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Background

1.1 Power Electronics Converter Topologies and Applications in Modern Power Systems

1.1.1 Introduction

In modern society, electrical energy is the most convenient and widely available form of energy, making it the most crucial energy source. However, in recent years, with rapid economic development, global electricity consumption has surged, leading to prominent issues of energy scarcity and environmental pollution. On one hand, electrical energy cannot meet the demands of industrial production and people's daily lives. On the other hand, extensive reliance on traditional fossil fuels for electricity generation has caused severe environmental problems and inefficient utilization of electrical energy [1].

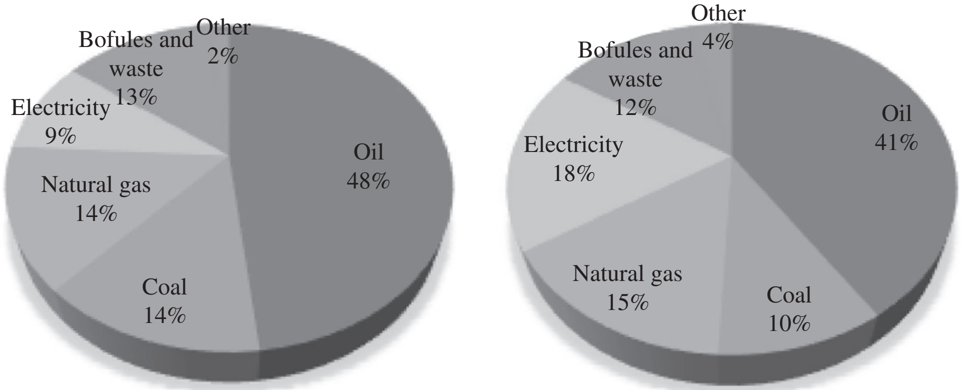
According to statistics from the International Energy Agency in 2014, from 1973 to 2012, the proportion of coal and oil in global terminal energy consumption decreased by 3.6% and 7.5%, respectively. In contrast, the share of electricity consumption increased from 9.4% to 18.1%, ranking second only to oil, as shown in Figure 1.1. It is projected that by 2030, electricity will constitute 25% of global terminal energy consumption, and by 2050, this share is expected to surpass 50%, as depicted in Figure 1.2 [2–5].

Power electronics technology, serving as the vital link for energy conversion and a necessary means to address environmental pollution in the context of new energy sources, has permeated various aspects of electrical applications. This includes applications in power systems, industry, transportation, aerospace, information technology, and telecommunications, as depicted in Figure 1.3 [6]. It has directly or indirectly generated significant economic and societal benefits. In the future, approximately 90% of electrical energy will need to be processed through power electronics technology to enhance energy efficiency and production efficiency, thereby maximizing the utilization of renewable energy sources [7].

AC variable frequency drive technology is a significant application of power electronics in energy-efficient and high-capacity AC transmission control systems. Within this technology, AC converters play a crucial role as integral components of AC speed control systems. Currently, AC converters are extensively employed in high-power AC motor drive systems and power systems [8]. The classification of converters can be seen in Figure 1.4 [9].

The frequency converter, known as a thyristor-based AC/AC converter circuit, directly converts AC power of a certain frequency into adjustable-frequency AC power. As it lacks a direct current (DC) stage, it falls into the category of direct-frequency conversion circuits. However, this type

Impedance Source Matrix Converters and Control, First Edition.
Yushan Liu, Xiao Li, Baoming Ge, Haitham Abu-Rub, and Frede Blaabjerg.



(a) (b)

Figure 1.1 (a) Comparison of energy consumption structure between 1973 and 2012; (b) Global terminal energy consumption structure from 2010 to 2050.

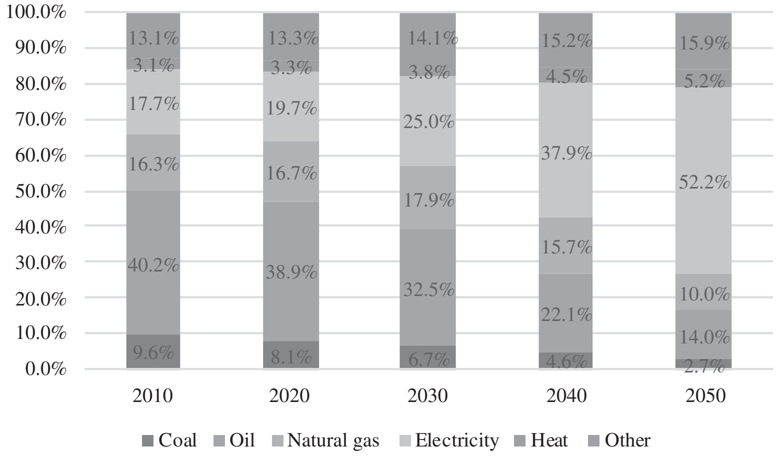


Figure 1.2 Global terminal energy consumption structure from 2010 to 2050.

of converter has notable drawbacks, with its output upper-frequency limit not exceeding 1/3 to 1/2 of the grid frequency. For single-phase AC circuits, two sets of converters are needed, while three-phase circuits require six sets, resulting in numerous components and highly complex control systems.

AC/DC/AC converter is presently one of the most widely used AC/AC frequency conversion circuits. This converter first rectifies AC power into DC power and then inverts DC power back into AC power. Due to the presence of a DC stage, this circuit falls under the category of indirect-frequency conversion circuits. Depending on whether the intermediate DC stage is composed of capacitors or inductors, it can be classified into voltage-source indirect AC/DC/AC converters and current-source indirect AC/DC/AC converters [8]. Among them, the voltage-source AC/DC/AC converter can be further divided into non-controlled rectifier + inverter (Figure 1.5a), which lacks boosting capability and generates high-input current harmonics, resulting in severe grid pollution. The controlled rectifier + inverter (Figure 1.5b) utilizes a boosting rectifier at the input stage, requiring the addition of an inductor. To mitigate harmonic pollution to the grid,

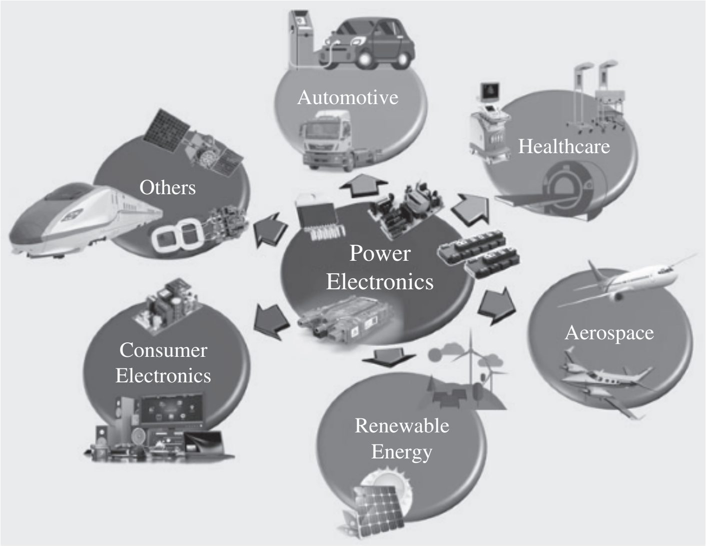


Figure 1.3 Application fields of power electronics [6].

