Chapter 1

Introduction

Extensive usage of non renewable energy resources such as coal, gas and oil to produce large amount of power generation has made them difficult to last for forthcoming years. To meet the demand of power generation, many countries are focussing towards distributed renewable energy resources. Wind generated electrical energy is one of the viable solutions which comes under clean energy. The problem with distributed renewable energy is their tendency to vary from time to time. Harnessing the power from wind energy and deliver to the consumer requires generators and power electronic converters. Conventional wind energy system consists of turbine, gearbox, three phase AC generator, power converter, and step up transformer connecting the system to the grid, as shown in Figure.1.1.

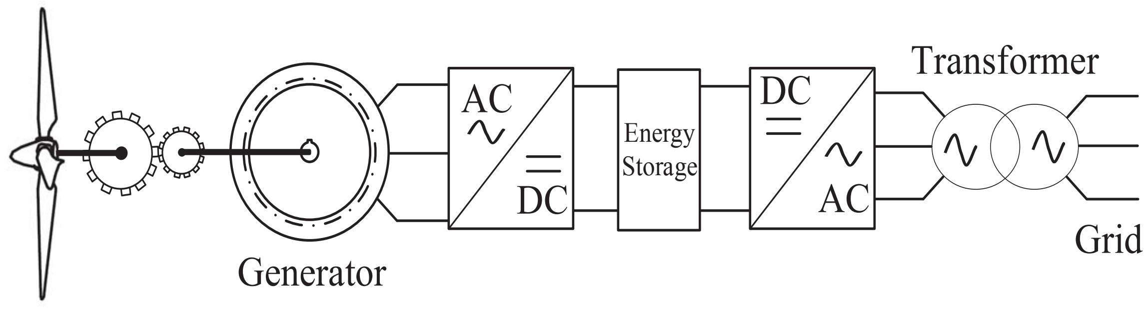

Figure 1.1: Conventional wind energy system

Recent advancement in direct drive wind generator system is more efficient and reliable as compared to geared wind generator system, resulting in increased production of electrical energy, and less maintenance issues. In addition, permanent magnet synchronous generator (PMSG) have higher energy yield, and power to weight ratio compared to wound rotor induction generator and doubly fed induction generator [1]. Voltage and frequency available at the output generator terminal tend to vary with turbine speed. To counter this voltage and frequency variation, AC-AC conversion is required. Conventionally, AC-AC conversion is realised in two stages AC-DC conversion followed by DC-AC conversion. Though it is established method, it suffers from the following limitations

- Require bulky capacitors to maintain DC link voltage
- Efficiency decreases as number of conversion stages increase
- Control action is required to mitigate operation upto some extent
- Protection against shoot through is required
- Converter lifetime and range of operation is limited

In another approach a direct AC-AC conversion for fixed voltage and fixed frequency at the output would provide a promising solution, as shown in Figure.1.2.

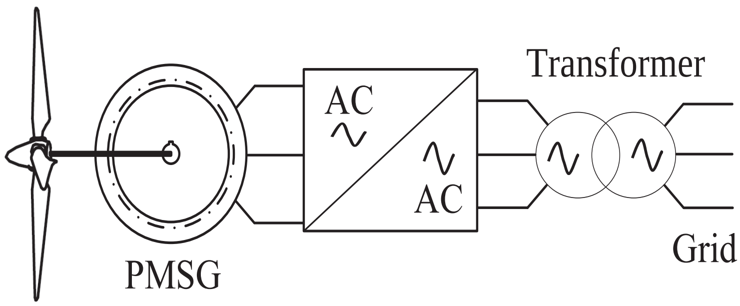

Figure 1.2: Proposed wind energy system

The aim of this thesis is to propose new topologies for AC-AC conversion. In order to control the power generation, a modulation technique is required which can taken care to boost the voltage level to synchronise it with the grid. Off grid cases like stand-alone operation with unbalanced voltage condition is also discussed to take the advantage of proposed topology.

1.1 Literature overview

Since wide variety of AC-AC converters are reported in literature, it becomes difficult to classify them in one form. In this dissertation, classification of converters is followed on the basis of article given in [2]. Figure.1.3 shows the classification of converters, as per the present state of art topologies. This section discusses the overview of AC-AC converters and explains their working principle, advantages and limitations. Conventional popular converters which industry has adopted lies in the group of converters with DC link energy storage. On the other side, matrix converters are in the research phase as futuristic converter. Recent trends are towards the evolvement of hybrid matrix topologies which overcomes the limitations of matrix converters by making use of impedance network.

