Recognition and Analysis of Unexpected Modes of Modular Multilevel Converter

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ABSTRACT The modular multilevel converter (MMC) with the clamp double submodule (CDSM) performs outstandingly on the handling of DC fault current. As CDSM is composed of multiple switching devices, different operating modes can be produced according to the combination of switching states. Among the effective operating modes, there are inevitably some unexpected modes, which may cause abnormal operation or even failure of the MMC. In order to improve the reliability of MMC, it is necessary to identify all the effective operating modes of CDSM and analyze their trigger conditions. In this article, a novel mode identification method for power converter with multiple switches is used. According to reasonable combination of switching states, the components of CDSM are connected in an orderly manner to obtain all effective operating modes. Based on the operating principle of CDSM, the unexpected modes are further recognized from the effective operating modes, so that the impact of the unexpected modes on the MMC can be obtained. Finally, the recognition and analysis results of the unexpected modes in CDSM is verified by Simulink and Plecs RT Box.

INDEX TERMS Modular multilevel converter (MMC), clamp double submodule (CDSM), operating mode, mode identification.

I. INTRODUCTION

In 2003, the concept of modular multilevel converter (MMC) was firstly proposed [1]. Due to the distinguish advantages of high modularity [2], small harmonic content [3] and low converter losses [4], MMC has been widely used in high-voltage direct-current (HVDC) system. The topology of 3-phase MMC is shown in Fig. 1, which is composed of six arms. In each arm, n submodules (SM) and one inductor are connected in series. By controlling the output voltage of each SM, MMC can generate sinusoidal AC voltage [1].

As an important part of HVDC system, the reliability of MMC is crucial. Normally, MMC should have the ability to handle DC fault current and identify the component failures. There are three approaches to limit DC fault current: employing ac-side circuit breakers, employing dc-side circuit breakers and embedding submodules with DC fault handling capability. Since embedding submodules is more

effective than adding breakers, more attention is attracted on submodules [5].

Among the submodules used in MMC, the clamp double submodule (CDSM) has the ability of handling DC fault current because it can output negative capacitor voltage [6], [7]. In addition, compare with other types of submodule, CDSM can output more voltage levels and is more cost-effective, so it has become a popular SM in the MMC system [8], [9].

As shown in Fig.2, CDSM consists of five IGBTs with anti-parallel diodes, two clamp diodes and two capacitors. It is known that the on-off combination of switching devices will make the submodule operate in different modes [10]. Normal operating modes are those designed for certain functions, whereas unexpected modes or sneak circuit modes would not appear in normal cases but will occur in some specific conditions [11]. The appearance of unexpected modes will affect the output performance and bring potential risk on the operation of converters. By identifying all the unexpected modes in advance, further analysis on their trigger conditions as well as effects can be obtained. Therefore, the recognition of unexpected modes helps to ensure the performance

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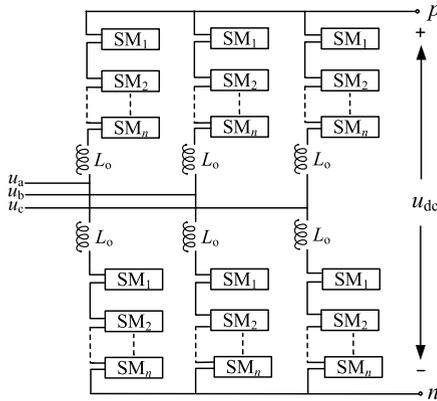
FIGURE 1. Topology of MMC.
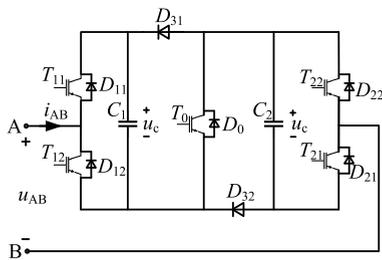
FIGURE 2. Topology of CDSM.

of converter as well as improve the reliability of operation. Generally, unexpected modes can be triggered by component failure [12], [13], control signal failure [11], variation of parameters [14] and so on. Not all unexpected modes are caused by component failure, so it is difficult to be detected. A complete view of detailed interrelationship between components and function is helpful to avoid the appearance of unexpected modes [15]. Furthermore, unexpected modes are controllable or avoidable if the trigger conditions of them are obtained [15].

