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Field Exploration and Analysis of Power Grid Side Battery Energy Storage System

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ABSTRACT Emergency control system is the combination of power grid side Battery Energy Storage System (BESS) and Precise Load Shedding Control System (PLSCS). It can provide an emergency support operation of power grid. The structure and commission test results of Langli BESS is introduced in this article, which is the first demonstration project in Hunan. The composition and operating principle of BESS are comprehensively analyzed. Additionally, the architecture, strategies and test methods of emergency control system are deeply discussed. Moreover, the calculation model of the power grid side energy storage power station is established and the cost-benefit analysis of Langli BESS is analyzed. The relevant discussions have been verified by engineering project and have certain practical value.

INDEX TERMS Battery energy storage system, precise load shedding, emergency control system, control strategy, cost-benefit analysis.

I. INTRODUCTION

The fast-growing economy of China is facing multiple challenges when it comes to energy generation, particularly the population growth and economy pressure on energy demand [1]. However, with this rapid increase in energy consumption coupled with the heavy reliance on coal, various environmental problems started to arise in China, with the air pollution being the most well-known one. The renewable energy law has been implemented in China since 2006, and 26.7 percent of generated electricity is from renewable in 2018, increasing 10.6 percentage points from the level in 2005 [2], [3].

The increasing penetration of renewable energy sources on power grids poses a great challenge for power grid operation, including increased frequency variability, voltage transients, power quality reduction, and loss of reliability. The development of renewable plants and their continuous integration to power grid necessitate the balance of electric power. Battery Energy Storage System (BESS) has many important applications, especially in the field of power frequency regulation and control. It enables power system operators and utility providers to store energy for alter use and enhance the flexibility of the grid. They are increasingly being utilized to store the output from intermittent energy resources such as wind turbines and solar panels. Most of existing research so far is concentrated on the modelling studies. The field test results on an actual power grid side BESS operating under real conditions are quite few.

To achieve low-carbon development, China has vigorously developed clean energy, which brings unfavorable effects [4] to grid regulation and safety operation. Compared with other energy storage methods, such as flywheels energy storage, pumped storage and compressed air storage, the BESS has become a focus for its recognized advantages of high specific energy storage, flexible site selection, good cycle performance, convenient installation, no memory effect, environment friendly [5]–[7] and so on. Thanks to the effectiveness of BESS in grid connection, especially new energy power generation, it becomes a key technology to support the clean energy development in China.

Nowadays, the PLSCS is rapidly expanding the field of applications, where the power grid side BESS is connected due to its fast response characteristics [8]. The timely jump of the operation mode in station could provide strong support for the safe and stable operation of grid, in case of the power of the transmission line drops significantly. The BESS equipped with a PLSCS response terminal and a source