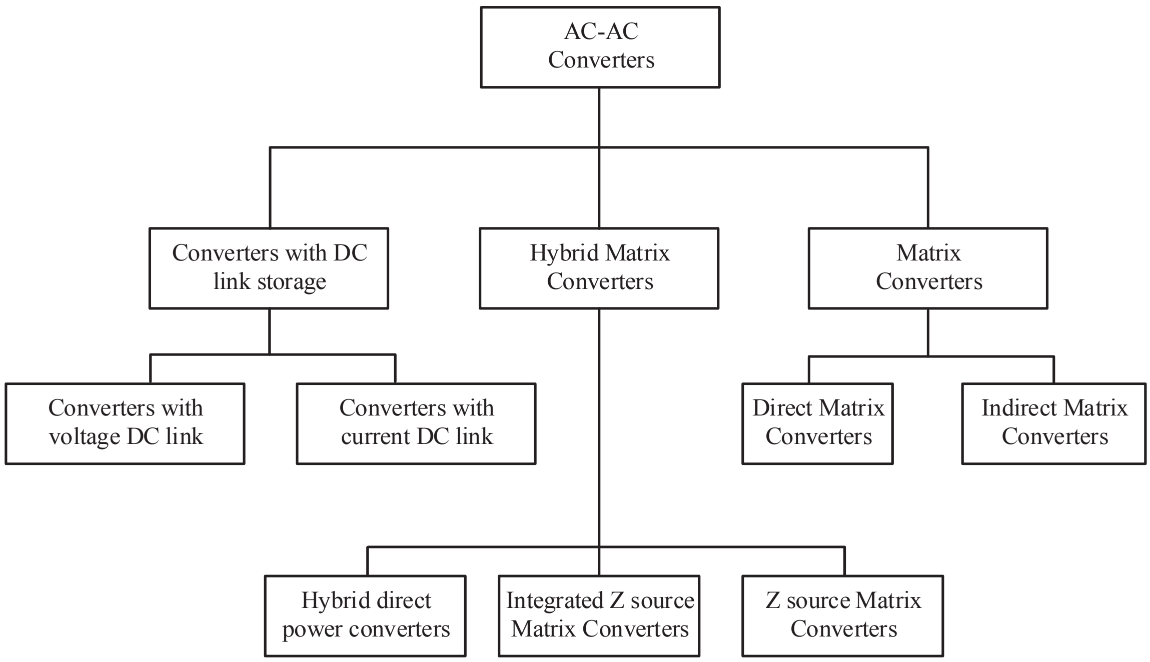

Figure 1.3: Classification of AC-AC converters

1.1.1 Converters with DC link energy storage

Converters which contain either capacitor, inductor or combination of both as energy storage element, are referred in this category. These converters are widely accepted for practical applications due to its peak efficiency $\geq 90\%$ and simple control. Figure.1.4 shows the basic converter in this category to achieve variable voltage and variable frequency operation. It consists of diode bridge rectifier circuit followed by voltage source inverter (VSI) having capacitive DC link energy storage. The converter is controlled only by using switching devices of VSI. The switching harmonics generated in VSI is absorbed with the help of capacitor. The design of capacitor depends upon the voltage across it and harmonic current provided by the capacitor during loading. The main drawback of this converter is, it doesn't have any control over input side in terms of power quality and voltage transfer ratio. A bulky DC link capacitor is mandatory in this arrangement.

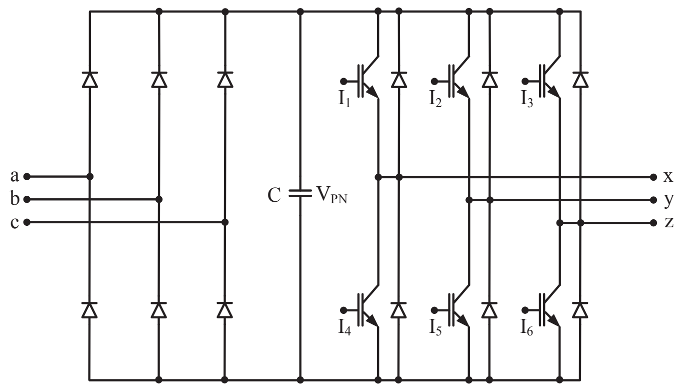

Figure 1.4: Diode bridge cascaded with voltage source inverter

To improve power quality and achieve high voltage transfer ratio, researchers modified previous circuit by incorporating switching devices at the input side along with three input inductors, as shown in Figure.1.5. Inductors charge and discharge during switching at the rectifier section. The stored energy in the inductors transfer its energy to the DC link. Thereby boosted DC link voltage is modulated by the VSI. The main limitation of voltage source back to back converter is higher number of switching devices as compared to diode bridge cascaded VSI. On the other hand back to back converter improves the power factor and injects less THD as compared to diode bridge cascaded VSI.

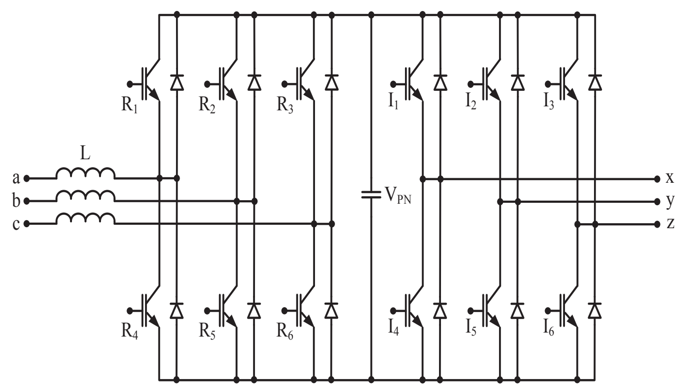

Figure 1.5: Voltage source back to back converter

Analogues to voltage source back to back converter, current source back to back converter is shown in Figure.1.6. In this circuit the main energy storage element is an inductor (L). The operation of converter is similar to voltage source back to back converter. This converter produces more conduction losses due to the presence of series combination of switch and diode. In a switching instant, the current flows through more number of switching devices than back to back voltage source inverter. In addition, the capacity to store energy per unit volume is more for capacitor than inductor.

