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A Review of Power Conversion Systems and Design Schemes of High-Capacity Battery Energy Storage Systems

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ABSTRACT Battery energy storage systems (BESSs) are one of the main countermeasures to promote the accommodation and utilization of large-scale grid-connected renewable energy sources. With the rapid increase in the installed capacity of BESSs, the security problem and economic problem of BESSs are gradually exposed. On the one hand, fire accidents happen on occasion; on the other hand, the operation efficiencies and battery utilizations of BESSs are not high, resulting in considerable economic losses. In this paper, the relationship between the construction scheme of a BESS and the power conversion system (PCS) is analyzed. The structures, control methods, and grid-connected/islanding control strategies of PCSs are categorized, evaluated, and compared in detail. And the design schemes of high capacity BESSs as well as relevant considerations are systematically discussed. The test waveforms of a 10-kV BESS based on a cascaded H-bridge high-voltage straight hanging PCS are shown to prove the feasibility of this advanced transformerless BESS scheme. Finally, the future development directions of high-capacity BESSs and PCSs are prospected.

INDEX TERMS Battery energy storage system (BESS), high-capacity, power conversion system (PCS), design scheme, control strategy, high-voltage straight hanging.

I. INTRODUCTION

In recent years, with the transformation and upgrading of the energy industry, the installed capacity and proportion of renewable energy represented by wind and photovoltaic power generation continue to increase in power systems [1], [2]. As of 2020, in China, the grid-connected capacities of wind and photovoltaic power generation reach 281.53 million kilowatts and 25.343 million kilowatts respectively, which together account for 24.3% of the total installed capacity of various types of electricity [3].

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Renewable energy sources have the characteristics of randomness, volatility, and low inertia, so high proportion renewable energy fed into the grid will have a significant impact on the safe and stable operation of the power system [4]. Energy storage is one of the main techniques to promote the accommodation and utilization of large-scale grid-connected renewable energy sources [5]–[9]. Compared with traditional energy storage methods represented by the pumped storage, the electrochemical energy storage has the advantages of few geographical restrictions and short construction period, and has developed rapidly in recent years [10]–[12]. Among the electrochemical energy storage devices, lithium-ion batteries have the advantages of high energy density, high power density, and relatively low cost,

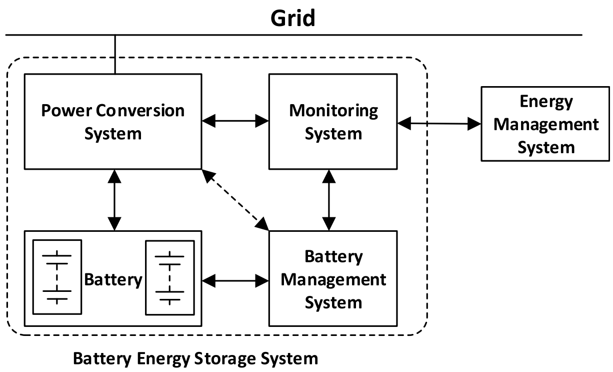

FIGURE 1. Composition of a BESS.

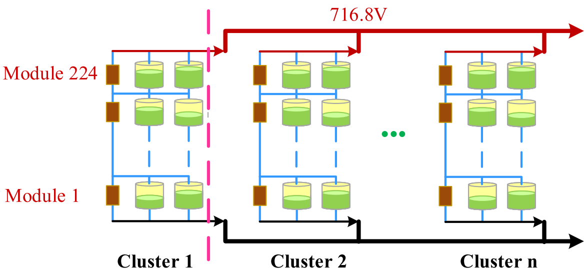

FIGURE 2. Composition of a battery stack.

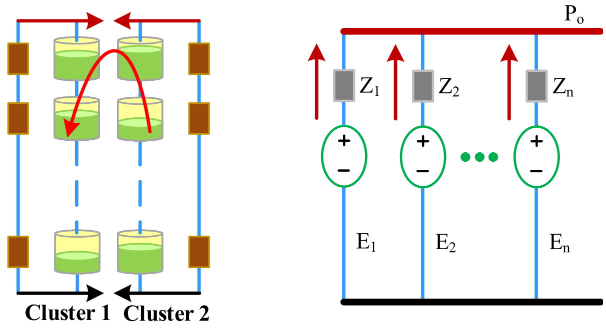

FIGURE 3. Schematic diagram of inter cluster circulation of battery stack.

and account for more than 80% of installed electrochemical energy storage power stations [13], [14]. In China, the industries of ternary lithium batteries and lithium iron phosphate batteries are comparatively mature. Battery energy storage systems (BESSs) mainly use Lithium iron phosphate batteries with a better security [15].

Generally, energy storage systems (ESSs) can be applied on grid side, power supply side or user side [16]–[23]. An ESS on the grid side is mainly used to improve the flexible management capability of the local power grid. Its main functions include peak and frequency modulation, and it can also be used as an emergency power support for the local power grid [19]. An ESS on the power supply side is generally combined with a thermal power plant or renewable energy generation. When combined with a thermal power plant, it is mainly used to improve the flexible management capability of the local power grid with the same functions as a grid-side ESS [21]. Because a BESS can respond to the commands from the grid frequency control system in milliseconds, it can significantly improve the overall response capability of the thermal power plant, and avoid possible damage effect to the generator set. An ESS combined with renewable energy generation can not only promote the accommodation of renewable energy, but also greatly improve the primary and secondary frequency modulation capabilities as well as the operational stability of the power grid [23]. A user-side ESS is mainly used for peak shaving and valley filling to save energy costs, and it can also reduce the cost of capacity expansion by adjusting the load capacity [24]. Moreover, it can be used as an emergency power supply for the operation and maintenance of a low voltage district.

As the installed capacity of BESSs and the capacity of single BESS continue to increase, their security and economic problems have gradually become prominent in recent years. On the one hand, fire accidents occur frequently in BESS stations all over the world. Nearly 30 fire accidents occurred in South Korea during 2017-2020, which caused enormous economic losses [25], [26]. On the other hand, there are great differences in storage performances of different BESSs, and their system efficiencies range from 70% to 90%. Because of inconsistent operation statuses of batteries, more over-provisioning battery capacity is required to meet the available capacity demand. Some BESSs have the problem of rapid decline in actual available capacity year by year, and the overall life of the battery system is much lower than the nominal life of single battery [27], [28].