Thus, to prevent the impact of unexpected modes of CDSM on MMC, a novel mode identification method is used in this article. The remainder of this article is organized in the following sections. Section II gives the introduction of mode identification principle. Section III introduces the mode recognition process of CDSM. After identifying all the effective operating modes of CDSM, unexpected modes are recognized and their trigger conditions as well as effects are further analyzed in section IV. During the recognition of unexpected modes on MMC, the novel mode identification method can obtain all the effective current paths which is effective and convenient. Then, simulation on Simulink/Matlab and experimental results on Plecs RT Box verify the impact of unexpected modes of CDSM in section V. In the end, the summary of this article is described in section VI

II. MODE IDENTIFICATION PRINCIPLE

Some methods have been invented to identify operating modes of power electronic converters including generalized connection matrix method, adjacency matrix method, and mesh combination method [10], [14], [16], [17]. However, the above methods are not suitable for converters with large number of switching devices because the calculations and analysis complexity increase dramatically with the growing number of switching devices. To simplify the procedure of identifying modes and promise the completeness of result, a novel mode identification method is adopted in this article.

The basic process of this method is to obtain effective operating modes by connecting passive components with combinations of switching states. The main steps are as follow:

1) Generate component tree diagram based on the current paths of power electronic converter.
2) Classify switching states of switches in each level in the component tree diagram and then passive components in the same level are connected under the constrain conditions, so combinations of components in the same level can be obtained.
3) Connect combinations of components in each level successively, and effective operating modes can be generated.

This method takes topology of converter and operating principles into consideration when identifying effective operating modes. It is clear that the result of this method is intuitive and complete. Besides, the analysis process is also simple and fast.

A. MODE RECOGNITION OF CDSM

First, the component tree diagram can be obtained according to current paths. It starts with input port, grows with the current paths, and ends up with output port. Points in the component tree diagram represent components, and lines represent current paths. To simplify the analysis procedure, IGBT with anti-parallel diode can be considered as a bidirectional switching device S in the tree diagram, for example, both T_0 and D_0 are represented by S_0.

Since current can flow into the CDSM from both port A and port B, two component tree diagrams can be generated according to the current direction, which are shown in Fig. 3. In the component tree diagram, the input port is set as the first level component and the output port is set as the last level component. The rest of components in the tree diagram can be classified into different levels according to the sequence of current flow. Therefore, when $i_{AB} > 0$, the tree diagram is depicted in Fig.3(a); when $i_{AB} < 0$, the tree diagram is depicted in Fig.3(b).

The second step is to obtain combinations of components in each level. Components in the tree diagram can be sorted into switching devices and passive components. For switching devices, switching states can be divided into "ON" and "OFF" states. For example, there are two components (S_{12} and C_1) in Level 3 of the component tree diagram in Fig.3(a). Since S_{12} has two switching states, connect passive components C_1 to them will obtain two kinds of combinations of components in this level.

Thirdly, after obtaining combinations of components in each level, connect components in different levels orderly.
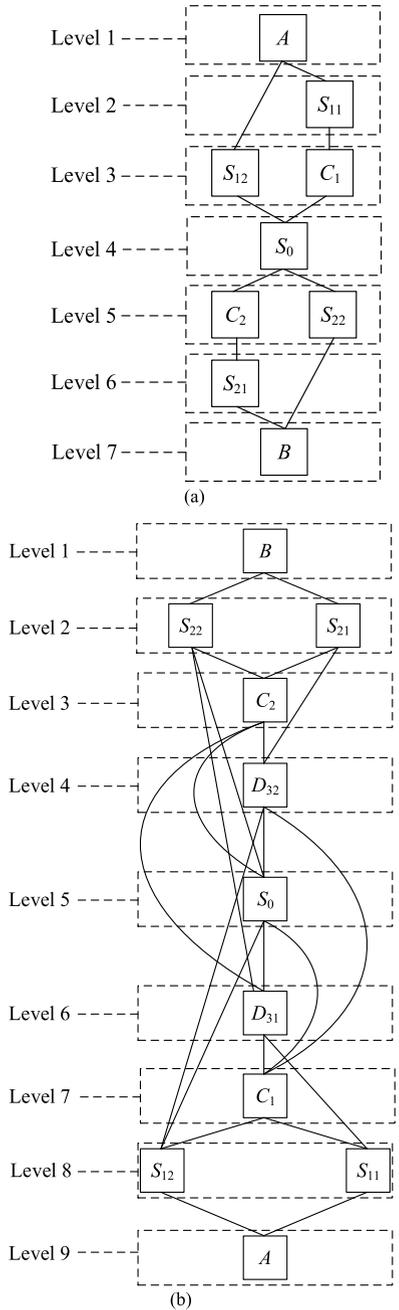
FIGURE 3. Tree diagrams of CDSM. (a) Current flows from port A to port B, $i_{AB} > 0$. (b) Current flows from port B to port A, $i_{AB} < 0$.

