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A NOVEL POWER REGULATION SCHEME FOR MEDIUM-VOLTAGE HYBRID AC/DC MICROGRID UNDER UNBALANCED GRID CONDITIONS

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ABSTRACT

Compared with conventional low-voltage hybrid AC/DC microgrid, a medium-voltage (MV) hybrid AC/DC microgrid is proposed in this paper. In this proposed microgrid, the MV interlinking converter is composed of front-end cascaded H-bridge (CHB) converters and back-end dual active bridge (DAB) converters. In order to make system normal operation with grid fault-tolerant ability, a novel power regulation scheme is proposed. First, the idea of virtual faulty-cell is proposed to bypass certain healthy bridge cells and adjust the power consumption between the three-phase clusters under unbalanced grid conditions. Then, this paper presents a modified modulation strategy combining phase-shifted (PS) PWM and sort and select algorithm, where no carrier reconfiguration is necessary with bypassed bridge cells. The proposed method can generate a balanced grid current and require a lower injected zero-sequence voltage under unbalanced grid conditions. Finally, based on an MV hybrid microgrid system (3 kV/150 kW). Verification results verify the effectiveness of the proposed structure and control method of this MV microgrid. By the proposed scheme, AC current balancing of the three-phase grid, DC capacitor voltage balancing of front-end CHB converters and DC bus voltage stability of DC microgrid can be realized simultaneously.

Keywords: Medium-voltage microgrid; hybrid AC/DC microgrid; zero-sequence voltage injection; balancing control; unbalanced grid; grid-voltage sags; stability control

1. INTRODUCTION

With high penetration of distributed generations (DGs) and storage devices integrated into the grid, microgrids have been widely studied [1]-[2]. Nowadays, with the increasing modern DC loads demand, hybrid AC/DC microgrids have attracted increasing interests recently [3]-[4]. As a key component linking the DC bus and AC bus, the interlinking converter (ITC) plays a crucial part in maintaining the reliable operation of a hybrid AC/DC microgrid. The conventional ITC, conventional three-phase 2-level AC/DC converter (Fig. 1), has widely applied to connection into the low-voltage (LV) grid where the line-frequency transformer is required to realize voltage transformation and electrical isolation [3]-[4]. However, there are many shortcomings for this conventional transformer, including high system loss, low conversion efficiency, much weight, and large space occupation, etc.

The recent trend of ITC is the direct connection to medium-voltage (MV) three-phase grid system without this conventional transformer to fulfill large-scale DGs integration and high-power transfer. In order to implement the above scheme, cascaded H-bridge (CHB) converters are feasible to work as the AC port of three-phase grid, due to many advantages such as higher system conversion efficiency, lower THD and switching stress, and simpler scalability for direction connection

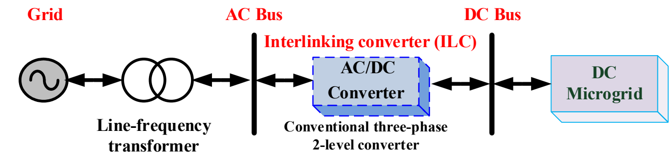


Fig. 1. Conventional low-voltage hybrid AC/DC microgrid.

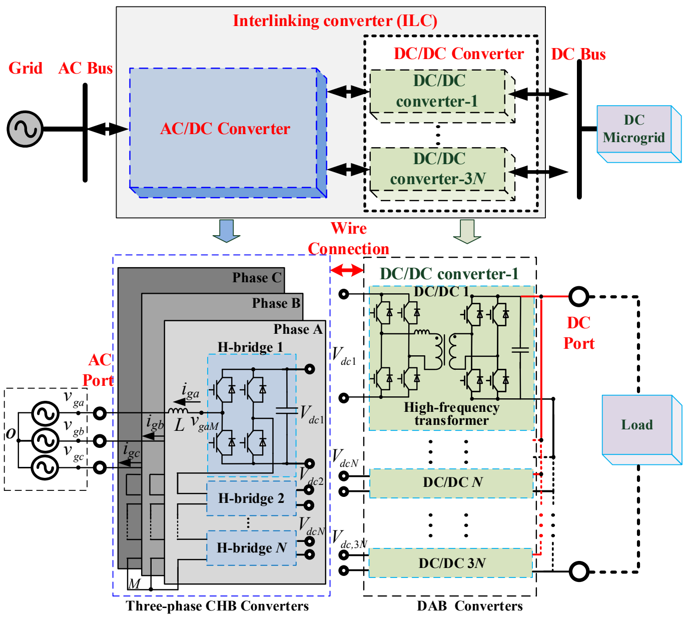


Fig. 2. The proposed MV hybrid AC/DC microgrid.

