A Control Strategy for Paralleled Bi-Directional DC-DC Converters Used in Energy Storage Systems

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***Abstract*—According to the control requirements of modular power used in energy storage systems, a parallel control strategy for bi-directional DC-DC converter is proposed and applied to the bi-directional DC-DC converter combined by current-fed half bridge and voltage-fed half bridge. While converters operate in parallel, the master-slave control based on digital communications can solve the problem of unequal current distribution caused by different parasitic parameters between parallel modules, and the strategy is with strong anti-interference ability. When running, each slave module will modify the reference of its own internal current loop by comparing its bus side current with the master module's bus side current via its current-sharing loop, so that the current sharing at the DC bus side can be achieved. Meanwhile, with the auto-master-selected strategy, a new master module will arise immediately when the former master module fails, which solves the problem of system failure when master module breaks down with traditional master-salve control. The simulation and experimental results prove the validity of the parallel control strategy.**

Keywords—parallel control; bi-directional DC-DC converter; digital communications

I. INTRODUCTION

In distributed power supply system, energy storage devices are usually used to restrain the power fluctuation caused by the randomness and uncertainty of new energy power generation [1]. Among various energy storage devices, storage batteries are widely used in many storage systems due to the advantages of low cost, high power density, high reliability [2]. As seen in Fig. 1, by connecting storage batteries to the DC bus of distributed system with bi-directional DC-DC converters, active management of the battery energy can be achieved through the control of converters. So that, the power fluctuation of the DC bus can be reduced and the power quality will be improved.

However, with the increase of system power levels, the design of high power bi-directional DC-DC converter becomes more and more difficult, and the reliability also reduces. So one solution is to design the converter in the form of modular power that can be used in parallel. As seen in Fig. 2, the converters are connected to the DC bus of the distributed power supply system as modular power. Appropriate number of modules will be added according to the requirements, so the difficulty of system design can be greatly decreased. Also it is helpful to the redundancy design and stability of the system [3]. But due to the different output impedance caused by different parameters between each module, when they are used in parallel, the current of each module will be unequal. So how to achieve the current sharing between each module will be an unavoidable problem.

