IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 9, Issue 1, September 2020
Impact Factor: 4.819

# Reviews on Modulation Techniques and Multilevel Converter

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**Abstract:** *The multilevel converter, (MC) had been recommended for high- and medium-level power applications for decades. It is one of the most popular converters due to its ability to decrease the harmonic distortion in the output waveform without decreasing the converter power output. This paper presents the basic concept of four different types of multilevel converter: the neutral-point clamped, flying capacitor, cascaded H-bridge and modular. This paper also reviews five different modulation techniques for multilevel converters: pulse width modulation, space vector pulse width modulation, phase shifted carrier pulse width modulation, sinusoidal pulse width modulation and selective harmonic elimination pulse width modulation. In addition, recent publications regarding developments and improvements of fundamental concern to MCs and modulation techniques are reviewed in this paper. The implementation of MCs within renewable energy systems is also discussed here.*

**Keywords:** *multilevel converter*

## I. INTRODUCTION

A. Generating electricity by using renewable energy (RE) has become an important topic. The most researched forms of RE are wind energy and photovoltaic/solar (PV). However, power quality issues caused by the stochastic attributes of RE and the harmonics generated from electronic power inverters are crucial issues when feeding the RE power to the grid. Hence, due to the lower harmonic characteristics and electromagnetic interference noise, a multilevel converter is inserted into the line to overcome these power quality issues [1].

B. Multilevel converters have been recommended for high- and medium-level power applications for decades [2]. They have received widespread attention because of their attractive features which consist of staircase waveform quality, small common-mode voltage, input current with low distortion and low switching frequency [3,4]. In fact, due to their increasing number of levels, MCs have the ability to synthesize the desired output voltage from several levels of DC voltage input source [5]. Recent multilevel converter topologies have overcome the need for series switching when addressing lower switching loss and improved power quality. However, there are several challenges in integrating multilevel converters as the number of levels keeps on increasing. Besides, the fundamental concerns in operating the multi- level converters are the capacitor voltage-balancing strategies, suppres- sing methods of circulating current and fault tolerance modules. Thus,

C. to address these concerns, there has been extensive research work into upgrading circuit topologies [6,7] and improving control strategies to overcome their drawbacks [8–10]. Modulation techniques and simple designs are other important factors when operating a multilevel converter at its highest efficiency. Hence, there are numerous publications on improved modulation techniques [7,11]. There have been several publications on reviewing the implementation of MCs in RE systems. For example, Barghi Latran [7] gave a comprehensive review of the MCs topologies and related control strategies in improving power quality (PQ) problems in large-scale PV systems. Another excellent technical review paper on handling the PQ problem using a PV system and a 15-level M-MC [12] has revealed that a fuzzy logic control - a dynamic voltage restorer (FLC-DVR) - is able to mitigate the sags and swells rapidly during grid-side fault conditions. Plus, a comprehensive analysis based on qualitative and quantitative indices of recent hybrid MC topologies has been carried out [13]. The influence of a MC in grid-connected PV systems, WECS and micro grids is also explained.

D. This paper aims to provide detailed reviews of the basic configura-

E. tions, advantages, disadvantages, and related recent research work on four types of multilevel converter and five modulation techniques. The multilevel converters that will be discussed in this paper are neutral- point clamped (NPC), flying capacitor (FC), cascaded H-bridge (CHB) and modular (M) multilevel converters. The modulation techniques are

F.

G. pulse width modulation (PWM), space vector pulse width modulation (SVPWM), sinusoidal pulse width modulation (SPWM), phase shifted carrier PWM (PSC-PWM) and the selective harmonic elimination pulse width modulation technique (SHEPWM). These multilevel converters and modulation techniques are selected for review in this paper due to their well-known and developing technology in electronic power systems. Furthermore, the latest publication on the implementation of multilevel converters with RE considers design complexity, the power quality problem and the switching strategies problem are also reviewed here.

