Letters

A Novel DC Chopper With MOV-Based Modular Solid-State Switch and Concentrated Dissipation Resistor for ±400 kV/1100 MW Offshore Wind VSC-HVDC System

Chaoqun Xu, Xiangyu Zhang, Zhanqing Yu, Biao Zhao, Zhengyu Chen, and Rong Zeng

***Abstract*—A dc chopper (DCC) is one of the key equipment in voltage-sourced converter-based high-voltage dc transmission systems with offshore wind power access. Combining the complementary advantages of concentrated and modular DCCs, a novel DCC with modular solid-state switches and a concentrated resistor (MC-DCC) is proposed. The non-long-term work attribute of the DCC provides opportunities to apply metal oxide varistors in modularizing series solid-state switches, thereby removing the capacitors for voltage balance. A method of designing the MC-DCC is introduced on the basis of the analysis of system requirement. Finally, prototype experiments are conducted to verify the effectiveness of the MC-DCC.**

***Index Terms*—DC chopper (DCC), metal oxide varistor (MOV), offshore wind, solid-state switch.**

I. Introduction

VOLTAGE-SOURCE converter-based high-voltage dc (VSC-HVdc) transmission systems have become an internationally recognized advantageous transmission method for accessing renewable energy including offshore wind power in recent years [1], [2]. In China, a growing number of offshore wind power VSC-HVdc projects have been planned for construction to access clean energy and rebuild the energy internet in the country. The first and largest project (±400 kV/1100 MW) is currently being built. Fig. 1 illustrates the construction drawing of this project.

The offshore wind farms are connected by a VSC-HVdc system. When an ac grid short-circuit fault occurs, the ac grid voltage at the point of common coupling dips and the power output capability of the onshore VSC-HVdc station is reduced. However, as the speed of wind turbines cannot alternate within a short time, the wind power on the offshore wind farm side is basically maintained. There is thus an imbalance in active power between offshore and onshore VSC-HVdc stations. The excess power gets accumulated in the VSC-HVdc system capacitance. To ensure that the dc-link voltage remains below its upper limit, the excess power has to be dissipated or the offshore wind power has to be reduced [3], [4]. In severe cases, this imbalance generates dc-line overvoltage that interrupts the VSC-HVdc system [5]. Therefore, to ensure the offshore wind VSC-HVdc transmission system can ride through the short-circuit fault of the onshore ac grid, this letter investigates the fault ride through of the offshore wind VSC-HVdc system.

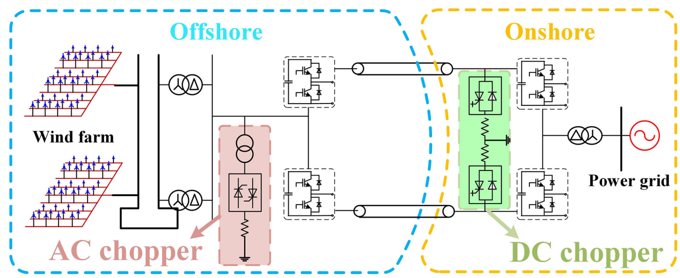

Fig. 1. Construction drawing of a ±400 kV/1100 MW offshore wind VSC-HVdc project.

The reliability of the communication system and the delay of the signal transmission increase the possibility of fault ride-through failure [5]. Therefore, a fault ride-through method that does not depend on a communication system has increasingly attracted attention [6]–[10]. The most typical approach is to develop a chopper circuit including an energy dissipation resistor. Subsequently, the surplus power of the VSC-HVdc system can be consumed as heat. If the power rating of the resistor is large enough to match the power of the VSC-HVdc system, then the fault ride through of the offshore wind VSC-HVdc system can be realized, and there is no wind farm recovery after the fault.

The chopper circuits can be divided into two categories, namely, the ac chopper (ACC) and the dc chopper (DCC). The DCC has three advantages over the ACC.

