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Solid State Hybrid DC Transformer Based on Series Resonant Converters and DAB Converters for Interconnection of MVDC and LVDC Grids

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ABSTRACT

Generally Interconnection between MVDC and LVDC grids requires DAB converters with series connections in MVDC side and parallel connections in LVDC side. A solid state hybrid DC transformer topology is proposed with a combination of series resonant converters (SRCs) and DAB converters for achieving high efficiency. The solid state hybrid DC transformer contains more no of SRCs and less no of DAB converters for better efficiency and voltage regulation. This proposed hybrid converter facilitates bidirectional power flow and integration of renewable energy sources, BESS etc. As more no of SRCs are used, the control circuit complexity will be reduced and only DABs require complex control circuits and controls algorithms. The operating methods of the proposed solid state hybrid Dc transformer are analyzed in detail and the important design parameters are presented in this paper. A Matlab/Simulink model is constructed and simulation results are obtained and analyzed to validate the theoretical analysis.

KEYWORDS: *DAB converter, SRC, MVDC, LVDC, Solid state hybrid Dc transformer*

I. INTRODUCTION

Now days, the conventional ac distribution gird is facing numerous challenges, more and more distributed renewable energy sources (wind, PV etc) and energy storage systems (BESS, super capacitors, ultra capacitors etc) with natural dc power characteristic are connected into the distribution grid, and on the other hand, more dc loads such as light-emitting diode lighting systems, electric vehicles, data centers, are emerging [1]-[4]. The Dc distribution grid is considered as a promising option for integrating distributed dc power sources and dc loads, enhancing transfer capacity, and providing increased power conversion efficiency [5]-[6].

The Fig.1 shows a typical schematic of conventional Dc grid and Fig.2 shows a typical schematic of dc distribution grid with two voltage levels, i.e., medium-voltage dc (MVDC) and low-voltage dc (LVDC), where a dc transformer (DCT) is main equipment in the dc distribution grid to interconnect the MVDC and LVDC grids for flexible power transfer, voltage conversion, and to provide electrical isolation [7].

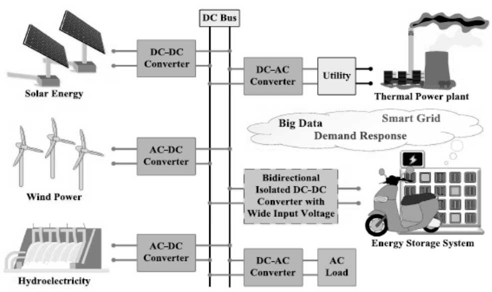


Fig.1 conventional Dc grid

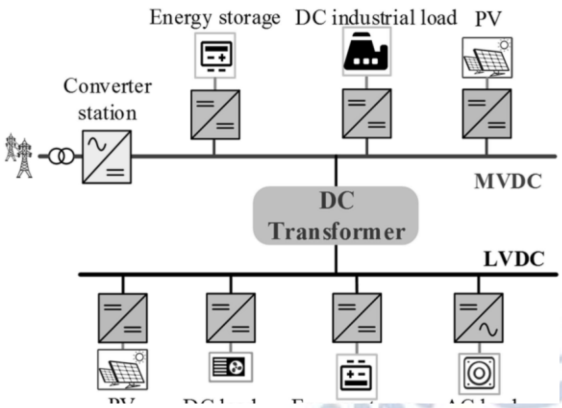


Fig.2 proposed topology

Different medium or low-voltage DCTs have been presented in the literatures such as three-level converter based DCTs medium voltage device based DCTs modular multilevel converter (MMC) based DCTs and multi module converter based DCTs [8]-10]. The sub module capacitor voltage balancing schemes are explored. By using a trapezoidal current modulation, the SM capacitor voltages are inherently balanced without extra feedback control [11]. However, only one single phase or three-phase medium voltage large power high frequency transformer is employed, which is very difficult to design and fabricate. Some researchers proposed a MMC based DCT with multiple single phase full bridge modules connected in parallel at the LVDC side, in which the power rating of high-frequency transformers can be significantly reduced. In general the MMC based converters are more suitable for hundreds of kilovolts applications, while it seems a little complex and costly in the MVDC applications [12].

