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A Hybrid Isolated Bidirectional DC/DC Solid-State Transformer for DC Distribution Network

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ABSTRACT The isolated bidirectional DC/DC solid-state transformer (DCSST) plays an important role in connection of renewable energy sources, voltage conversion, bidirectional power transmission and electrical isolation for DC distribution network. To connect the renewable energy, energy storage and DC loads with DC distribution network, a hybrid DCSST scheme is proposed in this paper. Compared with the existing DCSST schemes, the proposed hybrid DCSST is composed of modified full-bridges and modular multilevel converter (MMC) topology, achieving flexible connection and large voltage boost ratio for renewable energy system, realizing fault handling capability, avoiding the application of DC circuit breakers and reducing the volume and construction cost. Besides, the high-frequency-link (HFL) voltages in proposed scheme are hybrid waveform and adjusted adaptively to match HFL transformer voltage ratio, reducing the current stress, reactive power and power loss of DCSST under the fluctuation of power flow from renewable energy sources and distributed loads. The topology, operation principle, fault handling process and hybrid wave HFL voltages adjustment strategy of hybrid DCSST scheme are investigated. The experimental results verify the correctness and effectiveness of proposed scheme, promoting the adaptability and practicality for DCSST and DC distribution network.

INDEX TERMS DC distribution network, renewable energy system, hybrid DCSST scheme, fault handling capability, HFL voltages adjusting strategy.

I. INTRODUCTION

With the rapid development of renewable power source, energy storage device and distributed direct-current (DC) loads, the DC distribution network has been significantly attracting global attentions and an important element for future power grids [1], [2]. Compared with the conventional alternating-current (AC) power distribution network, the DC distribution network obtains higher power conversion efficiency, flexible access to renewable energy and devices, avoid the synchronization and reactive power compensation issues, reduction of power converters, power consumption and construction costs [3], [4]. The current development on DC distribution networks not only focus on the low-voltage DC (LVDC) but also extend to medium-voltage (MVDC) and high-voltage DC (HVDC) distribution networks. Many projects are completed, such as Gotland project in Sweden, Zhoushan multi-terminal DC transmission project in China, and Tj Reborg project in Denmark, and more projects are under construction [5], [6]. The system structure of DC distribution network is presented in Fig. 1.

To connect renewable power system, energy storage and distributed loads with DC distribution network, the isolated bidirectional DC/DC solid-state transformer (DCSST) is an essential equipment and responsible for DC bus connection, voltage conversion, electrical isolation and bidirectional power transmission in DC distribution network [7]–[9]. With the advantages of symmetric topology and control structure, bidirectional power transmission and zero-voltage-switching for switches, dual-active-bridge (DAB) topology becomes

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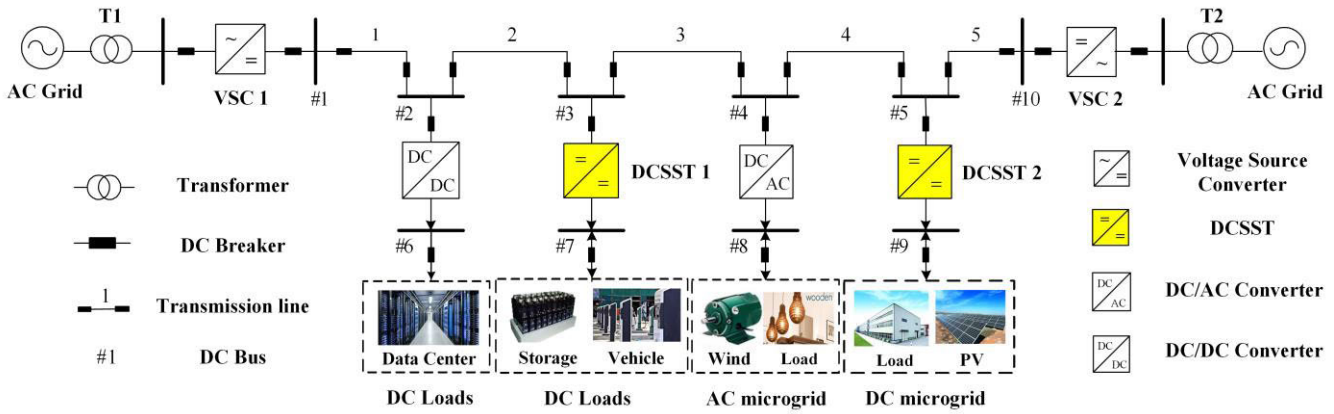

FIGURE 1. The system structure of DC distribution network.

a typical scheme for DCSST [10], [11]. Nowadays, with the rapid increase of voltage and power levels in DC grids, the voltage, current and power requirements for DCSST are constantly increased. However, due to the limitation of manufacturing capability for switches and devices, a single DAB cannot satisfy the voltage and power requirements for MVDC and HVDC application scenarios [12].

To increase the voltage and power ratings of DCSST, the modular multilevel DCSST scheme based on MMC topology provides scheme for MVDC and HVDC applications [13], [14]. The single-phase MMC structure is to increase the voltage rating, and its modular architecture enables flexible operating voltage and power ratings by changing the number of half-bridge sub-modulars (SMs) [15], [16]. However, the modular multilevel DCSST scheme is composed of lots of SMs, and its switching operation, control process and SM capacitor voltage balance realization are complicated, increasing the application difficulty and computing burden. Moreover, its switching frequency is limited to a certain range, and it does not obtain soft-switching operation, hindering improvement and practical application in DC distribution network [17], [18].

Therefore, the multiple modular DCSST scheme including input-series-output-parallel (ISOP), input-series-output-series (ISOS), input-parallel-output-series (IPOS) and input-parallel -output-parallel (IPOP) structures provides another scheme for MVDC and HVDC applications [19], [20]. The multiple modular DCSST scheme brings distinctive features such as modular topology and control structure, flexibility of voltage and power extension and redundant operation capability, and this scheme becomes a preferred option for MVDC and HVDC applications [21], [22]. However, large DC capacitors still exit in these structures, leading to the increased volume and construction cost of DCSST. Besides, when a DC fault occurs in grids, these structures are lack of fault handling capability, and the DC circuit breakers are needed to be applied to cut off fault current and prevent damage towards DCSST and the DC grid. However, a lot of technologies in DC circuit breaker are still under investigated and improved, and the DC fault handling and recovery time for a system with DC circuit breakers is long that prevents flexible and rapid control for DC distribution network [23]–[25]. Moreover, the construction cost of DC circuit breaker is relatively high at present, and the widely use of DC circuit breaker is not economical and realistic currently. Besides, multiple modular DCSST based on switch-capacitor (SCDCT) was proposed, and its switch-capacitor interfaces disconnect DCSST and renewable energy system when a fault occurs. However, the additional interfaces increase control difficulty and cost, and the fault handling on LVDC link is not realized yet [26], [27]. Therefore, the DCSST scheme with fault handling capability is urgent required.

