Community Research Report

Research Report on GW-Level Data Center 800 V DC Power Supply and Distribution

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1 Evolution of the Power Supply Chain

The rapid development of generative AI and foundation model technologies has led to an unprecedented exponential growth in global computing power demand. From GPT and Gemini to various industry-specific foundation models, there is an increasing demand for higher performance and density of computing hardware. This has directly driven the energy consumption of AI servers in a single rack to surge sharply. In just a few years, the energy consumption has jumped from tens of kilowatts to over 100 kW, and is rapidly evolving towards 200 kW, 500 kW, or even megawatt (MW) levels.

However, the underlying power supply architecture supporting this transformation faces severe challenges. The traditional AC power supply architecture, which has been used for decades, with AC power entering the rack and 54 V DC power being supplied, has reached its physical limits when dealing with ultra-high power density. Its inherent design constraints have become the core bottleneck that hinders further development of AI computing power. In contrast, the 800 V DC architecture, by increasing the voltage by one order of magnitude and reducing the current to less than 1/15 of the original current, fundamentally solves the problems of loss, temperature rise, and cabling caused by low voltage and high current. This makes MW-level racks possible.

2 Comparison of 800 V DC Power Supply Modes

2.1 Background Overview

With the rapid development of AI technology, computing power, as the backbone of AI, has also experienced explosive growth. The ultimate limit of computing power is electricity, and the demand for AI power has grown exponentially. The evolution of GPUs and supernodes has driven the power per rack from over 30 kW to over 130 kW, with planned power reaching over 600 kW, and future projections exceeding one MW—boosting rack power density to 60 times that of traditional IT racks. Beyond this high power density, an even more challenging issue is the volatility of power loads: loads can suddenly surge to 1.9 or 1.6 times the rated power, then instantly drop to zero, with such fluctuations occurring several times per second continuously. High power demand, high per-rack power density, and frequent load fluctuations have become the three defining characteristics of future AI data centers (AIDCs). These features make it difficult for traditional power supply solutions to cope effectively.

Traditional data center power supply uses AC UPS, which employs a multi-stage conversion architecture: AC converted to DC, batteries connected to the DC busbar, and then DC inverted back to AC. The full-link efficiency is 96% (including the industrial frequency transformer). This solution works without issue in general equipment rooms. However, when addressing the three characteristics of AIDC, its output voltage is low (requiring larger copper busbars), compensation for fluctuating power is complex, and it occupies significant space with higher costs. In contrast, with DC power supply, batteries (or energy storage capacitors) can be directly connected in parallel to the DC output via DC-DC converters, which can more easily resolve load fluctuation and backup power issues. By increasing the DC busbar voltage, the use of copper busbars can be reduced. Additionally, the DC busbar provides a natural access interface for green power sources such as photovoltaic and energy storage systems, better aligning with the trend toward greener data centers. DC power supply is a trend worth considering.

DC power supply was first applied in communication power supply systems, where 48 V DC was used to supply power to communication equipment. In data center applications, due to higher power requirements, to achieve greater power supply efficiency and extend the power supply radius, China introduced DC power supply solutions with nominal voltages of 240 V and 336 V in 2010. The main reason for the widespread adoption of 240 V in China is that traditional servers can directly connect to 240 V DC. However, with the sharp increase in power density per GPU rack, the limitations of 240 V DC power supply have become evident. The 1000 kW power supply in a single rack is used as an example: when the voltage is 240 V DC, the current is 4160 A, and the cross-sectional area of the copper bar is

at least 2000 mm²; when the voltage is increased to 800 V DC, the current is 1250 A, and the cross-sectional area of the copper bar is 600 mm², greatly reducing the amount of copper used and, more importantly, reducing the volume of copper bars in the AI rack, and leaving valuable space for GPU computing power. 800 V DC is still a low voltage (lower than 1000 V DC) in the power system, so it has low requirements on operators. In addition, 800 V DC is widely used in ultra-fast charging stations of electric vehicles and energy storage systems, and its supply chain is very mature. Therefore, 800 V DC is one of the preferred options for powering AIDCs.

In May 2025, NVIDIA announced that it would use 800 V DC power supply starting from 2027. In October 2025, NVIDIA officially released the white paper "800 V DC Architecture for Next-Generation AI Infrastructure" at the OCP Global Summit in North America, clearly stating that 800 V DC would become the mainstream solution for powering AIDCs in the future. China's postal and telecommunications authorities and other related organizations have also recently released their own white paper on 800 V DC power supply.

2.2 HVDC Overview

The traditional high-voltage DC (HVDC) solution in China is used to increase the output voltage to 800 V DC. As shown in Figure 1, 10 kV AC (or 35 kV AC) is connected to a traditional transformer, which decreases the voltage to 380 V AC (or 480 V AC) and then to a three-phase rectifier module. The three-phase rectifier module contains power factor correction (PFC) and isolated DC-DC conversion, and outputs 800 V DC. All modules are connected in parallel and supply power to downstream loads through power distribution.

The PFC level generally uses Vienna rectification to convert the AC voltage into 800 V DC. The core of this technology is to control the input current to track the input voltage and control the power factor to be close to 1. As shown in Figure 2, this architecture was patented in 1993, and the patent has expired, so it is not restricted by the patent.

The DC-DC level generally uses the LLC topology to convert the 800 V voltage into isolated 800 V DC. The core of the LLC topology is isolation, voltage regulation, and current limiting. It controls the output voltage to be constant and low ripple, and limits the output current, as shown in Figure 3. This architecture was patented in 2006, but there were earlier articles that disclosed the topology, so it is not restricted by the patent.

In this solution, SiC devices (600 V for the PFC level and 1200 V for the DC-DC level) can be used to improve efficiency and power density, and the peak efficiency can reach 98%.

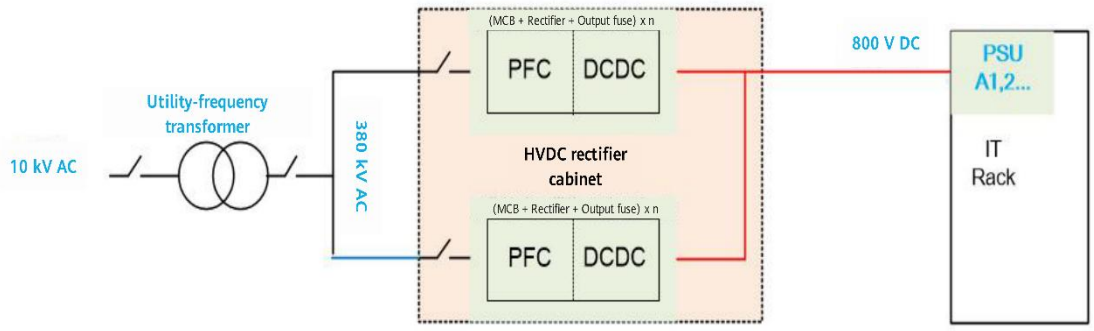


Figure 1 Traditional 800 V HVDC

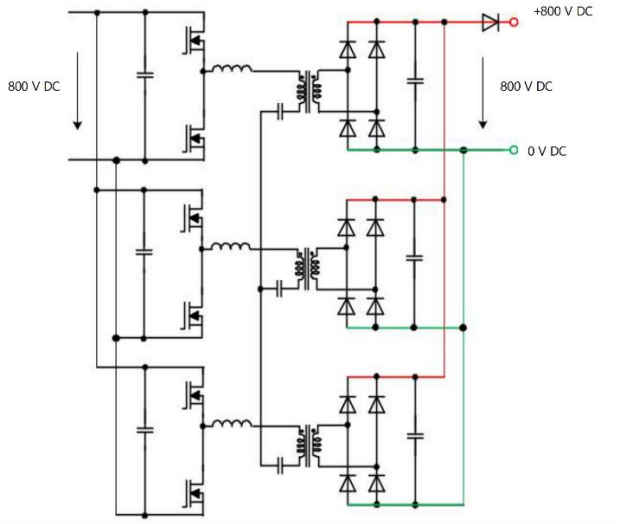


Figure 2 Circuit topology at the PFC level

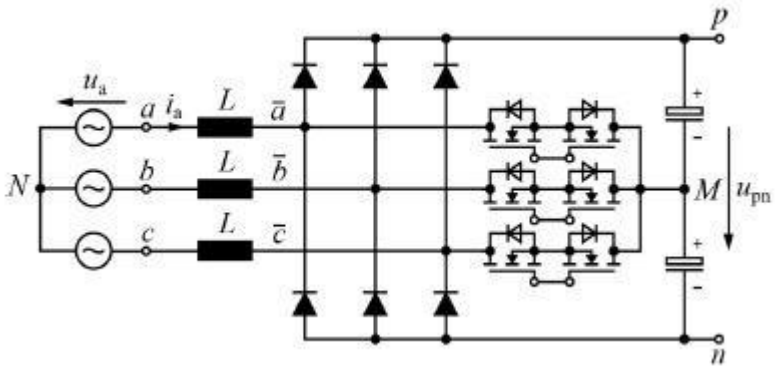


Figure 3 Circuit topology at the DC-DC level

2.3 DC UPS Overview

According to the national standards for HVDC, the DC output must be floating from the ground, which is safer and more reliable. The power factor must be 0.99 to reduce the demand on the power grid. In traditional HVDC, the module needs to contain two PFC levels and an isolated DC-DC level, which is complex. If a phase-shift transformer is used, the PFC level can be implemented by the transformer, and the PFC is not required for the rectifier module. In addition, the secondary side of the phase-shift transformer has multiple floating windings. The DC-DC level can be simplified to a non-isolated level through the floating windings on the secondary side. This greatly simplifies the implementation of the rectifier. This solution is the multi-winding phase-shift transformer solution (Panama or DC UPS solution). As shown in Figure 4, 10 kV AC (or 35 kV AC) is connected to a multi-winding phase-shift transformer, which steps down the voltage to a certain level. Then, the voltage is connected to a three-phase rectifier module, which contains diode uncontrolled rectification. The non-isolated DC-DC level outputs 800 V DC. All modules are connected in parallel and supply power to downstream loads through power distribution.

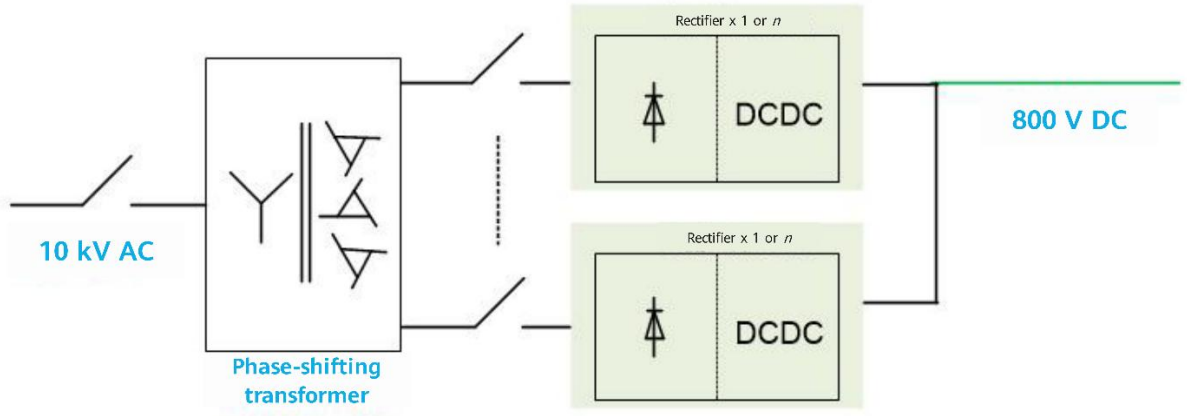


Figure 4 800 V solution with multi-winding phase-shift transformer (Panama)

2.4 SST Overview

The 800 V DC solutions mentioned above have a common point: using power frequency transformers. Both phase-shift transformers and multi-winding transformers are in the low frequency range (50 Hz), and use silicon steel sheets as the iron core and copper as the winding. With the increasing power of AIDC, the number of used transformers and the amount of used copper also increase. To reduce the size of the transformer and the amount of used copper, solid-state transformers (SSTs) can be used to directly convert medium-voltage AC to 800 V DC, as shown in Figure 5. After 10 kV AC is connected, it is divided into three single-phase systems. Each single-phase system consists of seven to nine modules connected in series (see Figure 6). Each module contains the PFC function and the DC-DC function with high-frequency isolation. The output voltage is 800 V DC, and the outputs of all modules are connected in parallel. Then, the power is distributed to loads.

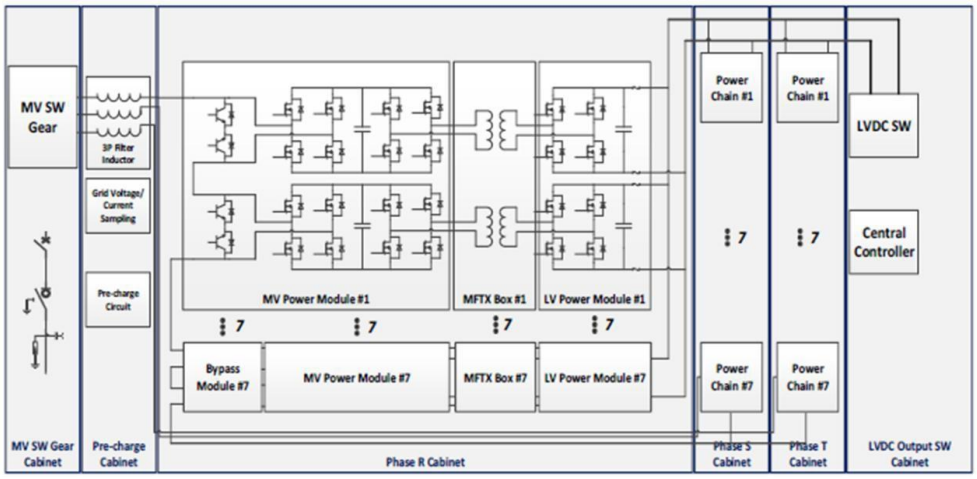


Figure 5 800 V DC system block diagram of the SST solution

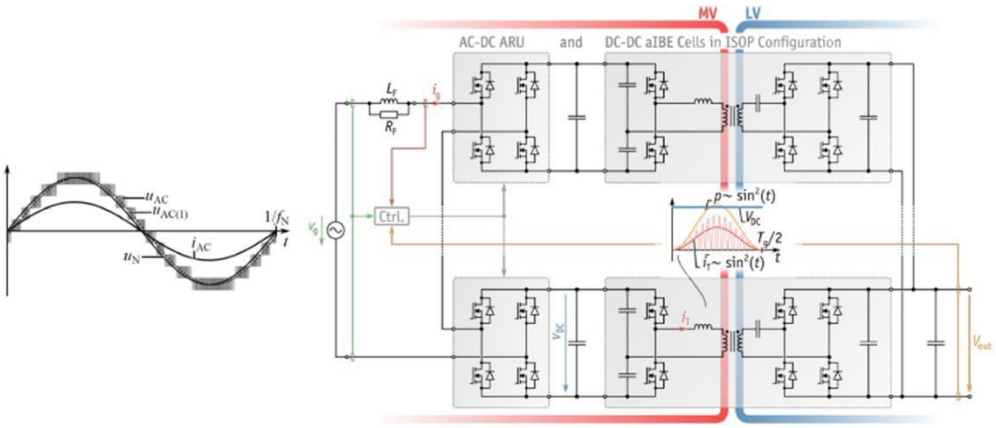


Figure 6 Block diagram of each single-phase system in the SST solution

In this solution, the transformer is operated at a high frequency (about 50 kHz), which greatly reduces the size of the transformer and the amount of used copper. The core uses a high-frequency magnetic conductive material, ferrite, which has low loss. Compared with a traditional transformer, the no-load core loss is much lower, and there is no excitation inrush current. The system efficiency can reach 98%.

This solution has the following limitations: 1. The series connection of modules is less resistant to power grid quality issues than traditional transformers. Although there are three reactors in the SST, the series connection of modules will directly add the power grid fluctuation to the module side when the power grid fluctuates abnormally, causing overvoltage on the module side. 2. Medium-voltage power supply to the rack poses challenges to O&M. According to medium-voltage operation specifications, the input needs to be turned off during maintenance. However, if a module breaks down and is maintained, the entire power supply system will break down, which has a great impact. In addition, O&M personnel need to be trained. 3. High-frequency high-voltage insulation. Compared with a traditional transformer, the SST transformer is very small, only as big as a fist. In such a small size, insulation between 10 kV and the low-voltage side is required, and solid insulation must be used. However, solid insulation greatly affects heat dissipation. In long-term cold and hot applications, ensuring that solid insulation does not fail or crack is a great challenge.

As more and more investment is made in SSTs both domestically and internationally, the preceding problems will be gradually overcome. However, this will take some time. Currently, SSTs are being tested in several IDC equipment rooms, and the effect is expected.

2.5 Sidecar Solution Overview

The 800 V SideCar solution essentially removes the AC/DC rectifier, energy storage, protection, and power distribution units from the IT computer rack, making them independent racks deployed side by side next to the GPU computing power rack. Inside the SideCar, the AC mains is converted into 800 V HVDC power, which is then sent to the computing power rack through short-distance high-voltage cables. Finally, a level-1 DC-DC converter inside the server steps down the voltage to low voltage (12 V/48 V/54 V) for the GPU core. This solution is not mutually exclusive with the 2.1 to 2.4 solutions; rather, it is a new distributed deployment mode. The main power supply links are as follows:

380 V AC mains → original centralized UPS (optional) → 800 V SideCar (three-phase AC → 800 V DC rectifier) → 800 V DC power cable → built-in DC-DC module in the IT rack → 54 V busbar → GPU server. This solution can retain the existing UPS power distribution facilities and does not require the upstream high-voltage power distribution in the equipment room to be reconstructed.

A standard 800 V SideCar power rack consists of the following five units:

(1) AC input unit

- Single or multiple 380 V AC inputs, which are connected through connectors.

(2) Three-phase AC-DC rectifier module (core power unit)

- Input: three-phase 380 V AC; output: stable 800 V DC
- Topology: All power supply topologies from 2.1 to 2.4 can be selected in principle, but the deployment convenience must be considered.
- Power of a single module: 30–100 kW
- Module efficiency ≥ 98%, power factor > 0.99.

(3) Nearby energy storage unit (BBU and supercapacitor, optional)

- BBUs are unlikely to be deployed in China due to safety reasons. Instead, lithium batteries or lead-acid batteries are used. However, it is widely recognized in the industry that DC/DC modules should be configured instead of directly connecting to the busbar.
- Supercapacitors are still controversial, mainly in terms of the placement position and the choice between supercapacitors and electrolytic capacitors.

(4) High-voltage DC power distribution and protection system

- 800 V DC circuit breaker, electronic fuse, precharge circuit, and anti-backfeed circuit.
- High-voltage insulation monitoring, leakage protection, and fast protection against overvoltage, overcurrent, and short circuits.
- The 800 V DC hot-swappable design allows for maintenance without powering off the system, ensuring personal safety.

(5) Busbar output unit

- The multi-channel independent 800 V DC output terminals are directly connected to adjacent IT racks through short-distance high-voltage cables, avoiding long-distance low-voltage and high-current busbars.

2.6 Comparison Conclusion

In the global market, OTT/Cloud, COLO, and equipment vendors have released the 800 V DC power supply planning, which can be summarized into two categories and five technical routes. One is the distributed power supply, which is deployed in the data hall near the IT equipment. It includes SideCar ± 400 V and SideCar 800 V DC. The other is the centralized power supply, which is deployed in the power distribution room or power distribution container. It includes DC UPS, HVDC, and SST. The specific leading parties and application scenarios are as follows:

1. The SideCar ± 400 V, led by OTT customers such as Meta and Google, is used in 100 kW or higher power racks. In this solution, the traditional OCP 48 V DC and lithium batteries are deployed in the SideCar power rack. The power rack is configured with a BBU lithium battery module by default. In addition, the power supply from the mains to the low-voltage side of the power distribution transformer remains unchanged, and the existing architecture is retained.