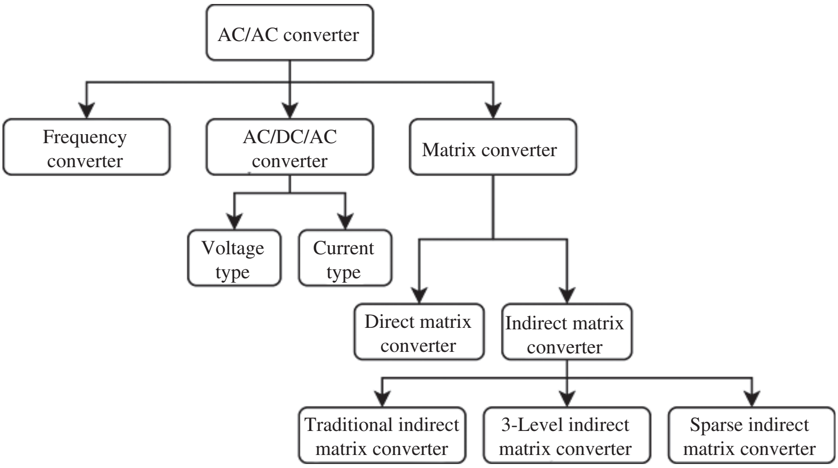


Figure 1.4 AC frequency converter classification.

inductor–capacitor (LC) or inductor–capacitor–inductor (LCL) filters need to be designed at the input stage. The primary drawback of both types of converters lies in the intermediate energy storage components, which not only have large volume and high mass but are also challenging to maintain, leading to lower power density in power converters.

The current-source AC/DC/AC converter Figure 1.6 introduces challenges related to the need for large-capacity flat-wave reactors and issues like current distortion and oscillations caused by AC-side LC filter. In comparison to voltage-source converters, it is more costly and complex to control, thereby limiting its application and research. However, with the advancement of superconducting technology, the current-source converter has found successful applications in superconducting energy storage. Furthermore, it has garnered significant attention in medium-voltage high-power wind power generation and motor drive applications [10, 11].

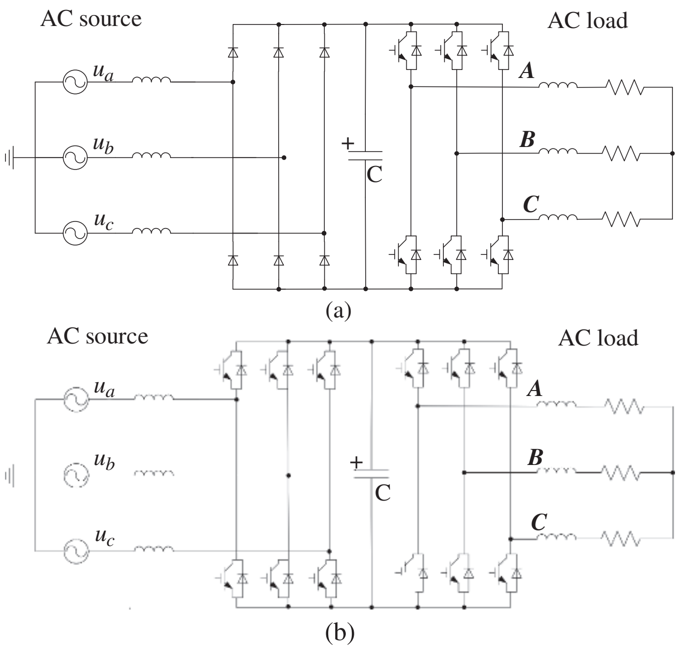


Figure 1.5 AC/DC/AC voltage-source converter (a) uncontrolled rectifier with inverter, (b) controlled rectifier with inverter.

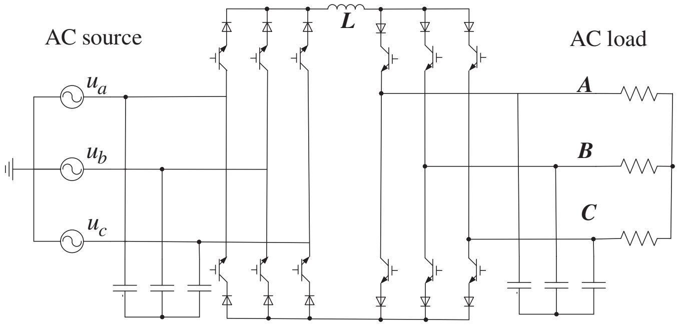


Figure 1.6 AC/DC/AC current-source converter.

To overcome the drawbacks associated with converters featuring intermediate energy storage components and to enhance the power density and reliability of AC/AC converters, researchers began to explore the possibility of AC/AC converters without the use of DC energy storage elements. It was at this juncture that matrix converter (MC) emerged. MC is an electrical conversion device based on bidirectional switches and utilizes pulse-width modulation to generate the desired output voltage. Among various novel AC power converters, MC has gained significant attention from researchers worldwide due to its simple structure and full silicon integration, among other excellent performance attributes [9]. Depending on their structural characteristics, MCs can be classified into two categories: direct matrix converters (DMCs) and indirect matrix converters (IMCs). IMCs not only inherit the advantageous features of DMC but also possess the advantage of zero-current switching at the rectifier stage, significantly reducing control complexity, making them one of the most promising types of AC power converters. IMCs have further led to the development of three-level MCs and generalized sparse IMCs.

1.1.2 Matrix Converter

MCs have been in development for over 40 years, and substantial progress has been made in key areas such as topology design, modulation strategies, control theory, and device development [12–14].

1.1.2.1 Direct Matrix Converter

The concept of DMCs and bidirectional switches was first proposed by Gugi and Pelly [15]. In 1980, Venturini and Alesina introduced the idea of using transistors to construct bidirectional switches for implementing MCs. They developed a prototype based on this concept and presented a series of attractive results. The topology of a DMC is shown in Figure 1.7. This topology employs nine bidirectional switches to interconnect each input phase with every output phase, allowing for the synthesis of the desired output and input currents through a single-stage transformation. Since each bidirectional switch consists of two antiparallel insulated gate bipolar transistors (IGBTs), a DMC requires a total of 18 IGBT power devices [16].

