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Review Article

A Review on Recent Advances in Matrix Converter Technology: Topologies, Control, Applications, and Future Prospects

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Matrix converters (MCs) are AC-AC power conversion topologies widely explored and applied in the industry for their attractive features of sinusoidal input and output currents, considerable size reduction, and reliable operation due to the omission of bulky passive components. Considerable research has made this technology a serious contender to the indirect AC-DC-AC topologies in industrial applications. This paper comprehensively reviews the state-of-the-art MC technology and its prospects. Furthermore, it presents the advancements in the topological structures of direct/indirect MCs and their modulation and control algorithms over the past decade. It also reports the recent progress in multiphase direct/indirect MC structural and control structures. This paper is aimed at providing comprehensive information to the researchers and engineers on MC technology's current industrial applications and the research scope as the world moves towards AI and digitalization.

1. Introduction

Reducing carbon footprint is one of the world's leading issues. It is proved that if the energy sources are utilized efficiently, it will impact the carbon emissions [1]. Furthermore, efficient power conversion technologies will affect energy prices in an urbanized environment. Renewable energy alternatives are being explored for possible integration into the existing grid [2, 3]. So modern power systems will be dominated by energy from such sources as solar PV and wind.

Power electronic converters are the power controllers of modern power systems that allow the integration of unconventional renewable power sources into the existing grid. AC-AC conversion is an inevitable requirement, enabling the available supply to drive a load that demands variable frequency and amplitude, or the generators with intermittent sources like wind to feed the existing grid at constant voltage and a frequency of 50/60 Hz [4]. The AC-AC conversion process in the industry is achieved by using diode-based front-end converters (FEC) in conjunction with inverters; back-to-back converters (B2B), where active rectification is employed; and the matrix converters (MCs) [5, 6]. The technology of the B2B structures is well developed and researched, making it reliable. However, the bulky and less reliable DC link capacitors and large inductors used for filtering make researchers and industrialists ponder new structures to support vulnerable and less space-occupying applications like aircraft and electric vehicles. Matrix converters offer the best operation by size reduction of approximately 30%. The other benefits, like lower operational and maintenance costs, are motivating the researchers to explore the possible applications of the MC in the field of wind energy conversion systems, electric vehicles, microturbine generator systems, microgrids, and energy storage systems [7–11].

Matrix converters are an emerging technology considered for industrial applications as a compact AC-AC solution due to the elimination of bulky capacitors. Its fundamental theory was explored in [12], but more focus was on cycloconverters then. A significant contribution was made by Alesina and Venturini when they proposed a viable modulation for the 3×3 DMC in multiple papers [13–15], after the advent of fast switching PWM technologies and switches. Then, other variants of MCs like indirect MC (IMC) [16], sparse IMC (SIMC) [17], and ultrasparse IMC (USIMC) [18] were introduced. Impedance (Z) sourced, admittance (Y) sourced, and quasi Z-sourced MCs were explored for their boosting effects [19, 20]. These topologies have also been explored for multiphase and multilevel structures [21, 22]. Further stating, many modulation strategies like space vector PWM (SVPWM) [23], indirect SVPWM [24], carrier-based [25], duty ratio-based [26], and their modified versions have been proposed [27, 28]. Advancements in control schemes solving the pertaining issues like common mode voltage reduction [29, 30] and optimum commutation were developed. Overvoltage, overcurrent protection [31], and necessary input current filters [32, 33] were also explored. All this exploration and research have convinced manufacturers like Yaskawa to build full-fledged drives based on this technology [34, 35].

Existing literature presents a few reviews in this field. A review is presented in [6], where structures of MCs are only discussed. However, the industrial applications of these converters were not explored. A critical comparative evaluation of three AC-AC inverter structures, B2B, DMC, and IMC, was performed in [36], where DMC was found to be better than IMC in terms of switch stress. The DMC was also deemed suitable for compressors, fans, mixers, blowers, and escalator drives. Another extensive modulation and control strategy-based review was presented in [37]. However, Empringham et al. in their review in [38] show a favorable application-based review of the MC-based drives. But this review lacks review of other areas of MC applications. On the other hand, in [39], a generalized review of the AC-AC converter topologies is presented, emphasizing the DMC and IMC structures. Alammari et al. performed the latest review in [40], where again some topological advancements were discussed with certain application areas of the MCs. However, even then, the current application's areas are not explored. Other reviews considering MCs as potential topologies in 3×3 or multiphase structures can be explored in [41, 42]. As technology is advancing rapidly in terms of control and rapid increase in renewable energy integration to reduce the carbon footprint, low-cost, less size, reliable, and resilient solutions are sought. So, it is essential to perform a review where all current and future applications and future research that includes rapid digitalization and artificial intelligence are needed to be considered.

Thus, a comprehensive review is required where the state-of-the-art MC technology and its prospects, targeting the researchers and engineers working in various AC-AC power conversion applications, are needed to be discussed. It is also required to establish the technology's inclusiveness in other industrial applications like renewable energy systems, energy storage, and microgrids. Furthermore, it is also required to explore the adoption of the technology for replacement or retrofit in the existing drive systems. In addition, this review will present the advancements in the topological structures of direct/indirect MCs and their modulation and control algorithms in the past decade. It will also report the recent progress in structures and control of multiphase matrix converters.

The rest of the paper is structured as follows. The overview of the MC with emphasis on the advantages of MCs is presented in Section 2. Section 3 presents the DMC and IMC structures, their auxiliaries, and their research progress. Section 4 compares the MC technology with the existing VSC technology. In Section 5, the progress in the multiphase converter research is presented. In Section 6, an exclusive review is performed on MCs' previous and new modulation and control strategies. The current applications and the application-based research being conducted recently in literature are presented in Section 7. Finally, the review is concluded with exclusive comments on the future of MC research to make it a more reliable and resilient AC-AC converter topology.

2. An Overview of the Matrix Converter Technology

Matrix converters are direct AC-AC converters that can produce any arbitrary frequency at the output, as classified in Figure 1. MC was earlier named as forced commutated cycloconverter due to the use of gate-commutating devices like transistors and insulated gate bipolar transistors (IGBTs) and metal oxide field effect transistors (MOSFETs) [43]. On the other hand, conventional cycloconverters employ naturally commutated thyristors and can operate only on a fraction of the input side frequency (50 or 60 Hz). MCs are further classified as direct (DMC) and indirect (IMC) topologies. The main difference in the structure is that the outputs in the former topology are directly connected to the input, while in the latter, the outputs are connected to the input via DC link. The number of switches employed in a DMC equals a conventional IMC. Such systems can easily translate to a $m \times n$ system. Matrix converter research has been going on a steady pace. This can be seen by the number of publications in the terms of topologies, modulation, control, and applications in reputed journals and conferences. For the sake of reference, IEEE platform is explored and presented in Figure 2.

A DMC is shown in Figure 3, and a DMC and IMC with multiphase input and output ports are shown in Figure 4. These converters in 3×3 configuration employ 18 IGBT switches. In DMC, a mesh of switches with bidirectional current flow capability and bipolar voltage blocking capability is used. The switches and the other components of the MC are discussed ahead in this section.

Conventionally, voltage source inverters along with rectifier circuit and bulky DC link capacitor are employed to

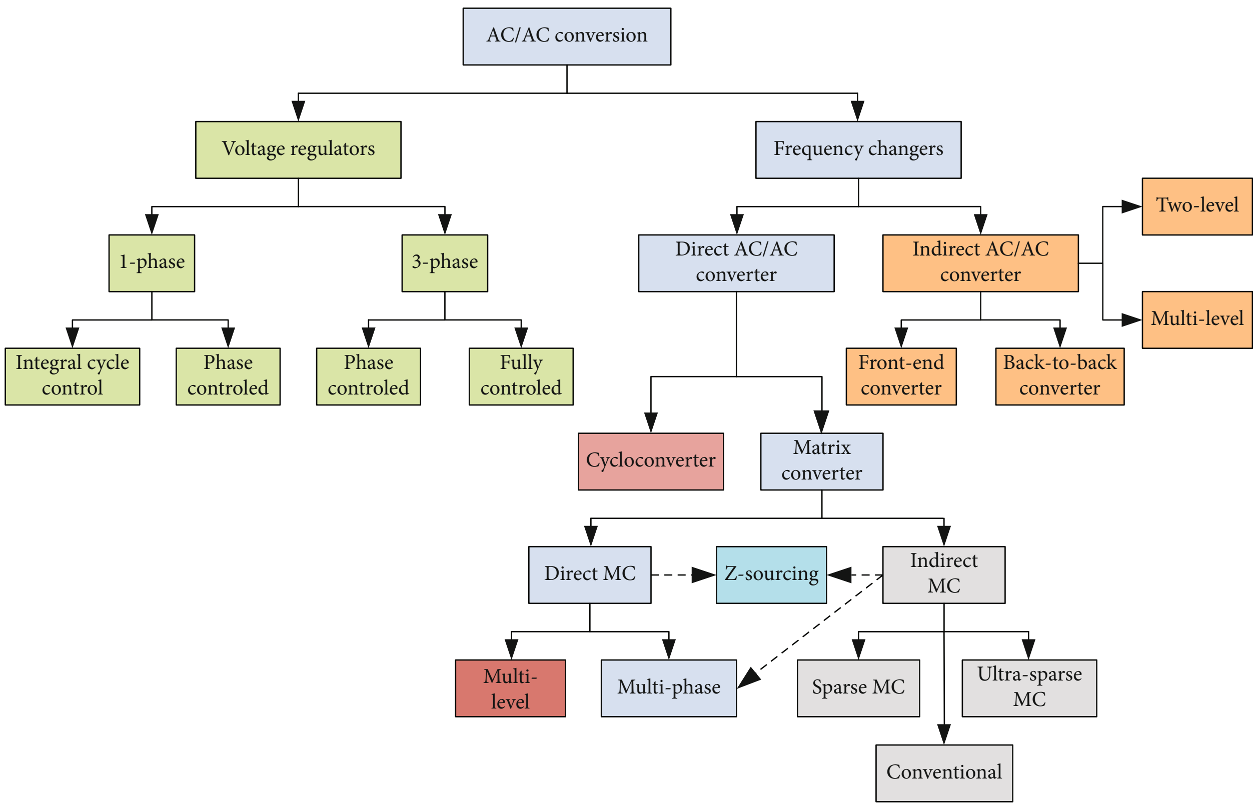


Figure 1: Classification of AC-AC converters, emphasizing MC and its variants.

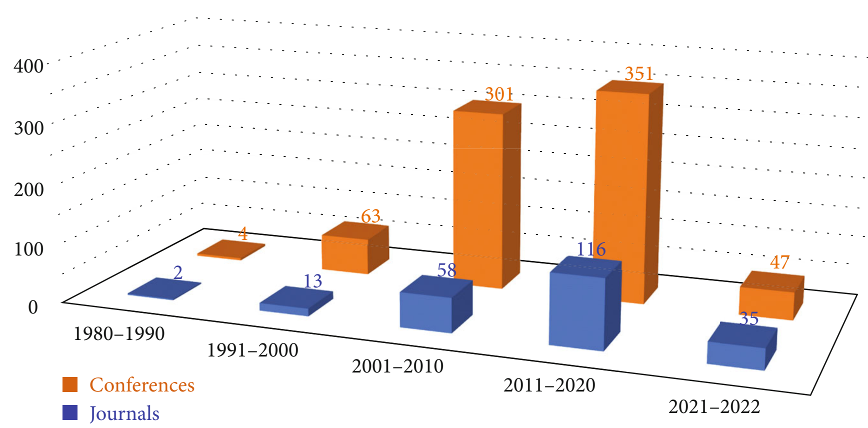


Figure 2: Publication statistics in IEEE journals and conferences until 2022.

convert a fixed AC supply to a required AC supply of variable voltage and frequency. MCs on the other hand omit the use of the DC link capacitor. In general, the MCs offer these advantages:

(i) Sinusoidal input and output currents

(ii) Controllable displacement factor

(iii) Regeneration capability

And the omission of DC link provides the following advantages:

(i) Enhanced reliability

(ii) Less maintenance

(iii) Compact circuitry and less weight

(iv) Resilient operation under high-temperature conditions

(v) Less voltage stress on the switches

The following subsections describe the major components and protection schemes of a direct matrix converter.