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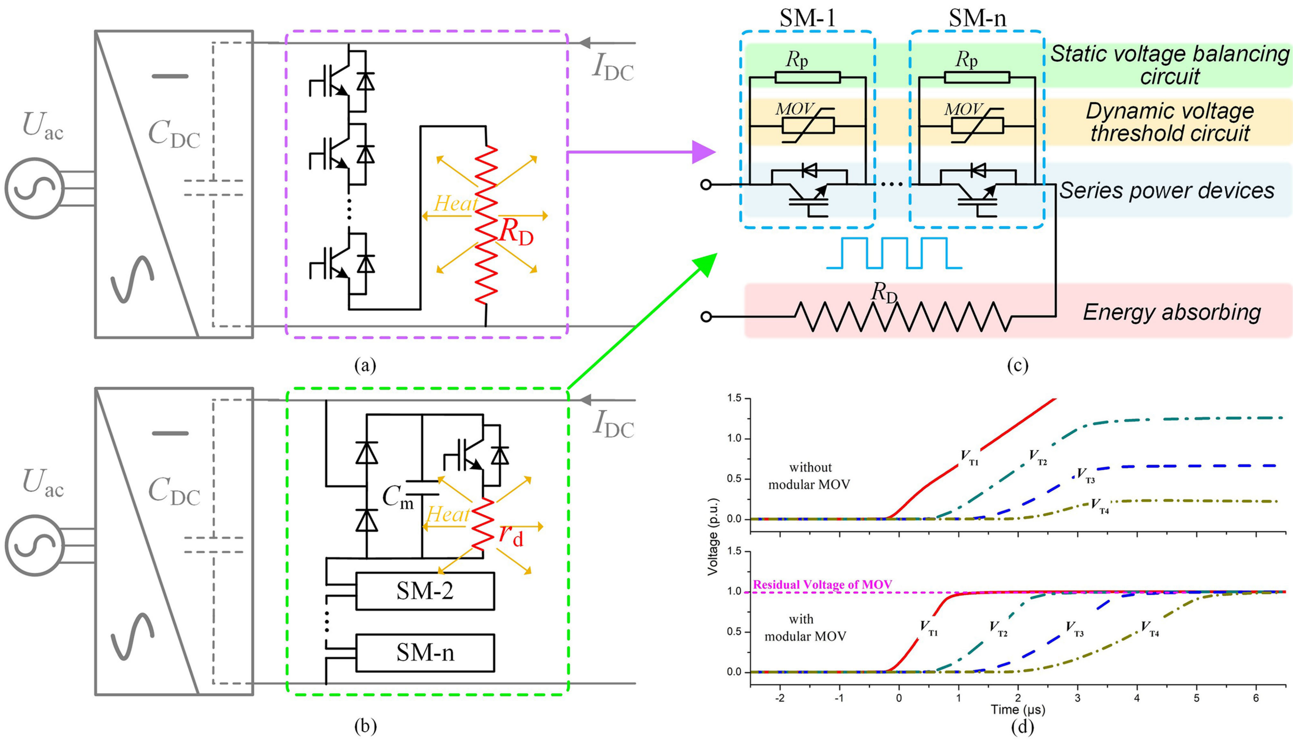

Fig. 2. Proposed DCC. (a) Concentrated DCC. (b) Modular DCC. (c) Proposed MC-DCC with modular solid-state switches and concentrated resistor. (d) Voltage threshold mechanism of the MOV [18].

1) The ACC must be installed offshore, which increases the cost and volume of an offshore platform. By contrast, the DCC can be installed onshore and integrated with the onshore VSC-HVdc station.
2) The operation of the ACC should be separated into several power rating levels because the ACC is typically composed of thyristors. By contrast, the DCC can adjust the power rating according to system requirements at any time. The dc voltage ripple of the DCC is therefore lower than that of the ACC.
3) The ACC comprises three-phase circuits, whereas the DCC comprises a one-phase circuit, which considerably reduces the total volume and cost.