H. A basic understanding of standard multilevel converter topologies will be presented in Section 2, while Section 3 covers the basic concept on how the modulation techniques switched the multilevel converters. The latest publication on the application of multilevel converters to RE systems is examined in Section 4. The conclusions are drawn in Section 5.Power Converters for Transmission Applications Based on fundamental network theory, voltage and current sources of electrical energy can be distinguished. Either a voltage source converter (VSC) or a current source converter (CSC) can be used in any dc/ac power conversion system. The presence of a voltage source that maintains a particular voltage across its ac terminal regardless of the magnitude or polarity of the current flowing through the source indicates that the VSC is connected to an active dc system, as depicted in Fig. 2 (a). Therefore, the converter functions as an inverter or rectifier with lagging or leading reactive power by controlling the phase angle and magnitude of the ac voltage through switching methods. The switches in VSCs typically have the capability of reverse conducting (RC) or bidirectional current conducting. This permits the power inversion in VSCs by controlling the Idc heading while Vdc has a proper extremity. A VSC cannot be directly connected to a strong air conditioning system, which should also be mentioned. A coupling reactance is required between the converter terminal and the AC system in this scenario. A CSC that functions as a double of the VSC, as depicted in Fig.2 (b), is an additional method for connecting ac systems to dc systems. By connecting a large inductor to the dc side pole, the CSC is a current stiff converter on the dc side. A shunt capacitor at the converter ac terminal is required as an interface because the AC system has a significant inductance. Rather than the VSC based HVDC framework, the CSC can lead current in one bearing while at the same time hindering voltage in the two polarities. CSC switches typically have reverse blocking (RB) or bidirectional voltage blocking capabilities. With the right switching control strategy, this makes it possible to directly control the ac current's phase angle and magnitude. In CSC-based systems, power reversal is therefore accomplished by reversing the dc voltage's (Vdc) polarity. In each switching cycle, a two-level voltage source (current source) converter uses just one dc level, Vdc (Idc), to produce an average that is the same as the reference voltage or current, as depicted in Figure. 3 (a). As a result, there is a fair amount of switching loss and total harmonic distortion (THD). In contrast, multilevel converters are capable of synthesizing a staircase waveform by utilizing multiple independent dc voltage or current sources (batteries, renewable sources) created by inductors, capacitors, or separate sources. The directing points of each source can be picked with the end goal that the absolute symphonious mutilation of the result voltage or current becomes least. In most cases, these angles are selected with the intention of canceling the predominant lower frequency harmonics and, ultimately, synthesizing waveforms that are as close to a sinusoidal shape as is practical. Figure shows this method. 3 (b). As a result, a two-level converter's filter size is significantly reduced. However, compared to a standard two-level converter, the total energy stored by passive components in multilevel converter structures is approximately ten times greater for the same rated power. The voltage stress (dv/dt) can also be reduced by the staircase waveform; which can moderate the issues related with Electromagnetic Impedance (EMI). The switching losses are significantly reduced as a result of the lower switching frequency and the lower voltage stress level on the devices. As a result, the advantages of multilevel converters over two-level converters are generally lower switching losses and significantly higher power quality [52-56].

### I. Monolithic Multilevel Converters

Alluding to the previously mentioned benefits, staggered VSCs are suitable for high voltage applications. Due to their non-modular configuration, known as the "monolithic configuration," monolithic multilevel VSCs, on the other hand, require a large number of series-connected switching components for high voltage applications. The overall system design is further complicated and incurs additional costs as a result. Based on various dc link voltage (or current) structures, a variety of monolithic multilevel converters have been proposed to generate staircase output voltage (or current) levels [52-64]. In industrial and high-power applications, the neutral-point-clamped (NPC) and flying capacitor (FC) topologies are well-known. Different current and voltage control strategies and heartbeat width balance (PWM) methods have been proposed for staggered converters to accomplish an impressively higher proficiency [65]-[71]. [76]-[77] also examine the multilevel VSC's operation in fault and unbalanced conditions. Other staggered VSC geographies, in light of the solid staggered voltage/current infusion