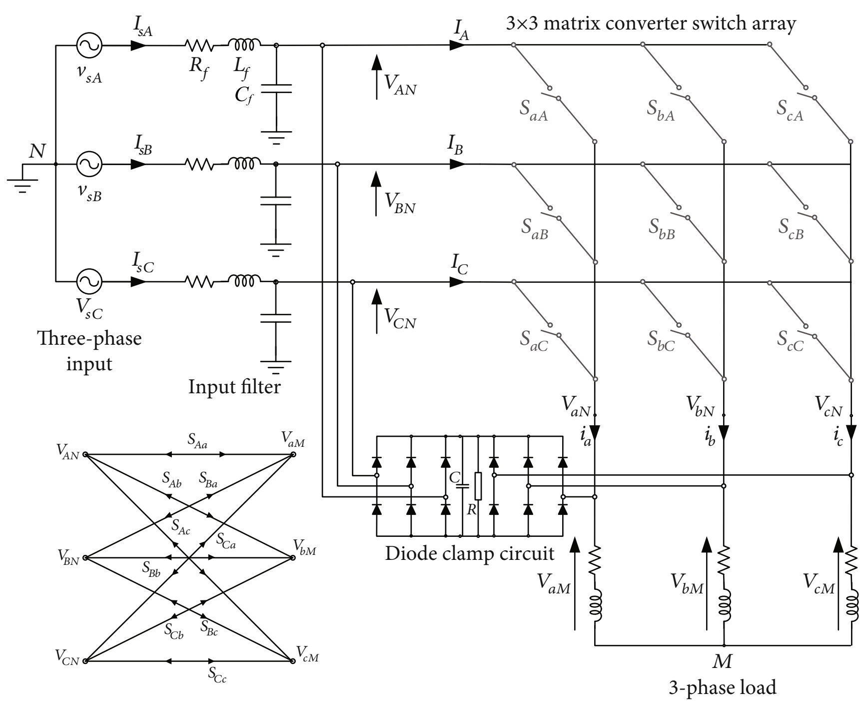


Figure 3: A 3 × 3 matrix converter circuit with input filter and clamp circuit.

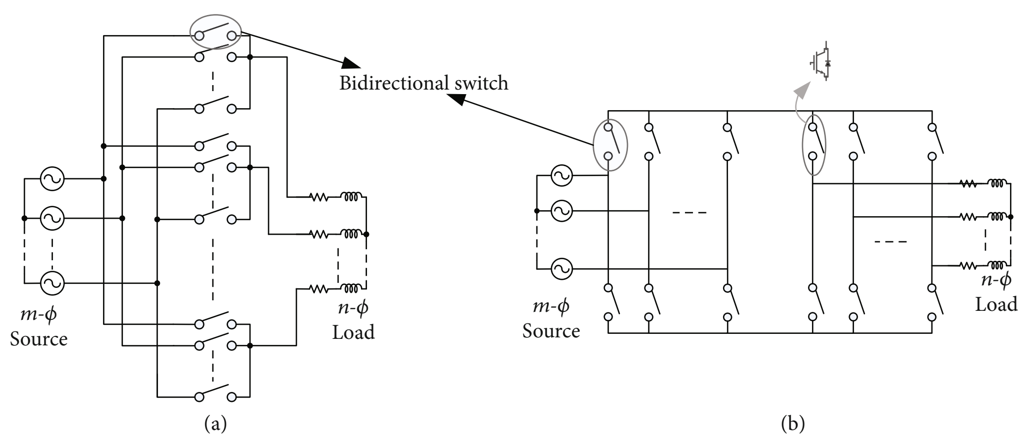


Figure 4: (a) Direct matrix converter and (b) indirect matrix converter.

2.1. Bidirectional Switches. In order to ensure the bidirectional power flow, AC switches are required that allow bidirectional current flow in on condition. In off conditions, they block bipolar voltage. Thus, a four-quadrant switch (AC switch) is required, which is formed through configurations shown in Figure 5. The first configuration is a diode bridge configuration with a controllable IGBT in the diagonal diode bridge structure. This switch is simple in structure, and it provides simplicity in programming a converter. This switch requires one gating signal, contrasting to two signals in other configurations. As a result, it will require only one gate driver circuitry, leading to a further reduction in cost as compared to other configurations. The drawback lies in the commutation from one switch to the other in the same leg. The simultaneous change may result in short circuiting of the sources while generating a dead time will result in the open circuiting of the inductive load. So, one has to resort to hard switching with an insertion of a minimum dead time and the load being freewheeled through a *clamp circuit*. Another drawback is that there will be more conduction losses as the current will flow through three devices at any instant.

The common emitter and common collector configurations are the most used due to the reduction in the switch stress. Also, the advent of soft-switching techniques has made them an obvious choice. Moreover, these configurations have only two devices in conduction mode at a time, which leads to comparatively low conduction losses. The common emitter configuration has the advantage that the two IGBT can be driven with respect to the common emitter junction, as it behaves as a local ground for the bidirectional switch. The drawback is that this configuration requires nine isolation transformers. The common collector configuration, on the

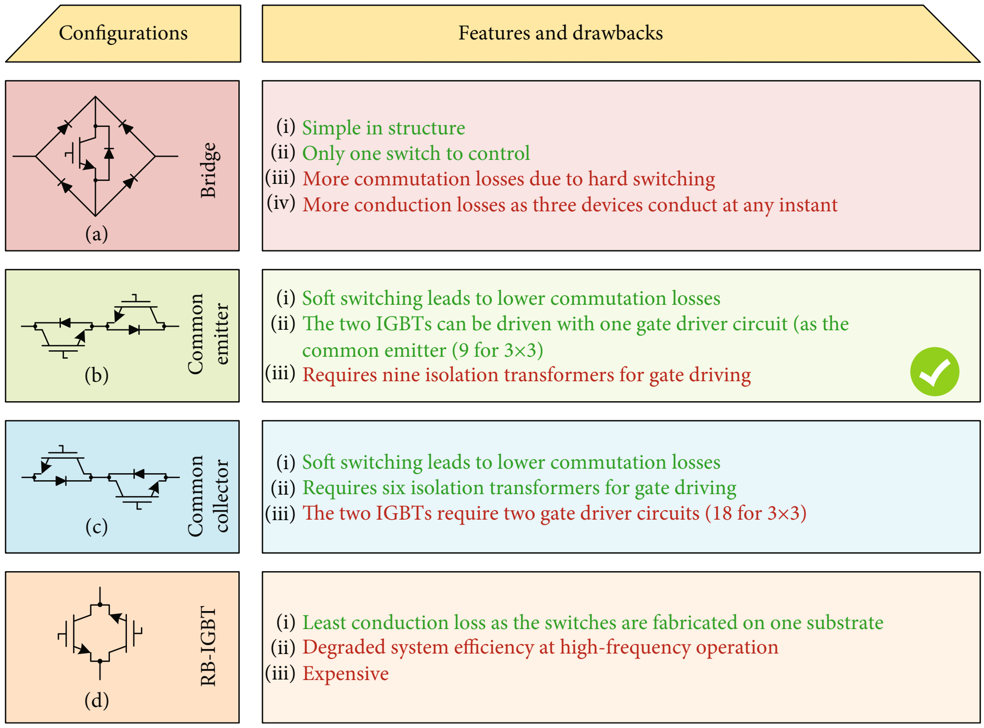


Figure 5: Configurations, features, and drawbacks of bidirectional switches: (a) diode bridge, (b) common emitter, (c) common collector, and (d) RB-IGBT AC switch configurations.

other hand, requires six isolation transformers as the point of reference with respect to the emitters behaving as respective local grounds [44]. Due to the availability of two switches for each bidirectional module, it becomes easy to implement the soft commutation technique (which is discussed ahead). As in most of the circuits, an optocoupler is employed for isolation in gate driving, and the common emitter is preferred.

Reverse blocking-IGBT (RB-IGBT) exhibits the least conduction loss of all the configurations as the diodes are removed. But this configuration tends to exhibit degraded system efficiency at high-frequency switching. They exhibit good performance if used in the rectification stage of IMC, as the RB-IGBT of the rectifier stage switch at zero current [45]. A novel super-junction RB-IGBT is also discussed in the literature [46]. As it is still a growing technology, RB-IGBTs are expensive.

2.2. Clamp Circuit. As the load side is predominantly inductive, in the open circuit condition of the connected switches, the stored energy must have a path to dissipate. As there is no freewheeling path on the switch side, an extra freewheeling path is required. This extra freewheeling circuit is known as a clamp circuit, which is shown in Figure 6(a). If the load side of the circuit is connected to the load ports, the excess energy will dissipate through the resistor. On the other hand, the disturbances on the grid side can be bypassed by connecting the grid side of the clamp circuit to the input side of the matrix converter, as shown in Figure 3. A small clamp capacitor, typically 2 μF for a 3 kW motor, is also connected in shunt to the resistor.

2.3. Input Filter. A three-phase single-stage LC filter at the input consisting of three capacitors in the star and three inductors in the line is used to adequately attenuate the higher-order harmonics and fetch sinusoidal input current from the source. The circuit is shown in Figure 6(b), and its connections are shown in Figure 3. The filter may cause a minor phase shift in the input displacement angle which needs correction. Another filter design can be seen in [32].

2.4. Commutation and Commutation Number. The MC does not contain freewheeling diodes, which usually provide safe commutation in the case of other converters. In one leg, as one switch turns off, the next switch in the sequence must be immediately turned on to maintain the continuity of the output current. This may lead to the overlapping of two switches in the on state in one leg and may lead to a momentary short circuit of the input phases and create an overcurrent issue. Many techniques have been proposed in the literature. For the AC switch configurations shown in Figures 5(b)–5(d), semisoft current commutation using a multistep switching procedure is employed to ensure safe commutation [47].

Herrero et al. in [56] have compared many techniques and have found the four-step commutation as the most suitable. This method requires independent control of each two-quadrant switch, sensing the direction of the load current and introducing a delay during the change of switching states. The switching rule for proper commutation from S_1 to S_2 of the arrangement shown in Figure 7(a) for $i_L > 0$, with the two quadrant switches for four-step commutation, is (a) turn off S_{1B}, (b) turn on S_{2A}, (c) turn off S_{1A}, and (d) turn on S_{2B}. Analogously, for $i_L > 0$, the switching rule will be (a) turn off S_{1A}, (b) turn on S_{2B}, (c) turn off S_{1B}, and (d) turn

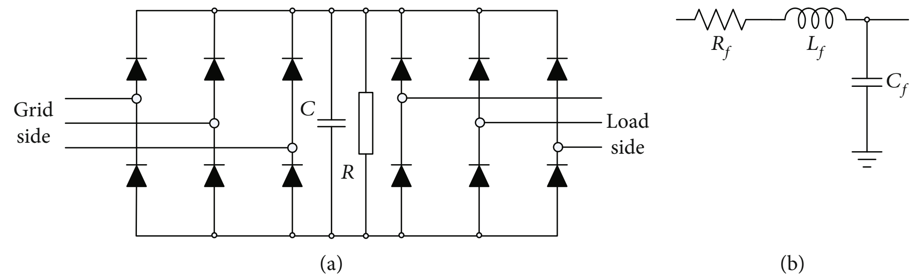


FIGURE 6: (a) Clamp circuit and (b) input filter.

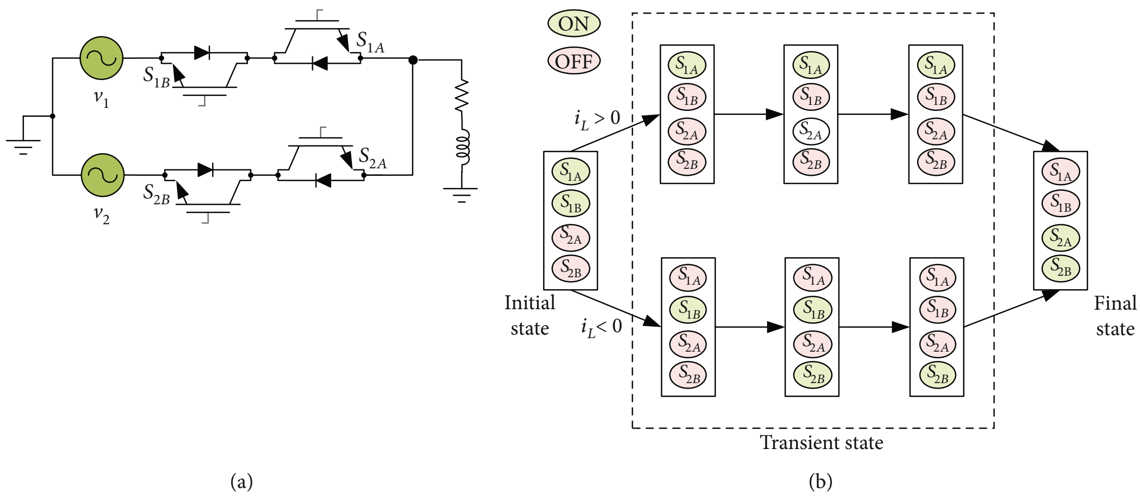


FIGURE 7: (a) Two bidirectional configurations connecting two sources to a load. (b) Steps of four-step commutation method.

on S_{2A}.These steps for both cases are shown diagrammatically in Figure 7(b).

