Letters

Ultimate Generalized Multilevel Converter Topology

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***Abstract*—There are various ways to derive multilevel converter topologies as pointed out by the author's previous work. This letter proposes a voltage-source generalized multilevel converter topology that unifies several generalized multilevel topologies and also incorporates bidirectional switches. Most of the known multilevel topologies can be derived from this topology and new topologies can also be derived from it. Examples have been given in this letter. This generalized topology helps to understand complicated converter topologies, especially those with bidirectional switches and it can also be used to determine the voltage requirements/ratings of the devices in various topologies. This letter has summarized the rules to derive topologies from this generalized topology and provides experimental results for one of the derived multilevel converter examples. It is expected that new topologies can be inspired or derived from this letter and used for existing and emerging applications, with this letter as a milestone in the research of multilevel converter topologies.**

***Index Terms*—Bidirectional switch, control, modulation, multilevel converters, topologies, voltage source.**

I. Introduction

MULTILEVEL converters have been widely used in various medium-voltage, high-power conversion applications, such as large motor drives, renewable (wind, solar) power generation, and utility systems. They are also being increasingly used for low voltage systems to achieve higher power density by reducing output harmonics, hence the filter requirements, and to achieve higher efficiency by reducing switching losses due to a lower switching voltage, i.e., a portion of the whole dc-link voltage. Multilevel converter topologies have been an extensively studied topic since the 1980s, from the conventional neutral point clamped (NPC) converters, flying capacitor converters, and cascaded H-bridge converters to T-type converters, active-NPC (ANPC) converters, and modular multilevel converters (MMC) as examples [1]. The invention of new converter topologies is highly valued in the power electronics research and many new topologies have emerged to suit various kinds of applications. There are always research questions, such as where the new topologies come from, whether there is a generic multilevel topology from which all or most multilevel converters can be derived, or there is a common way to form various multilevel converters as addressed in [2]–[6]. In the author's own paper [1], several generalized topologies and methods to derive existing and new topologies have been presented. However, an ultimate generalized topology, which can unify the existing topologies, has not been identified, especially regarding how to incorporate bidirectional switches (e.g., using back-to-back insulated gate bipolar transistor (IGBT) or MOSFETs) into the generalized topology, from which many existing and new topologies can be obtained, such as the three-level T-type converter, the four-level π-type converter [7], and other hybrid topologies [1], [8]–[10]. Some topologies with bidirectional switches are particularly difficult to understand and appreciate how they can be obtained. This letter therefore proposes a new generalized multilevel converter topology, which can incorporate bidirectional switches into the structure. This enables the derivation of many more existing topologies and new topologies.

Besides the research on topologies, the modulation and control must come hand in hand to make sure the proper operation of the topologies, e.g., balancing the voltages of dc-link capacitors and flying capacitors. There are mainly three types of modulation and control methods [11]. The first one is the selection of switching states within each phase leg (*Type I*), where there are redundant switching states for the same output voltage level within each phase leg. These redundant switching states can be used for controlling the dc-link capacitor voltages and flying capacitor voltages. An example is given in [9]. The second type of methods is the conventional space vector modulation, which normally uses the nearest three vectors or carrier-based modulation using zero-sequence voltage injection from a three-phase point of view (*Type II*). The redundant vectors in the multilevel space vector modulation and the optimal zero-sequence signal can be used to regulate the capacitor voltages [11]. This type of methods is unable to control the capacitor voltages in certain types of topologies, such as the NPC topologies with higher number of voltage levels (e.g., four levels and higher) at high modulation indexes and high power factors as well as some other simplified topologies. This is because this type of methods only allows the voltage changing by one level in each switching period, which causes the limitation on the control capability [11]. The third type of methods is the virtual vector modulation [12] or redundant level modulation [13] (*Type III*). This type of methods allows the use of multiple voltage levels within each switching period so the controllability over capacitor voltages has been