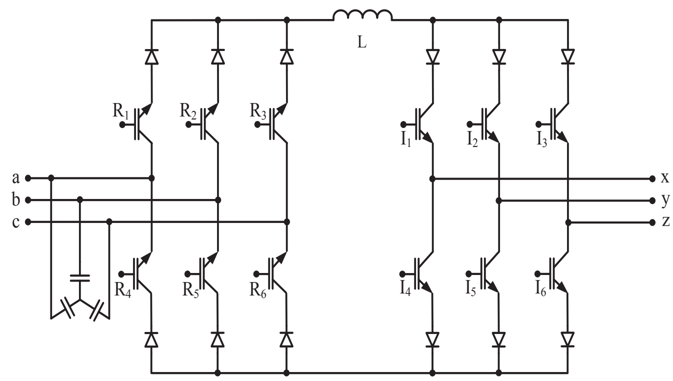

Figure 1.6: Current source back to back converter

The concept of impedance source network by F.Z. Peng [3] paved path to number of extended converters. The converter shown in Figure.1.7 is an extension of diode bridge cascaded VSI. The combination of energy storage elements L and C connected in 'X' shaped network boost the V_{pn} voltage to V_{dc} voltage. There by voltage available for modulation will be higher. Standard two level voltage source inverter has 8 switching states, out of which 6 are active states ($I_1I_2I_3 \Leftrightarrow 100, 011, 110, 001, 010, 101$) and remaining 2 are zero states ($I_1I_2I_3 \Leftrightarrow 000, 111$). For a Z source inverter, an additional shoot through state is required to operate the inverter. During this shoot through state, an inductor and capacitor stores energy. For remaining states these element discharges through the load, providing higher voltage available at V_{dc}. The main restriction of this converter is to maintain the criteria $m + d_{sh} \leq 1$, where m is the modulation index of the inverter, d_{sh} is the shoot through duty ratio. Larger duty ratio is required to get higher gain there by it operates inverter at lower modulation index which results in power quality issues.

Vienna rectifier cascaded with voltage source inverter is another type of AC-AC converter topology reported in literature, as shown in Figure.1.8. This converter produces better input power quality compared to others which are discussed above.

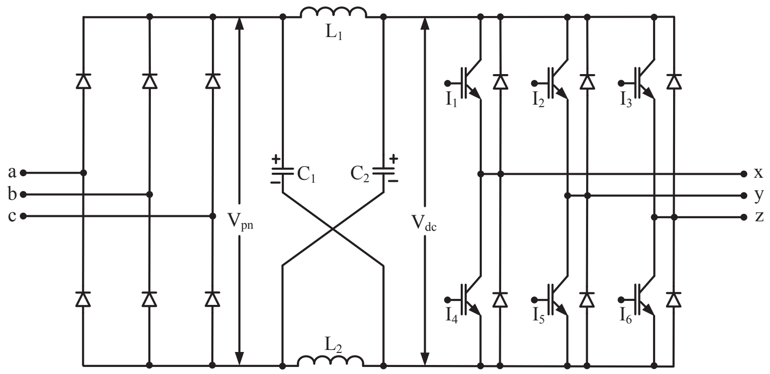

Figure 1.7: Diode bridge cascaded with Z source inverter

This converter produces three level of DC link voltage due to the rectifier switching characteristics, there by reducing the value of boost inductors. The main disadvantage of this topology is higher conduction losses than switching losses due to more number of semiconductor devices.

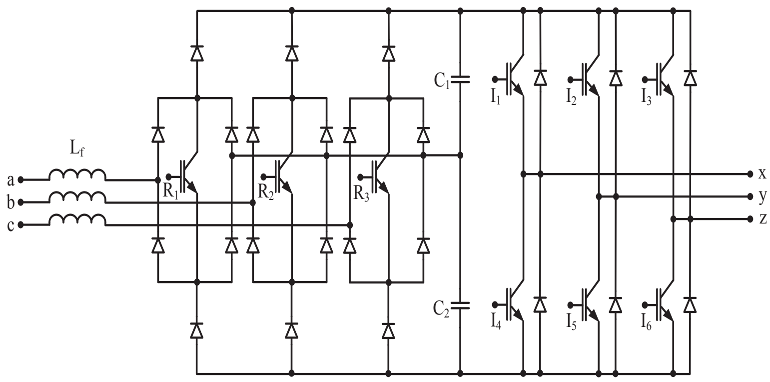

Figure 1.8: Vienna rectifier cascaded with VSI

Although converters with DC link energy storages are able to produce higher voltage transfer ratio ($G \geq 1$), variable output frequency with simple control. However when power density, degree of freedom in control and power to mass ratio are considered, these converters offer limitations. Aiming for higher power densities along with variable voltage and variable frequency operation can be achieved by matrix converters. The input filter requirement of matrix converter is reduced almost to 40% compared to voltage source back to back converter due to its input characteristics. Moreover, the efficiency of matrix converters is $5-7\%$ higher than the voltage source back to back converter at higher switching frequencies in [4].

1.1.2 Matrix converters

AC-AC converter topologies without any energy storage in the intermediate link are referred to as Matrix Converters (MC). The concept of matrix converter was initiated way back in 90's which was explained through rigours mathematical analysis by Alesina [5]. Matrix converter topologies are entirely based on semiconductor devices often called as all silicon solution. The name of the converter comes from the nine bidirectional switches arranged in the form of arrays in a direct matrix converter, as shown in Figure.1.9. As there is a direct connection of output phases with the input voltage sources, the input phases shall never be shorted. Similarly when the load is inductive, output terminals should never be open circuited. Since it doesn't contain any energy storage elements, the output voltages have to be generated from the input voltage envelope.