Above problems will be gradually exposed with the increase of operating time of a BESS. These problems are all related to the technical factors, such as the characteristics of batteries, the management and configuration of the BESS, and the topology of the power conversion system (PCS). This paper provides a comprehensive technical evaluation and review from the aspects including the structures of BESSs, the PCS structures, the control strategies, the design schemes of BESSs and so on. The technical factors that cause the security and economic problems of BESSs are also comprehensively analyzed. The design method for high-capacity BESSs is presented and the effectiveness of cascaded H-bridge high-voltage straight hanging PCS is verified by the actual operating results.

II. STRUCTURE OF BESS

The structure of a BESS is shown in Figure 1. A BESS is mainly composed of four parts, including battery system containing a number of battery stacks, PCS, battery management system (BMS), and monitoring system.

The battery system is the main carrier of energy storage. Its capacity and operating status are directly related to the energy storage capacity, safety, and reliability of the BESS. The PCS is the core energy processing equipment of the BESS. The main functions of BMS include real-time

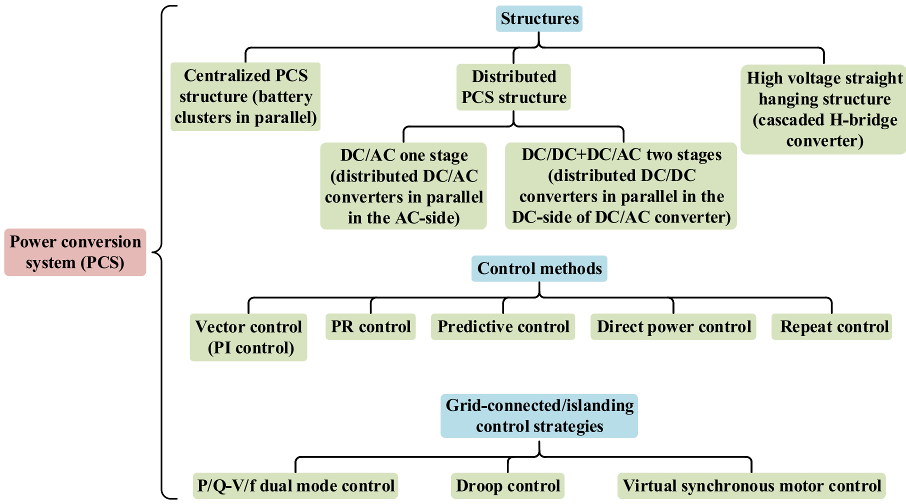

FIGURE 4. Categorization of structures, control methods, and grid-connected/islanding control strategies of PCSs.

monitoring of various states of batteries (voltage, current, temperature, state of charge (SOC), state of health (SOH), etc.), safe management of the charging and discharging process (such as the prevention of overcharge and overdischarge), alarm and emergency protection of possible faults, and control optimization, to ensure the safe, reliable and stable operation of the battery system. The monitoring system is the basis of information exchange between various parts of the BESS. The monitoring system, PCS, and BMS exchange information through a high-speed monitoring network, and the monitoring and protection commands between the controllers are reasonably distributed and coordinated according to different functional and response time requirements.

The battery stack is the key component of a BESS unit. The battery stack of a high-capacity BESS unit is composed of a large number of battery cells in series and parallel. As shown in Figure 2, a 2-MWh lithium iron phosphate battery stack contains 6,250 100-Ah battery cells. Due to the differences in battery characteristics, such as the internal impedance and the terminal voltage, the circulation current and cask effect occur among the battery clusters that are connected in parallel, resulting in a lower operating efficiency and capacity utilization of the battery system. It is difficult to solve the problem fundamentally only by improving the ability of BMS or optimizing the screening approach of battery cells. It is urgent to reform the architecture of BESSs to meet the challenge brought by the continuous increase in battery system capacity.

In most current BESSs, a battery cluster is formed by 224 280-Ah battery cells in series. If the rated voltage of one battery cell is 3.2V, the rated value of the cluster voltage is 716.8V. In actual operation, due to the difference in parameters of each cell and actual operating temperature of each battery cluster, the actual voltage of each cluster is different. If the voltage deviation between cluster 1 and cluster 2 is 1%, the voltage difference between the two battery clusters is 7.168V. When the two battery clusters are connected in parallel, a circulation current will be generated between the two clusters, which can be a few amperes to several tens of amperes, because of the considerable voltage difference and the small internal resistance of the battery clusters (tens of milliohms). In the actual operation, the terminal voltages of all battery clusters in parallel are forced to be equal, and the different inner electric potential in each cluster will cause the actual power contribute of each battery cluster to be different, as shown in Figure 3. The different power contributes mean that the battery clusters work at different states, and sometimes some of them even work above its rated power. A battery cluster with a higher power will have a higher operating temperature, leading to a shorter cycle life. This is the main reason why the overall life of a battery stack is significantly shorter than that of a single battery cell. As the running time increases, the characteristic differentiation of each battery cluster will become more and more obvious, making the operating state of the whole system more chaotic. Therefore, many inherent problems of the battery stack need to be paid enough attention to.

The construction scheme and topological structure of PCS determine the construction scheme of the battery system, and also determine the integration scheme of the BESS substantially. From the perspective of actual application, the integration scheme of a BESS greatly determines its safety performance and investment income in the entire life cycle.

From the above analysis, a suitable PCS solution has a positive meaning for improving the capacity utilization, security, economic value, and battery stack life of the BESS. Figure 4 illustrates a general categorization of the structures, control methods, and grid-connected/islanding control strategies of PCSs, which will be elaborated in the following sections.

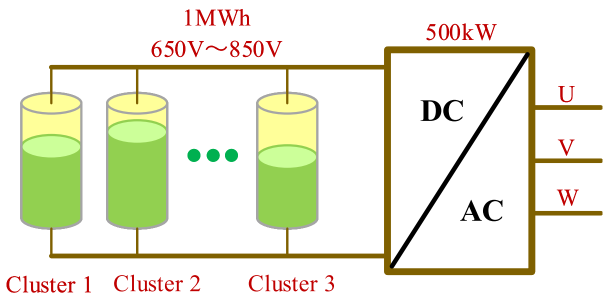

FIGURE 5. Schematic diagram of a 500-kW BESS unit with centralized PCS structure.