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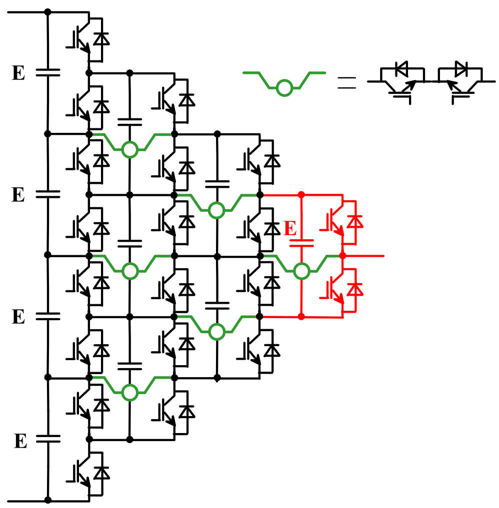

Fig. 1. Proposed generalized multilevel topology with bidirectional switches embedded in the structure.

greatly extended. With this type of methods, the four-level or five-level NPC converters and many simplified multilevel topologies with reduced number of switches and components [14] can now be used without the capacitor voltage balancing issue. Though this type of methods increases the number of switching actions hence the switching losses, this can be mitigated with the emerging fast-switching, low-switching loss wide-bandgap (e.g., SiC and GaN) devices. The invention of this type of modulation/control methods has really encouraged the work on new topologies as a lot of topologies that cannot be used due to the capacitor balancing issue can now be used and new topologies can be studied together with the advanced modulation/control to see whether they are usable and see which applications they will fit.

The main contribution of this letter is the proposal of a new ultimate hybrid generalized multilevel converter topology, from which many existing and new topologies can be derived. This proposed topology has successfully incorporated bidirectional switches into the structure, which is very important given the increasing use of bidirectional switches, e.g., back-to-back IGBTs and MOSFETs in various topologies. This work is expected to deepen the understanding of existing topologies and inspire new topologies and their applications.

II. Proposed Generalized Topology and Derived Topology Examples

The proposed generalized topology is shown in Fig. 1. The green device symbol in the diagram represents a bidirectional switch, which overcomes the shortcoming in the generalized topology in [3] that it cannot derive topologies with bidirectional switches. A five-level structure is shown here as an example and other numbers of levels can be easily obtained by having the corresponding number of layers from the right to the left. The bidirectional switch can be implemented with back-to-back IGBTs or MOSFETs or other devices. Fig. 2 shows three examples for implementing bidirectional switches, i.e., using common collector/emitter back-to-back IGBTs, using reverse blocking

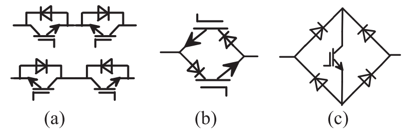

Fig. 2. Various ways to implement a bidirectional switch. (a) Back-to-back IGBTs with common emitter or common collector connection. (b) Using reverse blocking IGBTs. (c) Using four diodes and one active switch.

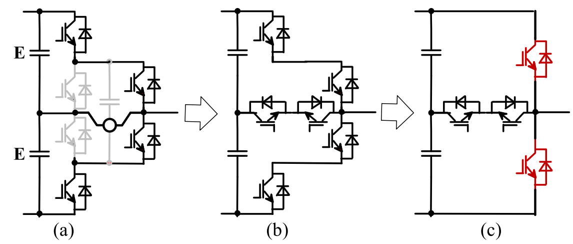

Fig. 3. Derivation of the three-level T-type converter.

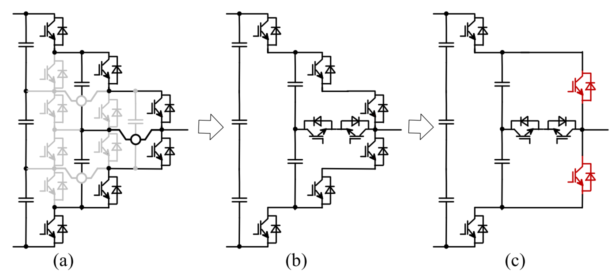

Fig. 4. Derived four-level converter topology.