into high-voltage grid with these traditional LV power modules [5]. Moreover, considering the necessary demand for electrical isolation and wide DC input voltage range, dual active bridge (DAB) converters are adaptive to work as the DC port of sub-grid [6]. Based on the successful application in power electronic transformer [6] and large-scale photovoltaic integration [7], an alternative topology of MV-ITC can be applied and feasible in a hybrid microgrid through the wire connection of three-phase CHB converters outputs and isolated DAB converters inputs. However, grid fault-tolerant control is rarely studied in this MV hybrid AC/DC microgrid due to the complex structure and DAB integration.

Some similar studies of unbalance power for multilevel converters can be described as follow. With regulate the floating neutral point of CHB converters, a popular scheme with zero-sequence voltage (ZSV) injection is applied to realize power balancing control in the storage system [8] and large-scale photovoltaic integration [9]. However, the submodule capacitor balancing problem is not involved. In addition, some modulation strategies of a hybrid space vector modulation [10] and a modified level-shifted pulse width modulation (LSPWM) [11] are proposed to realize system fault-tolerant operation. However, such methods have higher complexity and limited industrial application.

In order to achieve power readjustment under unbalanced grid conditions, a novel power regulation scheme is proposed to realize multiple control goals, including AC current balancing of the three-phase grid, DC capacitor voltage balancing of front-end CHB converters and DC bus voltage stability of DC microgrid. The remained parts of this paper are presented as follows. In section 2, topology, characteristics, and control issues of the proposed medium-voltage hybrid AC/DC microgrid are described. Then, the proposed power regulation scheme under unbalanced grid conditions and the corresponding analysis are presented in detail in Section 3. In addition, based on an MV hybrid microgrid system (3 kV/150 kW), main results of the test system has been given in Section 4. Finally, the conclusion is summarized in Section 5.

2. THE PROPOSED MEDIUM-VOLTAGE HYBRID AC/DC MICROGRID

In this section, system structure, advantages and control issues of the proposed medium-voltage hybrid AC/DC microgrid are described.

2.1 System structure

Compared with the conventional low-voltage hybrid AC/DC microgrid in Fig. 1, the proposed MV hybrid AC/DC microgrid is shown in Fig. 2, where MV-ILC consists of the AC/DC converter and the compact DC/DC converter. Each phase of front-end AC/DC converter is composed of N CHB cells [5] and back-end DC/DC converter is composed of 3N DAB converters [6], where each CHB output is connected to each DAB input [4]. Then, all the DAB outputs are parallel connected to DC microgrid. It is noted that in order to focus the power regulation study, the DC microgrid is replaced by load in this paper. Some detailed presentation can be found in this reference [4].

Some main advantages of this proposed MV microgrid can be described as follows:

1) Based on the frond-end CHB converters of the ILC, this microgrid system can be integrated to MV three-phase grid, without line-frequency transformer.
2) Compared with LV microgrid, this microgrid system can be easier to meet high-power transfer demand.

Due to the back-end DAB integration, power isolation can be achieved by high-frequency transformers, which are more compact and cost-effective than line-frequency counterparts.

