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White Paper on

Grid-Forming Energy Storage Systems



TrinaStorage

Trina Storage Co., Ltd. (Jiangsu)

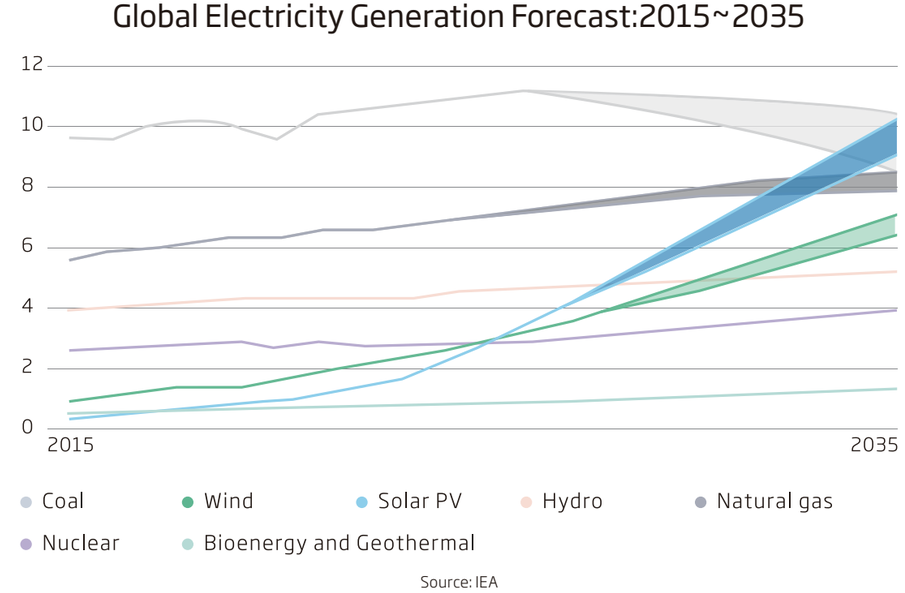
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Foreword

In response to rapid transition of global energy systems, the fundamental logic of the power industry is reshaping with unprecedented force. Guided by the "carbon peak and carbon neutrality" goals, renewable energy is transforming from a supplementary force into a primary source within the energy system. According to the IEA forecasts, the penetration rate of renewable energy in the electrical power sector will rise from 32% in 2024 to 43% by 2030, which highlights the characteristics of a "high renewable penetration and high power-electronic interfaced" power system. The large-scale integration of renewable energy sources, the intermittency and variability of renewable energy sources, along with the inherent features of conventional power electronic devices, namely "low inertia and weak grid support", are profoundly altering the operational dynamics of power systems. Grid stability is facing significant challenges, urgently necessitating the support of grid-forming technologies, which are available in the latest electronic converter products.

Trina Storage innovatively proposes a holistic grid-forming solution integrating three systems, namely ElecOS[1], Electra[2], and Elementa[3], enabling a transition from device-level functions to system-level capabilities. This integrated system has already been deployed across multiple projects in power grids worldwide, demonstrating its proven capability in real-world grid-forming applications and contributing to the development of stronger and smarter power systems.



Source: IEA

1 ElecOS: Plant-level energy management and power control system.
2 Electra: Integrated PCS and transformer solution for power conversion.
3 Elementa: DC-side battery energy storage system.