FIGURE 4. Effective modes of CDSM. (a) Mode 1. (b) Mode 2. (c) Mode 3. (d) Mode 4. (e) Mode 5. (f) Mode 6. (g) Mode 7. (h) Mode 8. (i) Mode 9. (j) Mode 10. (k) Mode 11. (l) Mode 12.

According to basic principles of circuit and operating principles of CDSM, some combinations of components are invalid, which should be abandoned. The constraint conditions are concluded as follow:

1) Diodes which connected in parallel operate in the same state. For example, when T_{21} and T_0 switch on, D_{22} and D_{32} connected in parallel, in this case, D_{22} and D_{32} will be "ON" simultaneously if $i_{AB} < 0$.

2) When capacitors C_1 and C_2 are connected in parallel, both of them are "Connected" or "Bypass" at the same time. For example, when D_{31} and D_{32} are "ON",

C_1 and C_2 are connected in parallel, they will be "Bypass" if S_0 switches on.

3) Capacitors C_1 and C_2 cannot be short-circuit. For example, when S_0 and D_{31} are "ON", C_1 will be "Bypass"; when S_0 and D_{32} are "ON", C_2 will be "Bypass".

Take components in Level 2 and Level 3 of Fig.3(a) as an example. Level 2 contains a switching component S_{11} while

TABLE 1. Normal operating modes and their corresponding switching states of CDSM.

Mode Type	T_{11}	T_{12}	T_{21}	T_{22}	T_0	u_{AB}	i_{AB}
NM 1	1	0	0	1	1	u_c	> 0 or < 0
NM 2	1	0	1	0	1	$2u_c$	> 0 or < 0
NM 3	0	1	0	1	1	0	> 0 or < 0
NM 4	0	1	1	0	1	u_c	> 0 or < 0
NM 5	0	0	0	0	0	$2u_c$	> 0
NM 6	0	0	0	0	0	$- u_c$	< 0

Note: "1" represents for ON state, while "0" represents for OFF state. "NM" represents for normal operating mode.

TABLE 2. Operating modes of CDSM and their current paths.

Mode No.	Type	Current path
Mode 1	NM2/5	$A\text{-}D_{11}\text{-}C_1\text{-}D_0\text{-}C_2\text{-}D_{21}\text{-}B$
Mode 2	NM 1	$A\text{-}D_{11}\text{-}C_1\text{-}D_0\text{-} T_{22}\text{-}B$
Mode 3	NM 4	$A\text{-}T_{12}\text{-} D_0\text{-}C_2\text{-}D_{21}\text{-}B$
Mode 4	NM 3	$A\text{-}T_{12}\text{-} D_0\text{-}T_{22}\text{-}B$
Mode 5	NM 2	$B\text{-}T_{21}\text{-}C_2\text{-}T_0\text{-}C_1\text{-}T_{11}\text{-}A$
Mode 6	NM 1	$B\text{-}D_{22}\text{-} T_0\text{-}C_1\text{-}T_{11}\text{-}A$
Mode 7	NM 4	$B\text{-}T_{21}\text{-}C_2\text{-}T_0\text{-}D_{12}\text{-}A$
Mode 8	NM 3	$B\text{-}D_{22}\text{-}T_0\text{-}D_{12}\text{-}A$
Mode 9	NM 6	$B\text{-}D_{22}\text{-}D_{31}\text{-}C_1\text{-}D_{12}\text{-}A$, $B\text{-}D_{22}\text{-}C_2\text{-}D_{32}\text{-}D_{12}\text{-}A$
Mode 10	UM1	$B\text{-}T_{21}\text{-}D_{32}\text{-}D_{12}\text{-}A$
Mode 11	UM2	$B\text{-}D_{22}\text{-}D_{31}\text{-}T_{11}\text{-}A$
Mode 12	UM3	$B\text{-}T_{21}\text{-}D_{32}\text{-}C_1\text{-}T_{11}\text{-}A$, $B\text{-}T_{21}\text{-}C_2\text{-}D_{31}\text{-}T_{11}\text{-}A$

Note: "UM" represents for unexpected mode.

