Derivation of Multilevel Voltage Source Converter Topologies for Medium Voltage Drives

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Abstract: Multilevel voltage source converters(MLVSCs) have been widely applied in the medium voltage drive(MVD) industry. The performance of a MVD system is strongly dependent on the utilized topology. As of today, many interesting topologies have been proposed and evaluated in literature. In addition to proposing new topologies, another important research topic is the MLVSC topology derivation. In this paper, two topology derivation principles, i.e. horizontal conformation principle and vertical conformation principle, are proposed from the standpoint of modularity. In both principles, a MLVSC topology can be considered as a certain combination of one base switching cell and several module switching cells. With the proposed principle, the derived topology will naturally have modularity, which is favorable in practical applications. In addition, voltage level extension based on cascaded H-bridge building blocks(HBBBs) is also introduced. The challenging issues faced by the emerging topologies for MVD applications are also discussed. It is hoped that this paper can provide a new perspective on the MLVSC topology derivation and inspire new topologies in the future.

Keywords: Multilevel converters, voltage source converters, topologies, medium voltage drives.

1 Introduction

Multilevel voltage source converters(MLVSCs) have been dominating in medium voltage drives (MVDs) due to merits like high quality output, reduced voltage stress on semiconductor devices, reduced switching frequency, and so on[1-5]. The performance of a multilevel converter is strongly dependent on its topology. Therefore the study on converter topologies has been a research hotspot. Summarized in Table 1 are the products and their topologies from world leading MVD manufactures. As seen from the table, popular topologies that have been commercialized in MVD industry, include cascaded H-bridge(CHB) converter and its modifications (e.g. NPC/H-bridge)[6-8], neutral point clamped (NPC) converter[9-12], neutral point piloted(NPP) converter (also known as T type NPC converter)[13-15], modular multilevel converter (MMC)[16-18], nested neutral point piloted(NNPP) converter (also known as stacked multicell converter)[19-20], flying capacitor converter (FCC)[21-23], and five-level active NPC(5L ANPC) converter[24-26]. In recent years, new topologies are coming out aiming at improving overall performances of MVD systems, for example the nested neutral point clamped(NNPC) converter[27], various new or modified 5L ANPC converters[28-31], dual flying capacitor(DFC) converter[32-33], and so forth.

In the topologies mentioned above, one type of topologies can be referred as full DC bus topology[42], such as NPC, NPP, NNPP, 5L ANPC, NNPC, etc. The topologies of these converters will be illustrated in the following sections. Compared to CHB and MMC, the full DC bus topologies have the advantages of simpler structure, easier control and modulation, and less device count. They also provide opportunities of power regeneration and transformerless operation if back-to-back connected. Therefore the full DC bus topologies have attracted much attention and have been extensively studied.

Table 1 MVD products in major manufacturers[34-41]

Manufacture	Model Name	Topology
Siemens	GH150	MMC
	GH180	CHB
	GM150	NPC
	SM150	NPC
	SM120	MMC & NPC
ABB	ACS1000	NPC
	ACS2000	5L ANPC
	ACS5000	5L NPC/H-bridge
	ACS6000	NPC
Rockwell	PowerFlex6000	CHB
GE	MV6	NNPP
	MV7000	NPP
Eato	SC9000	NPC
Ingeteam	MV100	NPC
	MV500	NPC
	MV700	5L NPC/H-bridge
Yaskawa	MV1000	5L NPC/H-bridge
Schneider	Altivar1200	CHB

In addition to proposing new topologies, MLVSC topology derivation is also an interesting research topic[43-45]. Previous studies try to derive topologies from a generalized topology. This kind of method is generic. But they usually ignore the modularity in the derivation. However, for the economic and maintenance concerns, it is still desirable to use modularized