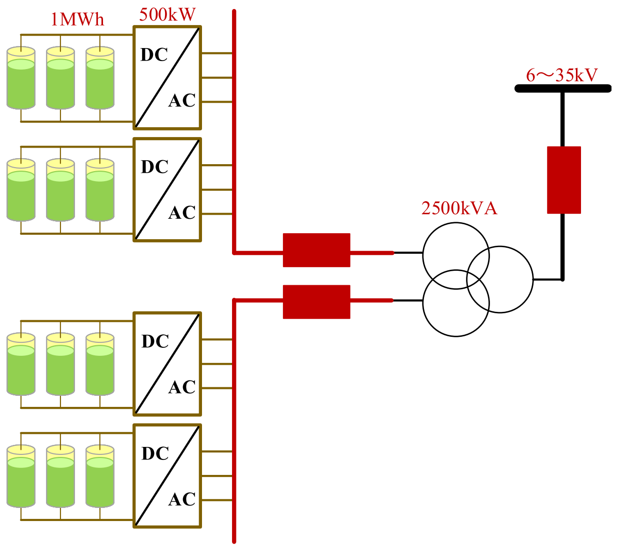

FIGURE 6. Schematic diagram of a 2-MW BESS with centralized PCS structure.

III. PCS STRUCTURES AND ITS IMPACTS ON THE PERFORMANCE OF BESS

A PCS is a device that realizes the power exchange between the energy storage batteries and the grid, and it is a key component that determines the performance of the BESS. This section focuses on the different types of PCS structures for high-capacity BESSs.

A. CENTRALIZED PCS STRUCTURE

Figure 5 is the schematic diagram of a single BESS unit with the common centralized PCS structure. A high-capacity BESS can be constructed by several basic BESS units connected in parallel, as shown in Figure 6.

The capacity of the BESS unit with centralized PCS structure can be improved by increasing the number of parallel battery clusters on the DC side or increasing the number of PCSs on the AC side. Generally, the battery stack capacity in a BESS unit with a centralized PCS is above 1MWh. In order to avoid too many battery cells or battery clusters connected in parallel and affecting the capacity utilization of battery stack, battery cells with a large capacity are used in general. However, there is a typical problem with this scheme. The actual output of each cluster is different because of the circulation current among the parallel clusters on the DC side, which can further increase the differences of the battery clusters as time goes on. In actual operation, some battery clusters may even work over their rated power, reducing the overall life of the battery stack and facing more safety risks. The above-mentioned factors may also lead to a rapid decrease in capacity utilization of the BESS. In addition, the grid-connected line frequency transformers that connect PCSs and the grid usually work on no-load state for a long time, because the BESS exchanges energy with the grid only for a short period of time. The power loss generated by line frequency transformers is equivalent to about 4% of the theoretical capacity of a BESS, which reduces the all-weather efficiency of the BESS seriously.

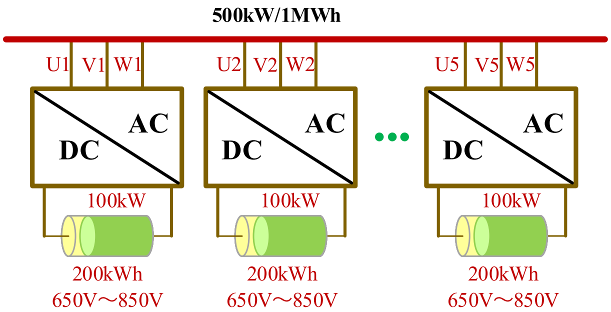

FIGURE 7. Schematic diagram of a 500-kW BESS unit with distributed single-stage DC/AC PCS.

B. DISTRIBUTED SINGLE-STAGE DC/AC PCS STRUCTURE

In order to solve the problems of the centralized PCS structure, BESS manufacturers have developed the distributed PCS structure that can improve the capacity utilization and the overall life of the battery stack. The converter topology in distributed PCS structure can be single-stage DC/AC topology or two-stage DC/DC+DC/AC topology. Figure 7 shows the schematic diagram of a BESS unit with distributed single-stage DC/AC PCS.

Distributed PCSs adopt modularization design concept with good applicability and expansibility. Each PCS module in distributed PCS structure has a much lower power level than that in centralized PCS structure. Each PCS module corresponds to a smaller battery stack, even a single battery cluster. Therefore, a finer management for battery energy can be achieved. The parallel connection of many battery clusters is abandoned, and in this way, the possibility of circulation current between different battery clusters is eliminated fundamentally. The charging and discharging power of each cluster can be strictly controlled below its rated power, and the impact caused by the differences among battery clusters can be minimized. Therefore, the capacity utilization of battery system is enhanced and the overall life is extended effectively. However, due to the low power level of single PCS module, it needs several times the number of centralized PCS to handle the same power. The efficiency of the distributed PCS is slightly lower than that of the centralized PCS, and multiple

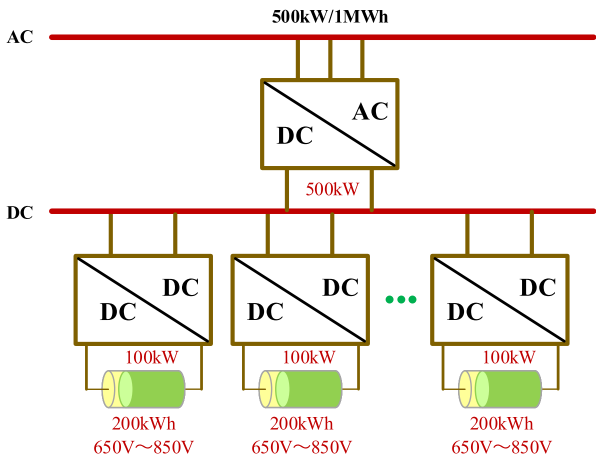

FIGURE 8. Schematic diagram of a 500-kW BESS unit with distributed two-stage DC/DC+DC/AC PCS.

