Review Article

DC/DC Modular Multilevel Converters for HVDC Interconnection: A Comprehensive Review

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High voltage direct current (HVDC) technology is a key component in power systems owing to huge benefits such as long-distance power transmission, lower losses, asynchronous grid interconnections, controllability, system availability, and limited short-circuit currents. HVDC transmission is a cost-effective method of transporting huge amounts of power across long distances with little loss. It can also link asynchronous alternative current (AC) networks while balancing the grid. DC/DC converters are one of the most important components for HVDC power transmission, and DC/DC modular multilevel converters (MMCs) are the backbone of HVDC grid interconnections. The DC/DC MMC is a highly regarded converter architecture for medium/high-voltage DC grid interconnection. DC/DC MMC topologies play a key role in modern HVDC networks with varying voltage levels. This paper’s fundamental aim is to offer a recent comprehensive review of HVDC topologies, current DC/DC modular multilevel converter (MMC) topologies for HVDC interconnection, and DC/DC MMC control techniques.

1. Introduction

HVDC power transmission technology is a critical key in power systems because of its numerous advantages, including long-distance power transmission, interconnection of large offshore wind farms to the main grid, connection of asynchronous AC systems and various areas needing underwater and subterranean lines, adaptability, flexible operation, and control [1–5]. In addition, HVDC transmission has been developed dramatically in recent years, specifically with the use of voltage source converter (VSC) and MMC technology. The interconnection of two or more HVDC power grids in a smart grid environment will soon be a critical requirement. With this respect, the demand for high-power DC/DC converters to connect HVDC systems with different voltage grids has been currently growing [6, 7]. To regulate the input voltage according to the application, several DC/DC converters and DC/DC MMC topologies are used. Isolated DC/DC converters and nonisolated DC/DC converters are the two basic types of DC/DC converters [8]. The most essential point in the interconnection of several high voltage HVDC power grids is the traditional MMC technology and DC/DC MMC topologies which are constructed by using basic DC/DC converter structures.

MMCs have emerged as a new species of multilevel converters in the last decade, with desirable features such as modularity, high-quality output waveforms, scalability to higher power and voltage levels, transformerless operation, high efficiency, fault-tolerability, lack of dc-link capacitance, lower electromagnetic interference, enhancement of power quality, motor deriver operation, low switching frequency, low harmonic content, high level of modularity, and ease of redundancy installation [9–15]. Due to significant characteristics, the MMC has recently attracted attention in the field of transportation and emerged as a promising candidate for HVDC transmission systems [13, 16, 17], electric railway traction [18, 19], railway power supplies [20, 21], static synchronous compensator (STATCOM) [22, 23], battery energy storage systems [24], emerging electric ship [25, 26], variable-speed motor drives [27, 28], battery charging infrastructure [29], active power filter [30], battery electric vehicles [31, 32], and solar photovoltaic energy systems [33].
MMCs are multilevel converters that constitute the fourth generation of VSC technology [34].

Control strategies are crucial for increasing the efficiency and effectiveness of DC/DC MMC topologies. The input voltage, duty cycle ratio, reference voltage, and output voltage are some control parameters for DC/DC MMC [35]. Several requirements which are obtaining efficient power output, lowest phase current magnitude, and phase current limitation under desired voltage under all circumstances, including DC faults, are the primary concerns of a DC/DC converter controller [36]. To regulate the rising fields of power DC/DC MMC, many modulation approaches have been explored and developed. Pulse-width modulation (PWM) and phase-shift modulation (PSM) are the two common switching control approaches for switch-mode converters [37]. Fundamentally, there are three forms of modulation such as high switching frequency PWM, medium switching frequency PWM, and fundamental switching frequency PWM [34].

Many smart HVDC power systems will exist with conventional AC power grids in the future. In other words, future electrical power systems will depend heavily on smart HVDC power grids. When compared with conventional AC grid systems, DC power systems offer numerous substantial benefits, including increasing performance, power system digitalization and implementation, high efficiency, optimized renewable power source interaction and reduction in costs, high electrical energy capacity, adaptability, charging of electric vehicle storage systems utilizing distributed DC power sources, increased operability, no reactive power, and no heavy line frequency devices [1–5, 38, 39]. Because of certain features, HVDC power grid architecture is a potential alternative for integrating a large number of renewable energy sources and power storage technologies that necessitate greater adaptable and controlled smart power systems. Many early studies have concentrated on DC/DC MMC architectures, as well as their control methodologies [13, 14, 40–47]. DC/DC MMC technology will be a fascinating issue for researchers in the future, thanks to the appealing properties indicated previously. Output current control, circulating current control, and SM capacitor voltage control ripple are all issues that exist in current DC/DC MMC topologies. Newly established DC/DC MMC topologies, as well as easy control approaches and PWM layouts for these topologies, are used to solve these challenges.

In this study, a deep literature search was conducted for DC/DC MMC topologies in light of the abovementioned situations. The primary goal of this review article is to provide the current state of the art in DC/DC MMC in HVDC, DC/DC MMC technology, and to provide a deeper knowledge of its operation and management, including SM topologies, the latest DC/DC MMC topologies and DC/DC MMC control approaches, PWM architectures, and general HVDC topologies. A complete evaluation of the key research concerns involving novel circuit topologies, mathematical modeling of conventional MMC and DC/DC MMC topologies, control systems of conventional MMC and DC/DC MMC topologies, comparison of various DC/DC MMC architectures, and modulation approaches for conventional MMC and DC/DC MMC topologies is undertaken in this context.

2. HVDC Topologies

HVDC transmission is a convenient method of transporting huge amounts of power across long distances with minimal losses [48–51]. Namely, HVDC is a highly effective power transmission technological advancement that allows for efficient power distribution across long distances, power transfer using subterranean and underwater cables, asynchronous power grid interconnections, lower power losses, controllability, environmental considerations, restricted short circuit currents, huge power transmission capacity, high-efficiency power output, and overhead power lines [52–55].

HVDC is separated into two types based on the commutation principle which are line-commutated converter (LCC) and voltage-sourced converter (VSC) [49, 56, 57]. LCC-HVDC transmission has been around for almost 60 years [49]. In contrast to LCC-HVDC transmission, VSC-based HVDC transmission is a relatively newer breed of HVDC technology that has arisen in the last 20 years. Remarkable benefits of VSC-HVDC include the absence of commutation malfunction and instantaneous and adaptable active and reactive power management. [49]. For bulk-power and long-distance transmission, LCC-HVDC transmission is extensively used [58–61]. Even though the conventional LCC-HVDC architecture has some issues, such as producing a set of harmonics in receiving end power flow, switch failure, and inability to control reactive power, most of the HVDC power systems are based on the LCC technology. Since the LCC-HVDC framework improves accuracy and availability, it is a viable technology [57, 62–64]. In addition to the aforementioned discussion, the benefits of VSC-HVDC versus LLC-HVDC are demonstrated in Reference [54]. Instead of a point-to-point interconnection as shown in Figure 1, DC/DC converters could be utilized to interconnect HVDC combination grids [42].

There are two basic topologies for HVDC transmission systems: monopolar and bipolar, which are independent of converter technology [65, 66]. The several popular HVDC transmission system designs and functioning modes are demonstrated as shown in Figure 2 [52, 67, 68]. Essentially, based on the unique capabilities, four fundamental types of HVDC transmission systems are used which are monopole, bipole, back-to-back, and multiterminal layouts [52].

Monopole HVDC architecture consists of two sub-architectures which are symmetric monopole and asymmetric monopole [68]. A symmetric monopole is a singular converter architecture having a grounding point in the middle of the terminals of the positive and negative voltage. A singular converter utilizing a ground connection with neutral is an asymmetric monopole design. This might be done using any metallic or ground returns [69]. Because just two converters and one high voltage isolated wire or line conductor are needed, monopolar arrangements are the easiest and cheapest way for medium power transmissions.
In underwater cable intersections, these arrangements have been employed to deliver the returning current using low-voltage conductor routes and seawater conductors [67].

The bipolar HVDC system is made up of two asymmetrical monopole arrangements that are operated separately. In comparison to monopole architectures, bipolar HVDC design provides greater dependability and versatility [70]. The bipolar arrangement, such as the monopole design, consists of conducting systems with ground return or metallic return. The multiterminal HVDC structure is another prominent HVDC configuration in power transmission systems. Three or more DC terminals are interconnected in parallel in a multiterminal configuration. With the increased use of high-power renewable energy alternatives in power systems, multiterminal HVDC grids have emerged as a popular method of transporting electricity with system stability, confidentiality, and efficiency [71].

Back-to-back configurations are the best design for interconnecting asynchronous power grid systems since they utilize AC connections on both sides of that configuration. In this HVDC architecture, no cables are needed. Therefore, no transmission loss occurs, and it has reduced costs. As a result, a more efficient voltage level is obtained due to the very low losses [52, 67, 68, 72]. Back-to-back converters are typically used to transmit electricity between unsynchronized AC networks. They can also be used to provide a specified power transfer inside a mesh power system. VSC and MMC technologies are employed in the back-to-back HVDC converter design, as shown in Figure 3. The back-to-back converter technology involves that the rectifier and inverter sides of the HVDC power transmission are squarely linked by short bus bars as shown in Figure 3(a). The VSC-based back-to-back converter is a typical architecture for controlling electric power transmission in a variety of application areas, such as renewable energy technologies. This converter’s prominence comes from its ability to modulate active and reactive powers individually [73]. In addition to the use of VSC architecture, MMC technology is also used in back-to-back HVDC converter architecture, as shown in Figure 3(b), due to its low switching frequency, low harmonic content, high level of modularity, and ease of redundancy installation [12–14] features.

Multiterminal HVDC is an appealing choice for transmitting renewable energy from huge and isolated regions, including sand photovoltaic, tidal power, or enormous offshore wind farms [74, 75]. Multiterminal direct current networks facilitate meshed linkages between local power networks and diverse renewable energy supplies, therefore increasing supply dependability and efficiency [76]. As presented in Figure 4, the multiterminal HVDC converter architecture is built using both VSC technology and MMC technology. In Figure 4(a), multilevel HVDC converter architecture based on VSC technology is given. VSC technology is an IGBT converter based HVDC power transmission methodology. VSC technology can adjust the voltages’ magnitude and phase angles separately, allowing it to manage the active and reactive power levels at the ends of the VSC-HVDC [77]. MMC technology is a multilevel converter that constitutes the fourth generation of VSC technology [34]. Figure 4(b) shows a basic MMC-based multilevel HVDC architecture. Compared to VSC technology, MMC technology has many advantages such as decreased voltage ranges, excellent effectiveness, enhanced power suitability for unfiltered operations, natural fault-tolerance ability, and fault prevention ability to optimize failure disruption effectiveness of MMC-based HVDC power grids. As a result, the MMC technology has formed the foundation for multilevel HVDC power grids [76].

3. DC/DC Converters

Power electronics is now dominated by DC/DC converters. According to the latest research, DC/DC converters account for the majority of converting technology output [78]. A DC/DC converter transforms a DC input voltage into a DC output voltage with the required magnitude. Interconnecting HVDC networks of various voltage levels requires the use of a DC/DC converter [4, 5, 42, 79–86]. Therefore, DC/DC converter technology plays a key role in interconnecting HVDC networks with different voltage levels, and the current growth of HVDC power transmission networks relies heavily on DC/DC converters. Conventional DC/DC converters are generally divided into two main categories such as isolated and nonisolated topologies [35, 87–90]. DC/DC converter topologies used in today’s literature are given in Figure 5.

