Research on control technology of multi-level battery cascade power supply for high-voltage large-current charging

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Abstract—As a high-voltage large-current rapid charging technology, the multi-level battery cascade charging technology has been gradually used in the charging of pulse power equipment, especially the large value capacitor. The control technology of the multi-level battery cascade charging power supply becomes the key to realize the charging effectively. This paper introduced a ten-level battery cascade power supply and researched the control technology, including the design of the optical fiber communication system and optical fiber drive circuit of cascade switches, the research of sequential control method, the design of voltage and current detection circuits and various faults synthetize circuits, the research of voltage feedback control and the realization of switchover charging method used in the multi-group loads. In the experiments of the ten-level battery cascade charging power supply, the average charging power is 92 kJ/s. The waveforms of the experiment results proved that the control system can work effectively.

Keywords—battery cascade; time sequence control; various faults synthetic; switchover charging; voltage feedback

I. INTRODUCTION

As the development of pulse power technology, the energy that pulse power equipment needed increase rapidly, so that the pulse power source module become much larger[1]. The high-voltage large-current charging technology of the primary power supply become one of the research direction in the pulse power technology development[2]. Using series resonant constant current charging power supply (CCPS) is a common method because of its characteristics of simple structure, high output power, easily control and so on[3]. But the higher requirements such as faster charging[4] and larger power are difficult to satisfy by using the CCPS. Developing a new CCPS with higher power is not appropriate because of the limitation of volume, device and thermal management[5].

As a kind of large capacity energy storage device, the battery is used widely as the primary power supply of the pulse power equipment. On condition that there is an effective control technology to connect multi-level of batteries together and make them discharging as a proper sequence, the high-voltage large-current charging for the capacitance load will be realized. Figure 1 is a diagram of multi-level battery cascade charging power supply (BCCPS). There is a switch and a control circuit in every level of the cascade battery, which used to connect the batteries together or break off the cascade circuit. The control signals of the switches are sent out by the top control system which composed by the industrial personal computer (IPC) and digital signal processor (DSP) control circuit. There also is a protect circuit with current detection and faults synthesis functions used in every level. The inductance L is used for the charging current waveform adjustment and after the L is the multi-group of load. The load select circuit and voltage feedback circuit are used for the multi-group control. To divide the load into groups can reduce the peak value of the charging current so that to design the inductance L will be easier, the current stress will be decrease

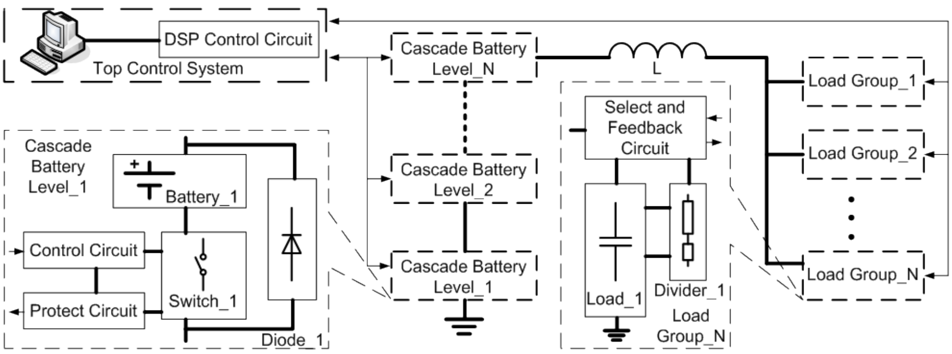


Fig. 1. Schematic diagram of multi-level battery cascade charging power supply

and the cost will be lower.

II. Optical Fiber Communication and Drive Circuit

The pulse power system is usually applied in the high-voltage large-current occasion, so that there is high electromagnetic interference (EMI) and the weak electric signals are easily to be interfered [6]. Using the optical fiber communication (OFC) system is an effective method to enhance the electromagnetic compatibility (EMC) of the control system of the BCCPS. The time sequence control of the switch device in the BCCPS is also realized by the OFC between the three of the IPC, the DSP control board and the control circuit of every level.

A. Optical fiber communication system

The OFC system include the communication among the IPC, the DSP control board, the control circuit of every level, the load select circuit and the voltage feedback circuit. The schematic diagram of the OFC system is as the figure 2 shows. The upper computer software can send the control signals by IPC with the 232 serial communication protocols and the optical module converts the electric signals to optical signals and transfers them by the optical fiber. The DSP control board receives the control signals and the relevant program will be executed to realize sorts of functions. The DSP also sends kinds of data and the status signals to the IPC by the optical fiber and the upper computer software interface will show them out. The time sequence drive signals and load select control signals that send by DSP control board are convert by HFBR1521 and transferred by glass optical fiber to the control board of every level of battery and every group of load select board. The fault signals of every level of battery and the voltage and current feedback signals are also converted and transferred to DSP by the OFC system.