2. The 800 V DC power supply architecture promoted by NV globally enables the NVL576 and future generations of intelligent computing PowerShelf to be integrated into the SideCar power rack, instead of being installed inside or outside the IT rack. This architecture supports built-in batteries for power backup, replacing the existing UPS architecture. In addition, the architecture supports the power supply from the mains to the low-voltage side of the power distribution transformer and the UPS system, which remain unchanged with the existing architecture.

3. The DC UPS architecture represented by Alibaba uses constant voltage power supply in the DC system. Batteries are no longer directly connected to the busbar, and the voltage is developing from 270 V DC to 800 V DC.

4. The traditional HVDC power supply widely used by Internet enterprises in China is evolving from 240 V DC to 800 V DC.

5. The SST is widely promoted in the industry. It is a solution for reconstructing the power supply on the medium-voltage side. It is generally believed that SST is one of the development directions of the future 800 V DC power supply architecture.

Based on the current mainstream transformer capacity specifications and excluding the differences brought by the power supply architecture, this document describes the system architecture, efficiency, floor area, and cost of a power supply project with a single system capacity of 2.5 MW and IT output not exceeding 2.25 MW. The following assumptions are made for the floor area and cost analysis: One AIDC generates 40 MW IT power, 72 560 kW/R racks are deployed, the 4 DR power supply architecture is used, and no STS is configured.

2.6.1 Power Supply Architecture

The power supply and distribution system has two common architectures: 2N and DR, and there are also other architectures such as N+R and RR. The 2N system features high availability, simple structure, and easy O&M, but the construction cost and basic electricity fees are high. The DR system has medium availability, complexity, O&M difficulty, and basic electricity fees among the three systems. It also features low construction cost and small system running loss. However, the DR system requires special attention to load distribution and redundancy of physical locations of devices and cables during the planning and design phase of the data center. The N+R and RR systems have low construction costs, but their availability, maintenance convenience, and disaster resistance capabilities are relatively low. For the five DC power supply technologies, mainstream customers choose different power supply architectures to help them build highly available, green, and cost-effective AIDCs that are suitable for their own applications.

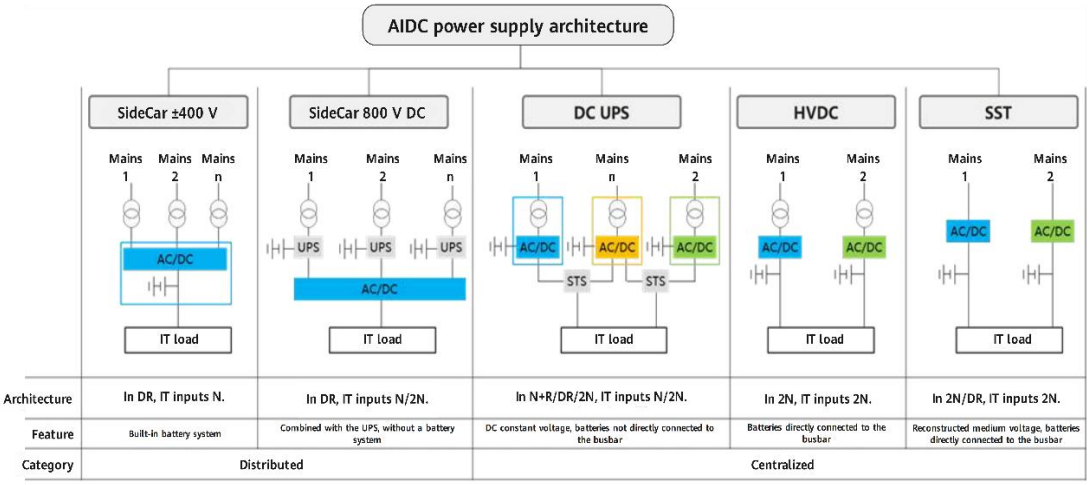
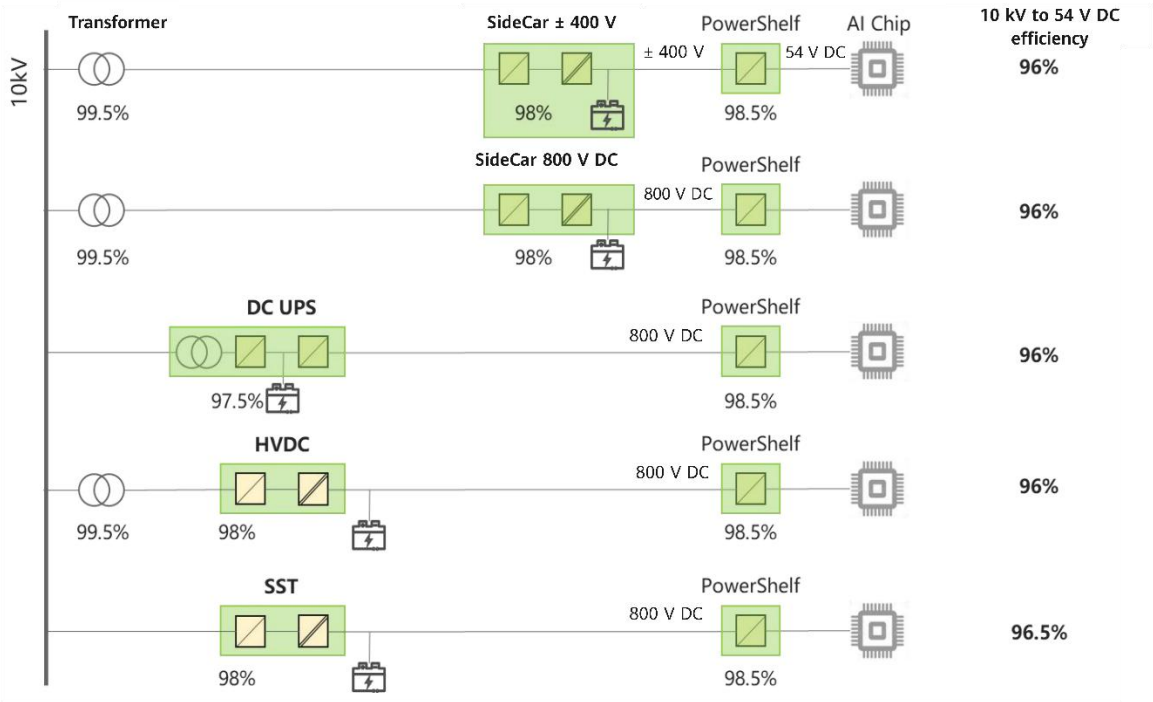


Figure 7

2.6.2 Power Supply Efficiency

Efficiency improvement is one of the core driving forces for DC power supply and high-voltage power supply. The link efficiency of the five DC power supply technologies varies. In terms of the link efficiency

from the 10 kV AC mains to the 54 V DC busbar in the rack: SST > DC UPS = SideCar ± 400 V = HVDC = SideCar 800 V DC.



2.6.3 Floor Area

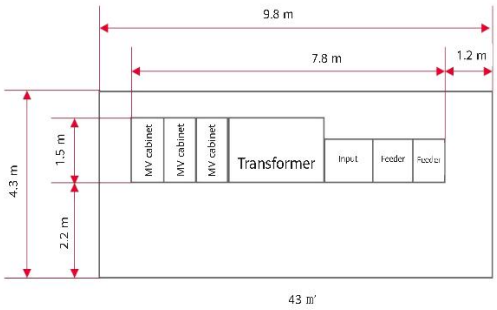
As the computing power of server chips increases, the average power of a single IT rack is evolving to 100 kW or even MW level. The ratio of the power supply and distribution space to the IT space is increasing, from 1:4 to 3:1. The IT space utilization (or the rack output ratio) is decreasing. Reducing the power supply and distribution floor area has become an urgent issue in the AIDC industry.

In terms of floor area: SideCar ± 400 V < SideCar 800 V DC < SST < DC UPS < HVDC.

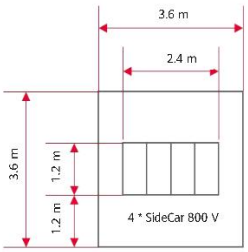
Category	DC Technology Route	Floor Area (m²)	Remarks
Distributed	SideCar ±400 V	1,266	24 sets of 2.5 MW transformer systems, 72 sets of SideCar ± 400 V with BBUs
	SideCar 800 V DC	1,626	24 sets of 2.5 MW transformer systems, 72 sets of SideCar 800 V DC, and external lithium batteries
Centralized	DC UPS	1,656	24 sets of 2.5 MW indoor DC UPSs and lithium batteries
	HVDC	1,920	24 sets of 2.5 MW HVDC systems and lithium batteries
	SST	1,632	24 sets of 2.5 MW SSTs and lithium batteries

Note: The following figures show the device layout of a single system.

SideCar ±400 V

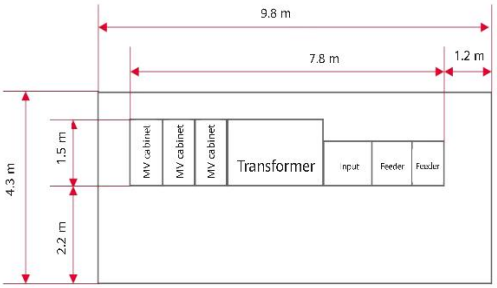


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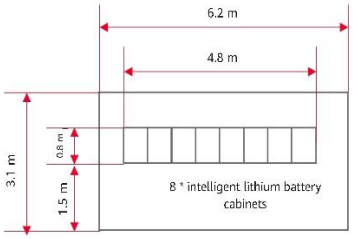


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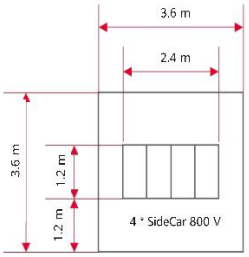
SideCar 800 V



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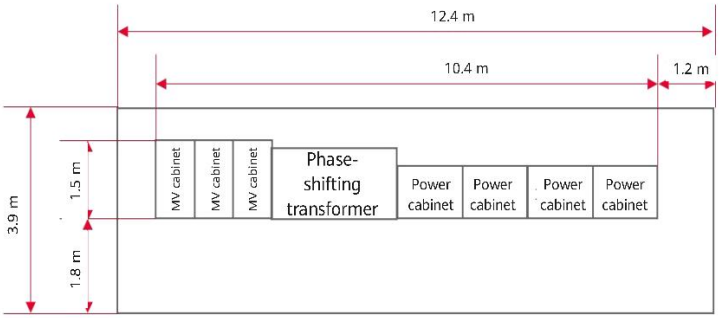


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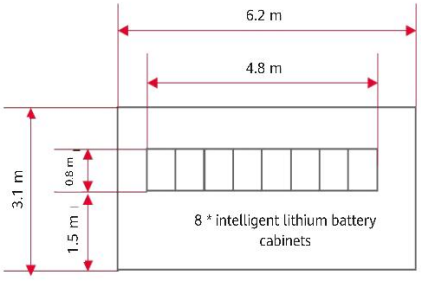


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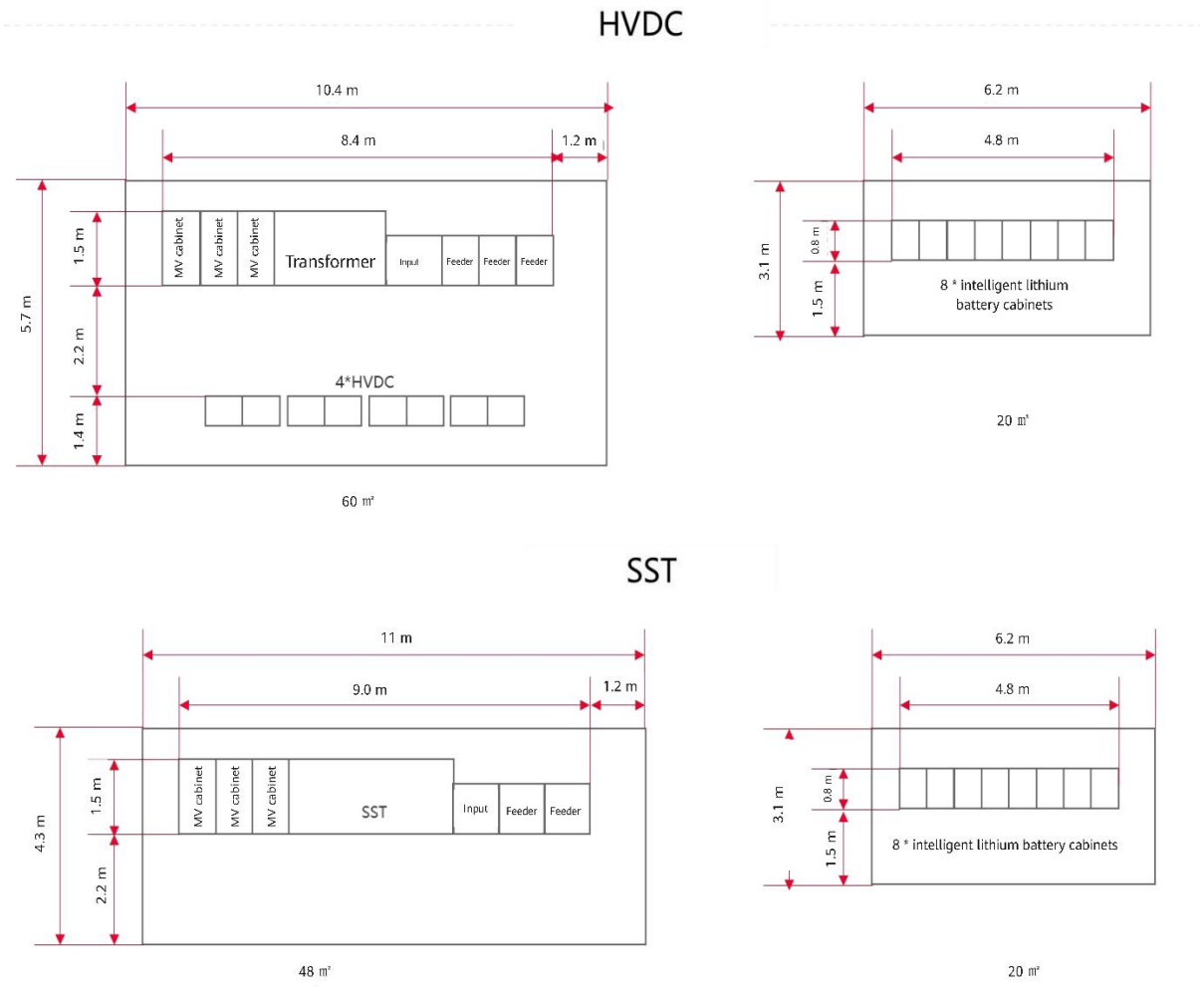
DC UPS



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20 ㎡



2.6.4 Cost

There are five technical routes and diversified architectures. In addition, most devices are still under development. Therefore, the cost of the devices is not yet available. The following analysis provides only a reference value.

In terms of power supply cost: DC UPS < HVDC < SideCar 800 V DC < SideCar ±400 V < SST.

Analysis Item	Quantity (Set)	Distributed		Centralized		
		SideCar ±400 V	SideCar 800 V DC	DC UPS	HVDC	SST
10 kV medium-voltage rack	72	360	360	360	360	360
Transformer	24	720	720		720	
Low-voltage power distribution	24	1,056	1,056		936	840

Analysis Item	Quantity (Set)	Distributed		Centralized		
		SideCar ±400 V	SideCar 800 V DC	DC UPS	HVDC	SST
SideCar ±400 V	72	8,280				
SideCar 800 V	72		3,816			
DC UPS	24			3,192		
HVDC	96				2,208	
SST	24					7,200
Lithium battery and cable	24		3,792	3,792	3,792	3,792
Intelligent busway/cable		1,368	1,368	605	605	
Subtotal (CYN10,000)		11,784	1,112	7,949	8,621	12,192
Cost factor (A)		0.97 A	0.91 A	0.65 A	0.71 A	A

In conclusion, the five DC power supply technologies are deeply integrated in terms of scenarios and architecture. In the distributed power supply, the SideCar 800 V DC solution has a lower cost, and the batteries can be external batteries or be compatible with the existing AIDC AC UPS power supply. This is a feasible solution with further cost reduction potential. The SideCar ±400 V solution requires less floor area, but lithium batteries need to be installed in the equipment room, which poses high requirements on O&M. In the centralized power supply, the DC UPS solution has obvious advantages over the HVDC solution and is the optimal solution for centralized DC power supply. The SST solution has advantages in efficiency and floor area, and its cost can be further reduced in the future.

3 800 V Data Hall Building Design Architecture

As the AI computing power industry rapidly expands, the power density of a single rack in intelligent computing centers has exceeded 200 kW and is evolving toward the MW level. The traditional 220/380 V AC and 240/336 V low-voltage DC power supply architectures have encountered systematic bottlenecks in terms of transmission loss, space utilization, dynamic load adaptation, and scalability. 800 V HVDC is becoming the mainstream innovation direction for the power supply and distribution system of next-generation high-density computing power equipment room buildings, with its core advantages such as lower transmission current, fewer power conversion levels, modular prefabricated deployment, and renewable energy grid connection.

This section describes the pain points of the traditional power supply architecture in high-density computing data halls based on engineering practices, and establishes the design principles of 800 V DC data hall buildings. It also compares and analyzes the dual-winding power frequency transformer, multi-winding phase-shifting transformer, and SST—three 800 V DC implementation paths. It systematically breaks down the power supply architectures of equipment rooms in 2N, DR, and RR redundancy topologies under centralized and distributed systems, and conducts a quantitative comparison in terms of conversion efficiency, space occupation, construction cost, and O&M difficulty. It also analyzes the existing technical difficulties in implementing 800 V DC power supply for equipment rooms and proposes a standard evolution roadmap. This provides an engineering reference for the

overall power supply and distribution design of the equipment room building of an MW-level intelligent computing center.

3.1 Background and Current Situation

The explosive growth of computing power density in intelligent computing scenarios poses great challenges to the design of data hall infrastructure.

First, the current overload loss in the traditional low-voltage architecture is out of control. When a single 54 V DC busbar is used for power supply, the busbar current of a 1 MW rack is nearly 20,000 A, and the copper bar consumables of a single rack exceed 200 kg. The problems such as cable heating, voltage drop, and excessive load cannot be solved. In addition, the 220/380 V AC system requires multi-level AC/DC and DC/DC conversion, and the power supply efficiency of the entire link is less than 85%. The annual electricity loss of a large computing campus can reach tens of millions of kWh.

Second, the supply and demand of physical space in the data hall are imbalanced. Traditional industrial-frequency transformers and UPS power distribution systems are large in size. In MW-level computing scenarios, the equipment room area shrinks sharply, and the proportion of the power transformation and distribution room area keeps increasing. The effective deployment area of the equipment room building is occupied by power distribution devices, and the floor layout, height, and load design of the data hall building are facing reconstruction pressure.

Third, the dynamic computing load affects the power supply stability. AI clusters have instantaneous peak loads and tidal load fluctuations. Traditional industrial-frequency transformers respond slowly, and multi-level conversion links amplify voltage disturbances, which may cause instantaneous frequency reduction and breakdown of GPU clusters. In addition, the energy storage access link of the traditional UPS AC architecture is complex, and it is difficult to connect renewable energy such as PV and wind power to the grid.

The mainstream 220/380 V AC and 240/336 V DC power supply systems in the industry cannot meet the long-term development requirements of MW-level high-density computing power. Against this backdrop, the 800 V HVDC power supply architecture has become the next-generation energy foundation solution for data halls, which is promoted by the industry. This architecture increases the power distribution voltage, reduces the transmission current, simplifies the power conversion level, and adapts to modular prefabricated data halls. Many organizations in China have started pilot planning and research on 800 V DC applications.