Typically, these commutation strategies are implemented using programmable logic devices such as field programmable gate arrays (FPGA) and programmable logic devices (PLD). Also, it is worth mentioning that the configuration shown in Figure 5(a) has to stick to a two-step commutation which, despite having the considerable advantage of employing less number of switches, will produce more spikes in the output voltages. Another way to achieve better commutation is by Z-sourcing the input of the matrix converter [19]. Other commutation techniques are discussed and compared in Table 1.

Another interesting aspect regarding the commutation is the commutation number. It is the number of times switching occurs in one switching cycle. Under normal circumstances in a 3×3 MC, this value is 6, which is reduced in the works presented by [53, 55]. For 3×5 DMC, [54] has reduced from 10 to 5. This leads to a considerable reduction in switching and commutation losses. Table 1 shows a brief comparison of commutation strategies.

3. Topological Advancement in Matrix Converters

In this section, the structural modifications of the DMCs and IMCs that lead to the performance enhancement of the overall AC-AC conversion process are presented. To begin with, the topological improvement in the DMC structure is discussed in the forthcoming subsection.

3.1. Progress in Direct Matrix Converters. This converter topology connects the input to the output through bidirectional switches, as previously shown in Figure 4(a). The number of AC switches depends on the number of input and output phases. For an $m \times n$ system, there will be $m \cdot n$ AC switches. As this topology is well defined, most of the recent work is being done in the field of its modulation strategies. Structurally, the main changes have been in terms of

(i) impedance (Z or Y) sourcing or quasi-impedance sourced matrix converters [19, 57–61]

(ii) multilevel matrix converters [22, 62–75]

(iii) multimodular matrix converters [76–81]

(iv) multiphase matrix converters [21, 82–89]

(v) modification in the auxiliaries, for example, input filter and sensors

3.1.1. Progress in Impedance Sourced Direct Matrix Converters. Z-sourcing is a method to enhance the voltage transfer capability of a matrix converter. The voltage-fed DMC (of Figure 4(a)) behaves as a buck converter. In order to obtain a higher voltage magnitude, the concept of shoot-through is adopted. One way is to connect two DMCs

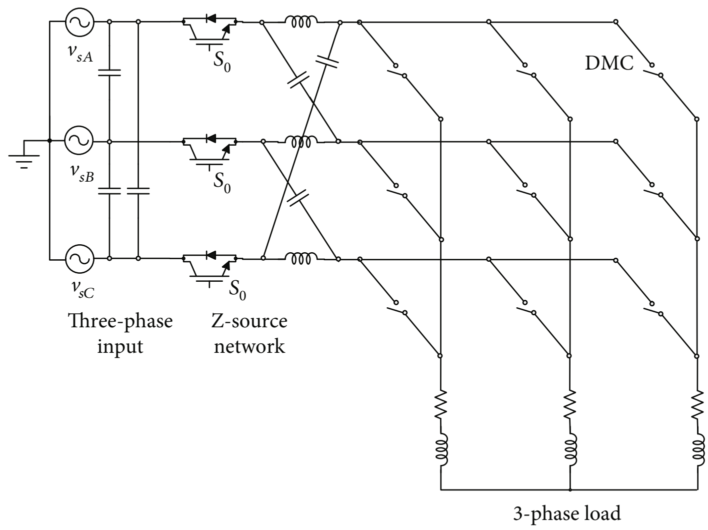
Table 1: Commutation techniques and commutation number of the AC switches of the MCs.

	Category	Types of commutation techniques/references	Advantages	Disadvantages
On commutation techniques	Current direction-based commutation	Four-step commutation [47]	No need for voltage detection	Misjudged current values at zero crossing may lead to undesired load's open circuit
		Three-step commutation [48]	Reduction in commutation time from one phase to other than [47]	Similar to [47]
		Two-step commutation [49]	Least time-consuming commutation process	A complex measurement circuitry is required that must measure each switch's voltage
	Voltage direction-based commutation	Four-step commutation [50]	Reduced commutation time in comparison to [47]	Based on the measurement of relative magnitudes of the phase voltages. The critical areas where the relative value is zero can be misjudged
		Two-step commutation [51]	Lower commutation time Prohibits commutation between two input phases with similar voltages	Complex measurement and calculation circuitry required
	Hybrid	Hybrid commutation [52]	It is a two-step commutation	Complex measurement hardware required
On commutation number	Works with reduced commutations	3×3 MC [53] 3×5 MC [54]	Commutation number reduces from 6 to 4 Commutation number reduces from 10 to 5	Increased output voltage harmonic distortion
		3×3 MC [55] is discussed	Reduction of commutation number from 6 to 4 Good current THDs	Increased output voltage harmonic distortion

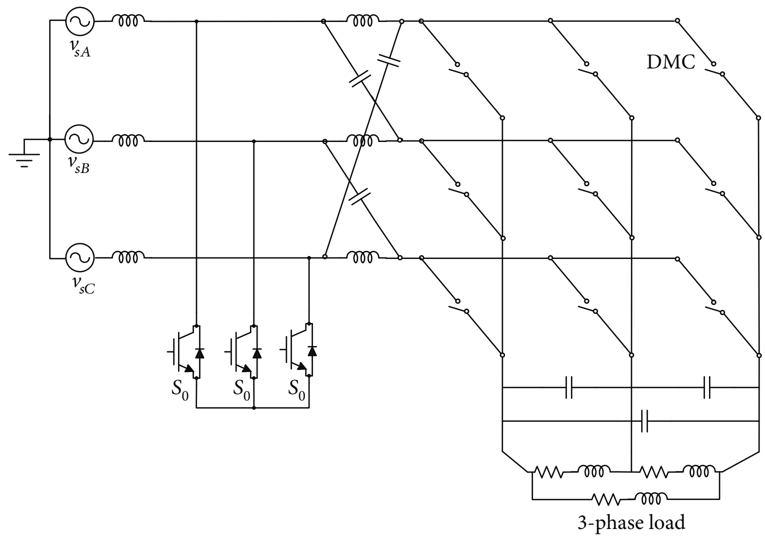
through an inductor bank [57]. Thus, the first DMC behaves as a voltage-buck converter, and the second DMC behaves as a current-buck converter, or if more appropriately said a voltage-boost converter. So, [57] has introduced a set of possible Z-source DMC topologies. This paper also discusses the possible quasi-Z-source DMC topologies and trans-Z-source DMC. However, the paper mainly concentrates on the performance evaluation of Z-source and quasi-Z-source DMCs only. In [58], a quasi-Z-source DMC is employed to drive a vector-controlled induction motor drive. Authors in [19] present a review on possible impedance-sourced MCs. Application-wise, quasi-Z-source DMC is modelled and analyzed in [59]. Alizadeh and Kojori have extended the concept of predictive control to the above set in [60]. A Z-source and a quasi-Z-source voltage and current DMCs are shown in Figure 8. Further research on quasi-Z-source IMC and Y-sourced IMC is presented in [20, 90], respectively.

3.1.2. Progress in Multilevel Direct Matrix Converters. The structure shown in Figure 9(a) was introduced in 2001 by Erickson and Al-Naseem by employing nine H-bridges in place of the nine bidirectional switches in a 3×3 matrix of a DMC [91]. A capacitor-clamped multilevel matrix converter (Figure 9(b)) was discussed in detail in [92]. The results clearly showed better performance in terms of output voltage harmonics. The stress per switch reduces to half. The drawback is the increment in the number of switches and capacitors, which becomes a cause of concern, as the number is just doubled. Moreover, the increment in the number of capacitors will reduce the reliability of the system. Work on suppression of common mode voltage (CMV) is done in [62]. In [63–71, 93], the researchers have discussed an incremental version of multilevel DMC. This topology is achieved by having multiple H-bridges in each line that connects the output to the input. The benefit of such schemes is a low ripple output voltage, which comes at an expense of a large number of switches and complex control strategies, which makes this topology suitable for niche applications. Other works on multilevel matrix converters like fault detection can be found in [74].

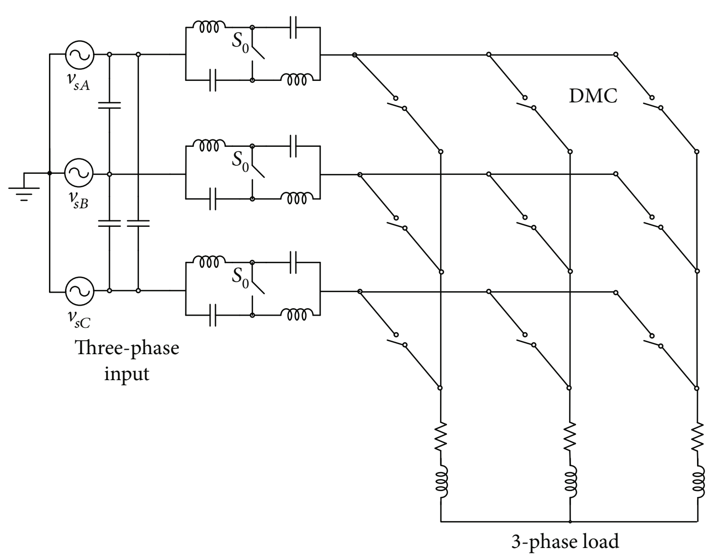
3.1.3. Progress in Multimodular Direct Matrix Converters. A multimodular MC (MMMC) is another topology discussed in the literature, whose structure is shown in Figure 10. The MMMCs are intended for possible use in high-power applications with four-quadrant operation capability and expected fast dynamic response. This converter consists of 3×2 DMC modules. Two configurations of such converters are discussed and experimentally validated in [77]. An indirect SVM-based modulation scheme is implemented in [81, 94]. A method based on mathematical construction is discussed in [79], and carrier-based strategies are discussed in [80]. In another work, two matrix converters are employed



(a)

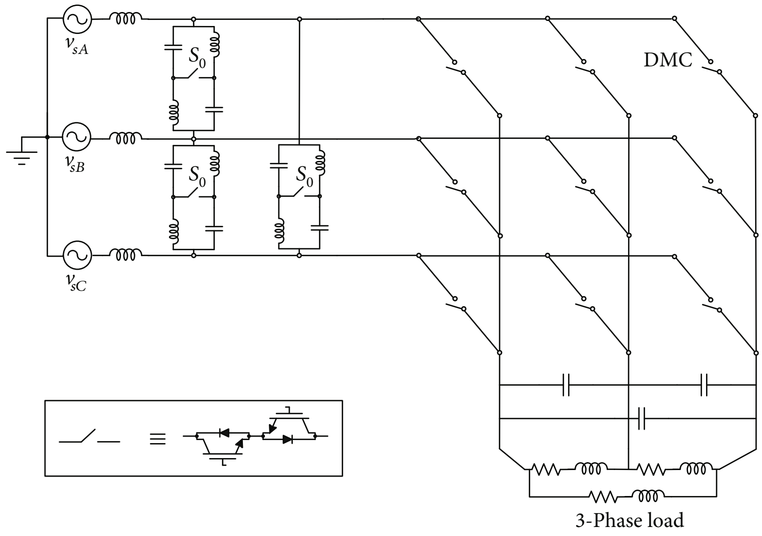


(b)



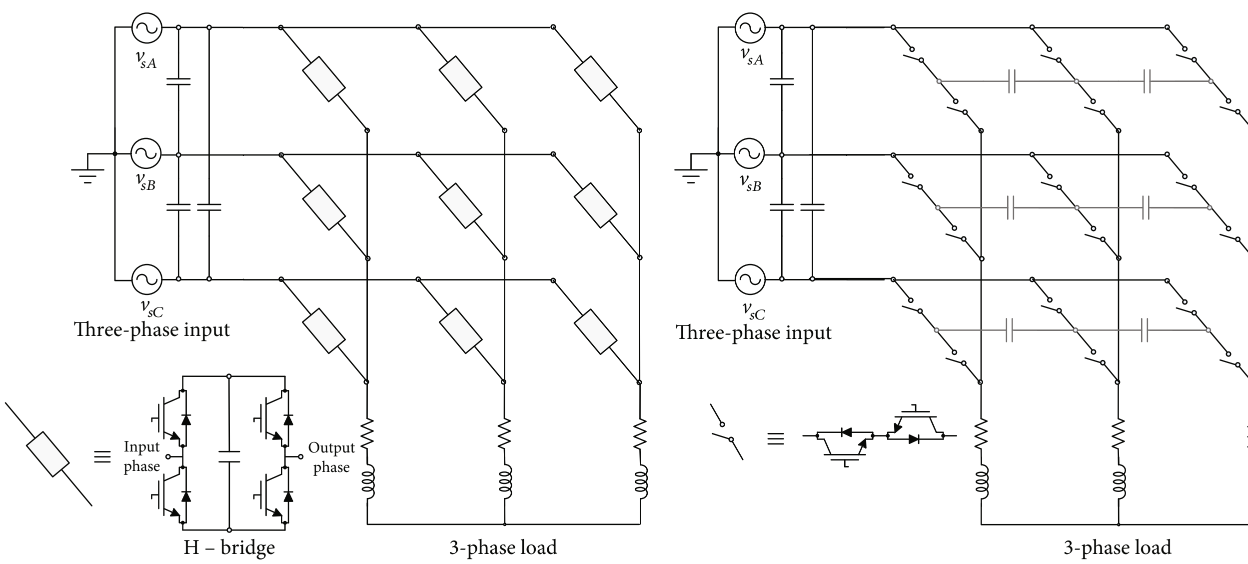
(c)

Figure 8: Continued.