3.1. Isolated DC/DC Converter Topologies. Isolated converters isolate the input and output sides of the power conversion process using a high-frequency transformer. Two AC/DC converters are connected by an interior isolation transformer within that configuration. This architecture has galvanic isolation, which is critical for workloads with large transformation ratios. It also comes in handy when connecting HVDC lines with different grounding methods.
3.1.1. Bridge Topologies. Bridge DC/DC converters are made up of half-bridge, full-bridge, single active bridge, dual active bridge, and boost half-bridge topologies. Figure 6 depicts several designs derived from bridge DC/DC converter layouts which are full-bridge DC/DC converter, half-bridge DC/DC converter, and dual active bridge DC/DC converter, respectively. A half-bridge converter is a DC/DC converter with an output voltage that can be positive or negative, greater or lower, than the input voltage and provides electrical isolation through the use of a transformer. In addition, the half-bridge architecture is a double-ended DC/DC converter topology. Figure 6(b) theoretically depicts a

Figure 2: MMC-based HVDC transmission system fundamental configurations.
half-bridge DC/DC converter design. When the power switches (Field Effect Transistor (FET); Insulated Gate Bipolar, Transistor (IGBT); and Metal Oxide Semiconductor Field Effect Transistor (MOSFET)) are conducting, energy is delivered to the output. In this configuration, the converter switches S1 and S2 are operated asynchronously. The topology of the full-bridge converter is similarly double-ended as shown in Figure 6(a). Since a full-bridge converter has more switches than the half-bridge, therefore, gains double-output voltage [91]. In other words, the full-bridge design’s output power is much higher than the half-bridge design’s output power. Based on whether the S1, S4, S2, or S3 power switches are on or off, the primary voltage of the transformer can be +Vs, −Vs or zero as demonstrated in Figure 6(a). By rectifying the AC voltage in the transformer’s secondary, the secondary voltage can be obtained. Depending on the PWM control, the secondary voltage ranges from zero to the values that Vs voltage will take based on the transformer conversion ratio. A typical architecture for getting high-efficiency bidirectional power transformation is a dual active bridge converter with two DC/AC converters coupled back to back through an AC inductor/transformer as shown in Figure 6(c). This configuration is made up of two full-bridge architectures connected by a high-frequency transformer. PWM technology controls the power switches in this bridge structure, and power switches in the same position of bridges such as S1-S5 and S2-S6 are controlled by phase-shifted gate signals [92]. Due to its structural form, bidirectional power flow functionality, zero-voltage switching, a large voltage gain range, ease of improvement of the process, potential high efficiency and power density, implicit smooth switching, galvanic separation, and a small percentage of passive components, the dual-active bridge converter is preferred among distinctive bidirectional isolated DC/DC converter topologies [93–98]. Because of its convenience and ease of control, the single-active bridge is the best choice for applications requiring unidirectional transmission of power. The single active bridge converter’s fundamental design is composed of an active bridge and a passive bridge coupled by a high-frequency transformer and so separated [99].
addition to that, the single-active bridge is a unidirectional variation of the reputed bidirectional dual-active bridge with great power density. The boost half-bridge generation is one of the most straightforward techniques to step up galvanically isolated DC/DC converters, capable of controlling up to several input voltage changes [100, 101].

### 3.1.2. Forward DC/DC Converter

The forward converter is an isolated buck DC/DC converter type. This arrangement is theoretically applicable to any transformer-type DC/DC converters with multiple outputs [91]. Along with its simplification, inexpensive, and outstanding active and passive operations, forward converters are popular in low-power systems. Nevertheless, like other single-switch transformer insulated converters, this configuration is not suitable for high-line input operations since the primary switch is subjected to high-voltage stress, leading to increased switching losses [106]. A basic forward DC/DC converter design is given in Figure 7. When the power switch (MOSFET) is turned on, that is, when the input source is powered on, the circuit current flows simultaneously from both the primary and secondary sides of the arrangement, in contrast to the flyback converter configuration. Current flows through the primary side of the system when the power switch is switched on. At the same time, electromagnetic induction in the transformer allows the current to flow from the secondary side of the circuit. In this circumstance, the D1 diode enables forward current to flow while the D2 diode is an open circuit, and the voltage changes depending on the transformer’s conversion ratio. The current on the primary and secondary sides goes to zero when the power switch is switched off. The secondary inductor resists the sudden current change, and the voltage induced on this inductor causes a reverse current flow. The diode D1 is in the open-circuit condition, while the diode D2 is forward-biased in this situation, and the transformer’s primary side is also turned off. This cycle continues indefinitely. PWM technology is used to turn on and off the power switch.

### 3.1.3. Flyback DC/DC Converter

The flyback converter is presented as a different version of the buck-boost converter topology. Because of its simple form, low cost, simple control technique, and galvanic isolation, it is favored in many power systems [108–110]. Flyback converters are commonly used in low-to-medium power systems on account of their inexpensive cost and uncomplicated circuit layout. Traditional stable frequency controlled flyback converters have the advantage of being uncomplicated to build and operate, but they lead to significant voltage tension switching losses and harsh MOSFET switching [111]. A traditional flyback DC/DC converter architecture is shown in Figure 8. When the flyback circuit’s power switch (MOSFET) is turned on, the primary current rises, storing energy in the transformer windings. The diode D1 in the circuit is polarized in a reverse way and changes to the cutoff condition in this operation because the secondary voltage is reverse produced. On the secondary side of the transformer, no current flows as a result. There is no power transfer from the primary end of the transformer to the secondary end of the transformer because there is no current on the secondary side. The C capacity is the circuit element that feeds the load in this operational condition of the circuit. If that switch is turned off, the magnetic field changes the polarization of the transformer windings, which causes the rectifier circuit to rectify the voltage. The complete energy in the core is transmitted to the load, and the operation repeats until the core’s power is diminished or the switch is switched on.

### 3.1.4. Resonant DC/DC Converter

Resonant DC/DC converters are a well-established technology that is mostly employed in applications that need a consistent DC voltage gain [114]. Resonant DC/DC converters exhibit excellent conversion rates, high power density, smooth waveforms, high efficiency, high switching frequency with sensitive switching implementations, and a considerably reduced number of magnetic components like transformers and passive filters [115, 116]. They have lately been improved by the use of boost rectifiers. A comprehensive review of recent DC/DC resonant converter topologies has been presented in Reference [117]. Resonant DC/DC converters consist of resonant boost, resonant SEPIC, and hybrid resonant configurations. A hybrid resonant series DC/DC converter with a secondary boost converter design is presented in

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**Figure 5: Conventional DC/DC converter topologies.**
Figure 9. To provide optimum performance, this DC/DC converter architecture works as a series resonant converter topology with a routine power supply. The converter architecture performs like a buck converter design featuring phase shifting on the primary side and synchronized conversion on the secondary side when the input voltage is under the high-level condition, then as a boost converter design featuring primary full bridge and secondary boost functionality when the input voltage is under the low-level condition [118].

3.1.5. Push-Pull DC/DC Converter. A push-pull converter is a kind of DC/DC converter that changes the voltage of a DC power source using a transformer. Having simplistic circuit forms, the solution adopted to perform the voltage control, the galvanic insulation, high-voltage conversion ratio, having low side switches, a simple gate driver circuit, and greater transformer use are all advantages of push-pull DC/DC converters, which are extensively employed in low-input voltage applications [120–122]. The push-pull DC/DC converter structure is a good compromise between cost and service, thanks to its easy and effective setup and high efficiency. As a result, it’s commonly used in medium-to-high power applications [123]. The basic push-pull DC/DC converter architecture design is presented in Figure 10. Depending on whether the S1 and S2 power switches (MOSFETs) are turned on or turned off, the input voltage is converted to the output voltage using the conversion ratios of the two transformers. The following is the operating concept of a push-pull converter: the current flows over the primary of the T1 transformer while the S1 switch is activated, and the magnetic field at T1 increases along with the core. The polarization is reversely biased; therefore, the D2 diode is forward-biased and the D1 diode is cutoff, and the increasing magnetic field in T1 provides a voltage at the secondary of T1. D2 sends a signal to the inductor, which

Figure 6: Bridge DC/DC converter architectures: (a) full-bridge DC/DC converter, (b) half-bridge DC/DC converter, and (c) dual-active bridge DC/DC converter [102–105].

Figure 7: Basic forward DC/DC converter architecture [107].

Figure 8: Traditional flyback DC/DC converter architecture [112, 113].
charges the output capacitance of the design. The higher polarity of the T1 transformer is negatively loaded when the S1 switch is turned off and the S2 switch is turned on. WhereastheD1 diode is cutoff in this scenario, the D2 diode is forward-biased. On the secondary side of transformers, current passes through diodes D2 and L. Because the capacitor is charged, no current will flow through it in the first scenario; however, in the second situation, it will operate as a power source and discharge, providing current to the circuit. As a result, the capacitor’s discharge current and the circuit current pass through the load simultaneously. The S1 switch turns on after a period of time, the S2 switch turns off, and the process repeats [124].

3.2. Nonisolated Topologies. Galvanic insulation is provided by isolated converters because they use a transformer to separate the input and output sides of the DC-DC converter. On the contrary, there is no galvanic isolation between the input and output sides of a nonisolated converter. In other words, while performing the power conversion, a high-frequency transformer is used in isolated converters; conversely, no high-frequency transformer is used in nonisolated converters [35]. A transformer is used in an isolated DC/DC converter to remove the DC route between the input and output. A nonisolated DC/DC converter, on the other hand, has a direct current pathway between its input and output. Nonisolated DC/DC converters, such as buck, boost, and buck-boost converters, are basic architectures in DC/DC converters. Hereby, several studies have been published in the literature to provide problem diagnostic and tracing methods for these converters [125]. The benefits of nonisolated DC/DC converters outweigh the benefits of isolated converters. Despite some minor drawbacks such as a high duty cycle ratio, low voltage gain, and extra equipment, those architectures are nevertheless a more practical alternative than isolated configurations [35].

3.2.1. Buck DC/DC Converter. A buck converter is a nonisolated step-down DC/DC converter type with a lower output voltage than the input voltage [126, 127]. The buck converter is by far the most widely used in the sector because of its tremendous performance and convenience, which derive from its own linear and minimal phase structure. A buck converter, as well called a step-down converter, is used in a wide range of electronic systems [128]. The output voltage of a buck converter is determined using the pulse width modulation technique [129]. Buck converters are currently used in lots of applications on account of their simplicity and inexpensive cost; however, they have limited performance at large switching frequencies and produce a lot of electromagnetic interference pollution owing to harsh switching [130]. A traditional buck converter architecture is given in Figure 11. In this architecture, the power switch is turned on, and it is sending current to the load side of the converter. Because energy is absorbed in the inductor, current flow to the load is firstly blocked; nevertheless, the current in the load and the charge on the capacitor steadily increase over time. The diode will be reverse-biased since there will be a significant positive voltage on the diode cathode throughout the time. The voltage over the inductor leads the current to travel across the circuit through the load and the forward-biased diode. When the inductor has returned a substantial piece of its power generated to the system and the load voltage continues to drop, the energy stored in the capacitor has now become the primary source of current, allowing current to pass through the load till the next on cycle starts.
3.2.2. 

**Boost DC/DC Converter.** A boost converter is a nonisolated step-up DC/DC converter type with a higher output voltage than the input voltage. In other words, this converter takes electricity from a DC voltage source and converts it to a higher DC voltage for delivery to a load. It is plausible to manage the duty cycle by employing passive components and semiconductor parts whereby the boost converter’s output voltage is higher than the input voltage [134, 135]. Along with its extensive application, step-up DC/DC converters have grown fairly prominent in recent years, notably since DC/AC converters often require high DC voltages. Even though transformation effectiveness is restricted at high duty cycle levels, the traditional boost converter is the most preferred architecture for such an application [135]. Figure 12 shows a conventional boost DC/DC converter design. When the power switch is turned on in this DC/DC converter design, a DC voltage is obtained on the inductor. As long as the power switch is turned on, the current through the inductor increases. Due to the inductor’s characteristics, the current passing through it does not alter immediately. As a result, when the power switch is turned off, the inductor continues to send current to the circuit, thus behaving like a power source. When the switch is repeatedly turned on and turned off, a voltage occurs on the load connected to the circuit which is higher than the circuit’s DC input voltage. The PWM signal applied to the power switch can regulate the voltage on the load. In this design, when the duty cycle of the PWM signal applied to the power switch is increased, the output voltage also increases. Conversely, when the duty cycle of the PWM signal is reduced, the output voltage also decreases.