The modular architecture based on multi module converters connected in series at the MVDC side and in parallel at the LVDC side, which also known as input-series output-parallel connection, is a viable option for medium/low-voltage DCTs with the advantages of lower voltage stress of power switches, lower power rating of high-frequency transformers and improved reliability by using redundant modules. The voltage balance control strategies for the input-series output-parallel connection DAB converter-based DCTs are explored in detail [13]. The voltage balance control strategy is eliminated to reduce the complex of controller because a voltage balance circuit is introduced into a conventional input-series output-parallel DCT, in which the voltage balance circuit also improves the power density and reliability when some dc–dc converters break down, however, the introduced voltage balance circuit cannot regulate the terminal voltages of dc–dc converters. To improve the performance of DCTs where sub modules are directly connected in series when a short fault occurs in MVDC grid and voltage match between the two sides of the high frequency link of DAB converter, multiple half-bridge switched capacitor sub modules are introduced into the conventional input series output parallel DAB converter based DCTs.

Considering the small soft-switching range of DAB converter with single-phase-shift (SPS) control, the literature proposed multiple phase-shift control and the extended phase-shift (EPS) control, respectively. Apart from the DAB converter, a bidirectional series resonant dc-dc converter (SRC) can also be used as the sub module for the input-series output-parallel converter-based DCTs. Compared with the DAB converter, the SRC operating at the resonant frequency is a highly attractive choice because of its high efficiency, moreover, the voltage ratio of SRC operating at the resonant frequency is almost determined by the transformer turns ratio, hence, the input voltage sharing among SRCs is achieved automatically without any voltage balance control strategy or external voltage balance circuit. However, in contrast to DAB converter, the SRC-based DCT does not offer any control possibilities and it couples the MVDC bus and LVDC bus tightly, the power transfer is mainly determined by the difference of the two dc voltages. With demand of the flexible regulation in output voltage, the variable frequency control or phase-shift control must be applied. As a result, not only the control complexity increases, but also the conversion efficiency decreases due to the lack of zero voltage switching (ZVS) or/and zero-current switching (ZCS) [14]-[15]. Hence, a DCT with both the features of DAB converter and SRC are desired.

This paper proposes a hybrid input-series output-parallel DCT composed of DAB converters and SRCs. However, the power rating of DAB converter is the same with that of SRC, which makes difficult to improve efficiency. If the total equivalent resistance of SRC is not taken into account in design process will have an important impact on the voltage stress of DAB converter. In this paper, a hybrid input-series output-parallel DCT structure consisting of multiple SRCs and one or several DAB converters is proposed to interconnect MVDC bus and LVDC bus. In the proposed hybrid DCT, the majority portion of power is transferred by the SRCs to achieve higher conversion efficiency and the remaining minority portion of power is transferred by the DAB converters to realize voltage and power regulation. This article is organized as follows. Section II introduces the proposed DCT topology and operating procedures, and Section III elaborates the design of circuit parameters. Simulation validation of various modes of operation is done and results are discussed and displayed in Section IV. Finally, Section V gives conclusion of the paper.

II. PROPOSED SOLID STATE HYBRID DCT

The proposed solid state hybrid DCT topology is shown in Fig.3, which is a combination of N SRCs and one DAB converter. It should be noted that number of DAB converters may be increased according to the output requirements. All the proposed N SRCs have the same parameters and share the majority portion of the medium voltage V_{MV}. The following section presents the operation principle of SRC and DAB converter in detail.