B. Optical fiber drive circuit of cascade switches

Using the IGBT as the switch in the BCCPS system can connect the batteries together or break them off effectively because of its advantages [7]. The DSP control board sends out the drive pulse signals of the IGBT and the control board receives and converts then to electric signals by HFBR2521. Because the output of HFBR2521 is a negative pulse signal, the optical coupler is used to convert the electric level. The protect circuit will send a level signal which obtained by synthesize the faults signals, then the pulse signal and the level signal will send to an AND gate in the control circuit so that to give out the ENA signal to enable the drive circuit of the IGBT. By this way the IGBT can be controlled to switch off when there are some faults in the BCCPS circuit. Figure 3 is the diagram of the drive pulse transfer and convert progress.

C. Time sequence control strategy

The time when the battery should be connected to the main circuit and the sequence of the multi-level batteries to connect is the key to realize the cascade charging in the BCCPS system. An upper computer software [8] control interface is designed to set up the time sequence of the batteries. Figure 4 is part of the screen capture of the interface in which the sequence can be set up by fill in the text box with the number of the batteries. The time interval between two adjacent batteries can be set up by fill in the text box with an appropriate value. The time sequence control strategy can balance the total working time of the batteries so that they can work as a relatively uniform state. At the same time, the output current and voltage can be regulated by setting different time interval when the parameter of the load or the inductance L changed and the charging time can also be controlled. The time sequence value can be send to DSP by press the Set Up button and the DSP will execute the program to drive the IGBT as the time sequence so that the multi-level battery cascade charging can be realized.

III. Current Detection and Various Faults Synthetic

Although the discharging current of the battery is relatively larger, the large current discharge instantaneously may damage the core of the battery. So it is necessary to detect the currents of the battery so that to ensure the battery can work normally. On the other hand, the IGBT and the Diode are also prone to failure when there is a large current flow through, so that the fault protect circuit is necessary in the BCCPS system. Figure 5 is the diagram of current detection and fault protect circuit.