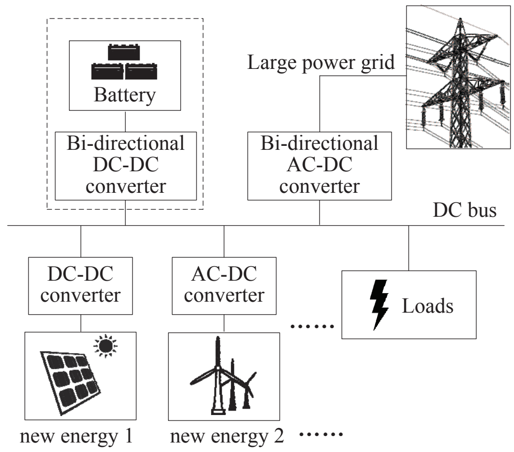

Fig. 1. Distributed power supply system with energy storage devices

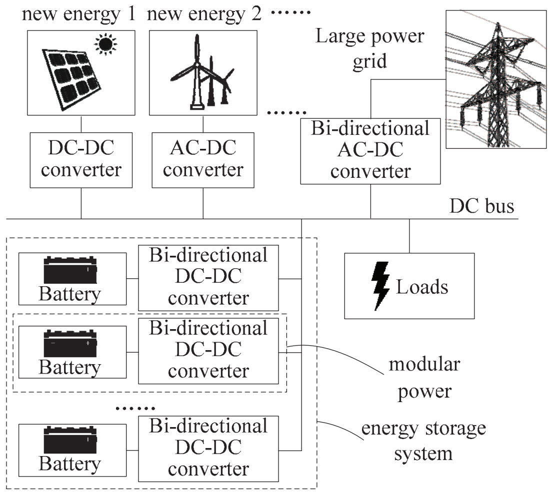

Fig. 2. Energy storage system with modular power

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Aiming at the requirements of the bi-directional DC-DC converter used in energy storage system, a bi-directional DC-DC converter based on current-fed half bridge is proposed in [4]. A buffering branch is introduced to this converter compared with traditional current-fed half bridge converter. By phase shift plus PWM control method, all power switches of the converter can achieve ZVS at full range of loads and the power flow direction can switch freely. And for parallel using, a lot of parallel control strategy have been researched [5-8], however most of them are designed for unidirectional converters that may not be suitable for bi-directional converters. A control strategy for modular dual active bridge is researched in [9], and the simulation results are given. However, the strategy is used for input series-output parallel system. A current-sharing method for paralleled bi-directional DC-DC converter used in storage system for photovoltaic power generation is studied in [10], and the method is used in an H-bridge topology successfully. But this strategy is based on traditional master-slave control, with which the master module is irreplaceable. Meanwhile, the output current sharing is achieved by the current-sharing control of the inductor current, so the output current is not controlled directly. The present parallel current-sharing methods are reviewed detailed in [11], and it is pointed out that the current-sharing technology is developing towards the digital direction.

For bi-directional converters, the power flow can be transferred in two directions. When they work in parallel, different parasitic parameters between each module may cause serious circulating power in the parallel system. Thus, compared with unidirectional converter, current-sharing control will be more important and difficult. However, there are still less researches on the parallel method of bi-directional converters. The parallel control strategy for the bi-directional DC-DC converter based on current-fed half bridge via digital communications is presented in this paper. The problem of unequal current distribution between different modules caused by parasitic parameters is solved, and the current sharing at the bus side is achieved. Finally, the simulation and experimental results prove the validity of the parallel control strategy.

II. Control of the Bi-Direction DC-DC Converter Based on Current-Fed Half Bridge

The topology of bi-directional DC-DC converter based on current-fed half bridge [4] is shown in Fig. 3. In this figure, U_{BA} is battery voltage, U_{DC} is bus voltage, C_c is buffering capacitor. In the low voltage side (LVS, the battery side), for each leg switches, both the top and bottom switches are gated with complementary PWM signals. The PWM duty cycles for S_{1u} and S_{2u} are the same, but the PWM signals are interleaved. In the high voltage side (HVS, the bus side), the duty cycles for S_{3u} and S_{3d} are fixed as 50%, and the PWM signals are interleaved too. By adjusting the duty cycles of the switches in LVS, the voltage of C_c (U_{cc}) can be controlled, so that the ratio of U_{cc} to $U_{DC}/2$ is equal to the turns ratio of the main power transformer. And the power flow of the converter is determined by the phase difference between the gate signals of S_{1u} and S_{3u}. When the gate signal of S_{1u} leads the gate signal of S_{3u}, power flows from LVS to HVS, and when the gate signal of S_{1u} lags the gate signal of S_{3u}, power flows from HVS to LVS. By

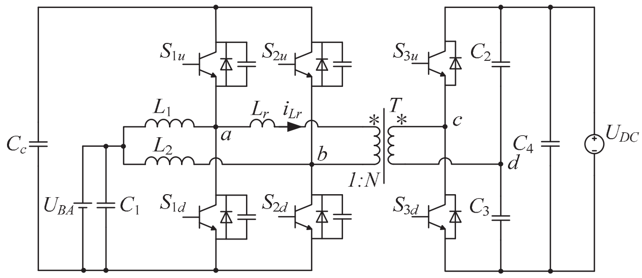

Fig. 3. Bi-directional DC-DC converter based on current-fed half bridge

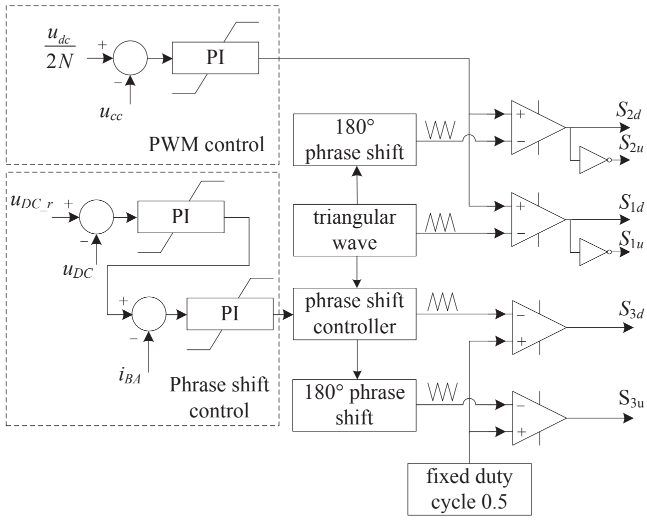

Fig. 4. Control diagram of single converter

PWM plus phase shift control, when the duty cycle of S_{1u} is less than 50%, the converter can achieve ZVS at full range of loads.