IGBTs, or using four diodes and one IGBT. Note that to avoid undesired voltage jumps, the third implementation [see Fig. 2(c)] is suitable for rectifier applications but not for inverter applications.

In the following, examples of derived topologies with various number of voltage levels will be shown. Fig. 3 shows how the popular three-level T-type converter can be derived from the generalized topology. It starts with a three-level generalized structure shown in Fig. 3(a). Then, the two switches and the flying capacitor in the structure are removed with the bidirectional switch remaining in the structure. Hence, the topology in Fig. 3(b) is obtained, where all the switches have the same voltage rating, i.e., half of the dc-link voltage (E). The topology in Fig. 3(b) can be further simplified to Fig. 3(c), where the switches in red represent two switches in series in Fig. 3(b). Therefore, those two red switches need to block twice of the voltage (2E).

Fig. 4 shows the derivation of a four-level converter by removing certain devices from the generalized four-level topology and the process is illustrated in the figure but not explained in detail for the brevity of this letter. As can be seen, with the proposed generalized structure and embedded bidirectional switches, the topology derivation process becomes straightforward. The final form of the topology is shown in Fig. 4(c), also reported in [1] and [15]. Again, from the derivation process, it can be easily seen that the two red switches in the figure needs to block twice of the voltages of the rest of the switches. In this topology, only

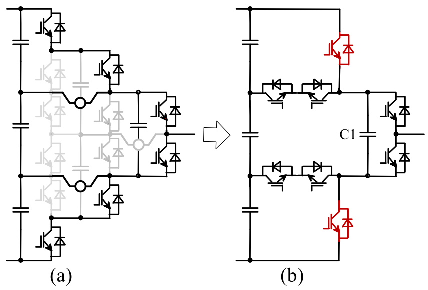

Fig. 5. Another derived four-level converter topology.

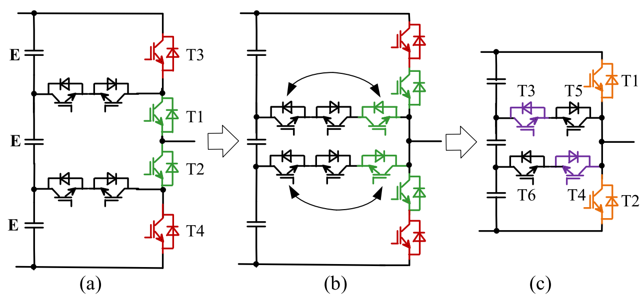

Fig. 6. Derivation of the four-level π-type converter.

six switches are required per phase leg. There are two flying capacitors in this topology, the voltage of which can be well regulated using the Type I method [15].

Fig. 5 shows another derived four-level topology, which was first proposed in [9] by the author. However, it was not straightforward to invent this topology. Now, it can be easily derived from the proposed generalized topology by having two bidirectional switches. The dc-link neutral point voltages and the flying capacitor voltages can be well regulated using the Type I modulation and control method [9].

If the flying capacitor C1 in Fig. 5(b) is removed, then the topology becomes the one shown in Fig. 6(a). As T1 needs to conduct when either the top branch (T3) is ON or the upper middle branch is ON, T1 can be moved into these two branches, similar for T2, as shown in Fig. 6(b). Then, by combining the series-connected switches, the four-level π-type converter [7] is derived, as shown in Fig. 6(c). It can also show that devices T3 and T4 need to block two-thirds of the dc-link voltage, i.e., 2E because they represent two devices in series, as illustrated from the derivation process. T1 and T2 need to block the whole dc-link voltage (3E) as they represent three switches in series. The balancing of the three dc-link capacitor voltages needs advanced modulation strategies, such as the redundant level modulation proposed in [13].

