Simulation Analysis of Fault Crossing of Three-phase Energy Storage System

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***Abstract*—The proposed goal of "double carbon" in China has attracted much attention from new energy generation. However, the new energy generation has intermittency, volatility and other characteristics to the stability of the grid has brought a certain challenge. Therefore, many new energy distribution and storage schemes have been introduced, so the stable operation of the energy storage system after grid connection is particularly critical. Based on the time domain simulation of PSCAD/ EMTDC three-phase energy storage system, this paper studies whether the system has the ability of stable fault crossing during the fault period.**

Keywords—Three-phase energy storage, Grid-connected converters, PQ double closed loop control, Fault traverse control

I. MODELING REQUIREMENTS FOR THREE-PHASE ENERGY STORAGE SYSTEM

The three-phase energy storage system is generally first connected to the DC bus through Buck-Boost circuit [1], and then connected to the AC power grid through the power converter system and filter circuit. Its structure is shown in Figure 1. The DC-DC circuit is used to maintain the voltage stability of the DC bus. The converter adopts the vector control strategy based on the rotating dq coordinate system to ensure that the system has the ability of power frequency active power and reactive power regulation. The filter circuit is used to filter the harmonics generated by power electronic devices to ensure that the output voltage and current meet the requirements of grid-connected harmonics.

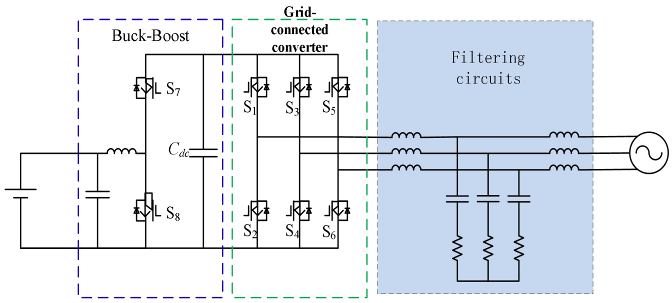

Fig. 1. Three-phase energy storage system

The Technical Regulations for Electrochemical Energy Storage System Access to the Power Grid [2] put forward specific requirements for the fault crossing capability of the lithium-ion energy storage system, that is, the system should run continuously without off-grid at a specific voltage drop/rise depth, and inject capacitive/inductive reactive current into the power grid to support voltage recovery when necessary. When the system fails, the control is put into the fault crossing control link, and the working mode is switched to reactive power priority mode [3].

A. Grid-connected converter control mode

There are many kinds of control methods of grid-connected converters in engineering, and there are great differences in working principles. In order to analyze the operation condition of the three-phase energy storage system after grid-connection, this paper adopts the most commonly used PQ double closed-loop control strategy, calculates the reference value of the D-axis current and the Q-axis current according to the active

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power and reactive power instructions, and then realizes the power control by PI control of the current. We build the PQ control model according to the above ideas. As shown in Figure 2, in this control strategy, the function of the PLL is to detect the direction of the voltage vector at the junction point, so as to provide a phase reference for the decomposition of the electrical quantity dq in the entire control system. Figure 2 is a logical diagram of the PQ control relationship.

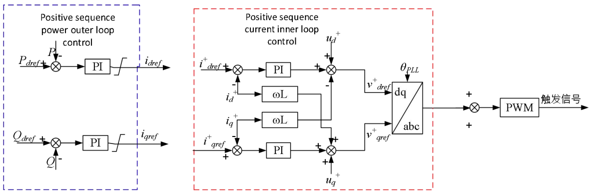

Fig. 2. PQ double closed loop control logic diagram

Where, P (Q) and Pref (Qref) are the measured value and reference value of active (reactive) power respectively; ud (id), uq (iq) and D-axis and Q-axis components of positive sequence voltage (current) respectively; idref, iqref positive sequence power outer loop, fault crossing control output current reference value; θpll is the output phase Angle of the phase locked loop (PLL). PI is the proportional-integral link; ωL is the reactance of the converter. The calculation formula of the current reference value is shown in formula (1). Finally, the SPWM pulse modulation is used to generate the pulse signal to control the switch device on/off.

$$\begin{cases} idref = \dfrac{2Pref}{3Ug} \\ iqref = -\dfrac{2Qref}{3Ug} \end{cases} \tag{1}$$

Where Ug is the D-axis component of the grid voltage.