In summary, the DCC is a better option for offshore wind power access VSC-HVdc systems. However, limited literature or research on DCCs has presently been conducted. There are two types of existing DCC topologies, namely, the concentrated DCC and the modular DCC [11]–[17], whose characteristics will be analyzed in detail in Section II-A. However, the existing DCCs are still difficult to implement [12]–[14]. In case of the concentrated DCC, it is difficult to achieve series voltage equilibrium, especially dynamic voltage equilibrium [15]. The modular DCC has disadvantages in economic cost, reliability, and volume, which limits its wide application [16].

The present study thus proposes a novel DCC for a ±400 kV/1100 MW offshore wind VSC-HVdc system. Section II analyzes the complementary advantages of existing DCCs and then proposes a novel DCC. Section III presents the design method of the proposed DCC. Section IV introduces experimental results that verify the effectiveness of the proposed DCC. Section V concludes the article.

II. Proposed DCC

A. *Complementary Advantages of the Concentrated DCC and Modular DCC*

The most straightforward way to realize the DCC is applying series fully controlled power devices to replace the thyristors in the ACC [12], as shown in Fig. 2(a). This mechanism is referred to as the concentrated DCC. Through switching control of the series devices, the energy dissipation resistor can be set parallel to the dc bus to absorb surplus power when needed [14]. Moreover, continuously adjustable dissipation power can be achieved by changing the duty cycle. However, as the required voltage increases, the series number of power devices also increases, resulting in a serious voltage imbalance problem, especially a dynamic voltage imbalance, owing to the inconsistent turn-OFF transient process of the series devices [15].

The modular DCC was proposed in [16] to overcome the series voltage imbalance. Fig. 2(b) illustrates the modular DCC. Its mechanism is similar to that of the modular multilevel converter. Furthermore, the modular DCC is divided into many submodules. Each module contains its own dc capacitor, a fully controlled power device, several diodes, and a corresponding energy dissipation resistor. The dc capacitor is adequately large that short-term current does not cause a sudden change in voltage. The module therefore works as a voltage source that can independently control its voltage using its own chopper. The overall voltage and the dissipation power can be stabilized by orderly controlling each module.

However, heat generated by the resistor should be avoided as it affects the safe operation of the power devices. The resistor in the concentrated DCC can be placed far enough away from the power device valve or can be placed outdoors. However, the resistor in the modular DCC must be placed inside each module, near the power device. Thus, a sufficient water cooling system must be adopted to effectively reduce the temperature of both the resistors and power devices.

In summary, the concentrated DCC suffers a voltage equalization problem for series power devices, but has inherent advantages for the design of the heat diffusion of resistors. The modular DCC allows voltage equalization, yet it not only has an increased cost in terms of dc capacitors and diodes but also requires expensive water-cooling equipment, thereby reducing its reliability.

B. Proposed DCC With Modular Solid-State Switches and Concentrated Resistor (MC-DCC)

Considering the complementary characteristics of the concentrated DCC and modular DCC, we propose an MC-DCC. Fig. 2(c) presents the proposed novel MC-DCC. The energy dissipation resistor adopts a concentrated design to solve the heat diffusion problem and omit the water cooling system. Thus, the external characteristics and control mode of the MC-DCC are similar to those of the traditional concentrated DCC. The series solid-state switches are modularized by paralleling a metal oxide varistor (MOV) to each device [18]. The MOV exhibits a voltage threshold characteristic, and it effectively replaces the storage dc capacitor in the traditional modular DCC. Fig. 2(d) shows that when the turn-OFF processes of the series solid-state switches are inconsistent, the voltage of each module does not exceed the residual voltage of its MOV, which effectively solves the voltage imbalance problem of the traditional concentrated DCC. In fact, the voltage threshold function of the MOV is produced at the cost of absorbing a certain amount of pulse energy. However, the non-long-term work attribute of the DCC provides opportunities to apply the MOV.