Fig. 7 shows the derivation process of a new four-level topology. There is an option whether capacitor C1 in Fig. 7(b) is reserved or not. If reserved, the topology can balance the capacitor voltages with ordinary Type II modulation and control methods. If C1 is removed and further simplified into the topology in Fig. 7(c), then it requires redundant level modulation (Type III) to balance the dc-link capacitor voltages. Again, the red devices in Fig. 7(c) represent three devices in series and need to block the whole dc-link voltage.

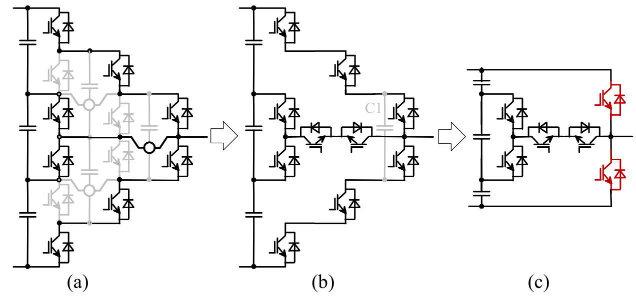

Fig. 7. Derivation of a new four-level converter topology.

From the aforementioned derivation process, some general derivation principles can be summarized: The outermost two devices in each layer must be kept in the first derivation step. Elements (switches, capacitors) within the generalized topology should be removed symmetrically from the upper and lower half of each layer. Some series-connected devices can be replaced with a single device of higher voltage ratings. If the capacitors are removed to simplify the topology, this will reduce the concern regarding the reliability, cost, and volume of capacitors. However, this will likely reduce the controllability of the voltages of the remaining capacitors. It will also make the switching devices connected in series. If the switching devices are removed, it will reduce the number of switching devices and associated cost, gate drives, etc., but it will likely mean that the remaining switching devices need to handle a higher voltage or current. If the bidirectional switches are kept in the structure, it will lead to a more simplified topology, but the capacitor voltage control challenge and the voltage rating of the remaining devices can be higher.

The capacitor voltage balance is a challenging issue in multilevel converters. As given in Section I, there are three types (Types I, II, and III) of modulation/control strategies for controlling the capacitor voltages. Which type of modulation is needed depends on the topology. In [1], how to judge whether the dc-link capacitor voltage can be balanced with Type I or Type II methods is elaborated (see [1, Figs. 19 and 20]). If the dc-link capacitor voltages cannot be balanced using Type I or Type II methods, then the Type III method should be used, which provides more controllability at the cost of more switching actions/losses and harmonics. The demonstration of using the Type I method can be found in [9] as an example. The demonstration of using the Type II method can be found in [11]. The demonstration of using the Type III method can be found in [13] according to specific topologies.

For five-level converters, Fig. 8 shows the derivation process of a five-level converter, which uses two bidirectional switches and the capacitor voltages can be controlled using a combination of Type I and Type II methods.

It should be noted that this generalized topology can also be used to derive converters without bidirectional switches and a lot of examples were given in [1]. For example, Fig. 9 shows the derivation of the five-level ANPC converter [16]. Fig. 9(a) shows the version with three flying capacitors, which does not need series-connected devices. Fig. 9(b) shows the version where the capacitors are removed and higher voltage devices are used as

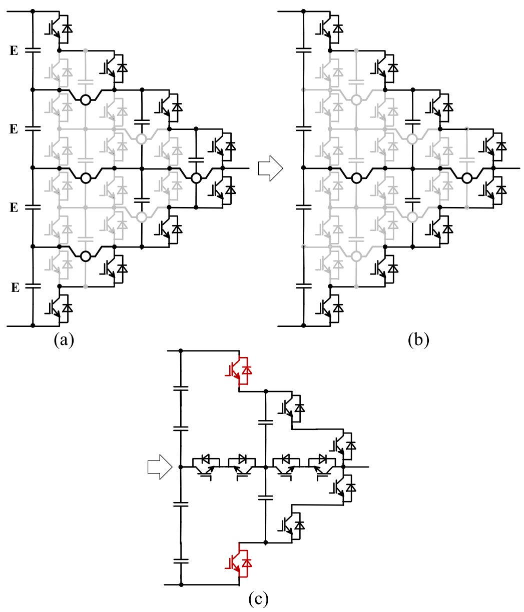

Fig. 8. Derivation of a five-level converter topology.