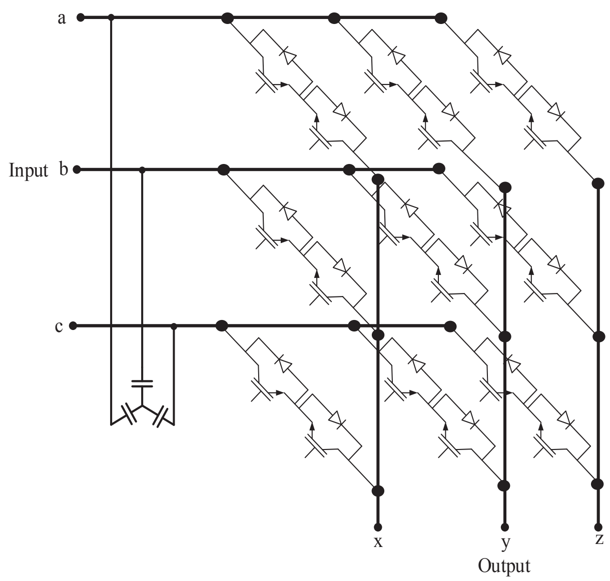

Figure 1.9: Direct matrix converter (DMC)

Initially it was controlled by using switching function based on Venturini algorithm for bidirectional switches in the matrix converter. The voltage gain that upto $G \leq 0.5$ can be achieved with this algorithm. By injecting third harmonic component in the reference wave the voltage gain can be increased to $G \leq 0.866$. The authors in [6] proposed the scalar method to enhance the gain upto $G \leq 0.866$. To generate balanced sinusoidal input and output waveforms with variable input displacement angle, matrix converters are controlled by the above mentioned modulation techniques. Over each switching period, the modulation strategy controls duty cycles of the switches.

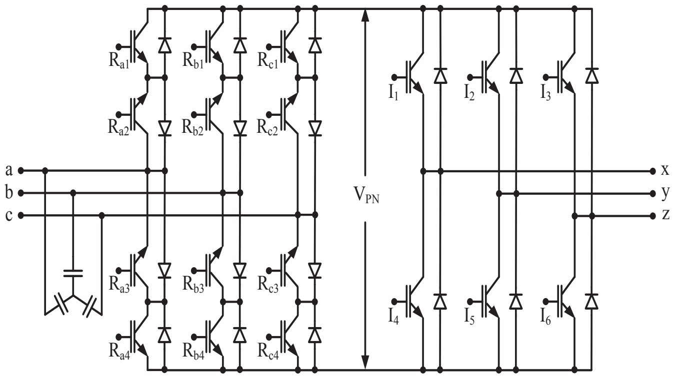

Figure 1.10: Indirect matrix converter (IMC)

For better controlling in respect of reduced switching states with less protection elements, matrix converter was reconfigured as indirect matrix converter (IMC) [7]. It has a combination of current source rectifier and voltage source inverter section, as shown in Figure.1.10. The basic functionality of both DMC and IMC topologies are quite similar. Their different physical structure results in different operating characteristics. Unlike DMC, IMC is based on decoupled control of the rectifier and inverter stages. The instantaneous input phase to output phase matrix transfer function can be represented as rectifier and inverter transfer functions. The IMC requires capacitors at the converter input to provide power factor control, similar to the conventional current source rectifier.

Carrier based PWM method is the basic modulation technique to operate any converter. Changing slope of carrier wave and using offset voltages is the theme to control the switches of matrix converter in [8]. Space vector modulation concept was implemented for both (IMC and DMC) matrix converters topologies [9]. It has flexibility in adjusting switching states and power factor by using set of equations. Due to the structural difference in matrix converter topologies, IMC can easily be commutated compared to DMC. In IMC, intermediate DC link voltage and current is accessible, which allows implementation of zero current and voltage commutation techniques for reliable operation of converter [10]. Switching between high and medium levels of input line voltages results in high voltage SVM (HVSVM) technique. Similarly switching between medium and low voltage levels of input line voltages results in low voltage SVM (LVSM) technique, Likewise switching between high, medium and low levels of input line voltage results in three vector SVM (TSVM) technique [10] [11]. With space vector modulation the gain of IMC was restricted to $G \leq 0.866$,

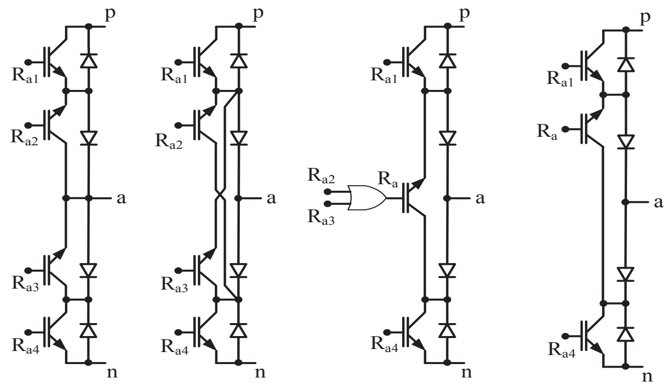

Figure 1.11: Switch reduction stages in one leg of IMC

Researchers focussed on reducing the controlled switches from 18 to 15 which is termed as sparse matrix converter [12] having functionality equivalent to IMC. Switch reduction stages in one leg of IMC is shown in Figure.1.11. Sparse matrix converter (SMC) is shown in Figure.1.12. There is another topology reported in literature with reduction in controlled switches from 15 to 12. It is referred as very sparse matrix converter (VSMC), as shown in Figure.1.13. Both SMC and VSMC converters possess similar characteristics such as bidirectional power flow and input displacement factor control. The difference is in usage of less number of control circuits and number of semiconductor devices conducting in a path at any instant. The VSMC has 6 controlled switches at rectifier stage instead of 9 switches required by SMC.

