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AC-AC Converter Topologies for Power Applications

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***Abstract:* -** Power electronic converters are an essential component of modern power system. They are used due to their advantages in various applications like power system stability and reliability, reducing weight and size of the system, improving system life, etc. This paper overviews various AC-AC converter topologies, starting with AC choppers, including converters with and without energy storage elements. Further, different matrix converter topologies for power conversion, e.g. single-phase, three-phase, and multilevel matrix converters, are introduced to provide a quick overview. Subsequently, direct, indirect, and hybrid matrix converter circuits are considered. Various individual converter topologies are reviewed and compared to provide one-stop information.

Keywords: AC-AC Converter, AC Chopper, Matrix Converter, Multilevel Matrix Converter, Power Converter.

I. INTRODUCTION

Power converters have numerous benefits, including increased system performance and reliability, improved transmission and distribution capability, enhanced stability, and power systems' ability to deliver auxiliary services [1]. Power Electronic (PE) solutions have been adopted in various domains in recent decades, including domestic applications, Industrial applications, Electrical energy storage systems, FACTS, Microgrids, and others [1-6]. For inductive power transfer (Wireless charging system) in commercial electric vehicles, power converter topologies have been briefly explained in [7], along with technical considerations and future opportunities.

AC chopper is an AC-AC converter similar to conventional DC choppers like a Buck, Boost, Buck-Boost, and others [8-16]. Besides having simple control and smaller power ratings of switches, these converters have the drawback that they cannot control output frequency [12-17]. In [10, 15], with less number of power electronic switches with lower ratings, an efficient direct AC-AC converter is analyzed for a Buck-Boost converter. In some power system applications where AC-AC power conversion is needed, normally, two-stage energy converters (e.g. AC-DC-AC) are used. An AC–AC converter configuration with two converter stages for rectification and inversion is shown in Fig. 1 (a). Because of the presence of a capacitor, the converter stages are largely decoupled for the control process. This DC-link is the main cause of the increase in the converter's size and is a costly component that is usually damaged while in use. The life of a converter is determined and shortened by energy storage elements like batteries and capacitors [18-22].

A converter without DC-link, as shown in Fig. 1 (b), reduces costs, reduces size, and increases the dependability and life of the entire system. Sometimes, it is recommended to use the converter with an energy storage element to decouple the two frequencies, and sometimes, in a power system with AC-AC conversion, AC-DC-AC converters are replaced by AC-AC converters having no energy storage elements [23-26]. A PE converter without DC energy storage can connect two systems with different parameters. On the other hand, for systems with the same output frequency, solid-state transformers and hybrid transformers are employed as regulators and system couplings [27-30].

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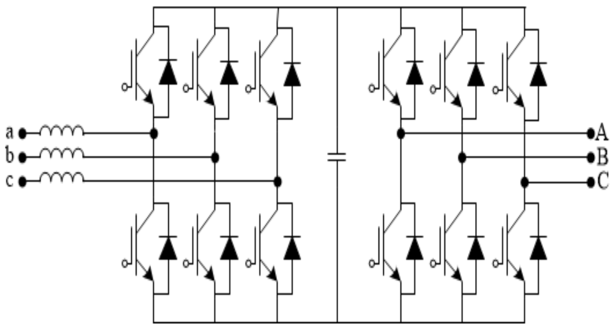

Fig. 1 (a) AC-AC Converter with DC-Link

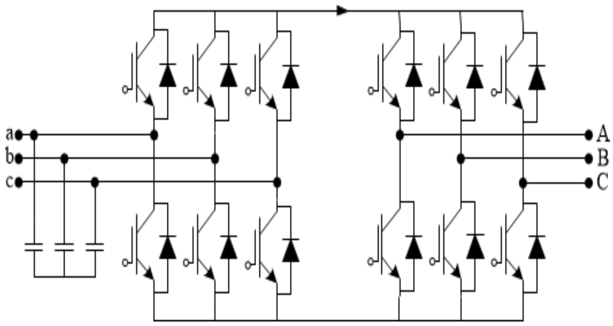

Fig. 1 (b) AC-AC Converter without DC-Link

Many direct converters can't operate at a fully variable frequency without a simple configuration and control. In contrast, indirect converters provide output voltage and frequency regulation while using large capacitors and bulky filters. These large and bulky elements raise total costs while also reducing reliability. Therefore, Matrix Converters (MC) are preferred because of their small design, eliminating the need for these DC-link elements or bulky energy storage systems [31-34]. Because of its appealing qualities, a Matrix Converter topology has been extensively explored and compared to standard AC-DC-AC topologies. The MC is mainly composed of controlled semiconductor switches with considerable passive components. This converter controls single, three, or multiphase loads directly. Based on the phases and levels, this paper reviews MCs' different topologies, developments, and classifications [31-62].

This paper aims to provide a comprehensive review of AC–AC converter configurations, including AC Chopper and AC-AC converters with and without DC-link, and, finally, to review the different Matrix Converters for electric power conversion. The paper is organized into the following sections: various AC chopper circuit configurations are introduced in section II. Section III presents two main groups of AC–AC converter systems with variable and constant output frequencies. Section IV and Section V address AC–AC converters with and without DC-link respectively. Section VI provides an overview of Matrix Converter topologies. Finally, section VII concludes the findings.

II. AC CHOPPERS

AC choppers are generally used for power conditioning and voltage control. They are simple to control and use a smaller number of power semiconductor switches but incapable of controlling the frequency, as shown in Fig. 2 to Fig. 5 [8-11]. For power grid applications, a combination of bipolar direct AC chopper and traditional transformer is examined in [12] to achieve variable voltage and phase angle adjustment following load needs.