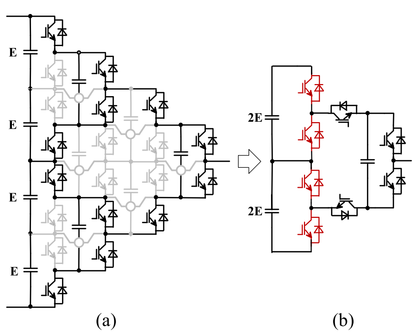

Fig. 9. Derivation of the five-level ANPC converter topology.

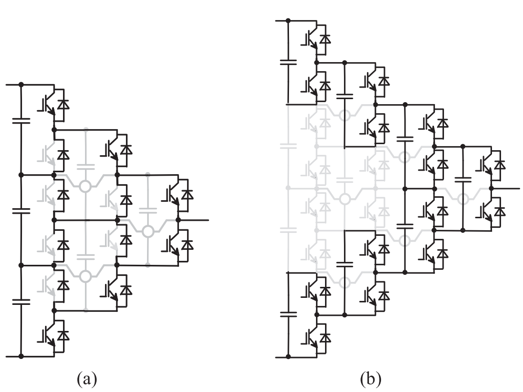

Fig. 10. Two derived topologies. (a) Four-level diode NPC. (b) MMC.

shown in red. The capacitor voltages can be controlled using the Type I method.

Fig. 10 shows a derived four-level diode NPC topology with symmetrical clamping diodes and a version of the MMC topology.

Fig. 11 shows another five-level topology, which can be derived from the generalized topology as well. This topology was derived in [1] and also reported in [10] recently for motor drive applications. The capacitor voltage can be controlled using the Type I method.

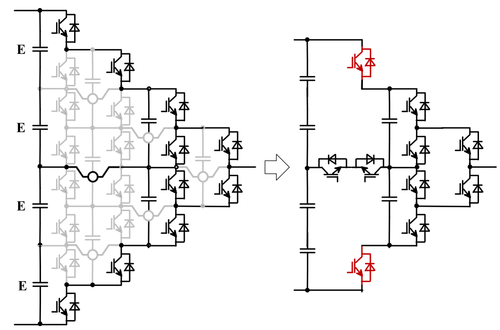

Fig. 11. Five-level topology derived from the generalized topology.

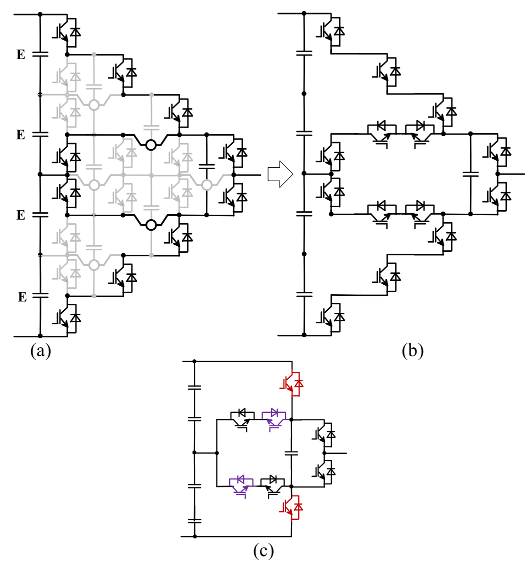

Fig. 12. Five-level converter topology.

Fig. 12 shows another five-level topology derived [8], which only requires eight switches and one flying capacitor in each phase leg, as shown in the version of Fig. 12(c), and the capacitor voltages can be regulated using the Type I method.