### J. Modularity in Multilevel Converters

Modular multilevel converters have made their way into commercial high-power applications over the past decade thanks to their breakthrough. In general, modularity is a method for creating systems that are comparable in size by combining smaller subsystems. This refers to a cascaded connection of converter cells, or chain-links, for power converter topologies [63], which appears to be an intriguing approach for achieving high voltage and high quality waveforms. However, a transformer and rectification stage are required to transfer active power from isolated dc sources. This basic issue has been tended to in [82], opening another field of conceivable new arrangements. By utilizing an intermediate voltage source or current source, such as an inductor or capacitor, floating with respect to the ground potential in the converter circuit, the solution proposed in [61] eliminates the requirement for separate sources in high power converters. Through the converter's switching process, these passive intermediate sources are actively balanced. In order to make use of the modularity and scalability for high power applications, other circuit configurations, such as voltage or current sources or their combinations, can be tailored. 4. A proper cell or structure of building blocks is required for these solutions. The power electronics building block is a step up from modular power converters, which combine power devices, passive components, and other parts into functional blocks. Building blocks can be easily added in series or parallel to handle much higher voltages or to increase current carrying capacity. This paper aims to provide an overview of modular multilevel converter topologies, from the fundamental building blocks to the modularity at the system level, with a focus on high-power applications, specifically HVDC.

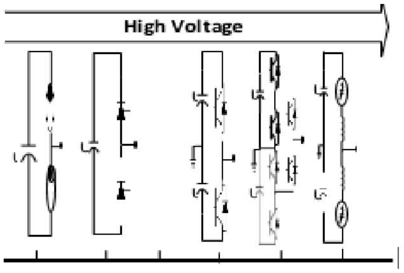
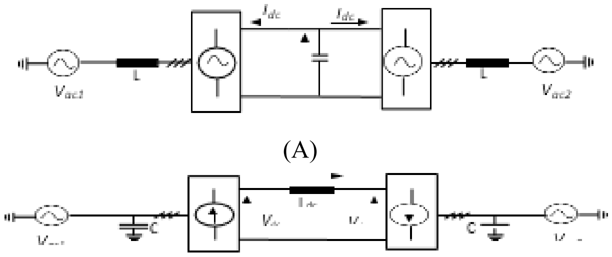


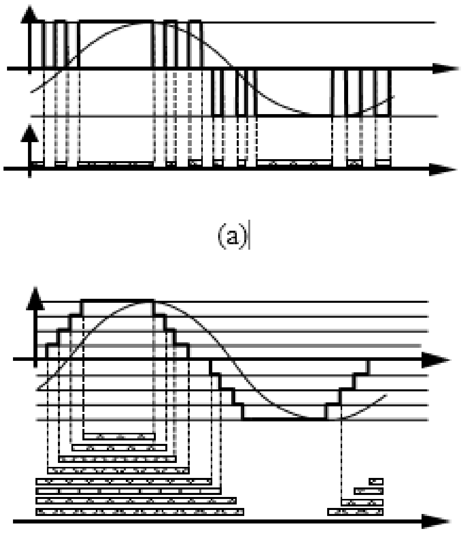
Fig. 1. Evolution of HVDC converter topologies versus power device technologies.



(A)

(B)

Fig. 2. Point to point HVDC system based on (a) VSCs, (b) CSCs.



(a)

(b)

Fig. 3. Waveforms synthesized by (a) two-level dc source, (b) multilevel dc sources.

## I. MODULAR VOLTAGE SOURCE CONVERTERS

Modular multilevel converters (MMCs) are becoming attractive for use in academic and industrial research. The ability of these converters to deliver a very high voltage with excellent harmonic performance is their most distinctive feature. Additionally, stacking the low voltage rating modular cells results in a relatively low switching frequency for the device. In this manner, the measured quality and the adaptability of the particular converters permit it to be cutthroat in high voltage applications. Modular multilevel converters outperform monolithic converters in a number of other ways, including simplified mechanical design and maintenance, reduced high voltage insulation coordination requirements, and so on.