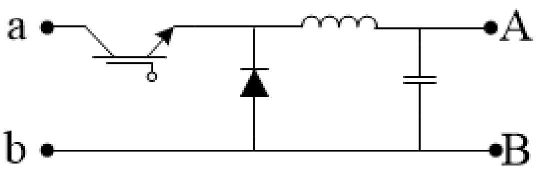

Fig. 2 (a) Single-phase Buck Converter

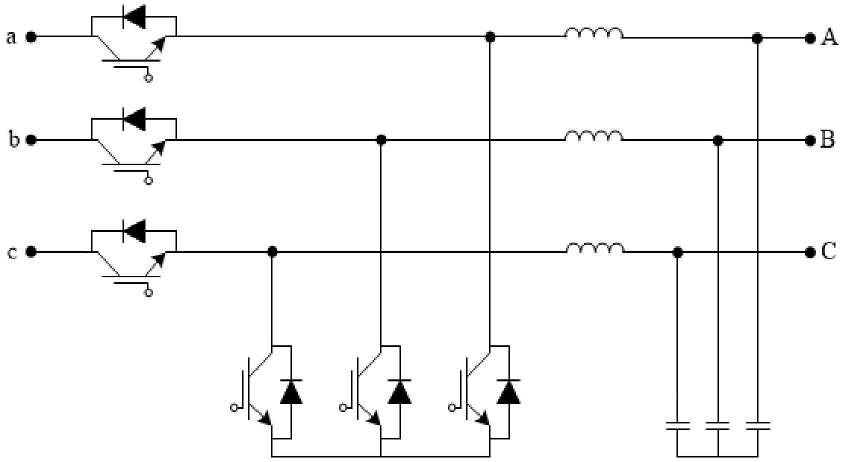

Fig. 2 (b) Three-phase Buck Converter

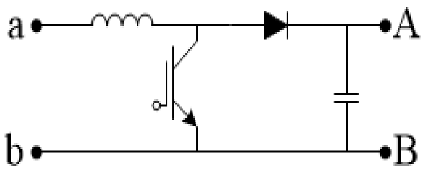

Fig. 3 (a) Single-phase Boost Converter

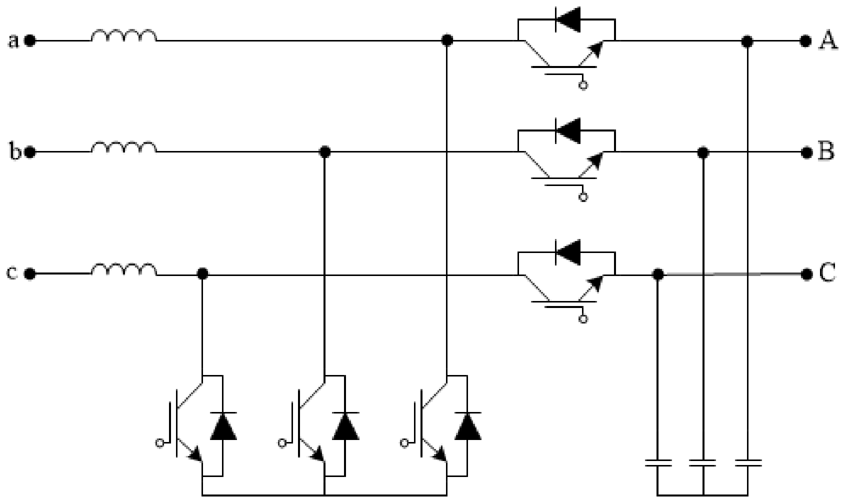

Fig. 3 (b) Three-phase Boost Converter

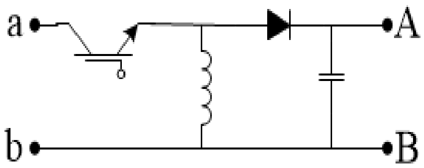

Fig. 4 (a) Single-phase Buck-Boost Converter

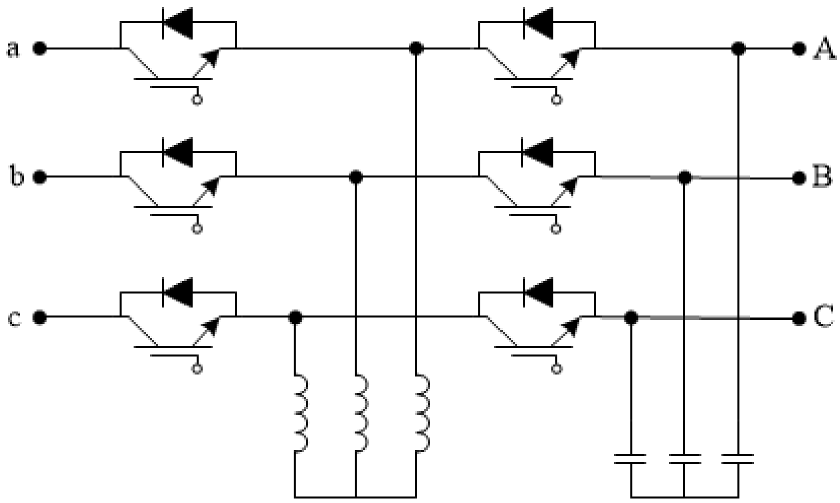

Fig. 4 (b) Three-phase Buck-Boost Converter

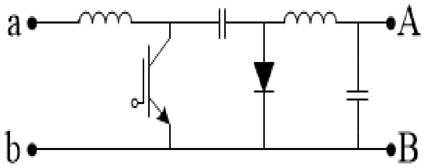

Fig. 5 (a) Single-phase Cuk Converter

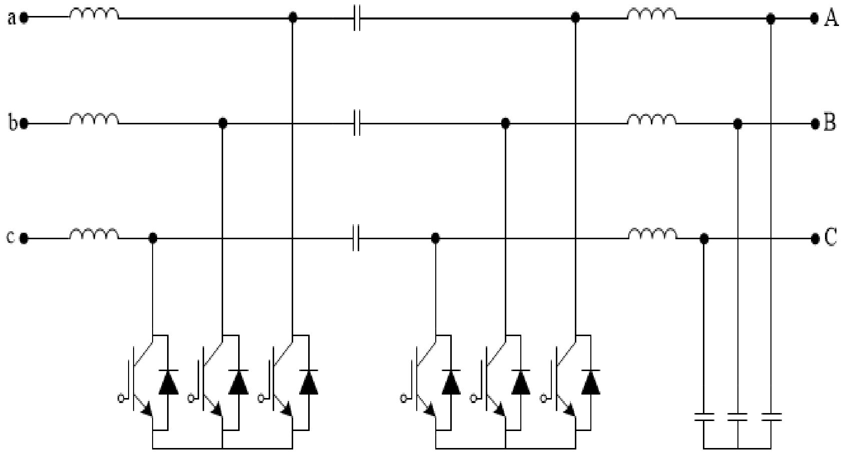

Fig. 5 (b) Three-phase Cuk Converter

III. CONVERTER WITH DC-LINK

Nowadays, AC-AC converters with voltage DC-link, current DC-link, or voltage-current DC-link are mostly practiced for energy conversion with a variable voltage magnitude and frequency for three-phase systems, such as variable-speed drives [11]. Diode Bridge topology is the simplest configuration for converters with voltage DC-link storage, but it has drawbacks such as high reactive power consumption and relatively high distortion at mains [19-20]. Bidirectional power flow can be achieved by integrating the DC-link between the rectification and inversion stages [18-21]. A capacitor for the voltage DC-link converter, as shown in Fig. 6 (a), or an inductor for the current DC-link converter, as shown in Fig. 6 (b), impresses the energy storage element. The energy storage element is larger than the entire converter size, and when capacitors are used as DC-link, the converter's life may be shortened [18].