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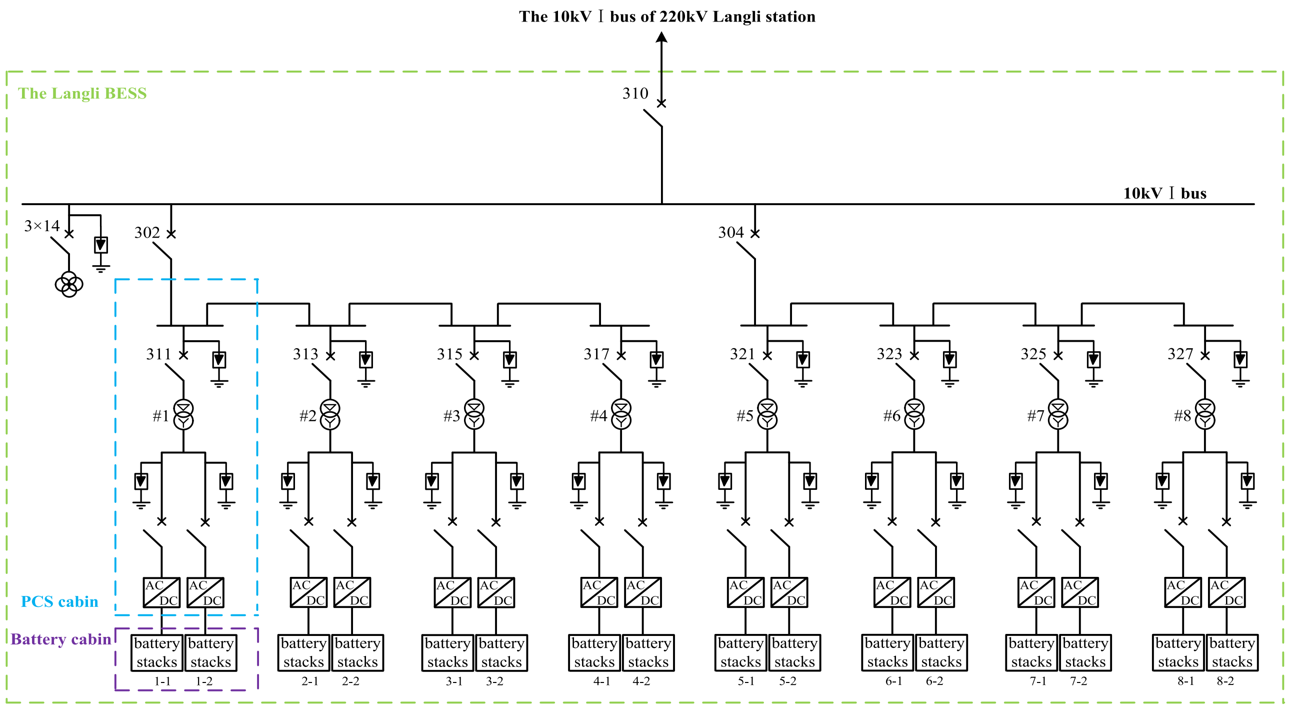

FIGURE 1. One-line diagram of Langli BESS.

network load interactive terminal (SNLIT) can mitigate the power supply shortage during the peak hours and solve the filling of lacking merit while applying a reactive power compensation device [3].

Nonetheless, the PLSCS and the BESS severely restrict the safety, quality and progress of project commissioning for the limited relevant standards and engineering experience [9]. Based on the engineering debugging experience of Langli BESS, the first demonstration project in Hunan, the test methods and precautions of the emergency control system are comprehensively analyzed in this article.

II. OVERVIEW OF BESS PROJECT

Currently, the capacity of Variable Structure Control (VSC) is restricted by IGBT and its electrical withstand performance, the power grid side BESS is composed of many VSCs in parallel and the cabin-type BESS is equipped with a large number of battery cabins and power conversion system cabins [10].

In recent years, extensive research has been done on modular multi-level energy storage technology. Changing the IGBT bridge from parallel mode to series mode can significantly increase the capacity of energy storage converters [11].

The total capacity of Langli BESS is 24 MW/48 MWh. It is composed of 24 PCS cabins, 24 battery cabins, a master control cabin and a 10 kV cabin. The 10 kV cabin consists of three sections which are connected to the 10 kV I bus and II bus respectively of the adjacent 220 kV Langli substation. The PCS cabins are uniformly distributed on the three sections of 10 kV bus. The wiring scheme of each bus is the same as each other except for one more station transformer connected on the III bus. The main wiring of the I bus is shown in Fig. 1. It can be seen that each PCS cabin is composed of two VSCs and a dry-type transformer. Each battery cabin contains two battery stacks, that is, the entire station contains 48 VSCs and 48 battery stacks with 500 kW rated power for each VSC. The formation of the battery stack goes through five levels: battery cells, battery modules, battery packs, battery clusters, and battery stacks. The nominal voltage of a battery module, composed by 12 battery cells in series-parallel connection, is about 13.2 V. Three battery modules are connected in series to form a battery pack, of which the nominal voltage is about 40 V. A battery cluster is formed by 18 battery packs in series, thus, the nominal voltage of each cluster is about 710 V. 6 battery clusters are connected in parallel to form a battery stack, of which the rated power is 500 kW and the rated current is about 700 A.