When the system fails, the grid-connected converter control is put into fault pass control mode and the working mode is switched to reactive power priority mode. Reactive power is generated during voltage drop, and reactive power is absorbed during voltage rise to support voltage recovery of the grid. The fault crossing control link is used to maintain the system's on-grid operation and support the voltage recovery of the grid during the fault period, so as to ensure that the energy storage system has the fault crossing capability, as shown in Figure 3. VT is the effective value of the voltage at the junction point.

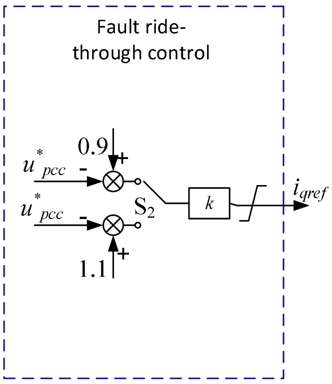

Fig. 3. Fault control link

According to the requirement of reactive power support capability during fault crossing, iqref1 and iqref2 of Q-axis current during low voltage crossing and high voltage crossing are shown in formula (2) respectively.

$$\begin{cases} iqref1 = k(0.9 - VT) & 0.2 \le VT \le 0.9 \\ iqref2 = k(VT - 1.1) & 1.1 \le VT \le 1.3 \end{cases} \tag{2}$$

In the formula, VT is the effective value of the grid voltage; k is a constant coefficient greater than 1.5.

During normal grid-connected operation, the inner ring is connected with the positive sequence power outer ring; Once the voltage drop/rise is detected, the outer ring switches to the fault crossing control link, which includes low voltage crossing and high voltage crossing, which is controlled by switch S1; After the voltage returns to normal, the inner ring is connected to the positive sequence power outer ring.

B. DC-DC control policy

The electrochemical energy storage system needs to achieve bidirectional energy transmission [4], so the DC-DC converter should have the ability of bidirectional conversion. A DC-DC converter is a device that converts a DC voltage or current into a different DC voltage or current [5]. It achieves smooth output by controlling the Boost and Buck working modes of the power tube on/off. It can be used to boost or reduce voltage, and can also be used to control the charge and discharge of the battery [6].

The specific working principle is shown in Figure 4. The IGBT of the upper bridge arm is s7, and the IGBT of the lower bridge arm is s8. When the battery is charged, s7 is turned on, s8 is turned off, Udc side inductance L1 is charged and the battery is charged. When the battery is discharged, s7 is turned off, s8 is turned on, and the battery is charged to the inductor L1.

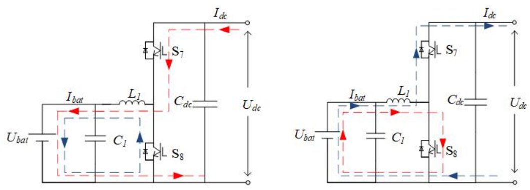

Fig. 4. DC-DC control principle

We take PSCAD to build a simulation model as an example. According to the above principles, the main circuit diagram of DC-DC is shown in Figure 5 below.

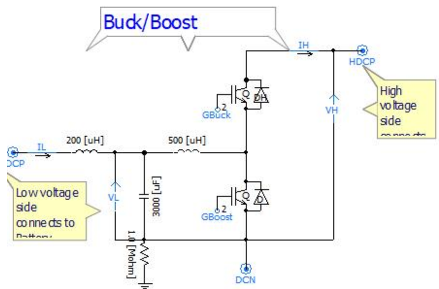

Fig. 5. DC-DC main circuit diagram

Taking battery charging as an example, the DC-DC control circuit is shown in Figure 6. When the battery is charged, the output signal of the control circuit to EnBuck is high level, and the output signal of EnBoost is low level [6]. At this time, EnBuck triggers the IGBT of the upper bridge arm in Figure 5 to work, outputs the pwm signal of GBuck, and controls the upper bridge arm to turn on and off periodically. Lower bridge arm IGBT is not put into operation due to low EnBoost output. The signal diagram of the simulation results is shown in Figure 7.