TABLE 3. Comparison results between normal operating modes and unexpected modes ($I_{AB} < 0$).

Mode No.	Mode Type	Common Components	Different Components
7	NM	T_{21}, D_{12}	C_2, T_0
10	UM		D_{32}
6	NM	D_{22}, T_{11}	C_1, T_0
11	UM		D_{31}
5	NM	T_{11}, T_{21}, C_1, C_2	T_0
12	UM		D_{31}, D_{32}

Level 3 contains a switching component S_{12} and a passive component C_1. Under the constrain conditions, the effective combinations of components in these two levels are:

    a. $S_{11}$is "ON", S_{12} is "ON", C_1 is "Bypass";
    b. S_{11} is "ON", S_{12} is "OFF", C_1 is "Connected";
    c. S_{11} is "ON", S_{12} is "OFF", C_1 is "Bypass";
    d. S_{11} is "OFF", S_{12} is "ON", C_1 is "Connected";
    e. S_{11} is "OFF", S_{12} is "ON", C_1 is "Bypass".

TABLE 4. Performance of different operating modes.

T_0 Fails	Mode No.	u_{AB}	States of C_1 C_2
Before	5	$2u_C$	discharge
After	12	u_C	discharge
Before	6	u_C	C_1 discharge
After	11	0	/
Before	7	u_C	C_2 discharge
After	10	0	/
Before	8	0	/
After	9	u_C	$C_1 C_2$ charge
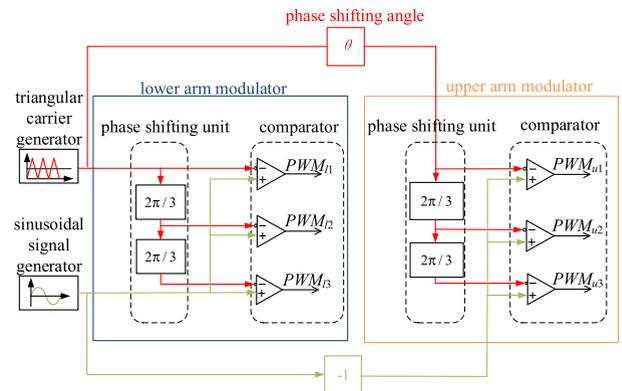
FIGURE 5. Diagram of the PSC-PWM applied to MMC.

TABLE 5. Simulation parameters of CDSM.

Item	Value
number of submodular in each arm N	3
capacitor C_1, C_2 (μF)	200
DC voltage V_{dc} (V)	200
triangular carrier frequency f_c (kHz)	1.25
reference frequency f_r (Hz)	50
inductance of bridge arm L_i (mH)	1
resistance bridge arm R_i (Ω)	2
resistance load R_z (Ω)	500
inductance load L_z (mH)	1
modulation ratio	0.87

Therefore, according to the tree diagrams of CDSM, effective operating modes can be obtained by connecting switching states and passive components under constraint conditions. In Fig. 3(a), when S_{11}, S_0, and S_{21} are "ON", the corresponding current path is A-S_{11}-C_1-S_0-C_2-S_{21}-B and Mode 1 is generated (Fig. 4(a)). Similarly, other modes in Fig. 3(a) can be obtained, which are
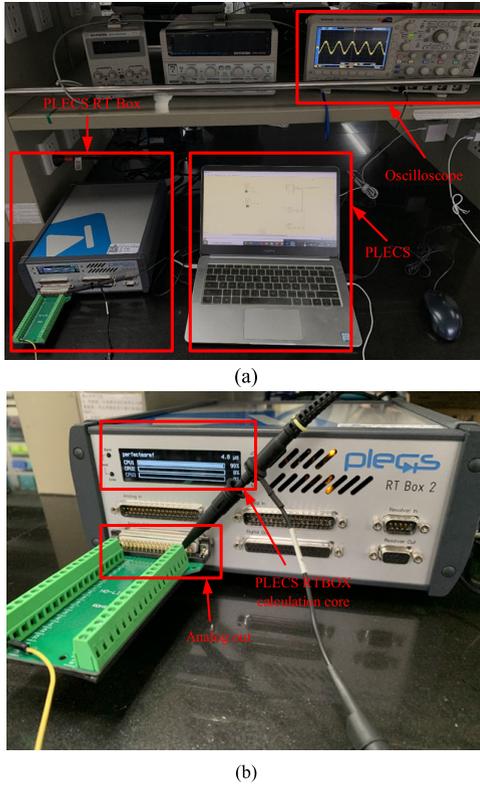
FIGURE 6. Setup of plecs RT box.

