Chapter 1

Introduction

Although fossil fuels are currently the primary source of energy, their adverse effects on the environment have led researchers to search for alternative sources of power generation. Besides, the daily rise in energy consumption may cause power distributors to experience outages. Renewable energy is a better solution to meet additional power requirements. According to the Renewable 2023 global status report [1], global wind energy capacity and annual additions have steadily increased in recent years, as shown in Figure 1.1. A typical wind energy system (WES) consists of a wind turbine, which is connected to a permanent magnet synchronous generator (PMSG) to convert mechanical energy into a three-phase alternating current (AC) supply. This AC supply is first converted into direct current (DC) and further to the standard three-phase AC (AC-DC-AC conversion), as shown in Figure 1.2. This process needs more energy conversion stages and hence lead to a lower efficiency. The AC-DC-AC conversion has the following limitations:

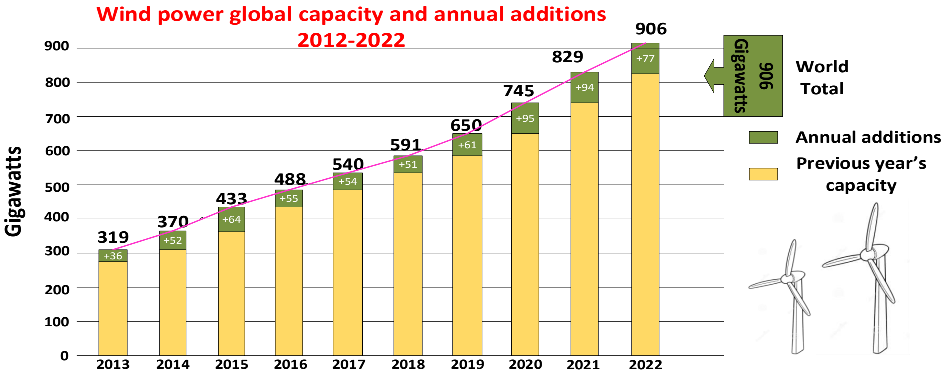

Figure 1.1: Wind energy report

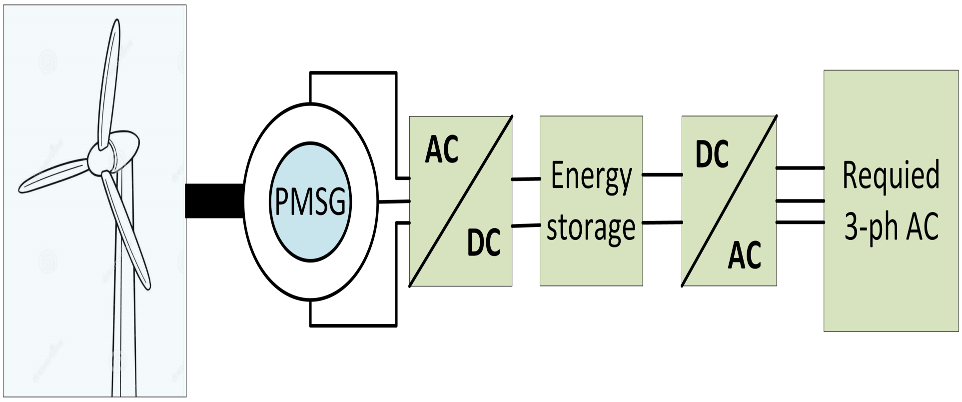

Figure 1.2: Wind energy system with AC-AC converter

- The AC-DC-AC converter requires more conversion stages to get the required three-phase AC. The presence of these additional conversion stages has a significant impact on the overall efficiency of the WES. With each additional stage, there is increased energy loss, resulting in lower efficiency.

- The functionality of the AC-DC-AC Voltage Source Converter (VSC) relies heavily on a large-size DC-link capacitor, essential for stabilizing the DC voltage output. However, incorporating such a substantial passive element contributes to an increase in the overall size and bulkiness of the system, rendering it larger in physical dimensions. The DC-link inductor within a Current Source Converter (CSC) also poses a significant cost and bulkiness challenge [2].

- Due to the presence of large-size passive elements, the overall reliability of the system is reduced. The presence of large-sized passive elements introduces constraints on the overall reliability of the system. Factors such as component degradation over time and potential points of failure contribute to the limitations in the system's reliability.

So, WES requires a direct AC-AC power electronic converter that delivers the required voltage and frequencies. Besides WES, an AC-AC converter is also essential for AC motor drive applications. In the following session, the classification of AC-AC converters is discussed.

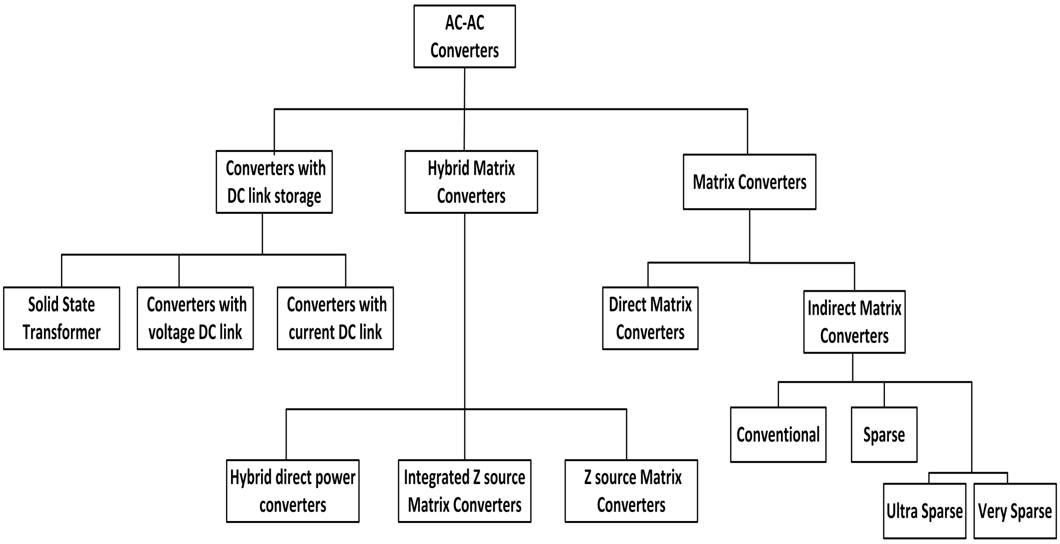

Figure 1.3: Classification of AC-AC converters

1.1 Classification of AC-AC converters

AC-AC converters can be classified into various groups [3], as shown in Figure 1.3. In industries, established converters predominantly fall into the category featuring DC-link energy storage. Matrix converters, positioned as forward-looking solutions, are currently undergoing through rigorous research phase. A noteworthy trend is the emergence of hybrid matrix topologies, which reflects a recent shift in focus. These innovative configurations aim to transcend the constraints associated with traditional matrix converters by integrating impedance networks. This strategic integration promises to overcome limitations and elevate performance, marking a promising development in the field of AC-AC converters. Basically, AC-AC converters without transformer are of three types 1) Converters with DC-link storage, 2) Matrix converters, and 3) Hybrid matrix converters.