3.2 Core Benefits of the 800 V DC Data Hall Architecture Reconfiguration

Superb energy efficiency: The power conversion is simplified to two levels: medium-voltage AC → 800 V DC → DC-DC on the rack side. The redundant inverter of the UPS is eliminated, and the end-to-end power supply efficiency is improved to 92% to 98%. A 30 MW intelligent computing center saves more than 10 million kWh of electricity per year, and the power usage effectiveness (PUE) is reduced by 0.1 to 0.25.

Space saving: The transmission current is greatly reduced, and the cross-sectional area of the busbar and cables is reduced by more than 45%. The size of the SST is only 1/2 to 1/3 of that of the industrial-frequency transformer, and the area of the IT power transformation and distribution room is reduced by more than 40% for the same computing power scale.

Dynamic load adaptation: SiC high-frequency power electronics components can respond in microseconds, suppressing the instantaneous current impact of GPUs and improving the busbar voltage stability. The DC busbar is naturally compatible with lithium batteries, PV, and wind power for direct grid connection. The microgrid scheduling and cold start functions are supported by default.

Modular and flexible construction: The 800 V conversion unit and power distribution unit (PDU) support factory prefabrication and modular stacking. The plug-and-play design for phased capacity expansion adapts to the batch deployment mode of AI equipment rooms, reducing the initial investment in fixed assets.

3.3 Design Principles of 800 V DC Power Supply Data Hall Buildings

Based on the data hall engineering framework, four design principles are established for 800 V data hall buildings in scenarios with high-density computing power of 200 kW to 1 MW per rack.

3.3.1 High Reliability and Full-Link Fault Tolerance

The power supply system of the equipment room building must meet the A-level fault-tolerant data center standards to eliminate single points of failure. First, the conversion devices are deployed in modular N + *X* redundancy mode (*X* ≥ 1), so that the failure of a single module does not affect the output of the entire system. Second, the power supply architecture uses a redundancy isolation design without single points of failure. In this way, only the faulty section is isolated in the case of a local short circuit, ensuring continuous power supply to computing power racks. Third, the multi-level DC arc, overcurrent, and overvoltage protection is implemented. Considering that the 800 V DC power supply has no zero-crossing point and arcs are difficult to extinguish, ultra-fast solid-state circuit breakers (SSCBs) and pre-charging loops are configured. Fourth, two independent medium-voltage mains are connected, and energy storage batteries are used as backup power supplies to ensure zero power interruption in the case of power grid fluctuation or power outage.

3.3.2 Collaborative Evolution of Ultimate Efficiency and High Dynamic Response

Hierarchical management and control of full-link efficiency: The target efficiency of the medium-voltage conversion stage must be greater than or equal to 97%, the transmission loss of the 800 V DC busbar in the equipment room must be less than 0.8%, and the DC-DC conversion efficiency on the rack side must be greater than or equal to 97%. In terms of dynamic response, the voltage regulation response time of the 800 V conversion unit must be less than 100 μs, which can cover the millisecond-level peak load fluctuation of GPUs. The unit must maintain high efficiency when the load is between 20% and 100% to avoid a sharp drop in energy efficiency in low-load conditions.

3.3.3 Highly flexible prefabricated modular deployment

The equipment room building can use the architecture of pre-fab. power module + liquid-cooled computing module. All 800 V rectifiers, power distribution units, and energy storage units are prefabricated and commissioned in the factory. Only pipeline interconnection is required onsite. The delivery period is shortened by 50%. The capacity is flexibly adapted to as follows: 250 kW, 500 kW, and 1 MW racks can be deployed together. In the future, the civil work structure of the data hall does not need to be reconstructed for capacity expansion. Only standard 800 V power modules need to be added and stacked to connect to the busway. Standard power distribution compartments are reserved in the data hall building floor, allowing for flexible switching between centralized and distributed architectures.

3.3.4 Adaptation Principles of MW-Level End Power Distribution Units

For the MW-level power density of a single rack, the end power distribution system of the equipment room is reconstructed. The large-sized AC PSUs built in traditional racks are removed, and the SideCar power architecture is used. The 800 V-to-low-voltage DC-DC unit is placed in the power rack on the side of the rack, freeing up the space inside the rack for deploying computing power.

The specifications of the end busway cabling and connectors are optimized. Customized copper bars with high current-carrying capacity and low impedance are used to meet the continuous power supply requirements of 1 MW racks with nearly 1300 A current. In addition, independent DC branch protection is configured. If a single rack is faulty, other racks on the same busway section can still run properly. This meets the fault isolation requirements in high-density scenarios and supports the implementation of next-generation ultra-high-density computing power racks.

3.4 Power Supply Architecture Design of the Data Hall Building

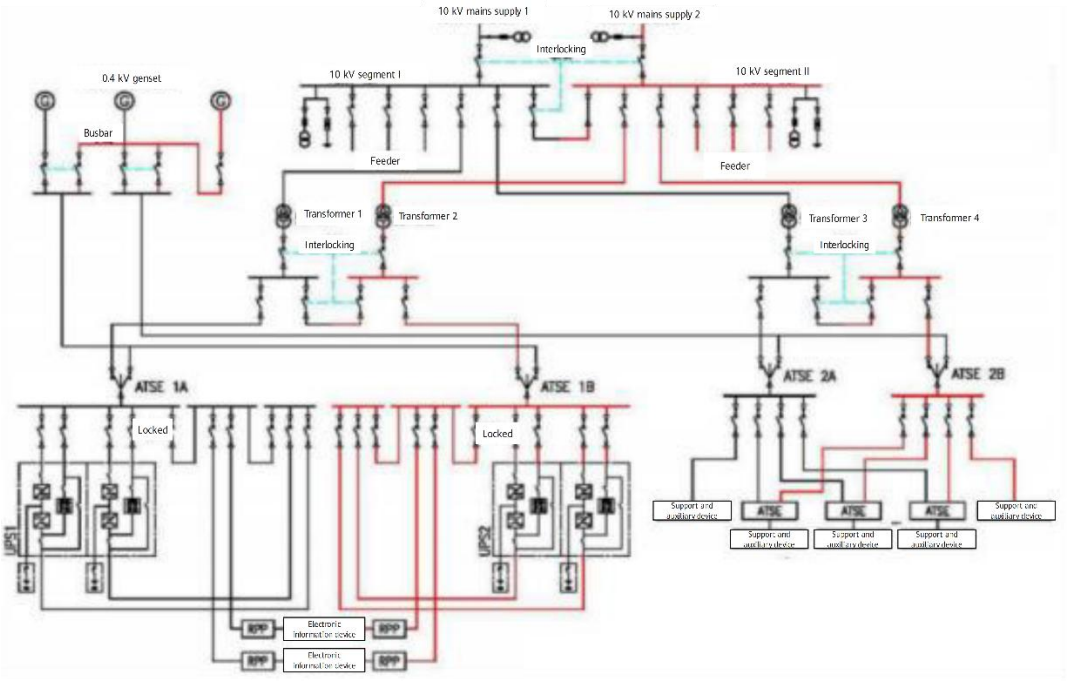
Under the AIDC 800 V DC power supply technology system, the three types of electrical architectures that comply with the GB50174-2017 A-level standard and have no single point of failure are still 2N redundancy, distribution redundancy (DR), and repetition redundancy (RR). These three types of highly reliable topologies have their own advantages and disadvantages in terms of reliability, cost-effectiveness, power adaptability, and O&M complexity, and can be used in different computing power service scenarios. The following compares the three types of topologies in terms of topology principles, reliability, lifecycle cost, and O&M convenience.

3.4.1 800 V Power Supply Architecture of the Data Hall Building

3.4.1.1 2N Architecture: A Classic Fault-Tolerant and Highly Reliable Solution

A. Topology principle

The 2N architecture consists of two completely independent power supply and distribution units. The capacity of a single power supply and distribution unit can meet the 100% full-load power supply requirements of the equipment room. From the perspective of access links, this architecture requires two independent mains power supplies to be introduced. After that, medium-voltage power distribution racks, transformers, HVDC/UPSs, and end racks are configured. Two completely independent feeder loops are used to connect to the dual redundant PDUs in the rack, supplying power to the dual power modules of the server. There is no common series node between the two units, ensuring complete electrical isolation.



Typical topology of the 2N architecture

Normal operation logic: Each of the two units carries less than 50% of the total load, operating at a lower load rate to share the normal power supply pressure.

Failover logic: When any unit is faulty or under planned maintenance, the other unit can take over all loads in the data center without interruption or perception. The switchover process is free of interruption and voltage fluctuation.

B. Reliability

The 2N architecture is the electrical topology solution with the highest reliability level in the industry. All power transformation and distribution devices at each level are dual-powered. The two independent units are clearly isolated from each other. The power supply lines of the two units are routed along different paths and are not affected by the same fault. This ensures that the fault locating and troubleshooting of one unit will not affect the other unit, and the fault impact scope is controllable. The overall power supply system has high reliability and continuity.

The system availability can reach 99.999%, and the theoretical annual downtime is less than 5.26 minutes. This architecture is applicable to high-priority scenarios that require uninterrupted services, such as core computing services for intelligent computing training and inference, and core financial computing services.

C. Total cost of ownership (TCO) over the lifecycle

The initial construction cost of the 2N architecture is the highest among the three architectures because all power transformation and distribution devices are configured in 1+1 redundancy mode. Compared with the other two architectures, the device utilization rate of the 2N architecture can only reach 40% to 50%, and redundant resources are idle for a long time. In addition, the power distribution construction cost per unit of computing power is the highest. During the operation phase, the basic inspection and maintenance of idle devices still need to be performed, which generates additional O&M costs. Based on the initial investment and long-term operation costs, the TCO of the 2N architecture is the highest among the three architectures.

D. Construction and O&M

The 2N architecture has the best O&M convenience among the three architectures. The design logic of the two independent busbars is clear, and the electrical boundary between the faulty device and the running unit is clear. O&M personnel can perform isolation and maintenance, device replacement, or capacity expansion on any unit without interrupting the power supply to loads. In addition, this architecture is highly compatible with the traditional technical habits of O&M personnel in China. The fault locating duration is significantly shorter than that of other architectures, and the O&M difficulty is significantly lower than that of the other two architectures.

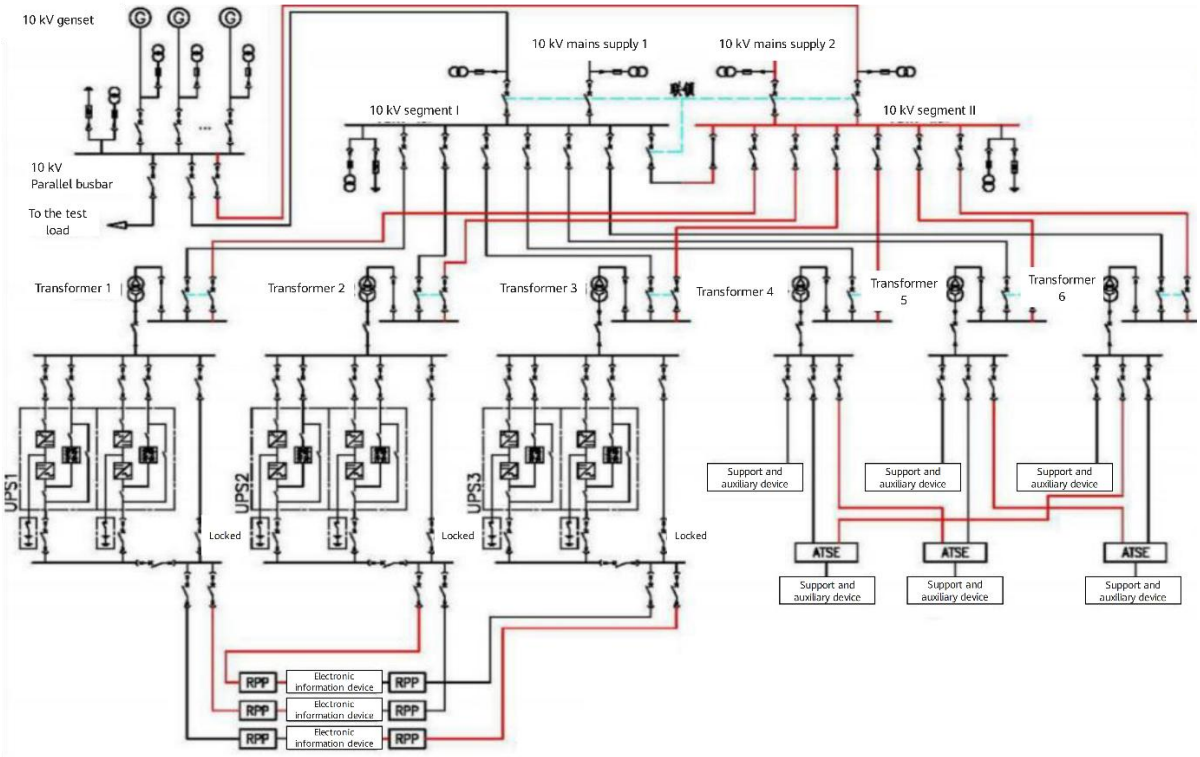
3.4.1.2 DR Architecture: A Cost-Effective Large-Scale Solution

A. Topology principles

The DR system consists of N + 1 (N ≥ 2) power supply and distribution units with the same configuration. These N + 1 units operate simultaneously and function as backup for each other, forming a hand-in-hand power supply mode. According to the typical redundancy level of the DR architecture, the 3 DR (2 + 1 redundancy) or 4 DR (3 + 1 redundancy) configuration is usually adopted. Each power supply and distribution unit can include an independent medium-voltage input switch, transformer, and HVDC/UPS host. Two completely independent feeder loops are distributed from the end rack to the dual-redundant PDUs in the rack, supplying power to the dual power modules of the server. When any

unit fails, the remaining units can collectively take over its load, ensuring continuous power supply without additional switching operations.

Compared with the 2N architecture, the DR architecture provides unit-level independent redundancy in (N + 1) mode, with loads distributed across units. When any unit fails, the remaining units only share the load of the failed unit equally. There is no single point of failure in the entire topology. Redundancy is achieved through distributed load sharing among units. This architecture retains the independent isolation of multiple units and avoids the problem of a large number of redundant resources in the 2N architecture being idle for a long time. In addition, the DR architecture requires that loads be evenly distributed among multiple power supply and distribution units; otherwise, the power capacity cannot be fully utilized.



Typical topology of the 3 DR architecture

Normal operation logic: Taking the standard configuration of the 3 DR (2 + 1 redundancy) or 4 DR (3 + 1 redundancy) power supply and distribution units as an example. Under normal conditions, the load rate of each unit is 66% or below 75%. All units operate online synchronously, and loads are evenly distributed in the ring network.

Failover logic: Taking the standard configuration of the 3 DR (2 + 1 redundancy) or 4 DR (3 + 1 redundancy) power supply and distribution units as an example, when any unit fails, its corresponding load is automatically transferred to the adjacent two or three power supply and distribution units through the dual power supplies at the end. Each adjacent unit takes over approximately 33% or 25% of the additional load. When any unit experiences a device failure or is under planned maintenance, the other two or three units can take over all loads in the equipment room without interruption or awareness. During the failover process, there is zero interruption and zero voltage fluctuation.

B. Reliability

Compared with the 2N system, the DR architecture has certain limitations in fault tolerance: within the N + 1 power supply group, only a single power supply and distribution unit failure can be tolerated. Although there is no single point of failure, the redundancy level is lower than that of the 2N system. In addition, in the DR architecture, the power load is supplied to each unit in a cross manner. During fault locating, the impact scope of the faulty unit needs to be confirmed, which poses higher requirements on the professional capabilities of O&M personnel. There is also a potential risk that the impact scope of the fault may be expanded. However, as long as daily load management and control are properly performed to avoid load imbalance, the system can maintain stable and reliable operation, fully meeting the requirements for reliable power supply.

The system availability of this architecture can reach 99.99%, and the theoretical annual downtime is no more than 52.56 minutes, which is sufficient to meet the requirements of high-priority core computing services such as intelligent computing key training and inference.

C. Full-lifecycle cost

The DR architecture uses the ring mutual aid networking logic. The standard configuration is N + 1 power supply and distribution units with identical specifications. These units collectively form a capacity backup, creating a hand-in-hand ring power distribution network.

The core advantage of the DR architecture is the precise balance between reliability and cost-effectiveness. Through the distributed backup design, the redundancy resource is optimized from "full replication" to "on-demand mutual aid". Under normal operating conditions, the load rate is increased from 2N architecture's 50% to 66% (3 DR) or 75% (4 DR), and the initial construction cost is reduced by 20% to 30% compared with the 2N architecture. From the perspective of long-term energy consumption, the normal load rate of devices is increased by 16% (3 DR) or 25% (3 DR), which meets the cost control requirements of ultra-large AIDC campuses.

D. Construction and O&M

The construction and O&M of the DR architecture are significantly more difficult than those of the 2N architecture. The core pain points are summarized as follows:

First, the electrical pipelines are crisscrossed during onsite construction, the routing of the ring network is complex, and the power distribution lines are interconnected. This poses higher requirements on the technical capabilities of construction and O&M personnel.

Second, cross-unit fault locating is required. Because the load is distributed across the ring network, after a fault occurs, the running status and cable connections of each unit need to be checked one by one to locate the specific fault point. This poses higher requirements on the technical proficiency of O&M personnel.

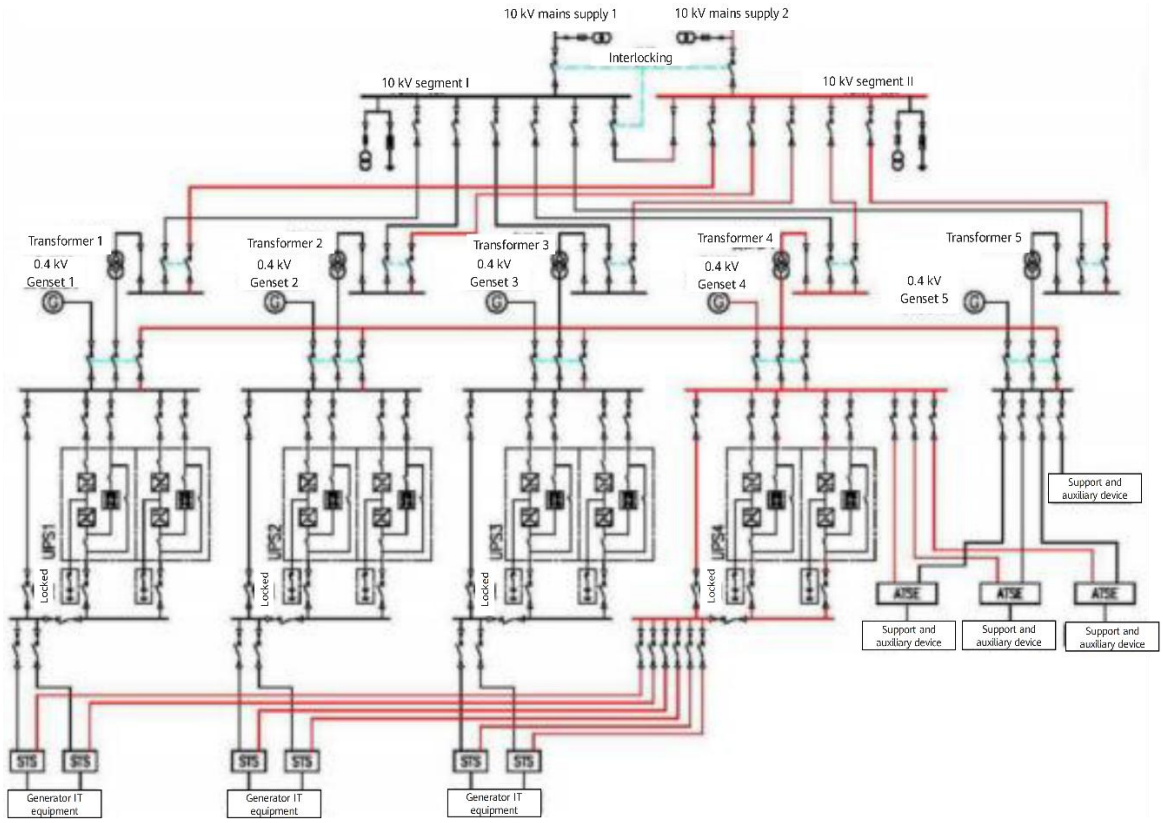
Third, planned maintenance requires adjusting the load distribution of the entire ring network. The operation process is relatively complex. If the load transfer is not properly configured, additional power supply risks may be caused.