DC/AC PCS modules operating in parallel on AC-side is also an obvious technical challenge. Overall, due to the independent control for each battery cluster, the performance improvements of BESSs and more practical value can be achieved.

C. DISTRIBUTED TWO-STAGE DC/DC+DC/AC PCS STRUCTURE

In order to solve the problem caused by the parallel connection of multiple DC/AC PCS modules, some scholars proposed a distributed PCS structure with two-stage DC/DC+DC/AC topology, in which multiple DC/DC converters are connected in parallel, as shown in Figure 8. Through the combination of battery clusters and DC/DC converters, the circulation current between the battery clusters can also be suppressed. The DC/DC converters are not sensitive to the difference in battery cluster voltage, and the DC/AC converter can work under a stable DC voltage, which means the design of the DC/AC converter becomes more convenient. However, in general, two-stage energy conversion leads to a lower PCS efficiency.

Neither of the above two distributed PCS structures can solve the mismatch problem among the battery cells in series in the battery cluster. In order to realize a finer management to the battery cluster, smaller battery modules and power converters can be combined to suppress the internal cask effect of the battery cluster, as shown in Figure 9.

D. CASCADED H-BRIDGE HIGH-VOLTAGE STRAIGHT HANGING PCS STRUCTURE

The voltage levels of the PCSs mentioned above are much lower than the voltage of medium-voltage AC grid, and line frequency transformers are necessary for grid connection. In order to further improve the overall performance and efficiency of BESSs, [28] proposes a transformer-less high-voltage straight hanging PCS structure based on the cascaded H-bridge topology, as shown in Figure 10.

The overall PCS in Figure 10 adopts star connection, and the PCS are connected to the medium or high voltage power grid through filter inductances, AC fuses, and pre-charging devices. Each phase in the PCS is formed by N cascaded power modules, and each power module is composed of a H-bridge circuit, bus capacitors, DC fuses, and a battery-side pre-charging device. The DC side of each power module is connected to a battery cluster.

The remarkable feature of this PCS structure is the AC output can be directly connected to the power grid without line frequency step-up transformers, and each power module controls an independent battery cluster with a charge or discharge current strictly lower than the rated current. It has the same effect as the distributed PCS presented in Section III-B in terms of the capacity utilization and overall life of the battery system. Since line frequency step-up transformers are omitted, the system efficiency is greatly improved. There is almost no power loss in the primary electrical system of BESS on no-load state, because the open circuit loss of line frequency transformers is eliminated. The PCS structure can significantly improves the power capacity of a single PCS and bring higher cost performance than low voltage PCS structure. At present, this type of PCS structure has been put into the commercial application with 10-kV grid-connected voltage and 10-MW rated power of a single PCS.

Due to the high voltage level of straight hanging PCS structure, H-bridge power modules and corresponding battery clusters need to maintain a high insulation strength to the ground, and the cost of maintaining insulation will be higher than that in the low voltage PCS solutions, which is one of the main technical problems of this PCS structure. A reasonable insulation design can ensure the safe operation of the battery clusters at high potential. In the current scheme, several battery cells are installed in a metal pack box, and the box is placed on a highly insulated metal bracket. In this way, the discharge phenomenon can only occur between the metal bracket and the ground under extreme situations. The metal bracket and the pack box have a good shielding effect to the battery cells. This insulation scheme is proved very safe for the battery cells by hundreds of high-voltage insulation tests. Similar insulation design is already used for a large number of engineering applications, such as valves at ultra-high voltage potential and high-voltage SVGs.

IV. CONTROL METHODS OF PCS

The control methods used for three-phase PCSs mainly include vector control, PR (proportional resonance) control, predictive control, direct power control, and repetitive control, etc.

A. VECTOR CONTROL (PI CONTROL)

Vector control is a representative PI control method [29], [30], and it is the most widely used control method in grid-connected inverter products. The vector control is usually based on a d-q coordinate system with the advantages

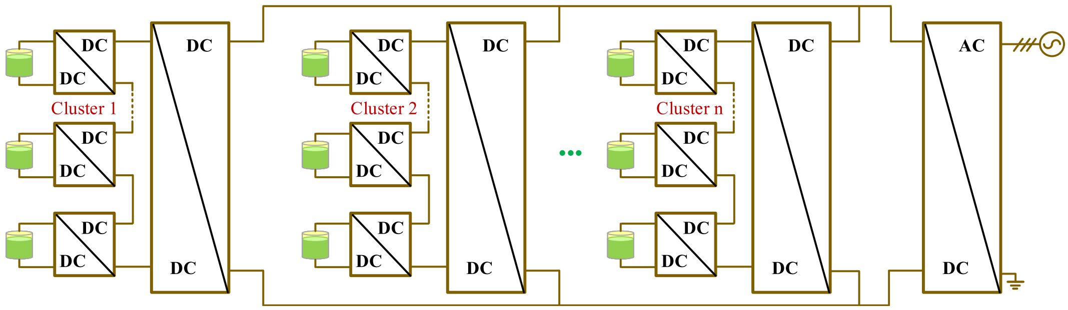

FIGURE 9. PCS structure with DC/DC converters managing split battery modules in each battery cluster.

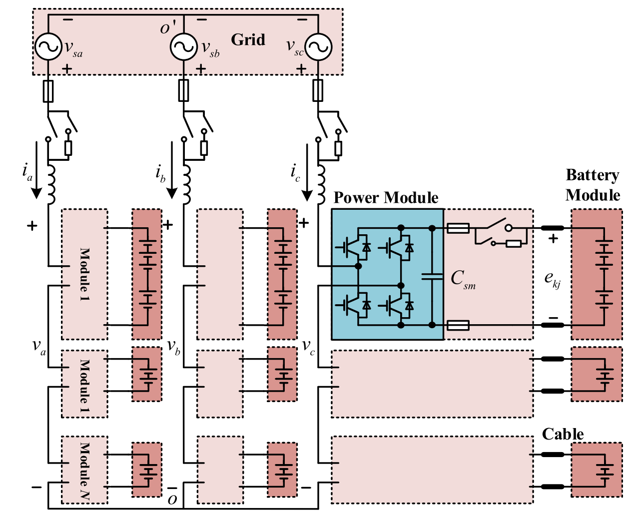

FIGURE 10. Schematic diagram of cascaded H-bridge high-voltage straight hanging PCS structure.

of high reliability, mature technology, and no static-error tracing.