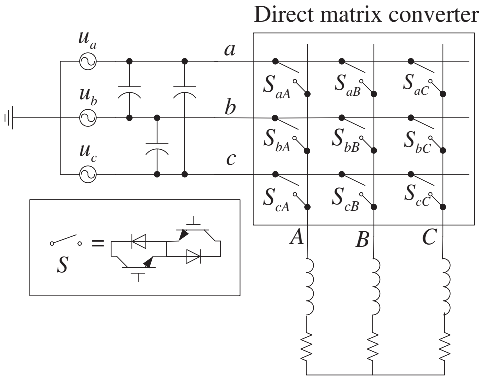
The advantages of a DMC include: (i) bidirectional energy flow, achieving four-quadrant operation; (ii) both input and output currents are sinusoidal; (iii) power factor at the input side can be unity for any load; and (iv) no need for a DC energy storage stage, resulting in a compact circuit structure and high integration level [17].

Despite over 40 years of development, MC technology still faces challenges preventing widespread industrial adoption [18]. These challenges include: (i) maximum boost ratio limited to 0.866; (ii) a relatively high number of power devices, leading to complex commutation control; (iii) difficulty in control under abnormal grid voltage conditions due to the absence of an intermediate DC stage, impacting system performance; (iv) interference on the load side directly affects input-side performance, leading to suboptimal electromagnetic compatibility with the grid; and (v) complex protection circuits, large physical footprint, and higher cost.

1.1.2.2 Indirect Matrix Converter

In pursuit of simplifying the structure of DMCs, reducing the count of power switching components, minimizing system energy losses, and alleviating control intricacies, scholars have introduced a category of IMCs, as depicted in Figure 1.8. In this topology, the input-side rectification employs bidirectional switches, while the inversion stage relies on unidirectional switches,

Figure 1.7 DMC circuit diagram.



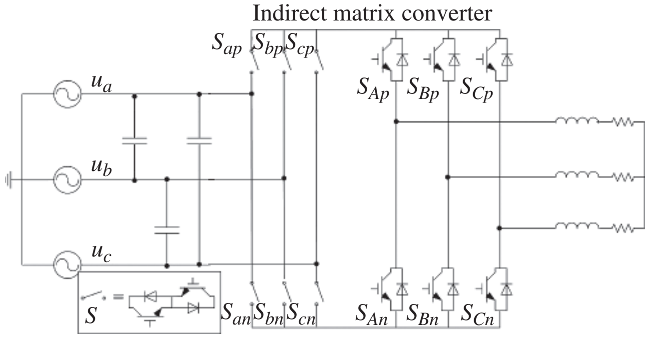


Figure 1.8 IMC.

necessitating a total of 18 IGBT power devices. The initial conceptualization of this topology was attributed to Wei at University of Wisconsin-Madison [19], USA. Subsequently, researchers, led by Kolar at wiss Federal Institute of Technology in Zurich, expanded and refined this concept, introducing various topological variants such as sparse matrix converters (SMCs), very sparse matrix converters (VSMCs), and ultra sparse matrix converters (USMCs) [20, 21], as illustrated in Figure 1.9. A comprehensive analysis of modulation techniques, commutation strategies, voltage transfer ratios, and switch losses for multiple MCs can be found in Table 1.1, as extensively discussed in [22].

IMCs have the potential to overcome the shortcomings of traditional AC-DC-AC PWM inverters and DMCs, making them a promising new category of AC-AC converters. Their advantages primarily manifest in the following ways: (i) they eliminate the need for large energy storage components like bulky inductors or capacitors in the intermediate DC stage; (ii) the rectifier stage switches can achieve zero-current commutation, simplifying the commutation control of the system; (iii) with an intermediate DC stage, mature PWM control methods can be separately applied to the rectifier and inverter stages, reducing control complexity; (iv) under certain constraints, they can reduce the number of switching devices; (v) by using the intermediate DC link as a common bus, they can facilitate multiple inverter outputs, supplying power to multiple AC motor loads [23–26].

In comparison to DMCs, IMCs offer more advantages. However, similar to DMCs, the limited system voltage gain is a significant hindrance to their industrialization.

1.1.2.3 Power Switches of MCs

The main circuit of a MC must employ bidirectional switches, also known as four-quadrant switches. To enable safe commutation and bidirectional power flow, these controllable switches can carry bidirectional current and block bidirectional voltage [27]. Since fully controllable bidirectional switch devices are not yet commercially available, the bidirectional switches used in MCs must be constructed from combinations of unidirectional switches. There are four common structures for bidirectional switches [12, 28, 29], as depicted in Figure 1.10.

Figure 1.10a,b shows antiparallel bidirectional switches with common emitter and common collector configurations, respectively. These bidirectional switches can be composed using two IGBTs (or MOSFETs) with internally integrated antiparallel diodes. These two antiparallel configurations possess the soft-switching capability and are commonly employed. By implementing a four-step commutation strategy [29], these bidirectional switches can control the switching sequence effectively, preventing input short circuits and providing a conduction path for inductive loads, thus avoiding voltage spikes. Each of these bidirectional switch configurations has distinct

Figure 1.9 Other IMC circuit diagrams: (a) SMC; (b) VSMC; (c) USMC.