1.1.1 Converters with DC-link energy storage

This category involves converters utilizing storage elements like capacitors, inductors, or a combination. This approach is widely accepted due to its straightforward control. The Solid State Transformer (SST) is reported in [4–6]. SSTs are capable of converting AC voltage at one frequency to AC voltage at another frequency. As illustrated in Figure 1.4, the SST comprises a cascaded multilevel AC/DC rectifier, Dual Active Bridge (DAB) converters with high-frequency transformers, and a DC/AC inverter.

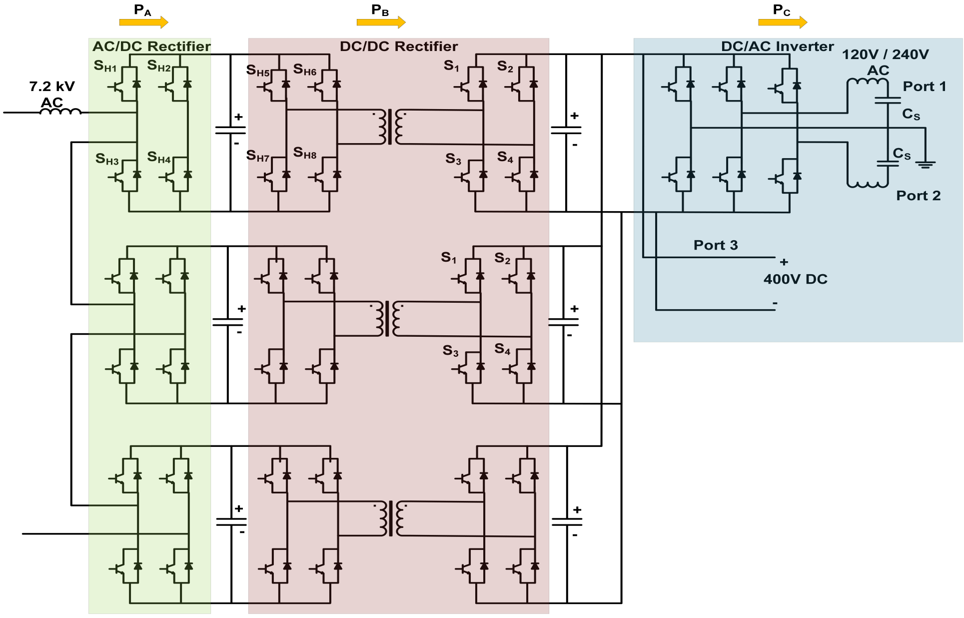

Figure 1.4: Configuration for Solid State Transformer

The rectifier stage features a cascaded H-Bridge converter, which manages the input power factor and regulates the high voltage DC bus. The DAB converter controls the low voltage DC bus, while the DC/AC inverter delivers a 60Hz AC residential voltage. One of the advancements in SST is the series-stacked capability. This design approach handle higher voltage levels. A drawback of the single-phase SST is the presence of a 120Hz low-frequency ripple in the DC bus voltage due to the single-phase input power varying at a 120Hz frequency. This necessitates a significantly larger capacitance to keep the DC voltage ripples within acceptable limits compared to a three-phase system. Illustrated in Figure 1.5 is the fundamental converter within this category, designed for achieving variable voltage and frequency operations. It integrates a diode bridge rectifier circuit at the input and a voltage source inverter (VSI) with capacitive DC-link energy storage at the rectifier output stage. The DC-link capacitor design depends on its voltage and load current harmonics, and it is more prominent in size. The VSI switches are the only devices that allow control over the converter's operation. However, a notable drawback of this converter lies in the necessity for precise control over the input side irrespective of power quality and voltage transfer ratio, accompanied by the mandatory inclusion of a large DC-link capacitor in this arrangement.

To improve power quality, researchers have modified the aforementioned circuit by incorporating switching devices on the input side, as depicted in Figure 1.6, named as a voltage source back-to-back converter (VSBBC). The VSBBC, a two-stage configuration, integrates a Voltage Source Rectifier (VSR) at the input stage and a Voltage Source Inverter (VSI) at the output stage, interconnected via the DC-link capacitor C. In comparison to the diode bridge cascaded VSI, the primary drawback of the voltage source back-to-back converter is its increased number of switching devices. Conversely, the back-to-back converter enhances the power factor and introduces lower total harmonic distortion (THD) compared to the diode bridge cascaded VSI. Similar to the voltage source back-to-back converter, the Current Source Back-to-Back Converter (CSBBS) is illustrated in Figure 1.7. In this circuit, the primary energy storage element is a DC-link inductor. The operation of the converter is the same as that of the voltage source back-to-back converter. As shown in Figure 1.8, another type of AC-AC converter topology in literature is comprised of the Vienna rectifier cascaded with a voltage source inverter. This particular converter is noted for its impact on improving the input power quality compared to the converters discussed earlier but shows higher conduction losses due to more diodes.

While converters employing DC-link energy storage can attain more voltage gain and variable output frequency through simple control, they exhibit drawbacks concerning power density, degree of freedom in control, and power-to-mass ratio. Matrix converters, on the other side, offer a solution by targeting high power densities along with variable voltage and frequency operations. The advantages often claimed for the matrix converter are:

- Matrix converters have the potential to be compact and lightweight, as they do not require intermediate storage elements.