3.2.3. 

**Buck-Boost DC/DC Converter.** Nonisolated buck-boost converter topology consists of a buck converter with an output voltage lower than the input voltage and a boost converter topology with a higher output voltage than the input voltage. Whether the converter operates in buck or boost configuration is determined by the pulse width modulation ratio. The converter produces an output voltage that is lower or greater than the input voltage [137, 138]. Buck-boost converters are familiar with their ability to increase and decrease input voltage magnitude to a specified limit while employing only a few components, as well as their numerous industrial uses [139, 140]. A basic buck-boost DC/DC converter architecture is presented in Figure 13. Buck-boost converter circuits, such as other DC/DC converters, are analyzed in two steps based on the power switching element’s conduction or cutoff position. The polarity of the input voltage changes at the output of the buck-boost converter design. In other words, although the DC input source’s upper polarity is positive, the output voltage’s lower polarity is positive. This situation can be explained as follows: when the power switch is turned on, the current from the circuit’s DC source passes through the inductor element and energizes the inductor in the circuit. The circuit current does not pass to the other side of the diode in this scenario because the diode element is now in the cutoff state. When the power switch in the circuit is turned off, the voltage of the inductor is reversely induced, and the current of the capacitor flows in the opposite direction since the average voltage of the inductor and the average current of the capacitor are zero in DC circuit systems. Because the diode is in the forward-biased state when the power switch is turned off, the circuit current flows to the opposite side. The coil powered from the input source in the previous scenario discharges its energy on the capacitor and the load in this operating stage of the circuit, and the capacitor, which previously transferred its energy to the load, is re-energized with the power flowing from the inductor in the second scenario. Turning the power switch turned on and off periodically repeats this process. PWM technology controls the power switch in the buck-boost DC/DC converter architecture, just as in other DC/DC converter designs.

3.2.4. Cuk and SEPIC DC/DC Converters. The Cuk converter is nonisolated with an output voltage that can be greater or smaller than the source voltage; however, the output voltage is polarized in the opposite direction [144]. Continuous source current, complete transformer usage, buck-boost capability, steady input and output currents, a low-side switch, a large conversion ratio, capacitive isolation between the source and the load, and capacitive energy...
transfer are all crucial properties of the Cuk converter [145, 146]. The SEPIC converter is a nonisolated converter that works by activating and shutting an electronic switch regularly, with the output voltage being either higher or lower than the source voltage and no polarization reversing [144]. A boost-buck architecture is used in the SEPIC converter. In contrast to the Cuk converter, it produces noninverted output voltage and has a minimum input current fluctuation. SEPIC is more efficient than the majority of conventional DC/DC converters [147]. The possibility to produce two outputs with the same voltage yet opposite polarity is provided by an unusual variation of SEPIC and Cuk converter [148, 149]. In Figures 14(a) and 14(b), basic Cuk and SEPIC DC/DC converter designs are given, respectively. The position of the power switch is controlled utilizing PWM technology to assure the operation of these converters. Depending on whether the power switch in Cuk converters is turned on or turned off, the circuit can be subdivided into two parts. When the power switch is turned on position, current flows through the L1 inductor, and the inductor is energized, as shown in Figure 14(a). When the power switch in the Cuk DC/DC design is turned off, the current starts flowing via the reverse polarized diode in the previous situation. Due to the closed-loop to the left of the diode, C1 is charged by a voltage with the same polarity as the input voltage. In this situation, the L1 transfer the power obtained in the previous mode of the circuit. The energy stored in the capacitor C2 and coil L2 provides the load through the D diode. Similar to the Cuk DC/DC converter design, the working principle of the SEPIC DC/DC converter design can be explained as follows: inductor L1 is induced by the input source voltage owing to current from the input source when the power switch is turned on, with the left side having positive polarity and the right side having negative polarity as shown in Figure 14(b). Because the capacitor C1 is charged in the first circumstance, it supplies a current to the left of the circuit. This current induces a voltage across the inductor L2 that is polarized in the opposite direction as the input source. In the second case, when the power switch is turned off, the energy stored in L1 is polarized in the opposite direction compared to its initial state. In this case, current starts to flow from the input source and the inductor L1 to the circuit. This flowing current starts to charge the capacitor C2, which is discharged when the power switch is turned on. In similar logic to inductor L1, the polarity of inductor L2 also changes. Along with the circuit current, the L2 inductor starts to transfer current to the circuit design. The sum of these currents flows towards the end of the circuit and starts to charge the capacitor C2 with the voltage having the same polarity as the input source. After the capacitor C2 is charged, it provides current flow to the load together with the circuit current. The output voltage obtained on the load has the same polarity as the input voltage. This cycle is continually repeated by turning the power switch on and off utilizing PWM technology, as in other converter systems.

3.2.5. Zeta DC/DC Converter. A zeta converter is a fourth-order nonlinear, nonisolated DC/DC converter that may buck or boost the applied voltage [152, 153]. Zeta DC/DC converter topology, like the Cuk and SEPIC converters, may be used in both step-up and step-down applications and has positive polarity for both input and output. The output voltage of the zeta converter is noninverting. In other words, the polarity of the output voltage and the polarity of the input voltage are the same sign in the zeta DC/DC converter architecture [154, 155]. Zeta outperforms SEPIC in terms of having a constant feedback system, which allows for a larger voltage supply, greater load transients, reduced output voltage ripple, and simpler correction [156]. It is being used in a wide range of applications such as high voltage gain applications [157], solar photovoltaic systems [158, 159], LED drivers [160], energy management systems [161], and brushless DC motor drives [162] due to its simple configuration and possibility to execute as a buck-boost converter with a noninverted output [163]. A DC/DC traditional zeta converter architecture is shown in Figure 15. When the power switch is turned on in that design, the diode D becomes reverse-biased, and both inductors L1 and L2 begin charging with the identical polarization of the power supply, as illustrated in Figure 15. In other words, the voltage over the two inductors is Vs, which is the supply voltage. Whenever the power switch is turned off and the diode D is

Figure 14: Basic DC/DC Cuk and SEPIC converter architectures: (a) Cuk converter and (b) SEPIC converter [8, 148, 150, 151].

Figure 15: Conventional DC/DC zeta converter architecture [155, 158, 164–166].
turned on position, the voltage transferred throughout the inductors L1 and L2 is negative which is equal the \(-V_o\) [158].

3.2.6. Multilevel DC/DC Converter. Nonisolated multilevel DC/DC converters are composed of diode-clamped, flying-capacitor, and cascade H-bridge topologies. The diode-clamped circuit is easy to design and has a smaller converter expense. However, the growing number of clamping diodes precludes it from being used at high voltage levels. The limited effectiveness of the flying capacitor converter has been observed to be acceptable. The enormous quantity of flying capacitors, on the other hand, makes using medium voltage challenging [167]. High-voltage and high-power DC/AC systems have traditionally employed flying capacitor converters. In comparison to many traditional topologies, flying capacitor multilevel converters provide significant efficiency and power productivity benefits [168, 169].

One of the most common multilevel converter structures is the cascaded H-bridge. The serial connecting of equivalent H-bridges forms a cascaded H-bridge. Cascaded H-bridge can reach large output voltages with excellent quality, which is one of its benefits. A cascaded H-bridge made up of a significant number of cells achieves these results. Furthermore, owing to the unique adaptability, cascaded H-bridge provides a fundamental failure capability, allowing cascaded H-bridge to be used in reasonable systems [170]. The cascaded H-bridge design can provide a considerably high output voltage while maintaining outstanding signal consistency, making it a good fit for medium- and high-voltage high-power systems [171–173]. Figure 16 depicts several designs of multilevel DC/DC converter architectures which are diode clamped, flying capacitor, and cascade DC/DC converter, respectively. The input voltage of the system is separated into a sequence of different output voltage levels in multilevel DC/DC converter topologies by a series of interconnected capacitors in the design’s output. In other words, the various voltage levels are achieved by connecting capacitors in sequence. Interconnected capacitors can separate the input voltage three levels in a diode-clamped multilevel DC/DC converter architecture, as shown in Figure 16(a). As demonstrated in Figure 16(b), desirable voltage output levels are obtained in a flying capacitor multilevel DC/DC converter topology by dispersing voltage among the interconnected capacitors. A cascade multilevel DC/DC converter, as depicted in Figure 16(c), is another arrangement multilevel DC/DC converter in which many H-bridge converters with different power sources are interconnected in sequence.

4. DC/DC Modular Multilevel Converters

4.1. DC/DC MMC Topologies. An MMC is a viable converter architecture that was presented in 2001 [175]. Marquardt initially proposed the MMC in a German patent in 2001 [176]. The DC to three-phase converter construction with series-connected submodules (SM), together with the inductances in each arm and half- and full-bridge SMs, is depicted in this patent [177]. Since the 1990s, MMC has been referred to as a “chainlink” converter [178], and it is considered suitable that can be used in both medium-voltage and high-voltage grids [179]. The classical DC/DC MMC configuration, which employs an identical and constant set of half-bridge-based SMs within every arm, was initially suggested in References [180, 181]. Moreover, a three-phase MMC’s typical architecture consists of a DC port, an AC port, and a conversion module with three-phase legs. The upper and lower arms of each leg are symmetrical. The upper and lower arms include a collection of extremely similar SMs coupled in series with a stopper inductor. Since the introduction of the initial MMC topology, much critical experimentation has been done to enhance and increase the performance of traditional DC/DC MMC [14].

Reference [184] provides an improved closed-loop control technique for DC/DC MMCs that boosts power transfer capabilities while lowering AC recirculating current which is shown in Figure 17. In this DC/DC MMC design, each arm creates an AC and a DC voltage element via the changing position of the power switch of the SMs. To achieve bidirectional power transfer between the DC terminals 1 and 2, the DC voltage device generates a DC, and also the AC voltage device generates an AC circulating current which allows the active power to be exchanged between the structure’s upper and lower arms. This study initially explores the DC/DC MMC’s power depreciation problem and develops the essential criteria for minimizing the AC circulating current, after which shows how full-bridge SMs can expand the peak power while decreasing the AC circulating current. The notion of higher SM capacitor voltages is used to suggest an improved closed-loop control technique. The suggested control technique takes the use of full-bridge SMs’ ability to provide an extending AC voltage element for every arm, combining it with half-bridge SMs to create a hybrid DC/DC MMC depending on half-bridge and full-bridge SMs. With this study [184], several achievements such as the increased converter’s power transmission efficiency, the AC flowing amplitude, and the size of the SM capacitor voltage fluctuations decreasing have been provided.

A phase-shifted square wave modulation approach for MMCs and DC transformers for medium voltage applications is presented in Reference [196]. Figure 18 depicts the architecture of an isolated modular multilevel DC/DC converter used as a DC transformer in an MVDC network. It is composed of two sides that are connected by a frequency transformer which is a medium-level frequency transformer. On the primary side of the design, an MVDC bus is interconnected. To accomplish separated DC and AC inductance, SM cell capacitors are mounted for every cell’s DC.
connection, and connected arm inductors are used. The opposite side of the design can be interconnected to an HVDC/MVDC bus using an identical MMC configuration or a low-voltage DC bus using a two-level converter, depending on the system requirements. The suggested method allows for a reduced cell capacitance volume without raising the overall device rating or compromising DC management.

In this study [197], a multiloop control method is proposed to provide sustainable functioning of MMCs in HVDC applications across fluctuations in MMC leg inductance and resistance and also load modifications. In this architecture, MMC1 generates DC power in the primary of the design, after that MMC2 uses this power in the HVDC arrangement as depicted in Figure 19. In this design, the control technique was carried out in three stages. The first stage, which is defined as the outside ring, is created using the passiveness controlling technique to encourage the MMC state parameters to maintain their baseline parameters, following the MMC’s control objectives.

The center string should give sufficient effectiveness for the MMC within changes in the MMC’s characteristics as a second-string under the sliding control form. Another important component of the suggested algorithm is the third

Figure 16: Multilevel DC/DC converter architectures: (a) diode clamped, (b) flying capacitor, and (c) cascade architecture [174].