The centralized control mode is employed in Langli BESS. The energy management system (EMS), PCS, and battery management system (BMS) are jointly used to monitor the condition of battery. The BMS can collect and analysis the status parameters of battery modules, including battery voltage, current, temperature, insulation resistance and so on. The PCS, energy storage inverter, realizes the control strategies of AC/DC conversion. The EMS is mainly used to collect and process the operation data to analysis and control the energy storage power stations. Therefore, the BMS, PCS and EMS correspond to a battery stack, a VSC and entire station, respectively [12].

The IEC 61850 protocol is wildly used in EMS real-time communication with the whole PCS to satisfy the synchronous operation of the entire station, and it enables the rapid response of the active and reactive power control commands from the dispatcher, local and precise load shedding control systems. Meanwhile, IEC 61850 protocol helps the real-time communication between EMS and BMS to collect the operating condition parameters and alarm information of each battery stack. The PCS is responsible for power command execution and the EMS is in charge of normal power command. When an abnormal message of battery stack is detected by BMS, the alarm will be sent to PCS and EMS immediately [13], [14]. Therefore, the PCS and EMS can also execute corresponding instruction.

III. EMERGENCY CONTROL STRATEGY FOR BESS

Langli BESS, shown in Fig.2, is equipped with a SNLIT cabinet, in which a PCS-992B SNLIT and a MUX-02E 2M protocol converter are installed. On the one hand, the SNLIT is connected to the A/B screen of the precise load shedding control system by 2M protocol converter and power data network. On the other hand, the SNLIT controls 48 PCS and communicates with EMS through the network cables, as illustrated in Fig. 3. The SNLIT of BESS collects the change of current maximum dischargeable power sent by EMS. The connected 48 PCS convey the action instruction to EMS and PCS after receiving the instruction of the superior PLSCS. The structure of entire emergency control system is described as follows: when receiving the action signal of SNLIT, the EMS prohibits the charging commands of PCS immediately and each PCS discharges with the maximum power for 1 second as soon as possible [15], [16]. Then, the EMS operation with the maximum dischargeable power according to PCS and battery status until the threshold value of the state of charge (SOC). During this period, if EMS receives reset signal from SNLIT, the AGC or AVC would take control for the operation of the BESS.

FIGURE 2. The Langli BESS project.

IV. TEST METHOD FOR BESS

A. INTERACTION BETWEEN EMS AND SNLIT

The EMS adjusts the operation status of BESS to check the controllable load of the entire station received by the SNLIT. Assuming that the output active power of BESS is positive

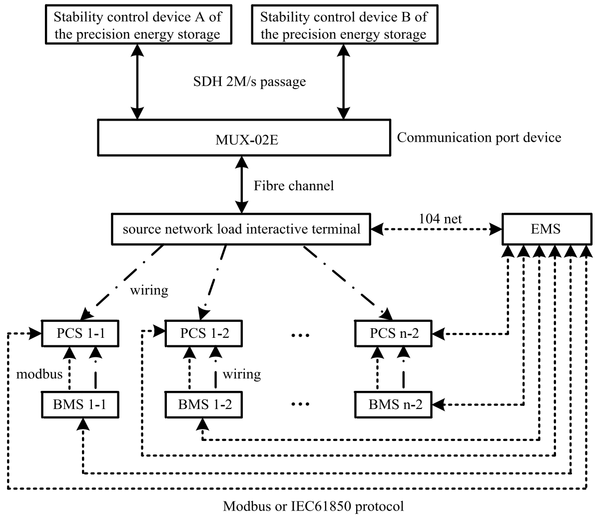

FIGURE 3. Structure of emergency control system.

and the input active power is negative, the controllable load transmitted by the EMS to the SNLIT is

$$\Delta P = P_t + 1.1P_n \tag{1}$$

where P_t is the current output power and P_n is the rated power of the entire station. 1.1 is the overload level for BESS. The entire station will discharge at 1.1 times of rated power immediately if the VSC or battery is abnormal once receiving the instruction of PLSCS.

