Achievement of Zero Voltage Switching at Light Load for Parallelly-Connected Dual Active Bridge Converter using Power-Circulating Operation

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This paper proposes a power-circulating operation at light load for a parallelly-connected Dual-Active-Bridge (DAB) converter in order to achieve zero voltage switching (ZVS) over entire load range. At the light load, a power flow of each DAB converter is controlled in such a way that the transferred power of each DAB converter satisfies the condition for ZVS, i.e. the power-circulating operation. Consequently, MOSFET with low voltage rating can be used due to no surge voltage in ZVS. At the heavy load, the power-circulating operation is no longer required due to the high power flow of each DAB converter. The heavy load efficiency is not only improved but also the light load is operated without the recovery surge. From experimental results, the converter efficiency is over 96% from the rated power of 14.4% to the rated power at the nominal voltage. At 75% of the nominal voltage, the maximum efficiency of 97.6% is obtained.

Keywords Dual active bridge converter, Zero voltage switching, Parallel operation

1. Introduction

Recently, energy storage systems have been actively installed to DC micro-grid systems [1]. a dual active bridge (DAB) converter is generally applied in such systems [2]. The DAB converter can obtain the high efficiency because zero voltage switching (ZVS) is achieved without additional components. ZVS not only reduces the turn-on loss but also reduces the surge voltage which occurs in the recovery mode of the body diode into MOSFET. However, the ZVS range is limited when the voltage fluctuates widely [2]. Due to the hard switching operation, the high voltage rating of MOSFET which has higher on-state resistance has to be selected.

In order to extend ZVS range, Pulse width modulation is employed with the phase-shift control [3]. However, it is not always possible to achieve ZVS over entire load range.

In this paper, the power-circulating operation of a parallelly-connected DAB converter is proposed in order to achieve ZVS range over entire load range with the power-circulating operation the power flow of each DAB converter is changed in such a way that ZVS for all DAB converters is achieved. In addition, the low voltage rating of MOSFET can be selected because no surge voltage occurs in ZVS. In addition, the power flow of each converter is changed depending on the output power and the voltage condition. Finally, the experimental results is conducued by using A 1.6-kW prototype in order to validity of the proposed method.

2. Proposed power flow control

Fig. 1 shows the circuit configuration of the parallelly-connected DAB converter. By employing the parallel connection to the DAB converter, the conduction loss and the copper loss are reduced in compared to those when only one DAB converter is applied. However, the ZVS range is limited when the battery voltage fluctuates from the nominal voltage [3].

Fig. 2 shows the power flow diagrams of the parallelly-connected DAB converter corresponding to the output power. Fig. 2(a) shows the parallel operation at heavy load where ZVS is simply achieved due to the high power flowing through each converter. Fig. 2(b) shows the single operation in which, only one DAB converter is operated under the ZVS condition. Fig. 2(c) shows the power-

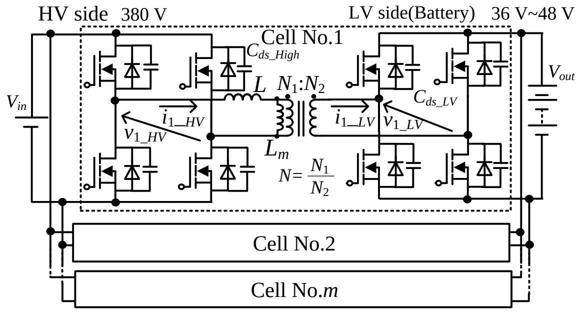

Fig. 1. Circuit configuration of parrallelly-connected DAB converter.

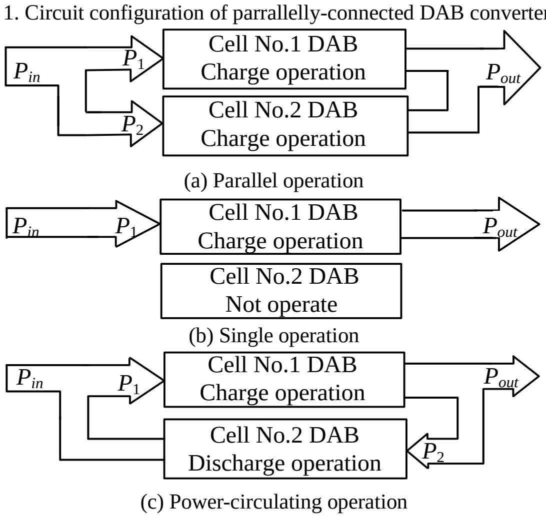

Fig. 2. Power flow diagrams of parrallelly-connected DAB converter.

circulating operation applied at light load. In the power-circulating operation, the power flow of each DAB converter is changed. The transferred power of each DAB converter P_1 and P_2 are designed to satisfy the condition for the ZVS achievement. If the parallel number of the converter is changed with the power-circulating operation, only two DAB converters are operated at light load because the transferred power P_1 will have to be increased if the number of the active converters increases. In other words, at light load, the No. 3~No. *m* DAB converter is inactive. In the power-flow control, the operation mode is changed depending on the relationship between the reference transferred power P_{ref} and the

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lower limit of the transferred power for ZVS P_{ZVS}. The conditions based on P_{ref} and P_{ZVS}. At the condition of $P_{ZVS}>P_{ref}$, ZVS is not achieved in each individual DAB converter, i.e. the parallel operation or the single operation. Therefore, the power-circulating operation is used. The transferred power of each DAB converter P_1 and P_2 are adjusted to be larger than P_{ZVS}. As a result, the transferred power of each DAB converter P_1 and P_2 are calculated by (1).