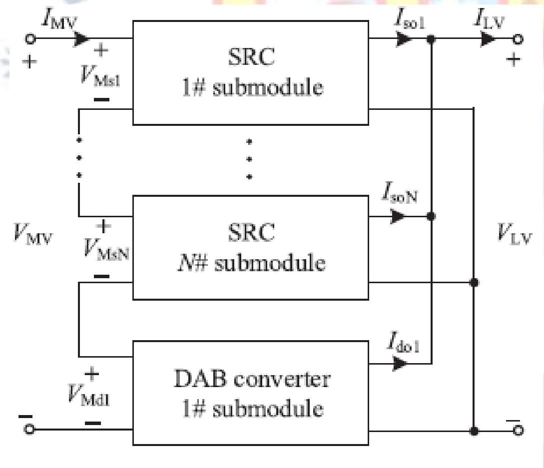


Fig.3 Block diagram of proposed topology

A. Series resonant DC-DC Converter

Fig.4 shows a bidirectional series resonant dc–dc converter. The SRC may have different operating modes according to the relationship between switching frequency f_{ss} and resonant frequency f_r, i.e., $f_{ss} > f_r$, $f_{ss} = f_r$, $0.5f_r < f_{ss} < f_r$, and $f_{ss} < 0.5f_r$. The mode when f_{ss} is equal to f_r can realize ZCS of all power switches, which is of high need for high-voltage high-power applications, where IGBTs are mostly the preferred semiconductor device, apart from that, there is no reactive current, leading to high efficiency. So, the SRC operating at f_r is chosen in the proposed DCT for its high efficiency. As shown in Fig.4, both full-bridges ($Q_{s1}-Q_{s4}$ and $Q_{s5}-Q_{s8}$) of two sides are driven by switching signals with the same frequency and 50% duty cycle, generating rectangular voltage waveforms V_{ABs} and V_{CDs} on two sides of the transformer. Assuming power is transferred from MV side to LV side, now the power formula of SRC operating at f_r can be expressed as

$$P_{SRC} = \frac{8K_s}{\pi^2 R_r} V_{LV}(V_{Ms} - K_s V_{LV}) \tag{1}$$

Where V_{Ms} the MV-side terminal voltage of SRC, V_{LV} is the voltage of LVDC bus, K_s is the turns ratio of the transformer and R_r is the total equivalent resistance reflected to the MV side. According to (1), it is seen that there is no controllability to its power magnitude and the direction of power flow. The power flow through the SRC adjusts automatically such that the dc voltages on either side stay equal. Therefore a switch is required to help the SRC to control its power magnitude and the direction of power flow, and the switch is a DAB converter in the proposed solid state hybrid DCT.

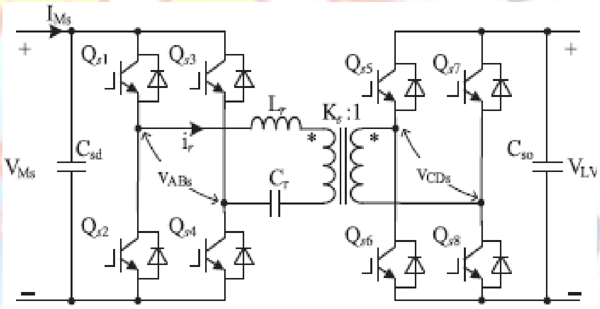


Fig.4 Circit of Series Resonant DC–DC Converter

B. Dual Active Bridge Converter

The dual active bridge (DAB) converters are widely studied and used in bidirectional power flow applications. Various control methods of DAB converter have been presented, such as single-phase shift (SPS), dual-phase-shift (DPS), triple-phase shift (TPS) and extended phase shift (EPS). SPS control strategy is adopted in this paper for its simplicity to analyze the function of DAB converter, even other advanced control methods can be used to reduce the current stress of power switches and improve the efficiency.

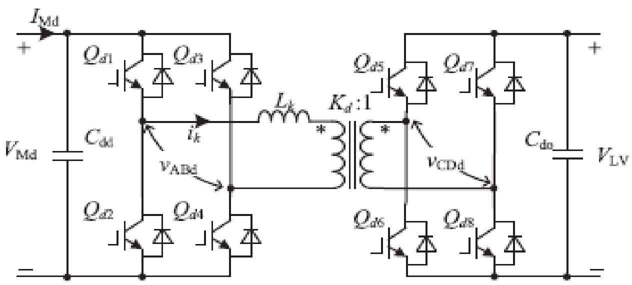


Fig.5(a) Circuit diagram of DAB converer

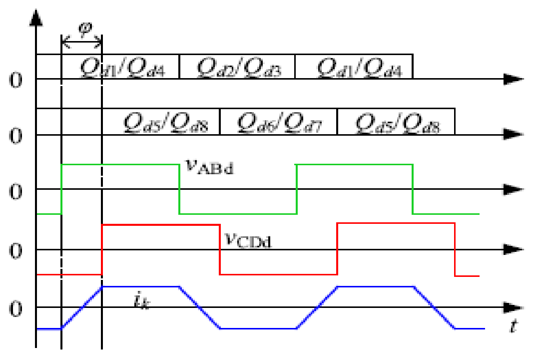


Fig.5(b) Waveforms of DAB converter

As shown in Fig.5, the switches Q_{d1} and Q_{d4} have the same driving signals, as well as switches Q_{d2} and Q_{d3} is out of phase. The switches on the LV side are the same, but there is a phase shift angle ϕ between the driving signals of Q_{d1}- Q_{d4} and Q_{d5}- Q_{d8}. The duty cycle of Q_{d1} - Q_{d8} is 50%.With the SPS control method, the transferred power and MV side input current of DAB converter can be expressed as

$$P_{DAB} = \frac{8K_d V_{Md} V_{LV}}{2\pi^2 L_k f_{sd}} \Phi(\pi - |\Phi|) \tag{2}$$

$$I_{Md} = \frac{K_d V_{LV}}{2\pi^2 L_k f_{sd}} \Phi(\pi - |\Phi|) \tag{3}$$

Where V_{Md} the MV-side voltage of DAB converter, L_k is the leakage inductance of DAB converter, K_d is the turns ratio of transformer, and f_{sd} is the switching frequency of DAB converter. According to (2) and (3), it is seen that the magnitude and the direction of power and current flow can be controlled by ϕ.