### A. Modular Multilevel Converter (M2LC)

The first group of modular multilevel converter which corresponds to the first idea of modular converters for HVDC application proposed in [93]-[104] and is called the modular multilevel converter (M2LC). As shown in Fig. 7, this circuit has a similar structure as the conventional two-level converter; however, the series connected RC devices in each converter phase arm have been replaced by a chain of switched capacitor cells shown in Fig. 6(a). In other words, the energy storage elements at the converter dc side have been distributed in the converter arms. This topology addresses, low losses, low switching frequency, slightly above the fundamental frequency, voltage scalability due to the simple cascading of identical cells, negligible ac filters due to the synthesized pure sine voltage waveform (for above 20 cells per arm), and mechanical simplicity. Each converter arm generates a multilevel voltage with a dc offset of the pole-to-ground voltage. A sinusoidal multilevel waveform at the ac terminal is synthesized by devising a proper modulation strategy [98] and creating appropriate insertion indices . A certain number of cells in each phase-arm always contribute to maintain the dc voltage. This requires a considerably higher number of switching devices (at least twice) compared to two- level converters. Since fundamental current flows through each converter arm, the energy storage required by each arm is considerably higher (at least ten times higher) [102]. However, there is no need for additional dc link capacitors and bulky ac and dc filters in this converter. Due to the high quality of the output voltage, which is the result of the high number of cells in each converter arm, the switching frequency of the semiconductor switching device is considerably reduced. Converter semiconductor loss calculation methods corresponding to the M2LC have been reported in [103]. Theoretically, the switching frequency can be reduced to a unity pulse number [94]-[101], however, there is a trade-off between capacitor ripple and switching frequency as the capacitors are actively regulated by the switching process [104]-[109]. Given the important features of this topology, it seems to be an invincible topology for HVDC applications with respect to today's technology. This converter has been developed recently by ABB known as HVDC LightTM [128] and by Siemens known as HVDC PLUSTM [129]. However, research activities are addressing the problems associated to M2LC for high and medium voltage applications such as HVDC, STATCOMs and high\medium power drives. One of the main challenges in order to control this type of converter is the energy variation in each converter arm which causes a circulating current [108]-[112]. Another critical challenge which corresponds to the HVDC application requirements is the internal and the external fault tolerance of the converter [114]. Various fault detection methods [113] and cell protection devices have been introduced to deal with critical internal faults. The Press PackTM power devices have been introduced by ABB for HVDC applications that employ a built-in short circuit failure mode (SCFM) capability [115]-[116]. The bypass switch using a mechanical or a high current thyristor valve is another solution proposed for internal cell faults [117]-[118]. Since VSCs are not inherently fault tolerant converters, controlling the converter when subject to internal faults such as dc short circuit faults or converter ac bus faults are challenging. Different dc and ac circuit breaker solutions have been proposed in order to prevent the converter feeding the short circuit faults [119]-[121].

### B. M2LC Arm Variants

By altering the cell structure or chain-link configuration, alternative M2LC topologies can be created. An elective steel structure in the M2LC geography offers various highlights comparing to the phone types. [124] examines modular multilevel converters made up of various cells. The configurations of the chain links in Fig. 6(b-g) permit the submodule capacitor to be embedded into the circuit with one or the other extremity. This makes it possible for the converter to prevent the fault current from flowing between the positive and negative dc terminals due to a short circuit—something that would not be possible with any of the other types of VSCs that came before it. In overhead line applications, this also provides additional flexibility for controlling the converter during the brief fault. The dc link of the VSC can now be in either polarity (similar to the Line Commutated Capacitor (LCC) HVDC scheme) by decoupling the ac and dc voltages using bipolar chain links in M2LC arms. The hybrid LCC and VSC HVDC systems can now be connected in a different way thanks to this feature. However, the disadvantages of this functionality include a significantly higher power loss and a greater number of power devices than in unipolar arrangements [122].

## I. FUTURE TRENDS IN MODULAR MULTILEVEL TOPOLOGIES

The development of measured staggered converters over the course of the past ten years has progressed a few business applications like HVDC and adaptable substituting current transmission frameworks (Realities). This technology can provide some insight into future trends, as this paper summarizes. Additionally, despite its industrial presence, the technology has not yet stabilized, posing numerous obstacles to its further development. This section discusses some of these issues and trends.