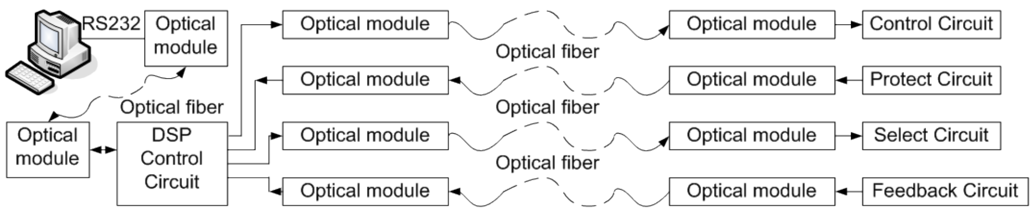


Fig. 2. Schematic diagram of the optical fiber communication system

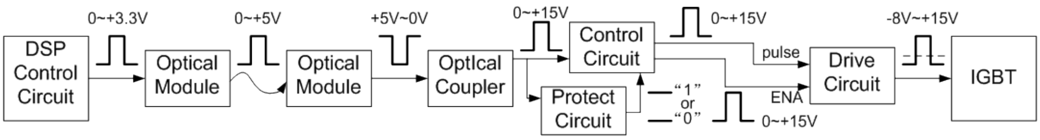


Fig. 3. Schematic diagram of the drive pulse transfer and convert progress

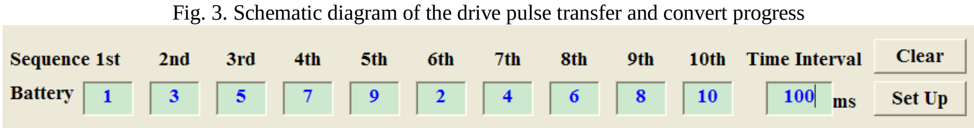


Fig. 4. Part of the screen capture of the interface

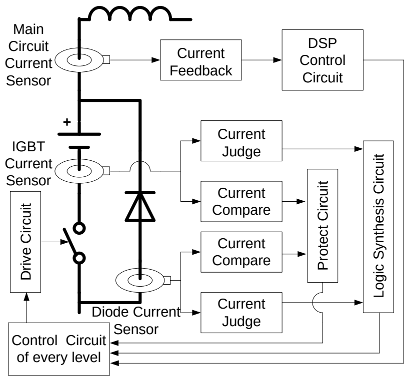


Fig. 5. Schematic diagram of current detection and fault protect circuit

A. *Current detection of switch devices and diodes*

In the control system of the BCCPS system, the Hall current sensor is used to detect the current which flow through the IGBT, the Diode and the main circuit. The IGBT and Diode currents of every level are detected so that the over current protection of every level can be realized. The current compare circuit is used to compare the maximum current value which has been preset and the detected current value and send out a fault pulse when the detected current is larger than the pre-set value. The detected current of main circuit will be feedback to the DSP and the waveform will be shown on the upper computer control interface.

B. *Logical relationship of drive signal and current signal*

In the control strategy of BCCPS, the drive signal of the IGBT decides if there is current flow through the IGBT theoretically. Define the following parameters: the drive signal of IGBT is I_F; the current which flows through the IGBT is I_G; the current flows through the diode is I_D and the "1" represents the current flows through the switch and "0" represents there is no current. A table can be obtained which describe the logical relationship of the signals and the faults, just like table 1 shows. By using logic gates device to build protect circuit is an effective method to judge the faults as table 1 shows and ensure the BCCPS to avoid the further enlargement of faults when there is some logical fault before the battery is connect into the circuit.

TABLE I. THE LOGICAL RELATIONSHIP OF THE SIGNALS

Switching Value			Fault or not	Fault Type
I_F	I_G	I_D		
0	0	0	N	/
0	1	0	Y	IGBT Short
0	0	1	N	/
0	1	1	Y	IGBT and Diode Short
1	0	0	Y	IGBT and Diode Open
1	1	0	N	/
1	0	1	Y	IGBT Open
1	1	1	Y	Battery Short

C. *Various faults synthetic and protect circuit*

The various faults such as the over current fault of IGBT, over current fault of diode, over voltage fault (OV), over heat fault (OH) and logic fault should be synthesized and feedback to the DSP control board. Figure 6 is the various faults synthesize circuit, which contains the logic gates protect circuit that introduced above. The various faults signals are synthesized by the OR gate then the fault signal is sent out. The fault signal is reversed by the NOT gate and synthesized with the pulse signal by the AND gate then the enable signal of the drive circuit is sent out.

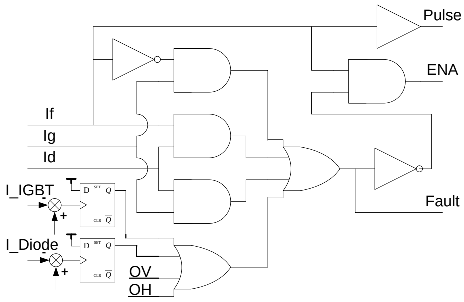


Fig. 6. Various faults synthesize circuit

IV. LOADS SWITCHOVER AND VOLTAGE FEEDBACK

The number of power supply module is increasing in the pulse power system, so that the charging power supply should be expansibility. The multi-level BCCPS has to charging for the load with certain value because of the limitation of the inductance and the output current of the battery so that the loads should be divided into different groups and the grouping control is necessary in the control technology of the BCCPS system. The voltage feedback control is also necessary to realize the accurate charging voltage control of every group of loads. Figure 7 is the diagram of loads switchover and voltage feedback control circuit.

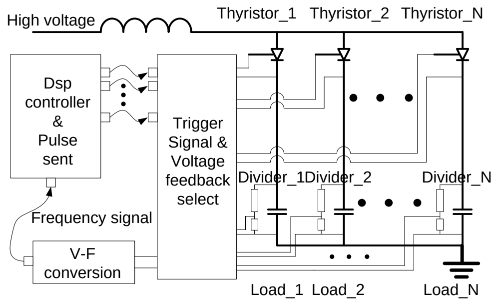
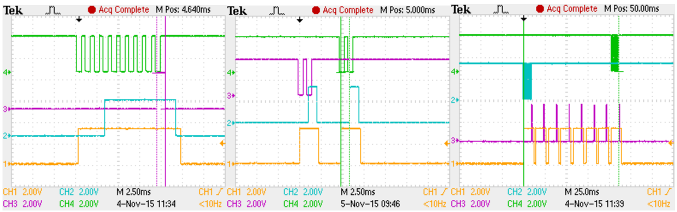