Figure 17: Proposed design of DC/DC MMC is in Reference [184].
internal ring, which is responsible for correct baseline value creation. The capability of the suggested controller to raise the MMC operational consistency limits when there are higher variances. Moreover, the suggested control system is capable of having robust over MMC leg inductance and resistance fluctuations while also having excellent dynamic monitoring that responds to MMC load alterations.

For medium-voltage and high-voltage implementation, the [198] study proposes a modular multilevel DC/DC converter having a high step ratio which is presented in

\[
\text{SM1u, SM2u, SMNu, SM1u, SM2u, SMNu, SM1l, SM2l, SM1l, SM2l, SMNl}
\]

**Figure 18:** Proposed design of isolated DC/DC MMC is in Reference [196].

**Figure 19:** Proposed back-to-back MMC circuit schematic is in Reference [197].
A high step proportion has been accomplished in this architecture by combining a fundamental half-bridge proportion, SM stack modulating, and transformer turn ratio. As a result of combining these criteria, the configuration and operation ease of the presented architecture have improved. The primary side of this architecture comprises two stacks of SMs in the upper and lower arms, which are producing a single-phase MMC arrangement using arm inductors. Two DC coupling capacitors are used to interconnect the transformer’s input winding to the phase middle and neutral point. On the low-voltage side of the design, a simplistic full-bridge diode converter has been utilized to interconnect the transformer output winding to a smoothing capacitor. FH and FL are high- and low-voltage filters made up of parallel inductors and resistors that keep AC current elements from flowing through the system. In order to balance all SM capacitor voltages, classic nearest level modulation technology has been used in the design. The goal of [198] the research is to produce cost-effective DC tap designs for multiterminal DC systems or DC grids by evolving architectures and modulating for low-power high-voltage ratio transformation.

This research proposes in Reference [43] an enhanced architecture strategy for the DC/DC MMC that takes into account both the control and hardware sides of the design. Figure 21 illustrates the design of a DC/DC MMC with two-phase arms. The suggested expanded architecture minimizes overall converter losses by determining the total count of SMs and their categories in each arm of the architecture, as well as the phase-shifting between arms’ AC voltages. To determine conductivity and power switching losses, substantially effective analytical and semianalytical approaches are provided. Concerning overall losses and the quantity of SMs, the effectiveness of the design constructed using the augmented technique is by comparison to that of the standard topologies. According to the results of the comparison research, the suggested architecture strategy produces a converter with lesser losses and fewer SMs.

A modular multilevel DC/DC converter perspective is suggested in Reference [13], which could establish an impactful interconnection to transfer power between a line LCC-based HVDC link and a VSC-based HVDC grid with identical or distinctive voltage levels. When integrating LCC-based and VSC-based HVDC grids, this research can show four-quadrant functioning. Moreover, an appropriate MMC-based DC/DC configuration is provided in this paper, which satisfies the goal of the four-quadrant operating condition, which is most suited to multiterminals HVDC systems with few magnetic components. For both voltage poles of the LCC-oriented HVDC network, this design can function reliably and with equivalent VA characteristics. This DC/DC MMC design can also work reliably when the LCC-oriented DC connection current reverses. Figure 22 depicts a schematic representation of the implementation. The DC/DC MMC by using a transformer, architecture proposed in this research [199], is designed to distribute power from the HVDC connection. As illustrated in Figure 23, the suggested architecture is composed of one DC/AC MMC and one AC/DC VSC linked by a transformer that performs two phases of power transmission, namely, HVDC to AC and AC to medium-voltage DC. Half-bridge SMs were used to achieve the desired architecture.

The MMC arms’ outputs are interconnected to the frequency transformer. On the input side of the design, there
are two filters set to the basic medium frequency AC. The suggested design decreases the quantity of MMC legs to two and adds a series LC passive filter adjusted at a middle frequency to the transformer’s main side. The serial LC filter (Ls and Cs) is interconnected in a parallel manner with the primary side of the MMC, providing a pathway for the essential medium frequency AC to circulate over both arms of the MMC design and transformer while blocking DC passage. The parallel-connected LC filter (Lp and Cp) is being utilized to resist the essential AC element of the current coming into the HVDC network. The suggested converter architecture has a high voltage conversion proportion and is suitable for use with an HVDC network. With an intermediary medium frequency transformer, the design permits bidirectional power transmission. The level-shifted (LS) PWM approach is used in the suggested architecture. With the established HVDC lines, the envisioned architecture is capable of transferring large numbers of megawatts of electrical power. As a result, the design may be utilized to supply isolated regional AC networks near the HVDC network or by a direct line integrate renewable energy sources into the HVDC power system [199].

The author of this study [200] presents a multiport DC/DC MMC for the linking of several HVDC grids. As illustrated in Figure 24, the DC/DC MMC comprises N arms in every phase leg. In this model design, the number of phases is taken as two. The low-voltage DC terminal is linked to the appropriate output end of every phase leg through the phase filter inductor. N – 1 lower voltage terminals have been obtained in this arrangement.

Furthermore, the quantity of phase legs is determined by the total system’s power capability. The recommended multiport DC/DC MMC design’s control structure consists of DC voltage and capacitance-voltage regulating controllers, which includes independent SM capacitors voltage regulating in the identical arm and mean SM capacitors voltage controlling across arms within the identical phases. The suggested multiport DC/DC MMC architecture utilizes the PSC-PWM modulation approach. The postulated multiport DC/DC MMC has numerous characteristics, including a lower number of submodules, a lower capital expense, and a lower size.

The authors of Reference [45] propose a dynamic model and current-mode control for a DC/DC MMC to eventually extend the converter to a three-leg design to minimize the DC terminals’ filtering needs. Figure 25 shows a suggested architectural design for a DC/DC MMC. Two DC networks have been integrated with this arrangement. The primary side voltage Vdc1 of the converter is higher than the secondary side voltage Vdc2. A PWM method is used to manage the conducting statuses of the SMs in order to create the requested arm voltages, which are the voltages of the upper and lower arms of the overall submodules of the leg, which regulate the power delivery inside the converter system. The extension from a single-leg to a three-leg arrangement is then exhibited, demonstrating that the three-leg converter greatly reduces the filtering needs on either the HV or LV sides in that research.

Reference [42] offers a novel front-to-front DC/DC converter relying on an MMC to link two distinct forms of HVDC networks which are LCC and VSC. A voltage source MMC and a current source MMC are used in the presented design, and both are connected through an AC connection that includes the isolation transformer and LC filter. As
illustrated in Figure 26, the voltage source MMC side of the converter is composed of two legs, and each leg has two arms that comprise serial connections of half-bridge voltage source SMs (VS-SM) to sustain the supplied high DC voltage. In the described architecture, power switches that are IGBTs in VS-SMs enable the bidirectional current flow. On the other hand, the converter’s current source MMC side is composed of two legs, and every leg has two arms containing half-bridge current source SMs (CS-SM) connected in parallel to sustain the high DC. To put it another way, the VS-MMC side of the design presents high DC voltage to the system, while the CS-MMC side provides high DC. Two alternative control techniques, which are phase shift control and V/I control for zero reactive power, are employed in the described architecture. The first control approach is convenient and uses fewer passive components, but the second control strategy assures that there is no reactive power across the whole active power transfer band. Owing to the use of just half-bridge SMs, the suggested architecture can satisfactorily offer an instantaneous bidirectional power supply, high DC voltage scaling with such a DC fault preventing capabilities, and a minimal number of semiconductors. Furthermore, the suggested topology’s capacity to withstand failures and provide DC protective region isolation on VS-MMC and CS-MMS DC ends in the absence of the requirement of circuit breakers has been proven.

The authors of Reference [201] study offer a novel MMC using a controlling method that enables the converter to link various HVDC line configurations. The suggested converter is shown in Figure 27. Every leg of the converter has three arms, which are made up of a sequence of SMs as well as an arm inductance. Half-bridge or full-bridge SMs can be implemented in this arrangement. The filter of the design shown as Zout is made up of an inductor and a resistance that function similarly to the arm inductor. The converter topology is derived from the notable DC MMC technology, and it can link symmetrical, asymmetrical, and bipole HVDC grid arrangements. DC currents are required to interchange power across the linked power systems in this converter architecture, while AC currents are used to balance the interior power. The author of this study provides a novel DC MMC with a control technique that enables the converter to connect various power network configurations. The control is verified using a specific example that is based on a probable real implementation which is mentioned in Reference [201].

The architecture of a modular DC/DC converter is studied in Reference [202] which presents a cost-effective method for constructing a hybrid interconnection in HVDC.
grids using existing MMC-based DC/DC converters. The proposed converter design is shown in Figure 28. The suggested converter architecture is beneficial for connecting bipolar VSC and LCC on HVDC connections, and it recommended a hybrid arm to reduce the amount of complete bridge SMs required across an established structure. The suggested converter has sustained power transfer in all stages of functioning, as well as reliable power reversing with output voltage reverse. To decrease losses while ensuring DC fault clearing capabilities, hybrid MMC is used to significantly improve the number of electronic components. The design is shown for three DC/DC converter modes of operation which are bipolar VSC to bipolar LCC, bipolar VSC to monopolar LCC, and monopolar VSC to bipolar LCC DC buses.
4.2. Conventional MMC Structure. The traditional three-phase MMC architecture is presented in Figure 29. MMC’s DC structure, also known as a DC-bus or DC-link, is interconnected across the converter leg’s positive and negative poles. The middle of every converter’s legs is linked to the three-phase AC network (a, b, and c). MMC has two arms for every leg. Upper arms (u) are connected to positive poles, whereas lower arms (l) are connected to negative poles. A collection of submodules and an inductor (Lo) make up every arm. The arm inductor reduces the overload current generated by the immediate voltage differential among the arms as well as reduces circulating currents. Every submodule contains a capacitor whose average voltage must be regulated to produce the required voltage waveform as well as to reduce the circulating current. Depending on the type of PWM technique being utilized (unipolar or bipolar), the voltage level of MMC becomes either $N+1$ or $2N+1$, where $N$ is the SM number.

In the literature, several MMC topology modifications have been published, each of which aims to enhance unique attributes or target a particular purpose [11, 177]. These topologies are illustrated in Figure 30. From the perspective of the general MMC architectures, one of the major objectives is to optimize MMC operation through different arrangements of leg and arm. The hybrid arm/leg construction is an important consideration for balancing technology costs, power dissipation, and DC fault-preventing capabilities [203]. The alternate arm converter (AAC), which is presented in Figure 30(a), has emerged as a viable alternative to the MMC for HVDC systems due to its lower count need for SMs, lower energy storage needs, and DC fault-tolerance capabilities [204]. Especially, regarding system design and control needs, the AAC has a DC fault-tolerance capability in the multilevel converter architecture that belongs to the identical category as the newest MMC [205]. Figure 30(a) shows an alternate arm of MMC architecture. Each arm consists of a sequence of $N$ interconnected FBsMs in series with a director switch and one inductor [34, 205–208]. In this MMC configuration, FBsMs provide multilevel scaled voltage, and a director switch picks the conductive arm such that the upper arm generates the positive half cycle of AC voltage and the lower arm generates the negative half cycle. Converter losses are significantly decreased in this design compared to traditional MMCs [34]. To sustain a similar DC voltage as a conventional MMC, the DC/DC push-pull MMC structure which is presented in Figure 30(b) needs lesser submodules. A center-tapped single-phase transformer connects individual converter phase components to their associated phases on the AC system, as well as provides galvanic isolation in general implementations. This MMC architecture enables the design desirable for implementations requiring high voltage and low current. In that method, the number of power semiconductor switches and passive elements is reduced while the MMC’s adaptability is preserved [209]. Figure 30(c) shows a flying-capacitor MMC arrangement, which is
Figure 29: Traditional three-phase MMC architecture.