3.4.1.3 RR Architecture

A. Topology principles

The RR architecture uses the centralized backup design logic. It consists of multiple active units and one or more common standby units. The capacity of the active units is matched with the grouped IT loads and supplies power in normal conditions. The common standby units do not carry loads in normal conditions and always remain in the hot standby state.

On the HVDC/UPS output side, the RR architecture uses the STS to switch the active and standby power supplies for each IT load group within 10 ms, without interrupting the power supply to IT equipment. On the UPS input side, the RR architecture uses the ATS to switch the active and standby power supplies for each UPS load group within 100 ms, without interrupting the power supply to IT equipment.



Typical topology of the RR architecture

Normal operation logic: All working units operate at full load, and the load rate can reach over 90%. The standby units remain in the hot standby state.

Failover logic: When any working unit is faulty, the transfer switch switches the active and standby power supplies without interrupting the power supply to IT equipment. The loads of the faulty unit are powered by the common standby units, ensuring redundancy in case of faults.

B. Reliability

The N + 1 redundancy RR power supply and distribution architecture has the following weaknesses in terms of fault tolerance: 1. The common standby unit is the only redundancy node of the entire system. If the standby unit in the hot standby state is faulty, the fault is difficult to be detected. If the active working unit is faulty at the same time, the redundancy protection capability will be lost. 2. Power supply fluctuation risks during the switchover. Although the switchover time of the STS is within 10 ms, some high-precision AI chips are extremely sensitive to power dips, which may trigger the chip protection mechanism and cause computing power frequency reduction or service packet loss.

The system availability of this architecture can reach 99.9%, and the theoretical annual downtime is less than 8.76 hours. To improve the power supply reliability of this architecture, the N + 2 redundancy mode can be used to enhance the configuration.

C. TCO throughout the lifecycle

The RR power supply and distribution architecture enables global reuse of redundant resources. Only one set of common standby units is configured to provide redundancy assurance for all active units. In normal operating conditions, the load rate of power equipment can reach more than 90%. However, the optimal efficiency range of power electronic equipment such as UPS or HVDC is around 50% load rate, and the energy consumption level is not excellent. Compared with the 2N architecture, the RR architecture adds a large number of STSs and ATSs, making the initial construction cost not lower than that of the 2N architecture. If the N + 2 multiple redundancy mode is used to enhance the configuration, the initial construction cost will be significantly higher than that of the 2N architecture.

D. Construction and O&M

The O&M complexity of the RR power supply and distribution architecture is the highest among the three architectures. First, the O&M verification during the switchover is difficult. The STS may fail in the AI impact load scenario, requiring a monthly switchover test. The test process is complex and involves many risk points. Second, the O&M pressure on standby units is high. The common standby units are in a "no-load hot standby" state for a long time, and the health status of power modules and batteries needs to be continuously monitored. O&M personnel must have extensive O&M experience, and the technical threshold is significantly higher than that of the other two architectures.

3.4.1.4 Comparison of Core Indicators

Based on the core features of AIDC, such as high power density, high reliability requirements, and large-scale deployment, the key indicators of the three architectures are compared as follows.

Dimension	2N Architecture	DR Architecture (4 DR, 3 + 1 Standard Configuration)	RR Architecture (3 + 1 Standard Configuration)
Power supply and distribution system reliability	2N fault tolerance	N + 1 DR	N + 1 RR
System availability	≥ 99.999%	≥ 99.99%	≥ 99.9%
Single point of failure (SPOF)	None	None	None
Rated load rate under normal conditions	To 50%	To 75%	To 90% (primary unit)
IT power supply and distribution investment cost	Baseline 100%	Approximately 75% to 80%	About 100%
Failover time	0 ms (naturally supported by the dual power system)	0 ms (naturally supported by the multi-power system)	< 10 ms (STS static switching) < 100 ms (ATS mechanical switching)

Dimension	2N Architecture	DR Architecture (4 DR, 3 + 1 Standard Configuration)	RR Architecture (3 + 1 Standard Configuration)
Impact scope of a SPOF	There is no global single point. A single fault does not affect the power supply to loads.	There is no global single point. A single fault only increases the load rate of the adjacent unit.	The standby unit is a global single point. Once the standby unit fails, the entire system loses redundancy.
O&M complexity	Low. The fault boundary is clear, and the device isolation operation is simple.	Medium. After a fault occurs, the overload risk needs to be continuously monitored during load transfer.	High. The switchover logic is complex, and the standby unit needs to be tested periodically.
Capacity expansion flexibility	Poor. Two complete power distribution units need to be added during capacity expansion.	Medium. Power distribution units can be added one by one, and load groups can be adjusted synchronously.	Excellent. Only working units need to be added, and the standby system can be reused globally.

3.4.1.5 Architecture Advantages and Disadvantages

A. 2N architecture: preferred for core computing power clusters

Core advantages: 1. The reliability is the best. Two independent systems on the entire link eliminate the SPOF, and can cope with multiple exceptions, such as mains outage, transformer failure, and maintenance of a single UPS. The system can take over services without interruption without relying on dual power supply switchover. The switchover does not trigger the protection mechanism of high-end AI chips. In addition, the fault boundary is clear and O&M is simple. This architecture is applicable to core computing power scenarios that have strict requirements on service continuity and reliability, such as core computing power services for intelligent computing training and inference, and core financial computing power services that require uninterrupted services. 2. The architecture has the best O&M and compliance. The architecture logic is simple, the fault boundary is clear, the skill requirements for O&M personnel are low, and it fully complies with the A-level requirements of GB50174-2017. The acceptance standards of housing and construction authorities across regions are unified, and there is no compliance risk.

Core disadvantages: 1. The initial investment cost is high, and more redundant resources are required, which is not cost-effective for ultra-large AIDC campuses. The number of power supply and distribution devices and cables is doubled, and the power distribution cost per unit of computing power is 25% to 30% higher than that of the DR architecture. 2. The space occupation is large. Two complete power distribution devices occupy a large amount of space in the power room. In first-tier cities with limited land resources, the deployment space of computing power racks will be directly occupied, reducing the computing power output per unit area.

B. DR architecture: cost-effective solution for ultra-large AIDC

Core advantages: 1. The balance between reliability and cost is the best. While meeting the A-level requirement of no single point of failure, the load rate of power supply devices in normal operating conditions increases from 50% in the 2N architecture to 66% in the 3 DR architecture or 75% in the 4 DR architecture. The investment cost per unit of computing power is reduced by 20% to 25% compared

with the 2N architecture. In addition, the utilization rate of space is improved by more than 30%, making it highly suitable for large-scale deployment in ultra-large AIDC campuses with tens of thousands of racks. 2. There is no interruption during fault switchover. Unlike the RR architecture, the DR architecture uses dual direct connections to loads at the end. When a fault occurs, the loads are naturally transferred without an STS switchover, preventing transient power supply interruption and adapting to the sensitivity of AI chips to power supply dips. 3. The scalability is better than that of the 2N architecture. Power distribution units can be added in batches according to the construction pace of computing clusters, eliminating the need for a one-time investment in a full set of redundant devices. This matches the construction period of gradually launching AI services, reducing the initial capital pressure.

Core disadvantages: 1. The fault tolerance capability has a clear boundary. Only one power distribution unit can be tolerated. If two adjacent units fail simultaneously (for example, a secondary fault in the adjacent system), the loads will be directly powered off. Additionally, after a single unit fails, the load rate of the adjacent unit increases from 66% (3 DR) or 75% (4 DR) to 100%. If this coincides with the peak of AI loads, overload protection may trip, causing secondary faults. 2. The end power distribution design is complex. The hand-in-hand networking requires that each group of loads be connected to two power distribution units. The cables and busways are crisscrossed, making construction and O&M difficult. In high power density scenarios, the routing of high-current cables and temperature rise control become significantly more challenging. 3. The standards and specifications are not unified. The current version of the national standards does not provide specific design details for the DR architecture. Acceptance criteria vary across different design institutes and regions, and some projects require additional fault tolerance verification, increasing uncertainties.

C. RR backup redundancy architecture: applicable to non-core scenarios

Core advantages: 1. The device utilization is maximized. The reuse mode of the common standby unit enables the active unit to operate at a high load rate of over 90% under normal conditions, reducing the number and capacity of core devices such as transformers and UPSs. However, compared with the 2N architecture, the RR architecture requires a large number of STSs and ATSs, which increases the initial construction cost, making it not lower than that of the 2N architecture. 2. the scalability is the most flexible. New computing clusters only require supporting working units, and the standby system can be reused globally. This is ideal for inference AIDCs, edge compute nodes, and test equipment rooms that are constructed in batches and gradually put into operation.

Core disadvantages: 1. The fault tolerance level is the lowest. It is difficult to accurately detect faults in the common backup power supply unit (PSU) during the "non-load hot standby" state, which increases power supply risks. The backup unit is the only redundant node in the entire system. If the backup unit itself fails, all working units will lose their backup. The impact scope of a single fault is far greater than that of the 2N and DR architectures, which does not meet the high reliability requirements of core training services. 2. Poor adaptability in high-power scenarios. The AI load has an instantaneous surge current of 1.5 times. The STS is prone to misoperations or component damage in high-current and high-surge scenarios. Currently, the maturity of high-current STSs at the hundreds of kilowatts level in China is insufficient, which restricts the application of the RR architecture in high-density AIDCs. 3. Voltage sags occur during the switching process. Although the switching time is less than 10 ms, some high-precision AI chips and storage devices may still experience issues such as computing power frequency reduction and data packet loss, which cannot meet the stringent requirements of training services.

3.4.2 Centralized and Distributed 800 V DC Power Supply Solutions

Core features of the centralized architecture: A centralized power transformation and distribution room is set up in the data hall building. All SST/industrial frequency conversion devices are centrally deployed on each floor or the entire floor, and power supply devices are managed in a highly centralized manner. The centralized 800 V DC power supply devices uniformly distribute 800 V DC power supply lines in a radial layout to the IT data hall, and the end DC-DC server power supply unit is configured inside the data hall.

Core features of the distributed architecture: Small modular SST/800 V rectifier units are distributed at the edge of each floor of the IT data hall and at the head of each rack row. Medium-voltage/low-voltage AC power is introduced into the data hall, and 800 V DC power is generated locally to meet the power demands of MW-level high-density racks.

The redundancy topologies corresponding to the centralized and distributed architectures can also be classified into three types: distributed 2N, DR, and distributed RR. The underlying redundancy logic is consistent with that of the centralized architecture. The difference lies in whether the 800 V DC conversion units are distributed inside the data hall modules and whether the power transformation and distribution room of the data hall building is configured only with medium-voltage power distribution or conventional power transformation and distribution.

Core advantages of the distributed architecture:

No need for large power transformation and distribution rooms. The entire floor area of the equipment room building can be used to deploy IT computing power racks, thereby increasing the computing power output per unit area.

Independent power supply by module. A fault in a single module does not affect the computing power operation on other floors, reducing the scope of fault impact.

High flexibility in phased deployment. To expand the computing power of a single floor, only the distributed power supply modules on the corresponding floor need to be added, without the need to modify the central power distribution system of the main building.

Disadvantages of the distributed architecture:

Power supply devices are scattered in data halls on each floor, prolonging the O&M inspection route. Power distribution devices on each floor occupy a small number of rack positions in the IT data hall, slightly reducing the computing power deployment per server.

Quantitative comparison of key indicators between centralized and distributed architectures

Evaluation Indicator	Centralized 800 V Architecture	Distributed 800 V Architecture
Difficulty in capacity expansion and reconstruction	High (central power distribution reconstruction)	Low (layered modular capacity expansion)
Fault impact scope	Large, affecting the racks within the power transformation and distribution room's supply range.	Small, affecting the racks in a single data hall.
O&M management difficulty	Low (centralized management and control)	Medium (distributed inspection)

3.4.3 Battery Backup Configuration Solution

The 800 V DC power system for data halls can be deployed in two modes: centralized architecture with large-capacity lithium batteries and lead-acid battery room. The battery groups are directly connected in parallel to the 800 V main distribution busbar, centrally providing backup power for the entire power supply system; the distributed architecture uses small-capacity lithium battery modules, locally connected to the 800 V distribution busbar in the SideCar on the data hall side, directly providing backup power for each intelligent computing device.

Lithium iron phosphate battery modules or lead-acid batteries can be used as required. The nominal voltage of the batteries matches the 800 V busbar, and DC-DC boost converters can be configured for the batteries. The backup power capacity is configured based on the full-load power for 15 minutes, which meets the requirements of power grid shutdown buffering and black start. In addition, the instantaneous peak load of AI can be reduced, and the peak capacity of the transformer can be reduced.

3.5 Conclusion and Prospect

3.5.1 Research Conclusions

In the future, as the power of a single AI computing rack evolves to 250 kW to 1 MW, the traditional AC and low-voltage DC power supply architectures will face system bottlenecks such as high power loss, low space utilization, poor dynamic load adaptation, and insufficient scalability. Therefore, 800 V HVDC power supply is an inevitable trend for the innovation of the power supply and distribution architecture in equipment rooms.

The design of 800 V DC power supply for equipment rooms must comply with four top-level principles: high reliability and fault tolerance, ultimate high efficiency and dynamic response, flexible deployment of pre-fab. modules, and MW-level end power distribution. These principles will guide the integrated design of civil engineering, power distribution, racks, and energy storage in equipment rooms.

The three types of 800 V energy conversion paths are adapted to different project phases. The dual-winding power frequency solution is suitable for short-term reconstruction of existing data halls. The phase-shifting transformer is suitable for new medium-sized data halls. The SST is the mainstream technology for ultra-large intelligent computing centers, with significant advantages in comprehensive efficiency, space, and scalability.

The centralized power architecture features centralized O&M and high reliability, making it suitable for high-level core computing power. The distributed architecture features low busbar loss and high equipment room area utilization, making it ideal for MW-level high-density racks. Therefore, the distributed architecture is the preferred choice for new AI data halls. The 2N, DR, and RR topologies can be flexibly combined based on the project reliability and cost requirements.

3.5.2 Development Prospect

The 800 V DC data hall will continue to evolve in three directions: First, deep integration of power electronics, with the SST, energy storage, and DC-DC conversion units integrated into a prefabricated unit, further reducing the size of power distribution equipment. Second, DC microgrid collaboration, with the 800 V busbar connecting PV, energy storage, and computing loads, enabling autonomous energy scheduling in the campus and reducing reliance on the mains. Third, full-link digital management and control, with the digital twin data hall monitoring the 800 V busbar loss, device status, and load fluctuation in real time, enabling predictive O&M of the power supply system.

As China's silicon carbide power components and HVDC power distribution equipment technologies make breakthroughs and industry standards are improved, the 800 V HVDC power distribution architecture will completely replace the traditional power distribution architecture and become the standard energy foundation for the next-generation intelligent computing center equipment room, supporting the sustainable, green, and low-carbon development of China's AI computing industry.

4 Campus-Level Backup Power and Energy Storage

4.1 Necessity of Reconstructing the Power Supply System for AIDC Campuses

Over the past decade, the energy issues of data centers have mainly focused on PUE optimization, cooling efficiency improvement, partial redundancy design, and reliability assurance of conventional power supply and distribution. In the traditional Internet, enterprise cloud, and general-purpose IDC era, the system centered on "mains + UPS + diesel generator" has effectively supported the development of data centers from small- and medium-scale centers to large-scale regional campuses. However, the rapid growth of new applications such as foundation model training, inference services, cloud native platforms, high-performance computing, and smart manufacturing is pushing computing infrastructure to a completely different stage. Computing centers are gradually evolving from "highly reliable power-consuming buildings" to new power load centers featuring ultra-large scale, ultra-high density, strong fluctuation, and strong coupling.

In addition, the power supply environment is also undergoing profound changes. In the global area, the grid access period is prolonged, capacity indicators are tightened, electricity prices fluctuate more sharply, and carbon restrictions are continuously strengthened. In addition, the proportion of renewable energy such as wind power and PV power is increasing. The entire power system is shifting from "predictable, centralized, and unidirectional flow" to "increased fluctuation, bidirectional interaction, and collaboration between generation, grid, load, and storage." In other words, both the computing load and the power system are changing. When these two factors are combined, the limitations of the traditional power supply mode for data centers are quickly exposed.

Globally, North America is one of the most active regions for hyperscale data center and AI infrastructure construction. However, its hotspot states and key campuses are already facing issues such as waiting for substation access, delayed power transmission and distribution support, and tight supply of high-reliability power resources. Although European data centers are relatively modest in individual scale, they face stricter carbon restrictions, electricity price fluctuations, and social and environmental constraints, leading them to explore renewable energy, energy storage, demand response, and low-carbon backup power earlier. The Middle East attracts large-scale computing projects with its land and energy conditions, but the high-temperature environment, long-distance power supply, and resilience requirements under extreme conditions are also driving the development of campus-level integrated energy systems. China exhibits typical "dual restrictions": the eastern region has strong demand for computing power, tight grid connection resources, and high costs for green electricity; the western region, rich in resources, offers lower electricity prices and a higher proportion of renewable energy, but often needs to resolve the conflicts between weak grid access, power quality, and high-level power supply assurance.

Therefore, the energy proposition for GW-level computing centers is no longer "how to configure a larger UPS and more gensets", but rather "how to build a new campus power supply system that can carry ultra-large-scale, high-quality computing power, with resilience, cost-effectiveness, and green collaboration capabilities." This means that the power supply system must be upgraded from device-level redundancy thinking to system-level collaborative thinking; from passive emergency response thinking to a multi-objective operating system that equally emphasizes backup power, peak shaving, frequency regulation, power supply assurance, green electricity consumption, and cost optimization; and from static planning thinking to an operational thinking of real-time sensing, dynamic optimization, and computing-power coordination. The AIDC power supply system needs to be built with the mindset of constructing a large power grid.

4.1.1 Logical Changes in External Power Supply

In many countries and regions around the world, computing projects are already experiencing the phenomenon of "waiting for power." It does not mean that the local area lacks power generation

capacity, but rather that there are insufficient high-quality, committed, and highly reliable large-capacity access conditions. This restriction will become more prominent in the era of hyperscale data centers. For computing centers, power must not only be available, but also stable, fast, scalable, and predictable.

In North America, where ultra-large cloud service providers and AI enterprises are concentrated, common practical challenges include long construction cycles for new substations, slow approval for transmission capacity expansion, and insufficient local grid capacity. Even if project owners have sufficient investment capabilities, they are often constrained by the pace of public infrastructure construction. In Europe, in addition to grid capacity, factors such as electricity price structures, carbon emission constraints, and environmental permits must be considered, making it increasingly difficult for campuses to balance economic efficiency and sustainability by relying solely on large-scale mains power access. In China, the "east data, west computing" hotspot regions face issues such as high load density, land scarcity, and limited grid connection quotas, making it increasingly difficult to "first secure sufficient high-quality power and then build computing centers."