B. PR CONTROL

PR control is usually based on a stationary coordinate system without complicated mathematical coordinate transformation, and it is equivalent to vector control in the mathematical sense. Theoretically, a PR regulator has an infinite gain at a certain frequency, and thus the static error free tracing for the sine ac signal with the certain frequency can be realized. PR control and multi-rotation coordinate system control have an equivalent relationship, but the computations of PR control are much less. So PR control is very suitable for engineering applications.

In [31], a parameter design method for PR regulators is proposed. In [32], the parameter design method is further studied and improved to realize a decoupling design of multiple regulators in the control loop. For renewable energy power generation applications, [33] and [34] apply PR regulators to back-to-back wind power converters and MMC converters that are used in wind farm for energy collection and grid connection, respectively. The current waveform can be improved, and the oscillation caused by specific harmonics can be suppressed.

C. PREDICTIVE CONTROL

Predictive control is also called model predictive control (MPC), and it predicts the future output according to the historical inputs and the discrete model of power electronic converter system. In the prediction process, a multi-objective multi-constraint optimization algorithm can be introduced, and the pulse width modulation in conventional control method can be removed, resulting in a simple structure, high reliability, and low latency.

[35] combines predictive control with sensorless control technology so that the inverter still maintains current control capability without grid and capacitor voltage sensors. In [36] and [37], this algorithm is applied to three-level inverters, and a series of optimization studies are presented, including multi-model adaptive feedback correction links, online identification, multi-objective satisfaction optimization and virtual vector prediction, etc. These researches lay the foundation for the further applications of predictive control.

D. DIRECT POWER CONTROL

The direct power control is similar to the direct torque control of a motor drive, and it is based on a α-β static coordinate system [38]. The direct power control is a typical bang-bang control based on the hysteresis comparison principle. This method has the advantages of fast dynamic response and short algorithm execution time, because it can directly control the power of the system [39]. However, it has the disadvantage of the unfixed switching frequency. Aiming at this shortcoming, [40] proposes an improved control strategy, which can be regarded as a reference for the practical application of the direct power control.

E. REPETITIVE CONTROL

Repetitive control is based on the internal model principle in control theory. Through periodic delay, the deviation signal can be reused to improve the tracking accuracy of the system. It has a better effect on tracking periodic signals and suppressing periodic disturbances. It has been widely used in active power filters (APFs), off-grid inverters, and other research fields or practical applications [41], [42].

In addition, some modern control methods such as neural network control [43] and fuzzy control [44] are also applied

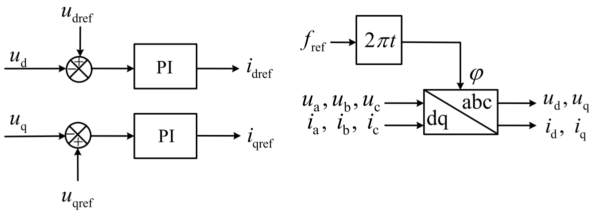

FIGURE 11. Outer voltage loop of constant voltage constant frequency control (V/f mode).

to PCSs in some applications, and some better performances are achieved.

F. GRID-CONNECTED/ISLANDING CONTROL STRATEGIES OF PCS

In microgrid applications, BESSs are required to have the abilities including parallel operation of multiple systems, providing effective support for the grid, adapting to both grid-connected and islanding operations as well as smooth transfer between the two conditions. The key to realization of these technical requirements is to select an appropriate grid-connected/islanding control strategy for the PCSs. Common grid-connected/islanding control strategies mainly include dual-mode control, droop control, and virtual synchronous motor control.

1) DUAL MODE CONTROL

A PCS based on the dual-mode control adopts constant power working mode (P/Q mode) during grid-connected operation, which directly tracks the active and reactive power commands given by the dispatcher through power-current double closed-loop control, and presents characteristics of a current source to the outside [45]. While it adopts constant voltage constant frequency mode (V/f mode) during islanding operation, as shown in Figure 11. The voltage amplitude command u_{ref} and frequency command f_{ref} are given by the dispatcher, and the phase of the output voltage is generated by the converter naturally according to the frequency. Generally, the voltage-current double closed-loop or triple closed-loop control is adopted here, and the PCS presents characteristics of a voltage source to the outside. The control algorithms in P/Q mode and V/f mode are independent of each other. Which operation mode should be adopted by the inverter is comprehensively judged based on the islanding detection, the impedance identification, and the state of the grid-connected switch. The dual-mode control technology is mature and widely used. However, due to the huge difference between the algorithmic structures of the two modes, the smooth transfer between two modes cannot be achieved, and it lacks the autonomous running capability.

2) DROOP CONTROL

The droop control determines the response action by itself based on a combination of the preset curves and the feedback signals of the bus voltage amplitude and frequency. Whatever

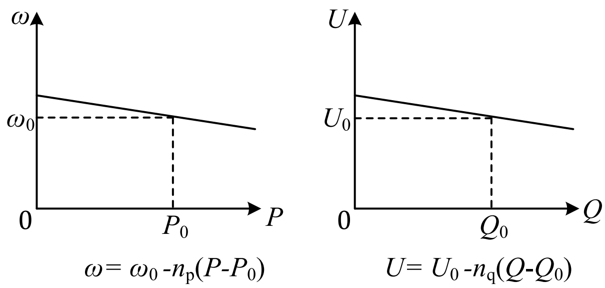

FIGURE 12. Droop characteristics.

the microgrid is working on grid-connected or islanding operation, the control algorithm structure is the same, as shown in Figure 12. It can maintain normal operation even when the upper layer communication is lost. Therefore, it is relatively easy to tranfer between grid-connected and islanding operations. Early droop control is often applied to the parallel control of uninterruptible power supplies (UPSs) without interconnection communication lines, which is equivalent to the parallel control of multiple converters in a microgrid in islanding operation. In [46], *Guerrero et al.* use the P-f/Q-U droop control and virtual impedance control to make a single UPS work as a voltage source with adjustable voltage amplitude and frequency, so that the parallel operation of online UPSs without interconnection communication lines is achieved. Based on this method, many scholars have finished a lot of exploratory research and achieved fruitful achievements on the power distribution and harmonic suppression strategies of parallel inverters [47]. Since a microgrid itself can be regarded as a special power source, the multiple inverters connected to the microgrid are similar to the parallel UPSs. In [48], the droop control is applied to the microgrid, and a preliminary analysis about the parameter design and stability of the control algorithm are presented, which confirms the feasibility of this control algorithm. After that, scholars propose several modified droop control methods with more or less improvements [49], [50]. Overall, the droop control is more suitable for energy storage micro-sources than dual-mode control. However, there are still some problems. For example, the droop control requires a more precise parameter design, and whether it can provide damping and inertia for the system is still inconclusive. Considering the perturbation and mismatch of inverter parameters, the possibility of instability still exist for the microgrid system based on the droop control.

