.476E-17	9.582E-01	6.695E+01	-7.198E+02

Table 4.9 Fourier analysis for the two stage power converter

TOTAL HARMONIC DISTORTION = 2.777301E+02 PERCENT

So the input current THD=27.77%=0.2777

4.4.2 Small Signal Bias Solution TEMPERATURE = 27.000 DEG C

NODE	VOLTAGE	NODE	VOLTAGE	NODE	VOLTAGE	NODE	VOLTAGE
2	610.6E-06	3	610.6E-06	4	412.6E-06	5	260.3E-15
6	0.0000	7	0.0000	8	675.5E-15	9	0.0000
10	.0016	11	.1986	12	412.6E-06	13	260.3E-15
14	0.0000	15	0.0000	16	675.5E-15	17	0.0000
18	.0016	19	0.0000	20	.0054	21	4.052E-12
22	0.0000	23	.0576	24	23.39E-12	25	0.0000
26	.2067	27	.2083	28	.2083	29	.2083
30	.0152	31	6.793E-12	32	0.0000	33	.2050
34	.2050	35	.2050	36	-192.6E-06	37	-18.94E-18
38	0.0000	39	0.0000	40	.2050	41	.2050
42	-192.6E-06	43	-18.94E-18	44	0.0000	46	.2050
47	.2050	48	-192.6E-06	49	-18.94E-18	50	0.0000

Table 4.10 Small signal bias solution for the two stage power converter

4.4.3 Voltage Source Currents

NAME	CURRENT
VA	4.720E-14
VX	0.000E+00
VZ	0.000E+00
VX	0.000E+00
VG1	1.041E-15
VG2	2.702E-15

VG3	1.041E-15
VG4	2.702E-15
VG5	1.621E-14
VG6	9.357E-14
VG7	2.717E-14
VG8	-7.576E-20
VG9	-7.576E-20
VG10	-7.576E-20

Table 4.11 Voltage source currents for the two stage power converter

4.4.4 Operating Point Information TEMPERATURE = 27.000 DEG C

Diodes

NAME	MODEL	ID	VD	REQ	CAP
D1	DMOD	2.13E-10	1.98E-01	1.22E+08	0.00E+00
D2	DMOD	2.95E-10	2.07E-01	8.76E+07	0.00E+00
D3	DMOD	2.13E-10	1.98E-01	1.22E+08	0.00E+00
D4	DMOD	7.97E-15	1.60E-03	1.96E+11	0.00E+00
D5	DMOD	2.55E-10	2.03E-01	1.01E+08	0.00E+00
D6	DMOD	7.97E-15	1.60E-03	1.96E+11	0.00E+00
DA	DMOD	1.74E-10	1.93E-01	1.48E+08	0.00E+00
DB	DMOD	2.79E-10	2.05E-01	9.29E+07	0.00E+00
DC	DMOD	2.79E-10	2.05E-01	9.29E+07	0.00E+00
DD	DMOD	2.79E-10	2.05E-01	9.29E+07	0.00E+00

Bipolar Junction Transistor

NAME	Q1	Q2	Q3	Q4	Q5
MODEL	MODQ1	MODQ1	MODQ1	MODQ1	MODQ1
IB	-8.11E-16	-9.35E-14	-8.11E-16	-1.32E-15	-1.44E-14
IC	4.56E-16	-6.35E-14	4.56E-16	-1.91E-16	-4.79E-14
VBE	-6.11E-04	-2.07E-01	-6.11E-04	-1.60E-03	-5.76E-02
VBC	-4.13E-04	-5.76E-02	-4.13E-04	-6.11E-04	-5.42E-03
VCE	-1.98E-04	-1.49E-01	-1.98E-04	-9.86E-04	-5.22E-02
BETADC	-5.62E-01	6.78E-01	-5.62E-01	1.45E-01	3.32E+00
GM	-1.95E-15	-2.80E-14	-1.95E-15	-9.52E-15	-1.83E-13

RPI	5.75E+12	3.08E+14	5.75E+12	5.90E+12	2.39E+13
RX	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RO	7.96E+11	9.73E+11	7.96E+11	7.97E+11	8.26E+11
CBE	4.49E-12	4.22E-12	4.49E-12	4.49E-12	4.41E-12
CBC	3.01E-19	2.46E-19	3.01E-19	3.00E-19	2.90E-19
CJS	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
BETAAC	-1.12E-02	-8.62E+00	-1.12E-02	-5.61E-02	-4.38E+00
CBX/CBX2	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
FT/FT2	-6.92E-05	-1.06E-03	-6.92E-05	-3.37E-04	-6.61E-03
NAME	Q6	QA	QB	QC	QD
MODEL	MODQ1	MODQ1	MODQ1	MODQ1	MODQ1
IB	-1.32E-15	-2.48E-14	3.30E-16	3.30E-16	3.30E-16
IC	-1.91E-16	4.30E-14	-5.73E-16	-5.73E-16	-5.73E-16
VBE	-1.60E-03	6.79E-12	-1.89E-17	-1.89E-17	-1.89E-17
VBC	-6.11E-04	-1.52E-02	1.93E-04	1.93E-04	1.93E-04
VCE	-9.86E-04	1.52E-02	-1.93E-04	-1.93E-04	-1.93E-04
BETADC	1.45E-01	-1.74E+00	-1.74E+00	-1.74E+00	-1.74E+00
GM	-9.52E-15	1.16E-13	-1.95E-15	-1.95E-15	-1.95E-15
RPI	5.90E+12	5.66E+12	5.66E+12	5.66E+12	5.66E+12
RX	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RO	7.97E+11	8.74E+11	7.92E+11	7.92E+11	7.92E+11
CBE	4.49E-12	4.49E-12	4.49E-12	4.49E-12	4.49E-12
CBC	3.00E-19	2.74E-19	3.02E-19	3.02E-19	3.02E-19
CJS	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
BETAAC	-5.61E-02	6.57E-01	-1.10E-02	-1.10E-02	-1.10E-02
CBX/CBX2	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
FT/FT2	-3.37E-04	4.11E-03	-6.89E-05	-6.89E-05	-6.89E-05

Table 4.12 Operating point information for the two stage power converter

4.4.5 Plot results for the two stage power converter

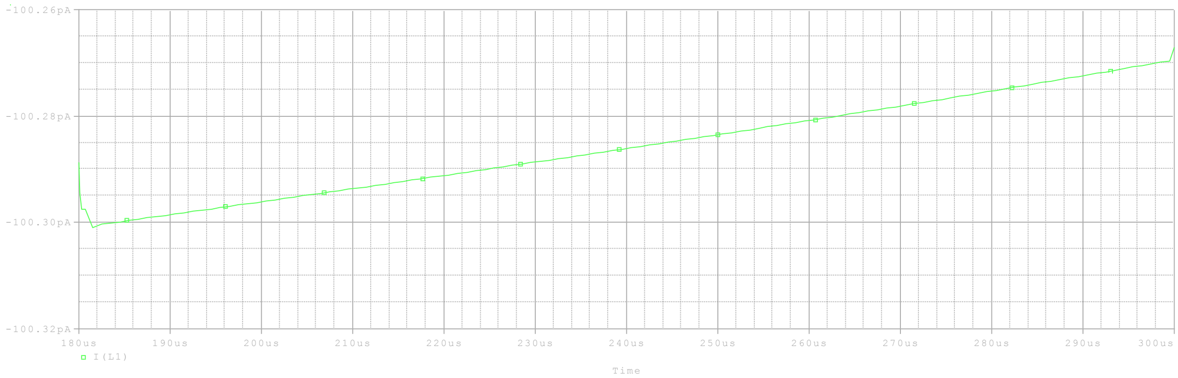


Fig.4.10 Variation of phase current with respect to time

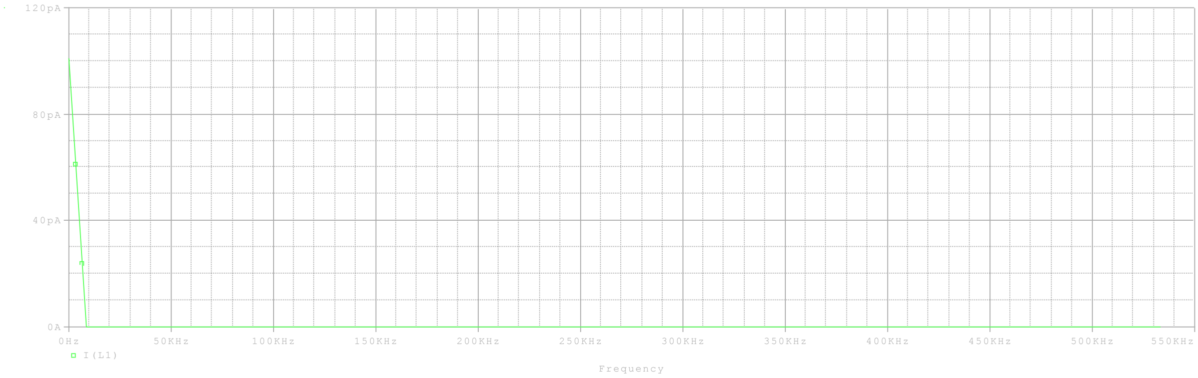


Fig.4.11Fast fourier analysis for the phase winding

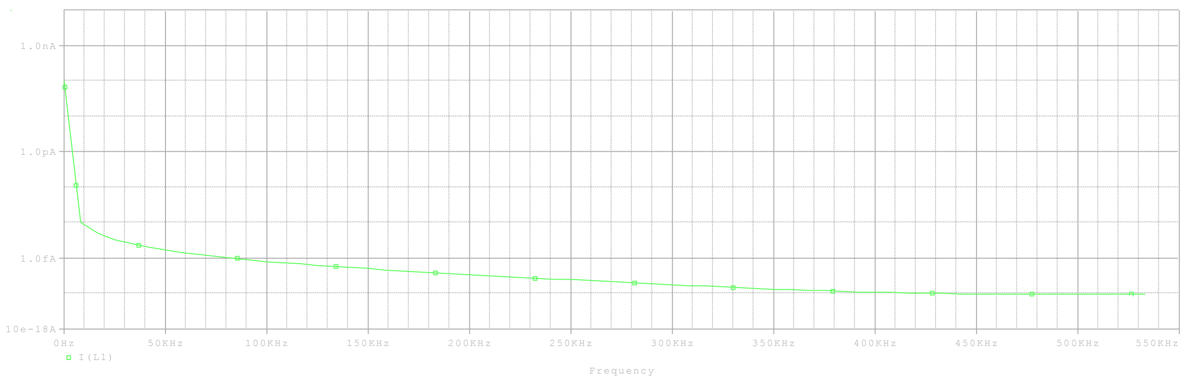


Fig.4.12Variation of phase current with respect to frequency

4.4.6 Conclusion

A scheme capable of transferring electrical power from the machine directly to the ac . However, this converter can return the power from the machine to the source directly without any limitations and eliminates the dc link capacitor. The elimination of dc link capacitor results in cost savings and in the enhancement of the reliability of the scheme and an increase in the power density of the scheme. The phase current, fourier , total harmonic distortion and operating point information analysis is done for this converter.