Against this backdrop, one of the core objectives of power supply system reconfiguration is to transform the computing campus from a "passive user completely dependent on the external grid" into a "new power node with partial autonomy and regulation capabilities." The campus needs to possess certain internal buffering, rapid support, local balancing, and fault recovery capabilities to cope with access delays, voltage fluctuations, frequency disturbances, regional power supply tension, and even extreme disaster events. Without these capabilities, the feasibility and scalability of GW-level computing centers will be severely restricted.

4.1.2 Renewable Energy Consumption Demand

In the regions where major intelligent computing centers are distributed globally, requirements for green electricity consumption and carbon emissions are continuously increasing. Different regions have different priorities. In North America, the region with the highest concentration of hyperscale data centers, there is a growing emphasis on increasing the proportion of green electricity through power purchase agreements (PPAs), renewable energy certificates (RECs), and local clean energy access. Leading tech companies have generally set goals to match 100% renewable or carbon-free energy. Europe has even stricter requirements, focusing not only on the proportion of green electricity procurement, but also on total carbon emissions, energy efficiency, waste heat recovery, and the impact of data centers on regional power grids and community environments. Some countries have already incorporated data centers into stricter energy efficiency and carbon regulation frameworks. In China, driven by initiatives such as "east data, west computing", dual carbon goals, and green data center policies, the country is continuously raising the requirements for green electricity consumption, PUE control, and energy conservation and carbon reduction in data centers. In particular, large intelligent computing centers are encouraged to be built in regions rich in renewable energy to increase the proportion of renewable energy consumption. In the Middle East and some emerging regions in Asia Pacific, although regulatory requirements are still being refined, with the implementation of large-scale AI and cloud computing projects, these regions are also beginning to pay more attention to low-carbon power supply, energy efficiency, and green campus construction. Overall, intelligent computing centers around the world are moving from the stage of "ensuring power supply" to a new stage of "ensuring reliable power supply while increasing green electricity consumption and reducing carbon emissions."

4.1.3 Dual Stability Challenges Brought by Renewable Energy Power Grids and AIDC Load Fluctuations

In the regions where major intelligent computing centers are distributed globally, the proportion of renewable energy power grids is continuously increasing. In Europe, the proportion of renewable energy in the electricity mix is relatively high, with some countries already seeing renewable energy (such as wind, solar, and hydropower) accounting for more than 40% or even 50% of their electricity generation. In China, the installed capacity of renewable energy has grown rapidly in recent years, with the proportion of renewable energy in the national electricity generation mix continuously rising, especially in resource-rich regions such as northwest and northern China. In the United States, the

overall proportion of renewable energy is also increasing, with some states already having a high proportion of wind and solar power in their electricity mix. Overall, the proportion of renewable energy in the electricity mix in the regions where major intelligent computing centers are located has generally entered a growth channel of 20% to 50%+.

The main characteristics of renewable energy power grids are green and low-carbon, large output fluctuations, uneven spatial and temporal distribution, and strong reliance on flexible regulation resources. Wind and PV are random, intermittent, and fluctuating, and their peak generation periods often do not coincide with peak load periods. Therefore, the higher the proportion of renewable energy, the more the power grid needs energy storage, flexible power sources, demand response, and stronger dispatching capabilities to maintain stability.

On the other hand, intelligent computing center clusters often experience significant transient power fluctuations during large model training, inference switching, and high-density computing power scheduling. The instantaneous load fluctuation rate of AI training clusters can reach 50%, and millisecond-level voltage fluctuations can cause GPUs to go offline and interrupt model training. This imposes higher requirements on both the power supply system of the intelligent computing center itself and the external "weak power grid." Within the campus, rapid load increases or decreases may cause busbar voltage fluctuations, intensify the impact on UPSs and power distribution equipment, and even increase the risk of protection misoperations, local overloads, and power supply interruptions. For the cooling, battery, and backup power systems, this also creates linked response pressure.

For "weak power grids", due to their inherently low short-circuit capacity, weak frequency and voltage support capability, and insufficient anti-disturbance capability, the large transient fluctuations of intelligent computing centers may further amplify voltage flicker, frequency deviation, and power flow impact. In severe cases, this can even affect the stable operation of the local power grid.

4.1.4 High Electricity Costs

Globally, the installed load of data centers is currently estimated to be around 50 to 80 GW. However, with the rapid growth in demand for AI training and inference, the load is expected to continue rising sharply in the coming years. The North America remains the largest region for data centers and intelligent computing centers, with a total load of approximately 25 to 35 GW. In Europe, the total load of data centers is estimated to be around 10 to 15 GW. In Asia Pacific, the total load is estimated to be around 15 to 25 GW, with China accounting for about 10 to 15 GW of operational load and the proportion of intelligent computing centers rapidly increasing. In the Middle East, Latin America, and other emerging regions, the total load is currently relatively small, estimated to be around 3 to 8 GW, but the growth rate is fast.

In the United States, data centers currently account for about 4% to 5% of the country's electricity consumption, with some hotspot states having a higher proportion. In Europe, the overall proportion is about 2% to 3%. In China, the overall electricity consumption of data centers accounts for about 1.5% to 2.5% of the total electricity consumption of the society, and this proportion is still increasing. With the rapid growth of foundation model training and inference loads, this proportion may further increase in the future.

From the perspective of cost structure, electricity expenditure is a key component of the entire lifecycle cost of intelligent computing centers. From the perspective of infrastructure, including power transformation and distribution, cooling, backup power, energy storage, and O&M, electricity costs typically account for 35% to 40% of the total lifecycle cost. For data centers with high electricity prices, high utilization rates, or high-density computing power, this proportion is even higher.

In other words, electricity costs not only determine the daily operating expenses of intelligent computing centers, but also influence the site selection, power supply solutions, green power configuration, and long-term return on investment (ROI). Therefore, the future competition of intelligent computing centers will not only be about computing power equipment, but also about the capabilities of energy acquisition, energy consumption efficiency, and electricity cost control.

4.1.5 Challenges of Gensets As the Backup Power Supply for AIDCs

As a long-term backup power supply for data centers, gensets are technically mature, widely accepted in the industry, and can quickly form a power supply assurance system. Therefore, gensets have long played the role of "ultimate backup" in the past. However, with the trend of energy transition, the limitations of genset solutions are becoming increasingly evident.

First, the emission and noise problems are becoming increasingly prominent. In particular, in Europe and some parts of North America, the long-term operation of gensets is strictly restricted by environmental protection permits, making them unsuitable as flexible resources for high-frequency use.

Second, the difficulty of fuel storage and supply chain management in ultra-large campuses is significantly increasing. If the power supply needs to be guaranteed for dozens of hours or even longer in extreme scenarios, the campus needs to be equipped with large-scale fuel storage, fire protection, and safety assurance systems. This increases investment and brings operational management pressure.

Third, from the perspective of asset utilization, gensets are mostly in standby mode and only play a major role in low-probability accident scenarios. This results in a high proportion of static assets and limited daily value release.

Fourth, the genset supply chain has limited capacity for increasing production, and the delivery period is uncertain. This leads to continuously rising costs of backup power supplies, and the proportion of gensets in the data center capital expenditure (CAPEX) keeps increasing.

Fifth, the renewable energy power grid is not stable, which leads to frequent switching and genset startup. In addition, new environmental protection regulations in Europe and America restrict the regular use of gensets, and the original redundant power supply system becomes invalid.

Sixth, gensets have a slow dynamic response, and the O&M pressure is high under frequent startup and shutdown and high-impact working conditions. As a result, gensets cannot adapt to the transient load impact of intelligent computing centers.

Therefore, global computing centers are shifting from the idea that "gensets are the only long-term backup power supply" to the idea that "gensets are the ultimate backup, and multiple resources are used in collaboration." Energy storage can provide fast support and short- and medium-term regulation. Gas turbines or gas engines can provide long-term support with higher utilization rates. Fuel cells and hydrogen ammonia routes provide directions for future low-carbon alternatives. The essence is not to immediately eliminate diesel, but to reduce the over-reliance on a single high-carbon backup power supply mode through power supply system reconstruction, and transform the backup power supply system from static redundant assets to a flexible resource combination that can participate in daily operation optimization.

4.1.6 Multi-objective System-Level Efficiency Improvement Becoming a Trend

In the system of generation, grid, load, and storage, GW-level intelligent computing centers cannot be merely energy-consuming terminals that pursue uninterruptible power supply. Instead, they need to gradually become adjustable entities in the power system. This is because, as the proportion of renewable energy continues to increase, the power grid operating environment becomes more complex, and the scale and volatility of intelligent computing loads continue to rise, the system operation objectives are no longer singular. Instead, they are characterized by multiple objectives.

In some phases, especially in scenarios involving power grid disturbances, local weak grid operation, or critical task assurance, the system must prioritize safety and stability, ensuring frequency, voltage, and power balance, as well as continuous power supply to critical loads. In phases where renewable energy is abundant, carbon constraints are tightened, or green computing power requirements are raised, the system may prioritize the proportion of green electricity consumption and carbon footprint optimization.

In environments with significant electricity price fluctuations and gradually improved ancillary service market mechanisms, maximizing economic efficiency and overall benefits becomes a key objective. This means that the computing and power collaboration system must have the capability to dynamically switch between different operation objectives and comprehensively balance them.

In this process, the role of energy storage systems (ESSs) is undergoing fundamental changes. In the past, ESSs were often regarded as assets primarily aimed at peak-valley arbitrage, with relatively limited revenue sources. However, in the integrated scenario of generation-grid-load-storage, ESSs have become a key resource for supporting multi-objective optimization. They can provide millisecond-level rapid response to ensure stability, and perform functions such as frequency regulation, voltage stabilization, power smoothing, fault support, and black start assistance. They can also absorb fluctuating renewable energy when green electricity is prioritized, increasing the proportion of local green electricity consumption and reducing the wind and solar curtailment rate. Additionally, they can participate in market-oriented services such as peak shaving, demand management, backup optimization, and grid peak shaving and frequency regulation when economic efficiency is prioritized, thereby forming a diversified revenue structure. Therefore, the value of ESSs is no longer determined solely by the electricity price difference in a single time period, but increasingly by the comprehensive regulation functions they provide in the entire system.

In addition, intelligent computing centers themselves must also shift from traditional "passive loads" to "active loads." Active loads do not mean sacrificing the stability of core services. Instead, they involve flexibly orchestrating non-real-time, migratable, and schedulable loads under the premise of ensuring the continuous operation of critical computing tasks, even with a very low probability. For example, when the power grid is strained or system stability is prioritized, non-critical training tasks can be appropriately reduced. When renewable energy is abundant, the intelligent computing center can also adjust its load based on the availability of renewable energy. When the output power is high, electricity prices are low, or there is an excess of green power, the training intensity and resource utilization can be increased. When energy storage and the power grid need to work together, task scheduling and cooling load optimization can be used to balance the system. In this way, intelligent computing centers are no longer just a "pressure source" for the power system, but become a "collaborative resource" that can respond to scheduling, participate in optimization, and create benefits.

In general, the entire power supply chain of "generation-grid-load-storage" needs to shift from modular segmentation to collaborative governance. The entire system needs to be dynamically optimized in terms of safety, greenness, and cost-effectiveness. This is also an important direction for intelligent computing centers to evolve from high-energy-consuming facilities to new energy infrastructure.

4.2 Discussion on Campus-Level Backup Power and Energy Storage Configuration Solutions

In terms of hardware configuration and software scheduling, the differences between GW-level campuses and traditional data centers lie in the reconstruction of energy storage and backup power. The differences are as follows:

1. From "data hall-level backup power" to "campus-level energy system"

In the past, data centers focused more on the electrical redundancy and equipment reliability of a single building or data hall module. However, in the future, GW-level campuses must design the power supply system from the perspectives of overall energy balance, capacity configuration, hierarchical protection, backup resource scheduling, and campus-wide collaboration. That is, the design object is upgraded from the electromechanical system of a single building to the campus-level integrated energy system. The power grid access, renewable energy, energy storage, gensets, gas turbines, cooling systems, IT loads, and control platform in the campus must be integrated into a unified framework.

2. From "static redundancy" to "dynamic adjustment"

The traditional N + 1 or 2N redundancy will not fail, but it is no longer sufficient to cope with the fluctuations of renewable energy, AI loads, and energy prices. The more critical capability in the future is dynamic adjustment, that is, the system can adjust its operation mode in real time based on the load, weather, electricity prices, equipment status, and power grid constraints. The millisecond-level response of energy storage, fast switching of microgrid controllers, and flexible orchestration of task scheduling will all become part of the power supply system capabilities.

3. From "isolated configuration of backup power" to "collaborative operation of multiple resources"

Gensets, UPSs, batteries, gas turbines, fuel cells, and renewable energy should no longer be configured in isolation, but should be operated collaboratively under a unified control platform. Energy storage can extend the UPS function, and also participate in daily peak shaving, frequency regulation, and power quality management. Gensets are not only used as backup power in case of accidents, but can also form a highly resilient stand-alone grid with energy storage in extreme scenarios. Gas turbines and fuel cells provide supplementary paths for low-carbon and long-term power supply. The actual system reconstruction is not about adding more devices, but about clearly defining the roles of these devices across different time scales and fault scenarios.

For a GW-level intelligent computing campus, instead of providing highly reliable power grid access for AIDC, areas with sufficient capacity but poor quality (weak power grid, remote power grid, and insufficient access quality) are transformed into new high-reliability power nodes that can support AIDC. In addition, the new energy outside the campus with the gensets and energy storage inside the campus are integrated to form an energy solution. The following solutions can be used for reference.

4.2.1 Solution 1: Mains Power as the Primary Power Source, Enhanced by Energy Storage, and Diesel Gensets as the Backup

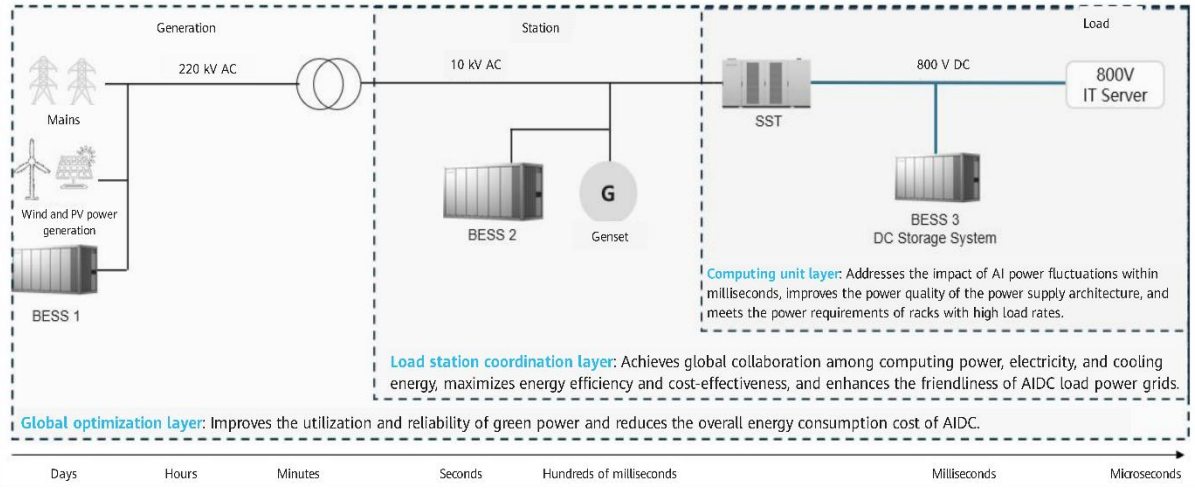
This solution is applicable to hotspot areas with good power grid conditions, high access level, and strong reliability foundation. The basic features of this solution are as follows: The primary power supply requirements are met by using high-level mains power access through multiple loops. A certain scale of energy storage is configured in the campus to improve transient support and peak shaving capabilities. Diesel gensets are used as the last resort in extreme accident scenarios. This solution is mature and can be smoothly integrated with the existing data center O&M system. It is suitable for large projects in first-tier cities and areas with strong power grids.

One of the most prominent features of AI computing loads is that the instantaneous power changes faster and more concentrated. The startup of training jobs, computing task scheduling, and coordinated changes of the liquid cooling system may cause a large power jump in a short period of time. Energy storage can respond in milliseconds to seconds, quickly fill the power gap during these transient processes, suppress voltage dips and frequency deviations, and significantly reduce the pressure on the upstream power grid and diesel gensets. This value is especially prominent in high-density GPU cluster environments.

After energy storage is introduced, gensets do not need to undertake dynamic response tasks, and the peak load can be borne by energy storage. Gensets are dedicated to long-term stable support and power supply in extreme accidents. The total capacity of gensets only needs to be configured based on the long-term average load, and the peak load does not need to be borne.

The following diagram shows the three-level energy storage solution from energy to servers. On the energy side, energy storage must be configured to smooth the power generation due to the time mismatch of wind and solar power generation. A certain amount of energy storage can be configured on the 10 kV side to smooth the second-level fluctuation of AI loads, reducing the transient load when gensets are carrying loads and enabling gensets to carry loads stably. At the rack level, a certain amount of energy storage can be configured to suppress millisecond-level load fluctuation. The

supercapacitor or lithium supercapacitor solution can be used. For details about the specific deployment positions of energy storage, see the following diagram.



(Solution 1 diagram)

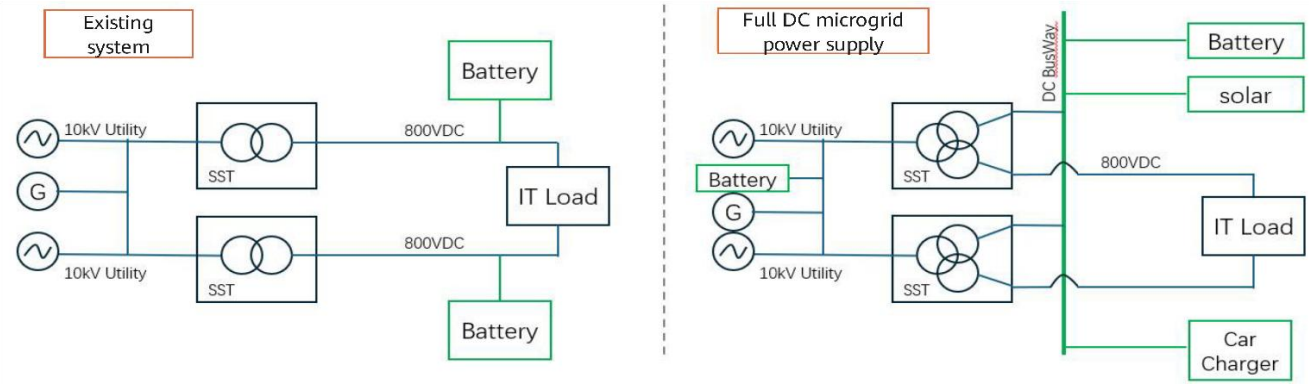
4.2.2 Solution 2: DC Microgrid for End Power Supply

The DC microgrid system is a DC microgrid power supply solution for intelligent computing centers based on the multi-port SST. Compared with the existing system, the DC microgrid solution no longer uses multiple relatively independent 800 V DC branches to supply loads separately. Instead, it uses a 10 kV AC power supply as the input, and uses the multi-port SST to uniformly transform and couple the power to build a campus-level DC busway. Then, the DC busway supplies power to and coordinates the scheduling of various devices, such as IT loads, energy storage batteries, PV modules, and charging facilities. In essence, this solution upgrades the original distributed power supply and distribution structure to a new power supply architecture featuring AC access, DC integration, multi-port collaboration, and unified scheduling.

The core of this technical solution is the multi-port SST. Traditional transformers are mainly used for voltage conversion and electrical isolation. The multi-port SST further integrates AC/DC conversion, power electronics control, multi-port energy routing, and flexible adjustment capabilities. Therefore, it can efficiently convert 10 kV AC power into 800 V DC power to supply power to high-density loads such as servers and liquid cooling systems, and can also directly connect battery energy storage, distributed renewable energy, and other DC devices to the same busway, implementing integrated linkage of generation, grid, load, and storage. For intelligent computing centers, this means that the system can reduce the number of intermediate conversion stages, reduce power loss, and improve power supply efficiency and dynamic response capability.