Moreover, with large-scale access of renewable energy sources and variety of loads in DC grids, the fluctuation of DC bus voltages and connected loads become more frequent and greater, and the high-frequency-link (HFL) voltages are not always match HFL transformer voltage ratio, leading to the large current stress, reactive power, power loss and deteriorated performance of DCSST and the unexpected false protection activation and potential instability, especially in the MVDC and HVDC application scenarios [28], [29]. To eliminate reactive power caused by HFL voltages mismatch phenomenon, the phase-shift control strategies including extend-phase-shift (EPS), dual-phase-shift (DPS) and triple-phase-shift (TPS) provide solutions [30]–[32]. However, these existing phase-shift strategies are realized by introducing inner phase-shift angle, the HFL reactive power is reduced at the cost of decreasing power transmission capacity.

According to analysis above, the existing DCSST schemes have drawbacks during practical operation. Besides, the lack of bidirectional DC fault handling capability and the HFL voltages mismatch phenomenon are the obstacles hindering widely application of DCSST connecting renewable power sources and energy storage with DC distribution networks. Therefore, a hybrid DCSST scheme composed of modified full-bridge and MMC topology is proposed in this paper, and

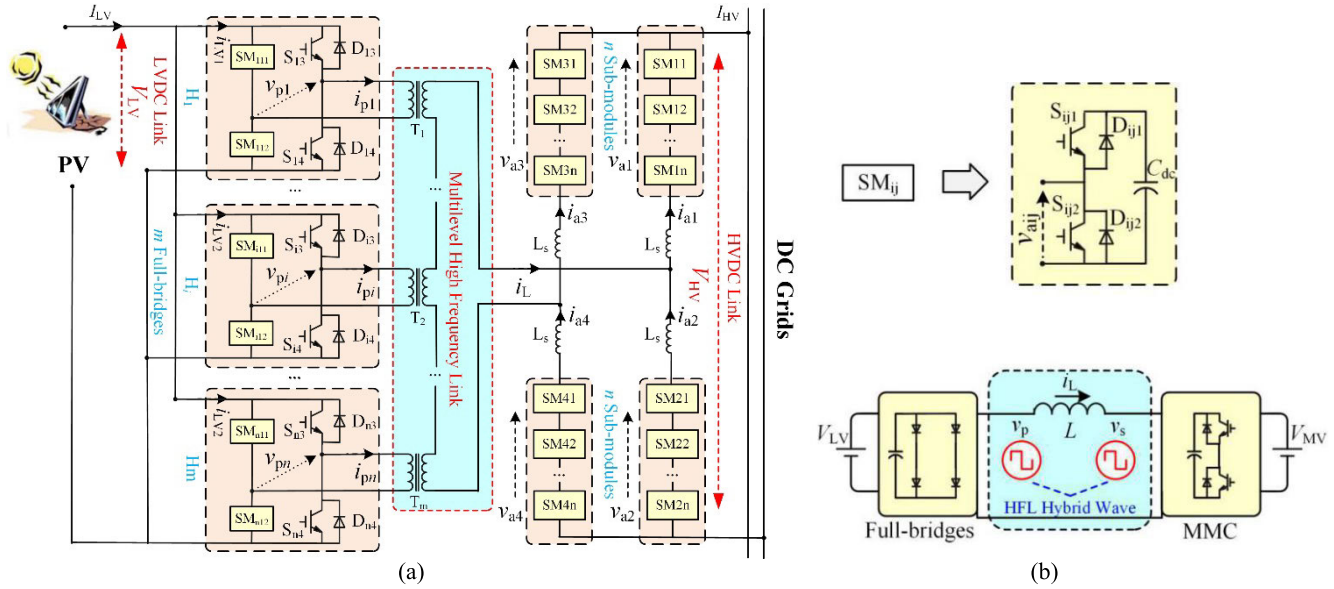

FIGURE 2. The topology configuration of proposed hybrid DCSST scheme. (a) Topology of DCSST connecting renewable energy (PV system) and DC distribution network. (b) Equivalent circuit of DCSST scheme.

the advantages and contribution of proposed hybrid DCSST scheme are presented as follows:

(1) The hybrid topology is flexible connect for renewable energy system and distributed loads. Large voltage step-up ratio for renewable energy such as photovoltaic (PV) system can be realized by applying more HFL transformers and full-bridges on LVDC link, and the MMC topology satisfies the HVDC requirement for DC distribution network.

(2) The DC faults handling capability can be obtained through half-bridge SMs in both the modified full-bridge converters on LVDC link and the MMC topology on HVDC link, avoiding the application and corresponding control of DC circuit breakers. Therefore, the implementation difficulty, operating complexity and construction cost can be reduced effectively for DC distribution network during the practical engineering application.

(3) The HFL voltages in proposed DCSST scheme are hybrid waveform and can be adjusted adaptively to match HFL transformer voltage ratio, reducing current stress and reactive power, solving dv/dt stress problem and maintain high DC voltage utilization for DCSST. The unexpected false protection activation and potential instability caused by the voltage fluctuation in DC buses and distributed loads can be greatly eliminated, and the energy conversion efficiency can be increased, resolving obstacles of large-scale application of DCSST connecting renewable energy system, energy storage and distributed loads with DC distribution network.

The topology, operation principle, fault handling process and HFL voltages adjustment strategy of proposed hybrid DCSST scheme are investigated in the rest of paper. Section II shows the topology and operation principle, Section III presents the fault handling process and Section IV discusses the HFL voltages adjusting strategy of proposed DCSST. The experiment verification in a hybrid DCSST prototype are presented in Section V. The proposed hybrid DCSST scheme becomes a feasible, efficient and practical scheme connecting renewable energy systems, energy storage and loads to DC distribution network.

II. TOPOLOGY CONFIGURATION OF PROPOSED HYBRID DCSST SCHEME

To connect renewable energy system and DC distribution network, achieve efficient bidirectional power transmission and realize DC fault handling features, a hybrid DCSST scheme composed of modified full-bridge converters and MMC topology is proposed in this paper. The topology configuration of proposed DCSST is shown in Fig. 2(a). From the figure, the hybrid DCSST is mainly composed of paralleled modified full-bridges on LVDC link connecting to renewable energy system, isolated HFL transformers and MMC topology on HVDC link connecting to DC grids. V_{LV}, V_{HV}, I_{LV} and I_{HV} are the LVDC and HVDC voltages and currents of DCSST, respectively. The power conversion through DCSST can be viewed as power exchange between two equivalent voltage sources v_p and v_s through equivalent inductor L, as shown in Fig. 2(b), where L is the sum of arm inductance L_s and transformer leakage inductance L_k. The HFL current i_L can be varied by adjusting the phase-shift angle between HFL voltages.