(1) When S_{11}, S_0, and S_{22} are "ON", the corresponding current path is A-S_{11}-C_1-S_0-S_{22}-B, and Mode 2 is generated (Fig. 4(b));

(2) When S_{12}, S_0, and S_{21} are "ON", the corresponding current path is A-S_{12}-S_0-C_2-S_{21}-B, and Mode 3 is generated (Fig. 4(c));

(3) When S_{12}, S_0, and S_{22} are "ON", the corresponding current path is A-S_{12}-S_0-S_{22}-B, and Mode 4 is generated (Fig. 4(d)).

The operating modes according to Fig. 3(b) can be obtained by the same method. As a result, there are 8 operating modes when $i_{AB} < 0$, which are shown in Fig. 4(e) - Fig. 4(l), respectively.

III. MODE IDENTIFICATION RESULT OF CDSM

From Fig.2, CDSM can be regarded as two series-connected half-bridge converters. MMC outputs the desired voltage when S_0 is "ON" in CDSM, and blocks the fault current by turning off all IGBTs in CDSM. Thus, all normal operating modes of CDSM are summarized in Table. 1.

Compare the effective modes in Fig.4 with Table. 1, those modes with the same current paths in Table. 1 are normal operating modes, and the rest modes in Fig.4 are unexpected modes. Table. 2 classifies the types of all effective operating modes of CDSM, it is found that Mode 1 to Mode 9 are the normal modes and Mode 10 to Mode 12 are the unexpected ones.

Based on the current paths of unexpected modes in Table. 2, the triggered conditions of unexpected modes can be
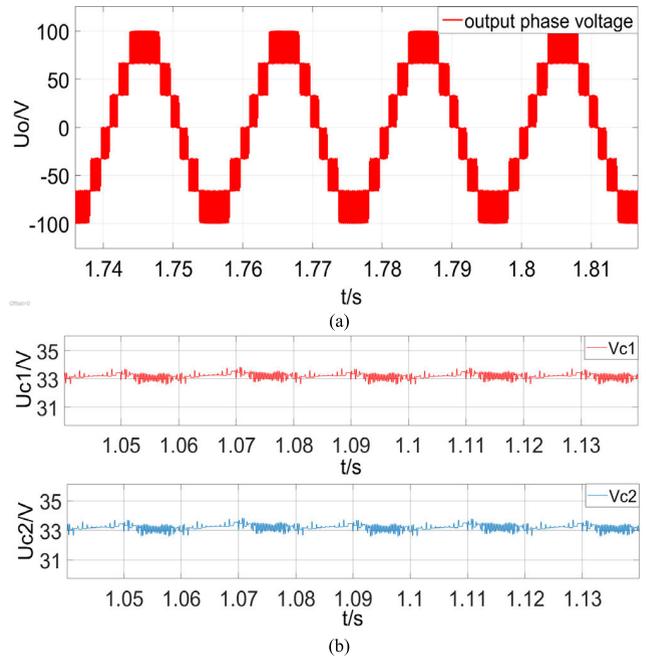
FIGURE 7. Simulation results when CDSM-MMC operates in normal operating modes. (a) Output voltage. (b) Capacitor voltage.
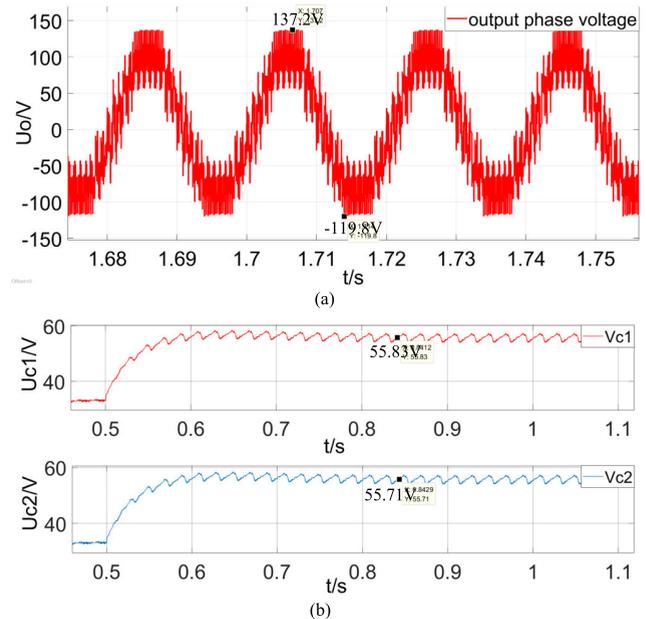
FIGURE 8. Simulation results when CDSM-MMC operates in unexpected modes. (a) Output voltage. (b) Capacitor voltage.

