Research status and development trend of PCS

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Abstract. Due to the shortage of conventional energy and serious environmental pollution, new energy (NE), such as wind energy, solar energy, biomass energy, etc. is getting more and more attention. However, the output power of NE is unstable. Energy storage is the most effective way to solve the problem of NE applications. The power conversion system (PCS) determines the output power quality and dynamic characteristics of the energy storage system. This paper reviews the development and application of PCS, conducts a detailed study of its working principle, topology, and key technologies. The main index system of PCS is established by consulting the relevant standards, and the requirements and detection methods of the main indexes are pointed out. This work provides a scientific basis for the selection of PCS. At the end of the paper, summarizes and prospects on PCS.

1. Introduction
With the development of society, people's demand for electric energy and the reliability of electric energy quality are getting higher and higher. Although the NE alleviate the problems of conventional energy shortage and environmental pollution, their distribution is not concentrated, and they are easily affected by environmental factors such as wind speed and light intensity, resulting in strong volatility, intermittency and randomness, and the output power is unstable. It will have a greater impact on the load and power grid, endanger the stability and security of equipment and power grid, if we directly use NE [1-3]. Energy storage system can effectively solve the problems faced in the use of NE, especially battery energy storage system (BESS), because of its no special requirements for the site, good dynamic performance, high energy density and other characteristics, is widely used in NE, to smooth fluctuating power, peak-cutting and valley-filling, emergency security. As one of the important components of BESS, PCS is the key component to determine the performance of BESS, and its research is of great significance.

2. Development and application of PCS

2.1. Development history of PCS
The evolution of PCS includes the development of circuit topologies and control algorithms.

2.1.1. Circuit topologies. According to the number of commutation stages, the circuit topologies of PCS can be divided into single-stage type and multi-stage type [4], and these two structures are also more often used in the current energy storage power station in China. They are shown in Table 1.
Table 1. Single-stage and double-stage PCS.

| Divided by the number of commutation stages | Single-stage type | Double-stage type |
|--------------------------------------------|-------------------|-------------------|
| Circuit topology                           | ![Single-stage PCS](image1.png) | ![Double-stage PCS](image2.png) |
| Major components                           | DC/AC converter.  | DC/AC converter and DC/DC converter. |
| Advantages                                  | simple structure, easy to control, low operating loss, high operating efficiency, low cost. | wide input voltage range, complex control, low efficiency. |
| Disadvantages                               | narrow voltage range | complex control, low efficiency |
| By number of output levels                  | Two-level         | Tri-level          |
| Circuit topology                           | ![Two-level PCS](image3.png) | ![Tri-level PCS](image4.png) |
| Advantages                                  | Most used         | High voltage withstand level, smoother output waveform, low harmonic content |
| Disadvantages                               | not for medium and high voltage level energy storage systems |

As shown in Table 1, the double-stage PCS adds a bidirectional DC/DC converter based on the single-stage PCS. The purpose is that the bidirectional DC/DC converter can work in Boost and Buck mode, which can adjust the voltage magnitude of the DC side and expand the voltage range of the battery, but accordingly, the control complexity increases. The applied voltage level cannot be too high due to the voltage stress of the switching tubes. In Reference [5], Fan Hui et al. used a Z-source boost network as the pre-stage circuit of the PCS, and the Z-source network can improve the voltage gain of the PCS while reducing the voltage stress of the switching tubes. In Reference [6], Gao Ning et al. proposed a double-stage PCS circuit topology using a Dual Active Bridge converter.

The current PCS circuit topology is basically two-level. A. Nabae et al. proposed a diode midpoint-clamped topology [7], which provides the basis for the study of Tri-level PCS. Tri-level PCS mainly adopts midpoint-clamped topology, including I-type and T-type, and the T-type topology is the most applicable. The higher the number of modulation levels, the closer the output voltage is to the ideal sine wave after filtering.