(d)

Figure 8: (a) Voltage-fed Z-source DMC, (b) current-fed Z-source DMC, (c) voltage-fed quasi-Z-source DMC, and (d) current-fed quasi-Z-source DMC [57].



(a) (b)

Figure 9: (a) H-bridge-based multilevel matrix converter [91]. (b) Capacitor-clamped multilevel matrix converter [92].

to integrate a six-phase wind energy generation system into a three-phase grid in [95].

3.1.4. Progress in Input and Electromagnetic Interference Filter Designs. To support the effective operation of the DMC circuit, auxiliary components and their advancement are discussed here. Input and output filters are employed for harmonic elimination, and conventionally, a second-order LC network is employed [6]. Rivera et al. in 2011 introduced coupled inductor-based filter [96]. [32] discusses a method to design an input filter in an automated optimal way. The input filter is designed by analytically estimating the ripple content in the unfiltered input current in [97]. EMI filter design for a DMC for aerospace applications is discussed in [98]. Current sensors are also an integrated and expensive part of the closed-loop operation of MC-based drives. In [99], the number of sensors is reduced from conventional three to only one, exhibiting a normal operation.

3.2. Progress in Indirect Matrix Converter. An indirect matrix converters (IMCs), as seen in Figure 11(a), consist of 18 controllable switches, which is equal to 3×3 DMC. The difference lies in the control of this converter structure. This configuration is easier to implement, as the control strategies of controlled rectifiers and inverters can be directly implemented. This topology is discussed in [100]. It employs 12 in rectification and 6 in the inversion process. The sparse

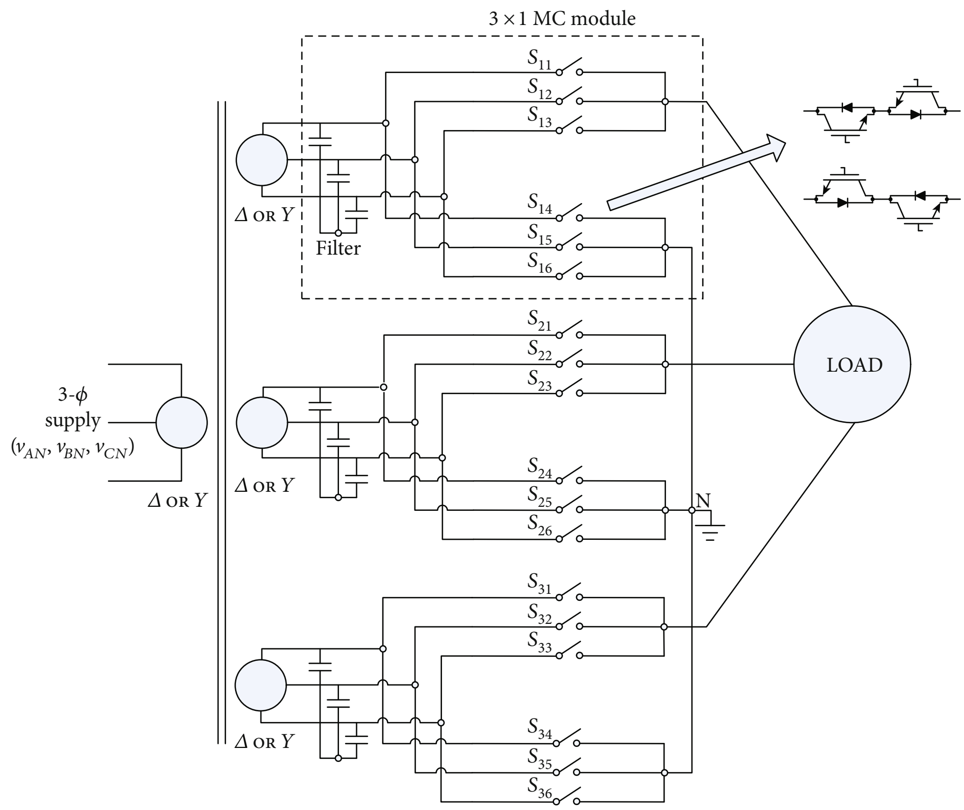


Figure 10: Multimodular matrix converter [77].

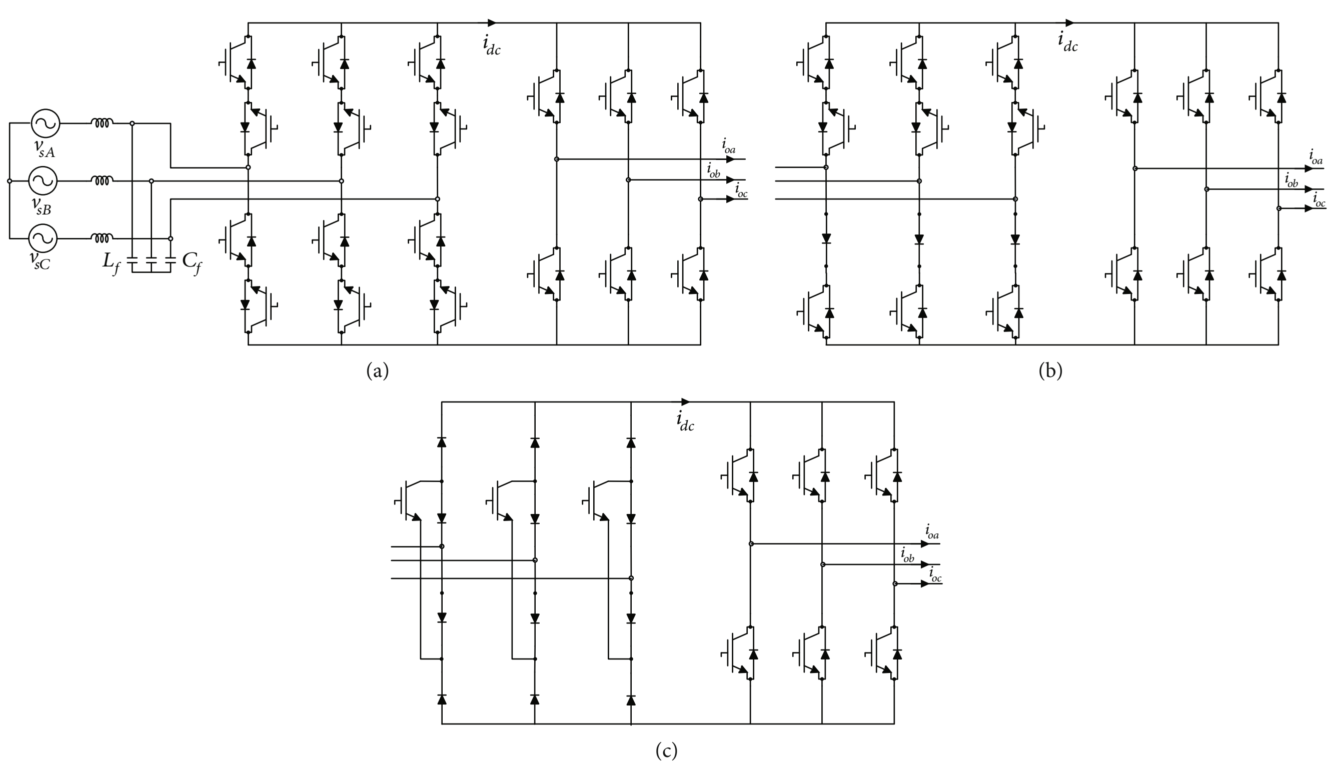


Figure 11: (a) Indirect matrix converter [100]. (b) Sparse matrix converter [101]. (c) Ultrasparse matrix converter [17].

matrix converter (SMC) (Figure 11(b)) is derived from the IMC, which is split into an input stage and output stage without any capacitance in the DC link. The input stage is arranged so that only nine switches are required, while the output stage has a standard 6-switch configuration. Thus, the SMC has 15 switches, compared to 18 for a DMC and IMC. The functional equivalence, the controllability, and the operating range of the SMC are the same as DMC despite the reduced number of unipolar turn-off power switches [101]. Further reduction of the number of IGBTs is possible with an ultrasparse matrix converter (USMC) (Figure 11(c)) having 12 IGBTs, with a restricted operation to a unidirectional power flow and controllability of the phase displacement of input voltage and current fundamental to $\pm\pi/6$ [17]. A 100 kHz SiC sparse matrix converter using 1300 V, 4 A SiC JFET cascade devices has been reported in [102], which is suitable for aircraft applications where a low volume/weight converter is desired. Real-time implementation of an IMC employing SVM algorithms can be seen in [103]. Two modulation strategies to suppress high THD in USMC are discussed in [104]. A modulation scheme to suppress the undesirable common mode voltages is shown in [105]. Topologically, the inverter side can be replaced by multilevel inverters like [106–108], to produce better output characteristic voltages.

4. Comparison between Matrix Converters and Conventional AC-DC-AC Conversion Technology

Conventionally, VSC-based technology is employed to convert an AC voltage to another AC voltage. If the rectification stage is controlled by using a VSC, then it is known as a back-to-back topology (B2B), and if an uncontrolled rectification stage is employed, then the topology is known as the front-end converter (FEC). But this technology requires a DC link capacitor in between that makes the overall system bulky and space-consuming. On the contrary, DMC and IMC technologies make the provision of the omission of intermediate DC link. So, in this section, a comparison is presented to show the merits and demerits of these topologies over the existing conventional topologies. All these topologies have merits and demerits over one other, and the selection depends on the type of application to be driven. As can be seen in the case of the industrial drives system manufactured by Yaskawa, a space reduction of 30% is expected with the DMC over the B2B [35]. This is illustrated in Figure 12.

The first comparison between DMC and B2B converters is given in [109]. This work gives a deep insight into the design and performance comparison of DMCs and B2Bs in machine drives with a reduction of the device current rating by 33%, and thus, the thermal device stress reduces. It is also concluded that at higher switching frequencies, the losses in MCs are lesser than the B2B in a wider operating range. However, it is required to build a *special motor* in order to compensate for a lower VTR.