C. Operating Principle of SSHDCT

Based on the system configuration in Fig.3, the solid state hybrid DCT can work in any of the three operation modes given below,

i). Power regulating mode where both MV and LV main voltage sources exist, the SSHDCT is controlled as a power/current source, managing the power flow between MV and LV sides. Assume all the SRCs have the same parameters, and then natural voltage equalization of the input voltages of SRC modules is shown below

$$V_{Ms1} = V_{Ms2} = V_{Ms3} = \cdots = V_{MsN} \tag{4}$$

Under steady state, all the SRCs and DAB currents of converters are the same as input currents given below

$$I_{Ms1} = I_{Ms2} = I_{Ms3} = \cdots = I_{MsN} = I_{Md} = I_{MV} \tag{5}$$

The total power of the SSHDCT is

$$P_{tot} = V_{MV} I_{MV} = \frac{K_d V_{MV} V_{LV}}{2\pi^2 L_k f_{sd}} \Phi(\pi - |\Phi|) \tag{6}$$

Comparing (6) with (2), it can be seen the proposed modular SSHDCT has the same transmission power characteristic with that of a DAB converter, although merely one DAB converter is employed in the solid state hybrid DCT. The phase-shift angle ϕ of the DAB converter determines the power magnitude and direction of power flow when both V_{MV} and V_{LV} are regulated by corresponding main voltage sources. If ϕ is positive, power flows from the MV side to the LV side; if ϕ is negative, power flows from the LV side to the MV side.

ii). LVDC voltage regulating mode where the LV main voltage source does not exist, the SSHDCT is controlled as a LVDC source to maintain the power balance in the LV side. The phase-shift angle control is applied to regulate the LV side voltage to its reference value. By Combining (1), (3), and (5), the MV side terminal voltages of SRCs are obtained

$$V_{Ms1} = V_{Ms2} = \cdots = V_{MsN} = V_{Ms} = \frac{P_{SRC}}{I_{MV}} = \frac{\frac{8K_s}{\pi^2 R_r} V_{LV} (V_{Ms} - K_s V_{LV})}{\frac{K_d V_{LV}}{2\pi^2 L_k f_{sd}} \Phi(\pi - |\Phi|)} = \frac{16 K_s L_k f_{sd} (V_{Ms} - K_s V_{LV})}{K_d R_r \Phi(\pi - |\Phi|)} \tag{7}$$

From (7) V_{Ms} and V_{Md} can be obtained as

$$V_{Ms} = \frac{16 K_s^2 L_k f_{sd} V_{LV}}{16 K_s L_k f_{sd} - K_d R_r \Phi(\pi - |\Phi|)} \tag{8}$$

$$V_{Md} = V_{MV} - N_{SRC} V_{Ms} = V_{MV} - \frac{16 N_{SRC} K_s^2 L_k f_{sd} V_{LV}}{16 K_s L_k f_{sd} - K_d R_r \Phi(\pi - |\Phi|)} \tag{9}$$

From (8) and (9) that $V_{Ms1}, V_{Ms2}, \ldots V_{MsN}$ increase and V_{Md} decreases with the increase of ϕ, which equals with the theoretical analysis. Since the input current of each module is equal to the system input current (I_{MV}), the ratio of the input power of each module to the total input power is equal to the ratio of the input voltage of each module to the total input voltage. Hence, the ratio of DAB converter input power is

$$\frac{V_{Md}}{V_{MV}} = \frac{P_{DAB}}{P_{tot}} = 1 - \frac{16N_{SRC}\,{K_s}^2 L_k f_{sd} V_{LV}}{V_{MV}\left(16K_s L_k f_{sd} - K_d R_r \Phi(\pi - |\Phi|)\right)} \quad (10)$$

iii). MVDC voltage regulating mode where the MV main voltage source does not exist, the SSHDCT is controlled as a MVDC source to maintain the power balance in the MV side. The phase-shift angle control is applied to control the MV side voltage to its reference value. In this mode, V_{LV} is considered to be constant which is clamped by a main voltage source in the Mean while, V_{MV} is regulated by the controller. What is more, the expression of V_{Ms} and V_{Md} are the same as that in the LVDC voltage regulation mode. Normally, the SSHDCT is controlled as a current source in power regulation mode while as a voltage source in LVDC voltage regulation mode and MVDC voltage regulation mode.