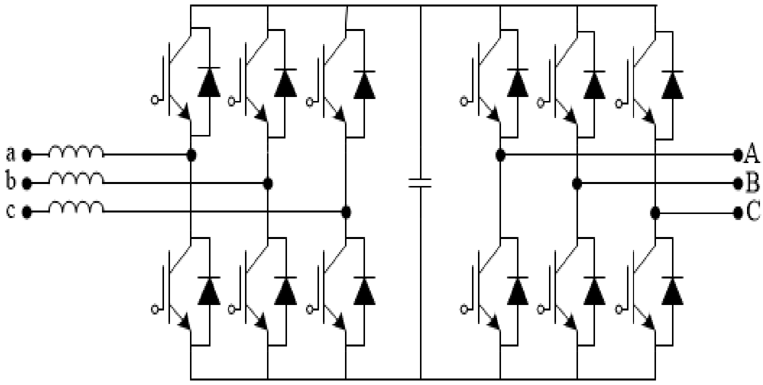

Fig. 6 (a) Voltage DC-Link AC-AC Converter

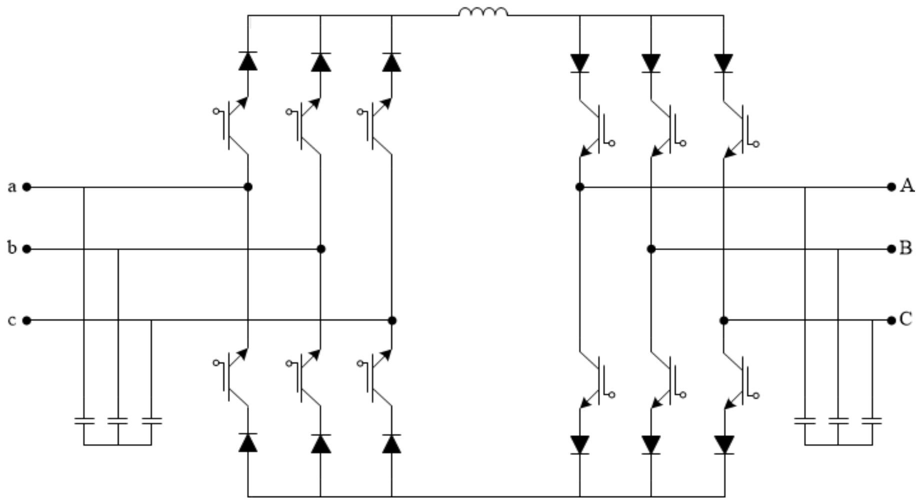

Fig. 6 (b) Current DC-Link AC-AC Converter

IV. CONVERTER WITHOUT DC-LINK

Over the last few decades, the progression of AC-AC converters without DC-link has resulted in various topologies with various control methods [23]. This section discusses three different types of AC–AC converters. The first category of converters does not affect the output frequency and is used as voltage controllers. These AC converters' advantages include sinusoidal current waveform, increased power factor, fast dynamic response, and small filter size [24-26].

Devices having galvanic isolation from the conventional transformer form the second category. The first topology uses a Solid-State Transformer [27-29]. Substation transformers are used to implement these devices in combination with converters to minimize the size of the overall system. Another benefit is the ability to regulate voltage settings and couple systems with various frequencies continuously. The hybrid transformer is another topology in this category in which only a portion of the energy is transferred during the power conversion [30].