3) VIRTUAL SYNCHRONOUS GENERATOR CONTROL

In traditional power systems, large synchronous generators are a kind of power sources with superior characteristics, and can provide strong support for the power grid. Therefore, a large number of scholars seek the control strategy that can equate an inverter with a synchronous generator. Among them, the concepts of the virtual synchronous generator (VSG) proposed by the Energy Research Centre of the Netherlands and Eindhoven University of Technology [51],

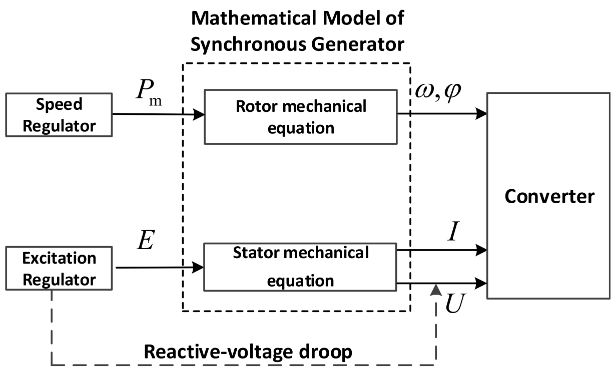

FIGURE 13. Structure of VSG control strategy.

Virtual Synchronous Machine (VISMA) proposed by Clausthal University of Technology in Germany [52], and Synchronverter proposed by professor *Qing-Chang Zhong* from the University of Sheffield in the United Kingdom [53], [54] are representatives.

In 2005, *J.Morren*, from Delft University of Technology in the Netherlands, was studying the maximum power tracking control of wind turbines. In order to increase the inertia of distributed generations to the grid frequency variation, he added an additional torque caused by the grid frequency variation to the reference torque of wind turbines. The additional torque represents virtual inertia and damping that enables distributed power generations to participate in the grid frequency regulation and improves grid stability [51]. In 2007, the European project "VSYNC", in which Delft University of Technology in the Netherlands was one of the leading institutions, first proposed the concept of VSG. The technology previously applied to wind turbines was extended to the distributed generations based on energy storage devices. By this way, the energy storage devices can not only calm the output fluctuations of renewable energy sources, but also provide additional power supplements for suppressing the frequency fluctuations of the power grid.

The VISMA control schemes proposed by the Clausthal University of Technology in Germany [52] can be divided into current-type VISMA and voltage-type VISMA, as shown in Figure 14 (a) and (b) respectively, according to the different implementation methods of the stator voltage equation. The difference between the two types of VISMA is whether it provides a voltage reference or a current reference for the inverter, and their control effects are similar [55]. Although the current-type VISMA presents the characteristics of the current source from the perspective of the inverter, its equivalent model is still a controlled voltage source from the perspective of the stator voltage equation shown in Figure 14.

Early VISMA did not explain the generation process of induced electromotive force. As shown in Figure 15, the Synchronverter control strategy proposed by professor *Qing-Chang Zhong* [53], [54] explains the excitation process of induced electromotive force on the basis of VISMA, making Synchronverter have the electromagnetic transient characteristics like a synchronous generator. Synchronverter control strategy directly executes open-loop control on the induced electromotive force and does not include a stator electrical equation.

The virtual synchronization control strategy helps to improve the external characteristics and own survivability of inverters, and at the same time helps to reduce the side effects and safety risks of conventional grid-connected technology. It is one of the effective technical schemes to realize the large-scale integration of renewable energy into the power system. At present, the current-type control strategies set in the strong power grid are still the mainstream control technology with the advantages of mature technology and flexible operation for multiple PCSs in parallel. The voltage-type control strategies represented by virtual synchronous control strategy can actively respond to and dampen the frequency variation of the power grid, and will be a competitive development direction of the control technology for the power grid with super-large capacity and high penetration BESSs.

V. DESIGN SCHEMES OF HIGH-CAPACITY BESS

A. SELECTION OF SINGLE PCS POWER CAPACITY

For a high-capacity BESS, the power capacity of a single PCS determines the number of PCSs in parallel, the complexity of the secondary coordinated control system, and the workload of construction and debugging on the site of project. A large number of high-voltage units (usually 2.5MW per unit) will cause a significant increase in engineering construction and secondary wiring. Therefore, for a high-capacity BESS, choosing a single PCS with a higher power level will significantly reduce the project implementation cost. When the power of a single PCS reaches 10MW and above, the control instructions from the power grid can be directly issued to the PCS controllers for direct scheduling. In this way, some taches in the communication link such as EMS and coordinated control system are omitted, and the response speed will be greatly improved, which is very important for providing support to the power grid in an emergency. Moreover, a single PCS with a higher power can avoid multi-machine parallel coordination control in islanding operation, which is beneficial to be used as a black-start power supply.