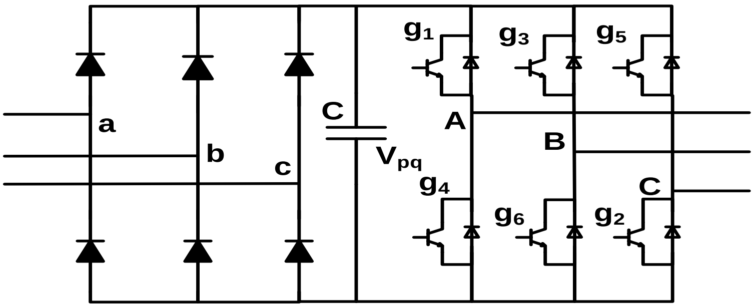

Figure 1.5: Diode bridge cascaded with voltage source inverter

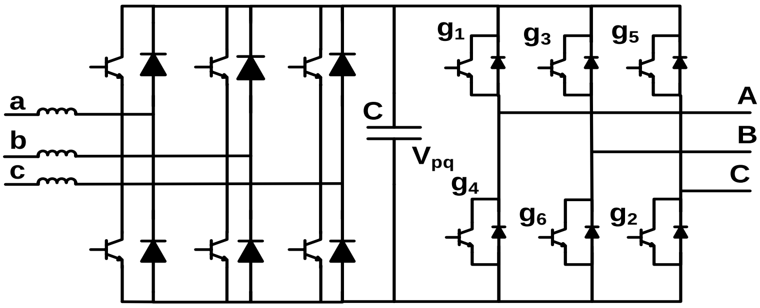

Figure 1.6: Voltage source back-to-back converter

- The input power factor can be controlled without depending on the output load current [7].

- Unlike the VSBBC, MCs do not have a DC-link capacitor. The utilization of electrolytic capacitors could potentially reduce the converter's lifespan due to thermal aging.

- Comparing the MC to the VSBBC, the passive components' volume is about 3.5 times smaller at higher frequency (=32 kHz) and around ten times smaller at lower frequency (=8 kHz) [8].

- Moreover, at high switching frequencies, the efficiency of the matrix converter surpasses that of the voltage source back-to-back converter by 5–7% [8].

- The harmonic content of the output voltage is another aspect to consider.

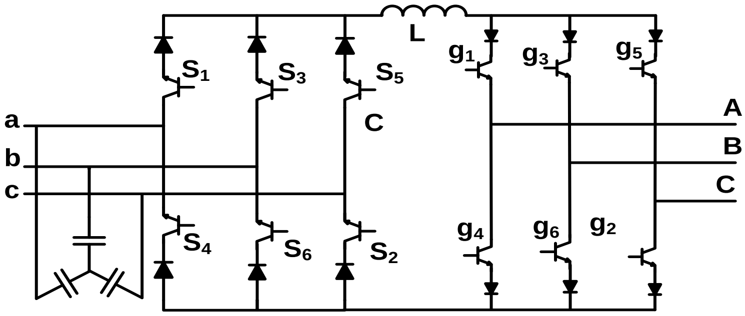

Figure 1.7: Current source back to back converter

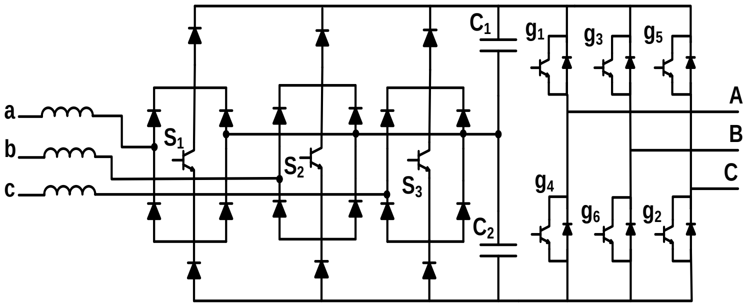

Figure 1.8: Vienna rectifier cascaded with VSI

1.1.2 Matrix converters

Taking into account the limitations associated with DC-link energy storage elements, the Matrix Converter (MC) was developed [9], [10]. The matrix converter presents a topology for AC-AC power conversion, predominantly relying on semiconductor switches, often called "all silicon solutions." Its design incorporates an array of bidirectional switches strategically arranged to allow the connection of any input phase to any output phase. The name "matrix converter" refers to the conventional configuration of a basic three-input, three-output direct matrix converter, which normally includes a "matrix" made up of nine bidirectional switches as illustrated in Figure 1.9. The desired output voltage in MC is made possible by controlling device gating. Due to the absence of energy storage elements and the direct connection of output phases with the input voltage, it is crucial to avoid short-circuiting the input phases. Similarly, in the case of an inductive load, the output voltages must be derived from the input voltages, and the output terminals should never be left open. Since there are no storage elements, the output voltage has to be generated from the input voltage envelope. Due to the relation between the input current and the switching control of the converter, MC can control the phase angle of the input currents. One of the critical issues when investigating a converter topology is switching commutation. Back-to-back converters are hard-commutated, but MCs can be semi-soft-commutated with a proper selection of bi-directional switches and commutation strategy. Based on the structure of the matrix converter, there are two types: 1) direct matrix converter and 2) indirect matrix converter.