The Frequency Converter is the last and largest category of these converters. The AC–AC converter without DC-link enables bidirectional power flow, an almost sinusoidal waveform, and a controlled power factor. The biggest disadvantage is the complex structure of topology and control of switches. Certain technological challenges, such as hardware reliability, must be achieved to increase its applicability in the industry. It is seen that the MCs should be considered, which enables AC-AC conversion without using an intermediary DC-Link [31-37], which is briefly discussed in the next section. The conversions are performed in one stage by Conventional (Direct) Matrix Converters (CMCs), as shown in Fig. 7 (a). Alternatively, an indirect conversion using an Indirect Matrix Converter (IMC), as shown in Fig. 7 (b), is possible.

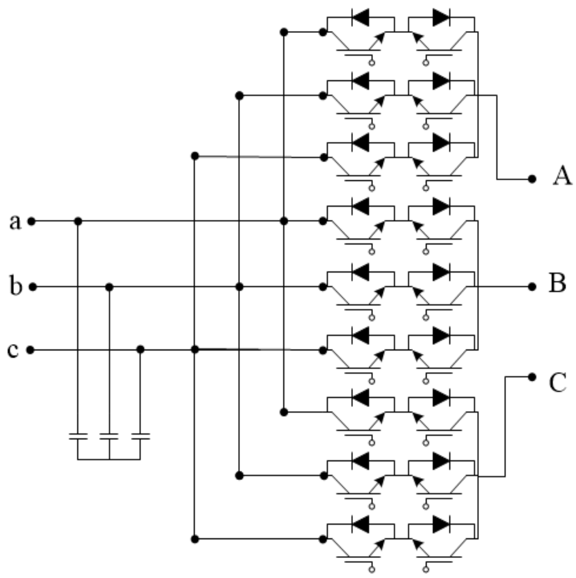

Fig. 7 (a) Direct Matrix Converter

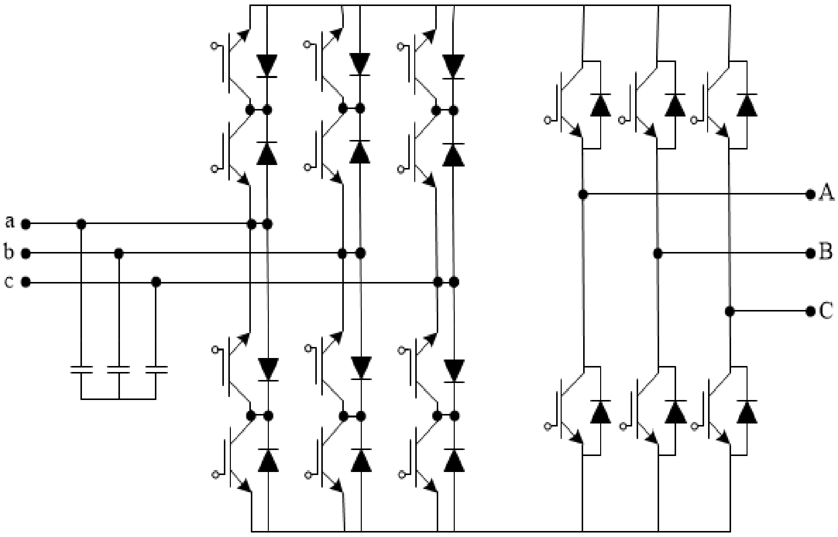

Fig. 7 (b) Indirect Matrix Converter

V. MATRIX CONVERTER FOR ELECTRIC POWER CONVERSION

Many direct AC-AC converters, despite their simple configuration and operation, cannot operate at variable frequencies. MCs are generally used in industrial practices, including aviation, wind energy, AC drive, and solar systems [31]. They are recommended because they provide single-stage power conversion without using massive energy-storing components or DC-link circuits. The four-quadrant bidirectional controlled switch is the most important component of a matrix converter [32]. The classification of Matrix Converters depending on the phases and levels is shown in Fig. 8.