The control diagram of single converter is illustrated in Fig. 4. It contains two control loops. The first one is PWM control loop, which is used to regulate the voltage of buffering capacitor C_c, so that the voltage of C_c can be matched with the voltage of DC bus (the ratio of U_{cc} to $U_{DC}/2$ is equal to the turns ratio of the main power transformer). The second one is phrase shift control loop which is used to regulate the phrase-shifted angle between the gate signals of S_{1u} and S_{3u}. It consists of HVS voltage loop and battery current loop. And the output of the HVS voltage loop is set as the reference of battery current loop, so that, the direction and the value of battery current can be controlled by the state of bus voltage.

This strategy achieves the control in two power directions with the same control loop and the power flow direction can switch freely, which greatly reduce the design difficulty of the control loop.

III. Parallel Control Strategy for Bi-Directional Converter

When more converters are used in parallel, due to the difference of parameters between each module, the HVS current of each converter will be unequal. For example, when power flows from LVS to HVS, the output current of the module will be higher whose output voltage is higher when operating independently, and the HVS current of other modules will be lower. At the same time, due to the converter is bi-directional, the direction of HVS current and power flow of the modules whose output current is low may reverse in some special cases, which may cause circulating power between parallel modules and make bad effects on system security and stability. Thus, for bi-directional DC-DC converter, how to realize the current sharing between different parallel modules is very important.

The control diagram for multi-converters run in parallel is shown in Fig. 5, where u_{dc} is bus voltage, u_{dc_r} is the reference of bus voltage, $i_{ba\_1} \cdots i_{ba\_i} \cdots i_{ba\_n}$ represent the battery current of each module, $i_{bus\_1} \cdots i_{bus\_i} \cdots i_{bus\_n}$ represent the bus current of each module. When converters shutdown, all of the parallel modules are equivalent, and they are connected by communication lines.

When converters run, one of the modules will work as the master module, and others work as slave module. Master module is generated by auto-master-selected strategy. For example, as shown in Fig. 6, module i is selected to be the master module, then its current-sharing loop and other modules' external voltage loop will be disabled (dark color in this figure). At the same time, the output of the master module's voltage loop will be sent to each slave module by communication cables, and the value will be set as the reference of internal current loop of each slave module. Then the direction and value of the power flow of each slave module can be controlled. In the meanwhile, to ensure the current sharing at the DC bus side, the master module will also send the direction and value of its HVS current to each salve module by communication lines. Salve modules will compare their own HVS current with the mater module's HVS current, and the comparison results will be regulated by their own current-sharing loops. Then the output of current-sharing loop will be added to the reference of their internal current loop, so that the HVS current can be adjusted and the current sharing can be realized.

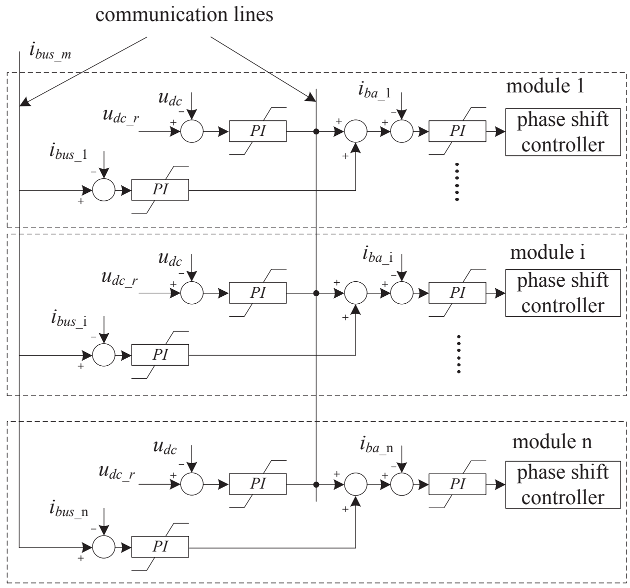

Fig. 5. Parallel control diagram of the modular power (converters shutdown)