Figure 30: Continued.
Figure 30: Continued.
created by connecting a mid-point of the lower and upper arms via a capacitor in each phase. The cross-connected capacitor is utilized to create a balancing of power between the arms and to reduce capacitor voltage ripple without raising the voltage in the common mode of the converter [167, 192]. A set of SMs interconnected in series is interconnected in parallel to each leg of the design in this MMC configuration, as shown in Figure 30(d). This topology shares many of the same characteristics as the FC-MMC, such as a reduced capacitor voltage ripple at zero or low speeds. The active submodules are regulated to restrict the current flowing across the cross-connected arm and to create a pathway for power transmission between the upper and lower arms. The upper and lower arm submodules are adjusted to provide the appropriate AC output waveforms whilst preserving the converter input and output stability of power, and they are regulated to reduce arm power variations whilst preserving an equilibrium among upper and lower arm powers [210]. A high step ratio DC/DC converter to facilitate higher voltage and medium voltage systems connectivity is accomplished by employing single-phase MMC in a half-bridge arrangement, a high-frequency transformer, and a single-phase diode rectifier, as illustrated in Figure 30(e) [198, 211]. The conventional three-phase MMC architecture can be utilized as a DC/DC converter by interconnecting all the terminals to a single terminal as illustrated in Figure 30(f). The control method must create a regulated DC output voltage within that situation, whereas a circulating current is required to flow between the arms to balance the capacitor voltages [184]. By interconnecting three more arms between the center point of every phase and the output, the conventional DC/DC MMC structure which is given in Figure 30(f) could be enhanced, as illustrated in Figure 30(g). The influence of the interior circulating current may be isolated from either the input and output DC currents by implementing additional submodules, reducing the control’s difficulty. When compared to alternative architectures for the implementation, this configuration reduces the massive filter, allows fault ride-through ability for failures on both the DC or AC side, and has a lower apparent switch rated power [212]. In addition to the MMC topologies mentioned above, some other valuable topologies used in the literature recently are presented in Table 1.

4.2.1. Submodule Topologies. An MMC’s central element is the submodule. Several submodule architectures have been presented over the last decades by scientists. The submodules may be divided into two types based on the output voltage level which are single-source two-level submodule architectures and multiple-source multilevel submodule architectures [203], as presented in Figure 31. In the literature, numerous submodule configurations have been presented; the most well-known are presented in Figure 32 [11]. Innovative SM approaches have been established in the literature in recent years, as demonstrated in Table 1.

4.2.2. Mathematical Analysis of MMC

(1) Mathematical Analysis of Conventional MMC. The single-phase equivalent circuit shown in Figure 33 is utilized for mathematical modeling of the conventional MMC
<table>
<thead>
<tr>
<th>Reference</th>
<th>Isolated (I)/ Nonisolated (N-I)</th>
<th>Simulation/ experimental</th>
<th>Simulation hardware</th>
<th>Modulation technique</th>
<th>Submodule type</th>
<th>Development board</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>[213]</td>
<td>N-I</td>
<td>Simulation</td>
<td>PLECS</td>
<td>Unspecified</td>
<td>Half-bridge submodule (HBSM) or full-bridge submodule (FBSM)</td>
<td>Unspecified</td>
<td>The design is an appealing multiport option for converter producers and power distribution engineers, providing features that make it suitable for use as a central DC port in a peripheral DC grid.</td>
</tr>
<tr>
<td>[184]</td>
<td>N-I</td>
<td>Simulation and experimental</td>
<td>MATLAB/ simulink</td>
<td>Unspecified</td>
<td>HBSM or FBSM</td>
<td>Unspecified</td>
<td>The suggested control technique, when used combined with a hybrid DC-DC MMC based on a mixture of full-bridge and half-bridge SMs, successfully increases the power transmission capabilities of the DC-DC MMC while also lowering the AC circulation current and SM capacitor voltage fluctuation.</td>
</tr>
<tr>
<td>[196]</td>
<td>I</td>
<td>Simulation and experimental</td>
<td>IM2DC hardware</td>
<td>PS-SWM</td>
<td>HBSM or FBSM</td>
<td>DSP and FPGA controller</td>
<td>This modulation approach may be used to minimize the size of the cell capacitor in an MMC.</td>
</tr>
<tr>
<td>[197]</td>
<td>N-I</td>
<td>Simulation</td>
<td>MATLAB/ simulink</td>
<td>SLPWM</td>
<td>HBSM</td>
<td>Unspecified</td>
<td>It provides sustainable functioning of MMCs in HVDC applications across fluctuations in MMC leg inductance and resistance, the capability of the suggested controller to raise the MMC operational consistency limits, and capable of having robust over MMC leg inductance and resistance fluctuations</td>
</tr>
<tr>
<td>[6]</td>
<td>N-I</td>
<td>Simulation and experimental</td>
<td>MATLAB/ simulink</td>
<td>NLC</td>
<td>Three-switch submodule with two capacitors</td>
<td>TMS320F28335 DSP plus and EP3C25Q240C8 FPGA</td>
<td>It has smaller semiconductors, cheaper capital costs, a smaller size, and minimal power inefficiencies, proving it excellent for connecting DC networks with voltage ranges less than two.</td>
</tr>
<tr>
<td>Reference</td>
<td>Isolated (I)/ nonisolated (N-I)</td>
<td>Simulation/ experimental</td>
<td>Simulation hardware</td>
<td>Modulation technique</td>
<td>Submodule type</td>
<td>Development board</td>
<td>Contribution</td>
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<tr>
<td>[198]</td>
<td>I</td>
<td>Simulation and experimental</td>
<td>MATLAB/ simulink</td>
<td>NLM</td>
<td>HBSM</td>
<td>OPAL real-time controller</td>
<td>The use of a near-square-wave current operation to generate near-constant instantaneous power for single-phase conversion is suggested, resulting in decreased stacking capacitance and filtering size and increased power equipment usage.</td>
</tr>
<tr>
<td>[214]</td>
<td>N-I</td>
<td>Simulation and experimental</td>
<td>PSCAD/ EMTDC</td>
<td>NLM</td>
<td>HBSM</td>
<td>OPAL-RT rapid control prototyping tool with an integrated FPGA</td>
<td>The suggested control mechanism can provide a faster dynamic reaction without putting too much computing power into it.</td>
</tr>
<tr>
<td>[215]</td>
<td>I</td>
<td>Simulation and experimental</td>
<td>Unspecified</td>
<td>PSPWM</td>
<td>FBSM</td>
<td>DSP and FPGA controller</td>
<td>Because of its advantages such as the structure of many ports, single-stage power transmission between the LV and HV sides, and z approach for simple control, it is particularly well suited to combination DC and AC power generating and transportation systems.</td>
</tr>
<tr>
<td>[216]</td>
<td>I</td>
<td>Simulation and experimental</td>
<td>PSCAD/ EMTDC</td>
<td>PSPWM</td>
<td>HBSM</td>
<td>dSPACE Micro lab-box</td>
<td>The architecture offers several benefits such as more voltage levels, lower capacitor count, smaller footprint, fewer submodules, higher efficiency, and no circulating current. In the laboratory, a prototype of the converter has been created for experimental analysis, and the findings have revealed that the maximum power point tracking is obtained overall submodules.</td>
</tr>
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Table 1: Continued.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Isolated (I)/ nonisolated (N-I)</th>
<th>Simulation/ experimental</th>
<th>Simulation hardware</th>
<th>Modulation technique</th>
<th>Submodule type</th>
<th>Development board</th>
<th>Contribution</th>
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<tr>
<td>[13]</td>
<td>N-I</td>
<td>Simulation and experimental</td>
<td>MATLAB/simulink</td>
<td>PSC-PWM</td>
<td>FBSM</td>
<td>FPGA Virtex 5</td>
<td>In the LCC-based HVDC terminal, the converter was shown to have symmetrically circulation volt-amper effectiveness for any polarization of voltage. Either for the polarization of LCC port output power, the results revealed a steady flow of power between LCC- and VSC-based HVDC interconnects.</td>
</tr>
<tr>
<td>[199]</td>
<td>I</td>
<td>Simulation and experimental</td>
<td>MATLAB/simulink</td>
<td>PSC-PWM</td>
<td>HBSM</td>
<td>DSP</td>
<td>This paper presents a novel isolated MMC architecture that only utilizes one MMC leg (two arms). The design is being used to connect isolated regional AC networks to the HVDC line or to incorporate renewable energy sources into the HVDC network straightforwardly.</td>
</tr>
<tr>
<td>[200]</td>
<td>N-I</td>
<td>Simulation and experimental</td>
<td>MATLAB/simulink</td>
<td>PSC-PWM</td>
<td>HBSM</td>
<td>TMS320F28335 DSP plus and XC3S500E-4PQG208C FPGA</td>
<td>This study presents a multiport DC-DC MMC that may be used to join numerous HVDC networks to establish a multiterminal DC grid.</td>
</tr>
<tr>
<td>[45]</td>
<td>N-I</td>
<td>Simulation and experimental</td>
<td>MATLAB/simulink</td>
<td>PSC-PWM</td>
<td>HBSM</td>
<td>FPGA of the cRIO</td>
<td>The enlargement of a single-leg converter to a three-leg design revealed that either the HV or LV sides filtering needs may be greatly lowered.</td>
</tr>
<tr>
<td>[217]</td>
<td>N-I</td>
<td>Simulation and experimental</td>
<td>PLECS and MATLAB/simulink</td>
<td>PD-PWM</td>
<td>HBSM</td>
<td>DSP and FPGA controller</td>
<td>Realistic modeling for different systems to lower the overall RMS value of arm current without utilizing extra sensors, strict control of capacitor voltage modulation to preserve acceptable output voltage reliability, and a standardized PWM approach for any n-level MMC</td>
</tr>
<tr>
<td>Reference</td>
<td>Isolated (I)/nonisolated (N-I)</td>
<td>Simulation/ experimental</td>
<td>Simulation hardware</td>
<td>Modulation technique</td>
<td>Submodule type</td>
<td>Development board</td>
<td>Contribution</td>
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<tr>
<td>[42]</td>
<td>I</td>
<td>Simulation and experimental</td>
<td>Unspecified</td>
<td>Unspecified</td>
<td>HBSM</td>
<td>TMS320F28335ZJZA DSP with OPAL-RT platform</td>
<td>Offering a unique DC/DC MMC to link HVDC transmission networks depending on LCC and VSC. Two novel control approaches, as well as the requisite system architecture for individual controllers, are presented.</td>
</tr>
<tr>
<td>[202]</td>
<td>N-I</td>
<td>Simulation</td>
<td>MATLAB/simulink</td>
<td>Unspecified</td>
<td>HBSM and FBSM</td>
<td>Unspecified</td>
<td>The research is valuable for integrating bipolar VSC- and LCC-based HVDC connections, as well as optimizing the amount of full-bridge submodules over an existing one by employing a hybrid arm.</td>
</tr>
<tr>
<td>[209]</td>
<td>I</td>
<td>Simulation and experimental</td>
<td>PLECS</td>
<td>PD-PWM</td>
<td>HBSM</td>
<td>Texas Instruments F28377S and Texas Instruments F28379D</td>
<td>The suggested design has all of the advantages of a standard MMC, including a modular arm construction and ripple-free DC. The size of submodules can be reduced by connecting the phases in series instead of in parallel as in MMC.</td>
</tr>
<tr>
<td>[194]</td>
<td>N-I</td>
<td>Simulation and experimental</td>
<td>Unspecified</td>
<td>PS-PWM</td>
<td>HBSM</td>
<td>DSP</td>
<td>The proposed converter maintains MMC’s flexibility, effortlessness, and scalability, making it suitable for high step-up DC/DC power conversion in renewable energy production and HVDC grids.</td>
</tr>
<tr>
<td>[218]</td>
<td>I</td>
<td>Simulation and experimental</td>
<td>MATLAB/simulink</td>
<td>LS-PWM or NLM</td>
<td>FBSM</td>
<td>FPGA</td>
<td>The proposed design provides high-quality sinusoidal output voltages while using lesser components and taking up less space than the HBSM MMC.</td>
</tr>
</tbody>
</table>
It has a dense construction since the number of submodules is decreased to 33% of MMC, resulting in much less power storage, and it reduces the number of capacitors required, as well as weight, cost, loss, and control complexity.