Table of Contents

Part 1. Grid-Forming Energy Storage in Practice ---- 01

1.1 PGT 250MW/500MWh_ Localized Compliance Delivery in Australia ---- 01

1.2 Copiapó Stages I+II 450MW/1700MWh ---- 02

1.3 Key insights from project practice ---- 03

Part 2. Grid Stability Concepts and Grid-Forming Technologies ---- 04

2.1 Metrics for Measuring Grid Strength ---- 04

2.2 Key Factors Affecting Grid Stability ---- 05

2.3 Grid Fluctuation Types ---- 07

2.4 Mainstream Grid Forming Technologies and Differential Analysis ---- 08

Part 3. Concepts and Challenges of Grid Forming Energy Storage ---- 10

3.1 Fundamental Concept of Grid Forming Energy Storage: The “Intelligent Anchor” of the Grid ---- 10

3.1.1 Comparison with Grid Following Energy Storage ---- 10

3.1.2 Voltage and Frequency Source Characteristics: Actively Establishing the “Rhythm and Tension” of the Grid ---- 10

3.1.3 Virtual Inertia and Damping Emulation: Injecting “Physical Memory and Stabilizer” into the Grid ---- 11

3.1.4 High Overcurrent and Short Circuit Support Capability: Providing Much Needed “Grid Strength” ---- 11

3.1.5 Black Start Capability: The “Spark of Life” for the Grid ---- 12

3.2 Current Technical Challenges ---- 13

3.2.1 Seamless Multi-Mode Switching and Stability ---- 13

3.2.2 Coupling of Frequency Response in Multiple Time Scales ---- 13

3.2.3 Dynamic Coordination of Voltage Support and Reactive Power Management ---- 14

3.2.4 Technical Bottlenecks in Black Start Scenarios ---- 14

Part 4. Trina Storage Grid Forming Energy Storage Solution ---- 15

4.1 Assurance: End-to-End System Integration Verification Capability ---- 15

4.1.1 Trina Storage Vertically Integrated System Layout ---- 15

4.1.2 20MVA Validation Center ---- 16

4.2 Grid-Forming Foundation: DC container ---- 18

4.3 Zero Awareness Adaptive Control Technology Under Grid Disturbances ---- 20

4.4 Multi-Scale Frequency Response Coordinated Control Technology ---- 22

4.5 Full Range Voltage Reconstruction Technology ---- 26

4.6 Full Process Black Start Technology ---- 28

Summary and Outlook ---- 30

Part 1
Grid-FormingEnergy Storage in Practice

Trina Storage has accumulated grid-forming project experience in key markets worldwide (Fig. 1.1), which present very different grid operating conditions and regulatory requirements, combining integrated system solutions with localized engineering and project delivery capabilities.

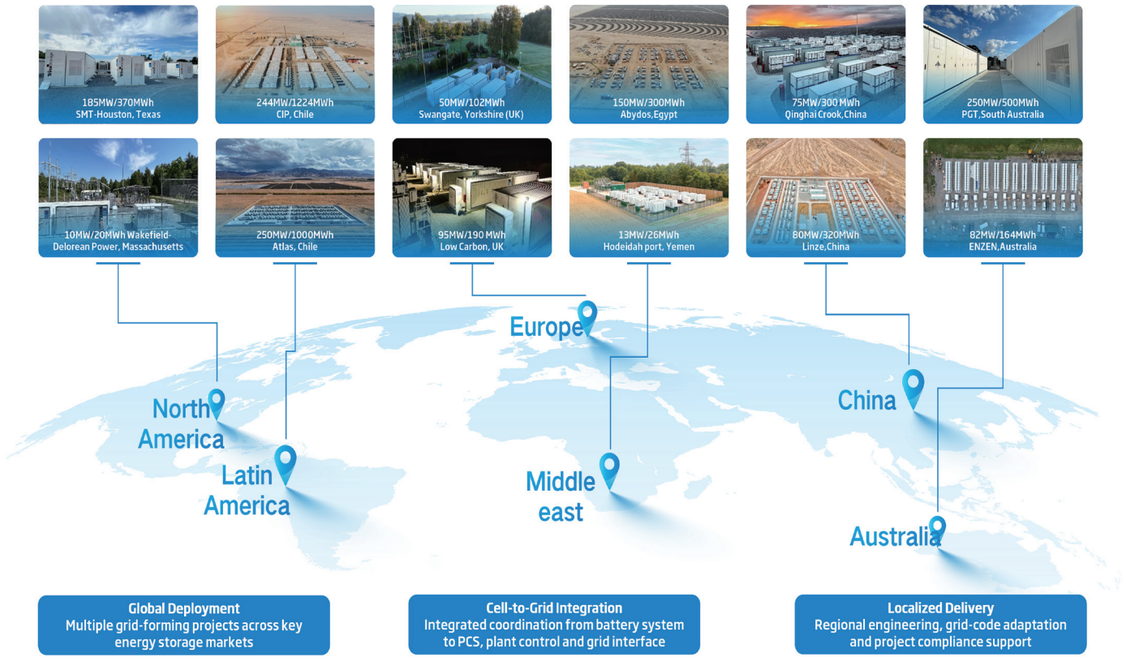


Fig. 1.1 28GWh+ Integration Experience in Global Markets

1.1 PGT 250MW/500MWh Localized Compliance Delivery in Australia

The power grid of Australia presents a typical "long radial" structure, where a single fault can trigger severe cascading failures (like falling dominoes), therefore, energy storage equipment deployed in Australian projects is required to possess grid-forming capability. As the largest standalone energy storage project in South Australia, the PGT project adopts a full grid-forming model (Fig. 1.2). Trina's local professional service team led the R1 model construction and validation, proactively identified risks affecting R1 model accuracy. Trina's proposed systematic solutions successfully passed the Australian Energy Market Operator (AEMO) technical compliance review, and all Battery Energy Storage System (BESS) (DC/PCS/PPC)-related technical Q&A on schedule.