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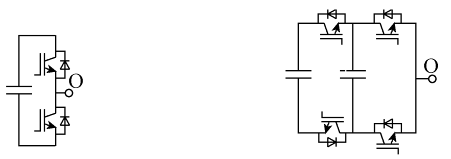
topology. This paper, on the other hand, studies the MLVSC topology derivation from the viewpoint of modularity. Herein, a module is defined as a type of switching cell that can be repeatedly used in a topology. To achieve real modularity, the repeated cells should have the same structure and the same rating. Some basic, well-known switching cells that can be used in a MLVSC topology are shown in Fig.1. With extended studies in the future, new switching cells will be identified. In this paper, two topology conformation principles, i.e. horizontal conformation and vertical conformation, based on combination of switching cells are introduced. Examples will be presented to explain the principles. Note that this paper focuses on the topology derivation, rather than operation, of the MLVSCs. Therefore the operation principle and waveforms of the considered MLVSCs are not presented.

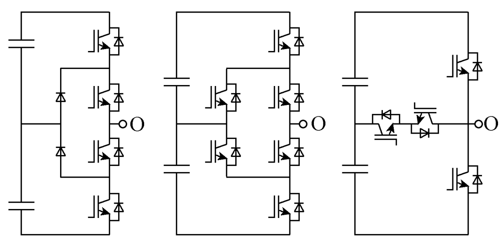
2 Horizontal topology conformation principle

In the horizontal topology derivation principle, the switching cells are classified as base cell and module cell. The base cell is the switching cell that is only used once in a topology; while the module cell is the switching cell and can be horizontally cascaded to extend the number of voltage levels. In other words, a MLVSC topology can have several module cells but only one base cell. The module cells used in one topology do not have to be the same. But in order to simplify the topology, usually no more than two types of module cells should be used.

The connecting rule between two cells is as follows: First the output point (the point O of the switching cells in Fig.1) of a switching cell is open circuited. Then, another switching cell is connected to the open-circuited point. Based on this rule, the horizontal MLVSC topology generalization principle, considering different positions of the base cell, can be illustrated as shown in Fig.2. It should be noted that the base cell, extended module 1 and extended module 2 can be either different or same.

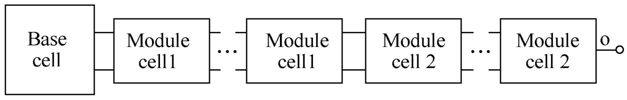


(a) Two-level (2L) cell (b) Three-level (3L) flying capacitor (FC) cell

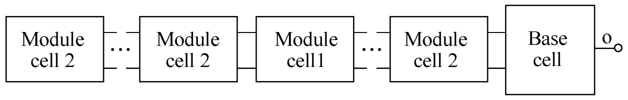


(c) 3L NPC cell (d) 3L ANPC cell (e) 3L NPP cell

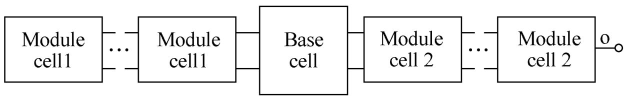
Fig.1 The basic switching cells



(a)



(b)



(c)

Fig.2 Illustration of MLVSC topology generalization with horizontal conformation principle

2.1 5L active neutral point clamped converter

The topology derivation of 5L ANPC converter is shown in Fig.3. As shown in the figure, the 5L ANPC can be seen as a combination of a 3L ANPC cell and a 2L cell. To conform the topology, first the output point O of the 3L ANPC cell is open-circuited, then a 2L cell is inserted into the open-circuited ANPC cell. In this topology, the 3L ANPC cell is the base cell and the 2L cell is the module cell. To extend the number of voltage levels, more module cells can be cascaded following the same method. The extension of 5L ANPC is illustrated in Fig.4, following the principle shown in Fig.2(a).