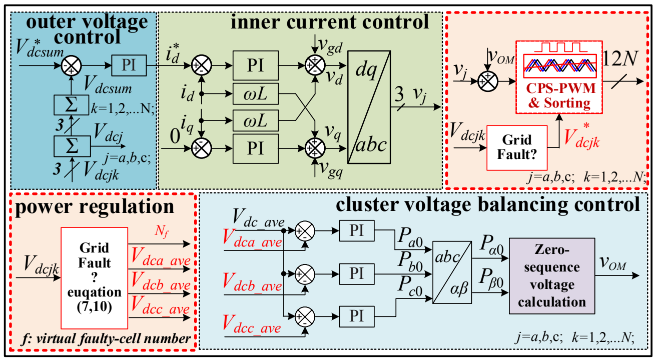
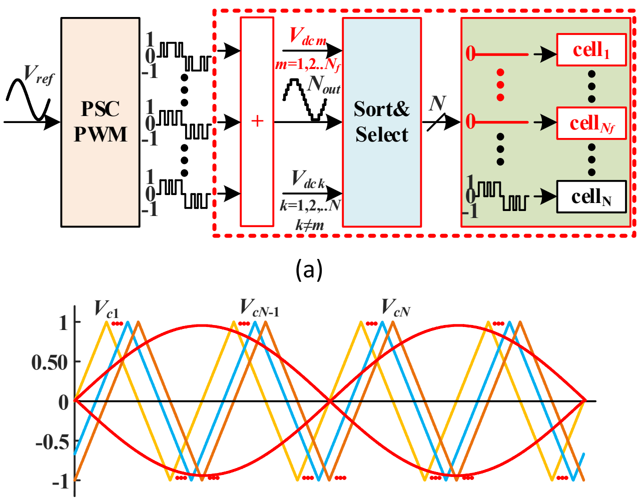


Fig. 3. The overall controller with grid fault-tolerant ability.



(a)

(b)

Fig. 4. Proposed PS PWM and sort&selelct algorithm under grid fault condition. (a) Overall diagram of the modualtion process. (b) Principle of PS PWM.

2.2 Problem description

In order to maintain this MV hybrid microgrid normal operation with grid fault-tolerant ability, multiple control goals should be achieved simultaneously as follows.

1) AC current balancing control of three-phase grid to improve power quality.
2) DC capacitor voltage balancing control of front-end CHB converters to make system stable operation condition.
3) DC bus voltage stability control of DC microgrid to realize stable power transfer between DC microgrid and AC grid.

3. THE PROPOSED POWER REGULATION SCHEME

In this section, the overall control method is described first. Then, the idea of the virtual faulty bridge cell is used to bypass the healthy bridge cells and adjust the power consumption between the three-phase clusters. In addition, with the bypassed healthy bridge cells, a modified modulation scheme combining PS PWM and sort and select algorithm is proposed.

3.1 The overall control method

Fig. 3 gives the overall control diagram with the proposed power regulation scheme under unbalanced grid voltage.

The outer voltage control is designed to generate the active current reference, which is used to control the sum of all cell capacitor voltages.

The output current control is adopted to control the active and reactive current reference, thus accurately compensating the reactive power in the distributed energy system. It is realized with decoupled PI controllers under *dq* frame, and the feed-forward signal of grid voltages is adopted to get better dynamic performance.

The cluster voltage balancing control is implemented with zero-sequence voltage injection calculated under *αβ* frame. The detailed injection principle is presented as follows. Based on the voltage deviation of the cluster voltage, three PI controllers are used to calculate the power to be injected in each phase. The injected zero-sequence voltage can be expressed as

$$v_{OM} = V_0 \cos\gamma \sin\omega t + V_0 \sin\gamma \cos\omega t \tag{1}$$

where V_0 is the amplitude of the ZSV voltage and the angle γ satisfy the following constraint

$$\begin{bmatrix} V_0\cos\gamma \\ V_0\sin\gamma \end{bmatrix} = \frac{1}{-I_d^{\,2} - I_q^{\,2}} \begin{bmatrix} -I_d & I_q \\ I_q & I_d \end{bmatrix} \begin{bmatrix} P_\alpha \\ P_\beta \end{bmatrix} \tag{2}$$

In addition, the modified modulation strategy combining PS PWM and sort and select algorithm is adopted. The proposed power regulation method and modified modulation strategy will be introduced in detail in the following subsection.

3.2 The proposed power regulation scheme

Suppose the voltage sag occurs at phase C, and the voltage sag index *D* is expressed as

$$\begin{cases} u_c = V_g \cos(\omega t) \\ u_c = V_g \cos(\omega t - \dfrac{2\pi}{3}) \\ u_c = (1-D)V_g \cos(\omega t + \dfrac{2\pi}{3}) \end{cases} \tag{3}$$

where V_g is the amplitude of the grid voltage.