2.1.2. Control algorithm. The operating modes of PCS are divided into grid-connected mode, off-grid mode and on/off-grid switching mode, with different control strategies in different operating modes [8].
In grid-connected mode, current control strategy is often used. The traditional strategy is proportional-integral (PI) control with a double closed-loop control structure. The control has the problems of coupling and poor dynamic performance, so the P/Q decoupling control strategy and the introduction of feedforward control are subsequently proposed to decouple and improve the response speed of the system. In addition to PI control, there are common control strategies such as predictive control, differential-free control, current hysteresis loop control, repetitive control, fuzzy control, proportional resonance (PR) control, quasi-proportional resonance (QPR) control, etc., all of which achieve better control results. In addition, composite control strategies can also be used.

In off-grid mode, the PCS is used as the main power supply for the load, so it needs to adjust the amplitude, frequency and phase of its output voltage to meet the load's power demand, so often use voltage control strategy. Such as constant voltage and frequency V/f control, sag control and so on. Among them, V/f control uses voltage and current double closed-loop control, which also has the problems of decoupling and poor dynamic performance, and sag control by sampling the frequency and amplitude of the feedback bus voltage, which has high requirements on parameters.

In on/off-grid switching mode, there are problems such as voltage transient fluctuations and inrush currents during switching, because the control strategies in the grid-connected and off-grid operation modes are different. In Reference [9], a controller state following off-grid/on-grid switching control strategy based on phase pre synchronization is proposed. Although the state follower can improve the voltage and current fluctuations, frequent switching will lead to controller instability and easy failure. In Reference [10], a seamless switching control strategy based on a linear self-turbulent controller is proposed to change the current inner-loop controller into a linear self-turbulent controller.

### 2.2. Application of PCS

PCS has a wide range of applications, which can be used to balance power fluctuations in NE systems such as wind solar energy storage, and can also be used to cut peaks and fill valleys in power grids to improve power quality.

Take the off-grid wind solar energy storage system as an example, the application of PCS in it is shown in Figure 1.

![Figure 1. Application of PCS in scenic storage system.](image1)

Figure 2. Block diagram of PCS efficiency detection loop.

As shown in Figure 1, when the power of wind solar generation is low, the PCS works in the inverter state, and the storage battery discharges to make up for the shortage of wind solar generation, and the storage battery and wind solar generation jointly supply power to the load; when the power of wind solar generation is high, the PCS works in the rectifier state, and the storage battery charges to absorb the surplus energy of wind solar generation.

PCS can be divided into two types: generation side and load side, according to the location of access to the grid. PCS connected to the generator side is mainly used to improve the stable operation ability of the generator. PCS connected to the load side can adjust the active power and reactive power of the access point.
3. Key technology of PCS

3.1. Control under three-phase unbalance condition

When the energy storage system supplies power to single-phase loads, there will inevitably be a three-phase voltage unbalance problem caused by the asymmetric access of the loads, which seriously affects the quality of power supply to the loads and even causes system instability. The International Electrotechnical Commission clearly stipulates that the three-phase voltage unbalance of power system should not exceed 2%.

In addition to the above-mentioned excessive single-phase load, the causes of unbalanced three-phase may also be inconsistent hardware parameters and line parameters of each phase of the system, asymmetric three-phase drive signals of the converter, unbalanced three-phase grid distribution, asymmetric short-circuit or short-circuit faults, etc. [11]. The traditional practice is to install active power quality regulation devices in the energy storage system, such as active power filters, static reactive power compensators, dynamic voltage restorers, distribution-type static synchronous compensators, unified power quality regulators, etc. The principle is to inject compensation current into the energy storage system to suppress the unbalanced voltage. However, the effect is not ideal, and the cost is high, the operation and maintenance work are time-consuming and labor-intensive, and it is not applicable to large-scale capacity systems. Reference [12] proposes to use the converter's own surplus capacity to suppress the unbalanced voltage and to constitute an integrated control system with functions such as reactive power compensation and active filtering.

3.2. Large capacity

With the development of equipment, large-capacity energy storage system is the general trend. High-capacity energy storage systems usually have high voltage levels, and generally use transformers to protect the energy storage system and suppress common mode interference, but correspondingly, the use of transformers makes it difficult to optimize the efficiency, volume, cost, noise, footprint and expansion of the energy storage PCS. To avoid the losses caused by transformers, many institutions have carried out transformer less research, and transformer less high-capacity solutions have been proposed to increase the battery module voltage and PCS cascade [13, 14].