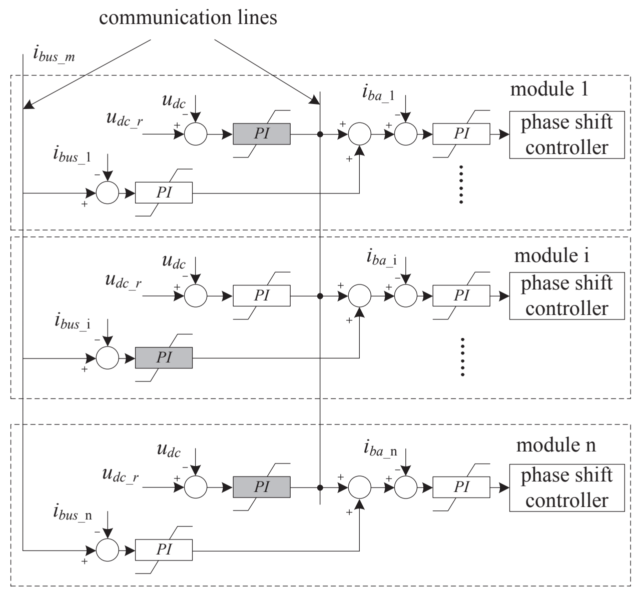

Fig. 6. Parallel control diagram of the modular power (converters run)

Fig. 7 illustrates the flowchart of auto-master-selected strategy. When running, the slave module will check if can receive data from master module. Once the slave module cannot receive any data from the mater module, it means that the former master module has broken down. Then it will check if can receive any request for being master module from any other salve modules. If so, it means there has been other salve module preparing for being the new master module and it will still work as slave module. Otherwise, it means there is still no other salve module asking for being new master module, then this salve module will send the signal of asking for being master module to all of the other modules, and switch itself to the master module, which will replace the former master module to send control instructions to other converters. And then the whole parallel system will work continuously under the control of new master module.

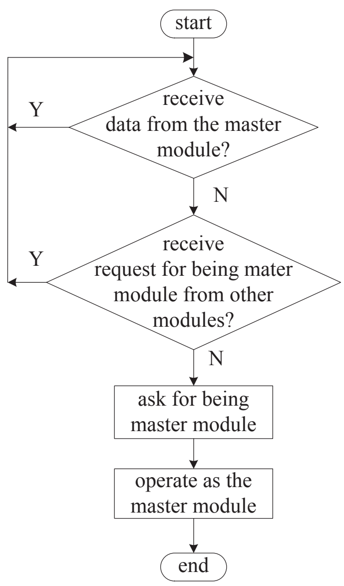

Fig. 7. Flowchart of auto-master-selected

And in actual systems, to avoiding bus conflict when more than one slave modules ask for being master module at the same time. The auto-master-selected strategy based on digital communications is realized by CAN bus communication.

By this method, master module of the parallel system is generated automatically, and it is no longer irreplaceable. So the reliability of the parallel system is improved.

IV. SIMULATION RESULTS

A 48/400V bi-directional DC-DC converter is designed, and the simulation of the converter is analyzed to confirm the control strategy.

The simulation result of two modules operate in parallel without any current-sharing strategy is shown in Fig. 8. In this figure, the horizontal axis is time, and vertical axis is HVS current. Simulation condition is: battery voltage 48V, bus voltage 397V (lower than 400V, batteries discharge), two converters' parameters are a little different. From the simulation result, it can be seen that the current of two converters at DC bus side is unequal due to different parameters between them. In addition, the difference of their HVS currents has an expansive tendency.