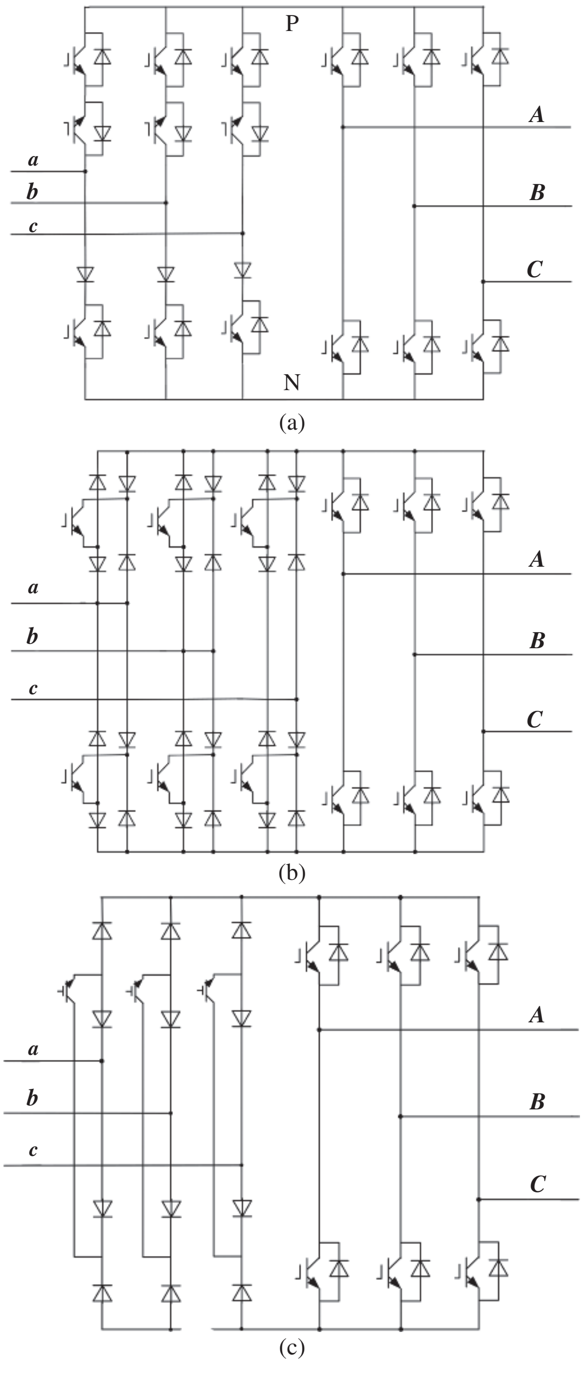


Table 1.1 Topologies comparison of MCs.

Topology	No. of switches	No. of diodes	Minimum No. of isolated drive power supplies
DMC	18	18	6
IMC	18	18	8
SMC	15	18	7
VSMC	12	30	10
USMC	9	18	7

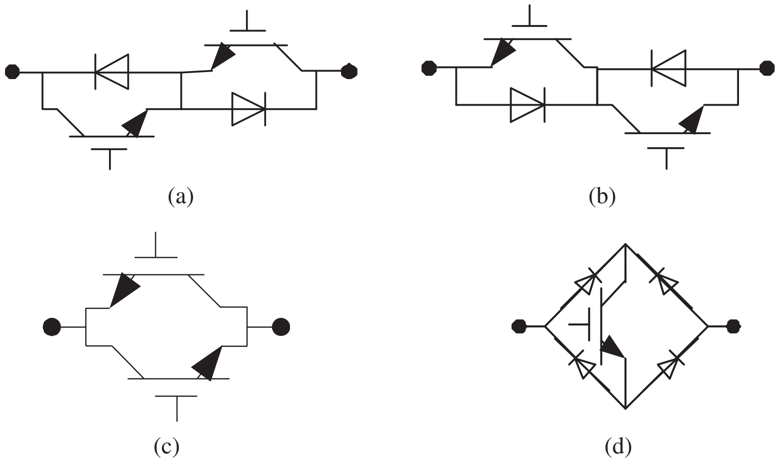

(a) (b) (c) (d)

Figure 1.10 Different bi-directional switch configuration of MCs, (a) Common emitter IGBT, (b) Common collector IGBT, (c) RB-IGBT, (d) Diode bridge switch cell.

Table 1.2 Characteristics of bi-direction configurations.

	Common emitter	Common collector
Isolated power supply of gate drive circuitry	9	6
Detect all IGBT terminals	Yes	Cannot detect collector
Advantages	Overcurrent protection and reliable drive can be achieved by monitoring the collector–emitter voltage	Input and output voltage and current transformers can be powered by gate drive circuitry

characteristics in their main circuit operation [12]. Table 1.2 provides a simple comparison of these two structural configurations.

Figure 1.10c represents antiparallel bidirectional switches featuring Reverse Blocking IGBT (RB-IGBT) [30–32]. Compared to other bidirectional switches, RB-IGBTs exhibit symmetric voltage blocking capability, low switch conduction loss, high power density, and reduced switch device size, enhancing overall system efficiency. However, their driver circuit design is intricate, and they suffer from relatively high switching losses [33], which has limited their current usage.

The bidirectional switches shown in Figure 1.10d consist of a bridge circuit composed of diodes and IGBTs. This configuration offers the lowest cost and does not encounter the four-step commutation issue. Its driver circuitry is relatively simple. However, it has the drawback of higher conduction losses due to the presence of two diodes and one IGBT in the conduction path, resulting in increased conduction losses.

1.1.2.4 Research Status of MCs

Based on the relevant literatures, researchers all over the world have primarily focused their efforts on various aspects of MCs:

1) Research on Novel Circuit Topologies:
   To simplify MC structures and reduce control complexity, researchers have proposed several derivative topologies, including: (i) single-switch-based matrix AC/AC converters [34]; (ii) SMC series, such as SMC, VSMC, and USMC, which vary based on the number of single-phase switches used in IMCs [25, 35]; and (iii) three-phase four-wire MCs designed for unbalanced loads [36].
2) Introduction of Innovative Modulation Methods:
   To improve output waveform quality and reduce input-side harmonic content, researchers have introduced a series of novel modulation methods, including: (i) phase voltage-phase voltage direct transformation switching function modulation algorithms [37]; (ii) dual-space vector modulation (SVM) algorithms based on input line voltage–output line voltage direct transformation [26, 38]; (iii) dual-line voltage modulation algorithms [39, 40]; and (iv) output current hysteresis current modulation methods aimed at tracking output circuit currents [41, 42].
3) Research on Control Methods under Abnormal Operating Conditions:
   MCs lack a DC energy storage element, making the input-side disturbances directly affect the output side. In response, researchers have proposed methods such as using auxiliary diode clamp circuits to buffer energy storage capacitors [43] and improved modulation methods for unbalanced power supply conditions [44, 45].
4) Application of Advanced Control Algorithms:
   In recent years, scholars all over the world have explored the application of advanced control theories in MCs, including: (i) robust control for MC systems [46, 47]; (ii) sliding-mode control for MCs [48, 49]; and (iii) predictive control for MCs [50–53].
5) Application Research on New Power Electronic Devices:
   To further reduce converter switching loss, numerous companies in Europe, the United States, Japan, and elsewhere have developed Reverse Blocking IGBTs (RB-IGBTs). The systems built using these devices have effectively reduced overall system losses [54–56]. Additionally, the emergence of power electronic switching devices based on new materials like SiC and GaN has significantly increased switching frequencies, and lowered the system losses [57, 58].
6) Developed Prototypes:
   As power electronic devices become more integrated and MC technology matures, researchers worldwide have developed a variety of prototypes [53]: (i) Siemens in Germany introduced an MC solution for industrial drives in 2001 [23]. (ii) Aalborg University in Denmark developed a 4 kW MC for driving asynchronous motor speed control systems in 2002 [59]. (iii) Fuji Electric in Japan created an RB-IGBT module in 2003, using it to build a 22 kW MC prototype in 2004 [60]. (iv) In collaboration with the military, University of Nottingham in the UK released