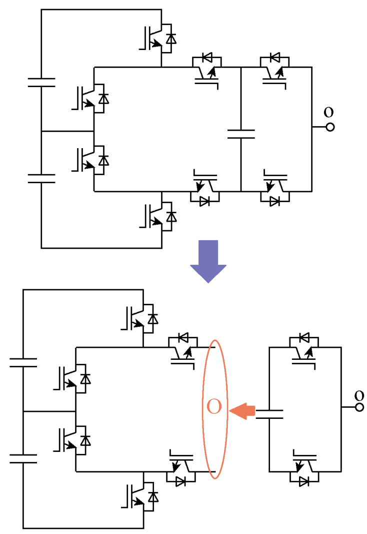


Fig.3 Derivation of 5L ANPC converter

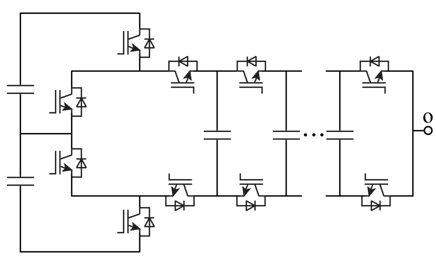


Fig.4 Generalization of 5L ANPC to N-level

2.2 Nested neutral point piloted converter

The topology and its derivation of a five-level NNPP are shown in Fig.5. The NNPP converter can be structured by two NPP switching cells. In this topology, both base cell and module cell are NPP cells. Similar to 5L ANPC, the NNPP topology can be extended by cascading more module cells following the principle shown in Fig.2(a). The generalization of NNPP topology is shown in Fig.6.

2.3 Nested neutral point clamped converter

NNPC converter is a newly proposed topology for MVD application. Its topology and derivation are shown in Fig.7 in single phase-leg configuration. This converter can be seen as a combination of a 2L cell and a NPC cell. The 2L cell is open-circuited where the NPC cell is inserted into.

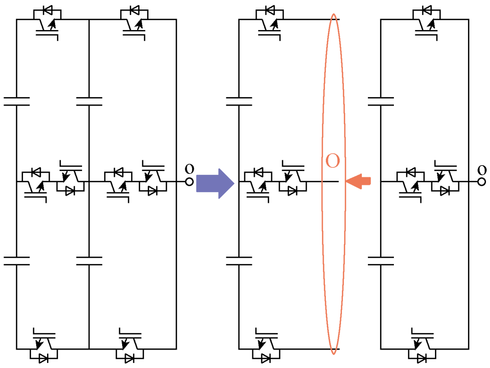


Fig.5 Derivation of the five-level NNPP converter

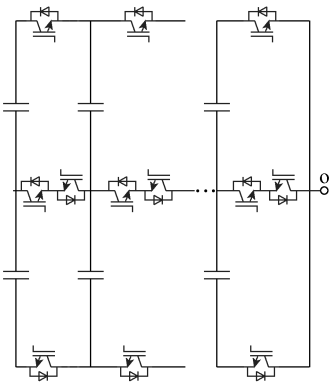


Fig.6 Generalization of NNPP to N-level topology

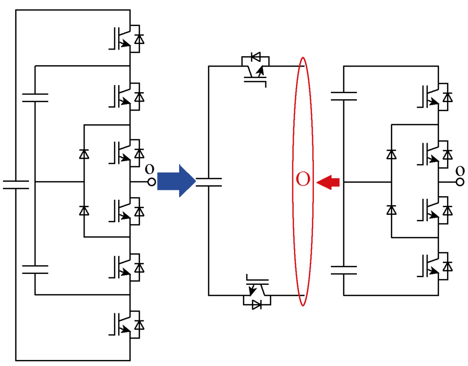


Fig.7 Derivation of four-level NNPC converter

In this topology, the NPC cell can be seen as the base cell while the 2L cell is the module cell. Different from the above 5L ANPC converter, NNPP converter, and FC converter where module cell is inserted into the base cell, in NNPC topology the base cell is inserted into the module cell. As the position of the base cell is not at the DC link side, the extension of NNPC converter follows the principle shown in Fig.2(b). Fig.8 shows the two extension method for NNPC converter. Following this method, a 5L NNPC converter is conformed and reported in [46].

2.4 Nested active neutral point clamped converter

Similar to the NNPC converter shown in Fig.7, if the base cell is ANPC cell, then a nested active neutral point clamped(NANPC) converter can be derived. A 7L nested active neutral point clamped(NANPC) converter is shown in Fig.9. However, different from NNPC converter, the extension of the NANPC converter can follow the principle shown in Fig.2(c), meaning that it can be extended from both directions. The generalization of NANPC converter is shown in Fig.10. Following this method, a 7L NNPC converter can be derived and reported in [47].