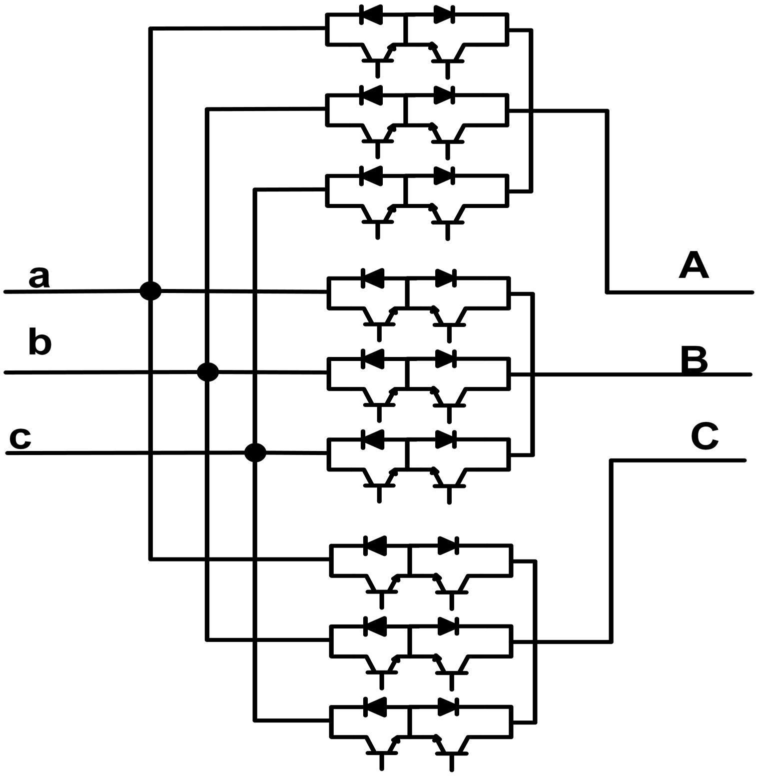

Figure 1.9: Direct matrix converter

Direct Matrix Converters

A standard three-input, three-output Direct Matrix Converter (DMC) [11–18] typically consists of a "matrix" containing bidirectional switches arranged to allow the connection of any input phase to any output phase. The modulation of these switches is crucial for achieving the desired output voltage. A four-quadrant switch can be implemented by a regular power switch with anti-parallel freewheeling diodes as the input stage of the MC as shown in Figure 1.9. With a direct connection to voltage sources, it is imperative that the input phases are never shorted. If the switches create a short circuit between the input voltage sources, a substantial current flows through the switches, leading to potential damage in the phase where the short circuit occurs. Additionally, owing to the inductive characteristics of standard loads, it is crucial to avoid open-circuiting the output terminals. Should any output terminal be left open-circuited, the voltage across the inductor (and consequently across the switches) becomes infinite, posing a risk of damage due to over-voltage. So, the commutation process of the DMC switches becomes complex due to this direct connection of input and output terminals. Achieving smooth operation requires the adoption of multi-step commutation methods [19–21]. Indirect matrix converters have been introduced to address commutation problems effectively and further reduce associated challenges.

Indirect Matrix Converters

An alternative MC exists as the Indirect Matrix Converter (IMC). The IMC has two separate stages, the input and output stages, but without any energy storage in the intermediate link. The study of IMC circuits involves analyzing the fundamental operations and modulation of both the AC-DC converter, which controls the output current, and the DC-AC converter, which controls the input voltage. The IMC consists of Current Source Rectifiers (CSR) at the input stage and VSI at the output stage [22–28], as shown in Figure 1.10. To gain control over the conductive state of the input stage, it is essential to initially insert a power transistor in series with each diode, as shown in Figure 1.10. However, when these series transistors are blocked, there is a risk of a forward voltage drop [29]. This voltage must not be present across the antiparallel transistor and is critical for facilitating reverse power flow. To address this, another diode is introduced. The input stage now comprises two current link rectifier stages connected in a mutually antiparallel configuration. In combination with the VSI output stage, they constitute the topology of the IMC. Therefore, the IMC requires a total of 18 switches and 18 diodes. Among these, 12 switches and 12 diodes are allocated to the CSR stage, while the remaining six switches and six diodes are designated for the VSI stage. As illustrated in Figure 1.10, the IMC input stage utilizes six four-quadrant switches (or 12 switches), enabling operation with both positive and negative link voltages. For the operation positive DC-link voltage ($V_{pq} \geq 0$), it explores the possibility

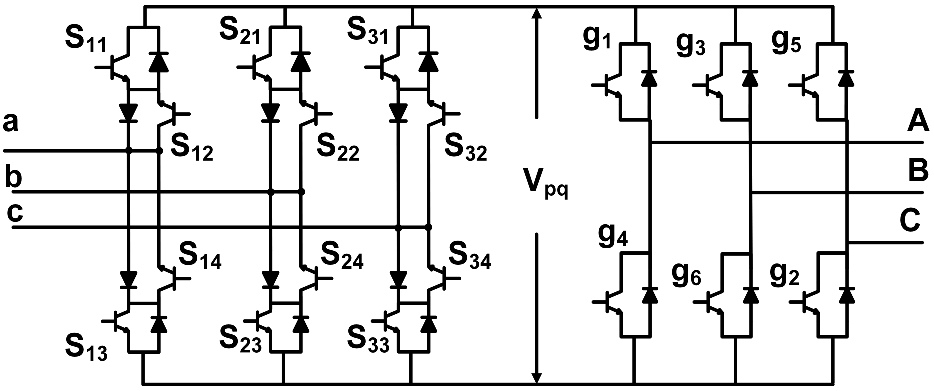

Figure 1.10: Indirect matrix converter

of minimizing the number of switches by restricting the CSR stage operating range to a unipolar link voltage [29]. This adjustment maintains the capability for bidirectional current flow.

By reducing the number of switches for the CSR stage, a Sparse Matrix Converter (SMC) was derived [30–32]. Further reduction of CSR switches, in Figure 1.11, reveals the Very SMC (VSMC), another fully bidirectional variant of the IMC. The VSMC features only 12 transistors but 30 diodes, as detailed in [32] and [33]. Nevertheless, this reduction comes at the cost of increased conduction losses due to the additional diodes. A more extensive simplification of the IMC circuit topology can be achieved by further reducing the switches of the CSR stage at the cost of unidirectional power flow. This leads to the Ultra SMC (USMC) formation, as shown in Figure 1.12. The USMC can control the input phase displacement angle, and thereby the output power factor angle is restricted to $(\pm\frac{\pi}{6})$. Table 1.1 provides the number of switches and diodes required for various matrix converters. Among all converters, USMC required 9 switches to complete the operation. With fewer switches, switching becomes simpler in USMC. This characteristic makes USMC the preferred AC-AC converter in the context of this thesis.

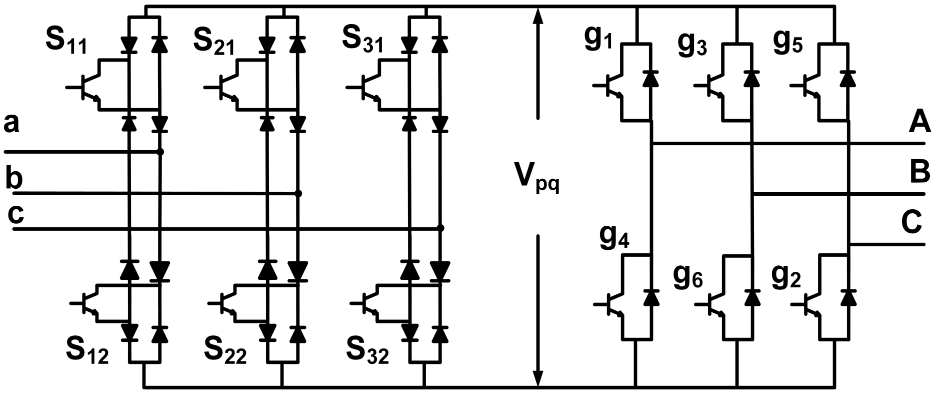

Figure 1.11: Very sparse matrix converter

The above-discussed USMC was developed without any storage elements. The maximum voltage transfer ratio of USMC is limited to 0.866. Due to this low voltage gain profile, USMC is not commonly used in industries. To improve this voltage transfer ratio (> 1), the impedance network is integrated with the converter and named as hybrid or matrix converters [29].