Increasing the battery module voltage means increasing the number of series and parallel connections of battery cells, however, limited by battery technology, the robustness and consistency of battery cells are not high, and increasing the voltage level will increase the cost of battery management and equalization, and bring challenges to battery safety.

Cascade has the advantages of high efficiency, modular design, and easy redundancy protection, etc. The most common structure is the H-bridge chain cascade. The main problem of this scheme is that the DC side of each H-bridge unit must be insulated, and the charging and discharging current has 2-frequency pulsation. Cai Xu et al. proposed a two-stage H-bridge cascaded energy storage PCS, which suppresses low-frequency current pulsation by inserting a one-stage Buck/Boost circuit [15].

3.3. Current harmonic suppression

The PCS converter bridge output current contains high harmonics, and if directly carried or incorporated into the grid, they can seriously reduce the power quality of the grid, which can lead to damage of power-using equipment in serious cases. There are many reasons for the generation of current harmonics, such as the modulation dead time of the upper and lower bridge arms of the power module, power switching device tube voltage drop, and DC input power fluctuations [16]. In particular, when operating off-grid, the active and reactive currents of the load are all provided by distributed power sources within the energy storage system due to the absence of grid clamping, and there may be nonlinear loads in the energy storage system, which makes the output current of the energy storage converter distorted.

There are three kinds of output filters commonly used in PCS, L-type, LC-type, and LCL-type. Filters can only filter out high frequency harmonics of the current, and low frequency harmonics need
to be suppressed by current closed loop controllers. Commonly used controllers are repetitive controller, PR, QPR, etc. The main principle is to extract and suppress the harmonic signal in the input signal.

3.4. Islanding detection

The islanding protection standards GB 50797-2012 and GB/T 29319-2012 stipulate that small PV plants and distributed generation systems are required to have the function of quickly detecting islanding and immediately disconnecting from the grid, and stop supplying power to islanding within 2s.

Islanding detection techniques can be divided into passive detection and active detection. Passive detection is to monitor the voltage amplitude, frequency, phase and other parameters at the point of common connection (PCC) between the energy storage system and the grid in real time to determine whether an islanding fault occurs; active detection is to add a disturbance signal to the output of the PCS, so that the voltage amplitude and frequency of the PCC point will be shifted after the loss of grid support, reaching the PCS protection value and triggering a shutdown. Commonly used passive detection methods are over-under frequency method, voltage phase abrupt change detection method, over-under voltage method, voltage harmonic detection method, etc.; active detection methods are voltage offset detection method, active frequency detection method, active power disturbance method. At least one passive and active islanding detection method is required to be set in the energy storage system.

4. Evaluation of PCS

4.1. Main index system

By interpreting the parameters of PCS, the main indicators of PCS can be divided into input side, output side, battery, and other parameters. The input side is connected to the distributed power supply and the battery, and the main indicators of the input side are the maximum input voltage and the rated input voltage. The parameters on the output side are related to the working mode of the PCS and are divided into grid-connected and off-grid. In comparison, the grid-connected adds two indicators of output power factor and total harmonic distortion rate of current, the reason being that to be connected to the local grid, it must comply with the local grid-connected standards. Battery parameters mainly specify the battery types, voltage and current, capacity and charging and discharging strategies that can be accepted by PCS. Other parameters include non-electrical parameters such as protection functions, operating environment, communication interface and size of the PCS.

4.2. Related standards

To evaluate the merits of a PCS, it is not enough to rely on product parameters, but also to pay attention to the requirements in the standards.