a 150 kVA MC prototype for military vehicle transmission systems in 2004 [61]. (v) In 2003, University of Nottingham in the UK developed a jet aircraft wing electrohydraulic control system based on an MC [62]. (vi) Several prototypes have emerged at various universities. These include the first domestic MC prototype built using discrete IGBTs by Chen and Lu at Shanghai University in 1998 [63], as well as a constant-frequency sampling current tracking control MC prototype developed by Tang and Fang at Fuzhou University in 1999 [64]. In 2000, Xiangtan University began researching AC/AC MCs and produced an experimental prototype [65]. In 2006, Huang and Sun at Tsinghua University developed a 3.6 kW MC prototype based on RB-IGBT modules [66]. In 2009, she at Huazhong University of Science and Technology developed a 5.5 kW prototype driving an induction motor using discrete IGBTs [67]. In 2010, Li and Mei at North China University of Technology developed an IMC prototype based on dual IGBT modules [68]. To date, researchers worldwide have publicly disclosed MC prototypes, as shown in Table 1.3.

Table 1.3 MC prototype research and development.

Year	Affiliation	Power	Power module	Application
1988	Westinghouse [28]	22 kW	Bridge Type	Induction Motor Drive
1995	Virginia Tech [69]	2 kW	Anti-parallel MOSFET	Algorithm Verification
1999	Shanghai University [63]	2 kW	Discrete IGBT	Algorithm Verification
2001	University of Bologna [70]	7 kW	IGBT Module	Induction Motor Drive
2002	Aalborg University [59]	4 kW	IGBT Module	IM Speed Regulation
2002	University of Nottingham [71]	10 kW	IGBT Module	Induction Motor Drive
2002	University of Nottingham [72]	30 kVA	IGBT Module	Ground level power supply
2002	University of Karlsruhe [23]	7.5 kW	IGBT Module	Algorithm Verification
2003	University of Nottingham [73]	20 kW	IGBT Module	Aircraft aileron control
2004	University of Nottingham [74]	10 kW	Discrete IGBT	Diesel engine generator power supply
2004	University of Sheffield [75]	0.7 kW	Anti-tandem MOSFET	PMSM Drive
2005	University of Nottingham [61]	150 kVA	Discrete IGBT	Electric chariots
2005	Aalborg University [76]	3 kW	IGBT Module	Induction Motor Drive
2005	University of Nottingham [77]	30 kVA	Discrete IGBT	IM Speed Regulation
2005	University of Bologna [78]	10 kW	IGBT Module	Induction Motor Drive
2005	Nagaoka University of Technology and Science [24]	22 kW	RB-IGBT Module	Induction Motor Drive
2006	Tsinghua University [66]	3.6 kW	RB-IGBT Module	Induction Motor Drive
2008	University of Stuttgart [79]	18 kW	Discrete IGBT	Induction Motor Drive
2009	Huazhong University of Science and Technology [67]	5.5 kW	Discrete IGBT	Induction Motor Drive
2010	North China University of Technology [68]	2.7 kVA	Two-in-one IGBT Module	Algorithm Verification

7) Research on Expanding the Gains of MC Systems:
   Given the characteristics of MCs, their most significant limitation is that the maximum voltage boost ratio is only 0.866. Many scholars are actively researching methods to improve this aspect. Current research focused on enhancing IMC gain primarily involves improving modulation strategies and adding auxiliary circuits. These approaches include overmodulation methods and combined modulation strategies [80–82]. While the gain improvement is not significant with overmodulation methods, the process is overly complex. On the other hand, adding auxiliary circuits to the intermediate DC bus, such as Boost circuits [83, 84], or Z-source/quasi-Z-source (ZS/QZS) circuits before and after MC, has been rapidly gaining attention in the field of voltage boost due to their structural symmetry and simplified control.

1.2 ZS/QZS Converters

ZS converter was introduced by Peng et al. in 2002 [85], as depicted in Figure 1.11a. By incorporating a ZS circuit between DC source and the inverter, it offers an alternative to traditional voltage-source and current-source inverters. ZS circuit consists of a diode *D*, two capacitors C_1 and C_2, and two inductors L_1 and L_2 interconnected. The distinguishing feature of ZS converter is its ability to achieve both voltage boost/buck and inversion in a single-stage power conversion, resulting in significant cost savings. Moreover, it permits a direct shoot through of the same bridge arm of the inverter, eliminating the need for a dead time, which greatly enhances the system's immunity to disturbances [86, 87].

In 2008, QZS, an improved topology of ZS converter, was proposed by Peng et al. [88], as shown in Figure 1.11b. This circuit possesses all the characteristics of ZS converter and offers the additional benefit of achieving continuous input current. Furthermore, the QZS network has a shared negative pole for input and output, which aids in suppressing electromagnetic interference (EMI). Due to the advantages of QZS network converter, various impedance network structures based on this architecture have been proposed, primarily aimed at maximizing voltage gain [89–91].

ZS/QZS converters were initially applied to DC/DC and DC/AC converters. Currently, ZS inverters (ZSIs) and QZS inverters (QZSIs) have garnered widespread research interest, especially in applications requiring voltage boosting, leading to significant breakthroughs. Based on available literature, scholars worldwide have primarily focused their research in the following directions:

1) Improvement of Topological Structures:
   Researchers have proposed enhanced ZS and QZS structures, such as extended ZS and QZS [89], switched-inductor-type ZSI structures [90], L–C coupled inductor-based current-fed ZSI

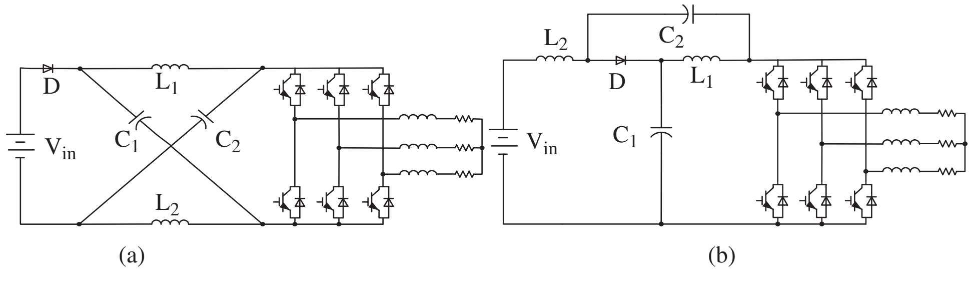


Figure 1.11 Classical topology of (a) ZSI; (b) QZSI.

(LCCT-ZSI) structures [92], and trans-ZS structures [93]. They have investigated the voltage boost ratios and characteristics of different structures.