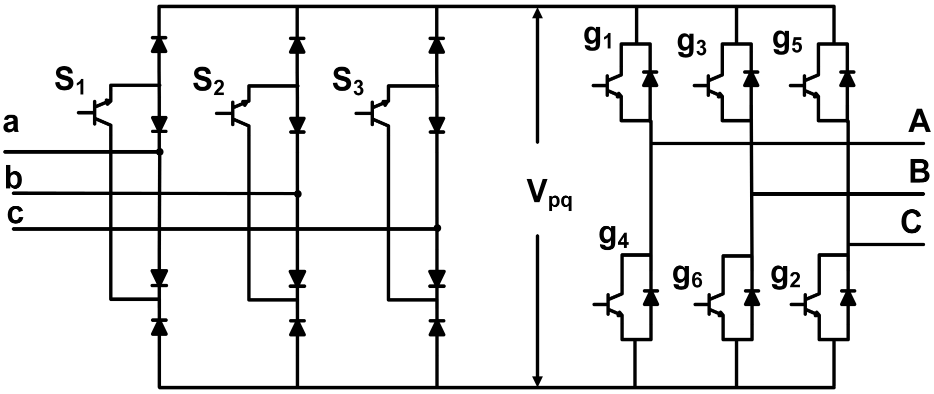

Figure 1.12: Ultra sparse matrix converter

Table 1.1: Different matrix converter typologies [32]

Converter	Transistors	Diodes
DMC	18	18
IMC	18	18
SMC	15	18
VSMC	12	30
USMC	9	18

Hybrid matrix converters

The restricted voltage control range inherent in basic MCs (DMC or IMC) presents a notable drawback when compared to converters featuring DC-link storage (CSBBC or VSBBC). To address this limitation, Hybrid MCs (HMC), which combine basic MC topologies with impedance networks, have been proposed as a solution. HMC consists of a matrix converter with an impedance network. The impedance network can be integrated between the three-phase input and CSR, or between CSR and VSI. Integrating the impedance network at the input side, as suggested in references [34–38] can enhance the voltage gain in the USMC. However, this improvement comes at the cost of requiring more switches, more passive components, and switches with higher ratings. The addition of a protection circuit becomes crucial in this configuration to mitigate the occurrence of spikes at the intermediate DC-link. These spikes can result due to the enhanced voltage gain and may pose challenges to the reliability and safety of the converter. To address these, the impedance network is integrated between the

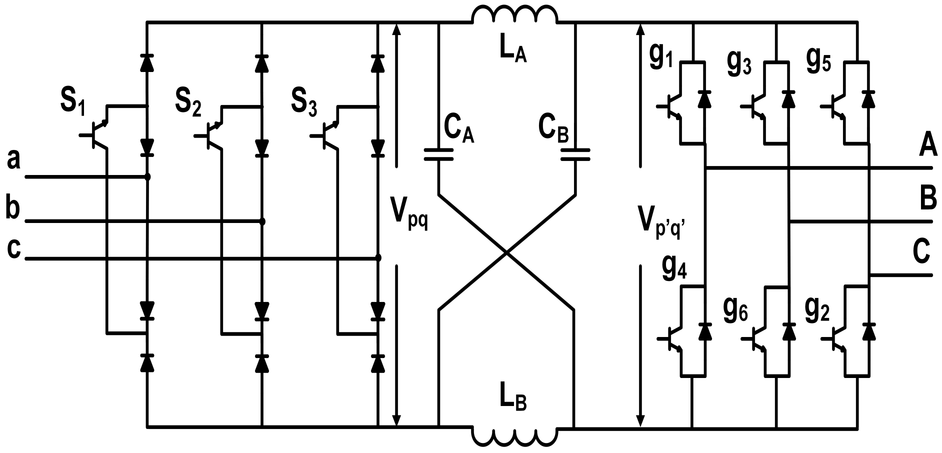

Figure 1.13: Integrated Z source USMC (ZS-USMC)

rectifier and inverter of USMC [39–44]. Another advantage of this topology is that there is no requirement for dead time, which is compulsory in conventional USMC. By integrating different types of impedance networks with USMC, various converters were developed.

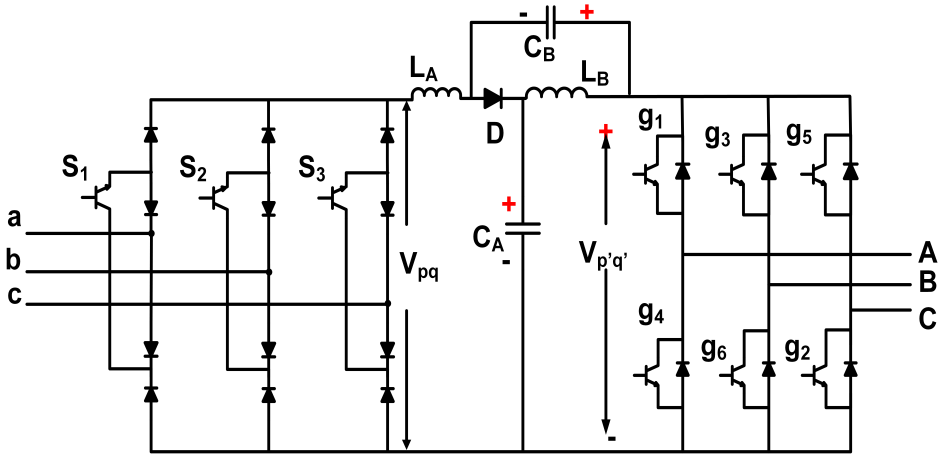

Figure 1.14: Integrated quasi Z source USMC (QZS-USMC)

The Z source (ZS) network is integrated with the USMC intermediate DC-link to develop the ZS-USMC [45, 46] as shown in Figure 1.13. The ZS network introduces a short-circuit capability, streamlining the commutation process within the ZS-USMC. This enhancement results in a more straightforward and efficient AC-AC conversion, making the ZS-USMC an economically viable, reliable, and high-performance solution for both buck and boost applications. This converter utilizes a shoot-through concept to boost the output voltage. The ZS network consists of two inductors and two capacitors. The main drawbacks of using Z source are: 1) High inrush current at startup, due to which ZS-USMC cannot achieve soft starting capability [47] and 2) The discontinuous nature of the input current leads to large input filter Considering the identified constraints of the ZS-USMC, the Quasi Z source (QZS) network has been incorporated into the USMC, resulting in the quasi Z source ultra sparse matrix converter (QZS-USMC). This converter has two capacitors, two inductors, and one diode in its network, as illustrated in Figure 1.14. [48]. In contrast to the ZS-USMC, the QZS-USMC demands a smaller capacitor size. Following the integration of a series Z source (SZS) network into the USMC, a novel converter emerged, designated as the series Z source ultra sparse matrix converter (SZS-USMC). The circuit diagram for the SZS-USMC is shown in Figure 1.15. This structure also requires two capacitors, two inductors, and one diode. This converter offers a notable advantage of reduced capacitor size for an equivalent boosting factor. However, it is important to note that the load power factor range for the SZS-USMC is limited to ≥ 0.866. A switched inductor Z source USMC (SWZ-USMC) has been developed for enhanced voltage boosting [49], as depicted in Figure 1.16. This configuration includes four inductors, two capacitors, and six diodes within its impedance network. However, it is essential to note that this structure creates a high inrush current during the startup phase. By streamlining certain elements within SWZ-USMC, a hybrid switched inductor USMC (HSWZ-USMC) has been developed [50], as depicted in Figure 1.17. However, the constraints of HSWZ-USMC lead to a diminished voltage gain. Furthermore the integration of a switched capacitor impedance network with the ultra sparse matrix converter (USMC) is depicted in