4.5 P-spice Simulation for the Variable DC link Converter

4.5.1 Fourier Analysis

TEMPERATURE = 27.000 DEG C

FOURIER COMPONENTS OF TRANSIENT RESPONSE I (VZ)

DC COMPONENT = 3.493008E-04

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE(DEG)
1	1.200E+02	6.984E-04	1.000E+00	7.934E+01	0.000E+00
2	2.400E+02	6.977E-04	9.991E-01	6.867E+01	-9.000E+01
3	3.600E+02	6.967E-04	9.975E-01	5.801E+01	-1.800E+02
4	4.800E+02	6.952E-04	9.954E-01	4.734E+01	-2.700E+02
5	6.000E+02	6.933E-04	9.927E-01	3.668E+01	-3.600E+02
6	7.200E+02	6.909E-04	9.893E-01	2.601E+01	- 4.500E+02
7	8.400E+02	6.881E-04	9.853E-01	1.535E+01	-5.400E+02
8	9.600E+02	6.850E-04	9.808E-01	4.681E+00	-6.300E+02
9	1.080E+03	6.814E-04	9.756E-01	-5.985E+00	-7.200E+02

Table 4.13 Fourier analysis for the variable dc link converter

TOTAL HARMONIC DISTORTION = 2.798721E+02 PERCENT

So the input current THD=27.98%=0.2798

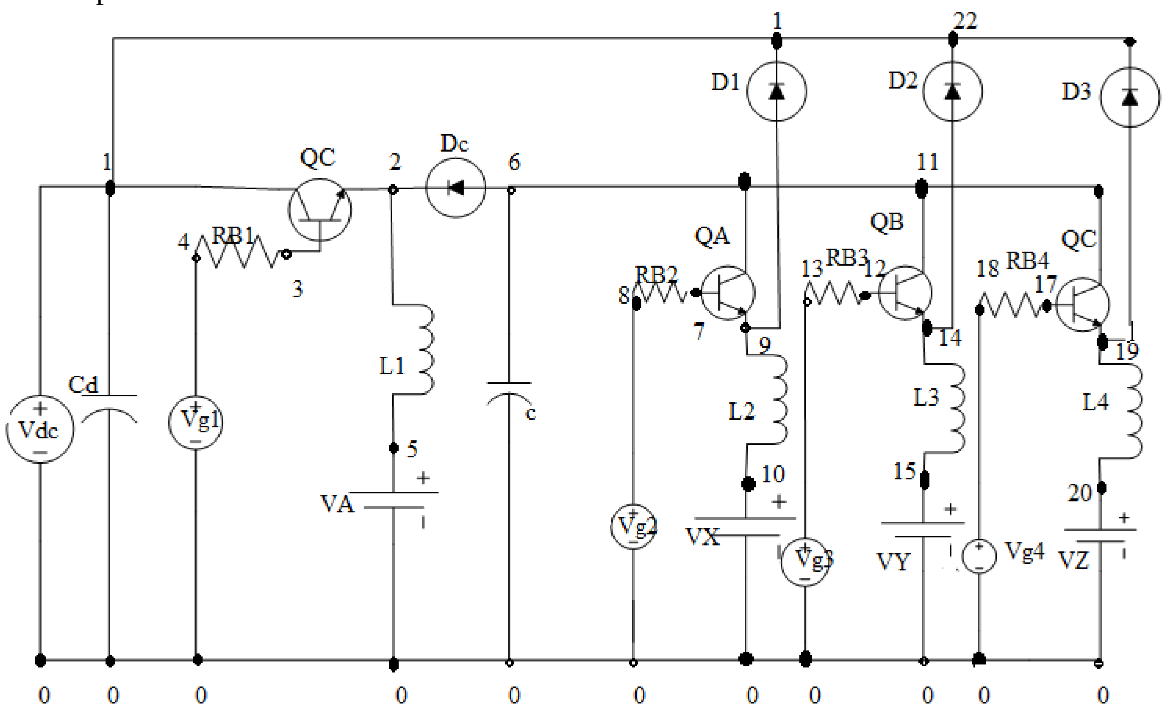


Fig.4.13 P-spice circuit for the variable dc link converter

4.5.2 Small Signal Bias Solution TEMPERATURE = 27.000 DEG C

NODE	VOLTAGE	NODE	VOLTAGE	NODE	VOLTAGE	NODE	VOLTAGE
1	.1911	2	0.0000	3	49.46E-12	4	0.0000
5	0.0000	6	-.0237	7	-6.468E-12	8	0.0000
9	0.0000	10	0.0000	11	-192.5E-06	12	-493.0E-30
13	0.0000	14	0.0000	15	0.0000	17	-493.0E-30
18	0.0000	19	0.0000	20	0.0000	22	-.2052

Table 4.14 Small signal bias solution for the variable dc link converter

4.5.3 Voltage Source Currents

NAME	CURRENT
VX	-4.853E-13
VY	2.021E-30
VZ	2.021E-30
VA	3.133E-13
VG1	1.978E-13
VG2	-2.587E-14
VG3	-1.972E-30
VG4	-1.972E-30

Table 4.15 Voltage source currents for the variable dc link converter

4.5.4 Operating Point Information TEMPERATURE = 27.000 DEG C

Table 4.16 Operating point information for the variable dc link converter

Diodes

NAME	DC	D1	D2	D3
MODEL	DMOD	DMOD	DMOD	DMOD
ID	1.74E-13	1.62E-10	2.79E-10	2.79E-10
VD	2.37E-02	1.91E-01	2.05E-01	2.05E-01
REQ	9.38E+10	1.60E+08	9.29E+07	9.29E+07
CAP	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Bipolar Junction Transistors

NAME	QA	QB	QC	QD
MODEL	MODQ1	MODQ1	MODQ1	MODQ1

IB	4.58E-14	3.29E-16	-2.68E-13	3.29E-16
IC	-7.96E-14	-5.72E-16	4.66E-13	-5.72E-16
VBE	-6.47E-12	-4.93E-28	-4.95E-11	-4.93E-28
VBC	2.37E-02	1.93E-04	-1.91E-01	1.93E-04
VCE	-2.37E-02	-1.93E-04	1.91E-01	-1.93E-04
BETADC	-1.74E+00	-1.74E+00	-1.74E+00	-1.74E+00
GM	-3.90E-13	-1.95E-15	2.60E-13	-1.95E-15
RPI	5.66E+12	5.66E+12	5.66E+12	5.66E+12
RX	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RO	6.06E+11	7.92E+11	1.00E+12	7.92E+11
CBE	4.49E-12	4.49E-12	4.49E-12	4.49E-12
CBC	3.95E-19	3.02E-19	2.40E-19	3.02E-19
CJS	0.00E+00	0.00E+00	0.00E+00	0.00E+00
BETAAC	-2.21E+00	-1.10E-02	1.47E+00	-1.10E-02
CBX/CBX2	0.00E+00	0.00E+00	0.00E+00	0.00E+00
FT/FT	-1.38E-02	-6.89E-05	9.22E-03	-6.89E-05