This solution has four main advantages. 1. Higher efficiency: The all-DC architecture eliminates the need for multiple AC/DC and DC/AC conversions in traditional AC power distribution, UPS, and PDU, reducing overall power loss. 2. More flexible architecture: The DC busway is naturally suitable for connecting energy storage devices, batteries, PV modules, and charging loads, facilitating expansion into a campus-level integrated energy system. 3. Stronger dynamic adjustment capability: The multi-port SST has the capability of fast power control, which can better adapt to the high density and strong fluctuation of loads in intelligent computing centers. 4. Better adaptability: It is more suitable for computing-power collaboration and microgrid operation, and has better adaptability in scenarios such as on-grid, off-grid, partial autonomy, and peak shaving.

This solution is applicable to new high-density intelligent computing centers, campus-level AI computing centers, all-DC microgrid pilot projects, and integrated energy scenarios that require simultaneous access to energy storage and various types of DC equipment. However, it imposes high requirements on the maturity of SST devices, protection strategies, DC system safety, and control system capabilities. Therefore, at this stage, it is more suitable for high-end new projects or demonstration campuses.



(Solution 2 diagram)

4.2.3 Solution 3: Low-Carbon Long-Duration Power Supply Route

When the campus power supply objective goes beyond the minute-level bridging assurance provided by UPSs or lithium batteries, and the use of fossil fuels needs to be minimized, a low-carbon long-duration power supply capable of continuous output must be introduced in addition to short-duration energy storage, forming a hierarchical power supply assurance system.

Typically, the architecture of "lithium battery energy storage + natural gas power generation/gas turbine/internal combustion engine + low-carbon power sources such as hydrogen energy, ammonia energy, and SOFC" can be adopted. In this architecture, lithium batteries are responsible for fast response in milliseconds to minutes, power fluctuation suppression, and switching bridging. Natural gas power generation units or gas turbines handle long-duration power supply in hours. Hydrogen energy, ammonia energy, and SOFCs serve as future-oriented low-carbon long-duration support technologies, gradually replacing traditional high-carbon backup power sources.

The advantages of this solution are mainly reflected in three aspects. First, the power supply assurance time is significantly extended. Although lithium batteries respond quickly, the longer duration indicates the higher cost, and the floor area and configuration scale increase rapidly. In contrast, technologies such as natural gas power generation units, gas turbines, and fuel cells are more suitable for long-term continuous operation, effectively compensating for the economic shortcomings of pure electrochemical energy storage. Second, the power supply structure is more flexible. Through the collaboration of multiple energy sources, the campus can select the optimal operation mode based on different working conditions: under normal conditions, the power grid and energy storage handle daily optimization; in the early stage of a fault, energy storage provides bridging; during long-term power outages, gas power generation or fuel cells take over, achieving a combination of fast and slow power supply and complementing each other in terms of long and short duration. Third, this solution is more aligned with the direction of low-carbon transformation. Compared with relying solely on gensets, natural gas power generation and SOFCs have advantages in emissions and efficiency. Zero-carbon or low-carbon fuels such as hydrogen and ammonia offer greater potential for future green computing campuses.

This solution is particularly suitable for projects that require both continuous power supply and low carbon emissions, such as GW-level intelligent computing centers, computing power bases in weak grid areas, and important industry computing centers. For example, in renewable energy bases in western China, high-temperature and high-load campuses, and large AI campuses outside China, the "energy

storage + long-duration power supply" mode is of great practical significance. However, this solution also poses higher requirements on system integration, fuel supply, control coordination, and initial investment. Generally, a unified energy management platform is required to optimize scheduling. This is the key technical path for intelligent computing centers to shift from short-duration power backup to long-duration power supply, low-carbon operation, and multi-energy collaboration.

4.3 Key Equipment of the New AIDC Power Supply System

The construction of a new AIDC power supply system based on "generation-grid-load-storage" cannot be separated from new power equipment, including smart wind turbines, grid-forming PV, and grid-forming energy storage, gas turbines (hydrogen, ammonia, and natural gas), solid oxide fuel cells (SOFCs), and multi-port SSTs.

Smart wind turbines: In addition to wind energy conversion, smart wind turbines emphasize status awareness, power prediction, active adjustment, and grid-friendly capabilities. They can improve output stability and grid-friendliness through intelligent control, and provide green power support for campuses in areas with suitable conditions.

Grid-forming PV: Different from traditional grid-following PV, grid-forming PV has certain voltage and frequency support capabilities. In weak grid or microgrid scenarios, it can participate in system stability control. It is no longer a passive power source that only generates as much power as possible, but has stronger system support attributes.

Grid-forming energy storage: As one of the core devices in the new AIDC power supply system, grid-forming energy storage can provide the bridging and short-duration power backup functions of traditional UPSs, and also support frequency regulation, peak shaving, black start, and on/off-grid switching at the campus level. It is the key link between energy storage and power backup. Compared with traditional battery systems, grid-forming energy storage features fast response, flexible control, and can participate in system stability as a voltage source.

Gas turbines: Hydrogen and ammonia gas turbines and natural gas turbines are more suitable for long-duration power supply scenarios. The natural gas route is technically mature and can be started quickly, making it a realistic long-duration and low-carbon power supply solution. In the future, with the advancement of hydrogen and ammonia fuels, gas turbines are expected to further reduce carbon emissions and become an important continuous power supply equipment for intelligent computing centers.

SOFC: It is a distributed power generation technology that features high efficiency and low emissions. It can generate electricity using various fuels such as natural gas, hydrogen, and ammonia. It features high power generation efficiency and low noise, and is especially suitable for scenarios that require high-quality power supply and combined heat and power (CHP) potential. However, the cost and engineering maturity of SOFCs still need to be further optimized.

Multi-port SST: It can implement traditional voltage conversion and isolation, and integrate AC/DC conversion, multi-port energy routing, and fast power control, providing core support for building all-DC microgrids, AC/DC integrated systems, and integrated architectures of power generation, grid, load, and energy storage.

In general, these key devices have their own functions. Some provide green power, some enhance system stability, some ensure long-term power supply, and some reshape the power supply architecture. Together, they form the technical foundation of the new AIDC power supply system.

4.4 Control Solutions for the New AIDC Power Supply System

The reconstruction of the power supply system is not only a change at the device level, but also a change in the control logic and operation mode. The control logic of the power supply system in traditional data centers is relatively simple. In normal cases, the mains power is supplied. When an

exception occurs, the UPS seamlessly switches to the genset. In GW-level campus scenarios, the system may have grid access, energy storage, renewable energy, genset, gas turbine, and flexible loads. The operating status is no longer "normal/abnormal", but includes multiple boundary working conditions and target functions.

First, a hierarchical and zoned control system needs to be established. The site level is responsible for coordination with the external power grid, power boundary control, and large-scale fault handling. The campus level is responsible for energy storage scheduling, busbar segmentation, energy balance, and load priority management. The end level is responsible for ensuring the power supply for mission-critical loads, controlling the local power quality, and implementing device-level switchover policies.

Second, scheduling needs to be performed based on time scales. Millisecond-level to second-level scheduling depends on energy storage and power electronics devices to achieve dynamic stability. Minute-level to hour-level scheduling depends on the output adjustment of power generation units, energy storage charge and discharge policies, and chiller plant load optimization. Day-level to week-level scheduling requires global optimization based on electricity prices, weather conditions, renewable energy forecasts, and computing task scheduling.

In addition, computing and power collaboration will become an essential part of control strategies. Different services have varying requirements on latency, interruptibility, and real-time performance. In the future, campuses can classify and manage tasks, ensuring that critical inference and core service loads are always guaranteed. Non-real-time training jobs and batch processing tasks can be accelerated when energy is abundant, and postponed when the system resources are limited. In this way, the power supply system will no longer serve only computing power, but will instead form a collaborative operational whole with computing power.

Digital twin will be an important tool for the "generation-grid-load-storage" scheduling system. With the digital twin and simulation platform, the short-circuit capacity, fault scenarios, black start process, and multi-resource collaboration effect can be verified before project construction, and predictive scheduling and policy iteration can be performed during operation. This is a key step in transforming "device stacking" into "system capabilities."

Foundation models are another important tool for the generation-grid-load-storage scheduling system, mainly reflected in four aspects: prediction, decision-making assistance, collaborative optimization, and intelligent interaction. It can integrate weather, load, renewable energy output, device status, and power grid operation data to improve the accuracy of renewable energy generation and load prediction. It can also assist dispatchers in alarm analysis, fault analysis, and scheduling solution generation, improving response efficiency. In addition, it can support multi-objective optimization in generation-grid-load-storage collaboration scenarios, helping to balance safety, economy, renewable energy integration, and low carbon goals. Furthermore, foundation models can serve as the intelligent interaction entry of the scheduling system, enabling knowledge retrieval, operation assistance, and report generation through natural language, thus improving human-machine collaboration in complex power grid scenarios.

4.5 Work of the New AIDC Power Supply System

Building a new AIDC power supply system is not simply about adding a few types of devices or partially upgrading traditional electromechanical systems. Instead, it is a systematic project involving planning, design, verification, control, and engineering implementation.

First, in the frontend planning phase, it is necessary to carry out integrated planning for generation-grid-load-storage, and conduct a comprehensive analysis on the load characteristics of the campus, power supply reliability objectives, power grid access conditions, renewable energy access capabilities, energy storage configuration scale, and backup power supply routes. This will help clarify the balance between safety, economy, low carbon, and scalability of the system. Especially for high-density intelligent computing centers, special attention should be paid to studying the impact of load fluctuations, cooling load changes, and future capacity expansion on the power supply system.

Second, system modeling and simulation analysis are required. The novel AIDC power supply system typically involves the coordinated operation of the power grid, power electronics devices, energy storage, UPS, backup power supplies, and various types of loads. Traditional experience-based design can no longer cover complex operating conditions. Steady-state analysis, transient simulation, fault simulation, and control simulation are required to verify scenarios such as current distribution, short-circuit capacity, voltage fluctuation, switching process, off-grid operation, and black start, in order to identify system bottlenecks and control risks in advance.

Third, the integrated design of the system architecture is essential. This means that the mains connection, UPS, energy storage, backup power supplies, cooling power, and monitoring system should not be designed in isolation. Instead, they should be considered together from the campus-level perspective, including the voltage level, power supply topology, redundancy mode, control interface, protection coordination, and energy flow path, to form an overall architecture that features efficient operation under normal conditions, fast switching in case of faults, and resilience in extreme scenarios.

Fourth, subsystem testing and verification are required. Key devices such as energy storage systems, UPSs, grid-forming devices, gensets, and controllers should undergo function testing, interface commissioning, fault ride-through, on/off-grid switching, thermal management, and safety verification in the lab and prototype stages, to avoid problems being exposed in the field.

Finally, system integration and commissioning must be completed during the engineering implementation phase. The focus should be on verifying the coordination capabilities of each subsystem under real working conditions, including power distribution, control response, protection actions, load switching, black start process, and communication reliability.

In general, the key to building a new AIDC power supply system is not only to use advanced devices, but also to form a truly operable, scalable, and implementable system through planning, simulation, design, verification, and commissioning.

4.6 Challenges of Campus-Level Energy Storage Applications

Although the direction is clear, there are still several obstacles to be overcome in GW-level campus power supply reconstruction.

1. Site restrictions

If a large-scale energy storage system is deployed in an intelligent computing center, the system scale will increase rapidly as the energy storage capacity and duration increase. Especially when the energy storage duration needs to be longer than one hour, the effective energy storage capacity per unit site is often difficult to increase infinitely. This is because large-scale energy storage may not only occupy the space for deploying computing devices, but also increase the complexity of fire safety, thermal runaway prevention and control, noise isolation, and O&M organization. In particular, in high-level campuses, energy storage systems cannot be simply deployed in any available space, but must be planned in a dedicated manner.

2. Safety considerations

For intelligent computing centers, fire is the most severe hazard, even more severe than power outages. Large-scale battery energy storage systems require higher standards for fire suppression, isolation, thermal runaway control, O&M inspection, and fault handling. Mechanisms must be designed according to higher standards.

The generation-grid-load-storage systems significantly increases the complexity of control and protection. Parallel operation of multiple power supplies, mode switching, microgrid operation in island mode, black start, and AC/DC hybrid systems all pose higher requirements on relay protection, control interfaces, communication reliability, and O&M team capabilities.

3. Challenges to TCO

In GW-level campus projects, any power supply system reconstruction solution must consider the worthiness. Traditionally, the decision is often based on the one-time equipment procurement cost. However, for energy storage, multi-source power supply, and flexible power distribution systems, the initial CAPEX alone is not a reliable indicator, as it is difficult to implement the financial plan. A more reasonable evaluation should be based on the lifecycle cost.

First, the direct costs should be considered. These include investments in transformer stations and grid connection, UPSs and power distribution equipment, energy storage systems, gensets or other backup power units, civil engineering and fire suppression facilities, fuel storage and transportation systems, and digital control platforms. Second, the indirect costs should be considered. These include service losses caused by waiting time for capacity expansion, opportunity costs caused by delayed grid connection, service interruption losses in extreme accidents, and carbon costs. Third, the operational benefits and savings should be considered. These include peak shaving, reduced maximum demand charges, increased self-consumption of green electricity, reduced genset trial operation and maintenance costs, participation in demand response or ancillary services, and delayed capacity expansion of the upstream power grid.

For GW-level computing campuses, the value of power supply system reconstruction is not in a single benefit item, but in the comprehensive effect of multiple dimensions. This includes faster implementation, lower long-term electricity purchase costs, higher equipment utilization, higher proportion of green electricity, stronger resilience to accidents, and better policy and customer recognition. Therefore, the reconstruction should be evaluated based on whether it can reduce the operational risks and energy costs of the entire campus in the next decade.

4. Lack of engineering experience

Currently, new power supply system solutions still face the challenges of insufficient standards and engineering experience. For example, the coordination between grid-forming energy storage systems from different vendors, setting of protection parameters for AC/DC hybrid power distribution, and long-term reliability verification of fuel cells in data center scenarios all require more engineering practices. Therefore, the reconstruction of power supply systems in GW-level campuses should not simply pursue the most advanced technologies, but should be implemented in phases, with the principle of mature technologies being introduced and pre-researched in batches.

5 DC System Power Distribution and Protection

The 800 V HVDC power supply, distribution, and system protection are core issues that need to be addressed urgently in future GW-level data centers. The unique physical characteristics of the DC system, such as no natural zero-crossing point, strong global capacitance, and sharp step changes (EDPp) in AI loads, bring fundamental changes to the traditional power distribution architecture.

5.1 DC System Power Distribution

The 800 V DC power distribution solution can be classified into two types: centralized architecture and distributed architecture.

Centralized architecture: 13.8 kV AC power is uniformly converted to 800 V DC at the data center entrance and transmitted to each rack via the DC busbar. This architecture is suitable for new large-scale data centers, featuring centralized investment and easy management, but it imposes extremely high requirements on the reliability of the DC busbar.

Distributed architecture: Independent AC/DC conversion modules are deployed on each IT rack or rack row to output 800 V DC power locally. This architecture offers high flexibility and a small fault impact scope, making it suitable for renovation projects or phased construction scenarios. However, it involves scattered equipment and higher maintenance costs.

The DC power distribution system offers advantages such as high energy efficiency, friendly integration with renewable energy, and high space integration. However, it also has obvious disadvantages, including high initial investment, outdated technical standards, difficulty in protecting the 800 V DC system, and an immature supply chain.

5.2 DC System Protection

DC system protection is the key to ensuring the safe, reliable, and stable operation of the 800 V DC power supply solution for AIDCs. This section focuses on the protection system design under the 800 V HVDC power distribution architecture, and deeply analyzes its core challenges, evolution direction, and key technical measures.

5.2.1 Challenges to 800 V Power Supply Protection in Data Centers

The evolution of the power supply architecture in data centers from traditional AC to DC is not only a change in voltage form, but also a fundamental transformation of the underlying physical attributes of the system.

Table 1 Comparison between AC and DC systems

Feature Comparison	AC System	DC System
Impedance essence	**Inductive dominant:** Energy is stored in magnetic fields. Inductors have the "inertia" to resist sudden changes in current, providing a buffering effect.	**Capacitive/Resistive dominant:** Energy is stored in the electric field (DC capacitor). The system impedance is extremely low, and the capacitor discharges energy instantaneously. The current rises very quickly.
Inertia	**Rotational kinetic energy:** The huge physical rotational inertia of the generator set provides a stable "ballast" for the system.	**Virtual/Algorithmic inertia:** The physical inertia is extremely low (microsecond level). The "inertia" is simulated using control algorithms or parallel battery strings to provide flexible support.
Self-recovery capability	**Strong (automatic oscillation reset):** After the fault is cleared, the system automatically resets by converting electromagnetic field and mechanical energy. It is supported by excitation and grid inertia.	**Weak (external intervention required):** After the fault is cleared, the converter must be restarted using the control algorithm to perform the soft-start process, or battery intervention must be relied upon.
Short-circuit response characteristics	The short-circuit current has a natural zero-crossing point, making arc extinguishing easy. The rise speed is relatively slow. The protection time window can reach the second level.	There is no natural zero-crossing point, making arc extinguishing difficult. Capacitor discharge generates high di/dt and huge peak current spikes. If current limiting measures are not taken, the protection time window is only at the microsecond or millisecond level.

Based on the fundamental changes in the physical characteristics described above, the 800 V DC protection system for GW-level computing clusters faces the following challenges in actual engineering implementation:

- **Challenge of forcibly extinguishing arcs without zero-crossing points:** Since the DC lacks natural zero-crossing points, traditional air-blast or magnetic-blast AC arc-extinguishing grids are highly prone to failure when faced with HVDC arcs. The system must use DC-specific mechanical circuit breakers (MCBs) with stronger arc-extinguishing capabilities, or introduce SSCBs based on fully-controlled power devices (such as SiC MOSFETs and IGBTs) to achieve precise fault isolation.
- **Lack of standardization for the multi-fault characteristics of converters:** The DC system is dominated by a large number of power electronic converters. Its fault output characteristics no longer exhibit the constant impedance characteristics of traditional synchronous machines, but are highly dependent on the control loop algorithm (such as current limiting control), and exhibit nonlinear and multi-modal characteristics. Currently, the industry still lacks standards and test specifications in this field.
- **Changes in battery connection methods lead to reconstruction of the protection chain:** In the 800 V DC architecture, the backup battery system is no longer directly connected to the grid. Instead, it is coupled to the 800 V main busbar through a high-power bidirectional DC-DC converter. This topology change makes the dynamic response and protection coordination design of the DC-DC converter more complex.
- **High-frequency transient inrush current impact in a strong capacitive environment:** To meet the transient high dynamic load requirements of AI servers, a large number of support capacitors are connected in parallel on the 800 V DC busbar and the PSU side of the rack. When a metallic short circuit occurs in the system, if no restriction measures are taken, these capacitors will release charges in a microsecond-level window, generating extremely high short-circuit current peaks. This can easily cause thermal damage or dynamic stability damage to protective devices.
- **Selective coordination in a complex "multi-source and multi-direction" network:** The AIDC 800 V power distribution network has evolved from a traditional "single-source and single-direction" radial network to an active network with multiple energy nodes. During a short circuit, the fault current paths are intertwined, posing great challenges to system protection.

The following sections will discuss these challenges in detail.

5.2.2 Fault Output Characteristics of DC System Power Supplies

The fault output characteristics of DC system power supplies are critical to the design of DC system protection solutions. Different power supply fault output characteristics require different system protection solutions.