B. RESPONSE OF VSC

The machine is out of service during debugging, which makes it impossible to verify the correctness and effectiveness of the wiring between the SNLIT to each PCS [17]. Therefore, it should be verified one by one before debugging. Firstly, put the outlet plate of each VSC individually in turn. Secondly, simulate the instructions of the PLSCS at the SNLIT, and then check the corresponding power changes of VSC in the EMS. It should be noted that the communication network from SNLIT to EMS should be disconnected during the test.

C. COMMUNICATION TEST BETWEEN STATIONS

1) CHANNEL TEST

During the test, the hard and soft plate of SNLIT from Langli BESS are combined to check whether the equipment status of the precision energy storage sub-station and the SNLIT are operated correctly.

2) CHECK EXPORT PRESSURE PLATE OF SNLIT

During the test, each VSC tripping plate is tested one by one in the SNLIT, before checking the statue of the corresponding plate in the precision energy storage sub-station.

3) DATA INTERACTION BETWEEN EMS AND SNLIT

Change the operation status of the BESS through EMS, before checking the controllable load at the precision energy storage sub-station, which should be consistent with the results of the SNLIT.

D. VERIFICATION OF EMERGENCY CONTROL STRATEGY AND LOAD RECOVERY FUNCTION

1) TEST IN AGC MODE AND FULL POWER CHARGING STATE

The AGC remote control is simulated in the BESS and the charging power is set as 24 MW. When the instruction simulated in the PLSCS sub-station, the performance should be recorded in the BESS, including the operation status of VSC and EMS, the power displayed by the EMS before test, the instruction time of energy storage substation, the reaction of station-side SNLIT, and the changing time of power reaching the maximum discharge value.

2) TEST IN AGC MODE AND LOW POWER DISCHARGE STATE

The simulation parameters are as the same as 1) except the 2.4 MW discharge power. When the instruction simulated in the PLSCS substation, the performance should be recorded in the BESS. After recording data and checking status, the emergency reaction of SNLIT should be resumed.

3) TEST IN AVC MODE AND SEND REACTIVE POWER STATE

The AVC remote control is simulated in the BESS and the input reactive power is set according to the rated value. After rigorous simulations as before, the results are recorded to compare the response speed in active or reactive states. Once data recording and status checking have been completed, the emergency reaction of SNLIT should be resumed, and the VSC and EMS should be checked whether they are back to the primary state.

4) TEST IN AVC MODE AND RECEIVE REACTIVE POWER STATE

The AVC remote control is simulated in the BESS and the output reactive power is set to the rated value. The following steps are the same as 3).

5) TEST UNDER ACTIVE AND REACTIVE POWER

Simulate the remote control in the BESS, and the rated active and reactive power are both set as 10%. When the instruction simulated in the PLSCS substation, the performance should be recorded in the BESS. Once data recording and status checking been completed, the emergency reaction of the SNLIT should be resumed, and the VSC and EMS should be checked whether they are back to the primary state.

6) TEST IN THE HIGHEST SOC STATE

The highest SOC value is set slightly higher than the current in the EMS background, and set the charging power of entire station to 0. When the instructions simulated in the PLSCS substation, the accuracy of VSCs respond should be checked before data recording and system resuming.

7) TESTING IN THE LOWEST SOC STATE

The lowest SOC value is set slightly lower than the current in the EMS background, and set the charging power of the entire station to 0. When the instruction simulated in the PLSCS, the correct respond of VSCs should be checked before data recording and system resuming.

8) TEST UNDER THE FIRST LEVEL ALARM OF PART BMS

The AGC remote control is simulated in the BESS and the charging power is set to be 24 MW. 10 current limit alarms are simulated by modifying the alarm setting of BMS. The respond of VSCs should be checked during the simulating instruction in the PLSCS substation, especially the VSC with a current limit alarm.

9) TEST UNDER THE SECONDARY LEVEL ALARM OF PART BMS

The AGC remote control is simulated in the BESS and the charging power is set as 24 MW. Simulate 10 secondary undervoltage alarms by modifying setting value. When the instruction simulated in the PLSCS substation, whether the VSCs respond correctly should be checked before data recording and system resuming.