The quantitative size of the power device valve in MC-DCC is a little larger than that in the concentrated DCC. The usage of the concentrated dissipation resistor should be the same. Each module of the modular DCC has its own dc capacitor and requires a large water cooling system; thus, the size of modular DCC is estimated to be twice the size of the MC-DCC.

III. Design Method of the MC-DCC

A. System Requirement Analysis

To maintain the continuous operation of the VSC-HVdc system after the ac fault occurs, the MC-DCC is installed on the dc link, which consumes the surplus power injected into the VSC-HVdc system. For the ±400 kV/1100 MW offshore wind VSC-HVdc project, the proposed MC-DCC should be designed according to the system requirements and the characteristics of the MC-DCC. Table I gives parameters of a design sample.

The power rating of the concentrated resistor should track the operating conditions of wind turbines during the fault.

TABLE I
Design of the MC-DCC for ±400 kV/1100 MW VSC-HVDC System

Item	Value
System rated dc voltage and current	800 kV 1375 kA
Power rating of MC-DCC	0—1100 MW adjustable
DC voltage ripple range	0.95—1.10 p.u.
Maximum operating time	1.5 s
Energy dissipation resistor	581 Ω
Operating frequency	50 Hz

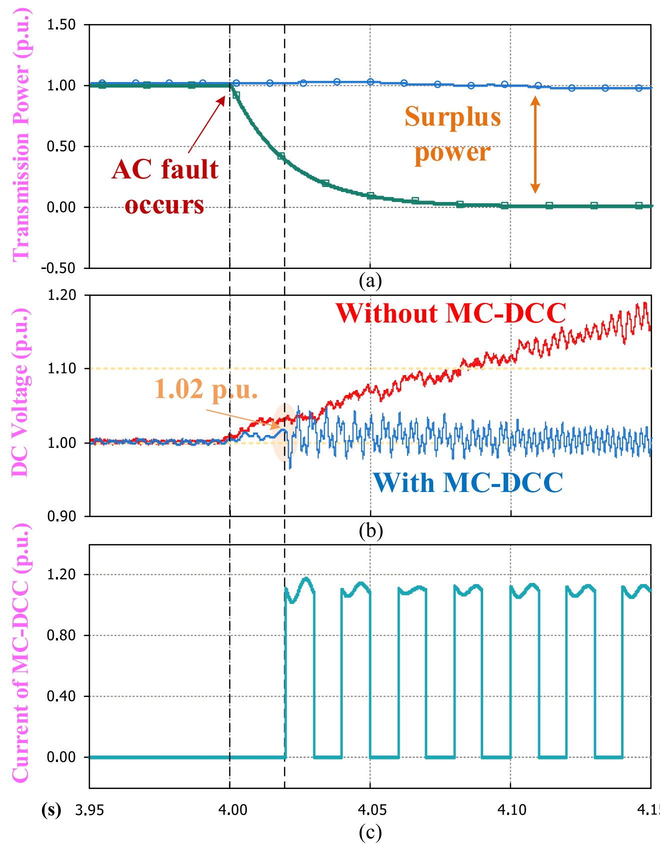

Fig. 3. Operating analysis of MC-DCC. (a) Transmission power during the fault. (b) DC voltage with MC-DCC and without MC-DCC. (c) current waveform of MC-DCC.

The resistance is adjusted by the switching control of the duty cycle of the MC-DCC. The fixed resistance is lower than or equal to the equivalent resistance, which is 581 Ω. The switching frequency of the MC-DCC is determined by the upper and lower ripple ranges of the dc voltage. In each MC-DCC operating cycle, the concentrated resistor consumes the injected wind power and surplus power of the modular multilevel converter. The operating frequency of the MC-DCC is thus determined as 50 Hz. Fig. 3 shows that when the fault occurs, the MC-DCC consumes the surplus power and effectively controls the dc voltage within 0.97–1.05 p.u.