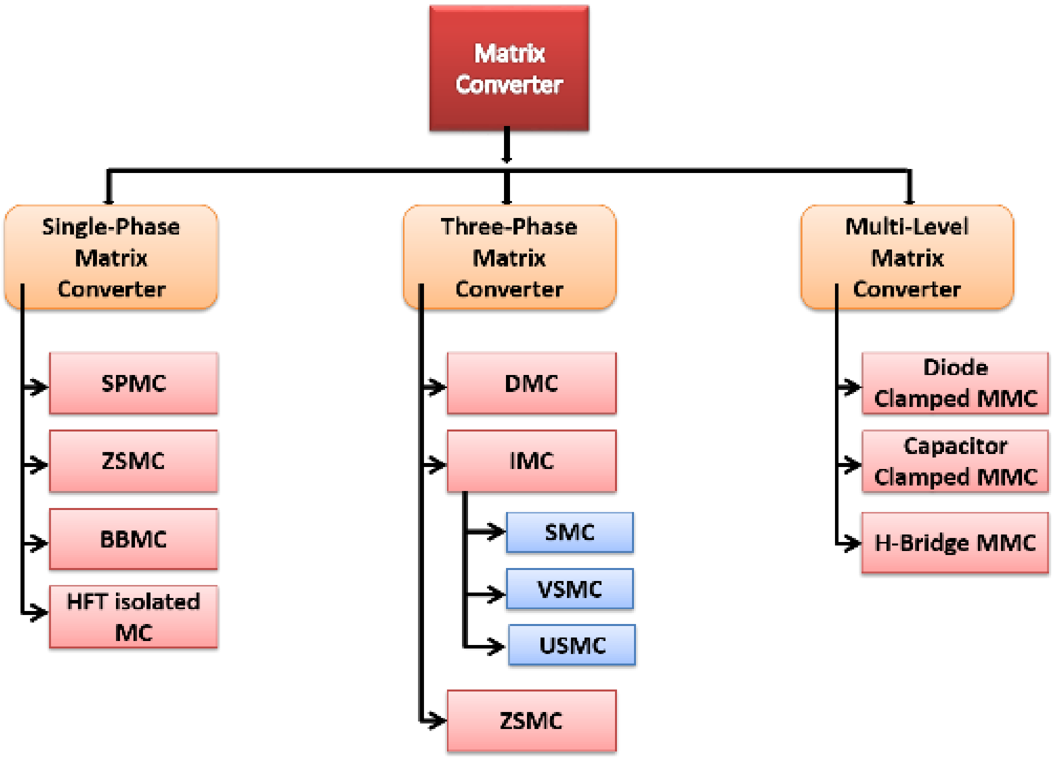

Fig. 8. Matrix Converter Classification

A. Single-Phase Matrix Converter

Single-phase converters, as well as three-phase and multilevel converters, are growing in popularity. Many novel single-phase converters have been proposed in recent years [38].

A conventional Single-Phase Matrix Converter (SPMC) provides magnitude and frequency modification at the output while maintaining a predefined switching period, as shown in Fig. 9 (a) [39]. To avoid short/open circuit issues, the switching in SPMC should ideally be instantaneous. Because perfect switching is impossible to achieve in practice, commutation methods are commonly used in MCs.

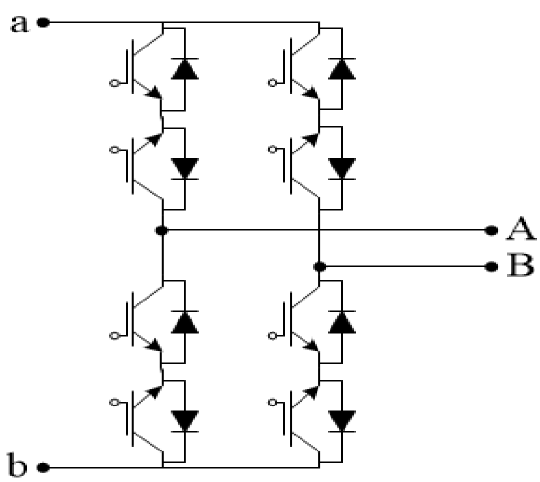

Fig. 9 (a) Single-Phase SPMC

Single-phase Z-Source Matrix Converters (ZSMCs) were developed to provide variable amplitude and frequency control [40]. These converters consist of five controlled bidirectional switches, a network having two inductors and capacitors and a filter at the input terminal shown in Fig. 9 (b). This configuration has been employed in various applications as it has a simple topology and reliability [41-42].

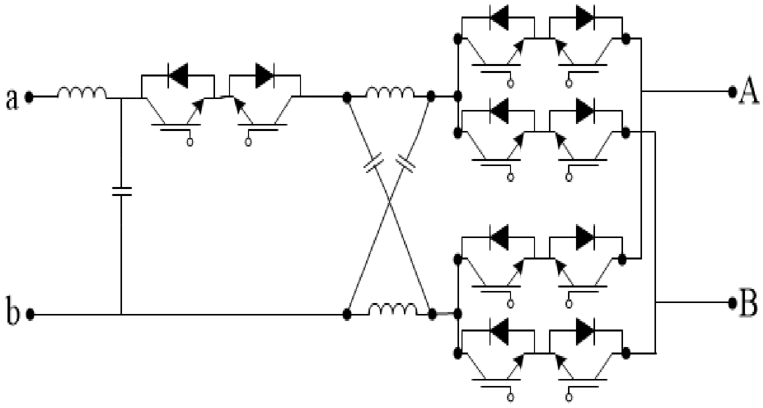

Fig. 9 (b) Single-Phase ZSMC

The six-switch Buck-Boost Matrix Converter (BBMC) also provides adjustable magnitude and variable frequency [43], consisting of six MOSFETs without having a commutation problem. It uses just an inductor to store energy, as shown in Fig. 9 (c), compared to ZSMC, which has inductors and capacitors.