Specifically, in the HFL link of hybrid DCSST scheme, the isolated HFL transformers are connected in series with lower voltage and power ratings, as shown in Fig. 2(a), thus the power capacity and manufacturing difficulty of each HFL transformer can be decreased, and the power capacity of DCSST can be altered flexibly. Besides, a large voltage step-up ratio for renewable energy source can be realized

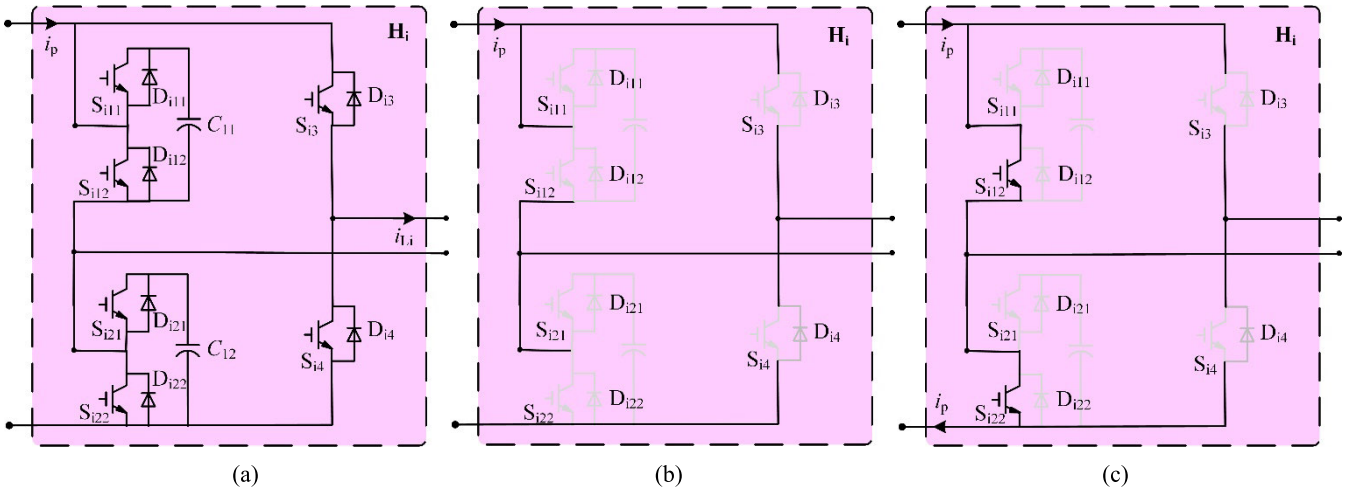

FIGURE 3. Switching process of modified full-bridges converter in hybrid DCSST. (a) Topology of modified full-bridge. (b) Fault isolated operation from connected renewable energy system. (c) Bypass operation of faulty full-bridge.

by implementing more HFL transformers and full-bridges according to practical requirements, facilitating the energy collection and large boost access of renewable energy sources such as PV system.

The LVDC link of hybrid DCSST scheme is composed of paralleled modified full-bridges connected to renewable energy system, as shown in Fig. 2(a). The full-bridges are connected in parallel to increase current rating, and more full-bridges can be applied to satisfy current and power ratings in practical application. Different from conventional full-bridge topology, the switches in front arms of modified full-bridge in proposed DCSST is replaced by half-bridge SMs. Each SM is a half-bridge structure with two switches, two diodes and a capacitor, and the SM has three working states: inserted state, blocking state and bypass state. By replacing the switches in front bridge arms with half-bridge SMs for full-bridges, the application of concentrated DC-link capacitors with relatively large value to stabilize DC voltages and reduce voltage ripple are not needed, thus reducing converter volume and construction cost of DCSST effectively. Besides, when a fault occurs, the discharge and recovery process of concentrated DC-link capacitors may take a long time, hindering the rapid and flexible operation. Without concentrate DC-link capacitor in proposed DCSST scheme, the inconvenient in fault handling and recovery process can be avoided. Moreover, the fault isolation and handling function can be achieved by half-bridge SMs, which are detailed discussed in Section III, reducing the application and rely of DC circuit breaker under certain operating scenario, the implementation difficulty, control complexity and construction cost for DC distribution network can be reduced effectively.

On the HVDC link of hybrid DCSST scheme, a single-phase MMC topology is employed connecting to the DC distribution network, as shown in Fig. 2(a), and advantages of MMC operation can be retained. The MMC topology is composed of four arms in a bridge arrangement, and each arm contains half-bridge SMs and an inductor L_s. Similar with the SMs in modified full-bridges, each half-bridge SM comprises a capacitor, tow switches and two diodes. The SM generates square voltage v_{aji} with voltage levels V_{dc} and 0, and the $v_{a1} \sim v_{a4}$ and $i_{a1} \sim i_{a4}$ are voltages and currents of corresponding arms in MMC topology. The inductors L_s in arms are applied to suppress circulation currents and limit DC fault currents. Besides, the scalable architecture of MMC enables a large operating voltage and power ratings by stacking required number of SMs in cascade, and the redundancy can also be realized by installing additional SMs. Moreover, the application of DC circuit breakers are also unnecessary on HVDC link because the fault blocking feature in SMs of MMC topology acts similar to a DC circuit breaker, which are also detailed discussed in Section III, eliminating the application and construction costs of DC circuit breaker and providing another secure solution for DC distribution network.

III. THE FAULT HANDLING CAPABILITY OF PROPOSED HYBRID DCSST SCHEME

The switching principle of fault handling process in full-bridge SM on LVDC link of DCSST connecting renewable energy system is presented in Fig. 3. With the operation of SMs in modified full-bridges, as shown in Fig. 3(a), the fault handling function can be realized for proposed hybrid DCSST scheme. Each SM has three working states: the inserted state, bypass state and blocking state. When a fault occurs in renewable energy systems, the switches S_{ij1} and S_{ij2} in half-bridge SM are turned-off, thus the SM is in blocking state, and other switches in full-bridge are also turned-off, as shown in Fig. 3(b). Under this switching state, the modified full-bridge can isolate from connected faulty renewable energy sources, preventing hazards and damage from connected faulty energy units. Besides, when the SMs are under