III. DESIGN OF CIRCUIT PARAMETERS

The main point of the parameters design of the proposed SSHDCT is to determine the minimum number of DAB converters to meet the voltage stress requirements of both DAB converters and SRCs, resulting in higher efficiency due to the majority power of the SSHDCT is transmitted by SRCs. A SSHDCT with the following specifications is taken as an example for design of circuit parameters shown in table I. As per the given V_{MV} and available power switches, 1700-V IGBTs are selected as the main power switches, the number of total modules N_{tot} is set to 10 and each module holds the voltage around 1kV at the MV side. However the majority portion of power is to be transmitted by the SRCs, the number of SRCs is selected as nine and there is only one DAB converter.

Table I

Specification	Value
MV bus voltage V_{MV}	10KV±3%
LV bus voltage V_{LV}	750V
Rated power P_{tot}	1MW
Switching frequency $f_{sd} = f_{ss} = f_r$	20kHz

The proposed SSHDCT has the same transmission power characteristic with that of a DAB converter. so, the maximum phase shift angle is designed to be ϕ_{max} = 45° under the rated power load condition in terms of ZVS condition and reactive power of DAB converter. From (6), we have

$$L_k = \frac{3K_d V_{MV} V_{LV}}{32 P_{tot} f_{sd}} \quad (11)$$

Substituting the value of L_k from (11) into (8) and (9), this gives

$$V_{Ms} = \frac{16{K_s}^2 V_{MV} V_{LV}^2}{32K_s V_{MV} V_{LV} - 2P_{tot} R_r \Phi(\pi - |\Phi|)} \quad (12)$$

$$V_{Md} = V_{MV} - \frac{3N_{SRC}\,{K_s}^2 V_{MV} V_{LV}^2}{3K_s V_{MV} V_{LV} - 2P_{tot} R_r \Phi(\pi - |\Phi|)} \quad (13)$$

A. Design of R_r

For a SRC, R_r is a sum of series resistances of the resonant inductor, resonant capacitor, transformer and the IGBTs, and diodes resistances and it is very difficult to calculate the exact value. But, R_r represents the power losses of a SRC and it can be calculated through the conversion efficiency. According to the power loss of SRC operating with variable frequency and phase shift is below 1%. What is more, it is desired to achieve high converter efficiency for SRC, e.g., η = 98.5%. Then for a SRC with the specifications of 1000V/750 V/100 kW and η = 98.5%.

I = 100KW/1000V = 100A,

P_{loss} = 1.5% of 100KW = 1500W

R_r = 1500/100^2 = 0.15 Ω.

B. Design of K_s , K_d and L_k

According to the analysis in Section II, the variation of V_{MV} only affects the MV side terminal voltage of DAB converter and the maximum MV side terminal voltage of DAB converter must be verified. Finally, the MV side terminal voltages of SRCs and DAB converter are selected as 1060 and 460 V at steady state, respectively. Then when V_{MV} is 10.3 kV and in the case of reverse transmission power, the MV side terminal voltage of DAB converter only reach 1089 V, which is reasonable for the device selection. Then, the K_s can be calculated from (12) as K_s = 1.39 . K_d = 460/750 = 0.61. From (11), we have L_k = 21.5 μH

C. Design of L_r and C_r

Resonant frequency $f_r = \frac{1}{2\pi\sqrt{L_r C_r}}$ (14)

For the SRCs, the leakage inductor is taken as the resonant inductor and its inductance is selected as

10μH and $f_r = 20kHz$ then at resonant capacitance is calculated as 6.3μF.

IV. SIMULATIOS OF VARIOUS MODES

A Matlab/Simulink model is constructed for the proposed SSHDCT and simulations are run for the three modes of operation discussed in Section II. The designed parameters required for simulation are given in Table II.