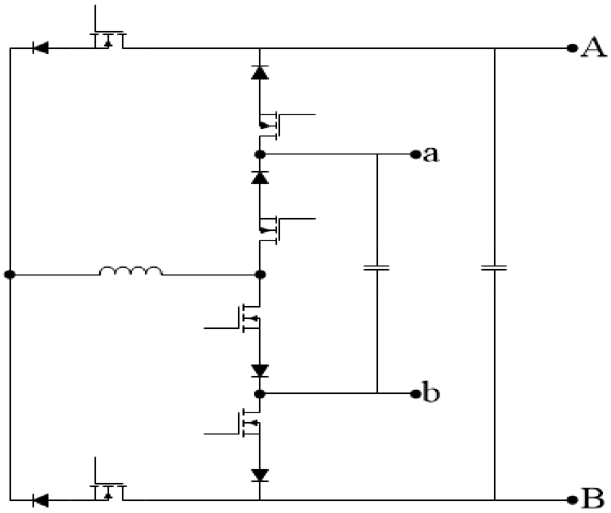

Fig. 9 (c) Single-Phase BBMC

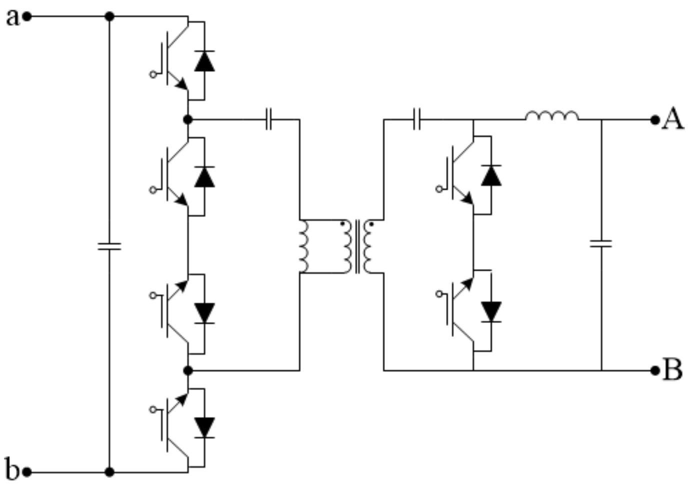

Fig. 9 (d) Single-Phase HFT–Isolated Matrix Converter

High-Frequency Transformer (HFT)-isolated Matrix Converter provides electrical isolation, removing the need for a traditional transformer [44]. It also delivers a controlled frequency output as well as controlled output voltages. On the primary side, it has one HFT, one capacitor, and four controlled switches; on the secondary side, it has two switches, a capacitor, and an LC filter shown in Fig. 9 (d).

B. Three-Phase Matrix Converters

Three types of three-phase MCs exist (a) Direct Matrix Converter (DMC), (b) Indirect Matrix Converter (IMC), and (c) Z-Source Matrix Converter (ZSMC). Wheeler et al. (2002), gave a full study of DMCs, but recent advancements in technology and the development of new topologies have left a lot of space to explore [32].

DMCs have nine bidirectional controlled switches that immediately couple the source to the load, eliminating the need for any DC-link storage to provide voltage and frequency control, as shown in Fig. 7 (a). Most of the research on DMC focuses on resolving commutation issues and developing new modulation schemes such as voltage commutation, current commutation, soft switching techniques, etc. [37].

IMCs consist of two conversion stages: the first stage uses six bidirectional controlled switches to form a rectifier, and the second stage consists of six unidirectional switches to form a voltage source inverter, as shown in Fig. 7 (b). IMC regulates voltage and frequency well, but the commutation technique is much simpler. There have been a few IMCs published in the literature [45].

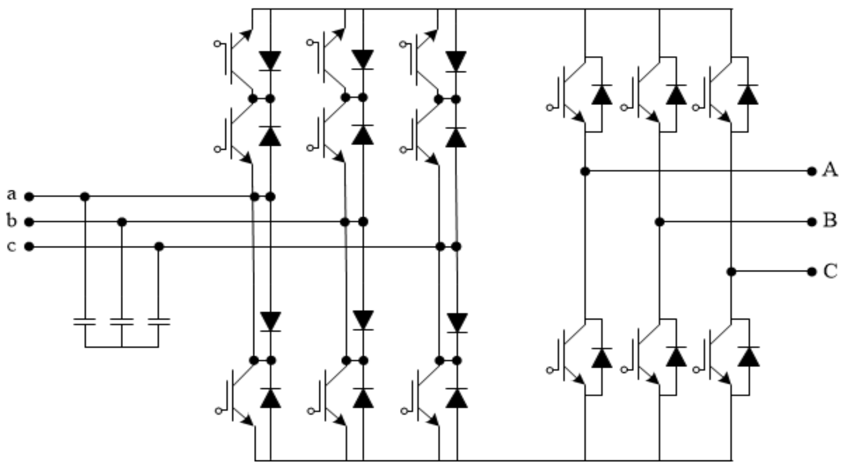

Fig. 10. Sparse Matrix Converter

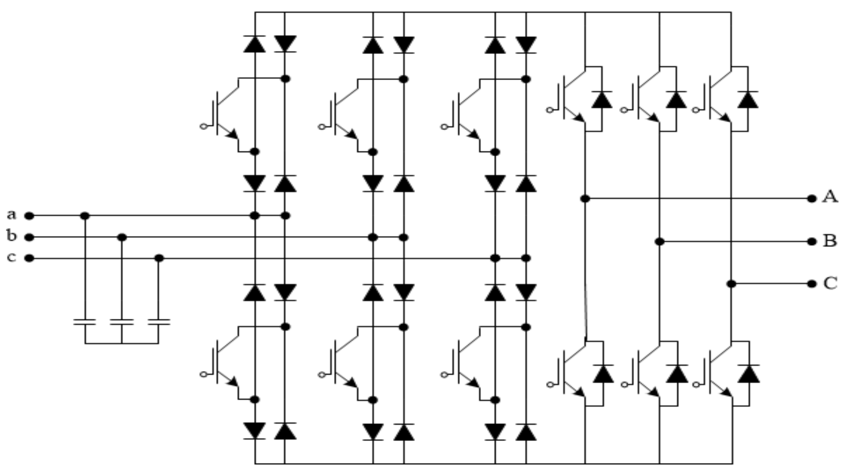

Fig. 11. Very Sparse Matrix Converter

A circuit variant of IMC, i.e., Sparse Matrix Converter (SMC), uses fewer switches than conventional IMC by limiting the input operation to DC link voltage, retaining the bidirectional flow of current shown in Fig. 10 [46]. Another circuit topology of IMC, called a Very Sparse Matrix Converter (VSMC) with 12 transistors and 30 diodes, shown in Fig. 11, has no functional limits compared to direct and sparse matrix converters [47]. These converters have low switching losses but high conduction losses.

Apart from the above two topologies of IMC, the Ultra-Sparse Matrix Converter (USMC) can also be configured with 9 transistors and 18 diodes, shown in Fig. 12, if the converter is required to limit for unidirectional power flow [48-50].

Z-source Matrix Converter (ZSMC) provides frequency control and step-up and step-down capabilities in a single step [51]. The three stages of ZSMC, shown in Fig. 13, have received much interest since its conception, and they now incorporate the complete family of PE converters.