5.2.2.1 Comparison of Fault Sources in AC and DC Systems

The main fault sources in DC systems are significantly different from those in AC systems. Different types of fault sources determine the direction, peak value, and attenuation characteristics of fault currents:

- **Main contributors to AC system faults:**
  - **Generators and motors:** As traditional rotating machines, they continuously deliver reverse electromotive force and short-circuit current to the fault point during the transient process of a fault due to their huge electromagnetic inertia.
  - **Upper-level power grid:** It provides stable power frequency fault current injection based on the infinite power capacity of the power grid.
- **Main contributors to DC system faults:**

- **Capacitor bank:** As the core component for voltage regulation and filtering on the DC busbar, the capacitor bank exhibits a discharge characteristic of "nearly zero impedance" during a short circuit, resulting in a microsecond-level ultra-high di/dt transient current spike.
- **Rectifier/converter:** The freewheeling and control response of the internal power electronic devices directly affect the current direction in the initial stage of a fault.
- **Energy storage battery:** As a distributed active node, the battery has extremely low internal resistance and can release a large amount of steady-state DC short-circuit current during a fault.

The fault source of a traditional AC system is usually an electromagnetic and mechanical coupling body, and the current increase is limited by the inductive impedance. However, the fault source of an 800 V DC system is characterized by "strong capacitance and multi-source distribution." Therefore, the protection of the 800 V DC system must break away from the traditional AC power distribution mindset.

5.2.2.2 Classification of Power Fault Output Characteristics in DC Systems

In the traditional AC power supply architecture, the power frequency transformer is used as the single power supply point. When a short circuit occurs, the transformer can be regarded as a Thevenin voltage source with internal inductive impedance. However, in the 800 V DC power supply system, the power supply point is transformed into a "multi-source and multi-directional" network consisting of multiple power electronic converters (AC/DC and DC/DC) and capacitors and energy storage batteries mounted on the DC busbar.

Due to the control loop and physical limitations of power electronic converters, the short-circuit calculation method of the DC system is essentially different from that of the AC system. Currently, the industry trend is that batteries are gradually shifting from the traditional "directly connected to the busbar" mode to being connected to the busbar through bidirectional DC/DC converters, to achieve stable output voltage and dynamic blocking control of fault current.

Based on the output and control response characteristics of the entire power supply, the power fault output characteristics of the DC system can be classified into the following four types:

1. **Current-limited power system**

   This type of system is usually composed of converters with active current limiting control capabilities, or consists of basic converters and independent current-limited devices (CLDs).

   - **Equivalent circuit model:** The fault output behavior model can be equivalent to the parallel connection of a controlled current source and the output port capacitor.
   - **Fault response phase:**
     - **Transient phase**: At the moment of a short circuit, the capacitor is discharged instantaneously only limited by the equivalent series resistance (ESR) of the output capacitor and the impedance of the fault loop, generating an extremely high di/dt and transient pulse current spike. This process is usually completed within 0.1 ms to 1 ms.
     - **Steady-state phase**: After the capacitor discharges, the internal control loop of the converter forcibly intervenes, switching from constant voltage (CV) mode to constant current (CC) mode. The steady-state short-circuit current is strictly locked to the current limit threshold (usually 1.5 times the rated current In) and maintained for a specific period (for example, 200 ms). If the fault is not cleared within this window, the converter enters the lockout protection state.

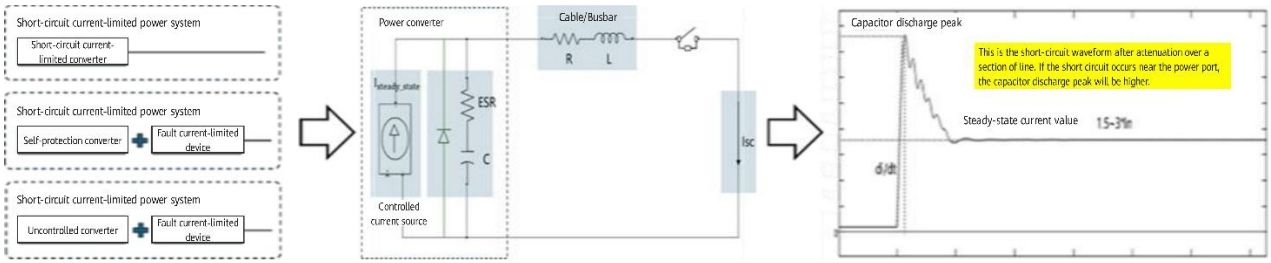


Figure 8 Equivalent model of the output short circuit of a current-limited power system

2. **Self-protection power system**

The power converter inside this type of system does not have the capability to limit the short-circuit current and maintain the output, but it integrates ultra-fast hardware protection logic.

- **Fault response characteristics:** When a short circuit occurs and the current begins to surge, the converter can quickly detect the fault and execute hardware fast lockout within a microsecond-level (μs-level) window, and proactively cut off the energy output to achieve self-protection.
- **Requirements on the protection system:** Because the energy cut-off speed is extremely fast, the traditional fuse or conventional MCB (usually with a millisecond-level response) at the end or cascaded with the converter cannot operate before the converter is locked out. As a result, the conventional cascaded selective coordination fails. The system protection must rely on SSCBs that have the same microsecond-level response.

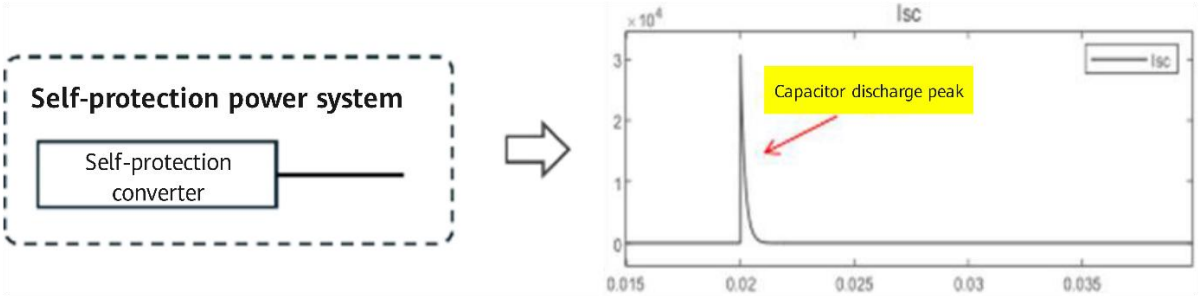


Figure 9 Short-circuit output characteristics of a self-protection power system

3. **Uncontrolled power system**

This type of system consists of power electronic converters that have neither the capability to limit the short-circuit current nor the capability to perform microsecond-level self-protection and lockout (or are not equipped with independent current limiting protection devices).

- **Typical topology risks**: For example, when a T-type three-level rectifier circuit is used, after a short circuit occurs on the DC side, the short-circuit current will directly pass through the antiparallel diode or body diode of the switching transistor to forcibly form an uncontrollable freewheeling loop, lacking an active current limiting and shutdown mechanism.
- **Fault response characteristics**: When a short circuit occurs on the DC side, it is equivalent to a metallic short circuit on the AC side after the rectifier bridge. The expected short-circuit current output is extremely high, depending on the short-circuit capacity of the AC system. If no external forced intervention or cascaded protection is taken, the short-circuit current will

continue to rise and generate severe thermal effects, which will eventually cause thermal breakdown and damage to the core power components of the converter.

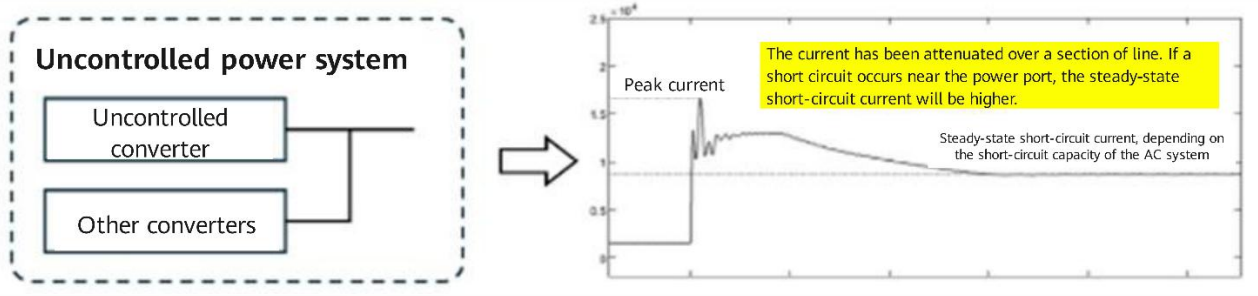


Figure 10 Fault characteristics of an uncontrolled power system

4. **Battery-connected power system**

Although the industry is evolving towards the DC/DC coupling architecture, in some scenarios, the solution of directly connecting batteries to the DC main busbar still exists.

- **Equivalent circuit model:** When a short circuit occurs, a large-capacity battery string can be equivalent to a pure DC voltage source with extremely low internal physical impedance.
- **Fault response characteristics:**
  - **Advantages and disadvantages for downstream protection:** When a fault occurs, the battery string directly connected to the system can release a large amount of steady-state short-circuit energy that is continuous and does not attenuate. From the perspective of protection coordination, this high and constant steady-state current is very helpful for downstream protection devices (such as fuses and circuit breakers) to accurately identify the fault and implement thermal fuse coordination or magnetic tripping.
  - **Safety risks:** If a large-capacity lithium battery or lead-acid battery string is directly connected to the system, the peak value of the total short-circuit current of the entire system may exceed the maximum rated breaking capacity (I_{cu}) of the conventional DC circuit breaker. Once the protection device fails to operate, the busbar may be damaged or the battery may experience thermal runaway. Therefore, in the design of the 800 V AIDC, the maximum short-circuit capacity must be strictly verified and limited.

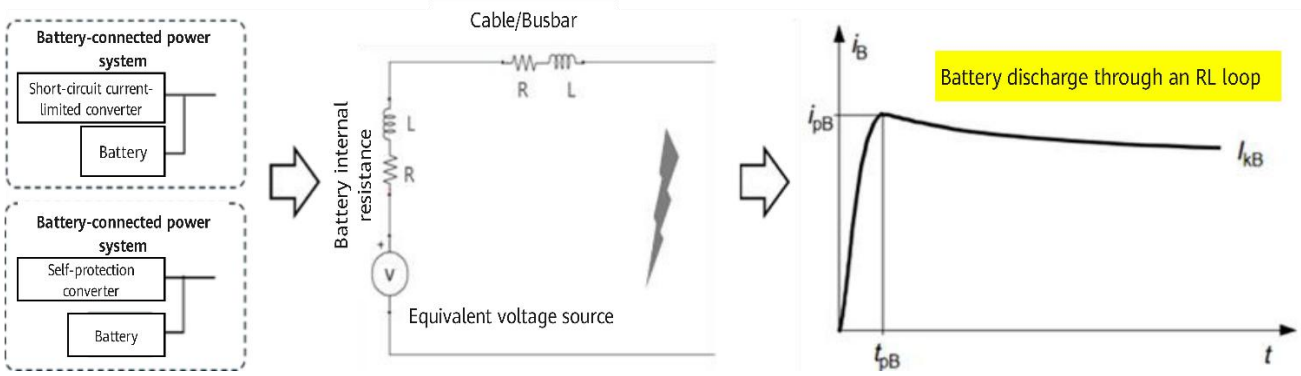


Figure 11 Battery-connected power system and short-circuit fault waveform

5.2.3 Characteristics and Selection of DC Protection Devices

The DC fault current does not have a natural zero-crossing point. If the traditional AC protection solution is directly applied to the 800 V HVDC system, the arc may not be extinguished, which may cause flying arcs or even equipment explosion. Therefore, the AIDC 800 V DC power distribution system must use DC-specific protection devices.

5.2.3.1 Comparison of Characteristics of Common DC Protection Devices

Currently, the mainstream protection and isolation devices in the DC power distribution system include fuses, mechanical DC circuit breakers, SSCBs, and hybrid SSCBs. Table 1 describes the core functions and technical features of each device.

Table 1 Comparison of comprehensive characteristics of different DC protection devices

Category	Fuse	MCB/MCCB	SSCB	Hybrid SSCB
Basic functions	Overload and short-circuit protection: The circuit is passively disconnected by the fuse when the fuse melts due to overheating.	Both circuit protection and control functions are provided. It can automatically or manually disconnect short-circuit and overload currents.	Based on power electronics technologies, the circuit breaker can quickly disconnect the circuit in microseconds using fully controlled components (such as SiC) and energy absorption circuits.	The topology of "mechanical main contact + power electronics branch + energy absorption branch" is used to achieve low conduction loss and fast disconnection within about 1 ms.
Core features	1. The action thresholds are discrete. If the current falls within the overload range, there is a risk that the fuse may be continuously burnt without melting. 2. The fuse status cannot be monitored in real time (auxiliary indicators are required). 3. It is a one-time component and must be	1. Thermal-magnetic two-stage or electronic protection is commonly used. 2. The action time of the thermal-magnetic circuit breaker is discrete. Therefore, the cascading coordination relationship needs to be carefully checked. 3. The disconnection time is long, which is generally at the	1. Provides ultra-high precision arc-free disconnection in microseconds. 2. According to the standard specifications, cascaded disconnector switches must be used to provide physical isolation points. 3. No mechanical wear, extremely long service life. 4. High conduction loss and heat generation during long-	1. During normal operation, the current flows through the mechanical main topology. The conduction loss and temperature rise can be close to those of the MCB, and no complex heat dissipation is required. 2. When a fault occurs, the current is forcibly transferred to the semiconductor branch through a high-speed mechanical switch for

Category	Fuse	MCB/MCCB	SSCB	Hybrid SSCB
	replaced as a whole after a fault occurs.	millisecond level. 4. The contact wear affects the service life.	term operation. In high-current applications, liquid cooling or special heat dissipation design is required.	blocking. 3. The structure is more complex than that of a pure solid-state switch, and the cost is high.
Arc extinguishing capability	Strong (using media such as quartz sand and ceramic particles to cool and absorb arc energy).	Stronger (using the magnetic blowout and grid plate arc extinguishing devices dedicated for DC to elongate and forcibly cool the arc).	Arc-free breaking (The current is directly cut off by the converter or fully-controlled device, and no physical arc is generated.)	Near-arc-free breaking (A very weak arc is generated when the current is transferred by the mechanical main contact.)
Operation with load	Not supported.	Supported and can be reused.	Supported and can be reused.	Supported. If the hybrid switch itself does not have the physical isolation attribute, a mechanical isolation breakpoint is still required.
Operation mode	No operation is required (passive thermal fuse).	Electric/Manual	Electric/Manual	Electric/Manual

5.2.3.2 Key Parameters for DC Circuit Breaker Selection

Considering the complex power fault output characteristics of the 800 V AIDC (such as high di/dt peaks in short-circuit current limiting mode and high steady-state capacity in battery direct connection mode) and the service continuity level requirements, the selection of DC circuit breakers must strictly verify the following core electrical parameters:

- Rated operating voltage (U_e): the maximum DC voltage (nominal value) that the circuit breaker can safely carry, connect, and disconnect under normal and fault conditions.
- Rated current (I_n): The rated current needs to be corrected based on the ambient temperature according to the cable current-carrying capacity specified in the standard, and the high dynamic transient load characteristics of the AI server.

MCB:

- Rated ultimate short-circuit breaking capacity (I_{cu}): the maximum short-circuit current that the circuit breaker can successfully interrupt at a specified voltage without causing explosion or damage to itself.

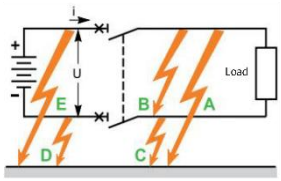
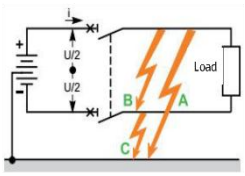
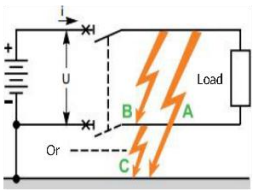
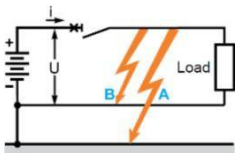
- Rated short-circuit making capacity (I_{cm}): the maximum peak short-circuit current that the circuit breaker can successfully close at a specified voltage, frequency, and time constant without causing contact welding.

SSCB:

- Maximum allowable rate of rise of short-circuit current (di/dt): Maximum allowable current change per unit time increased from zero (or a certain value) when a short circuit occurs or the circuit breaker is turned on. (The value needs to be considered for SSCBs.)

5.2.3.3 Impact of the Grounding System on Protection Selection

When a single or double fault occurs in different DC grounding systems (IT system and TN system), the short-circuit loop path and the voltage applied across the circuit breaker contacts are significantly different. Therefore, the following specifications must be followed during selection.

IT system	**TN system**		
Two-pole protection without grounding	Two-pole protection with midpoint grounding	Two-pole protection with positive or negative pole grounding	Single-pole protection with positive or negative pole grounding
			
Single fault: ◆ Maximum Isc@ under voltage U for two operating poles	Single fault: ◆ Maximum Isc@ under voltage U for two operating poles	Single fault: ◆ Maximum Isc@ under voltage U for a single operating pole	Single fault: ◆ Maximum Isc@ under voltage U with two poles connected in series

IT system	TN system	
◆ IEC 60947-2 does not define the performance requirements of circuit breakers in the case of dual faults. However, from the perspective of safety, dual ground faults should be considered. ◆ If an insulation monitoring system is available, the single ground fault must be eliminated. Therefore, only single ground faults need to be considered.		◆ According to the definition in IEC 60364 (Chapter 42), the TN system can only protect and disconnect the ungrounded pole. ◆ According to IEC 60479-1, the current flowing from the foot to the hand is more dangerous than that flowing from the hand to the foot. Therefore, to prevent electric shocks, it is recommended that the negative pole be grounded. For 800 V AIDC applications, it is not recommended that the positive pole be grounded.

5.2.4 DC System Protection Solution

The protection design of the 800 V DC power supply and distribution system must balance the transient fault suppression capability and global selective protection coordination. By efficiently coordinating the system-level power supply with downstream DC protection devices, faults can be isolated in the minimum local area, ensuring the power safety and service continuity of the GW-level computing power cluster.

Considering the complexity of transient faults in the DC system, it is recommended that system-level simulation analysis be performed before determining the protection solution for the 800 V DC power supply system of the AIDC. This helps determine the short-circuit current waveform and the short-circuit current path in various possible scenarios, providing a theoretical basis for selecting the system protection solution.

5.2.4.1 DC System Power Characteristics and Protection Solution Selection

The system needs to be configured with differentiated DC protection solutions based on the different DC power supply characteristics and backup battery coupling architecture of the data center.

Table 2 DC system power characteristics and protection solution selection

Power Characteristics	Battery Connection Mode	Source of Short-Circuit Energy	Recommended Protection Solution	Description
Battery-connected power system	Batteries are directly connected to the busbar.	Mainly from battery discharge.	◆ Fuse + MCB	The short-circuit current caused by battery discharge may exceed the breaking capacity

Power Characteristics	Battery Connection Mode	Source of Short-Circuit Energy	Recommended Protection Solution	Description
				of the MCB. Therefore, a fuse is required.
Short-circuit current-limited power system	Batteries are connected through DC/DC converters.	From the PSU itself or an independent current-limited device.	◆ MCB ◆ SSCB	If the MCB is used, the time for maintaining the current limiting of the power system is required.
Self-protection power system	Batteries are connected through DC/DC converters.	The short-circuit energy time is extremely short (at the μs level) due to self-protection.	◆ SSCB	The SSCB is used to disconnect the fault before the power module enters the lockout protection state.
Uncontrolled power system	N/A	AC system short-circuit energy.	◆ Fast fuse ◆ SSCB	The fast fuse can only prevent the fault from escalating in extreme cases, and cannot ensure that the power system itself is not damaged.

Note: In the AIDC architecture, it is not recommended to use an independent uncontrolled power system. Instead, an independent fault current-limited device must be installed.