2.5 Stacked multicell converter – type 2

The topology derivation of five-level stacked multicell converter – type 2 (SMC-2) is shown in

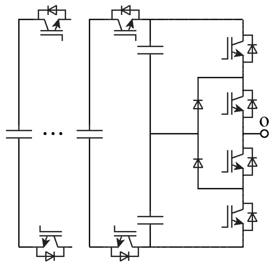


Fig.8 Generalization of NNPC converter

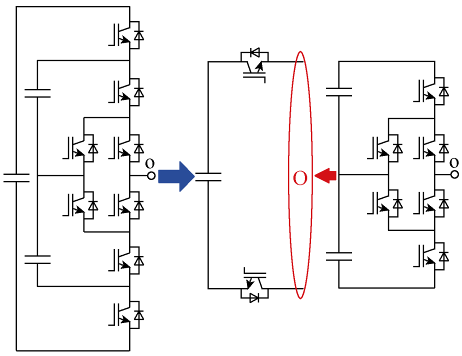


Fig.9 Derivation of NANPC converter

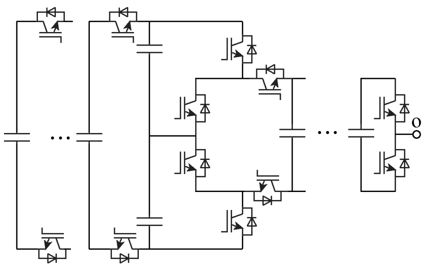


Fig.10 Generalization of NANPC converter

Fig.11. The SMC-2 is similar to the NNPP topology. The only difference is the output side cell is a NPC cell in SMC-2 while a NPP cell in NNPP. In SMC-2, the base cell is the NPC cell, and the module cell is the NPP cell. To extend the topology, additional NPP cell can be open-circuited and connected from the behind, following the principle shown in Fig.2 (b), as shown in Fig.12.

2.6 A 7L topology using 4L base cell

In addition to the switching cells introduced in Fig.1, new topologies can be obtained by new switching cells. For example, Fig.13 shows a 7L topology which can be realized by a 4L base cell and a 2L module cell.

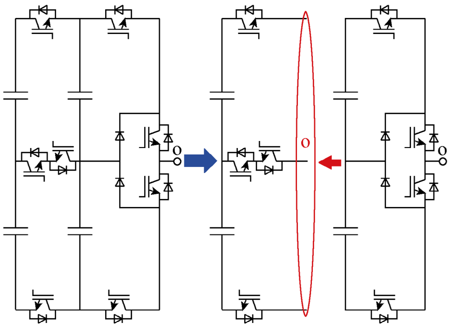


Fig.11 Derivation of five-level SMC-2 converter

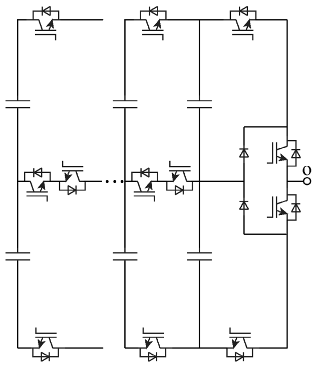


Fig.12 Generalization of the SMC-2 topology

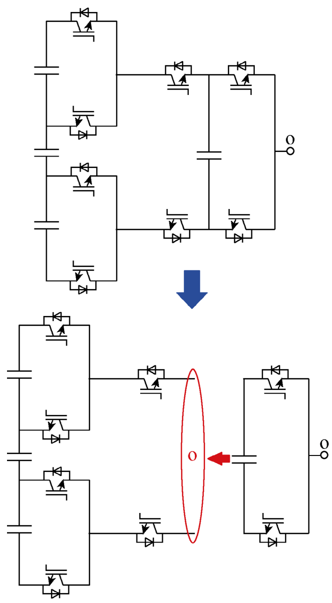


Fig.13 Derivation of a 7L converter[48]