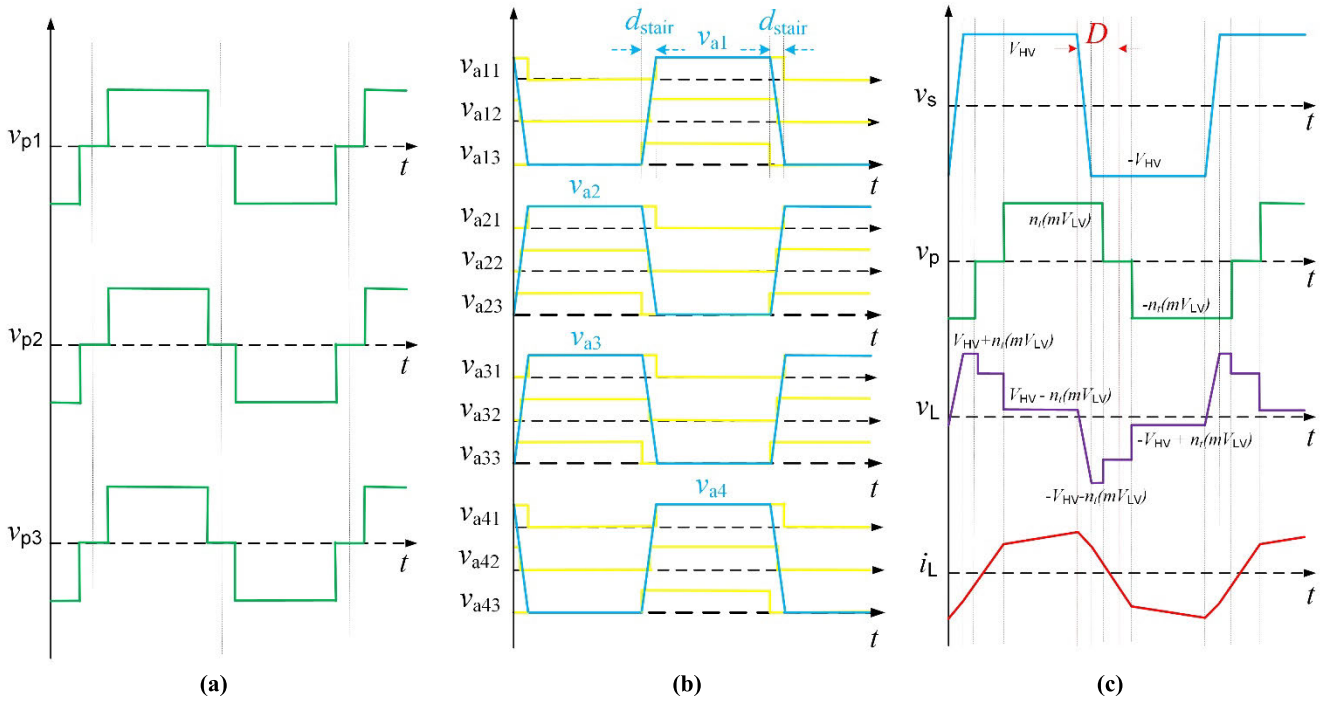

FIGURE 4. HFL waveforms of hybrid DCSST scheme under proposed hybrid-wave HFL modulation. (a) Modulation waveform in modified full-bridges, (b) Modulation waveform in MMC topology, (c) HFL voltages and current.

blocking state during fault handling process, the capacitors voltages in SMs are maintained, and the full-bridges resume to normal operation rapidly and smoothly when the fault is cleared, further enhancing the flexibility and practicality of DCSST.

Moreover, when the fault happens in full-bridges, the upper switches S_{ij1} is turned-off and lower switches S_{ij2} is turned-on in SMs, and the SMs are in bypassed state, as shown in Fig. 3(c). Therefore, the faulty full-bridges are bypassed and other full-bridges still operate normally. The output voltage of full-bridge is clamped at 0V, and the bypassed full-bridge has no influence on the voltage or current balances, ensuring the normal operation of DCSST. In addition, the capacitor voltages in SMs are maintained during the bypassed state, thus ensuring the rapid recovery capability of DCSST.

With the operation of SMs in modified full-bridges, the fault handling function can also be realized for MMC topology of hybrid DCSST scheme. When the SM is in the inserted state, and the MMC operates normally. When the SM is in blocking state, the MMC can isolated and prevent hazards and damage from DC buses in DC distribution network. Besides, when the SMs are under blocking state during fault handling process, the voltages of capacitors in SMs can also be maintained to realize the rapid recovery when fault handling is cleared. When the SM is in bypass state, the faulty SM can be self-bypassed and other SMs and MMC topology operate normally. According to analysis above, with the hybrid topology configuration in hybrid DCSST, the fault handling function including fault isolation and faulty unit self bypass can be achieved for both modified full-bridges and MMC structure. Therefore, the application and rely of DC circuit breaker is reduced, and the system volume and construction cost of DC distribution networks can be reduced effectively.

IV. HFL VOLTAGE MODULATION OF HYBRID DCSST

The HFL modulation in DCSST is also important for affecting the efficiency of voltage conversion and power transmission between renewable energy system and DC distribution network. To reduce the current stress and HFL reactive power and realize efficient power transmission, a hybrid-waveform modulation with HFL voltages adjusting feature is also proposed in this paper.

A. HYBRID-WAVE HFL MODULATION

Conventional HFL modulation methods such as square-wave, triangular-wave and quasi-square-wave have their own advantages and shortages during practical application [33]. The single HFL modulation method is contradictory in solving dv/dt stress issue and power transmission capacity, and it cannot achieve the optimal compromise solution. For the DCSST connecting renewable energy system and DC distribution network, the MMC topology connecting to DC grids on HVDC link needs to consider large dv/dt stress problem, and full-bridges connecting to renewable energy on LVDC link do not suffer the dv/dt stress issue. Benefit from the asymmetric structure of hybrid DCSST, a hybrid-wave HFL modulation composed of square-wave in full-bridge

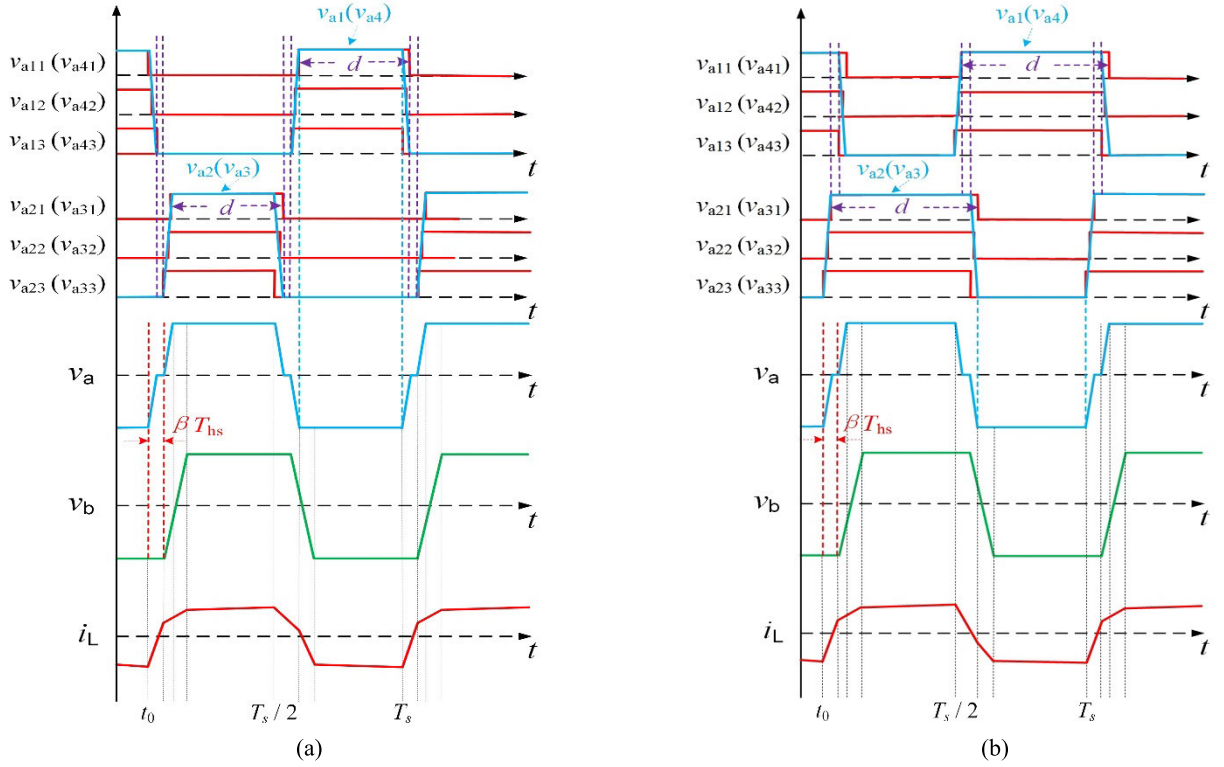

FIGURE 5. Waveforms of hybrid DCSST under proposed HFL voltages adjusting strategy. (a) $D < 0.5$, (b) $D > 0.5$.

converters and quasi-square-wave in MMC topology is proposed, as shown in Fig. 4.