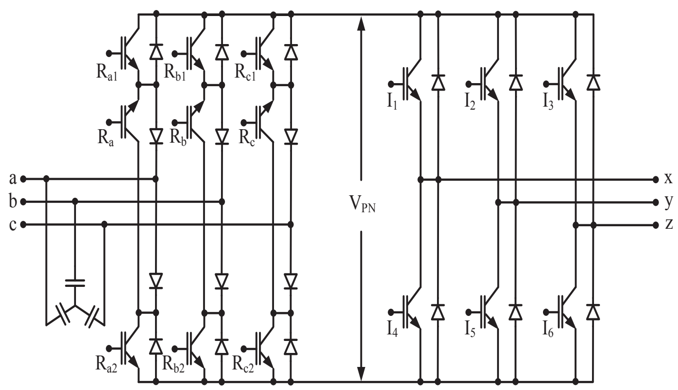

Figure 1.12: Sparse matrix converter

The switch reduction stages in one leg of sparse matrix converter is shown in Figure.1.14. Using this approach the total number of switches was further reduced to 9

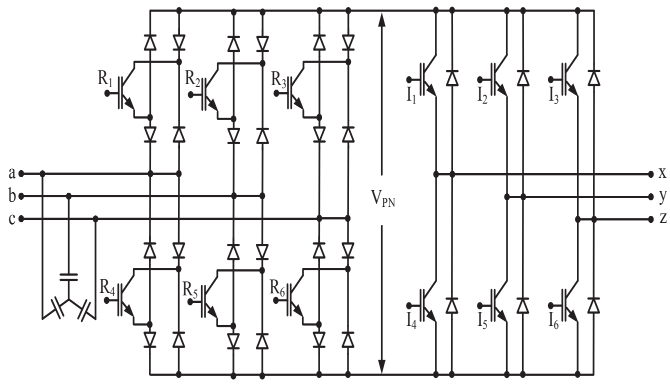

Figure 1.13: Very sparse matrix converter

switches, resulting in ultra sparse matrix converter (USMC), as shown in Figure.1.15. However, it has unidirectional power flow, controllability of both input phase displacement angle and output power factor angle is restricted to $\left[-\frac{\pi}{6}\ \ +\frac{\pi}{6}\right]$. All modulation techniques which are applicable to IMC could be applied to SMC and USMC topologies. Figure.1.16 shows the three level USMC with neutral point clamped inverter stage as reported in [12]. This converter produces three level voltage at the output terminals which reduces the filter size.

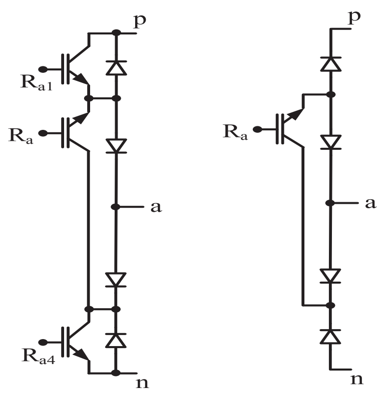

Figure 1.14: Switch reduction stage in one leg of SMC

Sparse type converters are better solution over direct and indirect matrix converters, that suffer from high number of power switches and control drivers. The sparse matrix converters operation with overmodulation schemes results in unity gain (around 1) but at the expense of increased total harmonic deviation (THD) for input currents and output voltages [13]- [14]. In addition, various modulation schemes for sparse matrix converters are reported which lower the switching losses [15], improve load power factor handling and ensure optimal switching for reactive power control [16] [17], but

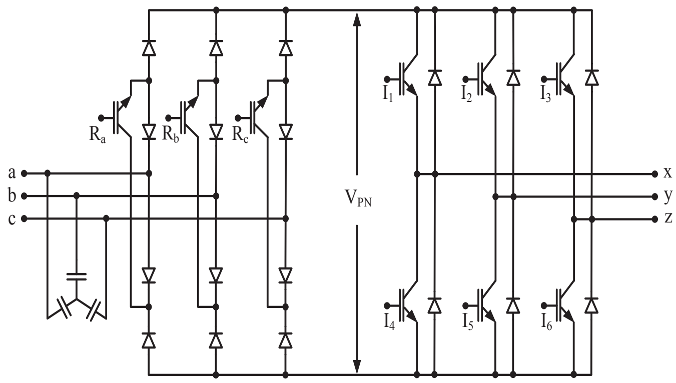

Figure 1.15: Ultra sparse matrix converter

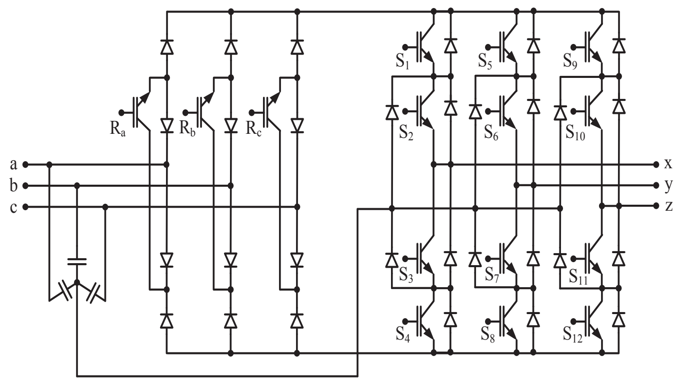

Figure 1.16: Three level USMC with NPC inversion stage

the converter voltage gain is restricted. Broadly, to enhance the voltage gain of matrix converter there are two approaches, one is through modulation scheme another is through topology modifications. Appropriate changes in modulation technique results in better commutation, enhanced output phase displacement angle and voltage gain up to 1.05 is achieved. However, the SMC fails to operate for pulsating loads [18].

Without additional circuitry, the desired gain $G \geq 1$ for SMC cannot be increased, as matrix converters are inherently buck type converters. In conventional approach, a transformer at line frequency is used to boost the voltage. However line frequency transformers results in more cost, large size and requires maintenance. In contrast, higher voltage transfer ratio $G \geq 1$ can be achieved by placing reactive elements in matrix converter, without compromising harmonics at input and output which leads to hybrid matrix converters.