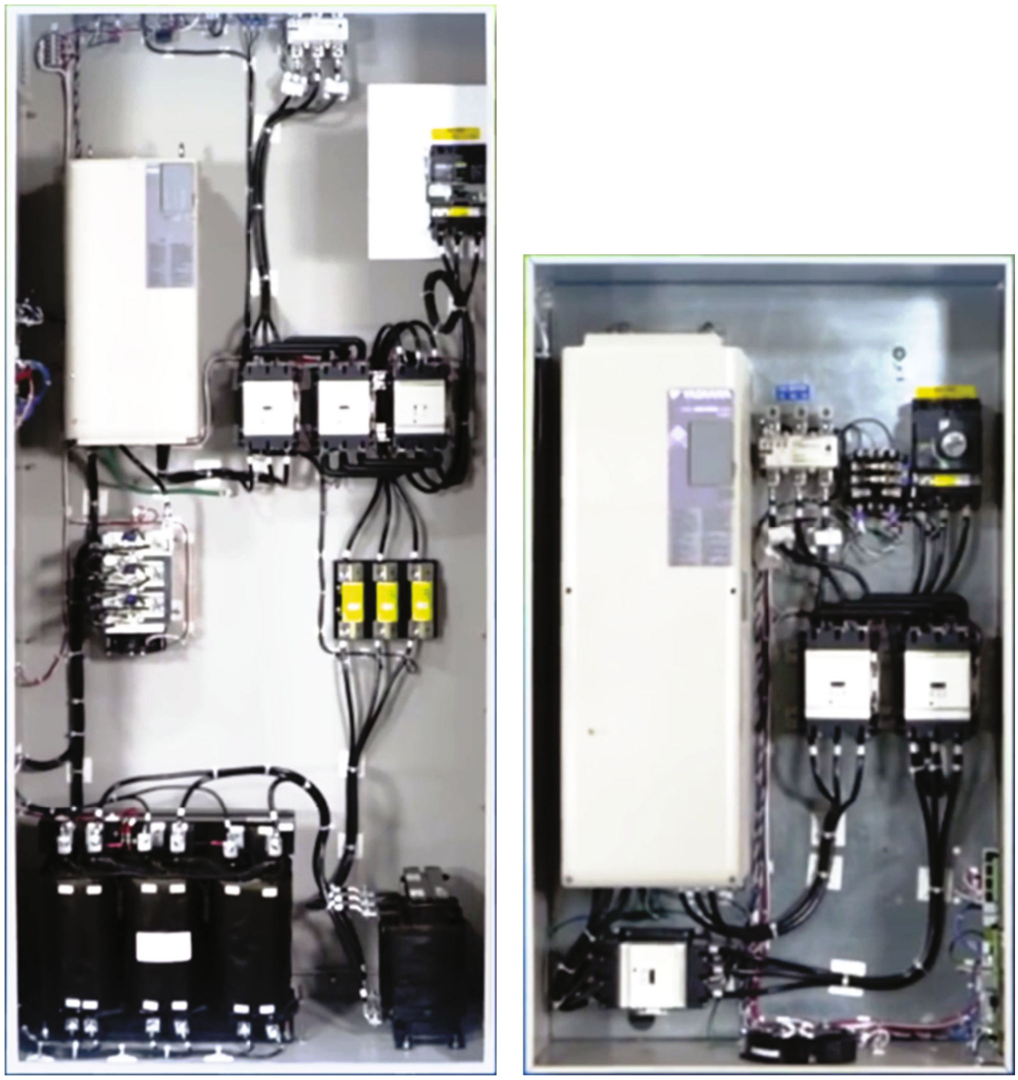
Aten et al. in 2006 in [110] checked the reliability of the matrix converter in accordance with the military handbook MIL-HDK-217F guidelines and concluded that, despite having more number of switches, the reliability of the converter is similar to the conventional VSC structure, due to lower voltage stress. However, the current stress is not considered. On the other hand, a detailed comprehensive comparison between B2B, DMC, and IMC is made in [36] when driving a 15 kW PMSM motor drive. According to the performance evaluation between B2B and DMC, it is concluded that MCs are suitable for compressors, blowers, fans, mixers, general pumps, and escalator drive systems. And, the comparative analysis of DMC and IMC shows that the DMCs are more apt in low-frequency range operation. IMC, however, can be chosen for high switching frequency operation. In [111], the temperature is used as a stress factor, and it is concluded that the DMC is more reliable than B2B. This is due to the omission of the DC link capacitor. However, in terms of VTR, FEC and B2B have an edge over the DMC and IMC.

5. Progress in Multiphase Matrix Converter Research

Until 2010, the VSIs were only considered in research to drive the multiphase drives, and a three to five transformer was developed using special transformer connections [112]. But, in 2010, the simulation of multiphase MCs with RL loads commenced with [113], which actually is an extension work of [114]. In another work, carrier-based and space vector-based algorithms simulated for a 5×3 DMC [115].

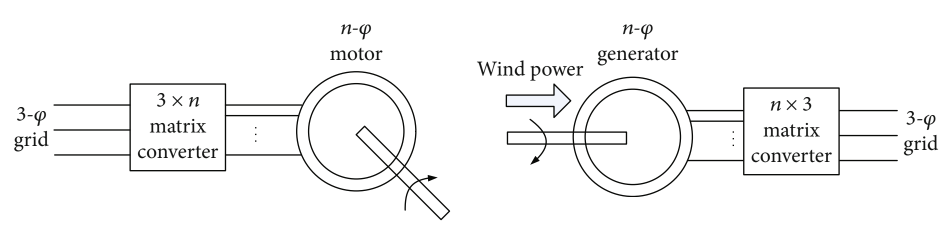
Multiphase matrix converters (MPMC) are an extension to the conventional 3×3 MCs in terms of input and output legs. These converters can be useful in interfacing a three-phase grid to a multiphase load or vice versa, as shown in Figure 13. Most of the research has been done on the modulation and control of MPMCs. This section deals with the progress of the research in this context. DMC and IMCs are only considered here. The literature review suggests that the work is currently concentrated on DMC and recently there is a shift towards IMCs.

In 2011, a 3×9 and several modulation strategies were implemented. A simple carrier-based modulation strategy was introduced in [25]. This method was an extension to the approach taken for the modulation of conventional VSIs and was different from [116] in a manner that the carrier signals in the latter approach were discontinuous. A generalized direct duty-ratio-based algorithm was discussed for $3 \times k$ DMC in [28]. In this approach, continuous triangular waveforms were employed in the generation of signals. The scheme was highly intuitive and flexible. The duty ratios were directly calculated with respect to the input maximum, medium, or minimum input voltage level (which can be any of the input voltages). In the same year, an indirect modulation strategy was implemented on 3×5 DMC [117]. Ali et al. in [4, 21] proposed a generalized modulation strategy extendable to $m \times n$ DMC. It was also proposed, analytically, that the Venturini modulation can be extended to $3 \times n$ MC only. In [83], the genetic algorithm-based technique was used to define the modulation functions of the $3 \times n$ DMC. In 2012, pioneer work was presented in [118], where the



(a) (b)

Figure 12: (a) DC link-based drive. (b) Matrix converter-based drive (courtesy: Yaskawa Inc.).



(a) (b)

Figure 13: Applications of matrix converter (a) to drive multiphase load and (b) to link a multiphase generator to the three-phase grid.

direct SVM approach was implemented on 3×5 DMC. In this strategy, 93 states out of 243 possible states of the converter were used by employing active vectors only. The results exhibit the unity power factor operation of the converter.

A review on multiphase systems was performed in 2016, where Levi in [42] has discussed the multiphase matrix converters and their merits. Direct space vector modulation is implemented on 5×3 MC in [119, 120]. The direct space vector method is also implemented on 3×7 DMC in [121]. A 9×3 DMC is discussed in [122], in which a 9×3 MC is implemented using predictive control. Direct as well as indirect space vector modulation is discussed from a simulation point of view for a 3×5 DMC in [123]. However, a space vector modulation strategy is discussed for a 3×5 indirect matrix converter in [124].

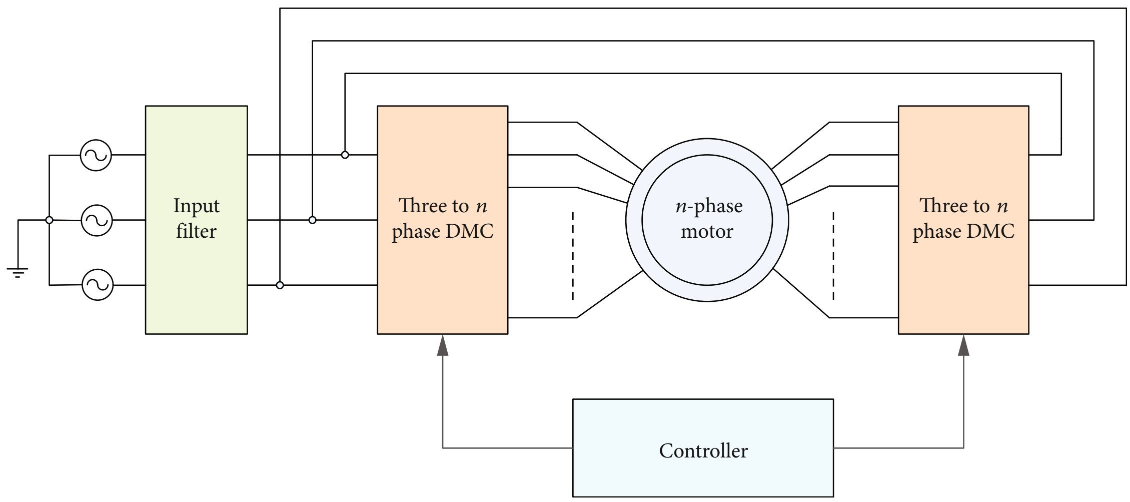


FIGURE 14: Schematic of an n-phase open-ended machine driven by dual $3 \times n$ DMC [125, 126].

Indirect space vector modulation is implemented on 3×5 and on 3×7 DMC in [127, 128], respectively, with full details of experimental implementation. Unity displacement factor is also achieved. Direct space vector modulation is implemented on 3×7 DMC in [129]. Common mode voltage (CMV) reduction is an important factor as it reduces the stress on machine bearings. The space vector method is employed to control the CMV through vector selection in a 3×5 DMC in [130]. Another approach to reducing the CMV is to use open-end machines that are controlled by two converters. In [125], such an attempt is made on a simulation platform on a seven-phase motor. Space vector PWM techniques for 3×5 IMC in overmodulation range are discussed in [131] and VTR_{max} of 0.923 is achieved, in contrast to the conventional 0.7886. A direct SVPWM is implemented on a 3×6 DMC in [132]. [133] presents an improved SVPWM method for a 3×7 DMC that employs only 129 states from 2187 states. Despite that, the performance is comparable to the conventional SVM's performance, as the THDs are below IEEE standards and are better than the THDs of the carrier-based algorithms. Another research is performed by same authors on the five-phase open-end load fed from two 3×5 DMCs to eliminate the CMVs and increase the voltage by 1.9 times [126], the schematic of which is shown in Figure 14.

Recent works include the application of 6×3 DMC for microgrids [9]. A fault-tolerant operation is presented on a 3×5 DMC for motor control applications in [134]. In [88], FOC of a 5-phase IM drive driven by 3×5 DMC is presented. In order to maximize the input reactive power range, a modulation strategy based on load information is presented for 3×5 DMC in [135].

6. Progress in the Modulation and Control of Matrix Converters

The modulation of the MC switches is considered a complex task, as it requires more in-depth analysis of the converter structure and the voltage waveforms [21]. Most of the schemes are an extension of the conventional two-level inverter topologies, like space vector and carrier-based approaches. In this section, first, the conventional modulation schemes are discussed and then the advanced techniques that have been introduced recently will be discussed. The schemes will also be evaluated against each other for their pros and cons. A chart of all the modulation and control schemes used for MC driving is shown in Figure 15, and a brief discussion on their methodology is shown in Table 2.