Compared with conventional HFL modulation, the HFL voltages v_P and v_S are different under proposed hybrid-wave HFL modulation method. For the full-bridges which do not suffer the dv/dt stress issue, the square-wave modulation is applied, as shown in Fig. 4(a), ensuring higher DC voltage utilization and power transmission capability. For the MMC topology suffer dv/dt stress problem, the quasi-square-waveform with rising and falling process forming staircase HFL voltage is applied, as shown in Fig. 4(b). During the voltage rising or falling period, the half-bridge SMs are inserted or bypassed one by one, thus each voltage stair is limited to one SM capacitor voltage, and the dv/dt stress upon HFL transformer is greatly reduced. Under different HFL voltages pattern, the HFL voltage and current are different compared with conventional HFL modulation method, as presented in Fig. 4(c), alleviating the dv/dt stress towards HFL transformer and achieving higher DC voltage utilization and greater power conversion and transmission capability simultaneously.

B. HFL VOLTAGES ADJUSTING STRATEGY

The proposed HFL modulation strategy for DCSST not only contains hybrid-wave HFL voltages but also realize HFL voltages adjustment adaptively. Under varied power sources and loads, the DC bus voltages in renewable energy source and distribution loads change frequently, thus the HFL voltages in DCSST are not always match the HFL transformer voltage ratio, leading to the increased current stress, HFL reactive power and power loss. To solve this problem, a HFL voltages adjusting strategy adjusts HFL voltages by varying the conduction width of modulation wave for switches in SMs, is also applied for DCSST, as presented in Fig. 5, thus ensuring the HFL voltages match HFL transformer voltage ratio in real-time according to the variation of renewable energy source and DC bus voltages, eliminating current stress, HFL reactive power and power loss. Compared with conventional phase-shift modulation method, the proposed HFL voltages adjusting strategy avoids power transmission capability reduction, control complexity and computational burden, maintaining a stable and ideal efficiency under low transmission power and expanding the operation range for both DCSST and DC distribution network.

From Fig. 5, v_P is HFL voltage on LVDC side, v_S is HFL voltage generated on HVDC side, β is phase-shift angle between HFL voltages v_P and v_S, T_s is switching period, and D is conduction width of modulation wave for switches in SMs in MMC topology. The upper and lower arm contains n SMs, respectively. When SM is in the inserted state, the SM voltage is capacitor voltage V_C; when SM is in the bypassed state, the SM voltage is 0. Thus, the following equation can be obtained:

$$\begin{cases} v_P(t) = \sum_{i=1}^{m} V_{Pi}(t) = mV_P(t) \\ v_S(t) = n_T\{v_{a3}(t) - v_{a1}(t)\} = n_T\{v_{a2}(t) - v_{a4}(t)\} \end{cases} \tag{1}$$

where m is the number of paralleled modified full-bridges, and n_T is the high-frequency transformer voltage ratio.

From Fig. 5(a) under $D < 0.5$ situation, during a switch period for SMs in MMC topology, when only the SMs in upper arm turn on or only the SMs in lower arm turn-on, the entire bridge arm voltage is nV_C, the arm inductor voltage is $V_{HV} - nV_C$, and the time length is $2DT_s$ during a switching period. In the same switching period, when the SMs in upper and lower arm are all turned-off, the entire bridge arm voltage is 0V, the arm inductor voltage is V_{HV}, and the time length is $(1-2D)T_s$. Therefore, under $D < 0.5$ situation, the following equation can be obtained:

$$V_C n(2D)T_s = V_{HV}T_s \tag{2}$$

where n is the number of SMs in MMC topology.

Likewise, from Fig. 5(b) under $D > 0.5$ situation, during a switching period for SMs in MMC topology, when the SMs in upper arm or the SMs in lower arm turn-on, the entire bridge arm voltage is nV_C, the arm inductor voltage is $V_{HV} - nV_C$, and the time length is $(2-2D)T_{hs}$ during a switching period. In the same switching period, when SMs in upper arm and lower arm are all turn on, the entire bridge arm voltage is $2nV_C$, the arm inductor voltage is $V_{HV} - 2nV_C$, and the time length is $(2D-1)T_{hs}$. Therefore, under $D > 0.5$ situation, the following equation can be obtained:

$$V_c n(2-2D)T_{hs} + 2V_c n(2D-1)T_{hs} = V_{HV}T_{hs} \tag{3}$$

According to (2) and (3), the relationship between SM capacitor voltage and conduction pulse width under both $D < 0.5$ and $D > 0.5$ situations can be derived as:

$$V_c = V_{HV}/(2Dn) \tag{4}$$

From (4), the SM capacitor voltage can be adjusted by varying the conduction width D. Since the upper arm and lower arm in MMC contains n SMs, respectively, the arm voltage v_{ai} in MMC topology of DCSST is:

$$v_{Si} = \sum_{k=1}^{n} V_{cik} = \sum_{k=1}^{n} \frac{V_{HV}}{2Dn} \tag{5}$$

where i is the MMC arm number, and v_{oik} is the output voltage of SM_{ik}.

Substituting (5) into (1), the HFL voltage v_S can be described as:

$$v_S = \frac{V_{HV}}{2Dn}\sum_{j=0}^{n}(S_{a3j} - S_{a1j}) = \frac{V_{HV}}{2Dn}\sum_{j=0}^{n}(S_{a2j} - S_{a4j}) \tag{6}$$

The SMs in arm a1 and arm a2 have the complementary switching states, so as are the SMs in arm a3 and arm a4. From (1) $\sim$ (6), the HFL voltage v_S can be described as:

$$v_S = \frac{V_{HV}}{2Dn}\sum_{j=0}^{n} S_{bj} \tag{7}$$

where S_{bj} is the switching function of MMC arms:

$$S_{bj} = \begin{cases} 1 & S_{3j1}/S_{1j2}/S_{2j1}/S_{4j2} = 1,\ S_{3j2}/S_{1j1}/S_{2j2}/S_{4j1} = 0 \\ -1 & S_{3j1}/S_{1j2}/S_{2j1}/S_{4j2} = 0, S_{3j2}/S_{1j1}/S_{2j2}/S_{4j1} = 1 \end{cases} \tag{8}$$

From (7), HFL voltage v_S can be regulated by HVDC voltage and conduction width for switches in SMs of MMC topology. Besides, the full-bridge generates square voltage, and the HFL voltage v_P is:

$$v_P = n_T m V_{LV} S_a \tag{9}$$

where S_a is the switching function for modified full-bridges:

$$S_a = \begin{cases} 1 & S_1/S_4 = 1, S_2/S_3 = 0 \\ -1 & S_1/S_4 = 0, S_2/S_3 = 1 \end{cases} \tag{10}$$