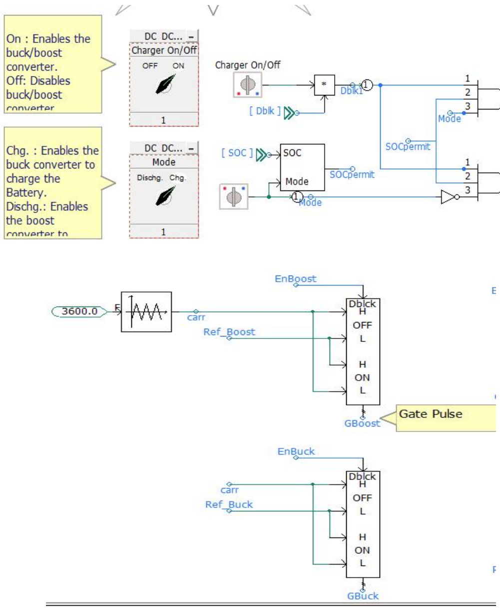

Fig. 6. DC-DC control circuit diagram

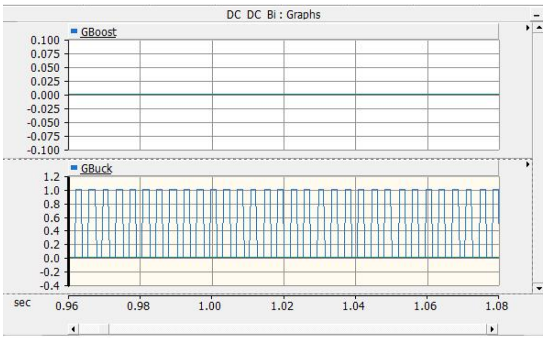

Fig. 7. Signal diagram

II. Simulation verification

According to the three-phase energy storage system structure diagram shown in Figure 8 above, the three-phase energy storage system model is simulated and built in pscad. As shown in Figure 8 below, the Buck/Boost converter is connected to a battery with a rated DC voltage of 500v on the left side and a DC line with a rated DC voltage of 1kv on the right side. The grid-connected converter is connected to the AC power grid with a rated voltage of 1kv. In this system, we take the most serious failure of the system, that is, three-phase simultaneous ground failure, as an example to study whether the energy storage system has the ability of low-voltage crossing.

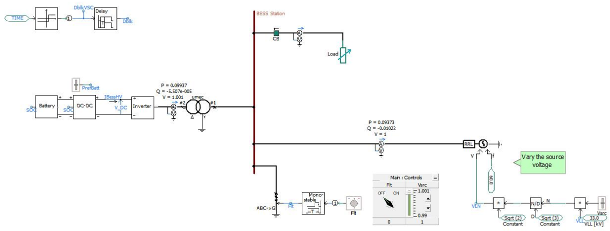

Fig. 8. Three-phase energy storage system

In order to better observe the fault crossing ability of the system, we need to observe the fault crossing ability of the energy storage system in the process of charging and discharging, and after charging when the voltage drop is caused by the three-relative fault of the system. Only when the energy storage system can achieve stable operation without off-grid in any case, the system can be put into actual use.

A. Battery charging fault crossing

According to the principles of Chapter 1, the battery is controlled to charge through the DC-DC control link. Under normal operation, it takes about 14s to charge the battery capacity from 90% to 100% in the initial state, as shown in Figure 9.

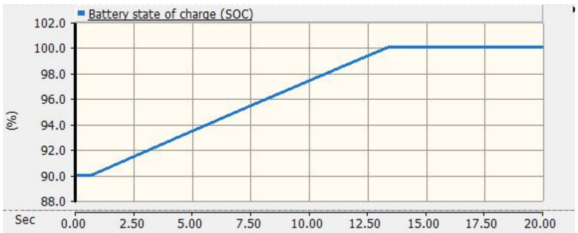

Fig. 9. Battery charging time during normal operation

In order to study the fault crossing ability of the energy storage system during and after charging, we set the fault before 14s and once after 14s respectively, and observe the power changes on the line to determine whether it has stable fault crossing ability.

In order to realize the above process, we use the fault control module as shown in Figure 10 to simulate the three-phase simultaneous ground fault. When the system runs normally, the Flt module is in the off state. When a fault needs to occur, the Flt module is turned on, in order to more intuitively observe the fault crossing ability, the fault duration is set to two seconds, after two seconds, the fault is removed, and then the power grid is normal operation. According to the above principle process, we will simulate the fault during the charging process and after the charging process to observe the change of line power.

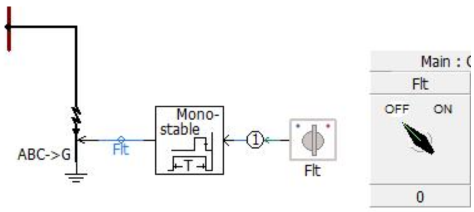

Fig. 10. Fault control module.