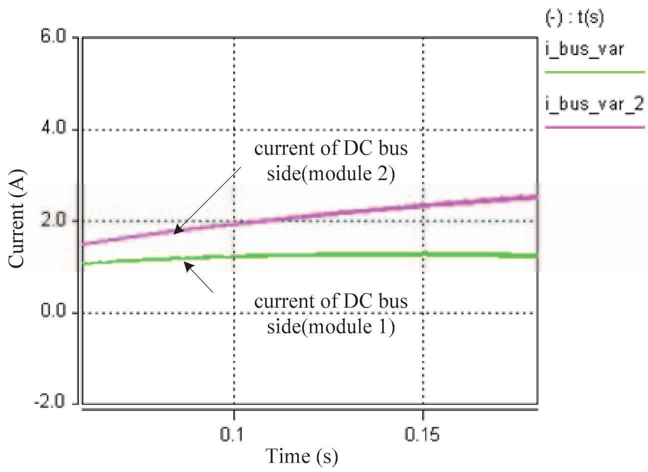

Fig. 8. Parallel simulation without current-sharing loop

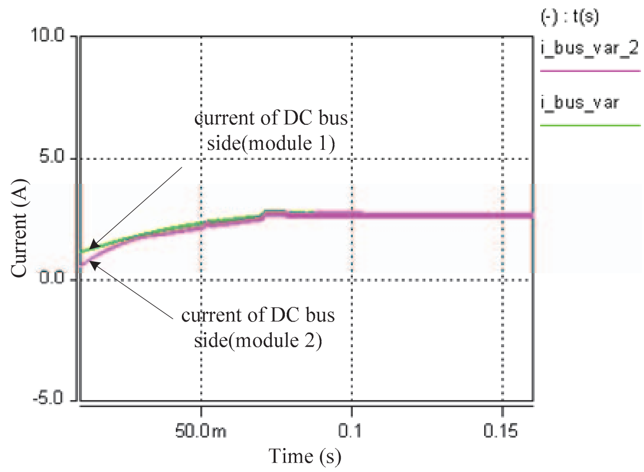

Fig. 9. Parallel simulation with current-sharing loop (batteries discharge)

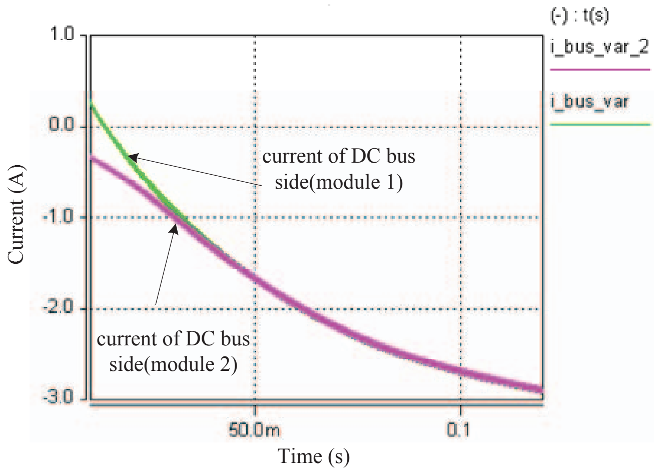

Fig. 10. parallel simulation with current-sharing loop (batteries charge)

The simulation results of two modules operate in parallel with current-sharing loop are shown in Fig. 9 and Fig. 10, where the horizontal axis is time, and vertical axis is HVS current. Simulation condition of Fig. 9 is: battery voltage 48V, bus voltage 395V (lower than 400V, batteries discharge); simulation condition of Fig. 10 is: battery voltage 48V, bus voltage 405V (higher than 400V, batteries charge). From the simulation results, it can be found that, with current-sharing loop, HVS current of the two converters are always equal, when they work in parallel.

The simulation of master module switching is shown in Fig. 11. The horizontal axis is time, and vertical axis is HVS current of three modules. Simulation condition is: battery voltage 48V, bus voltage 395V (lower than 400V, batteries discharge), three modules operate in parallel. As seen in the figure, when t = 0.5s, the former master module (module 1) breaks down, then module 3 becomes the new master module to replace module 1. Module 2 and module 3 work in parallel, and their HVS current increase as well. At the same time, due to the effect of current-sharing loop, the HVS current of the left two modules is still equal. From the simulation results, it can be seen that when a former master module breaks down, the new master module generated by the auto-master-selected strategy can replace the former master module completely. So the master module is no longer irreplaceable.