From (1) $\sim$ (10), it is possible to adjust SM voltage v_C by varying the conduction width D for switches in MMC arm, thus adjusting HFL voltage v_S to ensure the HFL voltages match HFL transformer voltage ratio, where $v_P = v_S$. Thus, according to (7) $\sim$ (10), to ensure the HFL voltages match HFL transformer voltage ratio, the following equation needs to be satisfied:

$$V_{HV}/2D = n_T m V_{LV} \tag{11}$$

From (11), defining $k_V = V_{HV}/V_{LV}$, the conduction pulse width d for switches in SMs can be expressed as:

$$D = \frac{V_{HV}}{2n_T m V_{LV}} = k_V/(2n_T m) \tag{12}$$

From (12), the conduction width for switches in MMC arm D is determined by HFL transformer voltage ratio and DC voltages on both link. When HFL voltages match HFL transformer voltage ratio, $k_V = n_T m$ and $D = 0.5$, and the conduction width D does not need to change to adjust the HFL voltage and still under normal width 50%. When the HFL voltages are not match HFL transformer voltage ratio and $k_V \neq n_T$, the conduction width $D \neq 0.5$ and it varies to adjust HFL voltage v_S, ensuring the HFL voltages match HFL transformer ratio. Besides, the voltage adjusting range of DC voltages ratio is $k_V \in (0, 2n_T m)$, and the voltage adjusting range of DC voltages and constraint relationship between DC voltages are $V_{LV} \in (V_{HV}/2n_T m, +\infty)$ and $V_{HV} \in (0, 2n_T m V_{LV})$, respectively.

Therefore, according to (12), when $V_{HV} > n_T m V_{LV}$, $k_V > n_T m$ and $v_S > v_P$, the conduction width D for switches in MMC becomes larger than normal width 50%. According to (2) $\sim$ (6), the SM voltage V_C and arm voltage v_{ai} are decreased to reduce HFL voltage v_S, ensuring the HFL voltages match HFL transformer voltage ratio. Likewise, when $V_{HV} < n_T m V_{LV}$, $k_V < n_T m$, and $v_S < v_P$, the conduction width D for switches in MMC arm becomes smaller than normal width 50% according to (12). The SM voltage V_C and arm voltage v_{ai} are increased to raise HFL voltage v_S, ensuring the amplitude of HFL voltages match

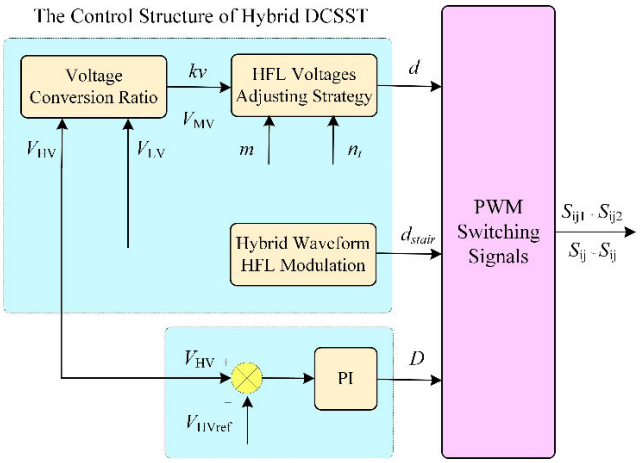

FIGURE 6. The control structure of hybrid DCSST scheme.

the HFL transformer voltage ratio. Besides, the fluctuation in DC voltages V_{HV} and V_{LV} may cause a sudden change of conduction width D that may lead to over-current. However, each arm in MMC topology contains inductor L_s to prevent the occur and harm of over-current.

The control architecture of the proposed hybrid DCSST with HFL voltages adjusting strategy is shown in Fig. 6. According to the figure, the LVDC and HVDC voltages are measured and calculate DC voltage ratio $k_V = V_{HV}/V_{LV}$. Then, the conduction pulse width d for switches in SMs of MMC obtains different values according to (12) under $k_V > n_T m$ or $k_V < n_T m$ situation, varying the SM voltage V_C and arm voltage v_{ai}. Therefore, under the HFL voltage adjusting strategy, the HFL voltage v_S can be adjusted adaptively with variation of DC voltages, thus ensuring the amplitude of HFL voltages match HFL transformer voltage ratio, reducing current stress, HFL reactive power and power loss and improving the efficiency of power conversion and transmission for DCSST and DC distribution network.

V. EXPERIMENTAL VERIFICATION

To verify the theoretical analysis and proposed control strategy, a hybrid DCSST prototype is constructed in the laboratory, as shown in Fig. 7, and the main parameters are presented in Table 1.

When the HVDC voltage connecting to DC distribution network is $V_{HV} = 300$V, $n = 6$, thus SM voltage $V_C = 50$V, and the LVDC voltage connecting to renewable sources is $V_{LV} = 110$V, $m = 3$, $n_t = 1{:}1$, thus $V_{HV} < n_T m V_{LV}$, and the mismatch between HFL voltages and HFL transformer voltage ratio occurs. The operating waveforms of DCSST without HFL voltages adjusting strategy under $V_{HV} < n_T m V_{LV}$ situations are shown in Fig. 8. From the figure, the HVDC and LVDC voltage maintain at 300V and 110V, respectively, as shown in Fig. 8(a). The HFL voltages v_P and v_S are both square waveforms, and the frequencies of HFL voltages and current are all 20kHz. The amplitude of HFL voltages do not match HFL transformer voltage ratio, as shown in Fig. 8(b), leading to large current stress and reactive power and decreased efficiency of DCSST.

TABLE 1. The main parameters of MDCT and experiment setups.

Symbol	Electrical Parameters	Quantity
V_{HV}	HVDC Link Voltage	300V
V_{LV}	LVDC Link Voltage	110V
n	Number of SMs in one MMC arm	6
m	Number of Modified Full-bridges	3
V_C	SM Capacitor Voltages	50V
n_T	HFL Transformer Voltage Ratio	1 : 1
L_T	Leakage Inductance	50μH
L_s	Arm Inductance	30μH
f_s	Switching Frequency	20kHz

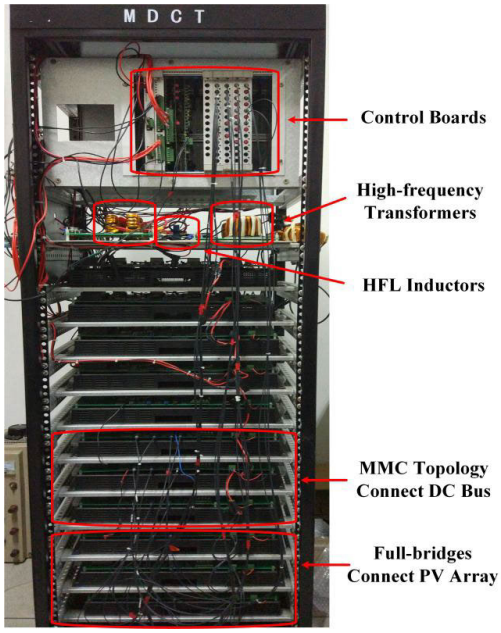

FIGURE 7. The hybrid DCSST prototype in laboratory.

Under the operating condition $V_{HV} = 300$V, $V_{LV} = 110$V, $m = 3$, $n_t = 1{:}1$, and the HFL voltages do not match HFL transformer voltage ratio $V_{HV} < n_T m V_{LV}$, by applying the proposed HFL voltages adjusting strategy, the steady-state waveforms of hybrid DCSST are presented in Fig. 9. From the figures, the conduction pulse widths for SMs in MMC topology in DCSST become $d = 0.45$, which is smaller than 0.5 to increase the HFL voltage v_S, as shown in Fig. 9(a). Therefore, the amplitudes of HFL voltages v_P and v_S are both 330V, as shown in Fig. 9(b), and the amplitude of HFL voltages are match HFL transformer voltage ratio. Compared with the HFL current without HFL voltages adjusting strategy presented in Fig. 8(b), the current stress with proposed HFL voltages adjusting strategy is reduced effectively under $V_{HV} < n_T m V_{LV}$ situation.