Though a lot of common topologies can be derived from the proposed topology. Some special multilevel converters with combined structures cannot be derived directly from the topology. For example, the one in [17] uses an H-bridge converter combined with multilevel sources to form a multilevel converter, which cannot be derived directly from the proposed generalized topology.

Generally speaking, the proposed generalized topology is more suitable for deriving multilevel converters with a symmetrical structure in terms of the upper half and lower half of the circuit, not asymmetrical structures. For example, some four-level or five-level NPC converters have unequal number of clamping diodes across the upper half and lower half of the circuit, which cannot be directly obtained from the generalized topology. Nevertheless, after some manipulation of the derived circuit, they can also be obtained.

Fig. 13 provides a classification of multilevel topologies. From the dc-link point of view, the topologies can be categorized

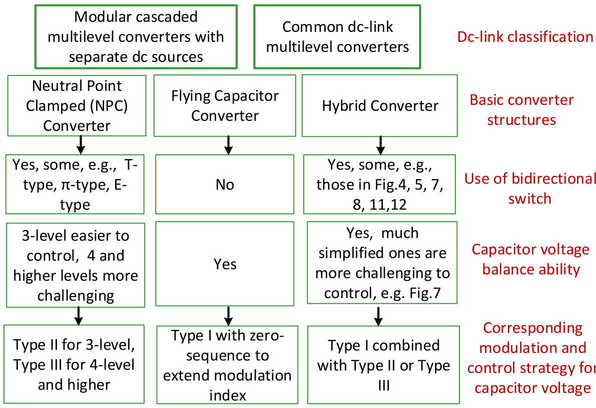

Fig. 13. Classification of voltage-source multilevel converter topologies.

TABLE I
PROTOTYPE PARAMETERS

Parameters	Values
DC-link voltage	V_{dc} = 300 V
DC-link capacitors	C1=C2=C3=2000 μF
Flying capacitor	C_{fc} = 300 μF
Carrier (switching) frequency	fs = 10 kHz
Fundamental frequency	f_o = 50 Hz
Load	R = 25 Ω, L = 5 mH
Modulation index	m = 0.95
Dead-time	t_d = 2 μs

by a common dc-link source or modular cascaded structures with separated dc sources. Then, there will be three basic structures, e.g., NPC converter, flying capacitor converter, and hybrid converters, noting they can also be used to form cascaded structures. Some NPC converters use bidirectional switches, such as three-level T-type, four-level π-type, and five-level E-type converters. Some hybrid converters also use bidirectional switches. Regarding capacitor voltage control and modulation, the four-level and five-level NPC converters are difficult to balance the dc-link capacitor voltages at high modulation indexes and high power factors, so the Type III method (e.g., redundant level modulation) is required to balance the capacitor voltages. For flying capacitor converters, the voltage balance can be achieved with the Type I method (switching states selection within each phase leg) plus zero-sequence voltage injection to extend the modulation index. For hybrid converters, the Type I method combined with Type II or Type III methods can be used to control the capacitor voltages.

III. Experimental Results of a Derived Four-Level Converter

The modulation and control can be developed according to specific topologies. As described in Section I, one of the three types of the modulation/control can be used. Here, the topology shown in Fig. 5 is used as an example and a phase leg has been built for experiments. A picture of the prototype is shown in Fig. 14 and its specification is given in Table I. By selecting the switching states within each phase leg, the dc-link capacitor voltages and the flying capacitor voltage can be well controlled. The details were given in [9]. The phase output has four voltage levels and the output current is sinusoidal, as shown in Fig. 15(a).