2) Modulation Algorithm Research:
   This includes investigations into modulation techniques like sinusoidal pulse-width modulation (SPWM) [94, 95] and SVM [96, 97].
3) Model Establishment and Analysis:
   By developing state-space average models, scholars have created small-signal models for ZSI/QZSI [98–100], providing mathematical foundations for the study of converter dynamic responses and controller design.
4) Introduction of Advanced Control Algorithms:
   Building upon model analysis, scholars have designed corresponding controllers, including sliding-mode variable structure control [101, 102] and model predictive control [101, 103, 104].
5) Multi-Level Expansion:
   In the field of photovoltaic power generation systems, an extensive research is the ZS multi-level technology. This includes the development and study of cascaded multi-level inverters based on QZS and energy storage-type cascaded multi-level inverters [105–108].

1.3 Advantages of ZS/QZS MCs Compared to Existing Technology

The characteristics of MCs and ZS/QZS converters demonstrate that their integration can effectively enhance the performance of MCs. Currently, through the efforts of researchers, the combination of ZS/QZS with MCs has resulted in several topological structures, primarily including ZS/QZS placed before DMC, referred to as ZS/QZS-DMC converters, ZS/QZS circuits positioned on the DC side of IMCs, known as DC-ZS/QZS-IMC converters, and those located before or on grid side (GS) of IMCs, denoted as GS-ZS/QZS-IMC converters [109–111].

Introducing ZS and QZS networks in front of the DMC, as illustrated in Figure 1.12a,b, respectively, overcomes the issue of low-voltage gain in traditional DMC systems. Furthermore, the ZS network allows the subsequent bridge arms to operate in a direct shoot-through mode, simplifying the commutation process of DMC [109]. However, ZS-DMC exhibits discontinuous input current. On the other hand, QZS-DMC does not suffer from phase-shift issues, possesses a high system voltage gain, lower voltage and current stresses on the switches, and, through structural adjustments, ensures continuous input current, as depicted in Figure 1.12c.

The combination of ZS or QZS with IMC results in ZS/QZS-IMCs that effectively inherit the advantages of IMC. Additionally, by utilizing the voltage boost/buck capability and robustness of ZS/QZS converters, these hybrid systems can overcome the drawbacks of traditional IMC, such as low-voltage gain and poor disturbance rejection. ZS/QZS-IMCs with ZS/QZS networks introduced into IMC can be divided into two categories [110, 111]: the first category is DC-ZS/QZS-IMC, and the second category is GS-ZS/QZS-IMC, as illustrated in Figures 1.13 and 1.14.

1) DC-Link ZS/QZS-IMCs
   The first category of ZS/QZS-IMCs, represented by DC-ZS-IMC and DC-QZS-IMC, is depicted in Figure 1.13. Aside from the distinction in ZS and QZS networks, these two variants are functionally identical, possessing the characteristics of both ZS/QZS networks and IMCs. However, the incorporation of ZS/QZS circuits on the DC side of the IMC disrupts the all-silicon structure of traditional MCs, resulting in a bulkier system. The primary drawbacks of this topology include: (i) discontinuous input current; (ii) the need for additional LC filters on GS,

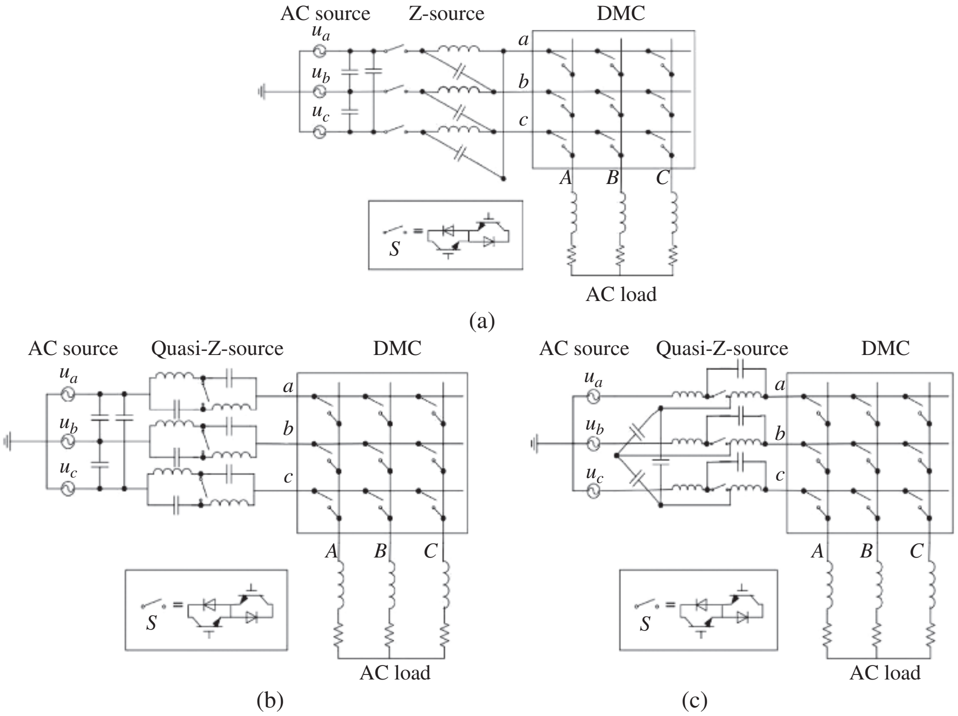


Figure 1.12 ZS/QZS-IMCs. (a) ZS DMC; (b) DCM-QZS DMC; (c) CCM-QZS DMC.