B. Design of Solid-State Switch Modules in the MC-DCC

On the basis of the previous system analysis, the modular solid-state switches must turn ON and OFF continuously at a

TABLE II
DESIGN OF SOLID-STATE SWITCH MODULES IN THE MC-DCC

Item	Value
Power device (IGCT)	4.5 kV/2 kA
Anti-parallel diode	4.5 kV/2 kA
Rated voltage of MOV	2.5 kV
Residual voltage of MOV	3.5 kV (at 5 kA)
Maximum energy of MOV	20 kJ
Static equalizing resistor	200 kΩ

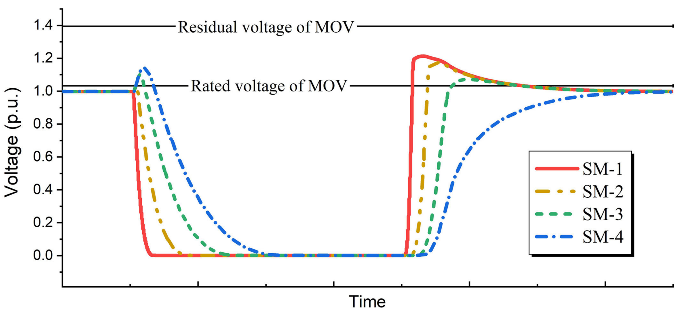

Fig. 4. Working process of the MOV in the MC-DCC.

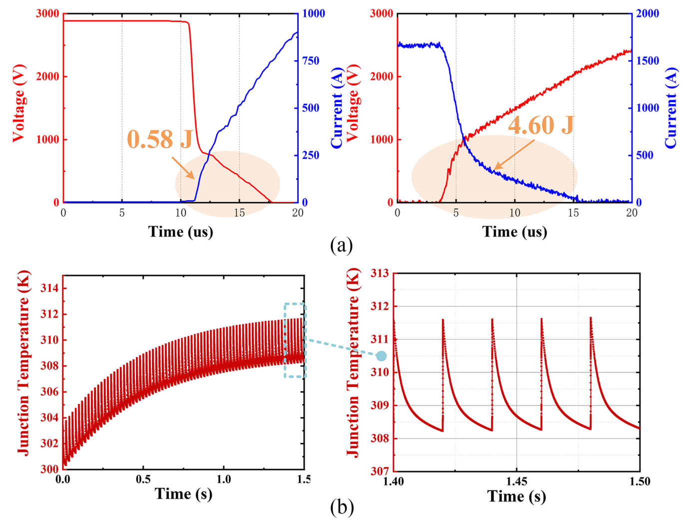

Fig. 5. Junction temperature evaluation of IGCT in MC-DCC. (a) Turn-ON and -OFF power loss of the IGCT. (b) Junction temperature extraction.

specific frequency within 1.5 s. The key component is the MOV. When switches turn OFF, the voltage threshold characteristic of the MOV turns the overvoltage of the integrated-gate commutated thyristor (IGCT) under the breakdown voltage. The peak off-state voltage of the IGCT is 4.5 kV; therefore, the residual voltage of the MOV is designed as 3.5 kV to ensure a safety margin. Owing to the aging effect of the MOV, voltages above the rated voltage should not be withstood for long periods. Therefore, given that the dc voltage of the VSC-HVdc system is ±400 kV and there are 360 solid-state switch modules, the voltage of each switch is under 2.5 kV. Additionally, a static equalizing resistor of 200 kΩ is applied in each module for static voltage balance. Table II summarizes the design parameters of the solid-state switch modules in the MC-DCC.