Figure 31: Traditional and novel submodule architecture.
architecture which is given in Figure 29. The \( a \)-phase of the MMC is the basis of all mathematical circuit analyses. For the remaining phases (phase-\( b \) and phase-\( c \)), the same methods can be applied. Because of the enormous number of cells, MMC mathematical modeling can be quite complicated, and simulating can take a long duration. To mitigate this major issue, numerous ways to simplify the model have been offered in the literature. The MMC’s functionality is determined entirely by the switching submodules number, which can be described as ideal continuous DC voltage sources. In Figure 34(a), the reduced equivalent structure of a three-phase MMC is depicted, in which the submodule terminal voltage in each arm is integrated into a single equivalent voltage source[14, 15, 36, 208, 220–229]. Furthermore, every MMC arm can be described as a nonlinear capacitor with a changing over time sinusoidal capacitance, and with capacitor voltage represented as a controllable voltage source as presented in Figure 34(b). The overall power generated in every arm is utilized to adjust the arm’s capacitor voltage to cope with capacitor voltage variations. The total of upper and lower arm power is modulated to recognize the load active power requirements, and the upper and lower arm power difference is modulated to keep the upper and lower arms in voltage equilibrium.

---

Figure 32: Traditional submodule architectures. (a) Half-bridge submodule (HBSM). (b) Full-bridge structure (FBSM). (c) FC-SM: flying capacitor SM. (d) M-ANPC-SM: modified active neutral-point clamped unipolar SM. (e) CD-SM: clamped-double SM.

Figure 33: Single-phase equivalent of three-phase MMC.
Figure 34: Three-phase MMC equivalent approaches. (a) MMC configuration with ideal voltage sources in the arms. (b) MMC configuration with nonideal voltage sources in the arms.
For easier mathematical analysis of the conventional three-phase MMC topology which is given in Figure 29, the single-phase equivalent circuit of this design is obtained as presented in Figure 33.

From Figure 33 and by applying Kirchhoff voltage law (KVL) [11, 34, 197, 220, 221, 225, 226, 230], the following expression has been revealed:

\[
\frac{V_S}{2} - U_{ua} - r_a i_{ua} - L_a \frac{di_{ua}}{dt} - v_a - r_o i_{oa} - L_o \frac{di_{oa}}{dt} = 0, \\
\frac{V_S}{2} - U_{ua} - r_a i_{ua} - L_a \frac{di_{ua}}{dt} = v_a + r_o i_{oa} + L_o \frac{di_{oa}}{dt} = 0, \\
\frac{V_S}{2} + U_{la} + r_a i_{la} + L_a \frac{di_{la}}{dt} - v_a - r_o i_{oa} - L_o \frac{di_{oa}}{dt} = 0, \\
\frac{V_S}{2} + U_{la} + r_a i_{la} + L_a \frac{di_{la}}{dt} = v_a + r_o i_{oa} + L_o \frac{di_{oa}}{dt}.
\]

From Figure 33, the upper and lower arm voltages of phase-a are given by

\[
V_u = \frac{V_S}{2} = U_{ua} + L_a \frac{di_{ua}}{dt} + r_a i_{ua} + L_o \frac{di_{oa}}{dt} + r_o i_{oa} + v_a, \\
V_l = \frac{V_S}{2} = U_{la} - L_a \frac{di_{la}}{dt} - r_a i_{ua} - L_o \frac{di_{oa}}{dt} - r_o i_{oa} - v_a.
\]

From the single-phase equivalent circuit shown in Figure 33, the upper and lower arm current of phase-a is given by

\[
i_{ua} = \frac{i_{ma}}{2} + i_{cc}, \\
i_{la} = \frac{i_{ma}}{2} - i_{cc},
\]

here \(i_{cc}\) represents the circulating current of MMC topology. The phase-a AC system current is given as follows:

\[
i_{oa} = 2i_a + 2i_{cmc},
\]

here \(i_a\) represents the phase-a AC output current and \(i_{cmc}\) represents the common-mode-current of MMC topology.

In the same way, the current that flows across MMC’s upper and lower DC-buses is provided by

\[
i_u = i_{ua} + i_{db} + i_{uc} = 3i_{cmc},
\]

\[
i_l = i_{la} + i_{lb} + i_{lc} = 3i_{cmc}.
\]

When the lower arm voltage in (3) is subtracted from the upper arm voltage in (2), the consequence is

\[
V_S = U_{ua} + U_{la} + L_a \frac{d(i_{ua} - i_{la})}{dt} + r_a (i_{ua} - i_{la}).
\]

Similarly, when the upper and lower arm voltages in (2) and (3) are added together, the corresponding expression is obtained:

\[
0 = U_{ua} - U_{la} + L_a \frac{d(i_{ua} + i_{la})}{dt} + r_a (i_{ua} + i_{la}) + 2L_o \frac{di_{oa}}{dt} + 2r_o i_{oa} + 2v_a.
\]

The difference between the upper and lower voltages of phase-a can be derived by rearranging equation (10) as follows:

\[
U_{ua} - U_{la} = L_a \frac{d(i_{ua} - i_{la})}{dt} + r_a (i_{ua} - i_{la}) - 2L_o \frac{di_{oa}}{dt} - 2r_o i_{oa} - 2v_a.
\]

In MMC topologies, circulating current is particularly essential since it generates system losses. As a result, in MMC designs, the circulating current must be theoretically represented. The AC circulating current is restricted to the converter legs. The amplitude of a circulating current in phase-a is determined by

\[
i_{cc} = \frac{i_{ua} - i_{la}}{2}.
\]

The magnitude of common-mode current \(i_{cmc}\) is obtained from (7) and (8) as follows:

\[
i_{cmc} = \frac{i_u + i_l}{6}.
\]

The following expression is obtained by substituting (6) and (13) into (10):

\[
0 = U_{ua} - U_{la} + 2L_a \frac{di_{cmc}}{dt} + 2r_a i_{cmc} + 2L_o \frac{di_{oa}}{dt} + 2r_o i_{oa} + 4L_o \frac{di_{cmc}}{dt} + 4r_o i_{cmc} + 4L_o \frac{di_{oa}}{dt} + 4r_o i_{oa} + 2v_a.
\]

The AC output current is transmitted uniformly between the upper and lower arms. The value of phase-a, the AC output current, is provided by (4) and (5).

\[
i_a = \frac{i_{ua} + i_{la}}{2} - i_{cmc}.
\]

\section{Mathematical Analysis of DC/DC MMC}

In DC/DC MMC topologies, mathematical analysis is just as crucial as it is in conventional MMC topologies. Because control strategies are established with the assistance of mathematical analyses that provide an impactful power transfer in the converter systems. In isolated DC/DC MMC designs, the architectural structure of the converter topology utilized to perform mathematical analysis must be thoroughly examined. Figure 35 depicts a well-known isolated DC/DC MMC configuration [182, 227, 228]. A medium-frequency transformer combines the primary and secondary MMCs in the architectural framework. Between the two DC networks, the transformer offers galvanic isolation. The primary and secondary structures in the isolated DC/DC MMC architecture are three-phase, such as in the conventional MMC architecture. Upper and lower arm modules are composed of multiple identical SMs and one arm inductor in every phase.
block. Each phase of MMC includes two arms, each of which includes $N$ SMs. As a consequence, each leg has $2N$ SMs [182, 227, 228].

The inductor within every arm is utilized to balance the voltage differential between the upper and lower arms that occurs throughout SM switching, as well as to restrict temporary currents [182, 227, 228]. The mathematical analysis presented below is performed for phase-\(a\) of the MMC positioned on the primary side of the converter design in this well-known isolated DC/DC MMC architecture. All remaining phases can be subjected to the same mathematical analysis. As stated in the conventional MMC design’s mathematical analysis section, every MMC arm can be described as an online arc capacitor with a changing over time sinusoidal capacitance, and with capacitor voltage represented as a controllable voltage source as presented in Figure 36.

From Figure 36 and by applying Kirchhoff Voltage Law (KVL) and Kirchhoff’s Current Law (KCL), for the upper and lower arms, the corresponding representations can be derived:

$$i_{ua} = i_{\text{ua}} + i_{\text{ul}}. \quad (16)$$

Due to the voltage differential between the DC link and phase legs, a difference current called $i_{\text{dif}}$ passes across the converter legs. Furthermore, the AC appears to be split evenly between the upper and lower arms. Thus, equations (17) and (18) are obtained as follows:

$$i_{\text{ua}} = i_{\text{dif}} + \frac{i_{\text{iso}}}{2}. \quad (17)$$

$$i_{\text{la}} = i_{\text{dif}} + \frac{i_{\text{iso}}}{2}. \quad (18)$$

The upper and lower arm currents of phase-\(a\) are represented by $i_{\text{ua}}$ and $i_{\text{la}}$, respectively. The phase current is denoted by $i_{\text{ao}}$. From equations (17) and (18), current $i_{\text{dif}}$ can be obtained as follows:

$$i_{\text{dif}} = i_{\text{ua}} - \frac{i_{\text{iso}}}{2}. \quad (19)$$

$$i_{\text{dif}} = i_{\text{la}} + \frac{i_{\text{iso}}}{2}. \quad (20)$$

When these two equations (19) and (20) are integrated, $i_{\text{dif}}$ can be obtained as follows:

$$i_{\text{dif}} = \frac{i_{\text{ua}} + i_{\text{la}}}{2}. \quad (21)$$

According to KVL, the following equations can be derived.

$$\frac{V_{\text{dc1}}}{2} + n_u U_{\text{ua}} + r_u i_{\text{ua}} + L_u \frac{di_{\text{ua}}}{dt} + U_{\text{ao}} = 0, \quad (22)$$

$$\frac{V_{\text{dc2}}}{2} - n_l U_{\text{la}} - r_l i_{\text{la}} - L_l \frac{di_{\text{la}}}{dt} + U_{\text{ao}} = 0, \quad (23)$$

Figure 35: DC/DC MMC architecture.
where $V_{dc1}$ and $U_{ao}$ are, respectively, the DC side and AC phase voltage.

$$U_{oa} = U_{lb} = \frac{V_{dc1}}{2},$$  \hspace{1cm} (24)

here the corresponding voltages across every upper and lower arm are defined by $U_{ua}$ and $U_{la}$, $n_u$ and $n_l$ show the number of SMs included in each arm and contribute to determining the output voltage value.

Equation (25) is obtained by subtracting equations (22) and (23) as follows:

$$\frac{di_{\text{diff}}}{dt} = \frac{V_{dc1}}{2L_a} \cdot \frac{n_u U_{ua} + n_l U_{la}}{2L_a} - \frac{r_a i_{\text{diff}}}{I_a}.$$  \hspace{1cm} (25)

As a consequence, we get equation (26) as follows:

$$\frac{di_{\text{diff}}}{dt} = \frac{V_{dc1} - (n_u U_{ua} + n_l U_{la}) - 2r_a i_{\text{diff}}}{2L_a}.$$  \hspace{1cm} (26)

In the steady-state condition, the arm current can be represented as the summation of the common and differential mode elements, according to the MMC operational characteristics.

$$i_u = \frac{i_{ao}}{2} + i_{CC},$$  \hspace{1cm} (27)

$$i_l = \frac{i_{ao}}{2} - i_{CC},$$  \hspace{1cm} (28)

here $i_{CC}$ represents the circulating current of MMC topology. The phase-α AC system current is given as follows:

$$i_{oa} = 2i_a + 2i_{cmc},$$  \hspace{1cm} (29)

here $i_a$ represents the phase-α AC output current and $i_{cmc}$ represents the common-mode-current of MMC topology.