3 Vertical conformation principle

In addition to the horizontal conformation principle introduced in last section, a MLVSC topology can also be realized by vertical stacking of switching cells. The basic principle is shown in Fig.14. To form a MLVSC topology, the module cells are stacked and connected to a voltage level selecting circuit. The voltage level selecting circuit usually works as an unfolder and switching at fundamental frequency. The extension of vertically conformed MLVSC can be realized by stacking more module cells, and using more complicated level selector circuit. However, it can also be extended by increasing the level of the module cells while still use low-level (e.g. 2L) selector. In fact, we can stack any topology and use a 2L selector to form a MLVSC topology. Note that in the cases of vertical conformation, the stacked module cells usually have the same topology. In the following, examples will be presented to facilitate the explanation of the vertical conformation principle.

3.1 Stacked flying capacitor converter

An embodiment (DFC converter presented in [32]) of the stacked flying capacitor (SFC) converter is shown in Fig.15, where one can see that two 3L FCC are stacked and connected to a two-level unfolder circuit. To extend the topology to higher levels, two ways can be used. First, one can stack more FC cells and using high-level selector circuit to increase the number of levels, as shown in Fig.16, a 7L topology[49]. This method, however, has a limitation as there are not many level selector topologies available for high-level converters. On the contrary, one can increase the level of the FC cells and still using 2L selector[33], as shown in Fig.17.

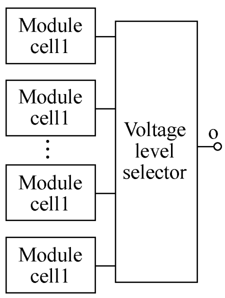


Fig.14 The principle of vertical conformation

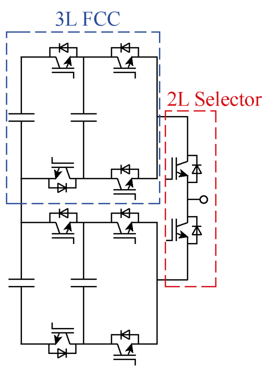


Fig.15 Topology of 5L SFC converter

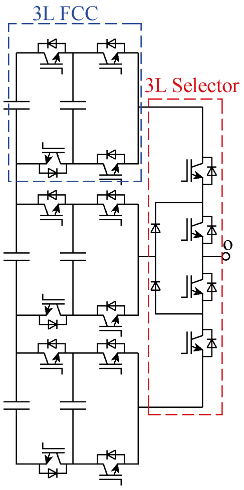


Fig.16 A 7L SFC converter with three stacked 3L FC cells and a 3L selector

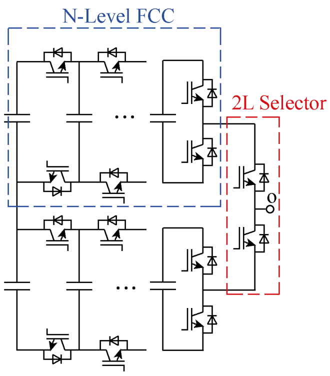


Fig.17 Generalization of SFC converter by increasing the level of FC cells

3.2 Stacked NPC converter

Similar to the 5L SFC converter, a new 5L stacked NPC (SNPC) converter can be realized by stacking two NPC cells, as shown in Fig.18. The extension of SNPC converter is complicated, and thus will not be shown here. However, modifications can be made to the 5L SNPC converter by replacing the NPC cell with NPP cell or ANPC cell. Fig.19 shows a 5L SNPP converter with two stacked NPP cells.

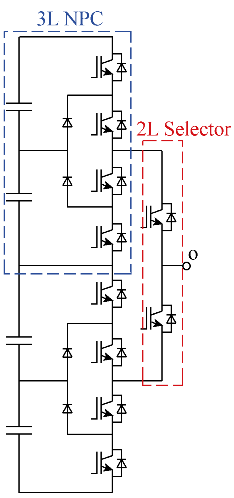


Fig.18 Topology of 5L SNPC converter.