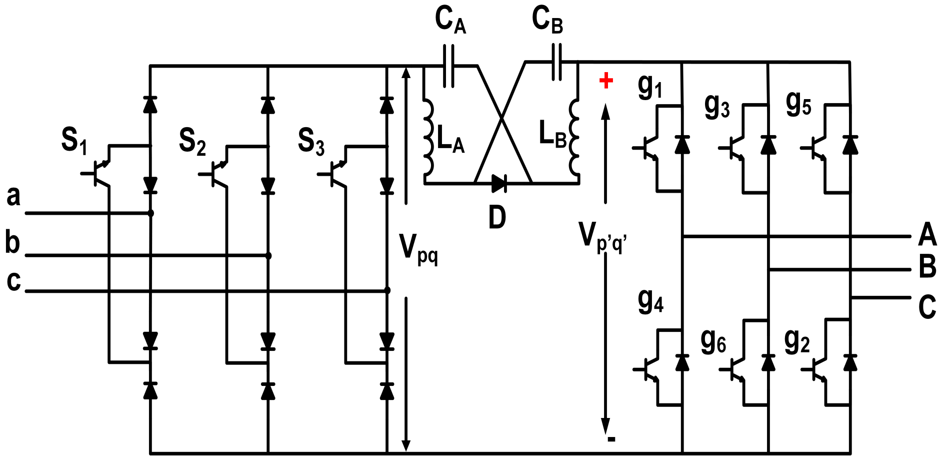

Figure 1.15: Integrated series Z source USMC (SZS-USMC)

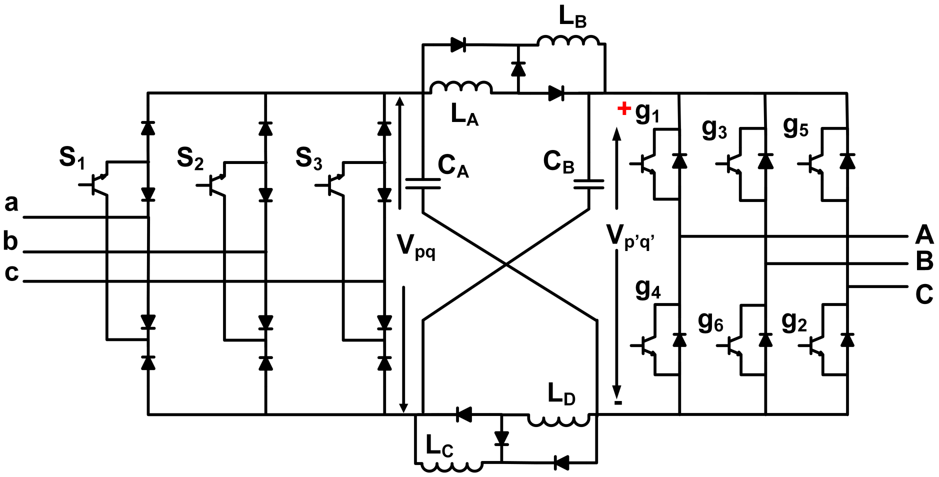

Figure 1.16: Integrated switched inductor Z source USMC (SWS-USMC)

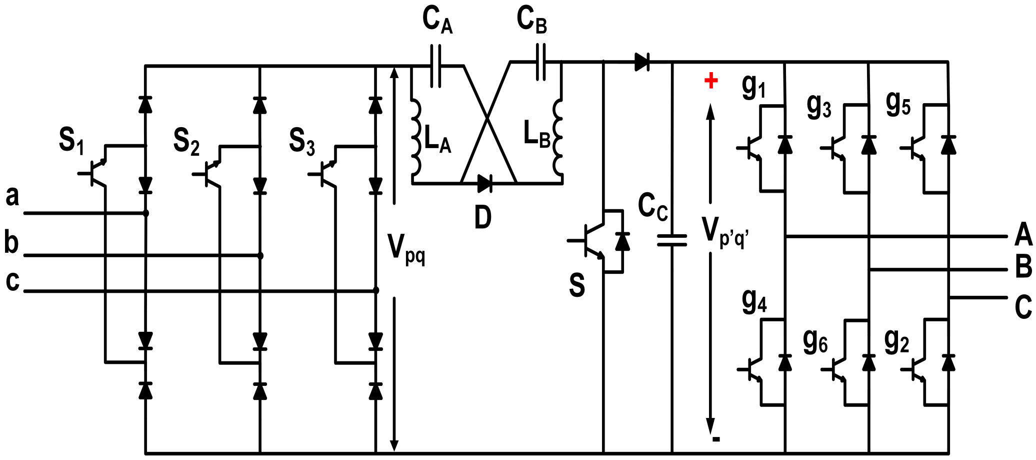

Figure 1.17: Integrated hybrid switched inductor Z source USMC (HSWZ-USMC)

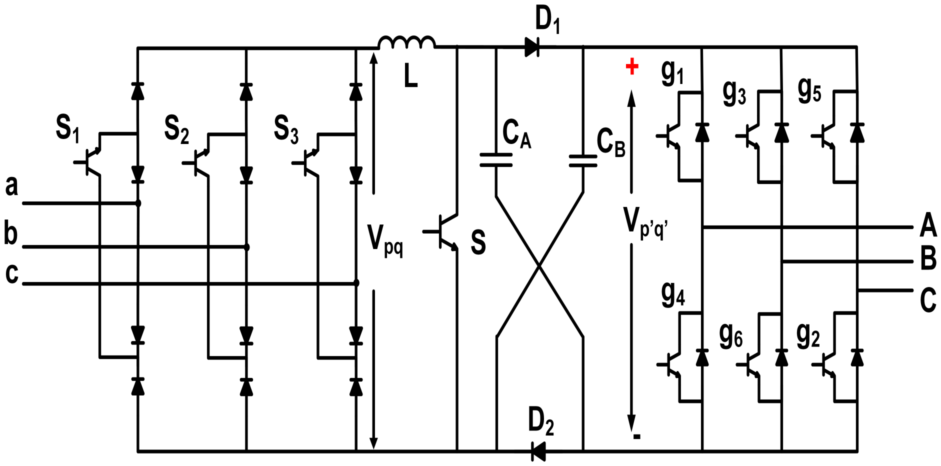

Figure 1.18: Integrated switched capacitor Z source USMC (SC-USMC)