Suppose the power consumption on the grid side is fixed as P_{rated}, the power consumed in the three-phase are equal and are expressed as

TABLE I. SIMULATION PARAMETERS

Type	Circuit parameters	Values
Three-phase grid	Rated power	150 kW
	Line voltage, frequency	3000 V, 50 Hz
	Input inductance	5 mH
AC/DC converter	Switching frequency	4 kHz
	DC capacitor, voltage reference	4 mF, 750 V
DC/DC converter	Switching frequency	4 kHz
	Leakage inductor	0.5 mH
	DC capacitor, voltage reference	1 mF, 700 V

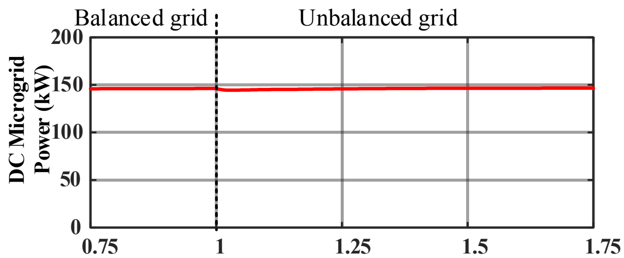


Fig. 5. DC microgrid power.

$$P_{con\_A} = P_{con\_B} = P_{con\_C} = \frac{P_{rated}}{3} \tag{4}$$

In addition, for the AC, the output grid currents is required to be balanced

$$\begin{cases} i_{ga} = I_g \cos(wt) \\ i_{gb} = I_g \cos(\omega t - \frac{2\pi}{3}) \\ i_{gc} = I_g \cos(\omega t + \frac{2\pi}{3}) \end{cases} \tag{5}$$

As a result, the AC power from the grid can be expressed as

$$P_a = V_g I_g, P_b = V_g I_g, P_c = (1-D) V_g I_g \tag{6}$$

As is shown in equation (4) and (6), the unbalanced power flow between three phases have to be adjusted by ZSV injection. As the ZSV has limited ability in power adjustment, the negative sequence current can be injected to the grid if D is too high.

In order to suppress the injected ZSV and keep the grid current balanced, the idea of virtual faulty bridge cell is used to bypass the healthy bridge cells in the phase where grid fault occurs.

The number of bypassed bridge cells can be expressed as

$$N_f = ceil\{DN\} \tag{7}$$

where *ceil* is the round function to the lower integer.

In order to further eliminate the power unbalance between the grid side and the DAB side, the power consumption on the DAB side should also be adjusted as

$$P^*_{con\_A} = P^*_{con\_B} = \frac{1}{3-D} P_{rated}, P^*_{con\_C} = \frac{1-D}{3-D} P_{rated} \tag{8}$$

The power of each DAB can be adjusted by phase-shift angle, and the power of individual DAB in each phase can be expressed as

$$\begin{cases} P^*_{con\_A\_indi} = \frac{P_{rated}}{(3-D)N} \\ P^*_{con\_B\_indi} = \frac{P_{rated}}{(3-D)N} \\ P^*_{con\_C} = \frac{(1-D)P_{rated}}{(3-D)(N-N_f)} \end{cases} \tag{9}$$

With the faulty SM bypassed, the measured voltage of the faulty phase should be multiplied and expressed as

$$V_{dcc\_ave} = \frac{N}{N-N_f} \sum_{k=N_f+1}^{N} V_{dcck} \tag{10}$$

3.3 Modified modulation method

Conventionally, with N_f virtual faulty bridge cell bypassed, the carriers in the faulty phase should be reconfigured to avoid the selection of the bypassed bridge cells.

This process can be avoided by the proposed modulation method combining PS PWM and sort and select algorithm.

When grid voltage sag occurs, the overall modulation method is shown in Fig. 4 (a), where the idea of virtual voltage for the bypassed bridge cells are used to unselect them. The principle of PS PWM is shown in Fig. 4 (b).

The virtual voltage for the virtual faulty bridge cells can be expressed as

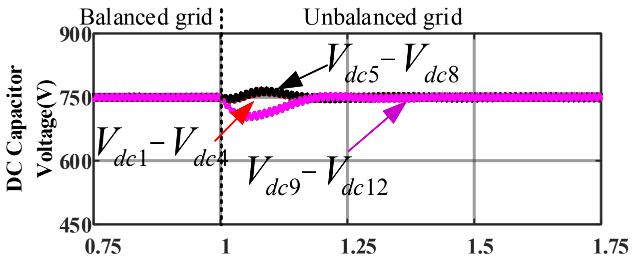
$$U_{dcm} = \begin{cases} U_{cap}^{up\lim} & i_j * N_{outc} < 0; \\ U_{cap}^{low\lim} & i_j * N_{outc} > 0; \end{cases} (m = 1, 2 ... N_f) \tag{11}$$

where U_{dcf} is the virtual capacitor voltage of the faulty cell and f is the order number of the faulty cells. i_j is the output current, and N_{outc} is the inserted cell number of the faulty phase C ($-N<N_{outc}<N$). U_{cap}^{uplim} and U_{cap}^{lowlim} are the upper limit and the lower limit of the capacitor voltage which will not trigger the alarm.