6.1. The Conventional Modulation Schemes. Several modulation strategies are reported on direct matrix converters in literature. Some of which are the Venturini approach [15, 148], Roy's scalar approach [149, 150], direct space vector approach [136], indirect space vector approach [24], carrier-based approach [116, 137], direct duty-ratio-based approach [26], and minimum voltage drop approach [53, 138, 151].Recently, a new control scheme zero-cross signal of the input voltage which is used for the modulation scheme was introduced [152] and validated on practical examples of air-conditioning motor and elevator motor drives. The modulation schemes are generally classified as scalar and pulse width modulation schemes, as shown in Figure 15(a). One of each of the methods is discussed below in brief:

6.1.1. Direct Method (Alesina-Venturini). It is the first modulation strategy that was given by Alesina and Venturini in [13] for a 3×3 MC and later on extended to optimum output with a VTR of 0.866 in [15]. This method is known as the direct method, as the solution is fetched for the switching matrix by linking the output and voltage directly. Later on, this method was once more explored by Ali et al. in [4, 21], where all the possible outputs (odd and even) were considered. Further, more optimum solutions were tried to be fetched by using the metaheuristic technique in [83]. The expression of the optimum output voltage for a $3 \times n$ MC as developed in [21] is given as

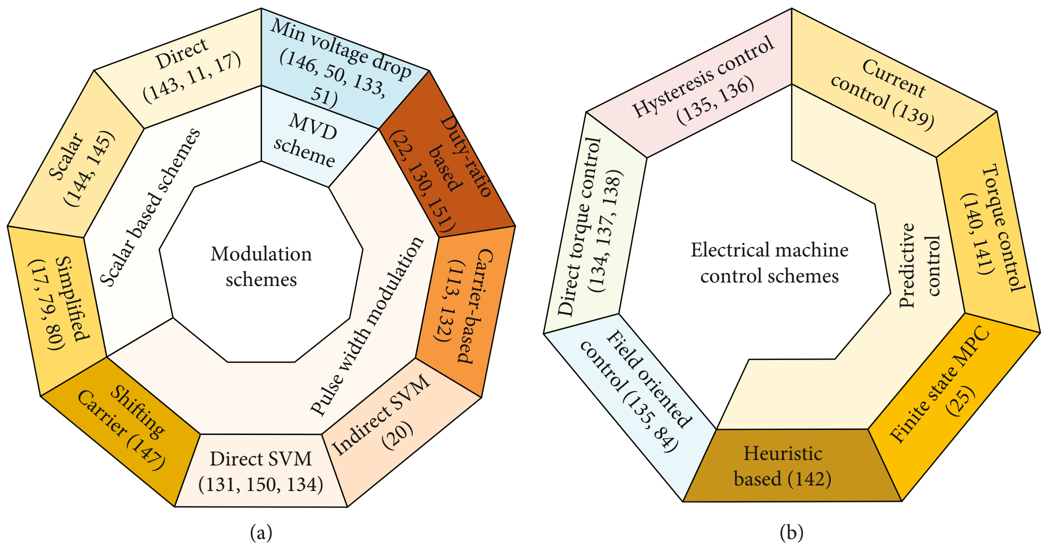


FIGURE 15: The (a) modulation and (b) control strategies for the matrix converters.

$$\underline{v}_o(t) = \left\{ V_{o_{\max}} \cdot \left(\cos\left(\omega_o t\right) + (j-1)\frac{2\pi}{n} \right) + \frac{1}{2}\left(1 - \cos\frac{\pi}{m}\right) \cdot V_{\text{in}} \cdot \cos\left(m \cdot \omega_{\text{in}} t\right) - \frac{1}{n} \sin\left(\frac{\pi}{2n}\right) V_o \cos\left(m \cos \omega_o t\right) \right\}_{j=1}^{n}. \quad (1)$$

And the corresponding generalized optimal modulation function is given as

$$m_{ji} = \frac{1}{m} + \frac{q}{m}\left[1 + \frac{\tan\phi_{\text{in}}}{\tan\phi_o}\right] \cos\left(\omega_{x_1} t + \frac{2(j-1)\pi}{n} - \frac{2(i-1)\pi}{m}\right) + \frac{q}{m}\left[1 - \frac{\tan\phi_{\text{in}}}{\tan\phi_o}\right] \cos\left(\omega_{x_2} t - \frac{2(j-1)\pi}{n} - \frac{2(i-1)\pi}{m}\right), \quad (2)$$

where $S_{ji} = 1$, if S_{ji} is closed, and $S_{ji} = 0$, if S_{ji} is open, where $i = A, B, C$ and $j = a, b, c$.

In comprehension, the above expressions state that the input side cannot be short circuited as they are voltage sources, and the load cannot be left open circuited because of its inductive nature. Also,

$$S_{jA} + S_{jB} + S_{jC} = 1, j = a, b, c. \quad (3)$$

6.1.2. Direct Space Vector Approach. The aim of the direct SVM algorithm is to generate the desired output line-to-line voltage vector $\bar{v}_o$ and the input displacement angle β_{in}. Due to the lack of any storage elements, the input current vector $\bar{i}_{\text{in}}$ is uncontrollable, but due to the availability of many vectors, β_{in} is easily controllable, and hence, a unity power factor operation is achieved. This method is based on selecting four active configurations applied for suitable dwelling times within a sampling time T_s; then, the zero configurations are applied to complete the T_s, as shown in Figures 16(a) and 16(b). Figures 16(c) and 16(d) exhibit the formulation of dwell times for the combination. And the dwell times on the four vectors are calculated from the corresponding duty ratios that are derived under certain constraints [136, 153].

Let d^{I}, d^{II}, d^{III}, and d^{IV} be the four duty ratios associated with four active vectors of a particular input and output configuration. Then,

$$-\leq \tilde{\alpha}_o \leq +\frac{\pi}{6}, \qquad -\leq \tilde{\beta}_{\text{in}} \leq +\frac{\pi}{6}, \quad (4)$$

$$d^{\text{I}} + d^{\text{II}} + d^{\text{III}} + d^{\text{IV}} \leq 1. \quad (5)$$

Under the subjection of these constraints, the dwelling duty ratios are calculated as

$$\begin{aligned}
d^{\text{I}} &= \frac{2}{\sqrt{3}}\frac{v_o}{v_{\text{in}}}\frac{\cos\left(\tilde{\alpha}_o - \pi/3\right)\cos\left(\tilde{\beta}_{\text{in}} - \pi/3\right)}{\cos\phi_{\text{in}}},\\
d^{\text{II}} &= \frac{2}{\sqrt{3}}\frac{v_o}{v_{\text{in}}}\frac{\cos\left(\tilde{\alpha}_o - \pi/3\right)\cos\left(\tilde{\beta}_{\text{in}} + \pi/3\right)}{\cos\phi_{\text{in}}},\\
d^{\text{III}} &= \frac{2}{\sqrt{3}}\frac{v_o}{v_{\text{in}}}\frac{\cos\left(\tilde{\alpha}_o + \pi/3\right)\cos\left(\tilde{\beta}_{\text{in}} - \pi/3\right)}{\cos\phi_{\text{in}}},\\
d^{\text{IV}} &= \frac{2}{\sqrt{3}}\frac{v_o}{v_{\text{in}}}\frac{\cos\left(\tilde{\alpha}_o + \pi/3\right)\cos\left(\tilde{\beta}_{\text{in}} + \pi/3\right)}{\cos\phi_{\text{in}}}.
\end{aligned} \quad (6)$$

Also,

$$v_o \leq v_{\text{in}} \frac{\sqrt{3}}{2} \frac{\left\|\cos\phi_{\text{in}}\right\|}{\cos\tilde{\alpha}_o \cos\tilde{\beta}_{\text{in}}}. \quad (7)$$

Table 2: Comparison of various modulation and control schemes.

S. no.	Method	Description
Modulation		
1.	Direct strategy [15, 21]	The first modulation strategy given for 3×3 DMC. Includes input pf control irrespective of load pf. Extendible to $3 \times n$ DMC.
2.	Direct space vector [136]	The dwell times are derived from the desired average transfer functions obtained from output voltage and input vector planes. The input current displacement factor can be varied regardless of the load power factor.
3.	Indirect space vector [24]	The DMC is emulated as a combination of VSC and VSI. The modulation functions of both converters are merged to obtain the final modulation function of the actual DMC.
4.	Carrier-based [116, 137]	Simple symmetrical carrier-based PWM strategy using carrier-based modulator for easier MC functioning.
5.	Duty ratio-based [26]	The proposed method uses a continuous carrier and the predetermined duty ratio signals to directly generate the gating signals and, thus, is referred to as duty ratio-based PWM.
6.	Min voltage drop [54, 138]	Reduction in the commutation number (losses as well) and the total harmonic distortion is achieved by synthesizing the output voltage by dwelling on two nearest input voltage levels.
7.	SVM with rotating vectors [139]	This technique presents a SVM based on rotating vectors. The scheme presented enhances the performance of a DMC by giving a VTR of 0.833, which is actually 0.5 when employing rotating vectors.
Machine control		
1.	Hysteresis control [140, 141]	Fixed-band and sinusoidal-band hysteresis current controls are proposed for a DMC. Comparative evaluation of the two methods exhibits lower THD of the later method. Both the methods have fast dynamic performance.
2.	Direct torque control [139, 142, 143]	DTC provides simple control structure, independence from motor parameters, and commendable dynamic performance and is thus fit for the MC.
3.	Field-oriented control [88, 140]	FOC is discussed for 3×3 and 3×5 DMC. FOC exhibits better current THD and low tracking error than DTC.
4.	Predictive current control [144]	The rotor current predictive control is used to perform speed regulation of the DMC. The combination of the DMC and control proves to be robust that naturally compensates for stator current issues, which arise due to a low-power-quality grid voltage.
5.	Predictive torque control [145, 146]	An MPC-based DTC strategy for a DMC-fed induction motor is implemented, where two new look-up tables derived to control the electromagnetic torque and stator flux by using all the feasible voltage vector and states.
6.	Multiobjective finite-state MPC [29]	Multiple objective finite set model predictive control (MO-FS-MPC) is used to eliminate the CMV and the sensorless speed control of an induction motor drive by employing the fuzzy decision-making approach.
7.	Heuristic-based MPC [147]	A genetic algorithm- (GA-) based optimization is used to fetch a global optimal solution of the cost function and the corresponding switching states in a parallel implementation of MPC that ensures good performance in terms of the input reactive power and output current in an IMC.

This equation defines the performance limits of the DMC when subjected to unideal input conditions.

6.1.3. Indirect Space Vector Modulation. As discussed earlier, in this method [24], a virtual DC link is assumed; as shown in Figure 17, the modulation functions determined in the rectification stage and the inversion stage are merged together to formulate the switching functions of the matrix converter. The basic idea is to decouple the control of the output voltage and the input current.

The merger of the inversion and rectification stage, as discussed in [24], is necessary in order to apply them to an actual nine-switch converter. The DC link voltage is established by two input line voltages determined by input currents I_γ and

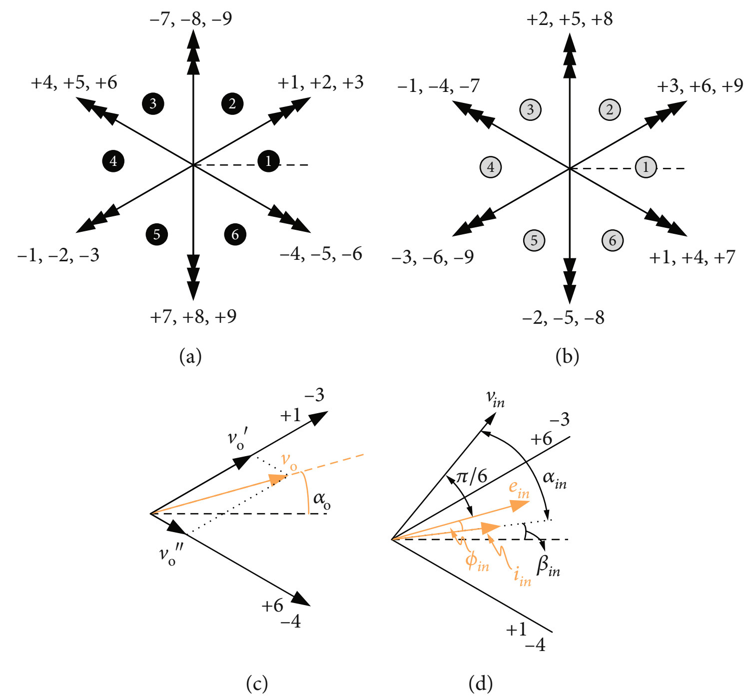


FIGURE 16: (a) Output voltage space vector combinations, (b) input current space vector combinations, (c) depiction of SVM of reference output voltage, and (d) depiction of SVM of reference input current with phase angle ϕ_{in}.

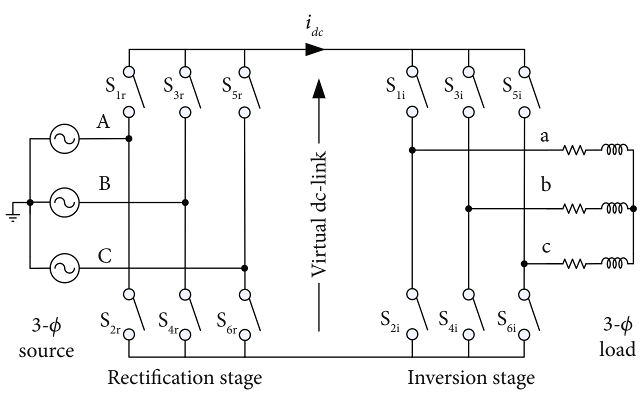


FIGURE 17: The equivalent circuit of DMC for indirect modulation strategy.