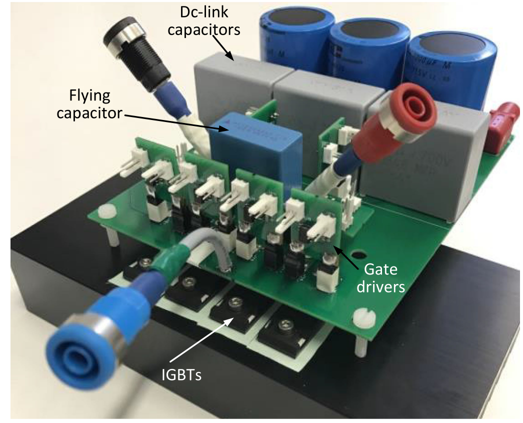

Fig. 14. Experimental prototype of a four-level converter.

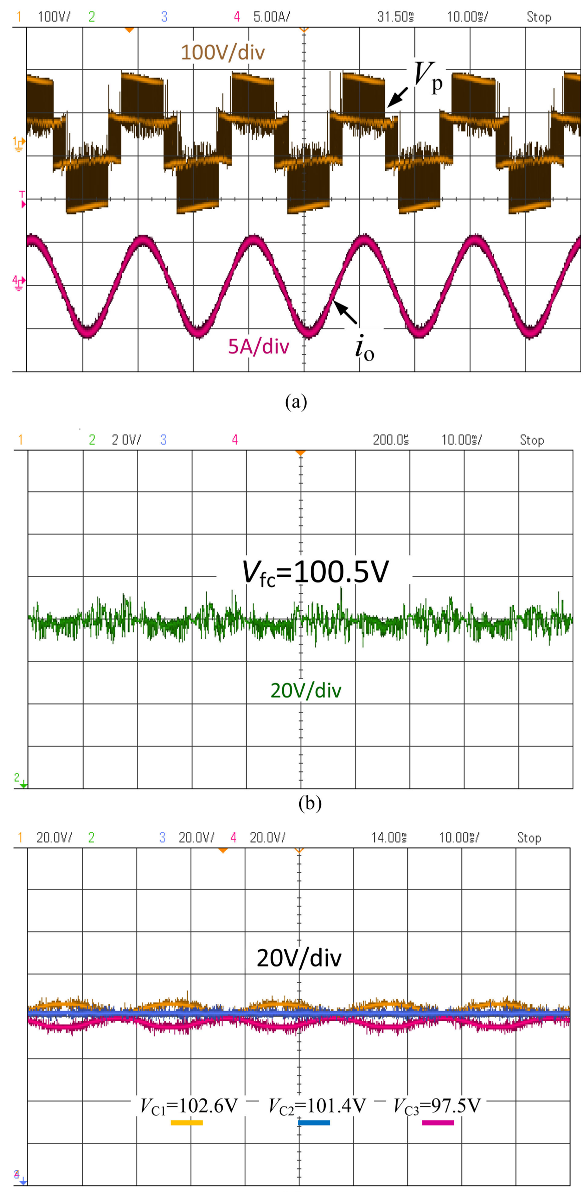

Fig. 15. Experimental results of the topology in Fig. 5. (a) Output phase voltage and current. (b) Flying capacitor voltage (average value 100.5 V). (c) Three dc-link capacitor voltages (average value denoted).

As seen in Fig. 15(b) and (c), with a dc-link voltage of 300 V, the flying capacitor voltage and the three dc-link capacitor voltages can all be regulated at around 100 V as desired. The efficiency of the converter at 10-kHz switching frequency is 98.7%. As it is a four-level converter, the switching voltage is low (one-third of the dc-link voltage) and, hence, the switching loss is also low. Compared to a two-level converter, as there are more switches in the conduction paths, the condition loss is higher.

IV. Conclusion

As demonstrated in this letter, the proposed generalized topology with bidirectional switches can be used to derive various topologies. It can also help to understand where these topologies come from and how to decide the required device voltage ratings from the derivation process. It is the author's hope that with this letter, other topologies can be derived from the generalized topology. More work needs to be done to develop control/modulation strategies for each derived topology and evaluate the performance (efficiency, power density, etc.) of each of them in a more detailed and unified manner. Together with the advances in modulation and control as well as wide-bandgap devices, these topologies can find use in existing and emerging applications.

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