4.5.5 Plot results for the variable dc link converter

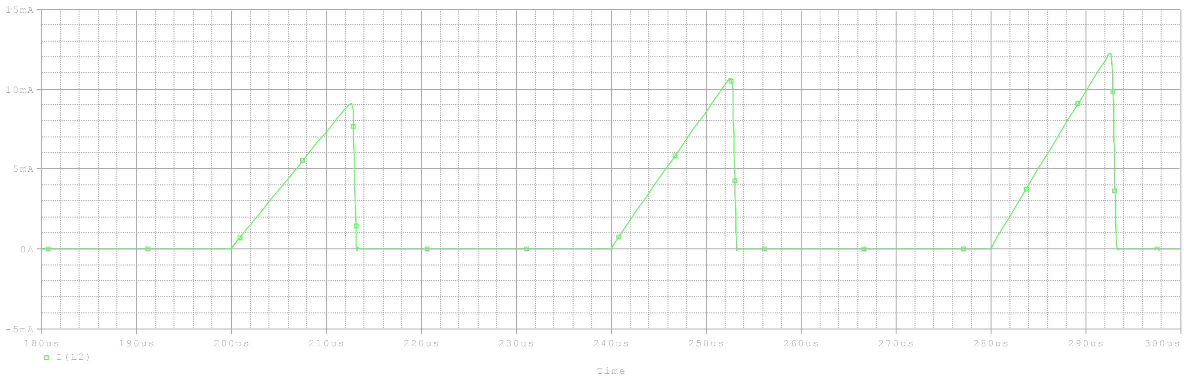


Fig.4.14Variation of phase current with respect to time

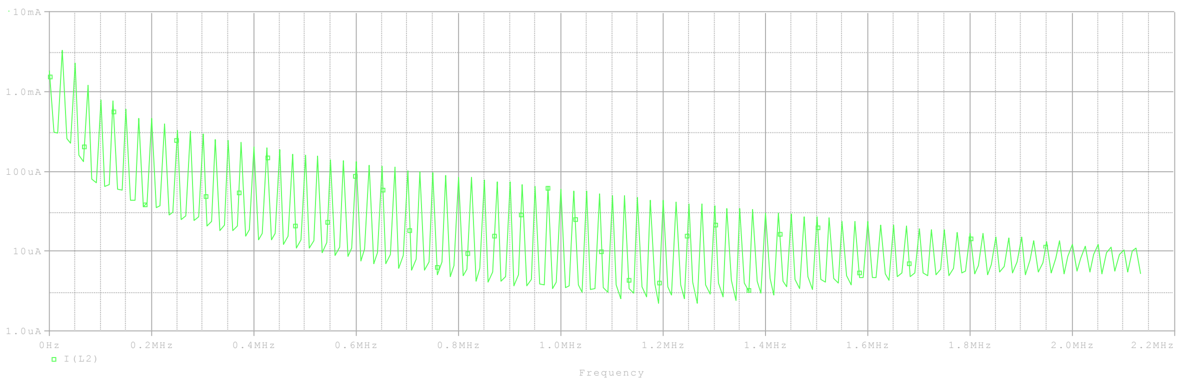


Fig.4.15 Variation of phase current with respect to frequency

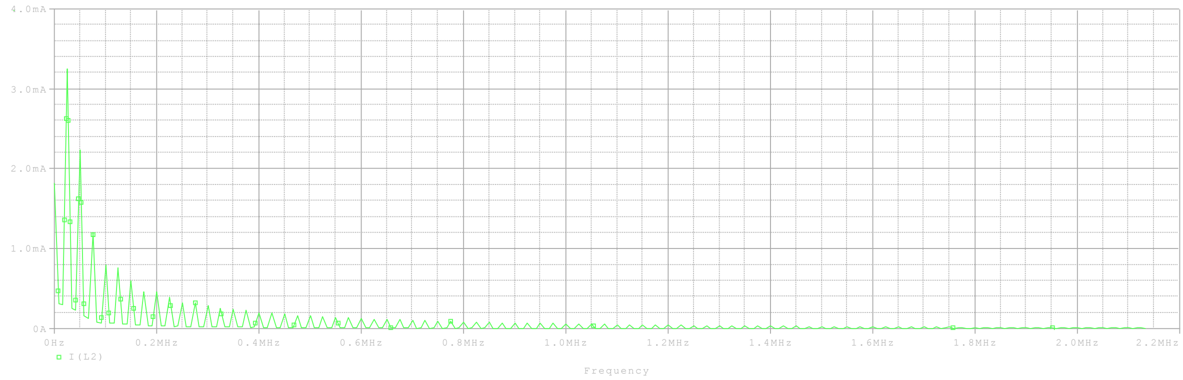


Fig. 4.16 Fast Fourier analysis for the phase winding

4.5.6 Power factor calculation

Input current THD=27.98%=0.2798

Displacement angle Ø1=79.34

DF=cos(Ø1)=cos (79.34)=0.184980577

The input PF=1/ (1+THD^2) ^1/2×Cos (Ø1)=0.1781 (leading)

4.5.7 Conclusion

In this converter the single pulse operation, acoustic noise and SRM core loss can be reduced. Its higher phase demagnetization voltage gives improved performance. This converter is targeted for variable-speed drives in consumer appliances where low acoustic noise is an important specification.

This converter provides much faster decay for the phase current as shown in plot so that motor can operate at higher speeds and also provide less shoot through faults. From the analysis it is shown that this converter can be used for SRM drives operating on leading power factor. The phase current, fourier, total harmonic distortion and operating point information analysis is done for this converter.

4.6 P-spice Simulation for the C Dump Converter

4.6.1 Fourier Analysis

TEMPERATURE = 27.000 DEG C

FOURIER COMPONENTS OF TRANSIENT RESPONSE I (VX)

DC COMPONENT = -9.993666E-14

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE(DEG)
1	1.200E+02	1.998E-13	1.000E+00	-1.006E+02	0.000E+00
2	2.400E+02	1.996E-13	9.991E-01	-1.113E+02	9.000E+01
3	3.600E+02	1.993E-13	9.976E-01	-1.219E+02	1.800E+02
4	4.800E+02	1.989E-13	9.954E-01	-1.325E+02	2.700E+02

5	6.000E+02	1.983E-13	9.927E-01	-1.431E+02	3.600E+02
6	7.200E+02	1.977E-13	9.893E-01	-1.538E+02	4.500E+02
8	9.600E+02	1.960E-13	9.808E-01	-1.750E+02	6.300E+02
9	1.080E+03	1.950E-13	9.757E-01	1.744E+02	1.080E+03

Table 4.17 Fourier analysis for the C- Dump converter

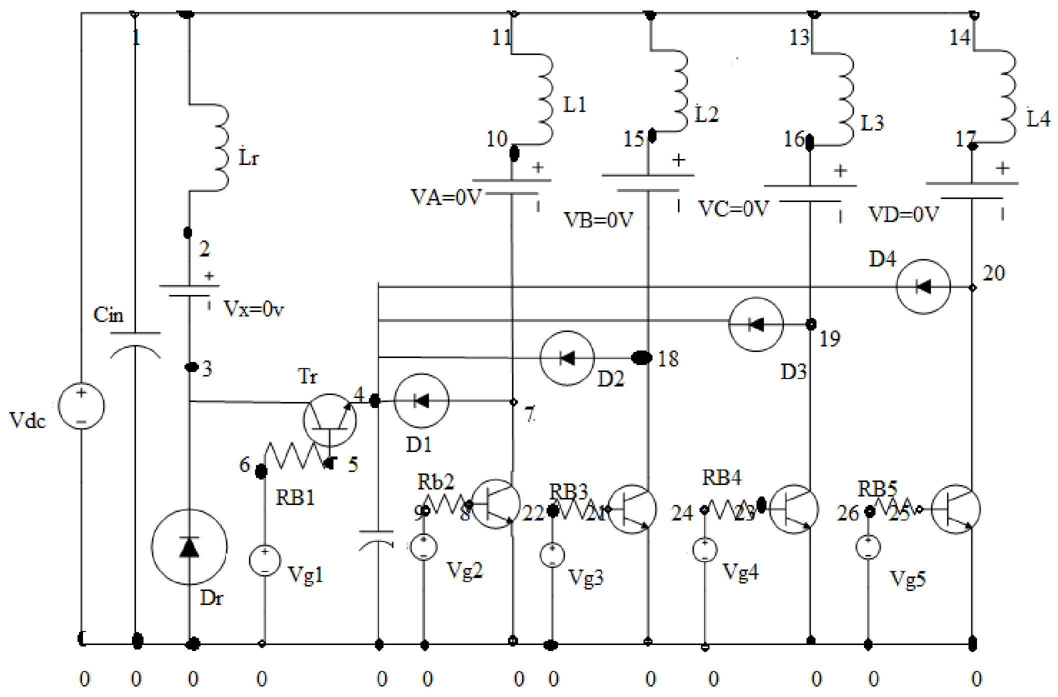


Fig.4.17 P-spice circuit for the C- Dump converter

TOTAL HARMONIC DISTORTION = 2.798798E+02 PERCENT

So the input current THD=27.98%=0.2798

4.6.2 Small Signal Bias Solution

NODE	VOLTAGE	NODE	VOLTAGE	NODE	VOLTAGE	NODE	VOLTAGE
1	965.9E-21	2	965.9E-21	3	965.9E-21	4	844.8E-21
5	580.1E-30	6	0.0000	7	204.3E-21	8	-17.06E-30
9	0.0000	10	204.3E-21	11	204.3E-21	15	204.3E-21
16	204.3E-21	17	204.3E-21	18	204.3E-21	19	204.3E-21
20	204.3E-21	21	-17.06E-30	22	0.0000	23	-17.06E-30
24	0.0000	25	-17.06E-30	26	0.0000		

Table 4.18 Small signal bias solution for the C- Dump converter

4.6.3 Operating Point Information

Diodes

NAME	DR	D1	D2	D3	D4
MODEL	DMOD	DMOD	DMOD	DMOD	DMOD
ID	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
VD	9.66E-19	6.41E-19	6.41E-19	6.41E-19	6.41E-19
REQ	2.05E+11	2.05E+11	2.05E+11	2.05E+11	2.05E+11
CAP	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Bipolar Junction Transistors

NAME	Q1	Q2	Q3	Q4	QR
MODEL	MODQ1	MODQ1	MODQ1	MODQ1	MODQ1
IB	-0.00E+00	-0.00E+00	-0.00E+00	-0.00E+00	-0.00E+00
IC	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.13E-30
VBE	-1.71E-29	-1.71E-29	-1.71E-29	-1.71E-29	8.45E-19
VBC	-2.04E-19	-2.04E-19	-2.04E-19	-2.04E-19	-2.04E-19
VCE	2.04E-19	2.04E-19	2.04E-19	2.04E-19	9.66E-19
BETADC	-4.81E-11	-4.81E-11	-4.81E-11	-4.81E-11	-1.13E-10
GM	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RPI	5.66E+12	5.66E+12	5.66E+12	5.66E+12	5.66E+12
RX	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RO	7.93E+11	7.93E+11	7.93E+11	7.93E+11	7.93E+11
CBE	4.49E-12	4.49E-12	4.49E-12	4.49E-12	4.49E-12
CBC	3.02E-19	3.02E-19	3.02E-19	3.02E-19	3.02E-19
CJS	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
BETAAC	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CBX/CBX2	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
FT/FT2	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table 4.19 Operating point information for the C- Dump converter