deduced. When T_{12} and T_{21} switch on, T_{11} and T_{22} switch off, current flows through D_{32} in Mode 10 rather than C_2 and T_0 in Mode 7. When T_{11} and T_{22} switch on, T_{12} and T_{21} switch off, current flows through D_{31} in Mode 11 rather than C_1 and T_0 in Mode 6. When T_{11} and T_{21} switch on, T_{12} and T_{22} switch off, current flows through D_{31} and D_{32} in Mode 12 rather than T_0 in Mode 5. Besides, all the above unexpected modes occur only when $i_{AB} < 0$. The comparison results of current paths between normal operating modes and unexpected modes are concluded in Table. 3.
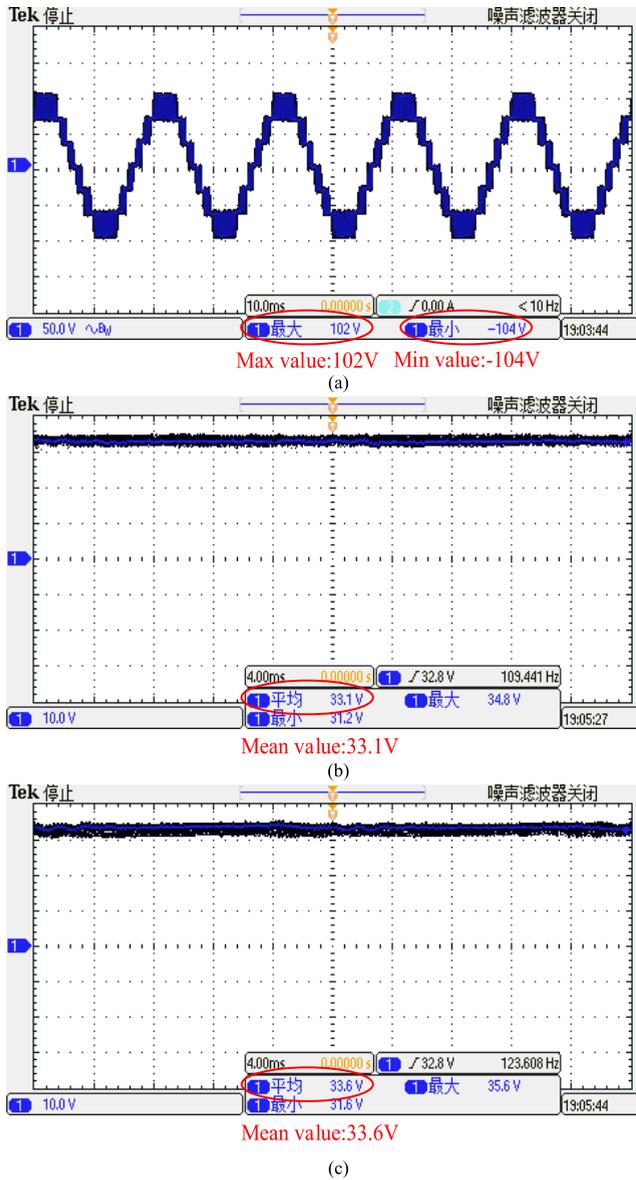
FIGURE 9. Experiment results when CDSM-MMC operates in normal operating modes. (a) Output voltage. (b) Capacitor voltage u_{c1}. (c) Capacitor voltage u_{c2}.