In fact, if the modular solid-state switches can ideally synchronize switching ON and OFF, then the overvoltage of the IGCT would not reach the residual voltage of the MOV. However, the asynchronization of switches is inevitable. In this case, the MOVs absorb a pulse current to limit the overvoltage when switching OFF as shown in Fig. 4. Suppose that the asynchronization of switches is $T_d = 1\ \mu$s. The maximum absorption energy of the MOV can be expressed as

$$E_{\text{MOV}} = 2T_d \cdot f \cdot V_{\text{res}} \cdot I_s. \tag{1}$$

Here, f is the operating frequency of MC-DCC, V_{res} is the residual voltage of the MOV, and I_s is the operating current of the MC-DCC.

For analysis of the junction temperature, the turn-ON and turn-OFF power loss of the IGCT is extracted in a single pulse experiment whose results are shown in Fig. 5(a). On the basis of the extracted power loss and established electrothermal model of the IGCT, the junction temperature of the IGCT in each solid-state switch modules operating at 50 Hz within 1.5 s is evaluated as shown in Fig. 5(b). Evidently, the junction temperature is still far from the maximum junction temperature. Therefore, no additional large-volume water cooling system is required.

The maximum breaking capability of MC-DCC should be taken into consideration according to the analysis in [19]. As the MC-DCC adopts solid-state switches and concentrated resistor, if the concentrated resistor is short circuited due to the flashover, the MC-DCC needs to withstand an overcurrent with a high rise rate. In this case, the MC-DCC behaves like an HVdc breaker to interrupt the overcurrent after the detection. Set 2 kA as the threshold value of overcurrent. The command issuance time of MC-DCC protection system is determined by the rise rate of the overcurrent and detection speed is typically less than 0.3 ms. The maximum breaking capability of MC-DCC should be higher than 4.1 kA.

It is unavoidable that one of the solid-state switch modules fails to operate in the MC-DCC. The IGCT has long-term reliable short-circuited failure mode owing to the design and housing structure. The insulated-gate bipolar transistor (IGBT) module is open circuited while the press-pack IGBT is short term unreliable short circuited (lasting several hours). As the MC-DCC adopts series solid-state switches, the IGCT is superior to the IGBT and used in the MC-DCC for the ±400 kV/1100 MW offshore wind VSC-HVdc project [20]. If one of the modules refuses to operate, a bypassing thyristor is applied in each module. Additionally, it is appropriate for the IGCT to apply a dual trigger unit in the gate driver. This greatly mitigates the communication failure of the control system.

IV. EXPERIMENTAL VALIDATION

A. Development of a Prototype and Test Scheme for MC-DCC

A 10 kV/12.3 MW prototype of the MC-DCC was built to verify the effectiveness of the proposed MC-DCC. Fig. 6(a) and