5.2.4.2 Comparison of DC protection solutions

The following table compares the two mainstream core protection technologies and their comprehensive benefits in the industry.

Table 3 Comparison of DC power supply system protection solutions

Solution	Power Module Current Limiting + MCB Solution	Power Module Self-protection + SSCB Solution
Characteristics	1. This solution is a classic electrical control and mechanical arc extinguishing collaboration solution. 2. When a short circuit occurs at the end, the upstream power module uses the fault ride-through algorithm to proactively limit the	1. This solution is a modern intelligent power distribution solution with all-electric power electronics. 2. The power module does not limit the current during fault ride-through. When a fault occurs,

Solution	Power Module Current Limiting + MCB Solution	Power Module Self-protection + SSCB Solution
	current within the safe threshold, providing a sufficient time window (millisecond level) for the downstream MCB to trip and extinguish the arc.	the downstream SSCB is used to cut off the current in microseconds. 3. The SSCB also needs to meet the di/dt requirements in transient state.
Advantages	1. **Reliable and cost-effective breaking performance:** This is a mature and standardized solution. MCBs have natural physical isolation points, and the overall system cost is low. 2. **Low operating loss and temperature rise:** The contact resistance of the mechanical contactor is extremely low (micro-ohm level) when it is normally closed. Therefore, the operating loss and junction temperature rise are almost zero, and the power distribution rack does not require a complex forced cooling or liquid cooling system. 3. **Simple structure and no need to configure additional isolation breakpoints:** MCBs have physical isolation attributes and do not need to be configured separately, which further reduces the operating loss.	1. **Ultra-fast isolation and unperceivable self-healing:** The fault breaking time of the SSCB is reduced to less than 10 µs. In such a short time window, the DC busbar voltage does not drop significantly. The non-faulty branches are completely unaware of the entire process. 2. **No arc and nearly infinite electrical service life:** Since the semiconductor fully-controlled device has no contact point, no physical arc is generated during disconnection, eliminating the risk of flying arc fire. There is no mechanical wear or contact erosion, and the device is suitable for extremely high-frequency protection operations. 3. **Highly integrated protection functions and software-defined design:** The internal high-frequency current/voltage sensor can be used to predict the di/dt change trend in real time through the software control algorithm, implementing adaptive and programmable protection curve design. 4. **No involvement of power modules:** Power modules are only responsible for their own self-protection and do not need to be configured with complex FRT current limiting algorithms.
Disadvantages	1. **Severe busbar voltage drop:** During the operation and arc extinguishing of the MCB, the upstream power modules are forced to be in the current limiting state. As a result, the DC busbar voltage drops sharply during the	1. **High energy consumption and heat dissipation during long-term operation:** Semiconductor power devices have an inherent conduction voltage drop. When a large current continuously flows through the devices,

Solution	Power Module Current Limiting + MCB Solution	Power Module Self-protection + SSCB Solution
	fault clearance period. 2. **Slow fault isolation:** It takes a long time to clear a short circuit fault, which may trigger the switchover of the redundant power supply in the data center, but will not affect service continuity. 3. **High dependency on the power module algorithm:** Once the FRT current limiting algorithm of the upstream power module fails, occasional failure or response during a short circuit. The system protection may fail due to the lag.	continuous static conduction loss and heat are generated. For large-current applications in GW-level equipment rooms, air-cooled heat sinks or even liquid cooling mechanisms need to be configured. 2. **High cost:** The cost of power modules and energy-absorbing buffer loop materials that meet the 800 V high voltage and high current specifications is high. Currently, the cost of SSCBs is several times higher than that of traditional MCBs. 3. **Significant vulnerability of power electronic devices:** They are sensitive to electrical stresses such as voltage and current, and have small heat capacity and small junction temperature margin. Therefore, irreversible damage may occur in transient and overload conditions. A proper safety margin must be considered during the design.

For the core pain points of GW-level AI supercomputing data centers, such as the sharp increase in power density of a single rack and huge economic loss caused by power failures, SSCBs will become the ideal choice for DC power supply system protection in the long run, when the technology matures and the cost decreases.

5.2.5 Capacitor Discharge and Multi-Power Supply Attributes of DC Systems

In the traditional AC power supply and distribution architecture of data centers, the power frequency transformer is used as the only active power supply point, and the current and power flow in a fixed unidirectional manner (single-ended power supply system). In this case, the protection device can be configured based on the classic radial network. The fault current flow path is clear, and the protection coordination is relatively simple.

However, when the GW-level AIDC is upgraded to the 800 V HVDC architecture, the fundamental physical characteristics of the system undergo a fundamental transformation. The entire system exhibits strong capacitive characteristics and complex distributed multi-power supply attributes.

5.2.5.1 Strong Capacitive Characteristics of the DC Flexible Power Supply System

To achieve voltage stability, smooth power ripple, and support transient high dynamic loads of AI servers, a large number of physical capacitor banks are connected in parallel in the 800 V DC network. These invisible or visible capacitors to ground and between poles form the physical capacitive basis of the system:

1. **Sources of the system's capacitive characteristics**
   - **Converter port support capacitors/bulk capacitors:** These are extremely large in number and are located in the upstream SST, high-power rectifier, and bidirectional battery DC/DC converter. They are used to absorb high-frequency switching ripples and reduce noise.
   - **Dynamic power capacitors (CBUs/capacitor racks):** These are independent devices on the power distribution side of the data center, and are specifically used to smooth the EDPp (dynamic power peak) caused by the intensive burst of AI servers. However, they are currently mostly connected to the busbar through DC/DC.
   - **Input filter capacitors on the load side:** These are connected in parallel to the PSU input terminals inside tens of thousands of high-density AI server racks.
   - **Parasitic stray capacitance:** This is generated by the parasitic capacitance of long-distance, large cross-sectional area cables, busbars to ground, between phases, and power components in the GW-level data hall.
2. **Dual-edged sword effect of capacitive characteristics**
   - **Engineering advantages:** Large-capacity capacitors act as energy buffers, achieving efficient voltage stability and dynamic decoupling, and smoothing the transient current disturbance and EMI caused by high-frequency switching of power electronic components. In addition, the microsecond-level energy charge and discharge provide instantaneous power support (or virtual inertia) for the system, enhancing the system's capability to suppress dynamic disturbances.
   - **Security disadvantages:**
     - **Surge during initial power-on:** The extremely low startup impedance causes complex precharge management problems. When the switch is turned on, a large number of capacitors are charged, causing a transient surge impact.
     - **Resonance risk:** The system may easily experience nonlinear resonance with the long-distance distributed inductance of the line, which can cause high-frequency voltage oscillation and destabilize the control loop of the upstream converter.
     - **Short-circuit fault peak:** Once a metallic short circuit occurs in the system, all capacitors on the entire link will discharge all their charge within a microsecond-level window, generating an extremely high current rise rate (di/dt) and a high peak value of the transient short-circuit current.

5.2.5.2 Impact of the Capacitor Discharge Waveform on Circuit Breaker Selection

According to the comparison and analysis between simulation and physical models, the waveform of the DC system short-circuit fault is fundamentally changed after the capacitor discharge is introduced. As a result, the traditional DC short-circuit calculation model in IEC 60947-2 is no longer applicable to the 800 V AIDC scenario.

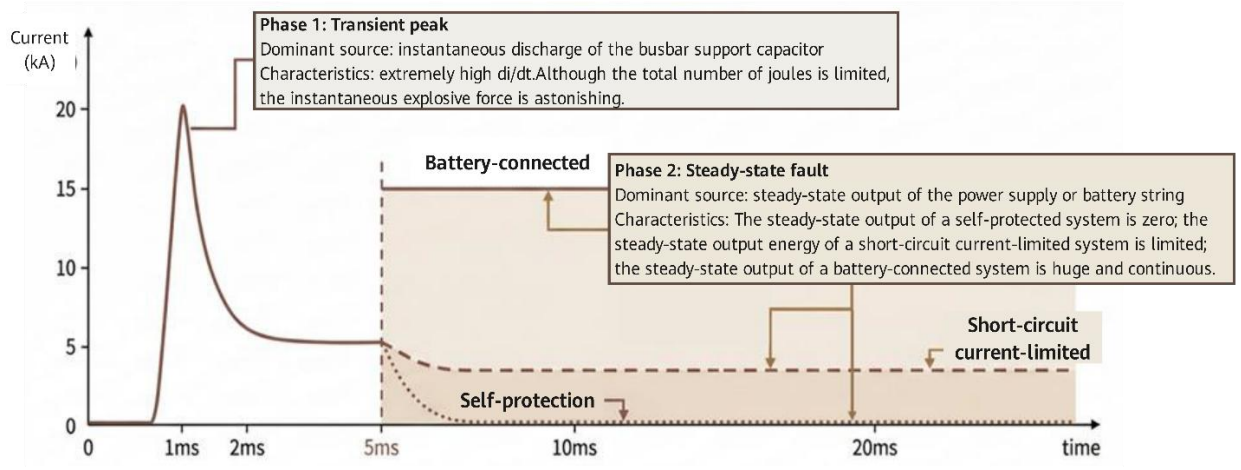


Figure 12 DC short-circuit current waveform

The short-circuit fault current of the system with the capacitor discharge transient state and the steady-state short-circuit output system shows a distinct two-phase evolution in the time domain:

- **Phase 1: Transient peak**
  - **Dominant feature:** In the microsecond-level window after a short circuit occurs, the busbar and port support capacitors discharge instantaneously.
  - **Mapping to circuit breaker selection:** In this phase, an extremely high di/dt transient surge peak is generated.
    - When the **MCB** is used, the **rated short-circuit making capability (I_{cm})** of the system is directly affected. The circuit breaker must be able to withstand the huge electromagnetic repulsion and mechanical impact caused by the current at the moment of closing. Therefore, the verification of I_{cm} becomes a key indicator, which is used to prevent contact bounce, arc flash, and welding.
    - When the **SSCB** is used, the interruption occurs in the transient rising phase, and the di/dt in the current rising phase needs to be considered.
- **Phase 2: Steady-state fault**
  - **Dominant feature:** After the millisecond-level discharge ends, the capacitor energy is exhausted, and the short-circuit current enters the steady state determined by the characteristics of the power supply side.
  - **Mapping to circuit breaker selection:**
    - When the **MCB** is used, the steady-state short-circuit energy in this phase is the main factor that determines the **rated ultimate short-circuit breaking capacity (I_{cu}/I_{cs})** of the circuit breaker. As mentioned above, in the modern AIDC flexible power distribution network, if a self-protection or short-circuit current limiting converter is used, the steady-state current in phase 2 will be quickly reduced or cut off. As a result, the actual steady-state energy faced by the circuit breaker during the interruption is limited, which reduces the rigid pressure on the arc-extinguishing thermal stress of I_{cu}.
    - When the **SSCB** is used, the disconnection occurs in the transient rising phase, which does not affect the selection of the SSCB.

5.2.5.3 Challenges in the Complex "Multi-Source and Multi-Directional" Topology

In addition to the overall strong capacitive characteristics, the 800 V DC power distribution network of the GW-level data center has completely overturned the traditional "single-source and single-directional" waterfall-type radiation network. As shown in "Figure 13 Multi-source and multi-directional system architecture", the power distribution network integrates the following:

1. The **mains active node**, which is composed of SSTs or medium-voltage rectifiers.
2. Multiple groups of **distributed large-capacity battery (BESS) nodes** that are directly connected to the grid through bidirectional DC/DC converters or directly on-grid.
3. **Load branch nodes** that may have reverse discharge of port capacitors (bulk capacitors and X capacitors).
4. Other possible energy access modes.

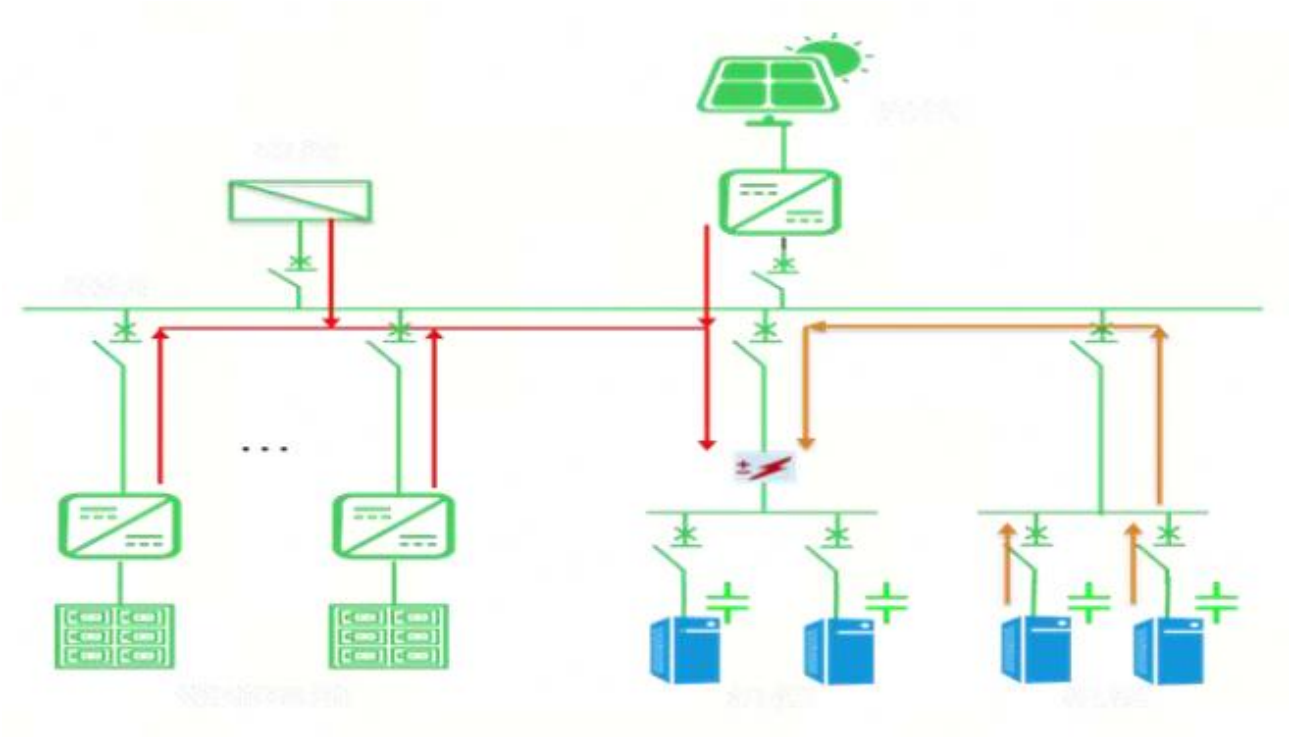


Figure 13 Multi-source and multi-directional system architecture

Three protection challenges brought by the multi-source network:

- **Multi-directional interleaving of fault currents:** When a metallic short circuit occurs on a rack branch or the main busbar of the power distribution system in the network, the short-circuit energy at the fault point is not only from the mains rectifier side, but also from all the capacitors at the input end of the PSU in the adjacent rack and the adjacent battery string. Considering possible capacitor discharge, all power distribution branches in the entire DC system may become actual fault sources at the moment of the fault.
- **Complex and variable magnitude and direction of short-circuit current:** The amplitude and direction of the total fault current depend on the relative physical position where the short circuit occurs, the concurrent access capacity of each power source, and the instantaneous state of charge (SOC) of each battery string. In a multi-source network, the traditional overcurrent tripping

or inverse-time protection benchmark, which is based on a single direction and fixed current direction, is prone to cause large-scale failure to operate or non-selective cascading misoperations.

- **Failure of traditional analysis tools and standard methods:** The analysis tools and simplified formulas based on single-ended impedance coordination are no longer applicable. A refined transient control simulation model with all active nodes must be established. It is recommended that directional protection be introduced to key backbone nodes to meet the strict selective disconnection requirements on each possible short-circuit path.

5.2.6 Insulation Monitoring

In the AIDC 800 V DC power supply system, in addition to overcurrent and short circuit protection components, insulation monitoring is also the core of ensuring global safe operation. The main purpose of insulation monitoring is to detect the insulation resistance between the positive and negative busbars and each power distribution branch and the ground in real time. This helps trigger early warnings before skin contact leakage, insulation layer thermal aging, or breakdown occurs, preventing single-phase grounding faults from evolving into severe inter-pole short circuits or electric shock accidents that endanger personal safety.

Faced with the high voltage (800 V), high-frequency ripple (converter PWM modulation noise), and impact on the ground capacitance of GW-level AI supercomputing centers, the mainstream insulation monitoring technologies in the industry exhibit distinctly different physical characteristics.

5.2.6.1 Solution 1: Traditional Balanced Bridge Method

- **Basic principle:** A precision high-resistance tap with the same value is connected in parallel between the positive and negative DC busbars and the ground (PE). The insulation resistance is computed based on the offset of the voltage between the midpoint and the ground in real time.
- **Technical advantages:** The topology is extremely simple, the hardware cost is extremely low, and no external signal source needs to be actively injected into the power distribution network.
- **Technical limitations: There is a complete blind spot for symmetric fault detection**. When the insulation resistance of the positive and negative poles to the ground decreases at the same time and in the same proportion, the system cannot detect the fault. In addition, this solution is susceptible to high-frequency switching noise, and the false positive rate is high in the 800 V high ripple environment. The detection principle depends on the busbar voltage, and the fault cannot be detected when the busbar voltage is zero.

5.2.6.2 Solution 2: Unbalanced Switching Bridge Method

- **Basic principle:** A controlled electronic switch is introduced based on the balanced bridge. By periodically switching the asymmetric state of the resistance between the positive and negative poles and the ground, two groups of different sampling points of the voltage between the ground and the positive and negative poles are used to construct a system of simultaneous equations. The algorithm is used to demodulate the insulation resistance between the positive and negative poles and the ground.
- **Technical advantages:** This solution overcomes the blind spot of the traditional balanced bridge method, which cannot detect symmetric faults. The hardware topology is relatively simple, the cost is moderate, and the solution can be easily deployed in a modular and distributed manner on power distribution branches at all levels.
- **Technical limitations:**
  - **Speed bottleneck:** In the case of a large capacitance, the RC time constant is extremely large, which greatly prolongs the measurement period and significantly reduces the resistance

detection precision. The detection principle depends on the busbar voltage, and the fault cannot be detected when the busbar voltage is zero.

- **High sensitivity to high-frequency interference:** In the case of high voltage and high ripple, the switching noise severely pollutes the sampling points, which significantly reduces the calculation precision in the high-power operating range.

5.2.6.3 Solution 3: Low-frequency Signal Injection Method

- **Basic principle:** A low-frequency (typically 0.1–10 Hz) sine wave or square wave AC signal is actively injected between the DC busbar midpoint and the ground (PE). The attenuated signal and phase difference in the loop are extracted using a high-precision current transformer and digital signal processing, thereby accurately calculating the insulation resistance to ground.
- **Technical advantages:** This technology perfectly addresses the comprehensive detection of both symmetric and asymmetric grounding faults. Due to the extremely low frequency of the injected signal, it can effectively penetrate the capacitive interference of the system to ground and resist high-frequency interference. Additionally, full-isolation high-voltage physical protection is achieved through coupling capacitors, ensuring high system security. It overcomes the issue of long single detection cycles associated with unbalanced bridges in high-capacitance environments, enabling fast response within seconds. By extracting the phase difference between the voltage and current of the injected signal in the loop, high insulation resistance detection accuracy can be maintained even in high-capacitance environments. The signal injection method ensures that detection does not depend on the busbar voltage, allowing detection even when the busbar voltage is zero.
- **Technical limitations:** The algorithm is complex, and the initial R&D and software computing power hardware costs are relatively high.

In summary, based on the physical conditions of GW-level AIDCs with high power density and large capacitance to ground, low-frequency active injection insulation monitoring technology will become a better choice in extreme computing environments.