4.6.4 Plot results for the C-dump converter

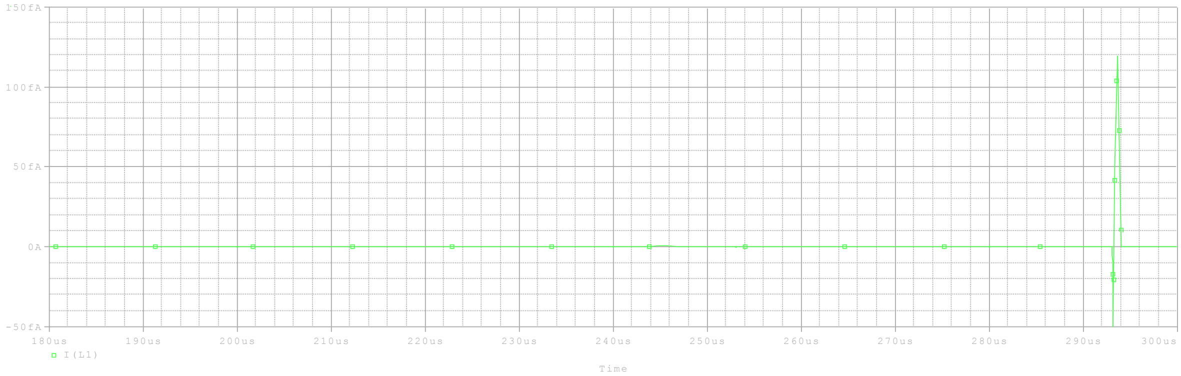


Fig.4.18 Variation of phase current with respect to time

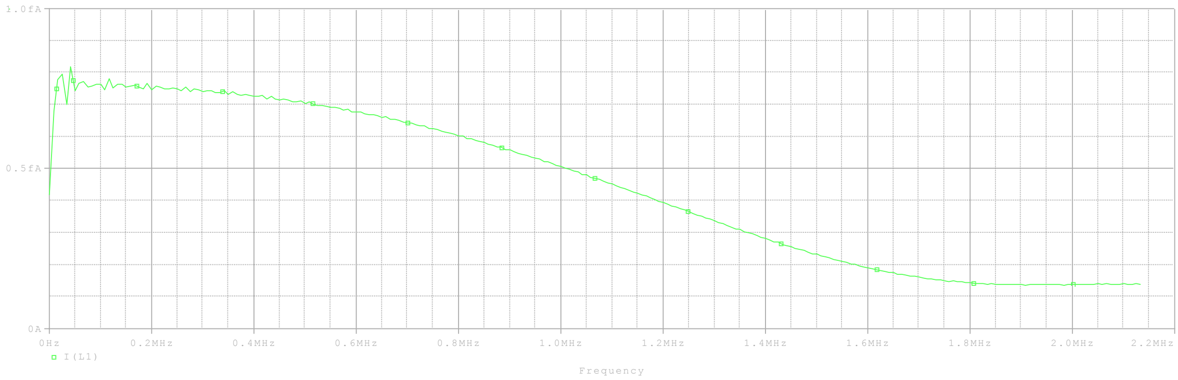


Fig.4.19 Fast Fourier analysis for the phase winding

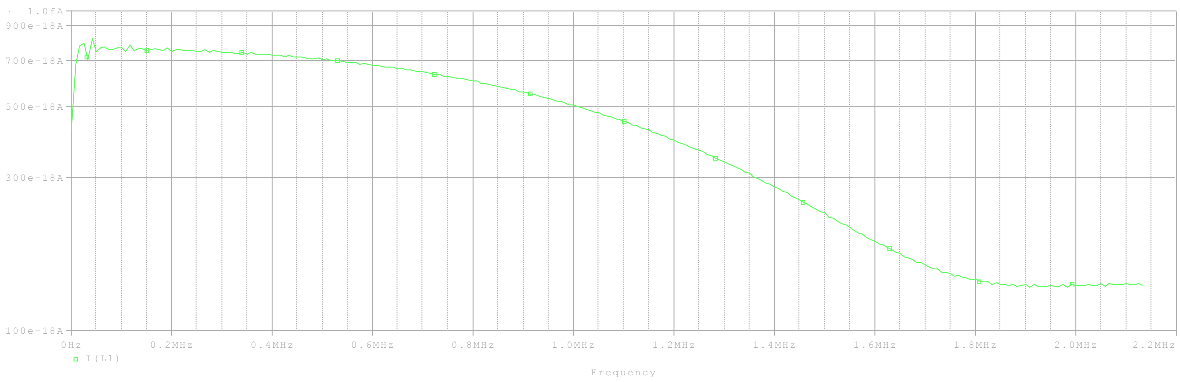


Fig.4.20 Variation of phase current with respect to frequency

4.6.5 Power factor calculation

Input current THD=27.98%=0.2798

Displacement angle Ø1=-10.06

DF=cos(Ø1)=cos (-10.06)=0.984625369(lagging)

The input PF=1/(1+THD^2)^1/2×Cos(Ø1)=0.9482 (lagging)

4.6.6 Conclusions

A C-Dump converter topology is designed which acts as both a power factor correction as well as phase-de fluxing component, reducing the device count. Better current regulation is achieved which makes it suitable for low voltage dc applications such as automotive circuits. The improved power factor achievement without the use-of any voltage or current sensors can be utilized in AC application. The simplicity and reduced parts count with compact packaging of the topology make it an attractive low-cost choice for many variable speed drive applications.

When C-dump converter is compared with asymmetric bridge converter, it has a benefit from cost and has more simple structure and control.

The phase current, fourier, total harmonic distortion and operating point information analysis is done for this converter. This converter provides distortion more than asymmetric and resonant converter. This converter is more suitable for SRM drives operating on lagging power factor.

4.7 P-spice Simulation for the Split DC Supply Converter

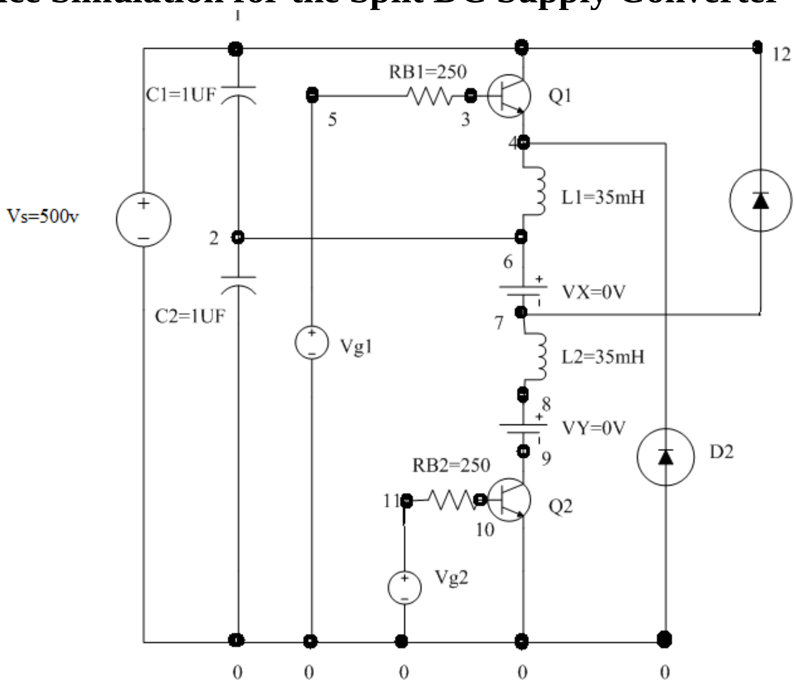


Fig.4.21 P-spice circuit for the split dc supply converter

4.7.1 Fourier Analysis

TEMPERATURE = 27.000 DEG C

FOURIER COMPONENTS OF TRANSIENT RESPONSE I (VX)

DC COMPONENT = -4.250385E-05

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE(DEG)
1	1.200E+02	8.496E-05	1.000E+00	-9.259E+01	0.000E+00
2	2.400E+02	8.483E-05	9.984E-01	-9.518E+01	9.000E+01

3	3.600E+02	8.460E-05	9.957E-01	-9.777E+01	1.800E+02
4	4.800E+02	8.428E-05	9.920E-01	-1.004E+02	2.700E+02
5	6.000E+02	8.388E-05	9.872E-01	-1.029E+02	3.600E+02
6	7.200E+02	8.338E-05	9.814E-01	-1.055E+02	4.500E+02
7	8.400E+02	8.281E-05	9.746E-01	-1.081E+02	5.401E+02
8	9.600E+02	8.214E-05	9.668E-01	-1.106E+02	6.301E+02
9	1.080E+03	8.140E-05	9.580E-01	-1.132E+02	7.202E+02

Table 4.20 Fourier analysis for the split dc supply converter

TOTAL HARMONIC DISTORTION = 2.777149E+02 PERCENT

So the Input Current THD=27.77%= 0.2777

4.7.2 Small Signal Bias Solution

NODE	VOLTAGE	NODE	VOLTAGE	NODE	VOLTAGE	NODE	VOLTAGE
1	-65.13E-09	2	-20.44E-09	3	108.1E-12	4	-20.44E-09
5	0.0000	7	-20.44E-09	8	-20.44E-09	9	-20.44E-09
10	58.87E-15	11	0.0000				

Table 4.21 Small signal bias solution for the split dc supply converter

4.7.3 Voltage Source Currents

NAME	CURRENT
VG1	4.325E-13
VX	7.380E-13
VY	4.090E-16
VG2	2.355E-16

Table 4.22 Voltage source currents for the split dc supply converter

4.7.4 Operating Point Information TEMPERATURE = 27.000 DEG C

Diodes

NAME	D1	D2
MODEL	DNAME	DNAME
ID	8.64E-13	-3.95E-13
VD	4.47E-08	-2.04E-08
REQ	5.17E+04	5.17E+04
CAP	0.00E+00	0.00E+00

Bipolar Junction Transistors

NAME	Q1	Q2
MODEL	MODQ1	MODQ1
IB	1.15E-19	3.50E-20
IC	-1.68E-19	-6.07E-20
VBE	2.06E-08	5.89E-14
VBC	6.52E-08	2.04E-08
VCE	-4.47E-08	-2.04E-08
BETADC	-1.46E+00	-1.74E+00
GM	-4.50E-19	-2.06E-19
RPI	5.66E+12	5.66E+12
RX	0.00E+00	0.00E+00
RO	7.93E+11	7.93E+11
CBE	4.49E-12	4.49E-12
CBC	3.02E-19	3.02E-19
CJS	0.00E+00	0.00E+00
BETAAC	-2.55E-06	-1.17E-06
CBX/CBX2	0.00E+00	0.00E+00
FT/FT2	-1.59E-08	-7.29E-09