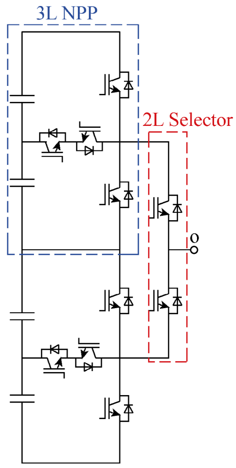


Fig.19 Topology of 5L SNPP converter

4 Realization of high-level topologies by cascading H-bridge building blocks

In previous sections, the horizontal and vertical conformation principles are introduced respectively. Extension of the topologies to higher level ones is also discussed for each example. In addition to the above methods, the number of voltage levels can be increased by cascading H-bridge building blocks (HBBBs). The topology of HBBB is shown in Fig.20. The principle is illustrated in Fig.21. The fundamental converter can be any topology.

With the cascaded HBBBs, the final number of output voltage levels, L, can be expressed in (1) for an *N*-level fundamental converter. In (1), H denotes the number of HBBBs.

$$L = 2^H * (N-1) + 1 \tag{1}$$

Compared to the extension methods introduced in horizontal conformation principle, cascading HBBBs is a more efficient way to increase the number of levels, in terms of using less flying capacitors. For example, a 5L ANPC converter with one cascaded HBBB, as shown in Fig.22, can produce a 9L output with only two flying capacitors in total. Whereas the 9L ANPC converter extended based on the principle in Fig.4 requires three flying capacitors. This is attractive for applications with power density requirements, as the film capacitor, which is usually used as flying capacitors, has the least energy density among all kinds of capacitors. However, it should be noted that the number of total devices with the two methods are same.

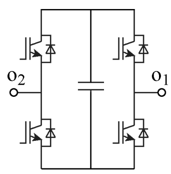


Fig.20 Topology of HBBB

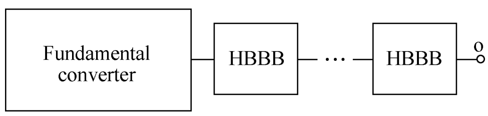


Fig.21 Extending levels by cascading HBBBs

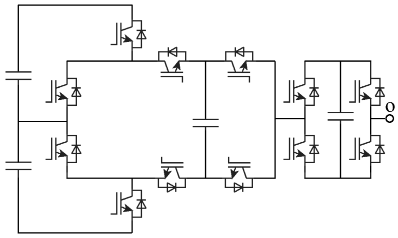


Fig.22 A 9L converter based on 5L ANPC converter and one HBBB[50]

When more than one HBBB is cascaded, the HBBBs have different device voltage ratings and flying capacitor voltage ratings, and as such the conformed topology actually does not have modularity. The HBBB at the output terminal has the lowest devices rating. The more HBBBs which are cascaded, the lower the last HBBB is rated. As a consequence, there may not be suitable device or capacitor that can be used if too many HBBBs are cascaded. Otherwise the system may end up being over-designed. This is not favorable from the consideration of device utilization. Therefore, for a given application, there is always an optimum number of HBBBs which should be taken into consideration.

5 Challenges in MVD application

Challenges faced by MVDs are discussed in this section. Considering that the features of emerging topologies, the following four challenges are focused on.

5.1 Device voltage stress

Switching device voltage stress is crucial for MVD applications. Available IGBT devices can withstand voltage up to 6500V. However, voltage derating is inevitable due to reliability consideration. For most power electronics applications, a semiconductor device can only be used lower than its 100FIT voltage, V_{1ooFIT}, meaning that the voltage at which the failure rating of the device is 100FIT. Here, FIT (failures in time) is the failure rate, indicting the number of failures per 1 billion hours. For a 6500V devices, V_{100FIT} is around 3500V. In practical applications, the commutation voltage must be lower than 3300V[51]. As a consequence, a topology that has device stress of $V_{DC}/2$ can only be used in applications with DC link voltage up to 6600V, corresponding to the AC voltage of 4321V considering a voltage margin factor of 1.08[51]. Indeed, devices can be series connected. However, this will involve voltage balancing techniques, and thus complicating the design. On the other hand, for applications higher than 4.16kV, the system can be constructed by IGCT. Nevertheless, the very limited switching frequency of IGCT will result in lower power quality. Moreover, the failure rate of PWM switched IGCT device is usually higher than an equivalent IGBT[52].