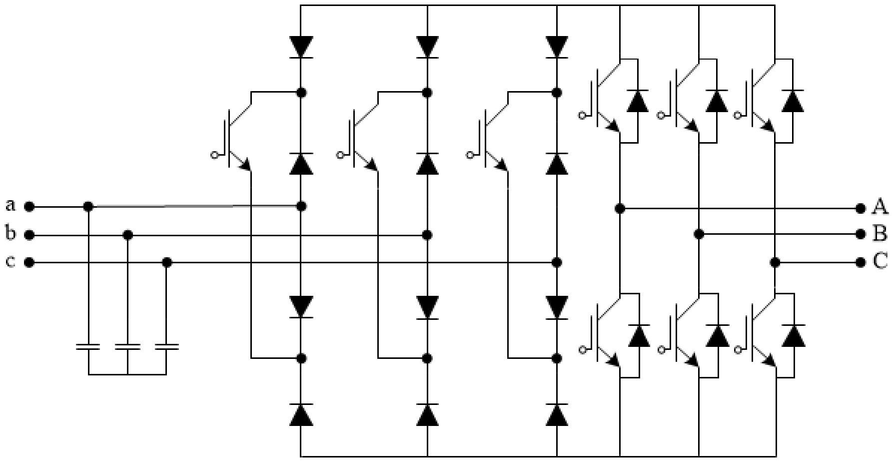

Fig. 12. Ultra Sparse Matrix Converter

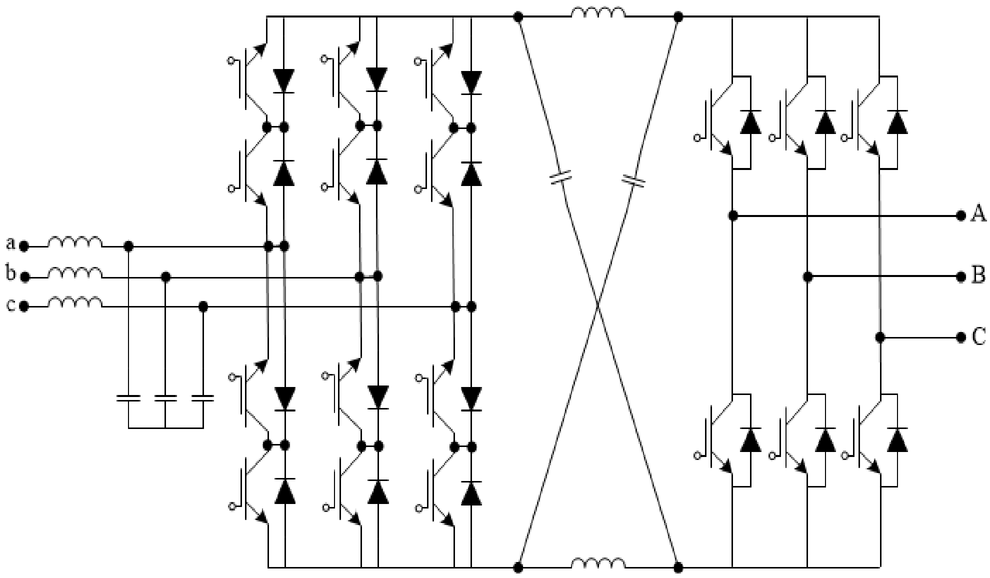

Fig. 13. Z-source Matrix Converter

VI. Multilevel matrix converter

One of the desirable topologies for improving output waveform quality while reducing harmonic distortions is known as a Multi-level Matrix Converter [52-57]. Despite their desirable qualities, MCs have limitations in medium to low voltage levels. Currently, three multilevel topologies have been proposed [58-62]: Diode-Clamped Multi-level Converter, Capacitor-Clamped Multi-level Converter, and H-Bridge Multi-level Converter. Combined with Matrix Converters, these topologies result in various configurations [33].

The Diode-Clamped Multi-level Converter has two power stages similar to the Indirect Matrix Converter [58], as shown in Fig. 14. However, it retains the other advantages of MCs while replacing the inverter step with a diode-clamped circuitry to improve the output quality.

A Capacitor-Clamped Converter with its new flexible controlling approach has been presented in [59-60], shown in Fig. 15. This converter comprises six flying capacitors and 18 bidirectional control switches. Compared to earlier MC, each bidirectional switch is replaced with two bidirectional switches connected in series. Flying capacitors are required in series linked switching devices to supply medium voltages and regulate the voltage variation. Commutation issues affect Capacitor-Clamped MMCs, just as other Matrix Converters.

The H-Bridge Converter, shown in Fig. 16, consists of nine bidirectional switches having capacitor-clamped switches between each input and output phase. The advantages of a Cascaded H-bridge Multilevel Matrix Converter include a large controllable voltage range, multilevel operation, and a modular structure. This converter is well-suited to high-power applications, particularly high-voltage motor drives [61-62].