As shown in the signal diagram in Figure 11, when the fault occurs before or after charging, the energy storage system can run stably without going offline. In other words, the fault traversal control strategy can ensure that the energy storage system has stable fault traversal capability when the fault occurs before and after the battery charging process.

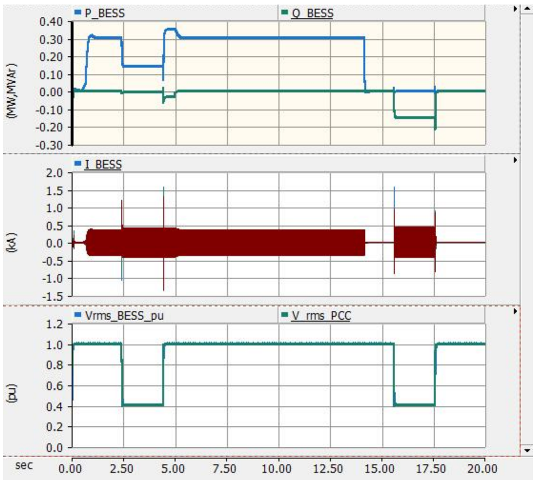

Fig. 11. Charging signal diagram

B. *Battery discharge fault crossing*

Under the above fault traverse control process, the energy storage system can realize the stable fault traverse ability of the battery during the charging process. According to the above analysis process, the signal diagram of power and other variables on the line is observed to analyze whether the system has stable fault crossing ability during the discharge process.

The DC-DC control ring realizes the discharge of the battery by controlling the on-off of the IGBT on the upper and lower bridge arms of buck-boost circuit. As shown in Figure 12, during the normal operation of the system, the capacity of the battery changes from 90% to 65% within 20 seconds of discharge. During this process, the fault control module in Figure 10 above is still used in this paper when a three-relative short circuit fault occurs within 20 seconds of discharge, and the power change on the line is analyzed to determine the fault traversal ability of the system during discharge. As shown in the discharge signal diagram in Figure 13, the energy storage system can also ensure stable operation without off-grid during the discharge process, and the fault control link also ensures the ability of the energy storage system to pass through the fault during the discharge process.

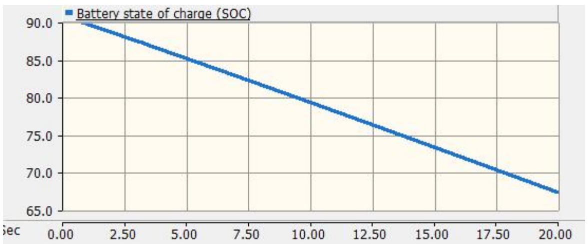

Fig. 12. Battery discharge time in normal operation

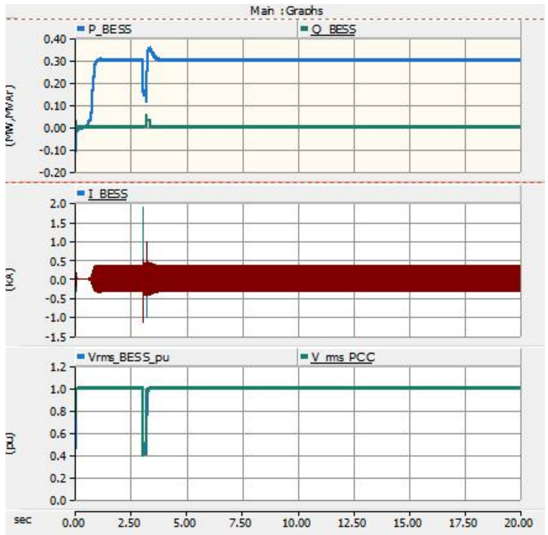

Fig. 13. Signal diagram

III. CONCLUSION

The three-phase grid-connected converters based on this paper play an important role in energy conversion and grid management, and have good flexibility to adapt to different grid environments and energy needs. It can be integrated with renewable energy sources to achieve smooth access and coordinated control, while also supporting distributed power supply access and energy scheduling.

Of course, the system has improved the fault protection function, during the system failure, the fault crossing control support system fault crossing, avoid the energy storage system off the grid, and realize the stable operation of the energy storage system.

In summary, the three-phase energy storage grid-connected converter has significant advantages and application value in energy conversion and power grid management. It can improve the efficiency of energy utilization, enhance the reliability and flexibility of the power grid, optimize the control of energy management, and reduce operating costs. With the continuous development and improvement of technology, the application prospect of three-phase energy storage grid-connected converters will be broader.

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