Besides, the hybrid-wave HFL modulation composed of HFL voltage square-wave v_P and quasi-square-wave v_S is

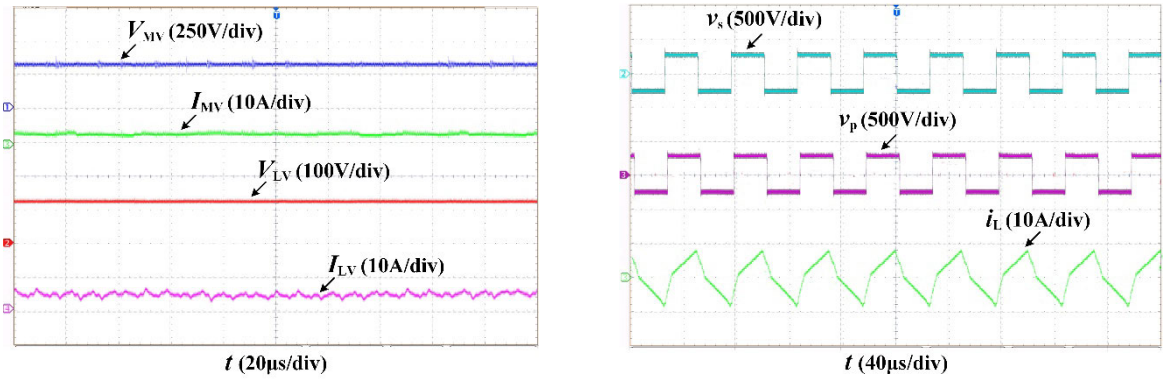

FIGURE 8. Steady-state waveforms of hybrid DCSST without HFL voltages adjusting strategy under $V_{HV} < n_T m V_{LV}$ situation. (a) HVDC and LVDC voltages and currents, (b) HFL voltages and current.

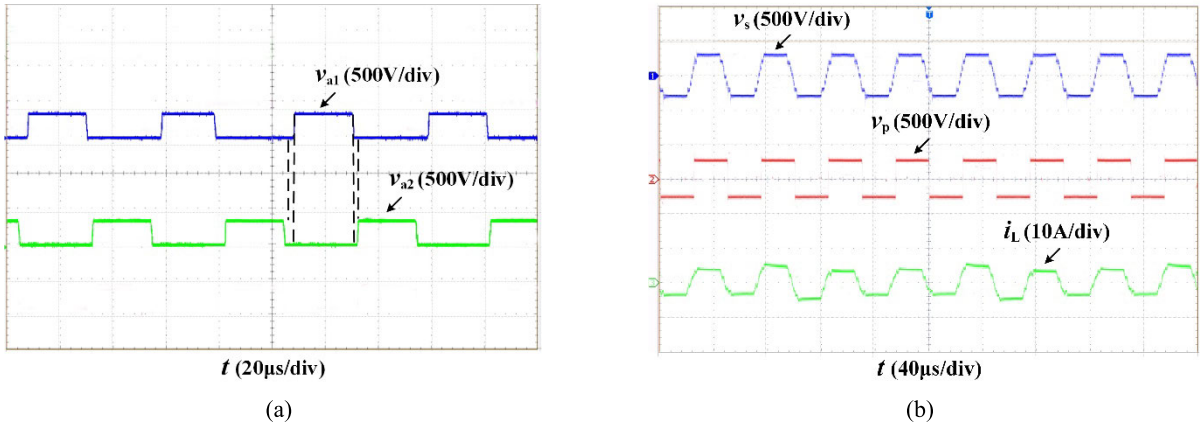

FIGURE 9. Steady-state waveforms of hybrid DCSST with HFL voltages adjusting strategy under $V_{HV} < n_T m V_{LV}$ situation. (a) Arm voltages, (b) HFL voltages and current.

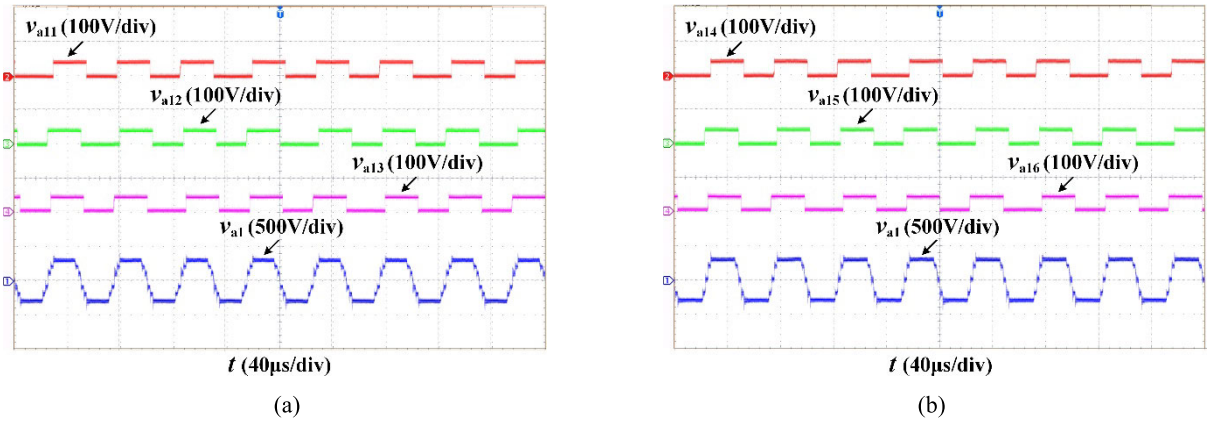

FIGURE 10. SM voltages balance in MMC topology under proposed HFL modulation. (a) V_{a11}, V_{a12}, V_{a13}, (b) V_{a14}, V_{a15}, V_{a16}.

realized, as shown in Fig. 9(b). The HFL voltage v_S is quasi square waveform, and the waveform during rising and falling process are all staircase. The five staircases exist in the rising and falling process because there are three SMs in MMC arm and two inner phase-shift steps bring by HFL voltage adjusting strategy. Therefore, each voltage step is limited to output voltage of a single SM and the dv/dt stress problem on HVDC link can be largely resolved. Moreover, since the modified full-bridges in DCSST are connected to LVDC link and there is no dv/dt problem towards HFL