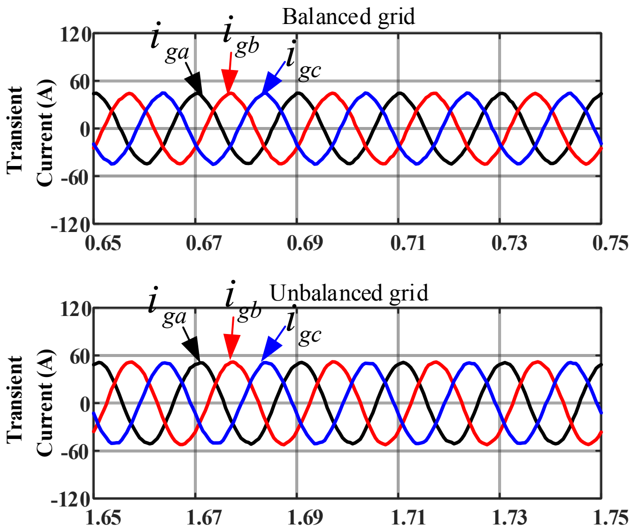
Therefore, the virtual faulty bridge cells are unselected by the sort and select algorithm.

4. SIMULATION RESULTS

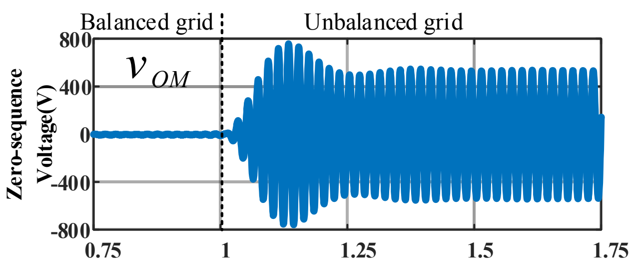
To test the proposed structure and power regulation scheme of MV hybrid AC/DC microgrid, the same topology of this test system as fig. 2 (N=4) is modeled in MATLAB/Simulink where the simulation parameters are shown in Table I. The conventional method (only the ZSV injection to regulate the inter-phase power of CHB converters) and the proposed method are verified based on two test scenarios. Scenario 1 simulates the normal



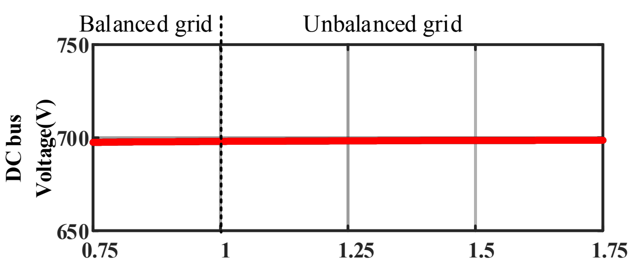
(a) DC capacitor voltages of CHB converters.



(b) AC currents of three-phase grid.

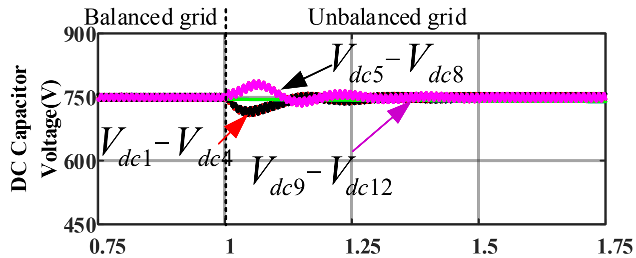


(c) Injected zero-sequence voltage.