Table 2. PCS efficiency test.

| Steps | Rectification efficiency | Inverter efficiency |
|-------|--------------------------|---------------------|
| (a) PCS works in the rectified state. (b) The DC side voltage of PCS is the upper limit, every 10% of rated power is one operating interval, recording of AC side and DC-side active power. | $\eta_1 = \frac{P_{DC}}{P_{AC}} \times 100\%$ | $\eta_2 = \frac{P_{AC}}{P_{DC}} \times 100\%$ |

$\eta_1$ is the rectification efficiency, $\eta_2$ is the inverter efficiency, $P_{DC}$ and $P_{AC}$ is the DC output power and AC input power, respectively.
4.2.1. **Efficiency.** GBT 34120-2017 and GBT 36558-2018 require that under rated operating conditions, the rectification efficiency and inverter efficiency of PCS should not be lower than 94%. NBT 42089-2016 requires that the optimal efficiency of the PCS should not be lower than 95%. GBT 34133-2017 gives the testing method. The testing circuit is shown in Figure 2, and the test steps and calculation formula are shown in Table 2.

4.2.2. **Loss.** The losses of PCS include standby losses and no-load losses, the test method is shown in Table 3. GBT 34120-2017 and GBT 36558-2018 require that the standby losses of energy storage converters should not exceed 0.5% of the rated power and no-load losses should not exceed 0.8% of the rated power.

| Table 3. PCS loss detection. |
|-------------------------------|
| **Testing steps** | PCS works in standby mode. Measurement of DC-side and AC-side voltage and current data | PCS works in the no-load state. Measurement of DC-side voltage and current data |
| Calculation formula | $p_{\text{backup}} = U_{DC} \times I_{DC} + U_{AC} \times I_{AC}$ | $p_{\text{no-load}} = U_{DC} \times I_{DC}$ |
| $p_{\text{backup}}$ is the standby power loss, $p_{\text{no-load}}$ is the no-load power loss, $U_{DC}$, $I_{DC}$ are the DC side voltage and current values respectively; $U_{AC}$, $I_{AC}$ are the AC side voltage and current values respectively. |

4.2.3. **Overload capacity.** GBT 34120-2017 and GBT 36558-2018 require that the AC side current of the PCS should last for not less than 10 min at 110% of the rated current, and for not less than 1 min at 120% of the rated current. GBT 34133-2017 requires that the overload capacity test method should meet the requirements of GBT 13422-2013 requirements.

4.2.4. **Power quality.** The power quality includes voltage accuracy, total voltage distortion rate, voltage unbalance, voltage transition variation range, etc. The requirements are shown in Table 4.

| Table 4. Electricity quality evaluation indicators and requirements. |
|-------------------------------|
| **Evaluation Indicators** | GBT 34120-2017 requires that AC side output voltage amplitude deviation should not exceed ±5% of the rated voltage, and the phase deviation should be less than 3°. NBT 42089-2016 requires that the voltage accuracy should be controlled within ±3% when the resistive load varies from 20% to 100%. |
| **Total voltage distortion rate** | GBT 34120-2017 requires that the total harmonic distortion rate of the output voltage on the AC side does not exceed 3% under no-load and rated resistive load conditions. NBT 42089-2016 requires that the total voltage distortion rate should be less than 5%. |
| **Voltage unbalance** | GBT 34120-2017 requires that the output voltage unbalance should be less than 2%. |
| **Voltage transition variation range** | GBT 34120-2017 requires that under resistive load conditions, the output voltage transient value of the PCS should be less than 10% when the load rises from 20% to 100% or drops from 100% to 20% in a sudden change. NBT 42089-2016 requires that when the resistive load is varied from 20% to 100%, the voltage transition change range is within 10%. |

5. **Conclusions**
Through the analysis of the development history, principle application, key technologies and main indicators of energy storage converters, this paper draws the following conclusions.
1. PCS are widely used and have development prospects. PCS has the function of regulating power, to apply NE on a large scale, it is necessary to solve the key technologies of PCS.

2. The key technical problems faced in the development of PCS include control under three-phase unbalance conditions and large capacity. Control under three-phase unbalance conditions can be realized by changing the control strategy of PCS, and the large capacity can be realized by cascading PCS, which not only can avoid the consistency problem of many batteries in series and parallel, but also has the advantages of modularity and high redundancy.

3. PCS technical indicators can be divided into input, output, battery, and other technical indicators. The study of PCS technical indicators and detection methods is not only convenient to grasp the existing PCS technical level, provide the basis for type selection, but also make use of PCS technology development.

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