In the same way, the current that flows across MMC’s upper and lower DC-buses is provided by

$$i_u = i_{ua} + i_{ub} + i_{uc} = 3i_{cmc},$$  \hspace{1cm} (30)

$$i_l = i_{la} + i_{lb} + i_{lc} = 3i_{cmc}.$$  \hspace{1cm} (31)

Consequently, the amplitude of a circulating current in phase-α is determined by using equations (27) and (28).

$$i_{cc} = \frac{i_u - i_l}{2}.$$  \hspace{1cm} (32)

The magnitude of common-mode current ($i_{cmc}$) is obtained from (30) and (31) as follows:

$$i_{cmc} = \frac{i_u + i_l}{6}.$$  \hspace{1cm} (33)

5. MMC Control Theory

5.1. Control Theory of Traditional MMC. MMC technology plays a significant role in HVDC power systems along with its benefits such as modularity, voltage, power scaling, fault tolerance and transformerless operation, and high-quality output waveforms. MMCs can be operated safely, reliably, and efficiently, thanks to modern control mechanisms. The adaptable and fairly constant effectiveness of such control mechanisms is outstanding. MMC control is difficult, as demonstrated in Figure 37, since it includes several performance criteria [11]. In a traditional control system of an MMC, primary control generally consists of output current control and submodule capacitor voltage control, while secondary control consists of circulating current control and submodule capacitor voltage ripple. An appropriate modulation
methodology and controller must be used to take advantage of the MMC’s outstanding power satisfaction.

5.1.1. Pulse Width Modulation Architectures. Pulse width modulation (PWM) is a method of regulating circuit design using the digital outputs of a microcontroller [229]. In other words, PWM stands for pulse width modulation, and it refers to the process of creating triggering impulses for switching equipment to get an output voltage with both the desired frequency and magnitude [221]. PWM is a suitable and successful method of generating switching signals with a period corresponding to the reference voltage [34, 231].

The PWM enables adjustment of the amplitude, frequency, and phases of the switching waveform’s essential components. PWM approaches, in general, are intended to decrease output voltage harmonics while also increasing the amplitude of the output voltage at a particular switching frequency [11, 34]. The PWM approaches of an MMC are classified into high switching frequency, low switching frequency, and fundamental switching frequency modulation techniques [11, 34], as illustrated in Figure 38. The investigation of PWM approaches of an MMC, as well as their properties, has been the subject of various research studies in the literature as shown in Table 1. In addition to this valuable research, numerous studies have been published that use modulation technique-based control systems. An MMC is characterized by high flexibility, adaptability of voltage, fault-tolerance, and higher harmonic efficiency of the design with the most promise for HVDC grids. The authors of Reference [232] developed a phase-shifted carrier pulse-width modulation approach as well as capacitor voltage balancing control, which combines the best features including both conventional and modeling forecasting control. When making a comparison to the traditional phase-shifted carrier pulse-width modulation-based proportional-integral controller approach, the suggested control technique minimizes the need for the time-consuming proportional-integral variables adjustment technique and enhances dynamic characteristics. Unlike the traditional PSC-PWM modulation techniques based on proportional-integral controllers, the suggested methodology is simple to implement since the proportional-integral variable adjustment process is not required, allowing for much increased dynamic characteristics.

A modified method of space-vector pulse width modulation (SVPWM) for an n-level MMC is presented in Reference [233]. By representing a two-level space architecture, this approach makes more use of accessible switching modes and determines switching durations. The suggested scheme’s computing overhead is regardless of conversion voltage level, making it theoretically affordable and very well adapted to MMCS with almost any quantity of submodules. The suggested method includes basic arithmetic operations and ignores complicated arithmetic computations. When comparison to traditional modulation systems, the suggested technique has better stable efficiency and faster variations.

This research [234] describes windowed PWM (W-PWM), which is a modulation method for MMC in adjustable velocity drive applications for electrified vehicles. The W-PWM is created by integrating the concepts of performance of traditional MMC modulation techniques relying on nearest level control (NLC) and PWM to integrate all unique characteristics and deliver an increased level of adaptability. When opposed to older PWM systems, this PWM technique can minimize switching losses while also lowering current harmonic deformation. For the functioning of MMCS, this research [235] provides a novel and simple PWM method with four fundamental sorts of switching cycles. All SMs of a leg are constrained to either a positive or negative DC bus within those cycles, which reduces dynamic switch switching losses.

At higher modulation parameters, the discontinuous pulse width modulation (DPWM) approach responds to reduced cumulative losses and capacitor voltage fluctuation, according to the experimental and theoretical findings. Moreover, using this method for MMCS improves the scheme’s dependability by extending the scheduled lifetime of the submodule devices.
The influence of the general method of DC offset implantation (or offset PWM) (OPWM) on the minimal average level of the capacitor voltage for the MMC is the topic within [236]. Further precisely, the thermal efficiency of MMCs within this type of modulation, particularly in HVDC transmission networks, is investigated, as well as the effectiveness across various operating situations with varied permitted offsets. The decrease in the quantity of power in submodule capacitors and enhanced efficiency under malfunctions with reduced total losses however a variance in the transmission of losses across components inside a submodule are exhibited in this study [236]. MMC’s strong effectiveness is mostly dependent on its modulation approach.

A submodule regrouped approach for MMC is provided in this research [237], and a sample period astonished space vector pulse width modulation (STS-SVM) methodology for MMC is developed depending on it. The STS-SVM has astounding achievement characteristics including a simple fundamental and convenient integration, substantially decreased predictive load contrast to conventional multilevel SVM, HVDC implementation, and outstanding output signals with increased smallest harmonic collective and repaired switching frequency. Every one of such benefits contributes to the eventual commercial implementation of MMC. Various control devices, such as digital signal processor (DSP), field programming gate array (FPGA), custom hardware [37], dSPACE, and a combination of software and custom hardware can be used to perform digital control of the aforesaid numerous modulation and control mechanisms.

5.1.2. Submodule Capacitor Voltage Control Mechanism. The fundamental controlling purpose of MMC is to regulate the currents and voltages at their input and output terminals. The converter behaves as an electrical energy gateway between the outputs and inputs, storing power inside the submodule cell capacitors. The average capacitor voltage needs to be regulated or managed for consistent fairly constant functioning [238]. The expected operating voltage of the MMC rises as the size of submodules rises, so every submodule has unsettled capacitors that must be kept at its reference voltage. Submodule capacitor voltage management might provide MMC functionality, consistency, and output energy purity. Submodule capacitor voltage management encompasses submodule capacitor voltage balancing, legs voltage, and arms capacitor voltage management [34]. To maintain MMC’s satisfactory performance, capacitor voltage balancing is crucial. The categorization approach is commonly utilized in MMC technology to balance capacitor voltages in SMs. The capacitor voltage on the submodules is determined initially, and then the capacitor voltages for the upper and lower arms are classified in this approach. When the flow direction of the currents passing through the branch currents changes, the capacitors in the SMs are charged and discharged. When the branch current is positive or negative, the capacitors charge and discharge, respectively. As a result of this, the capacitor voltages on the arm are unbalanced. To compensate for the disequilibrium, all SM capacitors are monitored and classified [221]. Figure 39 shows the basic concepts of MMC controlling approaches as well as the voltage balancing methodology [221, 238].

Numerous research studies on the control of submodule capacitor voltage balancing in MMC technology have been...
conducted in the last few years. The following are some of the most popular studies discussed in this paper. The basic goal of the developers of [239] imbalanced AC grid instances in MMCs is to enhance power stabilization. Voltage balancing is achieved by adopting a novel control mechanism. By implementing the suggested control technique to a power network linked to traditional MMC architecture, the feedback/feedforward control technique is examined in depth.

To achieve capacitor voltage balancing in the MMC, this paper [240] presents a current-less submodule individual voltage balancing control (SMIVBC). In the proposed study SMIVBC [240], every submodule capacitor voltage could be separately adjusted to match a reference point by modulating the DC equipment in every submodule capacitor current using modulation, allowing capacitor voltage balancing in the MMC, and also it eliminating the need for a sorting algorithm to pick the submodules in the MMC, and eliminates the need for current awareness within MMC, that decreases the number of sensors and sampled signals, lowers costs, and increases consistency.

In Reference [241], independent submodule gated signals are generated using a phase propensity dependent PWM approach. Modulating signals among submodules are rotated to accomplish voltage balance. For a high qualitative output voltage and needed submodule capacitor voltage equilibrium, modulating index is changed. Submodule voltage imbalance leads to submodule capacitor overcharge and lower operating dependability; thus, submodule voltage must be balanced at any time.

Novel feedback and feedforward power balanced devices using improved selecting algorithms are suggested in Reference [242] to increase the restricted configurable band of DC supply owing to voltage/energy imbalance. Within power balanced control, the feedback mechanism assures negligible fairly constant failure, whereas the feedforward control offers quick flexible behavior. The hybrid MMC can retain the power balancing across HBSMs and FBSMs in a large variety of DC supplies via using the suggested control strategy.

An improved energy grading strategy for stabilizing every submodule capacitor energy in modular multilevel converters is described in Reference [243]. Whenever the submodule voltage technique is multiplied by a lot of degrees, nevertheless, the voltage disturbances and circulation current are becoming progressively complicated, resulting in higher voltage disturbances and circulation current. An increased voltage grading technique is presented to resolve the issue, which indicates an expanded control logical functionality for capacitor voltage equilibrium in the converter. The modulation index approach is used to identify the switching arrangement of every SM floating capacitor, which is subsequently by comparison to the mixed state situation in the MMC utilizing the arms’ current direction.

The voltage balancing algorithm (VBA), which is based on reassigning switching periods, is developed in Reference [244] to enhance the rebalancing effectiveness of capacitor energies with a lower operative frequency. The RSFVBA (reduced switching frequency voltage balancing algorithm) is described in detail. The correlation between switching timings, switching frequency, and capacitor voltage variation may then be determined using this information. The voltage variations in the positive and negative periods of the leg current are thereafter thoroughly investigated. Independent surveillance and controlling to every submodule are
necessary in traditional systems for balancing a capacitor voltage, which adds to the converter’s expense and load.

With no need for extra instruments or processors, Reference [245] presents a simple logical method (SLM) for regulating the capacitance energy within every submodule. The capacitance energy of \( N \) submodules is regulated using a simple rational procedure, which balances the capacitance-voltage and decreases the voltage distortion of every capacitance.

The capacitor in every submodule connecting to the converter is balanced using a voltage balancing approach proposed in Reference [246]. The suggested approach additionally reduces capacitor fluctuation voltage. The phase placement carrier approach is first used to generate switching pulses for switching components, which are thereafter modulated by using a voltage balancing scheme and implemented in the converter.

5.1.3. Output Current Control. Industrially, the DC/DC MMC architecture is utilized in HVDC power grids, renewable energy systems, battery technologies and electrical vehicles, variable-speed motor drives, STATCOMs, and power electronic transformers. The output current control strategies are developed depending on the MMC implementations. In other words, almost every MMC application has uniquely improved its output currents as follows. Voltage-oriented controlling is employed in PV systems [247, 248], HVDC system fields [249], and renewable energy systems [250], whilst field-oriented controlling is used in induction motor driving implementations [251–254]. STATCOMs use output current controlling techniques to acquire the needed reactive power [11, 34].

5.1.4. Circulating Current Control. MMC is becoming an attractive architecture and is frequently utilized in HVDC power transmission because of its advantages of excellent modularity, low switching frequency, low harmonic content, ease of redundancy installation, the convenience of scalability, reduced distortions, and voltage stress. However, because of their architectural design and operating features, MMCs have a substantial disadvantage in terms of internal (do not flow outside) circulation current flowing among the phases. Internal circulating current can drastically raise system losses and diminish system lifetime, especially in high-power systems [255]. In most cases, circulating currents have little effect on the currents and voltages in the AC systems. Nevertheless, if circulating currents are not correctly managed, circulating currents can cause an increment in the root-mean-square/peak value of the arms current, which can increase the equipment’s rated current, energy losses, and capacitor voltage fluctuation [11, 34, 256, 257]. By interconnecting inductors to each phase or branch of the MMC and creating a closed-loop control technique, the circulating current flowing through each branch can be limited to a degree [34].