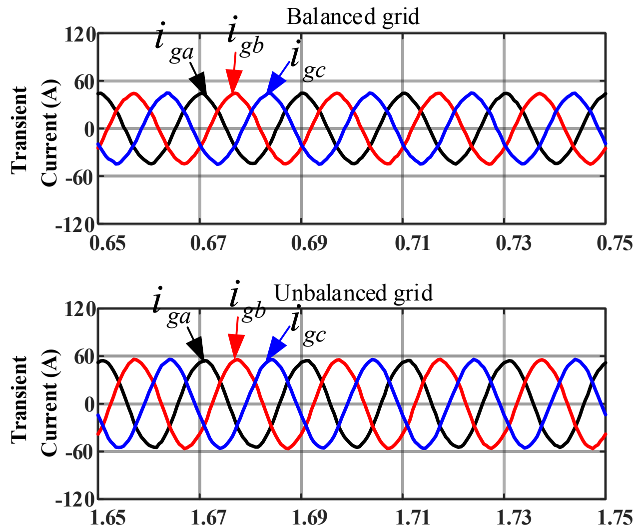


(d) DC bus voltage of DC microgrid.

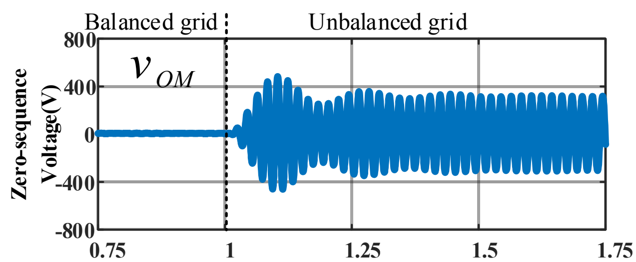
Fig. 6. Waveforms by the conventional method.



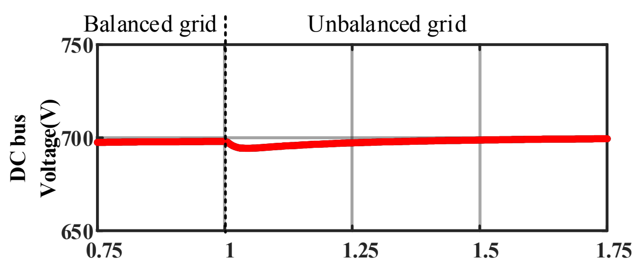
(a) DC capacitor voltages of CHB converters.



(b) AC currents of three-phase grid.



(c) Injected zero-sequence voltage.



(d) DC bus voltage of DC microgrid.

Fig. 7. Waveforms by the proposed method.

operation status under balanced grid condition in the first 1 s; Scenario 2 simulates the unbalanced grid case (grid-voltage of phase C sags 50%) from 1 s to 1.75 s in order to test system fault-tolerant ability.

The waveform of DC microgrid power is shown in Fig. 5, indicating that the system power of DC microgrid are constant at about 147 kW in scenario 1 and scenario 2.

Based on the conventional method and the proposed method, the main comparison waveforms are shown in Fig. 6 and Fig. 7, respectively. After minor voltage regulation, DC capacitor voltage balancing can both be achieved in two scenarios, shown in Fig. 6(a) and Fig. 7(a). In addition, based on different grid current values in scenario 1 and scenario 2, AC current balancing of the three-phase grid can be both achieved in two scenarios, shown in Fig. 6(b) and Fig. 7(b).

However, different ZSV values are injected based on the corresponding dynamic process, shown in Fig. 6(c) and Fig. 7(c). **It is noted that compared with the conventional method, the smaller ZSV in scenario 2 can be used by the proposed method, indicating that system can be in safer operation status with larger margin area and lower modulation index. Thus, the proposed method is better than the conventional method.**

By on the conventional method and the proposed method, DC bus voltage stability of DC microgrid can be both realized, shown in Fig. 6(d) and Fig. 7(d), due to the phase-shift control of DAB converters.

Based on these above results, by the proposed scheme, AC current balancing of the three-phase grid, DC capacitor voltage balancing of front-end CHB converters and DC bus voltage stability of DC microgrid can be realized simultaneously.

5. CONCLUSION

In this paper, to meet these demands of high-power transfer and direct MV grid connection without traditional line-transformer integration, a medium-voltage (MV) hybrid AC/DC microgrid is proposed and presented in detail where the interlinking converters are composed of CHB and DAB converters. Compared with the conventional method, a novel power regulation method with lower ZSV injection is proposed to achieve grid fault-tolerant operation. Simulation results show that by the proposed method, multiple control issues can be solved simultaneously, including AC current balancing of the three-phase grid, DC capacitor voltage balancing of front-end CHB converters and DC bus voltage stability of DC microgrid.

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