Figure 1.18, aiming to achieve a voltage gain greater than unity [51, 52]. In contrast to the above impedance mentioned source matrix converters, the switched capacitor ultra sparse matrix converter (SC-USMC) can potentially decrease the count of passive elements. Its impedance network comprises two capacitors, one inductor, two diodes, and one switch. This converter demands significant shoot-through time to generate a higher output voltage.

Above mentioned all converters are implemented by using high-frequency pulse width modulation (PWM) techniques. These modulation techniques generate higher common mode voltages and degrade the system performance.

1.2 Common mode voltage in AC-AC converters

For AC drive applications, the speed of the AC motor varies by the frequency of the AC-AC converter using PWM. The utilization of PWM inherently generates high magnitude and slew rate ($\frac{dV}{dt}$) of Common Mode Voltage (CMV), a significant concern in motor drive applications. CMV (v_{CMV}) of the AC motor drive system is defined as the voltage potential difference between three-phase load neutral (N) to three-phase input neutral (n) as shown in Figure 1.19. For a three-phase system, the CMV, defined as the mean voltage across the three AC output ports.

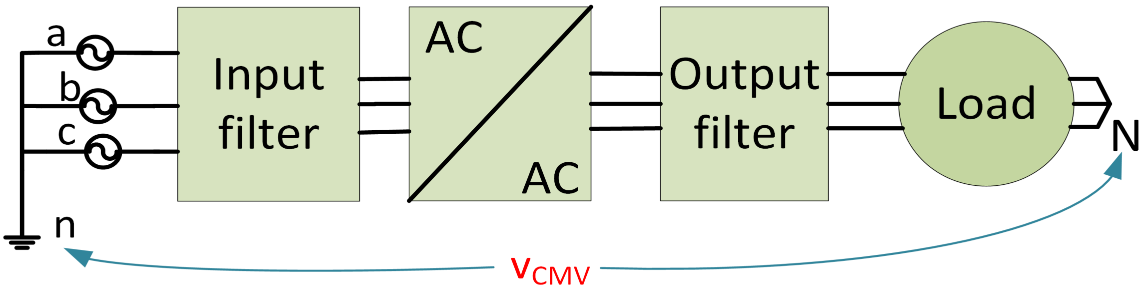

Figure 1.19: Common mode voltage in AC-AC converters

$$v_{CMV} = \frac{1}{3}[v_A + v_B + v_C] \tag{1.1}$$

Here v_A, v_B, v_C are the output phase voltages of a converter. Ideally, three-phase balanced sinusoidal signals result in zero CMV. However, this is not the case with PWM signals because they instantaneously sum up to non-zero while the drive is active and

creating CMV. This CMV plays a crucial role as follows: 1) Higher CMV increases the voltage level across the bearings in Permanent Magnet Synchronous Motors (PMSMs), leading to the generation of bearing currents. These currents flow through the PMSM frame to the ground, posing a significant risk of damage to the system. Extensive research has shown that this phenomenon contributes significantly to bearing system deterioration, accounting for more than 50% of motor failures [53–55].
2) A higher magnitude of CMV also causes higher Electromagnetic interference (EMI) noise, further disrupting the operation of nearby electronic devices [53, 56–58].
3) Higher CMV results in higher common mode current (CMV). Due to high voltage levels, this CMV problem is more common in hybrid or high gain matrix converters. So, it is necessary to reduce the CMV in AC-AC converters. Some approaches have been suggested to mitigate CMV in PWM inverters, employing various filter designs, either passive [59, 60] or active [61–63]. Passive filters use inductors and capacitors to suppress high-frequency components, as shown in Figure 1.20. Although passive filters are effective, they often exhibit bulkiness and might require multi-stage filtering to meet particular EMI standards. In contrast, active filters utilize controllable devices to produce an inverted canceling current or voltage, but they are generally more complex than passive solutions. A further concept derived from the Wheatstone bridge, known as impedance balancing, has been proposed in references [64] and [65] as a technique to mitigate CMV. However, achieving accurate impedance balancing presents challenges due to the frequency-dependent characteristics of parasitic inductance and capacitance

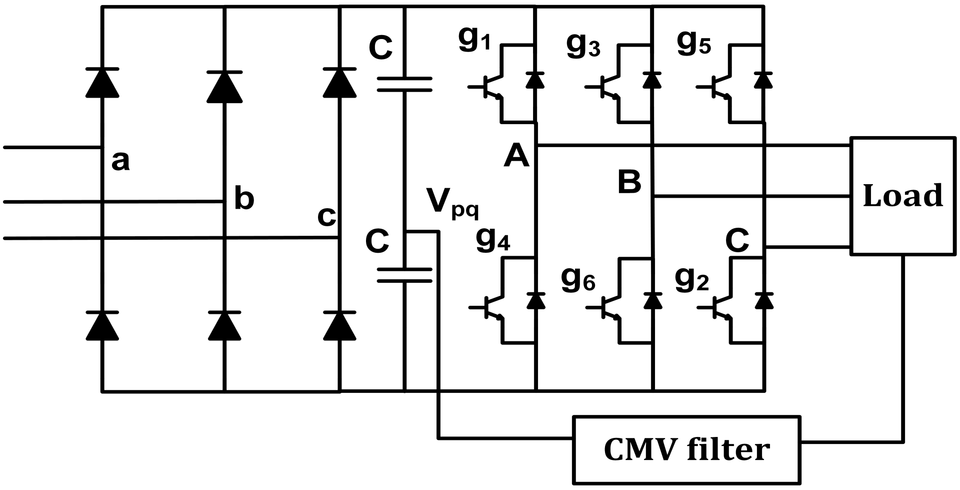

Figure 1.20: CMV reduction by using filter circuit

inherent in the system.