10) TEST UNDER THE THREE-LEVEL ALARM OF ALL BMS

The AGC remote control is simulated in the BESS whose charging power is 24 MW, and the EMS power adjustment outlet is blocked temporarily. Firstly, simulate the full cut command at the load terminal of source network at the station side. Once responding, the three-level alarm signal for each BMS followed one by one to check the corresponding operation of VSC. Since the wiring signal from BMS to VSC is the last line of defense, the three-level alarm should be tested twice or more.

V. COST-BENEFIT ANALYSIS

A. COST ANALYSIS

The operating costs of energy storage power stations mainly include charging costs and maintenance costs. Assuming that the battery capacity is Q, the annual charging amount is $Q_{c(n)}$, the annual operating cost is $C_{y(n)}$, the annual charging cost is $C_{c(n)}$, the charge of charging is P_c, the expense of operation and maintenance is $C_{w(n)}$, the depth of discharge (DOD) is p, the annual attenuation coefficient of battery capacity is σ, the annual charging and discharging number is N, and n is the year (n = 1∼10).

Thus, the operating costs can be formed as follows:

$$Q_{c(n)} = Q \times p \times N \times (1-\sigma)^{n-1} \tag{2}$$

$$C_{c(n)} = P_c \times Q_{c(n)} \tag{3}$$

$$C_{y(n)} = C_{c(n)} + C_{w(n)} \tag{4}$$

According to the debugging, the SOC of energy storage station is from 13% to 93%, namely, the discharging is stopped when the SOC is 13% and the charging is stopped when it comes to 93%. As a result, the DOD p is 80%. However, the configured battery capacity of Langli BESS is higher than the rated capacity to ensure that the battery can be fully discharged, so the DOD p is 100%. Assuming that the σ is 3% and maintenance expense is 0.05 yuan/kWh, the $C_{w(n)}$ is expressed as follow:

$$C_{w(n)} = 0.05 \times Q \times N \tag{5}$$

When the annual charging and discharging number N is 365, the battery capacity Q of Langli BESS is 48 MWh, the expense of operation and maintenance $C_{w(n)}$ is 0.88 million RMB.

B. INCOME ANALYSIS

According to the power grid peak and valley electricity price policy, the energy storage power stations absorb electricity from the grid during low loads periods and low electricity costs, while discharge to the grid when higher grid loads and more expensive electricity costs. The income of energy storage power stations comes from the peak-to-valley price difference.

Assuming that the annual discharging amount is $Q_{f(n)}$, the efficiency of charge discharge is η, the annual discharging income is $S_{(n)}$ and the electricity price in Changsha is P_f. Therefore,

$$Q_{f(n)} = Q_{c(n)} \times \eta \tag{6}$$

$$S_{(n)} = P_f \times Q_{f_{(n)}} \tag{7}$$

According to the debugging report and implementation of electricity price in Changsha, the η is 90%, the P_c is 0.3975 yuan/kWh and the P_f is 0.8475 yuan/kWh.

Then, the profit $W_{\Sigma(n)}$ can be introduced as:

$$W_{\sum(n)} = S_{\sum(n)} - C_{\sum(n)} = 6.3993 \times \sum 0.97^{n-1} - 0.88n \tag{8}$$

As a consequent, during the ten-year depreciation period of Langli BESS, the total profit $W_{\Sigma(10)}$ can still approaching 40.7946 million RMB.

VI. CONCLUSION

Taking LangLi BESS as an example, the operating principle and topology of BESS is introduced in this article. Detailed analysis of BESS composition and operating principles is investigated. Additionally, the architecture, strategies and test methods of emergency control system are deeply discussed. Moreover, the calculation model of the power grid side energy storage power station is established and the cost-benefit analysis of Langli BESS is analyzed. Furthermore, a number of test methods for emergency control strategy and load recovery are proposed. The relevant discussions have been verified by engineering project and have certain practical value.

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