FIGURE 10. Experiment results when CDSM-MMC operates in unexpected modes. (a) Output voltage. (b) Capacitor voltage u_{c1}. (c) Capacitor voltage u_{c2}.

As shown in Table. 3, when C_2 has open-circuit failure, unexpected Mode 10 will appear; when C_1 has open-circuit failure, unexpected Mode 11 will appear. When T_0 has open-circuit failure or drive failure, unexpected Mode 10, Mode 11, and Mode 12 will appear when current flows from port B to port A. CDSM will operate in different operating modes when T_0 fails, and the output voltage of submodule as well as states of capacitors may change. Once T_0 fails, apart from the trigger of unexpected modes (Mode 10 to Mode 12), normal operating mode will also be affected. Since current flows through T_0 in Mode 8, CDSM will not operate in Mode 8 but will operate in Mode 9 when T_0 fails. The output voltage as well as states of capacitors in CDSM of these modes could be obtained in Fig.4. Table. 4 concludes the different performance of CDSM before and after T_0 fails. It is shown

that the output voltage of submodule u_{AB} decreases when unexpected modes occur, which will lead the output voltage of CDSM-MMC to be distorted. Besides, the number of discharged modes for capacitors decreases, thus the capacitor voltages of CDSM will increase after the unexpected modes are triggered.

IV. VERIFICATIONS

In this section, Simulink/Matlab is used to verify the effects of unexpected modes of CDSM, and Plecs RT Box [18] is used in experimental verification. The RT Box is a technical solution of Plexim GmbH in which the simulation models are realized in the Plecs simulation environment. Then, the simulation models are transformed into real-time models with minimal changes [19]. As the results are

communicated by Ethernet, the real-time results can be captured [20].

The phase-shifted carrier modulation method (PSC) is applied here [21], [22], which is shown in Fig.5. In this figure, the phase shifting angle θ is related to the harmonic content. In order to output the least harmonic content, θ equals to 0 when the number of submodules in one bridge arm is odd; θ equals to π/N when the number of submodules in one bridge arm is even [23]. Assuming that MMC has three CDSMs ($N = 3$) in each bridge arm, in this case, $\theta = 0$. The simulation parameters of MMC are listed in Table. 5. In the Table. 5, there is a virtual resistor in each arm to represent the loss of MMC [24]. The experimental setup of Plecs RT Box is shown in Fig.6.

When MMC operates normally, simulation results are shown in Fig.7. If T_0 in SM1 fails, unexpected modes will be triggered, the corresponding simulation results are shown in Fig.8. The experiment results of the above two situations are shown in Fig.9 and Fig.10, respectively.

When CDSM-MMC operates in normal operating modes, the output voltage has 7 levels and the capacitor voltages are about 33V. When SM1 in CDSM-MMC operates in unexpected modes, the output voltage in MMC is distorted. The capacitor voltages of the failed SM1 will increase to about 56.1V and 56.4V, respectively. In conclusion, the simulation and experiment results are match with the analysis.

V. CONCLUSION

This article describes an unexpected mode identification method and applies it to CDSM-MMC. This method utilizes the ordered connection of components in the converter to obtain all effective operating modes, and some unexpected modes of CDSM are detected. After that, the trigger conditions and effects of unexpected modes in CDSM is further analyzed. Finally, Simulink/Matlab and Plecs RT Box are used to verify the analysis results of unexpected modes on output performance of CDSM-MMC. As the results show, when unexpected modes are triggered, the output voltage of CDSM-MMC will be distorted, whose max and min values will change from about ± 100V to $+136$V and -128V, respectively. The capacitor voltages of the failed SM1 will increase from nearly 33V to about 56.1V and 56.4V, respectively.

The mode identification method for power electronic converters has the following advantages: 1) it uses the constraint conditions to screen some invalid modes during the process of component connection, which can reduce the redundant modes; 2) all effective operating modes are obtained directly by connecting components orderly, so the results are concise and clear. Besides, this mode identification method can be applied to other power electronic converters which can help to find unexpected modes, analyze their triggered conditions and the effects of unexpected modes on the converter systems.

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