Table 4.23 Operating point information for the split dc supply converter

4.7.5 Plot results for the split dc supply converter

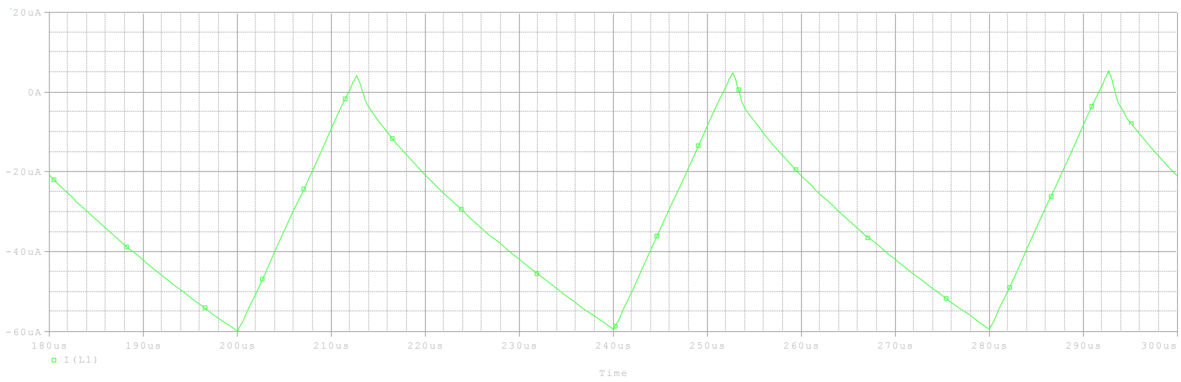


Fig.4.22 Variation of phase current with respect to time

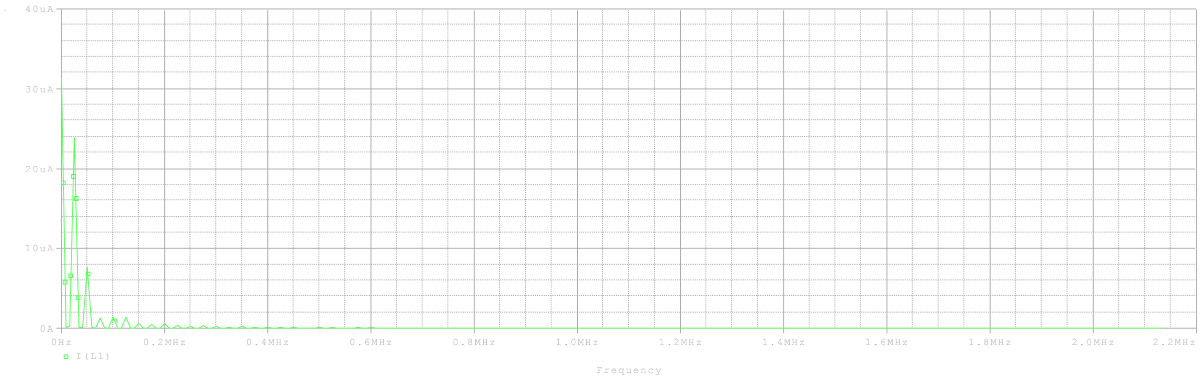


Fig.4.23 Fast fourier analysis for the phase winding

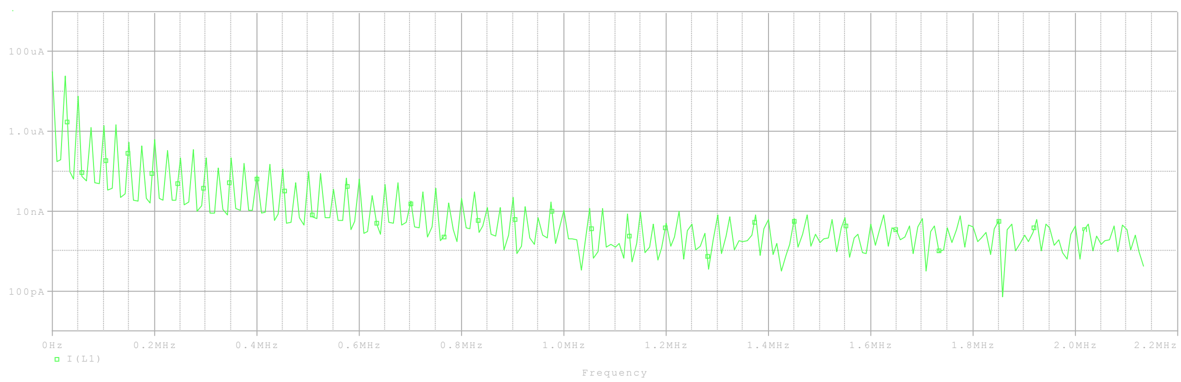


Fig.4.24Variation of phase current with respect to frequency

4.7.6 Conclusion

This topology provides fast suppression of the tail current in the phase winding and hence resulting in minimization of negative torque using doubly boosted voltage in the demagnetizing mode. This topology has higher efficiency and more output power than the other counterpart in the heavy load conditions and in high speed operations.

The phase current, fourier, total harmonic distortion and operating point information analysis is done for this converter. This converter provides distortion more than asymmetric and resonant converter. This converter from plot shows that it can provide fast increase and decrease for the phase current so that motor can operate on higher speeds and provide less shoot through faults.

4.8 P-spice Simulation for the Bifilar Winding Converter

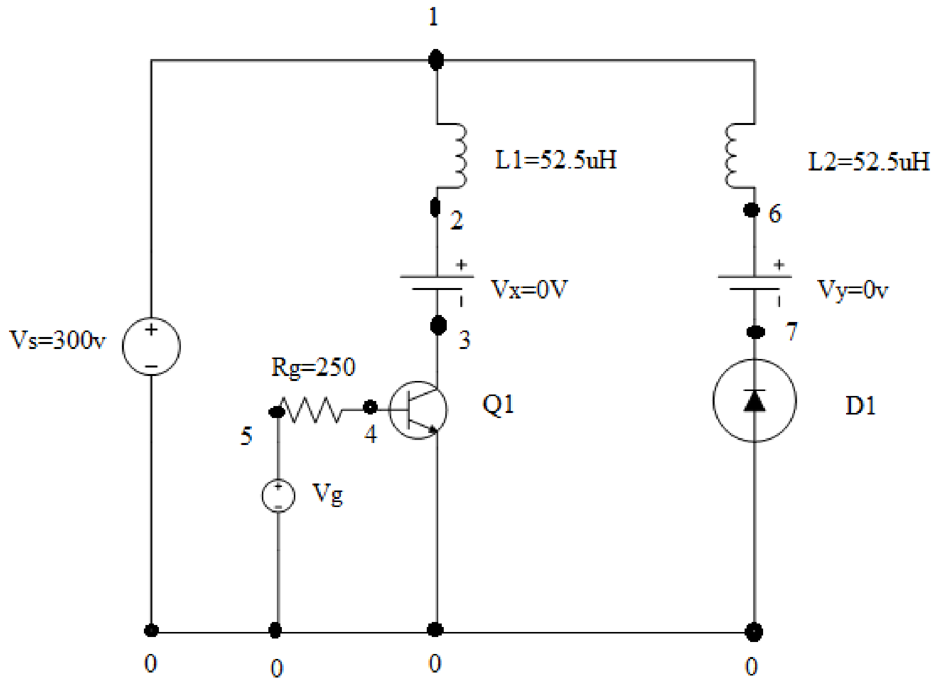


Fig.4.25 P-spice circuit for the bifilar winding converter

4.8.1 Fourier Analysis

TEMPERATURE = 27.000 DEG C

FOURIER COMPONENTS OF TRANSIENT RESPONSE I(VX)

DC COMPONENT = -7.020656E-09

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE(DEG)
1	1.200E+02	1.404E-08	1.000E+00	-1.005E+02	0.000E+00
2	2.400E+02	1.403-08	9.991E-01	-1.109E+02	9.000E+01
3	3.600E+02	1.401E-08	9.977E-01	-1.214E+02	1.800E+02
4	4.800E+02	1.398E-08	9.957E-01	-1.318E+02	2.700E+02
5	6.000E+02	1.394E-08	9.931E-01	-1.423E+02	3.600E+02
6	7.200E+02	1.390E-08	9.899E-01	-1.527E+02	4.500E+02
7	8.400E+02	1.384E-08	9.862E-01	-1.632E+02	5.400E+02
8	9.600E+02	1.378E-08	9.818E-01	-1.736E+02	6.300E+02
9	1.080E+03	1.371E-08	9.769E-01	1.759E+02	1.080E+03

Table 4.24 Fourier analysis for the bifilar winding converter

TOTAL HARMONIC DISTORTION = 2.800407E+02 PERCENT

So the Input Current THD=28.00%=0.2800

4.8.2 Small Signal Bias Solution TEMPERATURE = 27.000 DEG C

NODE	VOLTAGE	NODE	VOLTAGE	NODE	VOLTAGE	NODE	VOLTAGE
1	2.072E-09	2	2.072E-09	3	2.072E-09	4	59.93E-15
5	0.0000	6	2.072E-09	7	2.072E-09		

Table 4.25 Small signal bias solution for the bifilar winding converter

4.8.3 Voltage Source Currents

NAME	CURRENT
VX	4.164E-16
VG	2.397E-16
VY	-4.164E-16

Table 4.26 Voltage source currents for the bifilar winding converter

4.8.4 Operating Point Information

Diodes

NAME	D1
MODEL	DNAME
ID	4.01E-14
VD	2.07E-09
REQ	5.17E+04
CAP	0.00E+00

Bipolar Junction Transistors

NAME	Q1
MODEL	MODQ1
IB	-3.54E-21
IC	6.15E-21
VBE	5.99E-14
VBC	-2.07E-09
VCE	2.07E-09
BETADC	-6.15E-01
GM	2.09E-20
RPI	5.66E+12
RX	0.00E+00
RO	7.93E+11
CBE	4.49E-12

CBC	3.02E-19
CJS	0.00E+00
BETAAC	1.18E-07
CBX/CBX2	0.00E+00
FT/FT2	7.39E-10

Table 4.27 Operating point information for the bifilar winding converter

4.8.5 Plot results for the bifilar type converter

Fig.4.26 Variation of phase current with respect to time

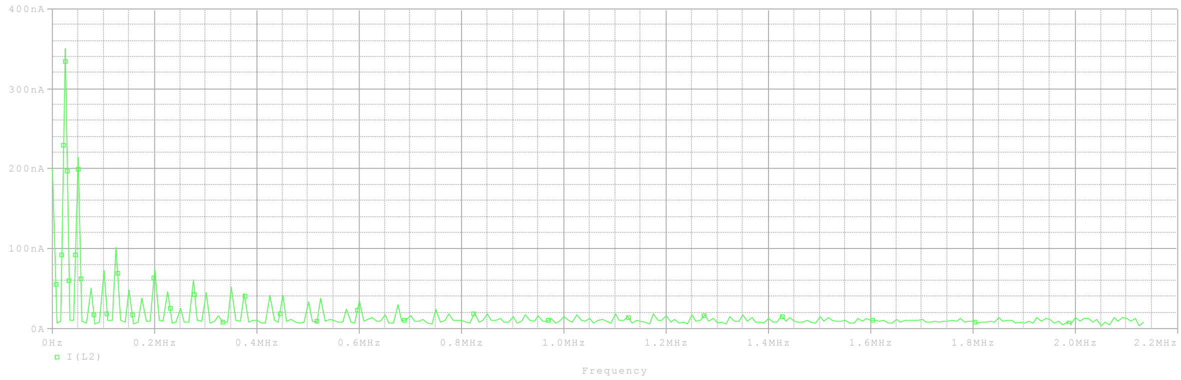


Fig.4.27 Fast fourier analysis for the phase winding

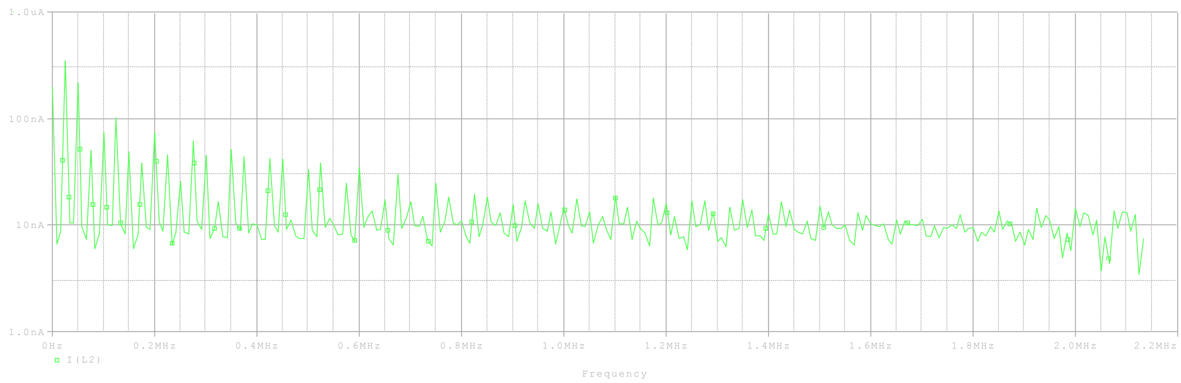


Fig.4.28Variation of phase current with respect to frequency

4.8.6 Power factor calculation

Input current THD=28.00%=0.2800

Displacement angle Ø1=-10.05

DF=cos(Ø1)=cos (-10.05)=0.984655841(lagging)