1.1.3 Hybrid matrix converters

The matrix converters which include reactive elements, are to boost the voltage in matrix converters are termed as hybrid matrix converters. There are two approaches possible for the placement of reactive network in a matrix converter. First approach is reactive network between input and rectifier section and second approach is reactive network between rectifier and inverter (DC link section).

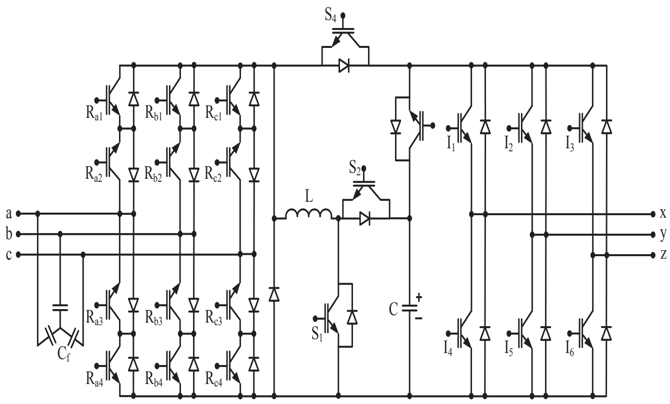

Figure 1.17: Auxiliary reversible boost integrated IMC

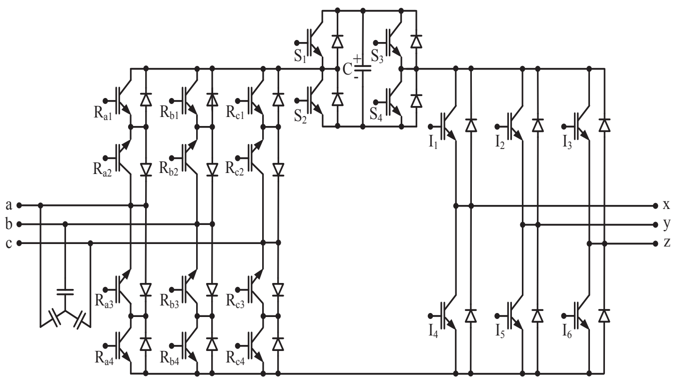

Figure 1.18: Integrated capacitive link VSI bridge IMC

A high frequency DC-DC converter is employed at intermediate DC link section to step up the voltage. However, the additional power conversion stage brings additional costs. A reversible boost type network at DC link is integrated, as shown in Figure.1.17, which is reported in [19]. The gain achieved by the converter is $0.866 \leq G \leq 1$. In [20] series voltage injection at DC link of IMC by a combination of four switches formed in a bridge manner, along with capacitor is reported, as shown in Figure.1.18. The maximum voltage gained through this converter is 1. The limitation of this converter is to maintain charge balance in the capacitor for every switching cycle. In [21] boost compensator, buck-boost compensator and its bypass circuit is placed at DC link of IMC to improve the voltage gain. External DC supply is boosted and injected at DC link section to lift the voltage gain reported in [22]. The converters discussed till now has achieved a maximum voltage gain of 1 even though with the inclusion of reactive power elements. The voltage gain $G \geq 1$ is made possible using the reactive elements of impedance source network.