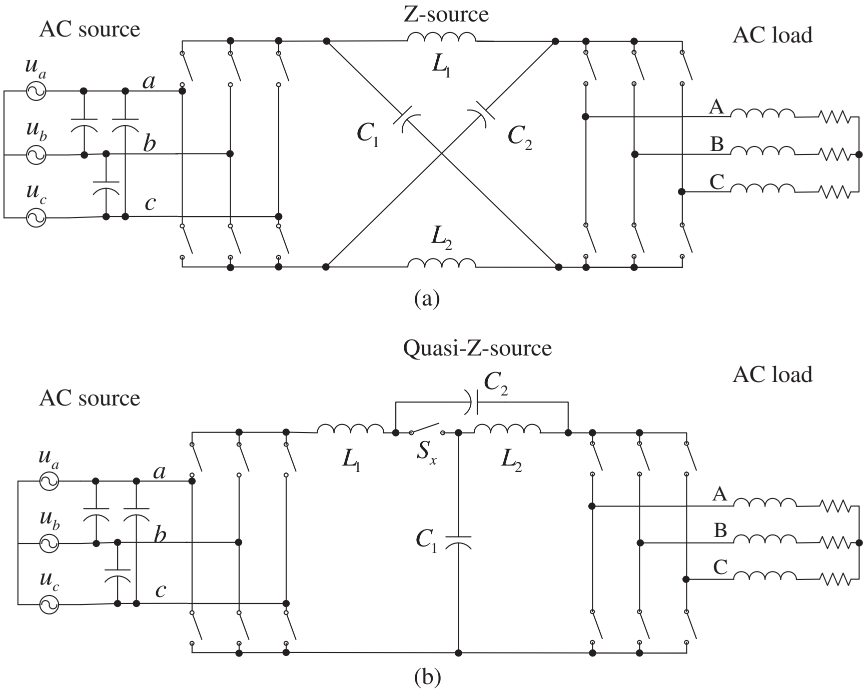
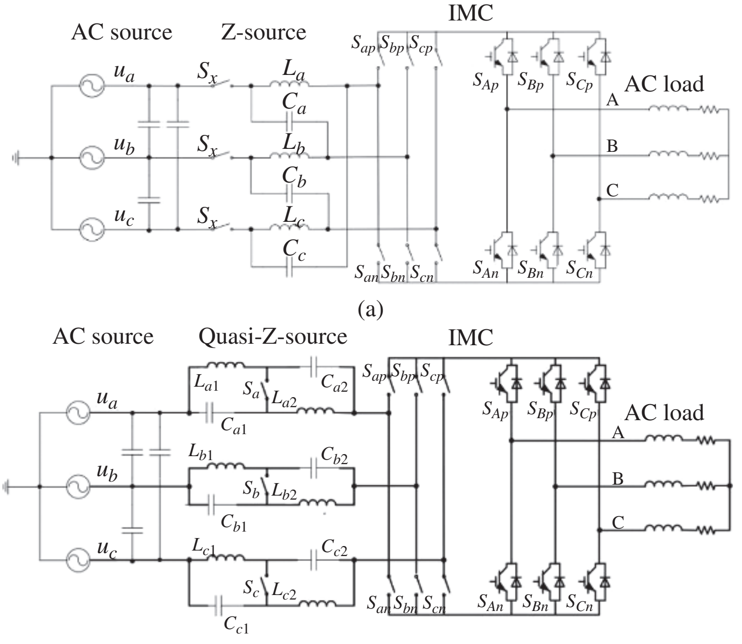


Figure 1.13 DC link ZS/QZS-IMC. (a) DC link ZS IMC; (b) DC link QZS-IMC.



(a)

(b)

Figure 1.14 GS ZS/QZS-IMC. (a) GS ZS IMC; (b) GS QZS-IMC.

leading to system complexity, higher cost, increased volume, and greater loss; (iii) the addition of ZS/QZS circuits on the high-voltage DC side leads to higher current (voltage) stress on the inductors (capacitors), contributing to increased system cost and loss [110].

2) GS ZS/QZS-IMCs
   The second category of ZS/QZS-IMCs involves placing ZS and QZS networks on the grid side of the IMC, resulting in GS-ZS-IMC and GS-QZS-IMC configurations, as shown in Figure 1.14. These topologies also retain the characteristics of both ZS/QZS networks and IMCs. By locating ZS and QZS networks on the grid side, the full silicon characteristics of the IMC remain intact, facilitating integrated system design. However, each of these two topologies has its own characteristics. For the GS-ZS-IMC, the phase-shifting nature of ZS network limits the maximum voltage boost ratio to 1.15, and the input current becomes discontinuous. In contrast, the GS-QZS-IMC topology achieves a high-voltage boost ratio. Nevertheless, both configurations require the addition of extra filters at ZS/Quasi-ZS front end, resulting in increased system volume, weight, and cost [111].

Considering the drawbacks of traditional MCs, which include: (i) the complexity arising from a large number of power switching devices; (ii) low-voltage gain, with the maximum output voltage amplitude reaching only 86.6% of the input voltage amplitude; (iii) vulnerability to abnormal input voltages due to the absence of an intermediate buffer circuit; (iv) the complexity of bidirectional switch commutation, necessitating real-time monitoring of input voltage and output current for complex system control; and (v) discontinuous input current, requiring additional filters on the input side.

Taking into account the advantages of ZS/QZS converters, ZS/QZS MCs studied in this book incorporate ZS/QZS networks into traditional DMCs or IMCs. These converters possess the following characteristics: (i) adjustable voltage boost and buck capabilities, allowing the system voltage gain to exceed 1, thus overcoming the deficiencies of traditional MCs; (ii) strong immunity to disturbances, featuring the ability to traverse through drops in grid voltage, a capability not presented in traditional MCs; and (iii) elimination of the need for four-step commutation, simplifying the commutation process and ensuring straightforward and reliable system control.

1.4 Current Status and Future Trends

Currently, the research on ZS/QZS MCs primarily focuses on the following areas: (i) derivation and analysis of system voltage gain, by analyzing the circuit's operational behavior and characteristics to derive the system gain and conducting comparative analyses among converters of the same kind; (ii) analysis of voltage and current stress on switching devices, considering the impact of the shoot-through ratio on device stress, in combination with the characteristics of ZS/QZS circuits; (iii) improvement of modulation techniques, particularly in the rectification and inversion stages of ZS/QZS-IMCs. Insertion of a direct-zero vector during inversion enhances the system's voltage gain [112]; (iv) stable control of output voltage, achieved by controlling the capacitor voltage in ZS/QZS circuits to obtain a stable output voltage, ensuring the system stability even under input voltage disturbances [113]; (v) reduction in the number of switching devices in ZS MCs, thereby reducing system complexity and enhancing reliability, such as reducing the number of switches in IMCs from 18 to 12 [114]; and (vi) application of ZS MCs to the motor speed control and wind power generation [115, 116].

Additionally, as previously mentioned, the QZS-IMC offers the advantage of high-voltage gain. However, as mentioned in section 1.3, GS-QZS-IMC exhibits discontinuous input current and requires additional filtering. Therefore, an integrated LC filter QZS-IMC was introduced in 2013 [117], as shown in Figure 1.15. This structure is based on the GS-QZS-IMC but integrates QZS network with an LC filter, simultaneously achieving voltage boosting and filtering functions.