The input PF=1/(1+THD^2)^1/2×Cos(Ø1)=0.94818(lagging)

4.8.7 Conclusion

This converter has the capability of regenerating the stored magnetic energy to the supply by the bifilar winding. Bifilar topology is suitable for low-power low-voltage application due to their high voltage rating. The phase current, fourier, total harmonic distortion and operating point information analysis is done for this converter. This converter provides distortion more than other converter as shown in results. This converter is more suitable for SRM drives operating on lagging power factor.

4.9 P-Spice Simulation for the R-Dump Converter

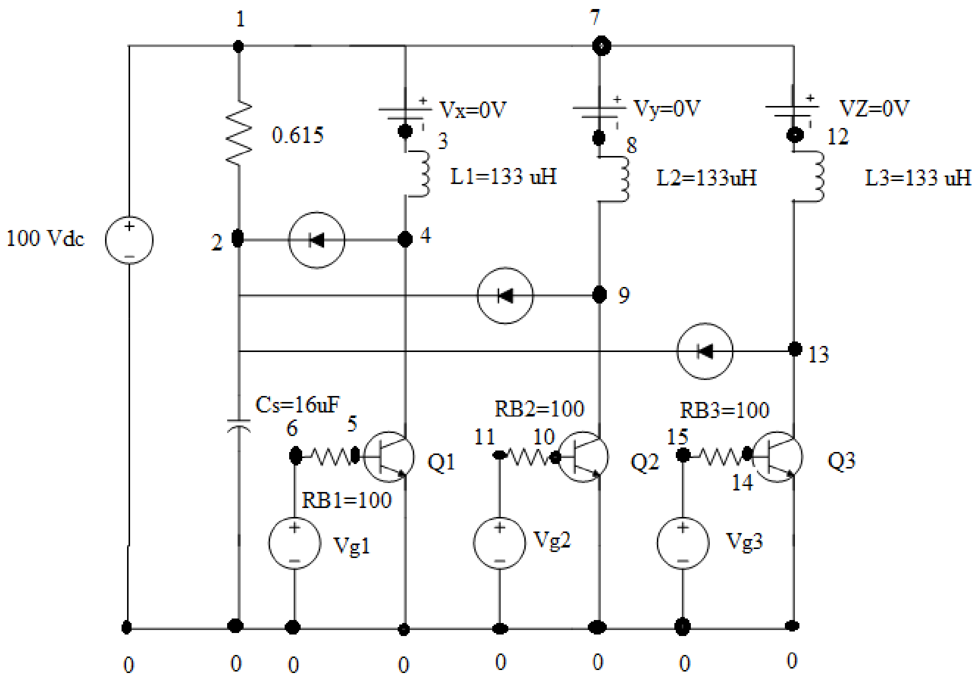


Fig.4.29 P spice circuit for the R-Dump converter

4.9.1 Fourier Analysis

TEMPERATURE = 27.000 DEG C

FOURIER COMPONENTS OF TRANSIENT RESPONSE I (VX)

DC COMPONENT = -3.277003E-07

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE(DEG)
1	1.200E+02	6.549E-07	1.000E+00	-9.285E+01	0.000E+00
2	2.400E+02	6.533E-07	9.976E-01	-9.570E+01	9.001E+01
3	3.600E+02	6.506E-07	9.935E-01	-9.853E+01	1.800E+02

4	4.800E+02	6.470E-07	9.879E-01	-1.014E+02	2.701E+02
5	6.000E+02	6.423E-07	9.808E-01	-1.042E+02	3.601E+02
6	7.200E+02	6.367E-07	9.723E-01	-1.069E+02	4.502E+02
7	8.400E+02	6.302E-07	9.624E-01	-1.097E+02	5.403E+02
8	9.600E+02	6.229E-07	9.512E-01	-1.124E+02	6.304E+02
9	1.080E+03	6.148E-07	9.388E-01	-1.151E+02	7.206E+02

Table 4.28 Fourier analysis for the R-Dump converter

TOTAL HARMONIC DISTORTION = 2.752785E+02 PERCENT

So the Input Current THD=27.52%=0.2752

4.9.2 Small Signal Bias Solution

NODE	VOLTAGE	NODE	VOLTAGE	NODE	VOLTAGE	NODE	VOLTAGE
1	-.0033	2	-.0033	3	-.0033	4	-.0033
5	355.4E-15	6	0.0000	7	-.0033	8	-.0033
9	-.0033	10	-177.7E-15	11	0.0000	12	-.0033
13	-.0033	14	-177.7E-15	15	0.0000		

Table 4.29 Small signal bias solution for the R-Dump converter

4.9.3 Voltage Source Currents

NAME	CURRENT
VX	6.173E-15
VG1	3.554E-15
VY	0.000E+00
VG2	-1.777E-15
VZ	0.000E+00
VG3	-1.777E-15

Table 4.30 Voltage source currents for the R-Dump converter

4.9.4 Operating Point Information

Diodes

NAME	D1	D2	D3
MODEL	DNAME	DNAME	DNAME
ID	7.34E-20	6.20E-14	6.20E-14
VD	3.80E-15	3.21E-09	3.21E-09
REQ	5.17E+04	5.17E+04	5.17E+04
CAP	0.00E+00	0.00E+00	0.00E+00

Bipolar Junction Transistors

NAME	Q1	Q2	Q3
MODEL	MODQ1	MODQ1	MODQ1
IB	5.66E-15	5.66E-15	5.66E-15
IC	-9.83E-15	-9.83E-15	-9.83E-15
VBE	3.55E-13	-1.78E-13	-1.78E-13
VBC	3.27E-03	3.27E-03	3.27E-03
VCE	-3.27E-03	-3.27E-03	-3.27E-03
BETADC	-1.74E+00	-1.74E+00	-1.74E+00
GM	-3.50E-14	-3.50E-14	-3.50E-14
RPI	5.66E+12	5.66E+12	5.66E+12
RX	0.00E+00	0.00E+00	0.00E+00
RO	7.72E+11	7.72E+11	7.72E+11
CBE	4.49E-12	4.49E-12	4.49E-12
CBC	3.10E-19	3.10E-19	3.10E-19
CJS	0.00E+00	0.00E+00	0.00E+00
BETAAC	-1.98E-01	-1.98E-01	-1.98E-01
CBX/CBX2	0.00E+00	0.00E+00	0.00E+00
FT/FT2	-1.24E-03	-1.24E-03	-1.24E-03