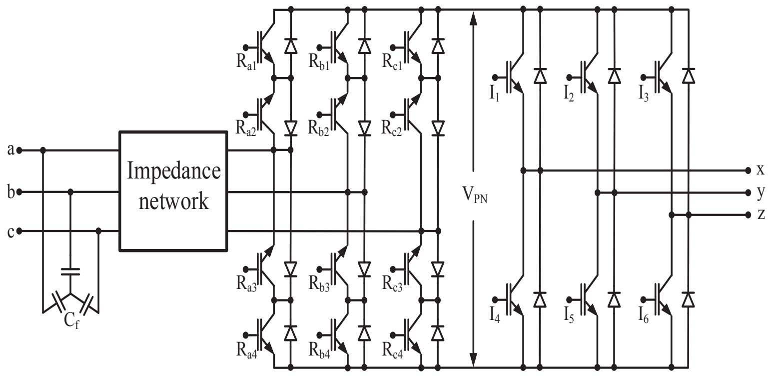

Figure 1.19: Impedance source IMC

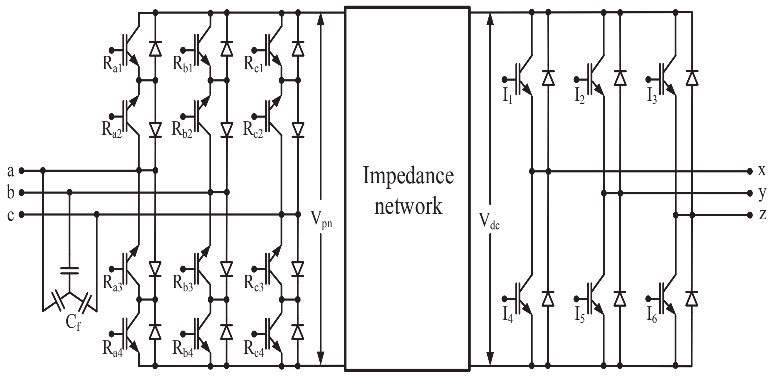

Figure 1.20: Integrated impedance source IMC

Impedance source network consists of inductors and capacitors. The combination of number of elements used and their connection results various networks which can be optimally designed to ensure small size and low cost. The integration of impedance source network within matrix converters are known impedance source matrix converters. The impedance source network utilises the shoot through period of the converter for boosting. Shoot through pulses are given to the converter during zero state. With the provision of shoot through period in a converter dead time is not required, therefore the control accuracy and harmonic content can be improved. This feature of impedance source network makes it immune to EMI problems. The main restriction imposed by this network on to the converter is to maintain $m + d_{sh} \leq 1$, where m is the modulation of the converter and d_{sh} is the shoot through period. Different types of impedance networks are proposed in literature, such as Z-source [3], Quasi Z-source [23], Switched inductor Z-source [24], and series Z-source [25]. For these impedance networks the insertion of shoot through pulse is possible at rectifier section or inverter section of IMC which lead to two cases: Case 1 placing impedance network before rectifier section [26], as shown in Figure.1.19. Case 2 placing impedance network at intermediate DC link section [27] as shown in Figure.1.20. Case 1 involves more number of passive elements and also higher rating of power devices are needed both for rectifier and inverter section. In case 2, network arrangement between the rectifier and the inverter section allows boosted voltage stress across inverter. Under case 2 the reported matrix converters include integrated Z source USMC (ZS-USMC), integrated quasi Z source USMC (QZ-USMC), integrated switched inductor Z source USMC (SL-USMC) and integrated series Z source USMC (SZ-USMC).

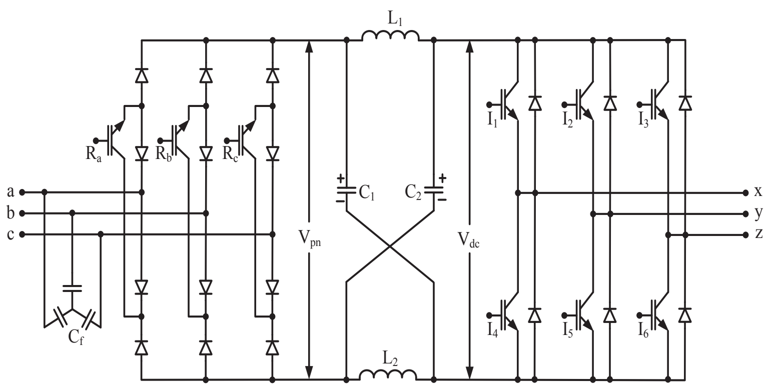

Figure 1.21: Integrated Z source USMC (CZ-USMC)

Figure.1.21 shows the integrated Z source USMC (ZS-USMC) as reported in [28]-[30]. This has boosting factor $B = \frac{1}{1-2d_{sh}}$ in the output voltage equation.

Integrated switched inductor Z source USMC (SWZ-USMC) reported in [31] requires less shoot through period to increases the boosting factor of an integrated Z source USMC (ZS-USMC). This is done by adding extra six diodes and two inductors. Considering the criteria between the modulation index and shoot through duty ratio improve the power quality and boosting factor. However, both the ZS-USMC and

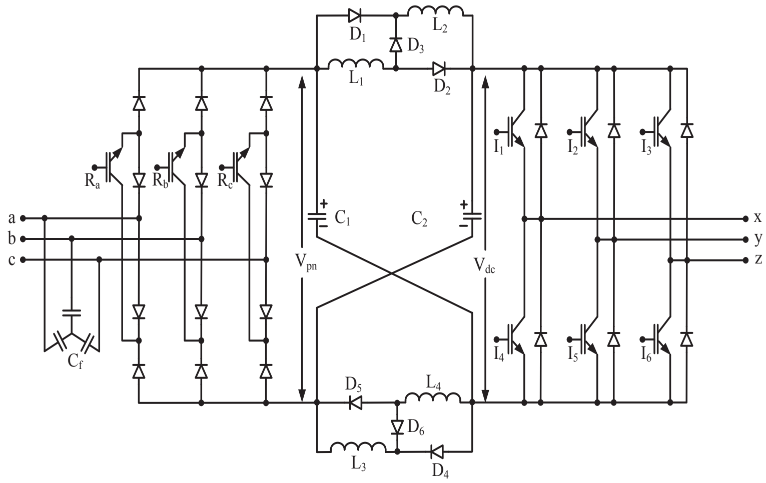

Figure 1.22: Integrated switched inductor Z source USMC (SWZ-USMC)

SWZ-USMC have drawbacks firstly the voltage across Z source capacitors are larger than the input voltage. This require the use of larger capacitors, which increases the overall cost and volume. Secondly, the inrush current and resonance in the Z-source network at startup.

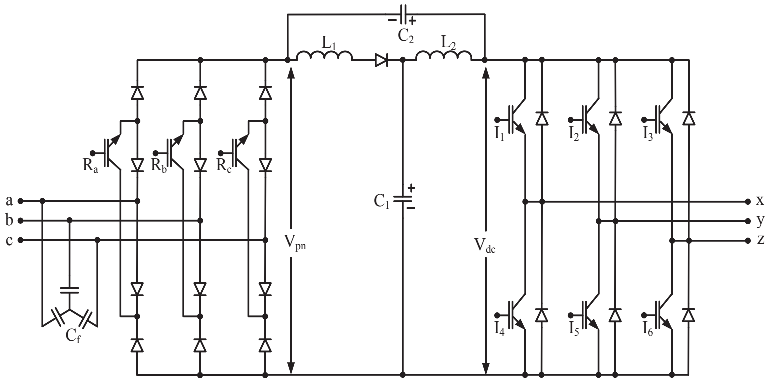

Figure 1.23: Integrated quasi Z source USMC (QZ-USMC)

To mitigate the drawbacks of ZS-USMC and SWZ-USMC, integrated quasi Z source USMC (QZ-USMC) is developed and reported in [32]. A circuit diagram of the QZ-USMC is shown in Figure.1.23. In this topology, quasi Z-source network constitutes a voltage boosting DC link based on two capacitors, two inductors and a diode. Here voltage stress across capacitors are unequal which requires less voltage rating of the components.