B. SELECTION OF BATTERY STACK CAPACITY AND MANAGEMENT MODE

Keeping a large number of battery cells in a consistent working state is the key consideration to the selection of the battery stack capacity and management mode. Otherwise, it will have a bad impact on the performance and safety of the BESS. The smaller the capacity of a single battery stack, the easier it is to ensure the consistency of the states of battery cells, which means a higher capacity utilization, higher economic benefit and lower safety risk. Therefore, the technical solutions that reduce the capacity of single battery stacks with fewer battery clusters connected in parallel are advised. It should be noted that the choice of a single high-power PCS described in

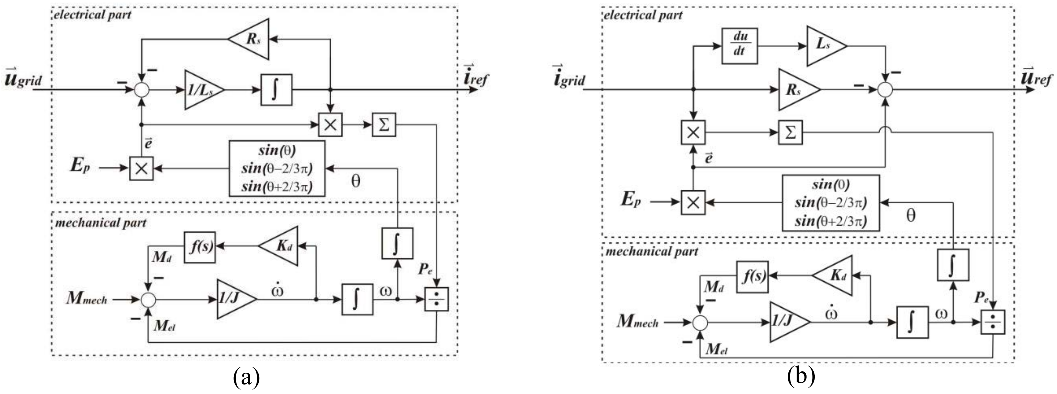

FIGURE 14. Structures of VISMA control strategies. (a) Current-type VISMA; (b) Voltage-type VISMA.

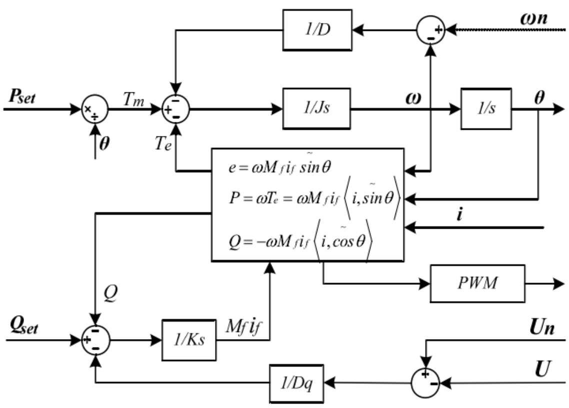

FIGURE 15. Structure of Synchronverter control strategy.

Section V-A does not mean a larger DC-side battery stack capacity.

C. EFFICIENCY OF BESS

Efficiency improvement of energy systems and associated equipments is always an important research priority. High-capacity BESSs should insist on reducing cost and increasing efficiency. At present, the system efficiency of some BESSs at 0.5C rate can be close to 91%, which has reached a very high level. Subsequent research directions include the reduction of battery internal losses and the increase of single PCS power capacity, in order to improve the system efficiency and increase the investment and application value.

D. GRID-CONNECTED VOLTAGE OF BESS

According to the development law of power system, to improve the efficiency and reliability, the larger the capacity of a stand-alone system, the higher the grid-connected voltage. Therefore, a high-capacity BESS should adopt energy storage equipments with a higher power, and a higher direct grid-connected voltage, such as 10kV or 35kV. It will significantly improve the system efficiency and reduce the complexity of the secondary system with less amount of engineering construction. As shown in Figure 16, there are significant differences in the dispatch control and the complexity of the secondary systems of two high-capacity BESSs with different PCS architectures.

VI. MEASURED OPERATIONAL DATA OF HIGH-CAPACITY BESS WITH HIGH-VOLTAGE STRAIGHT HANGING PCS

Based on the cascaded H-bridge high-voltage straight hanging PCS structure that is described in Section III-D, a 10MW/20MWh BESS with 10kV direct grid-connected voltage is constructed. Test waveforms are derived from a 5MW/10MWh subsystem. Each phase in the PCS is made up of 20 H-bridge power modules in series. When the BESS is connected to the power grid, the actual load is low. When the power grid fails, entire load is borne by the BESS. At this time the output current of BESS is about 125A, and the actual load is 2200kVA. Figure 17 shows the BESS can be switched from grid-connected operation to islanding operation seamlessly, and Figure 18 shows the BESS can also be switched from islanding operation to grid-connected operation seamlessly.

In terms of the efficiency, the charge and discharge tests are carried out twice a day for two consecutive months on the BESS, and the test results are shown in Table 1. It can be observed that the energy conversion efficiencies of the BESS are all above 91%.

VII. CHALLENGES AND DIRECTIONS OF FUTURE WORK

With the increase of BESS capacities and the diversification of applications, PCSs, as the core energy processing equipment of BESSs, are facing more and more challenges. In the application of grid frequency regulation, PCSs are required to have a faster dynamic response speed. In the user side BESSs, the higher the power density of the PCS, the better. In a BESS with a scale of 100MW or above, the improvements of PCS voltage and unit power capacity are very important to reduce system losses and system complexity. The development directions of PCSs with potential in the future are discussed here.

A. APPLICATION OF SiC SWITCHING DEVICES IN PCS

At present, most of the power switching devices used in PCSs are Si IGBTs. Limited by the intrinsic limits of Si

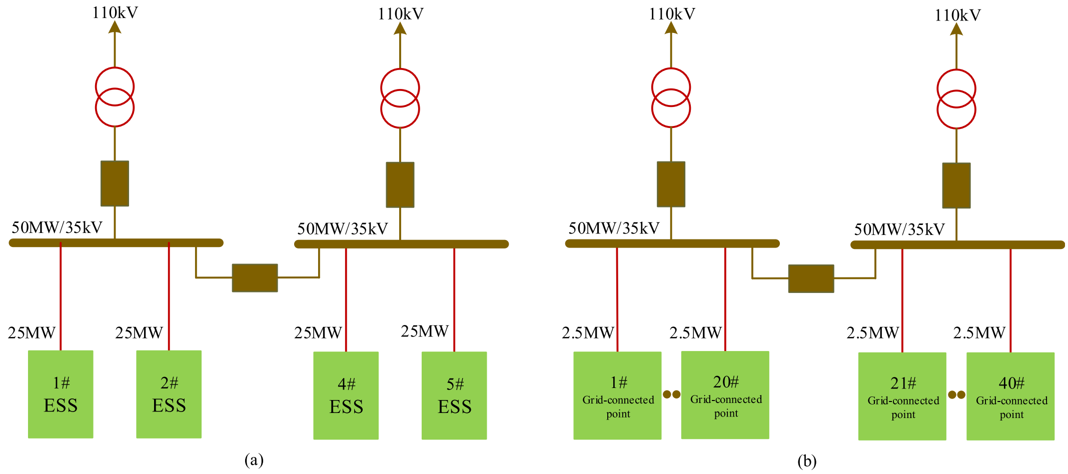

FIGURE 16. Comparison of 100-MW BESSs based on different PCS architectures. (a) High-voltage straight hanging PCS; (b) Centralized low-voltage PCS.