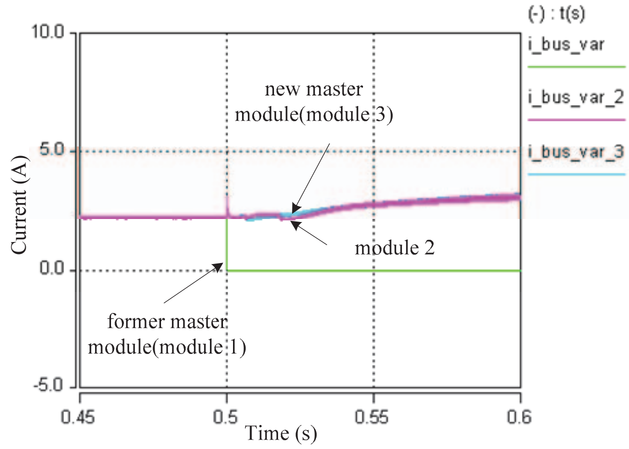

Fig. 11. Simulation of master module switching

V. Exprimental Results

In order to verify the validity of the proposed control strategy, a 1.5kW modular bi-directional DC-DC converter based on current-fed half bridge is designed. And waveforms of two converters work in parallel is analyzed in this section. Fig. 12 gives the prototype picture of single module.

The waveform of two converters work in parallel without any current-sharing strategy is shown in Fig. 13, where i_{dc1} is the HVS current of module1, i_{dc2} is the HVS current of module2. The experiment condition is battery voltage U_{BA} = 48V, bus voltage U_{DC} = 400V. As seen, the HVS current of two paralleled modules is unequal, and the direction of current is opposite (the HVS current is defined as positive, when batteries discharge), which means there exist serious circulating power between the two converters and may cause serious damage to the whole system (to prevent hardware failure, the maximum battery current of each converter has been limited). So when converters work in parallel, to avoid unequal current distribution between each module, an effective current-sharing control strategy is needed.

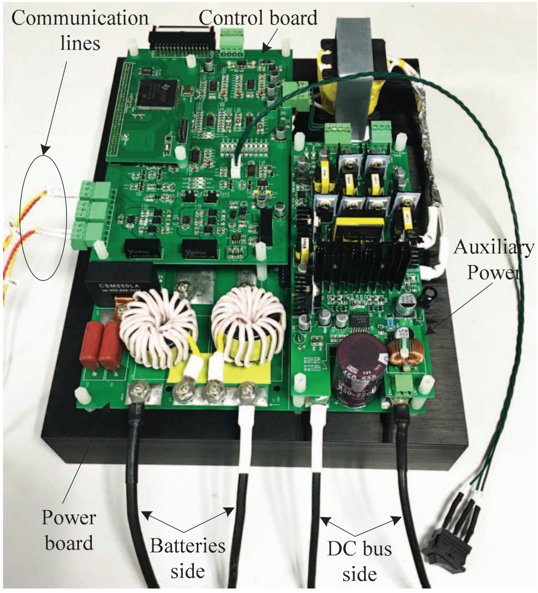

Fig. 12. Prototype picture of single module

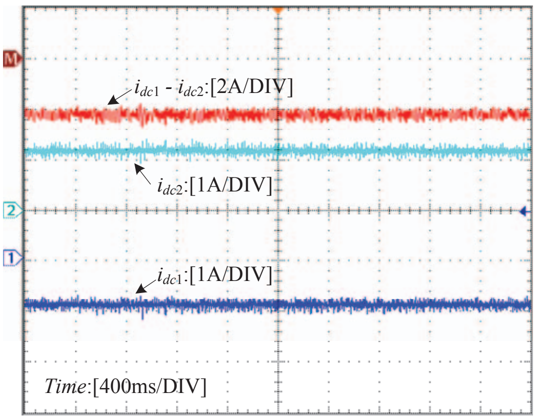

Fig. 13. HVS current of two converters when running in parallel without any current-sharing strategy

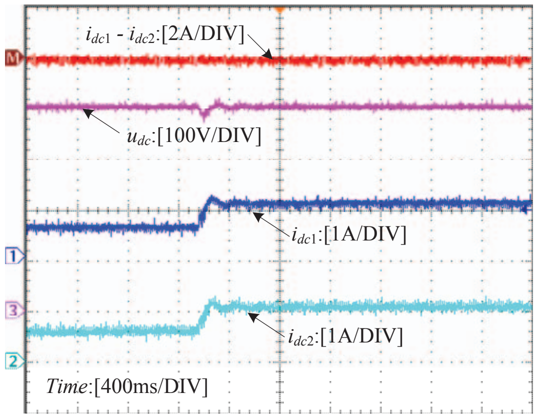

Fig. 14. HVS current when running in parallel (batteries discharge)