The integrated series Z source USMC (SZ-USMC) is shown in Figure.1.24. It is characterized by reduced capacitor voltage requirement and limited inrush current at the startup as compared to ZS-USMC, QZ-USMC, SWZ-USMC converters. The

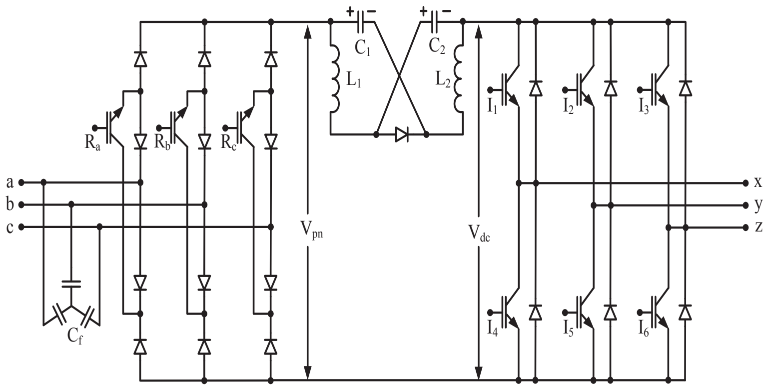

Figure 1.24: Integrated series Z source USMC (SZ-USMC)

gain of SZ-USMC remains same as that of ZS-USMC, QZ-USMC which are reported in [33]- [34].

As discussed above, the voltage available at the output terminals of impedance source matrix converters is two level. To reduce the output filter size and voltage stress across devices, multilevel output is a better solution. Implementation of Z source concept is widely popular for 2 level VSI. On the other side in multilevel inverters it is difficult due to unavailability of zero state at higher modulation index. In [35] shoot through period is equally distributed into upper and lower section of multilevel inverter. This makes multilevel Z source inverter operational even at higher modulation index. In [36], a new topology called Z source NPC based multilevel matrix converter as shown in Figure.1.25 is reported with carrier modulation technique. It has voltage transfer ratio ≥ 1. For same topology, space vector modulation technique is developed and explained in [37].

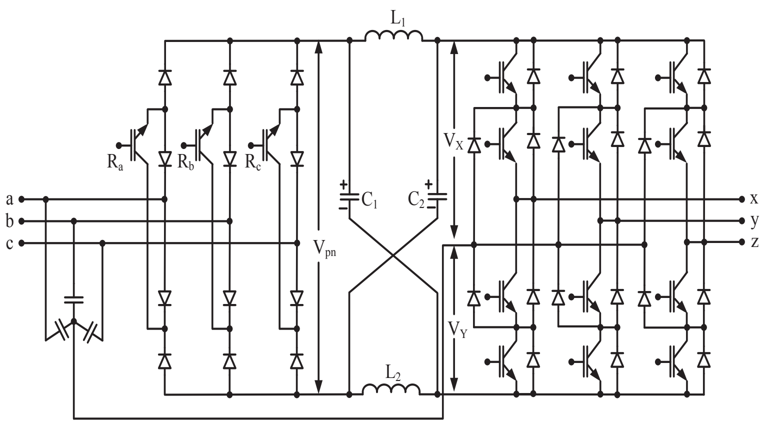

Figure 1.25: Three level Z source USMC with NPC inversion stage

Even though hybrid matrix converters give a reasonable solution to wind energy systems up to some extent, but there is requirement of research to tackle unbalanced conditions, reduce the passive elements count and their size.

1.2 Motivation

The motivation of this thesis is to initially find the existing topologies for wind energy systems, where a low voltage variable speed generator feed power to fixed higher voltage fixed frequency grid. Based on this theme the objective of the thesis is to design and develop high gain AC-AC power converters characterised by the following:

- utilising minimum number of passive elements
- minimum number of semiconductor devices
- produce voltage transfer greater than unity
- robust to external disturbance
- variable input voltage and frequency
- produce low THD in input currents and output voltages.

Moreover a modulation technique is developed to achieve high boosting flexibility and to minimize the ripple current of inductors which also reduces the size of the proposed converter.

1.3 Structure of the Thesis

This thesis is arranged into six chapters. Brief discussion of each chapter is as follows

Chapter 1 gives the introduction of the thesis along with a technological overview of matrix converter topologies and their modulation techniques. It also describes the research motivation and outline of the thesis.

Chapter 2 gives the description to implement space vector modulation for voltage source inverter and current source rectifier. Furthermore, space vector based zero current switching and zero voltage switching is discussed for indirect matrix converter.

Chapter 3 proposes switched capacitor ultra sparse matrix converter. The circuit analysis and operating principle are discussed with analytical derivations. A modulation technique is developed to achieve maximum gain from the proposed converter. Experiment and simulation results are shown to confirm the enhanced gain of the converter over conventional matrix converters.

Chapter 4 proposes switched boost ultra sparse matrix converter. Steady state analysis is done to derive the gain of proposed converter. A modulation technique is developed to achieve inductor current ripple minimization for the proposed converter. Experiment results confirm the effectiveness of the proposed converter.

Chapter 5 proposes a multilevel matrix converter for reducing the filter size along with boosted output voltage. Space vector modulation method for integrated Z source based multi level matrix converter is also presented. The technique is simulated in MATLAB to verify the feasibility of proposed converter. Furthermore, these results are validated using experiment results.

Chapter 6 presents the conclusion of the thesis. Possibilities for improving the investigated topologies are outlined for future work.