The device voltage stress issue can be alleviated if the high blocking voltage devices are only operating under fundamental frequency. In these topologies, the fundamental switching frequency devices can be built by IGCTs, instead of IGBT, without undermining reliability and efficiency[33,35,53]. As such, these topologies can easily be applied in MVDs up to 6.9kV[35]. In summary, from the device stress and utilization point of view, a MLVSC topology is practically favorable if the highest rated devices switch at fundamental frequency, as the case of 5L ANPC converter, SFC converter, SNPC converter.

5.2 Flying capacitor voltage balancing issue

Recently proposed topologies usually utilize flying capacitors to create voltage levels. As such, the voltage balancing of flying capacitor becomes very important. For some topologies, e.g. 5L ANPC, SFC, HBBB, etc., the voltage balancing can be realized under switching frequency simply through redundant switching states. This is favorable as the required capacitance is small and the voltage over flying capacitor has limited impact on the output quality.

However, for some other topologies, e.g. NNPC and the 7L converter in Fig.13, the flying capacitor voltage cannot be fully balanced due to the incomplete of redundant switching states. As a consequence, the fly capacitor voltage fluctuates under fundamental frequency. When motor is running at low speed, the voltage fluctuation can be very large. Even though sophisticated modulation and/or control methods can be applied to address this issue, the required flying capacitor capacitance is still large. Therefore, in practice such topologies are not recommended.

A common concern for flying capacitor based topologies is that the device switching frequency is not the theoretical value any more. In order to balance the voltage, the actual switching frequency of a device will be higher than its theoretical value[54]. This should also be considered in practical designs.

5.3 DC link voltage balancing issue

To generalize multilevel outputs, the DC link is usually split into several series connected parts. However, during operation, current can flow into or out of the neutral points. As a consequence, the voltage over each capacitor will fluctuate. For topologies with two-split DC link, the resultant voltage fluctuation can be self-balanced. With simple control or modulation techniques, the neutral point voltage can be controlled even under low fundamental frequency. However, for topologies with more than one neutral point, e.g. the 7L converter in Fig.13 and the SNPC converter, neutral point voltage cannot be self-balanced, especially when modulation index and load power factor is high. This has been an important limitation for this type of topology. To realize proper operation, additional balancing circuit based on DC/DC chopper can be used[55]. However, the required power rating for the balancing circuit is usually large, resulting in high cost and bulky system. On the other hand, studies have found that when used in back-to-back configuration, it is possible to balance the neutral point voltages with coordinated control of line side converter and motor side inverter[56].

5.4 Common mode voltage stress

Common mode voltage (CMV) is the source of common mode (CM) noise, leakage current, motor shaft voltage, bearing current, and other adverse effects. Many studies have been reported on mitigating CMV issues for MVDs[57-58]. For MLVSCs, in general, higher-level MLVSC tends to have friendlier CMV profile. Therefore high-level topologies, e.g. 7L, and 9L, become more favorable and should be the focus in future work. In addition, it is worth noting that even-level MLVSCs usually have worse CMV issues than odd-level converters, because of the bipolar CMV across zero voltage. This issue should also be considered in the design.

6 Conclusion

This paper presents two MLVSC topology derivation methods based on the combination of switching cells. From the viewpoint of modularity, proposing new types of switching cells is highly valued, as new topologies can be developed based on the presented principles. In addition to the two topology derivation methods, extension of voltage levels based on cascading HBBBs is also discussed. Challenging issues regarding the MLVSC topologies for MVD applications are overviewed. It is hoped that this paper can provide inspiration for researchers when looking for new topologies.

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