Implementing the above CMV reduction methods to matrix converters is difficult due to the absence of a DC-link capacitor, as shown in Figure 1.21. In matrix converters, CMV can be reduced by modifying switching strategies that are used in the converter. In matrix converter, the state vector modulation technique is preferred over other PWM methods due to its inherent flexibility in selecting active and zero vectors and their strategic placement within a switching cycle. Ref. [66], proposed modified space vector modulation techniques to reduce the peak CMV, but this method is limited to DMC and IMC. Methods proposed in Ref. [67–70,70–72] reduced CMV in IMC. These methods have limitations like limited modulation index range and loss of soft switching capability. These modulation techniques do not apply to hybrid matrix converters due to the presence of an impedance network, as shown in Figure 1.22. In high gain matrix converters, CMV also depends on the shoot-through duty period. A longer shoot-through period boosts the voltage level significantly, causing more CMV. Ref. [73] introduced a new modulation technique to reduce the CMV in ZS-USMC, QZS-USMC, SZ-USMC, and SW-USMC, but this method shows more THD in output voltage.

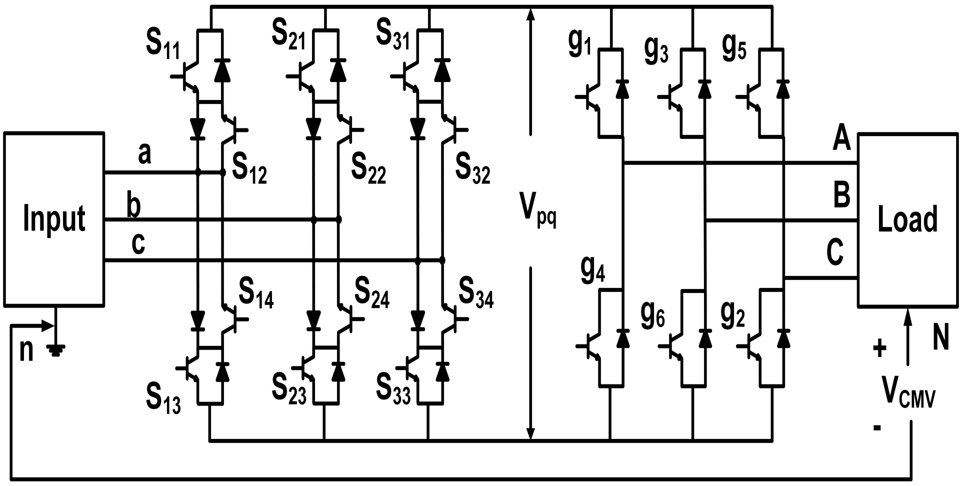

Figure 1.21: CMV in indirect matrix converter

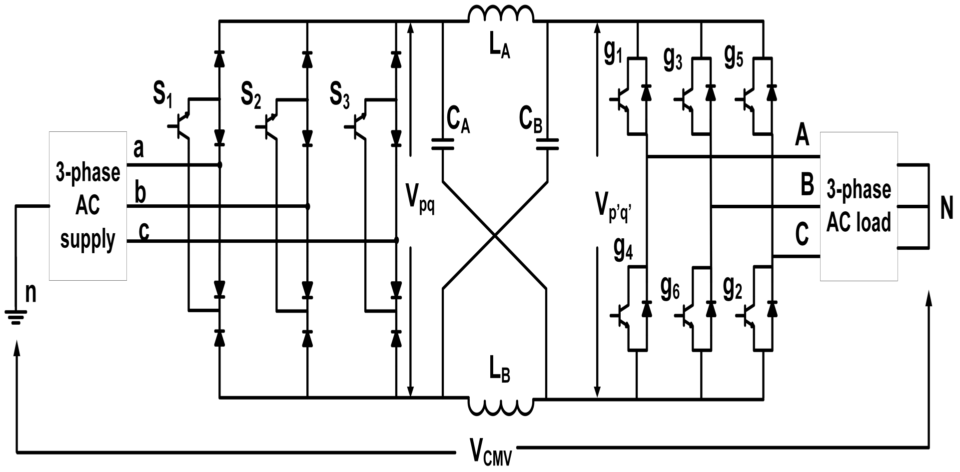

Figure 1.22: CMV in ZS-USMC

1.3 Objective

The CMV plays a critical role in certain applications such, as wind energy systems and AC motor drive. The CMV increases the voltage across bearings, leading to a bearing current in the electrical machines and deteriorating the system. It also creates higher electromagnetic interference (EMI), disturbing the operation of other electronic devices. A lower voltage gain profile limits USMC applications in industries. Implementing high-frequency PWM techniques to the conventional USMC results in higher CMV and lower output voltage. The impedance network is integrated into USMC to improve the USMC voltage gain profile. Most of the previously reported High gain AC-AC matrix converters have focused on voltage gain, stress across the devices and size of the passive elements. The objective of this thesis is

- To address and overcome specific challenges associated with the operation of conventional and impedance network ultra sparse matrix converters.
- To develop effective switching strategies in the conventional and impedance network USMCs that substantially reduce CMV.
- To synthesize novel control strategies and incorporate modulation techniques that actively target the reduction of inductor current ripple and CMV in impedance network USMCs.
- To enhance the converter's performance, making it more suitable for various applications, including renewable energy systems and electric drives.

1.4 Structure of the Thesis

This thesis is arranged into seven chapters. A brief discussion of each chapter is as follows:

Chapter 1 presents the introduction of the thesis along with an overview of various AC-AC converters and their CMV aspects. It also describes the research objective and outline of the thesis.

Chapter 2 presents the implementation of the conventional space vector modulation (SVM) technique and discusses various SVM methods to reduce the common mode voltage in matrix converter topologies.

Chapter 3 introduces the auxiliary shoot-through switches in the ultra sparse matrix converters to mitigate the common mode voltage and also compares various CMV methodologies.

Chapter 4 proposes a switching strategy for the quasi Z source ultra sparse matrix converter to reduce the ripple in the inductor current and the common mode voltage. The circuit analysis and operation principle are discussed with analytical derivations for this new switching strategy. Experiment and simulation results confirm the converters' ability to enhance voltage gain and reduce ripple in the current and CMV.

Chapter 5 proposes a switched boost-based ultra sparse matrix converter. Steady-state analysis is done to calculate the gain of the proposed converter. The analysis is done to obtain minimum operating load power factor angle and SB network design values. Simulation and experiment results are provided to confirm the effectiveness of the proposed converter.

Chapter 6 proposes three vector space vector modulation technique (TVSVM) to reduce the CMV in SB-USMC. The validation of the proposed method is done through both simulation and experiments.

Chapter 7 contains the conclusion of the thesis. Possibilities for enhancing the investigated topologies are outlined as future work.