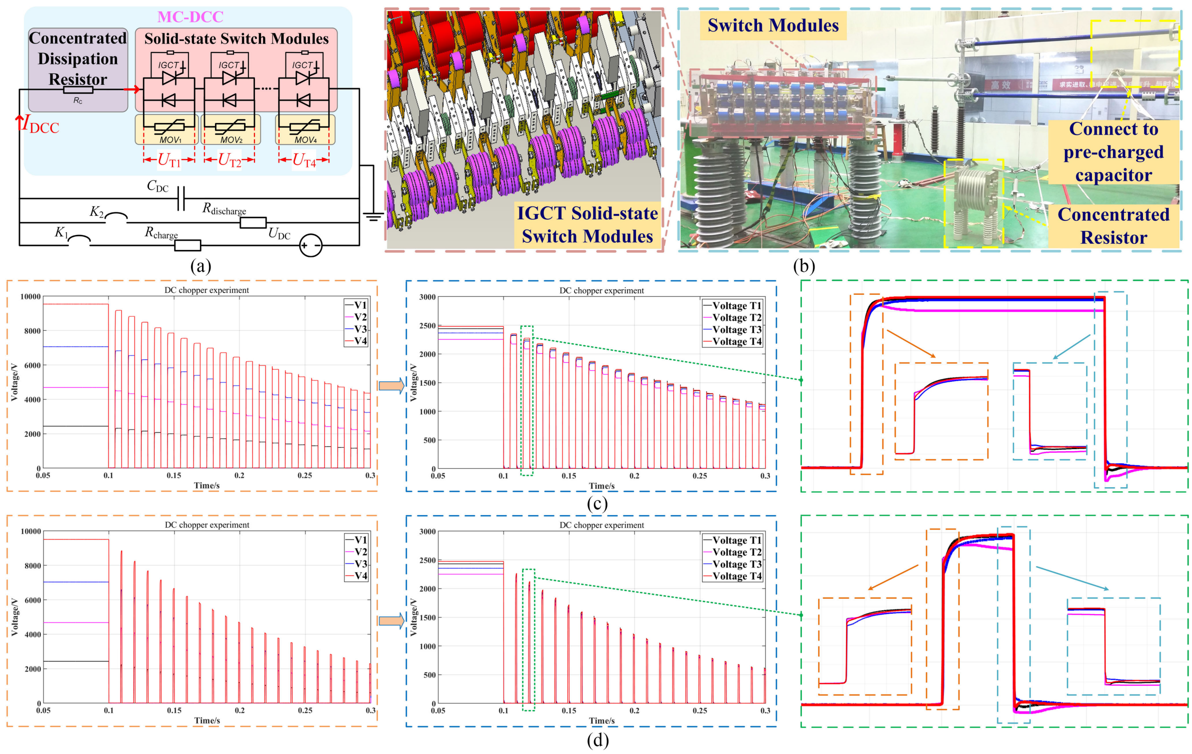

Fig. 6. Comprehensive experiment of MC-DCC. (a) Experimental platform. (b) MC-DCC prototype. (c) Waveforms of MC-DCC at duty ratio = 50%. (d) Waveforms of MC-DCC at duty ratio = 90%.

(b) presents the experimental platform and schematic diagram of the MC-DCC prototype. Four solid-state switch modules and the concentrated resistor are connected in series to form the MC-DCC prototype. The capacitor is precharged to a certain level. The MC-DCC works at an adjustable frequency and duty cycle, while the energy of the capacitor is dissipated by the concentrated resistor. This test scheme is built to modify the operating conditions of the MC-DCC.

B. Experimental Results

Fig. 6(c) and (d) presents the voltage waveforms in detail for the whole prototype operation, where V_n is the sum of the voltage of the first module to the *N*th module, voltage T_N is the voltage of the *N*th module. The MC-DCC prototype turned ON and OFF continuously at a specific frequency. The experimental results overall verify the voltage balancing of the MC-DCC and show that during the turn-OFF processes of solid-state switches, the voltage of each module is limited by its MOV and does not exceed the residual voltage of the MOV. The MC-DCC prototype successfully consumes 0.8 MJ energy in one experiment, which validates its properties for application in the practical projects.

V. Conclusion

A novel MC-DCC integrated with modular solid-state switches and concentrated dissipation resistor is proposed. The design methodology of the MC-DCC on the basis of ±400 kV/1100 MW offshore wind power VSC-HVdc system requirement analysis was discussed and presented in detail. Some constraints including maximum breaking capability of MC-DCC are considered for the proposed system. The non-long-term work attribute of the DCC provides opportunities to apply MOVs in modularizing series solid-state switches, thereby removing the capacitors for voltage balance. The MC-DCC combines the complementary advantages of the concentrated DCC and modular DCC, namely, the effective voltage balance of series solid-state switches, no water cooling system requirement, high reliability, and low cost. The 10 kV/12.3 MW prototype experiments demonstrated the correctness and effectiveness of the MC-DCC. The MC-DCC is appropriate for application in the first ±400 kV/1100 MW offshore wind VSC-HVdc project in China.

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