The integrated LC filter QZS-IMC exhibits the following characteristics: (i) QZS network is integrated into the input side of IMC, combining it with LC filter. This integration imparts 1) filtering capability to the QZS circuit, eliminating the need for additional LC filters on the input side, significantly simplifying the hardware of the system; (ii) exceptional immunity to disturbances, with the ability to withstand drops in grid voltage, a feature not present in traditional MCs; (iii) overcoming the drawback of discontinuous current in traditional ZS MCs; (iv) with the adoption of an IMC, the system control is simplified due to the two-step commutation process; and (v) inheritance of

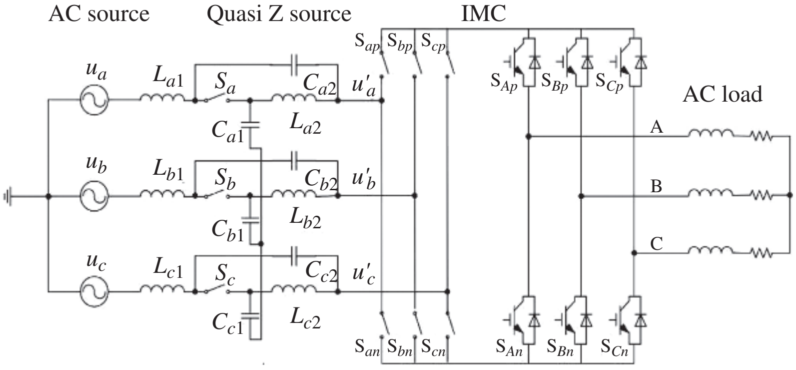


Figure 1.15 LC filter-Integrated QZS-IMC [117, 118, 121].

the full silicon characteristics of traditional MCs, resulting in a significant reduction in the size and weight of capacitors and inductors, leading to an improved efficiency [117, 118].

Given the numerous advantages of the integrated LC filter QZS-IMC, it has become a highly promising AC converter. Currently, researchers in the field are primarily focusing on the following aspects:

1) Analysis of the working principles and mathematical modeling of integrated LC filter QZS-IMCs.
   This includes inserting ZS/QZS circuits into the input side of IMC, analyzing the newly generated topology, mathematical modeling for small-signal analysis, non-minimum phase analysis, and filtering characteristics analysis [118, 119].
2) Research on modulation methods and common-mode voltage suppression methods for integrated LC filter QZS-IMCs.
   This includes the insertion of zero vectors during rectification, which significantly increases the system's switching frequency, analyzing the impact of different modulation methods on system switching frequency and input harmonics, and strategies for common-mode voltage suppression [120].
3) Research on the parameter design of the topology and circuit of integrated LC filter QZS-IMCs.
   This involves analyzing the stress on passive components and power switching devices in ZS/QZS circuits, methods for loss calculation, and parameter design standards [118, 121].
4) Research on three-phase-to-single-phase QZS MC.
   This includes an expansion of the integrated LC filter to three-phase-to-single-phase QZS MCs and research into methods to suppress double-frequency ripple for single-phase output [122].
5) Research on application of integrated LC filter QZS IMCs.
   It was applied to motor speed control systems, conducting dynamic and steady-state characteristic tests. [117, 123].
6) Research on integrated LC filter QZS-IMC systems based on new types of devices.
   This includes comparative studies of parameters, volumes, and losses between the systems composed of Si-IGBT, mixed SiC-IGBT, and SiC-MOSFET devices [124].
7) Optimization operation control.
   This mainly focuses on the operation curve optimization of the integrated LC filter QZS-IMC system based on constrained optimization theory, aimed at reducing losses and decreasing device stress [125].
8) Combining the D-minimization control laws of the integrated LC filter QZS-IMC with AC motor control.
   The comprehensive control methods were developed to significantly expand the variable frequency speed control capabilities of the integrated LC filter QZS-IMC, increase efficiency, and reduce cost [126].

In conclusion, due to its outstanding advantages, the integrated LC filter QZS-IMC is poised for further research and application in the field of electric power transmission. For instance, in modular dual-three-level QZS-IMCs [127], this technology can ensure high-performance operation of high-power motors, reduce harmonics, and promote theoretical advancement and innovation in variable frequency technology.

1.5 Contents Overview

Chapter 1 offers a brief introduction to the concept, classification, advantages, current status, and future trends in the field. The subsequent chapters in this book provide detailed and

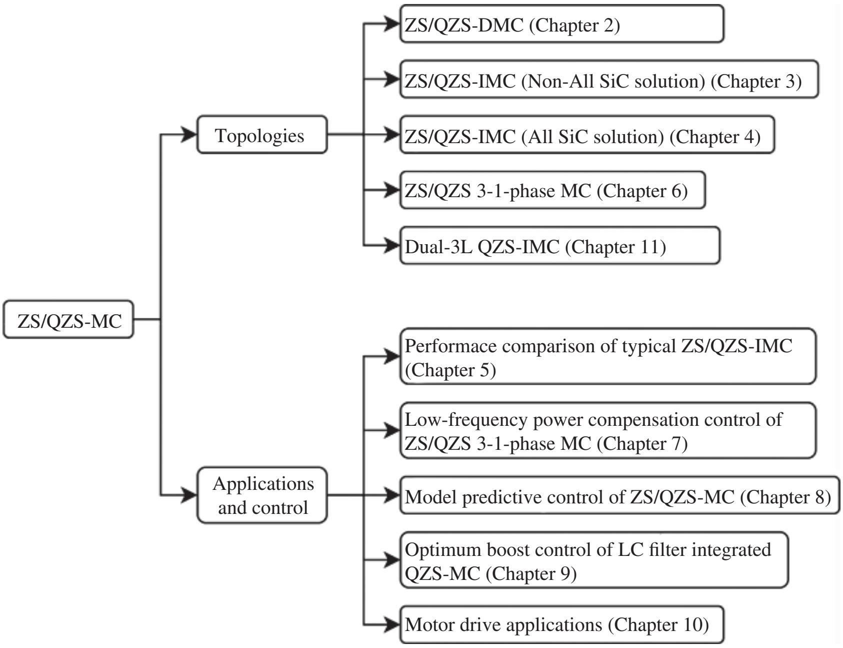


Figure 1.16 Summary of contents.

systematic content. Figure 1.16 illustrates the book's structure. In Chapter 2, ZS/QZS-DMC is introduced, covering its topology, operating principles, modulation methods, and demonstration results. Chapters 3 and 4 focus on ZS/QZS-IMC, with Chapter 3 addressing non-all SiC solutions and Chapter 4 exploring all SiC solutions. Chapter 5 conducts a comprehensive comparison of typical ZS/QZS MCs, including voltage gain analysis, filtering function assessment, parameters design, and verification results. Chapter 6 discusses ZS/QZS 3-1-phase MCs, while Chapter 7 presents a control method for low-frequency power compensation within this context. Chapter 8 details the model predictive control of ZS/QZS MCs. Chapter 9 demonstrates the optimal boost control in LC filter integrated QZS-IMC, and Chapter 10 explores its applications in motor drives. Finally, Chapter 11 outlines the future prospects of this promising topology.

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