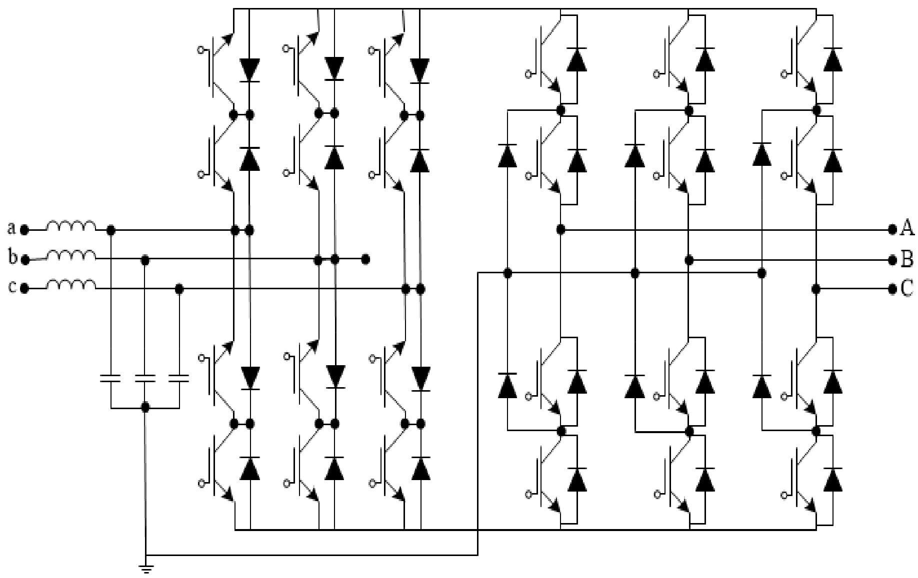

Fig. 14. Diode-Clamped Multilevel Matrix Converter

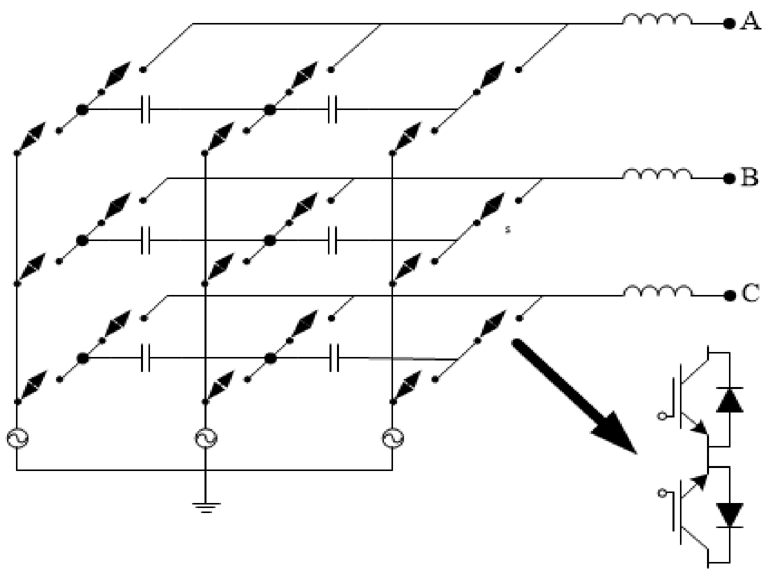

Fig. 15. Capacitor-Clamped Multilevel Matrix Converter

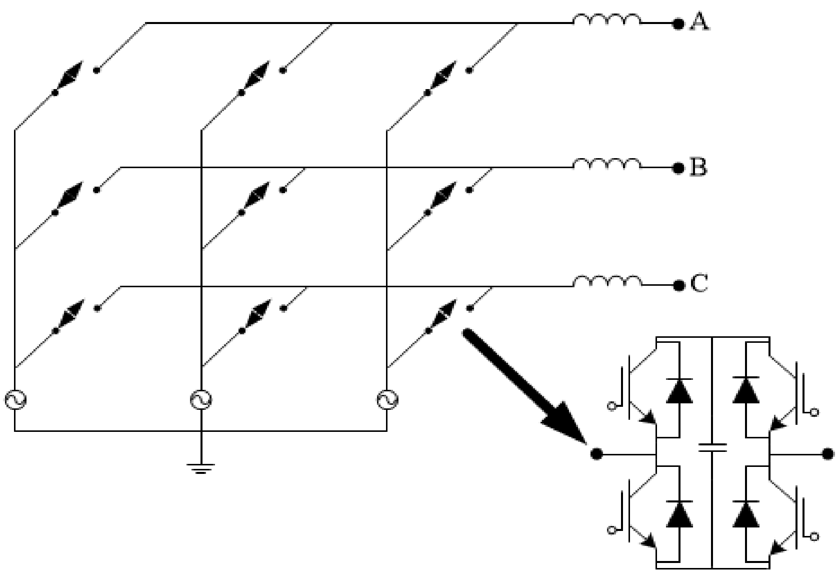

Fig. 16. H-Bridge Multilevel Matrix Converter

VII. Conclusion

This section compares the attributes of various AC converter topologies in depth. The number of elements (switches, diodes, capacitors, and so on) used in each configuration is included in this comparison. Table 1 summarizes the various Single-Phase and Three-Phase Matrix Converter topologies, the number of semiconductor switches, and energy storage elements.

It is concluded that all the topologies discussed here could be used as power converters in electric networks and various power applications. This paper also presented topologies of various Matrix Converter configurations based on phases and levels. Each topology suffers from the commutation problem between controlled switches that have been resolved to some extent. The filter requirement is one of the practical issues in minimizing harmonics at the input and output. Major topologies and circuit configurations have been discussed and scrutinized, but finding any exact configuration for any single application would be tough.

Table 1. Comparative Table of MC Topologies

	Configurations	**Number of Switches**	**Number of Storage Devices**
1-Phase	SPMC	8 IGBTs and 8 Diodes	None
	ZSMC	10 IGBTs and 10 Diodes	2 Inductor and 2 Capacitor
	Six-switch Buck Boost MC	6 MOSFETs and 6 Diodes	1 Inductor
	HFT-isolated MC	6 IGBTs and 6 Diodes	2 Capacitor and 1 HF Transformer
3-Phase	DMC	18 IGBTs and 18 Diodes	None
	IMC	18 IGBTs and 18 Diodes	None
	SMC	15 IGBTs and 18 Diodes	None
	VSMC	12 IGBTs and 30 Diodes	None
	USMC	9 IGBTs and 18 Diodes	None
	ZSMC	18 IGBTs and 18 Diodes	2 Inductor and 2 Capacitor

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