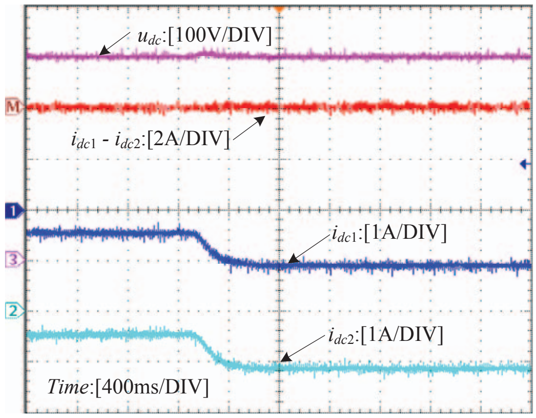

Fig. 15. HVS current when running in parallel (batteries charge)

Waveforms of two modules work in parallel with proposed current-sharing strategy are shown in Fig. 14 and Fig. 15. The experimental condition is battery voltage U_{BA} = 48V, bus voltage U_{DC} = 400V. In Fig. 14, batteries discharge and the HVS current is positive; in Fig. 15, batteries charge and the HVS current is negative. From the waveforms, it can be seen that ($i_{dc1} - i_{dc2}$) is always equal to 0, which means the HVS current of the two modules is always the same and current-sharing has been achieved in two power flow directions. Also, when bus voltage u_{dc} fluctuates, HVS current of the two modules can response at the same time, and in this period the HVS current is always equal.

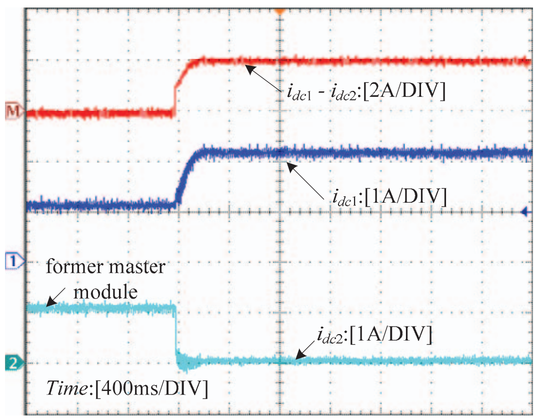

Fig. 16. Waveform of master module switching (batteries discharge)

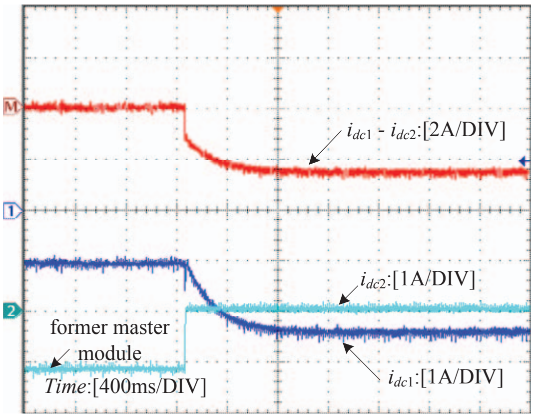

Fig. 17. Waveform of master module switching (batteries charge)

Waveforms of master module switching in different conditions (batteries discharge and batteries charge) are shown in Fig. 16 and Fig. 17. As seen, at the beginning the two modules run in parallel, and with the control of master module, ($i_{dc1} - i_{dc2}$) is always equal to 0, that is to say, current-sharing at the HVS has been achieved. And then, when former master module breaks down, the slave module switch itself to the new master module immediately, and its HVS current become larger as well. So, it can be seen, the auto-master-selected strategy is effective, when a former master module breaks down, a new master module will generate immediately to replace the former one.

VI. Conclusion

A parallel control strategy for modular bi-directional DC-DC converter used in storage system is proposed in this paper. Auto-master-selected strategy solves the problem of the irreplaceability of master module with traditional master-slave control. And the problem of unequal current distribution at the HVS of parallel modules caused by different parasitic parameters is solved. The simulation and experimental results prove the validity of this parallel control strategy.

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