Table II

Parameter	Value
Number of DABs	1
Number of SRCs N_{SRC}	9
Equivalent Resistance R_r	0.15Ω
Turns ratio K_s	1.39
Turns ratio K_d	0.61
Inductor L_k	21.5 μH
Resonant Capacitor C_r	6.3μF
Resonant Inductor L_r	10μH

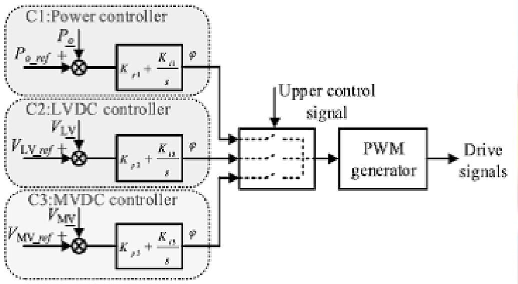
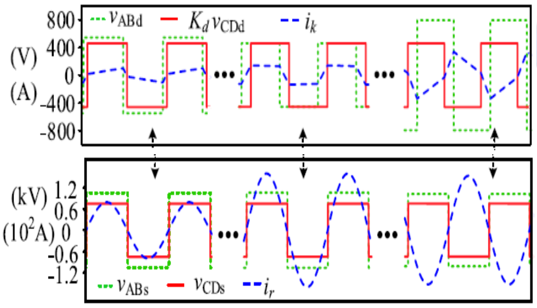
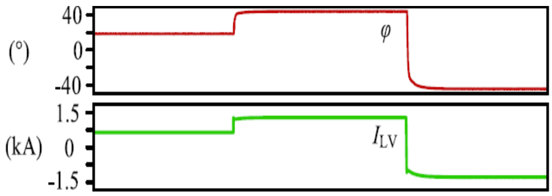


Fig.6 SSHDCT Controller

Figure 6 shows the controller for three operating modes. Figure 7(a), (b) shows the main simulation waveforms of SRCs and DAB voltage and currents for power regulation mode. At $t = 0.5$ s, the power of SSHDCT is stepped up from 0.5 to 1 MW, and at $t = 1$ s, the power of DCT is changed to be −1 MW. It can be seen that the transmission power is changed from the 0.5 to 1 MW by adjusting ϕ from 18° to 45°, and then to −45° to regulate the power to −1 MW after 1 s.



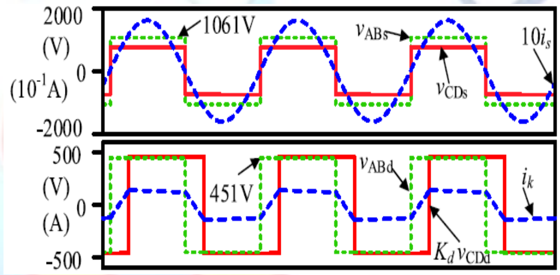
(a)



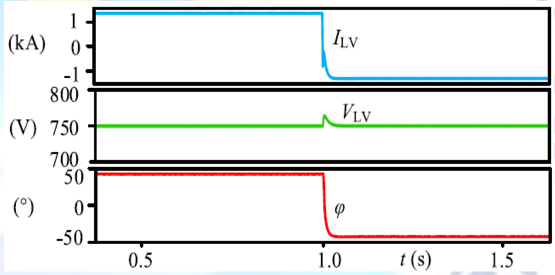
(b)

Fig.6 Simulation of power regulation mode

Figure 8 shows the main simulation waveforms of LVDC voltage regulation mode, in which the LVDC voltage is regulated by the SSHDCT. From Fig. 8(a) it can be seen that the MV side terminal voltage and currents V_{ABs} , V_{CDs} , i_s of SRCs are in phase. DAB converter terminal voltage and currents V_{ABd} , V_{CDd} , i_k are having phase difference of 45⁰. From Fig. 8(b) it is clearly seen that at t = 1 sec, when power is reversed phase and currents are also reversed.



(a)



(b)

Fig. 8 Simulation of LVDC regulating mode
(a) V_{MV} = 10KV, P_{tot} = 1MW (b) P_{tot} from1 to -1MW

V. CONCLUSIONS

This paper proposes a novel solid state hybrid DCT with input-series output-parallel configuration, which combines SRCs for majority of power transmission and DAB converters for the dc voltage and bidirectional power control. From the available hybrid circuit topology, the proposed SSHDCT can achieve a high efficiency, while maintaining the controllability of the dc voltage and power. As the SRC sub modules operate in open loop, the complexity of the control system is also reduced. The design of main parameters is discussed in detail. Simulation results are verified the operation principles of the SSHDCT and parameters design. This design can be extended by employing more DABs for better voltage regulation and power control.

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