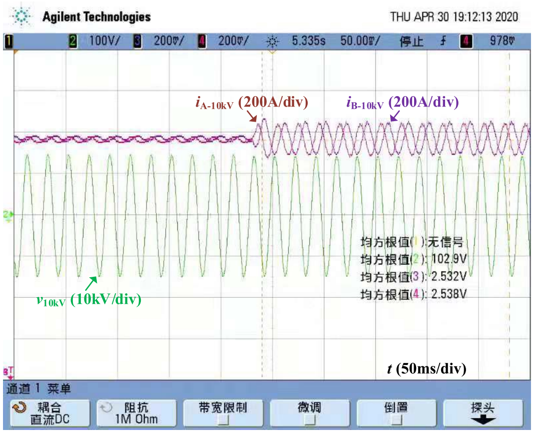

FIGURE 17. Test waveforms (A phase current $i_{A\text{-}10kV}$; B phase current $i_{B\text{-}10kV}$); line voltage v_{10kV}) in 10kV side of the cascaded H-bridge PCS under the transition from grid-tied state to off-grid state with load.

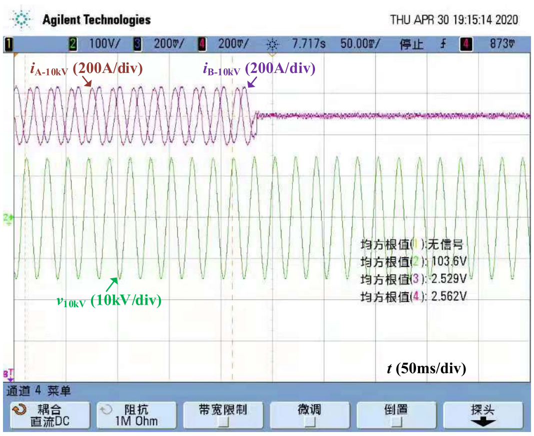

FIGURE 18. Test waveforms (A phase current $i_{A\text{-}10kV}$; B phase current $i_{B\text{-}10kV}$); line voltage v_{10kV}) in 10kV side of the cascaded H-bridge PCS under the transition from off-grid state to grid-tied state with load.

material, the switching losses and switching speed of Si IGBTs are difficult to be further improved, which hinders the further improvements of PCS performances. SiC MOSFETs have the advantages of high withstand voltage, fast switching speed, small on-state resistance, high temperature resistance and so on. The trend of SiC MOSFETs replacing Si IGBTs in medium voltage and high power applications has been formed. SiC MOSFETs have been applied to unmanned aerial vehicles (UAVs), automobiles, rail transit and other occasions where the high efficiency and high power density of power electronic equipments are required, and their application in the renewable energy field is also gradually expanding. In the future, with the improvements of PCS power density, efficiency and dynamic response speed, the application research of SiC MOSFETs in PCSs highlights a strong research value and practical significance.

TABLE 1. Units for magnetic properties.

Time interval	Number of cycles one day	Charge capacity (kWh)	Discharge capacity (kWh)	Efficiency
8.1-8.31	1	674880	616200	91.31%
	2	1349760	1232400	91.31%
9.1-9.30	1	586200	534000	91.10%
	2	1172400	1068000	91.10%

B. STRAIGHT HANGING PCS WITH HIGHER GRID-CONNECTED VOLTAGE LEVEL

At present, most BESSs are connected to the power grid through PCSs and line frequency step-up transformers. When this scheme is applied in high-capacity BESSs, there will be some problems, such as high system losses, large number of PCSs, and high control difficulty. High-voltage straight hanging PCS can improve the voltage level and power capacity of a BESS through power electronic methods, reduce the losses caused by heavy current, and save the cumbersome line frequency step-up transformers. It will have broad application prospects in high-capacity BESSs. At present, the voltage level of high-voltage straight hanging BESSs needs to be further increased to at least 35kV, in order to better meet the requirements for grid connecting. Besides, improvements need to be made in the following areas: the reduction of battery cluster insulation cost, the optimization of voltage distribution strategy of cascaded H-bridge power modules, fault module bypass strategy and so on.

VIII. CONCLUSION

In this paper, a technical review and evaluation of the battery assembly methods of the high-capacity BESSs, the topological structures of the PCSs, and the design considerations of the high-capacity BESSs are presented. Following conclusions can be obtained:

1) The parallel mismatch problem of multiple battery clusters in parallel will damage the capacity utilization, energy conversion efficiency and safety of the battery system. The cycle life decreases with the increases of parameter differences among battery cells. Through the distributed PCS structure and related control method, the cask effect and parallel circulation current of the battery system can be suppressed, and in this way, the economic value and safety of the BESS are improved;

2) The structures of PCS are directly related to the actual applications. With common batteries and semiconductor components, the transformerless cascaded H-bridge high-voltage straight hanging PCS can be applied to tens of MW applications. Because it does not require line frequency step-up transformers, its operating efficiency is higher than that of the conventional PCSs with line frequency step-up transformers. Therefore, it is particularly suitable for the single-unit high-capacity applications without the problems of system oscillation, communication delay and slow dynamic response caused by the parallel operating of multiple low power PCSs;

3) At present, the current-type control strategies set in the strong power grid are still the mainstream control technology with the advantages of mature technology and flexible operation of multiple PCSs in parallel. The voltage-type control strategies represented by virtual synchronous control strategy can actively respond to and dampen the frequency variation of the power grid, and will be a competitive development direction of the control technology for the power grid with super-large capacity and high penetration BESSs.

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