I_δ by employing d_γ and d_δ, respectively. Then, two output voltage vectors V_α and V_β are applied to synthesize the desired output voltage from the two virtual DC link amplitude inside each switching period T_s. When V_α and V_β are applied to the first current vector I_γ, two new vectors, $V_\alpha - I_\gamma$ pair and $V_\beta - I_\gamma$ pair, are created, and the duty cycle of new vectors becomes $d_{\alpha\gamma}$ and $d_{\beta\gamma}$, respectively. When V_α and V_β are applied to the second current vector I_δ, two new vectors, $V_\alpha - I_\delta$ pair and $V_\beta - I_\delta$ pair, are created, and the duty cycle of the new vectors becomes $d_{\alpha\delta}$ and $d_{\beta\delta}$, respectively. The four duty cycles for the new active vector pair can now be derived from the product of inverter duty cycles in Figure 18 and rectifier duty cycles in Figure 19.

$$
\begin{aligned}
d_{\alpha\gamma} &= d_\alpha d_\gamma = m_v \sin\left(\frac{\pi}{3} - \theta_v\right) \sin\left(\frac{\pi}{3} - \theta_c\right) = \frac{t_{\alpha\gamma}}{T_s}, \\
d_{\alpha\delta} &= d_\alpha d_\delta = m_v \sin\left(\frac{\pi}{3} - \theta_v\right) \sin(\theta_c) = \frac{t_{\alpha\delta}}{T_s}, \\
d_{\beta\gamma} &= d_\beta d_\gamma = m_v \sin(\theta_v) \sin\left(\frac{\pi}{3} - \theta_c\right) = \frac{t_{\beta\gamma}}{T_s}, \\
d_{\beta\delta} &= d_\beta d_\delta = m_v \sin(\theta_v) \sin(\theta_c) = \frac{t_{\beta\delta}}{T_s}, \\
d_0 &= 1 - d_{\alpha\gamma} - d_{\alpha\delta} - d_{\beta\gamma} - d_{\beta\delta} = \frac{t_0}{Ts}.
\end{aligned}
\tag{8}
$$

More details of this technique can be seen in [24, 154].

6.2. New and Modified Modulation Schemes. Conventional modulation schemes have been reviewed earlier in literature [37, 38]. It is a need of the hour that the new and modified schemes and their benefits may be discussed. Table 2 gives a summary of various conventional and modified modulation and control schemes. Here, we are going to discuss the latest modifications in the modulation schemes and their benefits.

In order to reduce the switching losses of the MC, Takeshita and Andou in [53, 138, 151] and Sayed and Iqbal in [54] use a novel technique, in which the output voltage is synthesized by riding on two nearest phases. The number of commutations reduces from six to three for 3×3 MC and from 10 to 5 for 3×5 MC. However, as the results suggest, this comes at a cost of deteriorated input current.

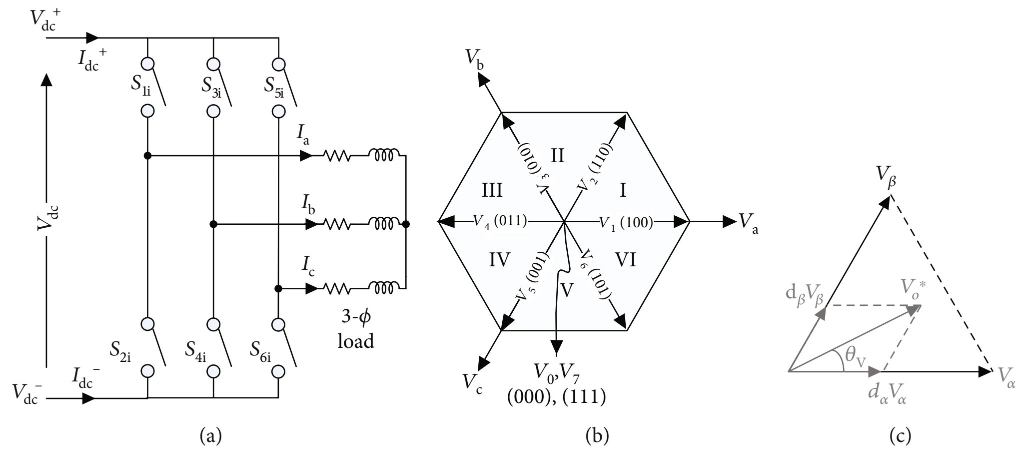


FIGURE 18: (a) The inversion stage. (b) Inversion voltage hexagon. (c) Calculation of dwell durations (for arbitrary m_v).

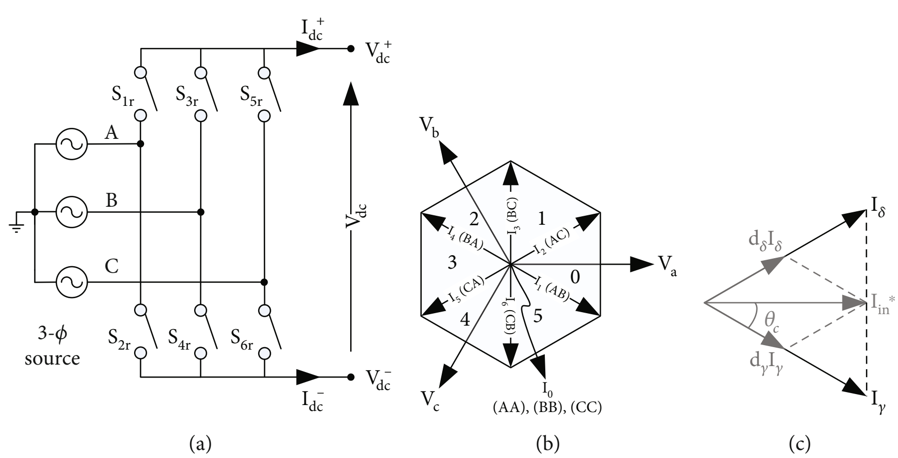


FIGURE 19: (a) The rectification stage. (b) Rectification current hexagon. (c) Calculation of dwell durations (for $m_c = 1$).

Li et al. in [155] present a modulation scheme where the DMC can operate in overmodulation zone. However, this leads to the deterioration in the output voltage of the MC. Space vector modulation is the most common method of VSI and MC modulation. In [139], the authors proposed a new SVM based on rotating vectors. Normally, if rotating vectors are chosen, the maximum output will be 0.5 of the input voltage (VTR = 0.5). However, in this work, the authors have proposed a novel SVM technique using the same rotating vectors, but the VTR increases to 0.833, which is comparable to the conventional 0.866 for 3×3 MC.

Another novel modulation scheme based on modified duty ratios is presented in [135]. A load information-based modulation algorithm is proposed for 3×5 MC to achieve a maximum input reactive power capability, and its benefits are illustrated visually through a 2D modulation graph. This work mainly presents the input power angle control through graphical means and claims its superiority over other conventional schemes. However, it does not mention any behavioural merits of their scheme over them.

Ichiki in [152] proposes a new modulation scheme in which he views the DMC as three inverters that operate in the same order but with different usage rates. This modulation scheme compares the control signal with the carrier. This scheme was verified for applications like elevator motor drives and air-conditioning systems. However, the major drawback is that it requires a zero-cross signal of the input voltage, which is a difficult task, especially if there is an unbalance on the input side. On the other hand, Li et al. in [155] discuss the overmodulation scheme when the supply is unbalanced, by utilizing more area in the voltage state space. However, this control strategy is complex and will take more computational time to execute. Last, but not least, Wang et al. in [156] have proposed a modulation scheme applicable to $3 \times N$ DMC. This is a modification of an indirect SVM scheme discussed in [24]. A phase-shifted carrier modulation strategy is applied to the virtual rectifier, and a modified carrier-based double-signal pulse width modulation strategy is applied to the virtual NPC inverter. By this, reduced switching losses and controllable input power factors are achieved. However, this scheme leads to a deterioration in the input side performance of the DMC.

U-1000 Industrial Matrix Drive
(5-800 HP, 0-400 Hz)
2016 *Engineers' Choice Award*

Z1000U Matrix Drive
(7.5-350 HP, 0-400 Hz)

AC7 Matrix Drive
(7.5-125 HP, 0-400 Hz)

Figure 20: Various matrix converter drives offered by Yaskawa Inc. (courtesy: Yaskawa Inc.).

7. Applications of Matrix Converters in the Industry

Matrix converters and their variants are being widely explored for many industry applications. Various Yaskawa made industrial drives are presented in Figure 20. Table 3 and Figure 21(a) accumulate recent applications where MCs are employed. Manufacturers like ABB believe that the MC technology is attractive, but it requires more research before it can be fully explored for industrial applications. Yaskawa is one of the manufacturers that make two DMC-based industrial drives named as U1000 [35] and AC7 [34]. U1000 is designed for higher power ratings and can perform with heavy-duty loads than AC7. Typical applications and the features of the U1000 are shown in Figure 21(b). The possible applications for which the drive is designed are escalators, winders, and conveyors. Further, the regenerative capability of the MC can be effectively used to supply local loads, as shown in the figure.

Matrix converters are very convenient to be used in less space zones, like aircraft. MC has been considered for aircraft applications, as shown in [162, 163]. The power supply generated by the engine-connected airplane generator can be very conveniently converted to 115 V, 400 Hz supply through an MC, as shown in Figure 21(d).

One of the recent applications of the MC is in the microturbine generators [7], where the 1×1 modular MC is used to connect single outputs of the generator to the load. In this configuration, the heterodyne method (more common in communication systems) controls the MC. Another application was found in the centrifugal pumps, where the drive was retrofitted by using an AC7 DMC drive for Chief Ethanol Fuels Inc. (Figure 21(e)). The online report suggests that the company was very satisfied with the performance features of the drive [164].

7.1. Wind Energy Integration. The best place for an MC to be utilized is the wind energy generator coupled with a turbine, either in the slip power zone in the doubly fed induction generator (DFIG) or the main lines of the wound-rotor generators. As seen in Figure 21(c), the wind turbine's intermittently rotating shaft rotates the generator, which is connected to the grid through a DMC. An MC was designed for a large-scale wind turbine in [161]. Another popular configuration is the DFIG, in which the DMC or IMC can be employed with low (slip) power ratings in the rotor path. One configuration with an IMC is shown in [10]. DMC is also used uniquely, where DMC is used in modular form in conjunction with the current source inverter for the WEGS [160].

7.2. Microgrid Application. Distributed generation units of the microgrid can be connected to a load of variable frequency requirements through a DMC or an IMC. The capability to incorporate as many legs at the input and output sides has made some unusual solutions that will lead to a small solution compared to the conventional solutions. An unusual proposal is discussed in [9], where a 6×3 DMC connects two 3-phase DGs to a single 3-phase load. The converters are controlled through a central control strategy, effectively delivering controlled active power to the load.

7.3. Electric Vehicle Wireless Charging. Recently, two topologies of MC were used for wireless power transfer (WPT) (or inductive power transfer (IPT)) for EV charging. The first one is proposed by Jafari and Sarwat in [8], where 1×1 MC is used for bidirectional power flow. Energy is injected during active states to the IPT compensation tank to increase the IPT's resonant current. The FPGA-based controller is used to facilitate single-stage AC-AC conversion and integration with the primary grid without an intermediate DC link. Another scheme is discussed in [157], where 1×3 MC drives the three-phase permanent magnet synchronous motor (PMSM) drive. A 1 kW, 85 kHz laboratory prototype is developed to verify the effective working of the proposed system.

7.4. Flywheel-Based Energy Storage. 3×3 DMC has been designed and analyzed in [158], and a case study is presented in [11], where it is claimed that the matrix converter complements the flywheel-based storage system due to its natural regeneration property. Therefore, a PMSM compatible with the matrix converter voltage levels was designed and optimized to perform as a dynamic voltage restorer (DVR).

7.5. Unified Power Flow Controller. As MCs allow direct AC-AC conversion without DC storage, line active and reactive power, together with AC supply reactive power, are directly controlled by selecting appropriate matrix converter states

Table 3: Recent industry applications of matrix converters and their description.