Table 4.31 Operating point information for the R-Dump converter

4.9.5 Plot Results for the R-Dump converter

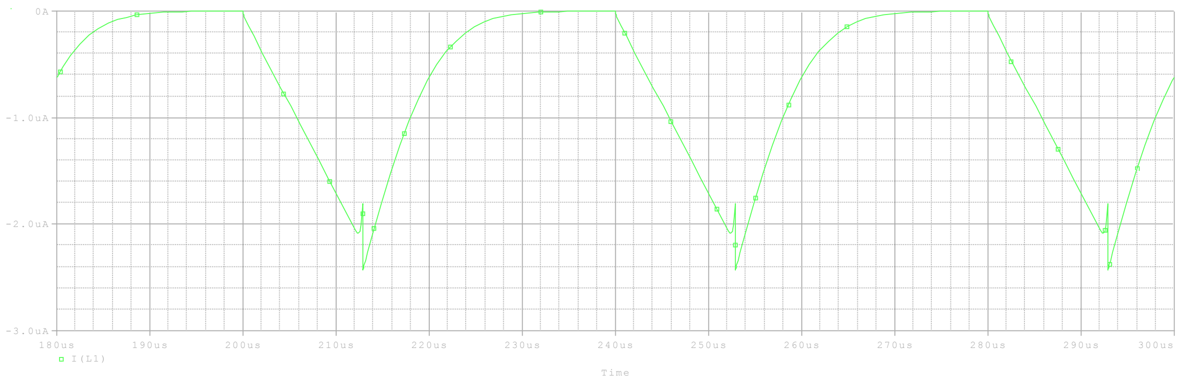


Fig.4.30 Variation of phase current with respect to time

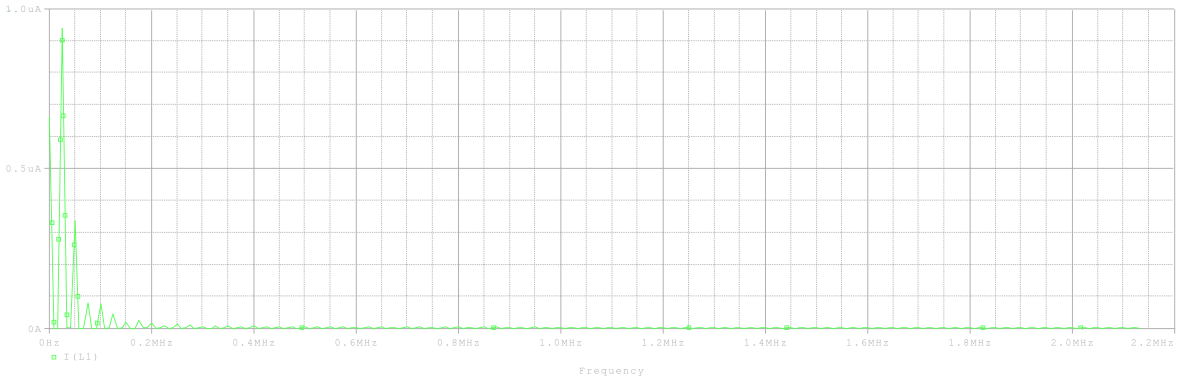


Fig.4.31 Fast fourier analysis for the phase winding

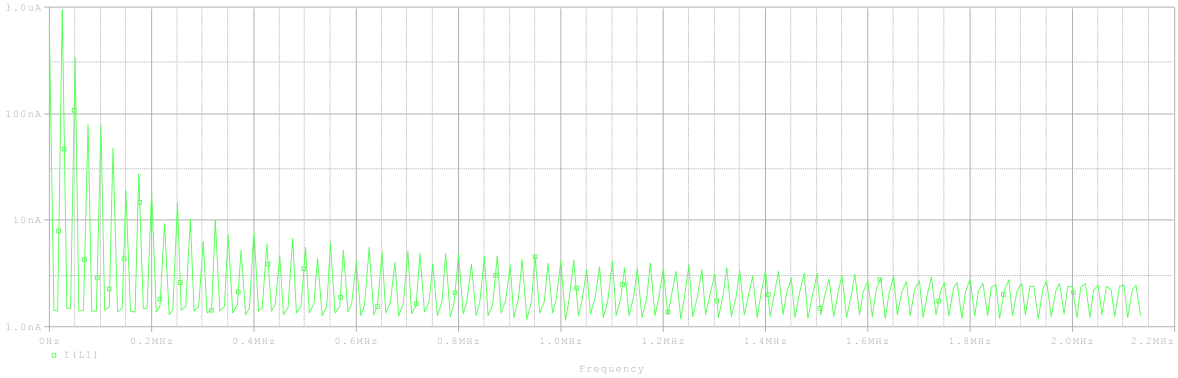


Fig.4.32 Variation of phase current with respect to frequency

4.9.6 Conclusion

This is a low cost, one switch per phase converter topology suitable for low-performance applications. The converter has the advantage of a minimum possible number of semiconductor devices in the power circuit without the attendant need for a bifilar winding. Its drive requirements are minimal and windings are simple. The phase current, fourier, total harmonic distortion and operating point information analysis is done for this converter. The plot for the phase current shows that it provide faster rise and fall for the phase current which permits the motor to operate on higher speeds.

4.10 Conclusions

The switched reluctance motor drive circuits have been critically reviewed in this chapter. Comparison of the most common drive circuit topologies has been held showing the major advantages and disadvantages of each topology together with its major field of applications. Finally comparisons of the different converter topologies have been made with respect to fourier analysis, total harmonic distortion and phase current of the winding. The respective results have already been shown earlier in this chapter

4.11 Future scope of Work

More analysis and research has to be conducted on the various parameters of the resulting current profile, such as the rise and fall times, the peak, average or RMS value for various converters using P-SPICE simulation. The switched capacitance circuit can be introduced for the SRM drives so that fast rise and decay of the phase current is achieved. In that case, the motor can operate at higher speeds and will have less shoot through faults. Moreover, a detailed study of the different resonant converters like ZVS, ZCS converters can be taken up in future. Only a general resonant converter has been discussed in this study.

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APPENDIX-A

1. Diodes Values

Saturation Current (IS=0.5 µA)

Reverse breakdown voltage (BV=5.20 Volt)

Reverse breakdown Current (IBV=0.5 µA)

Parasitic Resistance (RS=1.0 ohms)

2. Transistors Values-

P-N saturation current (IS=6.734F)

Ideal maximum forward beta (BF=416.4)

Base-Emitter leakage saturation current (ISE=6.734F Amps)

Ideal maximum reverse beta (BR=.7371)

Base –emitter zero-bias P-N capacitance (CJE =3.638P Farads)

Base-Collector P-N grading factor (MJC=.3085)

Base-Collector built –in potential (VJC=.75Volts)

Base –collector zero-bias P-N capacitance (CJC=4.493P Farads)

Base-Emitter P-N grading factor (MJE=.2593)

Base-Emitter built –in potential (VJE=.75 Volts)

Ideal reverse transit time (TR=239.5N Seconds)

Ideal forward transit time (TF=301.2P Seconds)

APPENDIX B

Converter Circuit Element Values

1. Asymmetric bridge converter [9]

Voltage supply- DC 25Volt

Phase Winding (L1) =28.8mH

Transistor Base –drive Resistance=250 ohms

2. Two stage power converter [12]

Voltage supply- AC 325.26 Volt

Phase Winding (L1, L2, L3, L4) = 52µH

Capacitance=8µH

Transistor Base –drive Resistance=250 ohms

3. Bifilar winding converter [12, 17]

Voltage supply- DC 300Volt

Phase Winding (L1) =52.5mH

Transistor Base –drive Resistance=250 ohms

4. C-dump converter [3, 4, 6, 13]

Voltage supply- DC 500 Volt

Phase Winding (L1) =700uH

Transistor Base –drive Resistance=250 ohms

5. R-Dump converter [12, 18]

Voltage supply- DC 100 Volt

Phase Winding (L1, L2, L3) =133mH

Resistance= 0.615 ohm

Transistor Base –drive Resistance=250 ohms

6. Resonant converter [10, 12]

Voltage supply- DC 100 Volt

Phase Winding (L1) =35mH

L r=50uH

Cr =1.0uF

Transistor Base –drive Resistance=250 ohms

7. Split dc supply converter [16, 19]

Voltage supply- DC 500 Volt

Phase Winding (L1) =35mH

Capacitance (C1, C2) = 1.0uF

Transistor Base –drive Resistance=250 ohms

8. Variable dc link converter [12, 13, 14]

Voltage supply- DC 50 Volt

Phase Winding (L2, L3, L4) =25Mh

Transistor Base –drive Resistance=250 ohms

APPENDIX C

P-Spice Program for the Various Converter

1. P-Spice program for the asymmetric bridge converter

```
Vdc    1     0      DC      25V
 CIRCUIT DESCRIPTION
Vx      4     5      DC       0V
VG      3     0    PULSE    (0V     20V     0   1NS   1NS    12.24US   40US)
VG1     8     0    PULSE    (0V     20V     0   1NS   1NS    12.24US   40US)
RB        2     3     250
RB1      7      8     250
L1         5     6     28.8UH
*L1 SPECIFIES THE PHASE INDUCTANCE OF THE MOTOR WINDINGS
D1        1      6     DNAME
D2        4       0    DNAME
*DNAME SPECIFIES THE DIODE PARAMETERSRS
.MODEL DNAME D (IS=0.5UA RS=1 BV=5.20 IBV=0.5UA)
Q1       1        2      4     MODQ1
Q2        6        7     0      MODQ1
* MODQ1 SPECIFIES THE TRANSISTORS PARAMETRS
.MODEL MODQ1 NPN (   IS=6.734F BF=416.4 ISE=6.734F BR=.7371
+CJE=3.638P MJC=.3085 VJC=.75 CJE=4.493P MJE=.2593 VJE=.75
+TR=239.5N TF=301.2P)
.TRAN      2US    300US   180US   1US   UIC
.PROBE
.OPTIONS ABSTOL=1.00N RELTOL=0.01 VNTOL=0.1 ITL5=20000
.FOUR 120HZ    I (VX)
.OP
.END
```

2. P-Spice program for the resonant converter

```
 VS        1     0     DC     100 Volt
    CIRCUIT DESCRIPTION
Q1      1        2       4      QM
RB1      2      3      250
```

```
VG1    3    0    PULSE (   0V    20V   0   1NS   1NS   12.24US   40US)
L1     4     5     35MH
VX    5     0    DC    0V
DA    15    4    DMOD
DB    15    8    DMOD
DC    15    13    DMOD
DR    16    0     DMOD
QR    15    18    20    QM
RB4   18    19    250
VG4   19    0    PULSE   (0V    20V    0    1NS    1NS    12.24US    40US)
CR    15    16    1UF
LR    16    17   50UH
VL    17    20    DC    0V
Q2     1      6    8    QM
RB2    6      7     250
VG2   7      0    PULSE (0V     20V     0   1NS    1NS     12.24US    40US)
L2     8     9    35MH
VY     9      0    DC    0V
Q3     1      11    13    QM
RB3   11     12     250
VG3   12      0    PULSE (0V      20V    0    1NS    1NS    12.24US    40US)
L3     13     14    35MH
V2    14      0     DC    0V
*DMOD DEFINES THE DIODE MODEL PARAMETERES
.MODEL DMOD D (IS=100E-15 RS=16 BV=100 IBV=100E-15)
*QM DEFINES THE TRANSISTOR MODEL PARAMETERS
.MODEL QM NPN (BF=100 BR=1 RB=5 RC=1 RE=0 VJE=0.8 VA=100)
.TRAN 2US    300US    180US    1US    UIC
.PROBE
.OPTIONS ABSTOL=1.00N RELTOL=0.01 VNTOL=0.1 ITL5=20000
.FOUR 120HZ I (VX)
.OP
.END
```