When it comes to lowering the total amount of energy required to process power in electrical transmission systems, the topology of the next generation of power converters takes on a significant role. In high-power applications, the average switching frequency of IGBTs and IGCTs is below 300 Hz. The device's limitations and the cooling system's practical limitations are the main reasons for this choice. The modulation technique can improve the switching loss, which is important for reducing low order harmonics. However, the conduction loss would take over, and once the topology is chosen, there is not much that can be done to reduce it. As referenced in the text, a few cross breed converters can decrease the general conduction misfortunes of the converter; Additionally, the converter switching loss can be significantly reduced by employing zero voltage switching methods. As a result, a trend is to achieve the efficiency of converter topologies with line-commutated thyristor valves while also gaining valuable insights and overcoming the difficulties of newer topologies. In the development of modular multilevel converters for high-power applications in the future, reliability and availability at lower costs are also key trends [153]. Making better use of modular building blocks to reduce the number of critical faults in power systems could be a significant application. As was mentioned earlier in this paper, some topologies of multilevel converters can function under dc fault conditions. This ability relies heavily on the fault detection techniques. Reconfigurations of converters and bipolar cell structures, as previously mentioned, are unquestionably obstacles to the advancement of this field's research and development. Modular current source converters or hybrid VSC/CSC topologies are another trend toward fault-tolerant converters. According to price trends, energy prices are rising, grid codes are becoming more stringent, and semiconductor prices are falling [154-155]. As a result, modular multilevel converters are becoming increasingly appealing for high-power applications due to the fact that their higher initial costs are justified by the reduction in long-term operational costs. The development of modular multilevel converters will center on the grid codes of the past, present, and future as well as the ever-increasing power demand from various applications. The decrease of the necessary energy put away in the aloof parts is profoundly significant. Additionally, power converters should use as little energy as possible [155]. These necessities spur the patterns towards planning building block cells with additional functionalities or making measured converters with resembled stages. The IGBT is currently the most popular semiconductor technology for modular multilevel topologies with high power. This approach has been extremely effective in particular staggered geographies because of the low exchanging recurrence, and is supposed to exist in the impending a long time in high power application fields. However, multilevel converters would benefit from the development of mature wide band gap devices like silicon carbide (SiC), gallium nitride (GaN), and diamond power devices, which would reduce switching losses significantly and reduce the need for a cooling system [156]. As a result, it is anticipated that modular multilevel topologies for high power applications will be impacted by high-voltage SiC devices in the future [157]. This should be additionally assessed with a legitimate demonstrating of the gadget and taking into account viable issues in HV applications [158]. High-power modular multilevel converter topologies are larger and heavier because they contain a large number of semiconductors, capacitors, and inductors within their structures [159]. A compact converter topology is essential for some applications, like offshore wind. One way to cut down on the volume of these converters is to use a converter with stacked phases, as previously mentioned. Nonetheless, a further improvement is expected to limit the volume of the converter geographies. In grid-connected high power applications, transformers provide galvanic isolation and voltage matching, but a transformer less topology is still desirable. The end of transformers gives a critical decrease in the expense, volume, and weight, framework intricacy and misfortunes. Because they can provide an additional level of freedom to control voltage mismatching in applications that are connected to the grid, the brand-new modular multilevel converter topologies that make use of bipolar cells are excellent candidates for transformer less topologies. However, transformer less modular multilevel topologies should be the focus of further study. Solid-state transformers can be used in place of conventional passive transformers to further improve the grid's functionality and effectiveness. The use of silicon devices results in a very high switching loss, and special considerations for core and winding losses are necessary, particularly for high-power applications [160]. This concept also faces a number of other difficulties.

## II. CONCLUSION

By discussing the most recent modular multilevel voltage and current source converter topologies, this paper has reviewed the state of the art in modular multilevel converters. On various modular converter families, research has been conducted on the modularity concept from the cell to the system level. Different modular converter topologies have been synthesized and categorized using the proposed modularity concept. Additionally, the new modular current source topologies were developed using the duality idea. For each category of modular converters, a comprehensive comparison of topologies to the main criteria of high-power applications was presented, followed by general trends and challenges in the field. Modular multilevel converter technology will undoubtedly be driven and shaped in the future by the development of power semiconductor devices and new regulations and requirements.

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