$$P_1 = P_{ref} + P_{ZVS} \\ P_2 = -P_{ZVS} \qquad (1)$$

In the condition of $P_{ZVS} \leq P_{ref} < 2P_{ZVS}$, ZVS is achieved if only one DAB converter is active, i.e. the single operation. Therefore, only one DAB converter is operated. The other is operated that zero voltage is output in each inverter. In the single operation, the transferred power of each DAB converter P_1 and P_2 are calculated by (2).

$$P_1 = P_{ref} \\ P_2 = 0 \qquad (2)$$

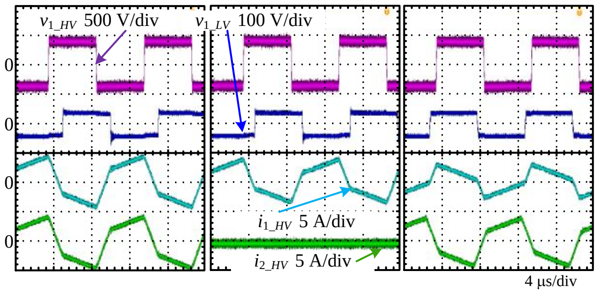
In the condition of $2P_{ZVS} \leq P_{ref} < P_{rated}$, ZVS is achieved in each individual DAB converter. Therefore, the parallel operation is active. In the parallel operation, the transferred power of each DAB converter P_1 and P_2 are calculated by (3).

$$P_1 = P_2 = P_{ref} / 2 \qquad (3)$$

3. Experimental Results

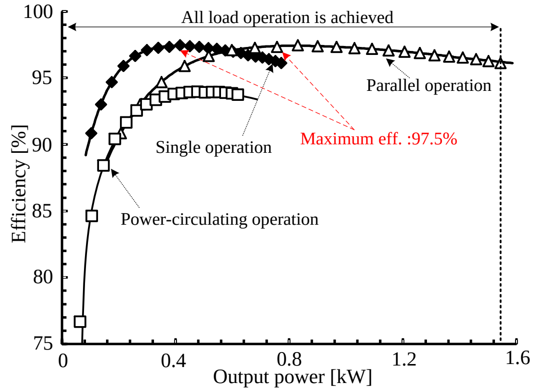
Fig. 3 shows the operation waveforms with three operations at the input voltage of 380 V and the output voltage of 36 V. Fig. 3 (a) shows the operation waveforms of the parallel operation at the output power of 1048 W, Fig. 3 (b) shows the operation waveforms of the single operation at the output power of 542 W, and Fig. 3 (c) shows the operation waveforms of the power-circulating operation at 268 W, i.e. the achievement of ZVS in each individual DAB converter. As shown in Fig. 3 (a), the parallel operation is confirmed at the same power flow. In Fig. 3(b), the single operation is confirmed because only one DAB converter is operated. Besides, the power-circulating operation is obtained because each individual DAB converter has difference power flow direction. By using the power-circulating operation, the low power at the light load is not flown in each individual DAB converter. As a result, ZVS is achieved at light load.

Fig. 4 shows the efficiency characteristics of two parallelly-connected DAB converter. Fig. 4(a) shows the efficiency characteristics when the output voltage is 48 V and the input voltage is 380 V, i.e. the nominal voltage. Fig. 4 (b) shows the efficiency characteristics when the output voltage is 36 V and the input voltage is 380 V. In Fig. 4(a), the converter efficiency at medium load is improved by using the single operation because the iron loss becomes zero with the halting the operation of the other DAB converter. By using the power-flow control corresponding to the output power, the converter efficiency is over 96.0% from the light load of 14.4% to the rated load. In Fig. 4(b), the maximum efficiency of 97.6% is achieved. However, the converter efficiency at the light load becomes lower by the power-circulating operation because the conduction loss and the copper loss are increased.

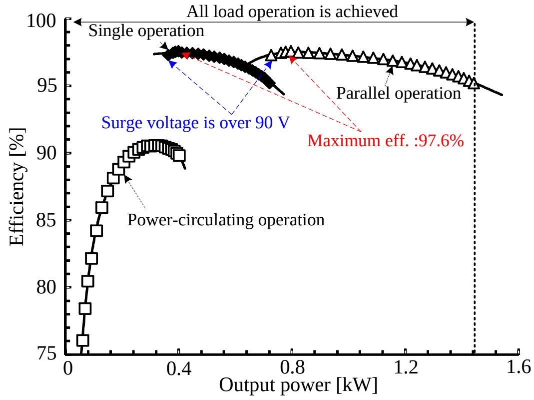


(a) Single operation (b) Parallel operation (c) Power-circulating operation

Fig. 3 Operation waveforms with each mode.



(a) V_{in}=380 V, V_{out}=48 V (Nominal voltage)



(b) V_{in}=380 V, V_{out}=36 V (75% nominal voltage)

Fig. 4. Efficiency characteristics of two parallelly-connected DAB converter with fluctuation of output voltage.

4. Conclusion

This paper proposed the power-circulating operation for the parallelly-connected DAB converter with the aiming of achieving ZVS over entire load range and wide battery-voltage variation. In the proposed method, the power flow and the transferred power were changed depending on the output power in order to operate all DAB converters at the ZVS condition. In experimental results, the converter efficiency is over 96.0% from 14.4% of the light load to the rated load by changing the power flow of each individual DAB converter.

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