S. no.	Applications	Type of MC	Ref.	Description
1.	Microturbine generator	1×3 DMC	[7]	A control method for an MC based on the communication's heterodyne concept is applied to convert the high frequency of a microturbine generator's (MTG) output voltage to the utility grid's frequency.
2.	Electric vehicle	1×1 DMC	[8]	The low-cost self-tuned, simple, and fast FPGA-based IPT power controller is designed and applied on single-stage AC-AC matrix converter to allows direct connection to the main grid eliminating DC conversion.
		1×3 DMC	[157]	A wireless power transfer permanent-magnet synchronous motor drive system based on MC is proposed. The direct conversion of low-frequency AC and high-frequency AC is realized.
3.	Microgrid	6×3 DMC	[9]	A 6×3 MC is used to control the active power of two DGs feeding a load. Instead of using two converters, successful modulation of a single 6×3 DMC is performed to create a microgrid of two DGs.
4.	Energy storage	3×3 DMC	[158]	Analysis of a flywheel energy storage system used as a dynamic voltage restorer along with the DMC and a PMSM drive.
5.	Unified power flow controllers	3×3 DMC	[159]	Direct power control (DPC) for 3×3 DMC operating as unified power flow controllers (UPFCs). Active and reactive power, with AC supply reactive power, can be directly controlled by selecting an appropriate DMC switching state guaranteeing good steady-state and dynamic responses.
6.	Wind energy application	3×1 DMC	[160]	The DMC is employed to connect the wind-powered generator and the HFT enabling it to work without the use of filter capacitors on the generator side, and enable more compact size.
		3×3 DMC	[161]	DMC fed through a PMSG is used for large wind turbines. This is the only medium voltage DMC applied for power generation.
		3×3 IMC	[10]	The wind-driven DFIG is controlled for its active and reactive power, and grid synchronization by using an IMC in the slip frequency zone of the machine (rotor side).
7.	More electric aircraft	3×3 DMC	[162, 163]	Three methods are proposed to avoid the power flow back to the aircraft power supply through a 3×3 DMC in the regenerative mode. The methods are validated experimentally.
8.	Centrifuge operation	3×3 DMC	[164]	A Yaskawa AC7 drive based on 3×3 DMC was employed to retrofit an existing centrifugal pump.
9.	PMSM drives	3×3 DMC	[142, 165]	Research on PMSM drives along with DMC is performed under fault conditions and CMV minimization, thereby increasing the reliability of the overall system.
10.	Induction machine drives	3×3 IMC	[90]	An open-ended machine is controlled by two Z-sourced IMCs. The system can produce voltages with double gain, making it an interesting configuration for high-voltage applications.
		3×3 DMC	[29]	MPC is employed of a DMC-fed IM drive. The main achievement is that the CMV reduces to zero.
		3×5 DMC	[88, 143]	DTC with the constant switching frequency and FOC are, respectively, performed on a 3×5 DMC-fed IM drive.
11.	SRM drives	3×5 DMC	[134, 166, 167]	Commendable performance of the five-phase SRM drives driven by DMC are simulated and experimentally validated under fault conditions on one phase.

resulting in good steady-state and dynamic responses. This work is presented in [159].

7.6. General Purpose Drives. Drives have a myriad of applications, from EVs to fans and pumps. Recent literature suggests that extensive work has been done in the field of motor drive systems to make the MC a reliable and operational topology. PMSM drives employing 3×3 DMC are explored extensively in the recent literature. In [165], Dan et al. have improved the PMSM drive operation by

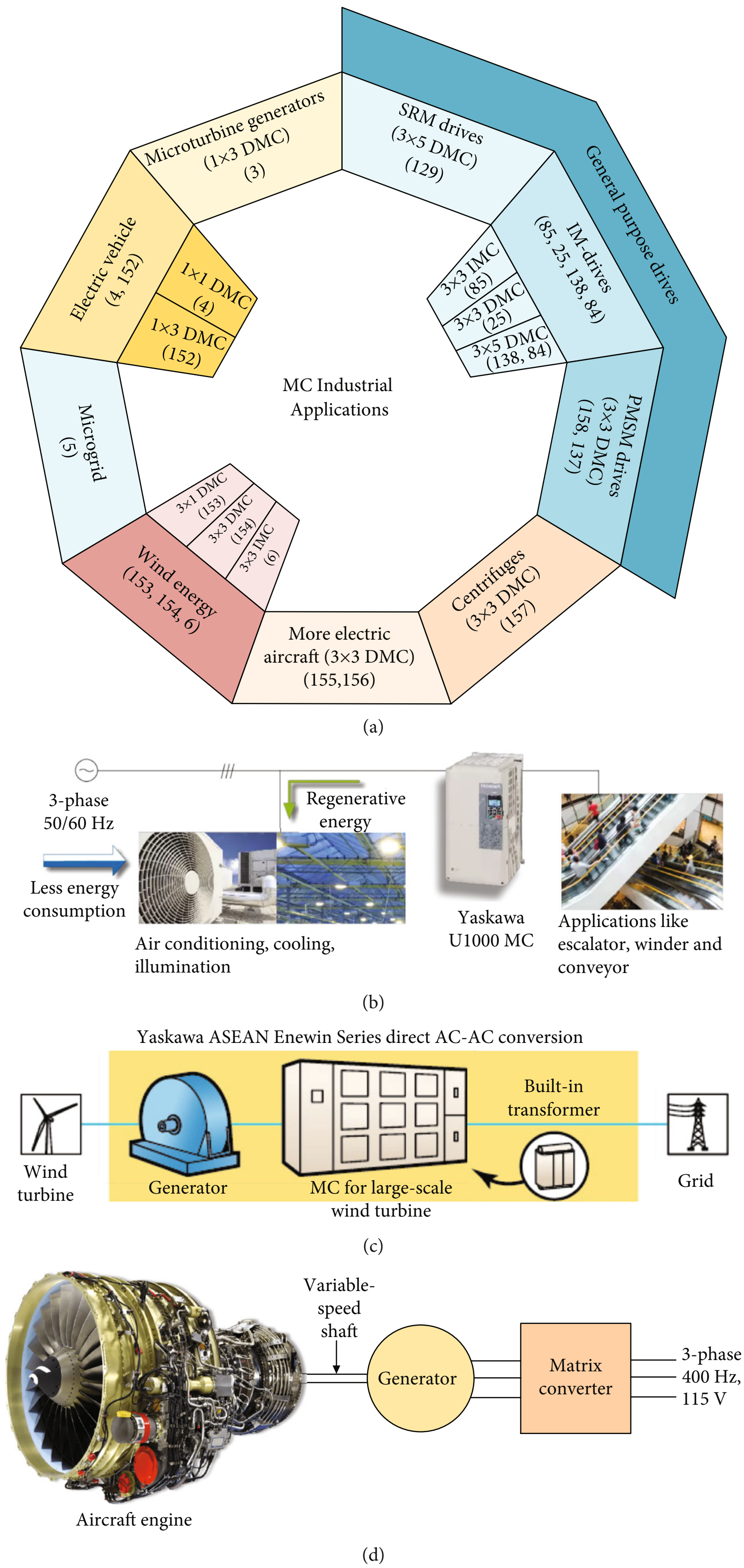
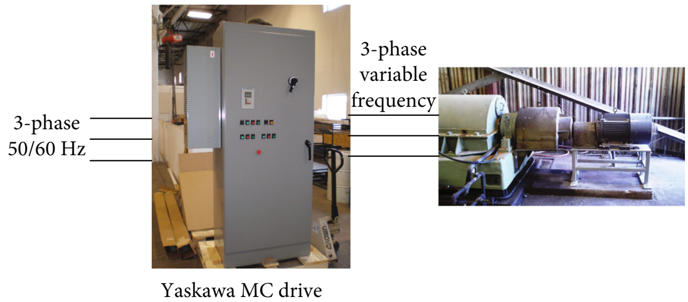


Figure 21: Continued.



(e)

Figure 21: Recent industrial applications of the matrix converters: (a) a general chart encompassing all the applications, (b) general applications of U1000 Yaskawa MC drive (courtesy: Yaskawa Inc.), (c) wind energy to grid integration, (d) application in airplanes, and (e) application in centrifuge retrofit.

proposing a reliable fault diagnosis and identification scheme. The error voltage of the switch is applied to locate the faulty switch. In [157], a PMSM is driven by a WPT-DMC system applicable for EV motor electric drive train. Further works can be seen in [142, 146]. In [142] common mode voltage is minimized by introducing a new direct torque control strategy, while in [146], predictive torque control of PMSM is performed.

Induction machine drives using IMC and DMC are also being explored constantly. In [90], a qZ-source IMC is applied to an open-ended induction machine. This boosts the output and reduces the CMV. In [168], a 3×3 DMC is used to drive a 6-phase machine for its speed control. According to Mir et al. in [29], finite-state MPC is employed to control the DMC-fed induction machine, which facilitates its sensorless control. In this method, the CMV successfully reduces to zero. Multiphase DMC is discussed in [88, 143] feeding 5-phase loads.

8. Conclusion and Discussion

Matrix converters have shown continuous development in topological advancements and control structures. A comprehensive review of the state-of-the-art MC technology and its prospects, targeting the researchers and engineers working in various domains of AC-AC power conversion applications, was presented. It has been established that the technology has moved beyond the drive systems and has ventured into new domains like renewable energy systems, energy storage, and microgrids. Furthermore, industry engineers have also considered retrofitting existing drive systems with this technology. This review has presented the advancements in the topological structures of direct/indirect MCs and their modulation and control algorithms in the past decade. It also reported the recent progress in structures and control of multiphase matrix converters.

Throughout the MC journey, the issues that made the engineers and researchers reluctant to choose them over the established BTB AC-AC conversion have been resolved amicably. One of the practical issues was the proper commutation between the AC switches. This was solved by four-step commutation and the clamp circuit. The input currents were made sinusoidal by employing the input side LC filters. However, these filters increased the input side reactive power in high-frequency applications like more electric aircraft. Another major issue was that of lower VTR. This was enhanced a bit by overmodulation techniques and the addition of impedance-sourced structures.

New modulation schemes have been proposed that have enhanced the performance of the MCs in terms of better output voltage and lesser commutation. The THD of the currents of the MCs has improved, along with fewer commutation losses with modulation schemes like MVD. Improved SVM schemes have been proposed to reduce or eliminate the CMV. Further, the motor control schemes have advanced by using modified predictive and torque control techniques. On the structural level, the MC structures have moved in both directions. The research has been performed using modular multilevel structures in the MCs. But as the number of switching devices increases by multifold, the control becomes complex. However, with modularity, the engineers will be happy to implement these structures in high-power applications. On the other hand, multiphase matrix converters are being explored extensively for drives and wind energy-based systems. This allows lower currents per phase, and lower rating switches are thus required. SVM methods are complex due to a large number of vectors; hence, simplified modulation schemes are now provided with controllable input power factor, which solves this problem. The most desirable feature of all the MC topologies is their frequency regulation, which has made the researchers implement it in a myriad of applications like wind energy applications, drives, and EVs. Recently, its implementation was considered for microgrids. Industrial applications have encouraged major players in the industry to involve in this field. Although Yaskawa is still the major player, other companies like Fuji have also shown interest.

As the MC technology has matured and is being employed for multiple industry applications, especially in the modern grid connections dominated by renewables and energy storage systems, there is a dire need to address more challenges. In wind energy and solar PV farms, for optimum power flow control, the data of the coupling points are constantly monitored, and the generation through these farms and individual generators has to be manipulated, which creates a need for constant communication between the equipment and the central controller. Thus, the online control of the power electronic controllers through communication channels makes these sophisticated systems prone to cyberattacks. This creates avenues for MC technology research in multiple directions. Firstly, it will be a need of the hour to convert the MC technology into *smart matrix converter* technology, where the active and reactive power generation can be efficaciously controlled, as demanded by the central controller. Second, tedious research will be required in the direction of cybersecurity attack detection and mitigation to make the operation of the individual generating component and the overall microgrid reliable and resilient. Third, in the world of digitalization, with the advent of new artificial intelligence techniques, heuristic optimization can be applied to predict future fault events and attenuate the cause leading to their occurrence. Lastly, with advanced machine learning tools like artificial, convolutional, and recurrent neural networks designed with feedforward learning or reinforced learning methods, efficient and environment-adaptable controllers can be designed for modern power systems' robust and resilient operations.

Data Availability

The research data supporting this review paper are from previously reported studies, which have been clearly cited.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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