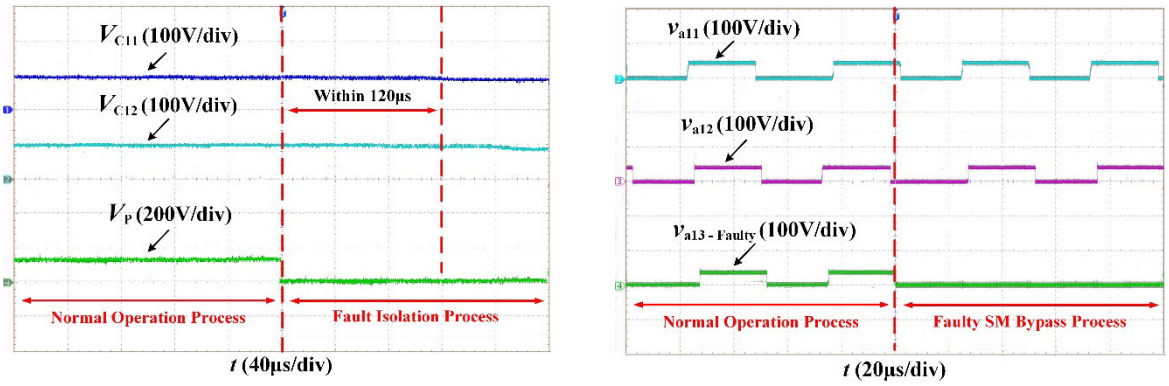

FIGURE 11. Experiment waveforms of hybrid DCSST when fault occurs. (a) Capacitor voltages of SMs in modified full-bridge, (b) Output voltages of faulty SM and normal SMs in MMC topology.

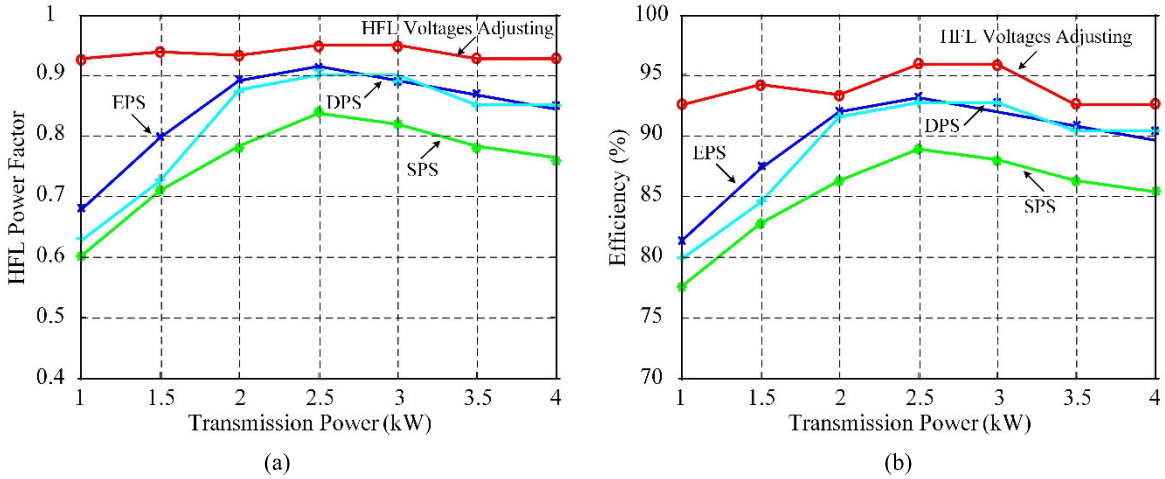

FIGURE 12. Comparative curves of hybrid DCSST under SPS, EPS, DPS and proposed HFL modulation strategy. (a) HFL power factor, (b) Efficiency.

transformer, the square-wave is retained for HFL voltage v_P in paralleled full-bridges architecture, thus maintaining strong power transmission capability and the ideal soft-switching performance.

Moreover, under the proposed HFL modulation, the SMs in one arm of MMC topology in hybrid DCSST generate square voltages v_{a11}, v_{a12}, v_{a13}, v_{a14}, v_{a15} and v_{a16} with the equivalent amplitude, as shown in Fig.10. From the figure, the positive and negative voltages of SM output square voltage are $V_C = 50V$ and 0V, and the SM output voltage waveforms vary alternately. The balance of SM voltages is realized under proposed HFL voltage modulation strategy, ensuring the stable operation and function realization for DCSST. The phase-shift exists between adjacent SM output voltages and composes the staircase rising and falling transitions in MMC arm voltage v_{a1} and HFL voltage v_S to alleviate dv/dt stress towards HFL transformer.

When a fault occurs in renewable energy sources, the experimental waveforms of fault handling process of SMs in modified full-bridge of hybrid DCSST are presented in Fig. 11. During the experiment, the voltage protection value is set at about 90% of rated SM capacitor voltage, where $V_{C\text{-protect}} = 0.9 * V_C = 0.9 * 110 = 99V$. According to Fig. 11(a), when a fault happens and the SM capacitor voltage drops to about 99V, the SM voltage protection is activated, and the switches in SMs are both turned-off and the SMs are under blocking state. The fault isolation procedure is less than 120us, thus protecting DCSST from malfunction and satisfying the requirement of rapid fault isolation for DC distribution network. Besides, SM capacitor voltages are maintained at 99V during blocking state, providing a rapid recovery function when the DC faults are cleared. Moreover, as presented in Fig.11(b), when the fault occurs in half-bridge SM, the faulty SM is blocked and switched to bypass state, and its output voltage drops from 50V to 0V. The other SMs still operate normally and maintain output voltages, ensuring normal operation of DCSST. Thus, the hybrid DCSST can realize bidirectional fault handling capability, avoiding the application of DC circuit breaker under certain operating occasions, effectively reducing the system volume and construction cost for both DCSST and DC distribution network.

With the varied transmission power, the comparisons of HFL power factor and efficiency of DSSCT under the SPS, EPS, DPS and proposed HFL modulation strategies are presented in Fig. 12. From Fig. 12(a), the HFL power factor under EPS, DPS and proposed HFL modulation strategies are always larger than that under SPS, and the proposed strategy obtains the largest HFL power factor of DCSST. Besides, compared with the efficiency of DCSST under conventional SPS, EPS and DPS strategies, the highest efficiency is achieved under proposed HFL modulation strategy, as presented in Fig. 12(b). Moreover, when the transmission power of DCSST is lower than 2kW, the HFL power factor and efficiency of DCSST under SPS, EPS and DPS strategies declines obviously. Correspondingly, the power factor and efficiency of DCSST under proposed HFL modulation strategy maintain strong performances, guaranteeing the stable and reliable operation with low transmission power and further expanding the control and application ranges for DCSST.

VI. CONCLUSION

The DCSST plays an important role in connection of renewable energy sources, voltage conversion, bidirectional power transmission and electrical isolation for the DC distribution network. To connect the renewable energy, energy storage and distributed loads with DC distribution network, a hybrid DCSST scheme is proposed in this paper. Compared with existing DCSST schemes, the proposed hybrid DCSST is composed of modified full-bridges and MMC topology, achieving flexible connection and large voltage boost ratio for renewable energy system, realizing fault handling capability, avoiding the application of DC circuit breakers and reducing the volume and construction cost. Besides, the HFL voltages under proposed scheme are hybrid waveform and adjusted adaptively to match HFL transformer voltage ratio during the whole operating range, reducing the current stress, reactive power and power loss of DCSST under fluctuation of power flow from renewable energy sources and distributed loads. Topology, operation principle, fault handling process and hybrid-wave HFL voltages adjusting strategy of hybrid DCSST scheme are investigated, providing an efficient and practical DCSST scheme, further promoting the engineering application and development of DC distribution network.

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