Fig. 7. Diagram of loads switchover and voltage feedback control circuit

A. *Switchover charging method of multi-group loads*

In order to control the loads by different groups, the select switch is needed to connect between the load and the inductance. The thyristor is an appropriate device to realize the grouping switchover charging control. The different group of loads can be selected by set up the load's number on the upper computer software interface and the DSP control board will send out the select trigger signal to the thyristor of the selected group. In order to ensure the thyristor will switch on when every level of battery is connected into the circuit, the trigger signal should be sent out when there is any pulse to drive the IGBT of every level. Figure 8 is the waveforms of the control signals. In the figure 8 (a), one group of load is select and ten level of battery is cascade so that there are ten trigger pulses as the CH4 shows. Figure 8 (b) is the waveforms of control signals when there are two level of battery charging for two groups of loads, in which it is easy to see that the trigger pulse will a little earlier than the drive signal so that the thyristor will be sure to switch on when the battery is connected in the circuit. Figure 8 (c) is the waveforms when there are ten level of battery and eight groups of loads, in which the pulsed beams of CH2 and CH4 is the trigger pulses of the first and the eighth groups of loads, and the CH1 and CH3 are the drive signal of the IGBT of the first and the tenth level.



(a) (b) (c)

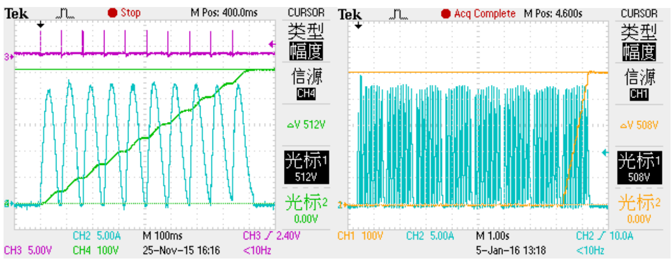
Fig. 8. Waveforms of the control signals

B. *Voltage feedback control*

The load voltage is sampled by a resistance voltage divider with a ratio of 1:1000 and the feedback voltage is in the range of 0 - 10V. This voltage is filtered and processed through the voltage-frequency converter and the frequency signal is converted to an optical signal and transferred by the optical fiber. The DSP control board receives the signal and converts it to a digital signal so that the voltage can be calculated and the charging process can be controlled [9]. As the limitation of the timer and counter of the DSP, the feedback voltage signals of the dividers should be also selected by the trigger signal of the thyristor of every group, so that the charging voltage will be controlled accurately.

V. Experiment Results and Conclusion

Ten levels of batteries that each voltage is 50 V are used in the cascade charging experiment to verify the control strategy of the BCCPS. Figure 9 is the experiment waveforms. As figure 9 (a) shows, ten batteries are connected to charge one group of load. CH2 is the waveform of the charging current; CH4 is the waveform of charging voltage which rises linearly; CH3 is the trigger pulse of the selected load which make sure the thyristor is switch on. Figure 9 (b) is the waveform of charge current and load voltage when use ten levels of batteries to charge for eight groups of loads. The current waveforms are almost the same of every group of load.



(a) (b)

Fig. 9. Experiment waveforms of 10 level of battery cascade

The high-voltage large-current charging experiment is carried out by using the upper computer software interface and ten levels of batteries with each voltage is 350V. Figure 10 is the screen capture of the interface which shows that the charging voltage of every group of load reached 3 kV and the peak value of the charging current is about 140 A. The value of each capacitance is 22.5mF and the total charging time is 8.8s. The average charging power can be calculated by using the formula (1), and the result is 92kJ/s. All the results of the experiments proved that the control strategy is effective and the BCCPS can realize the high-voltage large-current charging.

$$P = \frac{1}{2} CU^2 / t$$

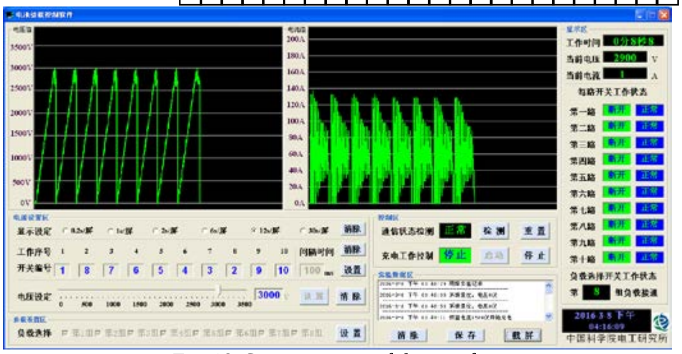


Fig. 10. Screen capture of the interface

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