3. P-Spice program for the two stage power converter

```
VS     1   2   3   0      SIN (   0       325.26V   50HZ)
 CIRCUIT DESCRIPTION
C1     2       3      8UF
C2     3       0      8UF
C3     2       0      8UF
D1    11       4      DMOD
D2    26       0      DMOD
D3    11      12      DMOD
D4    10       0      DMOD
D5   27       20      DMOD
D6   18        0       DMOD
DA   29      30      DMOD
DB   35      36      DMOD
DC   41      42      DMOD
DD   47      48    DMOD
Q1    4       5     2        MODQ1
Q2    23     24    26       MODQ1
Q3    12    13    3        MODQ1
Q4     2     8     10       MODQ1
Q5   20     21    23       MODQ1
Q6   3      16    18       MODQ1
QA   30    31     0      MODQ1
QB   36    37     0       MODQ1
QC   42    43    0        MODQ1
QD   48    49     0       MODQ1
VA    28    29     DC     0V
VY    34    35     DC     0V
VZ     40   41      DC    0V
VX   46    47      DC     0V
L1    27    28    52UH
L2    33    34     52UH
L3    33    40     52UH
```

```
L4    33    46      52UH
RB1   5      7        250
RB2   8      9        250
RB3   13    14      250
RB4   16    17      250
RB5    21    22     250
RB6    24    25    250
RB7    31    32    250
RB8    37   38     250
RB9   43     44    250
RB10   49    50    250
VG1       7          0       PULSE (0V     20V      0      1NS     1 NS      12.24US    40US)
VG2       9          0      PULSE   (0V    20V      0     1NS      1 NS       12.24US    40US)
VG3     14          0     PULSE (0V      20V       0     1NS      1 NS      12.24US    40US)
VG4     17          0     PULSE (0V      20V       0     1NS      1 NS      12.24US    40US)
VG5     22         0      PULSE (0V     20V        0     1NS      1 NS      12.24US    40US)
VG6     25         0     PULSE (0V      20V        0     1NS      1 NS      12.24US     40US)
VG7     32         0      PULSE (0V     20V        0     1NS       1 NS     12.24US     40US)
VG8     38         0      PULSE (0V     20V        0     1NS       1 NS      12.24US    40US)
VG9     44         0      PULSE (0V     20V        0     1NS       1 NS       12.24US    40US)
VG10     50       0      PULSE (0V     20V        0     1NS        1 NS      12.24US    40US)
*DMOD DEFINES THE DIODE PARAMETERS
.MODEL DMOD D (IS=100E-15 RS=16 BV=100 IBV=100E-15)
*MODQ1 DEFINES THE TRANSISTOR MODEL PARAMETERS
.MODEL MODQ1 NPN (IS=6.734F BF=416.4 ISE=6.734F BR=.7371
+CJE=3.638P MJC=.3085 VJC=.75 CJE=4.493P MJE=.2593 VJE=.75
+TR=239.5N TF=301.2P)
.TRAN       2US     300US     180US    1US    UIC
.PROBE
.OPTIONS ABSTOL=1.00N RELTOL=0.01 VNTOL=0.1 ITL5=20000
.FOUR           120HZ         I (VX)
.OP
.END
```

4. P-Spice program for the variable dc link converter

```
VDC     1    0     DC      50V
  CIRCUIT DESCRIPTION
CD      1      0     800MF
DC      2     6      DMOD
D1      1      9     DMOD
D2      14    22     DMOD
D3      19    22     DMOD
L1      2      5     25UH
C       6      0     250UF
VX      10     0     DC    0V
VY      15      0     DC    0V
VZ      20      0    DC    0V
VA      5       0    DC     0V
QA      6       7     9     MODQ1
QB      11      12    14    MODQ1
QC      1        2     3    MODQ1
QD      11      17    19    MODQ1
L2      9      10    25UH
L3      14     15    25UH
L4      19      20    25UH
RB1    3      4       250
RB2    7      8      250
RB3    12     13     250
RB4    17     18      250
VG1    4      0     PULSE (0V     20V      0      1NS      1NS     12.24US    40US)
VG2     8      0     PULSE (0V     20V     0      1NS      1NS     12.24US    40US)
VG3    13      0    PULSE (0V       20V     0      1NS      1NS      12.24US    40US)
VG4    18      0    PULSE   (0V       20V     0      1NS    1NS      12.24US   40US)
* DMOD DEFINES THE DIODE MODEL PARAMETERS
.MODEL DMOD D (IS=100E-15 RS=16 BV=100 IBV=100E-15)
* MODQ1 DEFINES THE TRANSISTOR MODEL PARAMETERS
.MODEL MODQ1 NPN (IS=6.734F BF=416.4 ISE=6.734F BR=.7371
```

```
+ CJE=3.638P MJC=.3085 VJC=.75 CJE=4.493P MJE=.2593 VJE=.75
+ TR=239.5N TF=301.2P)
.TRAN    2US    300US    180US    1US   UIC
.PROBE
.OPTIONS ABSTOL=1.00N RELTOL=0.01 VNTOL=0.1 ITL5=20000
.FOUR 120HZ    I (VZ)
.OP
.END
```

5. P-Spice program for the C- Dump converter

```
VDC     1     0     DC    500V
  CIRCUIT DESCRIPTION
CIN     1     0     8UF
LR      1     2     28.8 UH
DR      3     0     DMOD
VX      2     3     DC    0V
VA      10    7     DC    0V
VB      15    18    DC    0V
VC      16    19    DC    0V
VD      17    20    DC    0V
L1      11    10    700UH
L2      11    15    700UH
L3      11    16    700UH
L4      11    17    700UH
D1      4     7     DMOD
D2      4     18    DMOD
D3      4     19    DMOD
D4      4     20    DMOD
Q1      7     8     0    MODQ1
Q2      18    21    0    MODQ1
Q3      19    23    0    MODQ1
Q4      20    25    0    MODQ1
RB1     5     6     250
RB2     8     9     250
```

```
RB3     21        22      250
RB4      23       24      250
RB5      25      26       250
VG1     6        0       PULSE (0V     20V    0    1NS    1NS      12.24US    40US)
VG2     9       0        PULSE (0V     20V    0    1NS    1NS     12.24US    40US)
VG3    22      0        PULSE (0V     20V    0     1NS   1NS    12.24US   40US)
VG4    24      0       PULSE (0V      20V    0     1NS    1NS     12.24US    40US)
VG5    26      0       PULSE (0V      20V   0      1NS     1NS     12.24US    40US)
CD       4       0       8UF
QR       3      4     5     MODQ1
* DMOD DEEINES THE DIODE MODEL PARAMETERS
.MODEL DMOD D (IS=100E-15 RS=16 BV=100 IBV=100E-15)
*MODQ1 DEFINES THE TRANSISTOR MODEL PARAMETERS
.MODEL MODQ1 NPN (IS=6.734F BF=416.4 ISE=6.734F BR=.7371
+CJE=3.638P MJC=.3085 VJC=.75 CJE=4.493P MJE=.2593 VJE=.75
+TR=239.5N TF=301.2P)
.TRAN      2US      300US      180US      1US    UIC
.PROBE
.OPTIONS ABSTOL=1.00N RELTOL=0.01 VNTOL=0.1N ITL5=20000
.FOUR   120HZ   I (VX)
.OP
.END
```

6. P-Spice program for the split dc supply converter

```
 VS       1        0      DC      500V
CIRCUIT DESCRIPTION
C1        1      2      1.0UF
C2        2      0      1.0UF
Q1       1      3       4      MODQ1
RB1    3      5      250
VG1   5       0        PULSE (0V       20V      0     1NS     1NS     12.24US    40US)
L1      4      2      35MH
VX     2       7      DC     0V
L2      7       8      35MH
```

```
VY     8      9      DC      0V
Q2      9     10     0     MODQ1
RB2   10     11     250
VG2      11      0      PULSE (0V     20V     0     1NS     1NS     12.24US    40US)
D1         7       1     DNAME
D2        4       0     DNAME
* DNAME SPECIFIES THE DIODE MODEL PARAMETERS
.MODEL DNAME D (IS=0.5UA RS=1 BV=5.20 IBV=0.5UA)
*MODQ1 SPECIFIES THE TRANSISTORS MODEL PARAMETERS
.MODEL MODQ1 NPN (IS=6.734F BF=416.4 ISE=6.734F BR=.7371
+CJE=3.638P MJC=.3085 VJC=.75 CJE=4.493P MJE=.2593 VJE=.75
+TR=239.5N TF=301.2P)
.TRAN    2US     300US    180US    1US    UIC
.PROBE
.OPTIONS ABSTOL=1.00N RELTOL=0.01 VNTOL=0.1 ITL5=20000
.FOUR 120HZ   I (VX)
.OP
.END
```

7. P-Spice program for the bifilar winding converter

```
 VS       1     0     DC    300V
   CIRCUIT DESCRIPTION
L1          1     2      52.5UH
VX         2     3      DC      0V
Q1          3      4      0    MODQ1
RB         4      5      250 OHM
VG        5       0     PULSE (0V      20V     0    1NS    1NS    12.24US   40US)
L2        1       6     52.5UH
VY        6       7      DC    0V
D1       7       0     DNAME
* DNAME SPECIFIES THE DIODE MODEL PARAMETERS
.MODEL DNAME D (IS=0.5UA RS=1 BV=5.20 IBV=0.5UA)
*MODQ1 SPECIFIES THE BJT PARAMETERS
.MODEL MODQ1 NPN (IS=6.734F BF=416.4 ISE=6.734F BR=.7371
```

```
+CJE=3.638P MJC=.3085 VJC=.75 CJE=4.493P MJE=.2593
+ VJE=.75 TR=239.5N TF=301.2P)
.TRAN     2US    300US   180US   1US   UIC
.PROBE
.OPTIONS ABSTOL=1.00N RELTOL=0.01 VNTOL=0.1 ITL5=20000
.FOUR 120HZ I (VX)
.OP
.END
```

8. P-Spice program for the R-Dump converter

```
VS    1   0    DC   100V
 CIRCUIT DESCRIPTION
R      1       2    0.615 OHM
CS     2       0      16 UF
VX    1       3     DC     0V
L1     3       4     133MH
D1     2       4     DNAME
Q1     4       5    0     MODQ1
RB1   5      6     100OHM
VG1   6     0    PULSE    (0V    20V    0     1NS     1NS     12.24US    40US)
VY     7     8      DC    0V
L2     8     9    133MH
D2     2     9     DNAME
Q2     9     10       0     MODQ1
RB2   10    11     100 OHM
VG2   11     0      PULSE (0V     20V       0    1NS     1NS      12.24US    40US)
VZ     7      12      DC    0V
L3     12     13     133MH
D3     2     13      DNAME
Q3     13     14     0     MODQ1
RB3   14       15     100OHM
VG3   15      0       PULSE (0V       20V    0     1NS    1NS      12.24US    40US)
*DNAME DEFINES THE DIODE MODEL PARAMETERS
.MODEL DNAME D (IS=0.5UA RS=1 BV=5.20 IBV=0.5UA)
```

```
*DNAME DEFINES THE TRANSISTOR MODEL PARAMETERS
.MODEL MODQ1   NPN (IS=6.734F BF=416.4 ISE=6.734F BR=.7371
+CJE=3.638P MJC=.3085 VJC=.75 CJE=4.493P MJE=.2593 VJE=.75
+TR=239.5N TF=301.2P)
.TRAN     2US      300US     180US     1US    UIC
.PROBE
.OPTIONS ABSTOL=1.00N RELTOL=0.01 VNTOL=0.1 ITL5=20000
.FOUR 120HZ   I (VX)
.OP
.END
```