Researchers have recently developed a variety of modulation schemes and controlling technologies to mitigate the losses caused by circulating currents in DC/DC MMC architectures. A novel control strategy which is circulating current optimization control (CCOC) for reducing the maximum values of arms current in MMC has been suggested in Reference [258]. It allows the MMC to use reduced current rated switching devices or increase power handling using similar rated switching devices. By modulating the second harmonic ingredient in the circulating current, Reference [259] presents a coordinated control approach for power loss reduction and capacitor voltage stabilization for AC voltage enhanced full-bridge submodule MMC, which can minimize MMC power losses.

To prevent excessive circulating current within an MMC, Reference [260] provides an improved closed-loop circulating current control approach. The suggested approach [260] reduces the fluctuation in capacitor voltage whilst suppressing the amount of circulating current. Under both steady and unsteady AC network situations, the fluctuation in the DC link voltage is decreased without the use of a supplemental controller. As a consequence, the suggested circulating current control approach lowers conducting losses and equipment ratings whilst increasing converter quality and effectiveness. The effect of asymmetrical leg impedance on circulating current suppression (CCS) in the MMC-HVDC network is investigated in Reference [261]. A technique of employing a supplemental circuit for the MMC to implement CCS and enhance the productivity of the MMC-HVDC system is provided by relying on mathematical analyses. Reference [262] proposes a novel circulating current optimization control (CCOC) strategy for decreasing the maximum values of arm current in MMC whilst keeping the peak SMs capacitor voltage fluctuation constant. It is possible to construct a simplified solution for the magnitude of circulating current that can be delivered. A comparison study is provided employing the same statement to highlight the benefits of the recommended control strategy on the current methods. Two circulating current controllers are detailed that may be used to regulate the amplitude and phase angle of the second harmonic circulating current according to the deduced formulas.

5.1.5. Submodule Capacitor Voltage Control Ripple. Submodule capacitor voltage ripple issue is a key challenge with MMC technology. The submodule capacitors in the MMC architecture act like intermediate stations for transferring power between the input and output ends. The power transfer between the DC and AC polarities, on the other hand, frequently leads to unfavorable submodule capacitor voltage ripple [263]. In other words, the submodule capacitor voltage ripple arising from the power transmission between the upper and lower arms is predominantly varied at the basic frequencies in the typical MMC design [264, 265]. In submodule capacitor voltage ripple, the magnitude of every harmonic is inversely related to the submodule capacitor value and the associated angle frequency [265]. Previous studies have shown that a reduced submodule capacitor voltage ripple favors limiting the dimensions and mass of the submodule capacitors, which
accounts for the majority of the MMC scheme’s entire dimension and mass [263].

5.2. Control Theory of DC/DC MMC. For an efficient high-power transfer in DC/DC MMC technology, establishing an appropriate DC/DC MMC architecture as well as the optimal control approach is extremely vital. In recent years, control technologies based on the utilization of parameters such as controlling the SM capacitor voltages [266], arm voltage balancing [228], minimizing the circulating current [266], directly regulating the DC voltage ratio [267], active power control [36], and output voltage balancing control [191] for efficient and controllable power transmission in DC/DC MM topologies, as well as traditional MMC topologies, have been developed. The discipline of DC/DC MMC is comparatively modern technology. For DC/DC MMC, several new architectures, modulation methods, and control technologies have been presented, and much more investigative studies are needed to increase its effectiveness [268]. This research [185] describes the implementation and governance of an innovative DC/DC MMC that allows offshore wind farms to be integrated into the HVDC power network. The suggested converter’s flexibility allows for scaling across an extensive variety of voltage ranges. The suggested converter displays higher characteristics in respect of effectiveness, losses, and device usage. In this study, a proportional resonant (PR) technique is used to regulate the suggested converter that operates straightforwardly on the MMC’s AC output in a stable standard reference. The PR regulator provides identical stable and dynamic characteristics like a synchronous chassis PI regulator, as well as various subcontrol cycles such as SM voltage balancing management and circulating current reduction. The utilized controller performs straightforwardly on the primary side of the MMC AC, eliminating complicated transformations and ensuring structure solidity across network fluctuations. A schematic representation of the control technique used for this study [185] is given in Figure 40. The MMC is modulated using the carrier phase shift PWM (CPS-PWM) approach in this study.

The output of the control system, Vac, ref, is utilized to operate the power switches as modulating signals. This study’s control strategy is examined in detail. Reference [6] presents a unique hybrid architecture for attaining effective high voltage DC/DC transformation. It has fewer semiconductor devices, lower initial expenses, a compact structure, and reduced power losses, making it desirable in interconnecting DC power grids with a voltage proportion of lower than two. NLC: modulating and SM capacitor voltage stabilization, DC power management, circulating current control, thyristor activation control, and power storing regulation are all part of the control architecture, which are shown in Figure 41, of the proposed DC/DC MMC. The referential current of the secondary side of the converter architecture is generated by the DC power management. Power balancing between the primary and secondary is required to maintain the steady functioning of the DC/DC converter design. Because the power stored in the SM capacitors is affected by the power differential between primary and secondary sides, a storage technology controller is utilized to maintain the observed average voltage of all SM capacitors in every phase identical to the baseline SM capacitors voltage level. Optimizing the received current from the primary side of the converter accomplishes the above situation. The suggested research explains the comprehensive modulation and control technique in technical detail [6].

For output voltage management according to the set-point voltage value, and determining the ideal number of functional SMs rather than utilizing constant numbers like in two grade modulating whenever the elevation parameter is adjusted, this research [269] offers a finite control set model predictive control topology. The above control approach establishes a cost function depending on the output voltage value and tries to optimize a limited number of SMs to be implanted in each design arm. It takes into account the current state of SM voltages together with a single-step forecast of the voltage’s level. The output voltage achieved whenever that controlling approach is used is consistently closer to the desired voltage. Because the output voltage pursues the desired voltage level, the output current is likewise inside the limitations. The SMs’ voltages must similarly be adjusted, with whole SMs having nearly the identical voltage, that is identical to the average of whole SM voltage values in a certain arm. The block diagram of the control technique used in DC/DC MMC design is given in Figure 42.

A novel model predictive controller (MPC) for without arm inductance DC/DC MMC based on solid-state transformers is presented in this research [270]. In addition, this study suggested a PS-SWM MPC centered power transfer and stabilizing controller combined with model-based directional controllers, as well as an enhanced dynamic methodology for the arm inductor-less design architecture. Novel improvements such as interest in using the model-based linear editors to build current references, utilizing an inductor-less arm structure for MMC design, high power productivity, and obtaining inductor-less current management for MMC based solid-state transformers can be specified in the proposed DC/DC MMC control technique. The controller created specifically for the suggested converter architecture is a closed cycle system element, a directional regulator and a model predictive controller, and a cell exchanging technique that works in an open cycle system as shown in Figure 43. Notwithstanding the lower converter inactiveness, the improvement issue is formulated as an immediate, closed-form calculation within that unique control approach. Furthermore, it does not need a high sample speed to accomplish its controlling goals.

The interior and exterior variations of the DC/DC MMC are included in the MPC methodology in this study [271], which results in a specialized MPC method. For providing exact control throughout the converter design dynamics, three control targets are implemented. Each of these control targets is governed by the minimization of a distinct cost function. A fundamental product regulates one of the
control targets, and a one-second product increases converter effectiveness, according to the defined cost functions. Figure 44 depicts the complete control architecture of the DC/DC MMC.

The suggested MPC approach improves interior dynamics, such as capacitor voltage beside arms currents, as well as exterior dynamics, such as implanted current flow to DC systems. In addition, in stable conditions, the suggested MPC technique is greater capable of lowering the circulating current. Therefore, the entire configuration effectiveness improves. Owing to the gathered results, the suggested technique can withstand a 20% toleration in arm inductance.
of the design. Several good control techniques are provided in this research, which are commonly utilized in both conventional MMC and DC/DC MMC systems. These techniques are investigated thoroughly. Many other control approaches have been presented in the literature in addition to these control approaches.

6. Discussion

HVDC technology is a critical structure in power systems because of its numerous advantages which are specified in the introduction section of the paper. The contribution of MMC technology for HVDC architecture is crucial, in addition to the significant importance of HVDC architecture in high voltage power systems. MMC technology has become increasingly essential as a result of the widespread use of renewable energy sources in recent years, extraordinary advances in power electronics, the integration of offshore wind farms with HVDC power systems, and the necessity to interconnect HVDC power systems with different voltage levels. The significance of HVDC architecture and MMC technology in high power systems has drawn several researchers’ attention to these two themes. Researchers have put forward a huge amount of effort in recent years to create more efficient HVDC power systems with minimal losses and optimum reliability, and they have proposed many DC/DC MMC topologies for more efficient power transmission, particularly in HVDC network systems. Many studies in disciplines such as the use of fewer power electronic elements which are semiconductor components, the realization of more efficient SM designs, keeping the circulating current at lower levels, balancing the SM capacitor voltage, arm current control, keeping losses at lower levels during power transfer, and using more effective control techniques have been fostered to the literature. More inventive and distinctive DC/DC MMC architectures must be produced in these key areas, and innovative control techniques must be provided in order to control these designs more conveniently. HVDC power system topologies, conventional DC/DC converters, and conventional MMC architectures, particularly DC/DC MMC topologies derived from conventional MMC designs, and converter control theories are all addressed in depth in this paper. In addition, many DC/DC MMC topologies have been achieved in recent years, particularly in the last five years, and the control strategies employed in these topologies are explained.

7. Research Gap and Future Trends

HVDC power transmission is a cost-effective method of transporting huge amounts of power across long distances with minimal losses. The current growth of HVDC power transmission networks relies heavily on DC/DC converters.
Interconnecting HVDC networks of various voltage levels requires the use of a DC/DC converter. Therefore, DC/DC converter technology plays a key role in interconnecting HVDC networks with different voltage levels. Among the DC/DC converter designs, MMC technology is of vital importance in the interconnection of HVDC networks with different voltage levels. The MMC is the newest innovation for HVDC power transmission grids interconnection, and it has a vast range of applications. It’s an established method for long-distance high-power transmission in point-to-point systems and a key component of multi-terminal DC grids. In the recent past, many DC/DC MMC topologies, control strategies, different modulation techniques, and their applications have been implemented. Nevertheless, several issues need to be investigated to eliminate major disadvantages and increase their possible implementations. Submodule capacitor voltage ripple issue is a key challenge with DC/DC MMC technology. To overcome this problem, it is essential to develop more efficient and inexpensive submodule topologies in DC/DC MMC technology in the future. It is required to boost the power and minimize the inefficiency in conventional HVDC converters. Fundamentally, using modern power semiconductor materials for improving novel switching power electronic devices and cell architectures must be developed, as well as the serial and parallel interconnections of DC/DC MMCs must be investigated. To obtain quality and efficient power output in DC/DC MMC technology, new modulation techniques and control topologies must be investigated. Particularly for output current control, circulating current control, submodule capacitor voltage control ripple, and submodule capacitor voltage control mechanisms, innovative PWM approaches and control techniques must be implemented.

8. Conclusion

With excellent characteristics which include configurable multilevel output voltage, reconfigurable architecture, the minimal harmonic substance of output voltage and output current, modular and convenient configuration, high affordability, increased performance, redundancy, and excellent fault planning, the MMC is considered to be a favorable opportunity in medium- and high-voltage power implementations. The MMC’s desirable properties influenced the establishment of novel HVDC transmission networks, STATCOM, electric railway traction, battery energy storage systems, variable-speed motor drives, solar photovoltaic energy system, and power quality enhancement systems. Numerous research studies have been undertaken in recent years to promote the understanding of MMC behavior, as well as the improvement of novel architectures, mathematical analysis, modulation approaches, and control techniques. This paper provides an overview of the latest MMC circuit topologies, including traditional submodule architectures, recently designed submodule architectures, mathematical models of MMCS, pulse width modulation schemes, classical control schemes, new pulse width modulation, control schemes, power losses of MMC, high-performance model predictive control methods, capacitor voltage balancing, circulating current control of MMC, and MMC usage applications.

Data Availability

Data available on request—you can contact us using the details provided below if required. Abdurrahim ERAT—email: a.rahim_erat@sirnak.edu.tr.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References