South Australia's Largest Grid-Forming Project : PGT 250MW/500MWh

PGT is South Australia's largest stand-alone energy storage project, utilizing a full grid-forming model.

Managed end-to-end GPS process by a local professional service team

An local professional service team leads R1 model development and validation, proactively identifies risks to model accuracy, proposes systemic solutions, and ensures successful passage of AEMO technical compliance review.

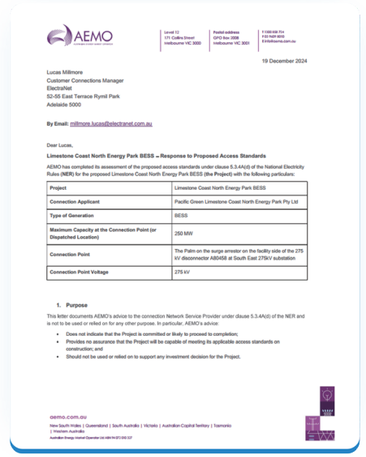
Leads the on-time completion of all BESS(DC container, PCS, PPC) technical Q&A.

- Provides all BESS control curves required for the R1 model
- Provides control logic documentation for the actual equipment

Possesses deep expertise in the AEMO R1 grid connection process for new projects. Capable of leading multi-party coordination (Consultant GSMT,BOP GGC, suppliers) and efficiently delivering all required technical submissions.

- Precise Project Schedule Control
- Drives the reduction of review cycles
- Ensures seamless project handover and delivery

Product certified to Australian standards AS3000/AS5139


AEMO

19 December 2024

Lucas Millmore
Customer Connections Manager
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Adelaide 5000

By Email: millmore.lucas@electranet.com.au

Dear Lucas,

Limestone Coast North Energy Park BESS – Response to Proposed Access Standards

AEMO has completed its assessment of the proposed access standards under clause 5.3.4A(d) of the National Electricity Rules (NER) for the proposed Limestone Coast North Energy Park BESS (the Project) with the following particulars:

Project	Limestone Coast North Energy Park BESS
Connection Applicant	Pacific Green Limestone Coast North Energy Park Pty Ltd
Type of Generation	BESS
Maximum Capacity at the Connection Point (or Dispatched Location)	250 MW
Connection Point	The Palm on the surge arrester on the facility side of the 275 kV disconnector ABS6/8 at South East 275kV substation
Connection Point Voltage	275 kV

1. Purpose

This letter documents AEMO's advice to the connection Network Service Provider under clause 5.3.4A(d) of the NER and is not to be used or relied on for any other purpose. In particular, AEMO's advice:

- Does not indicate that the Project is committed or likely to proceed to completion;
- Provides no assurance that the Project will be capable of meeting its applicable access standards on construction; and
- Should not be used or relied on to support any investment decision for the Project.

Fig. 1.2 Overview of the PGT project

1.2 Copiapó Stages I+II 450MW/1700MWh

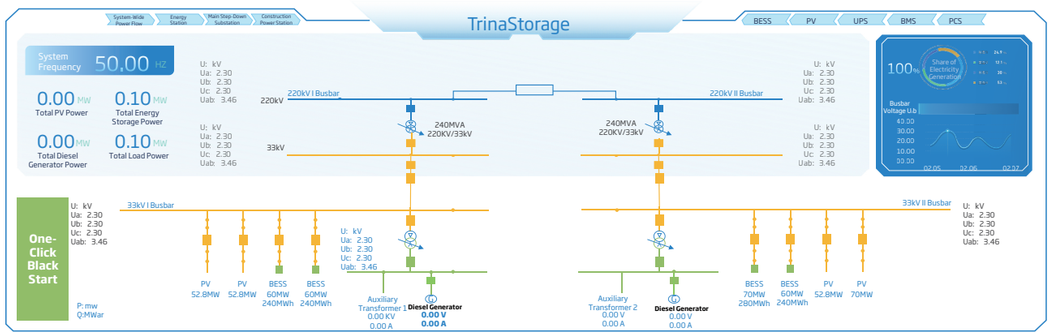
Trina Storage, partnered with Atlas Renewable Energy, a world-leading renewable energy developer, supplies and maintains the largest grid-forming energy storage project in Chile, and the whole Latin American area. This project aims to supply clean energy to Chile's national grid while enhancing its resilience (Fig. 1.3 and Fig. 1.4).

With the increasing renewable penetration across Latin America, reduced system inertia and deteriorated system stability (e.g., voltage and frequency stability) are proposing growing challenges for safe and reliable grid operation, particularly under weak-grid and high-volatility conditions. Trina Storage's local engineering and compliance teams work closely with the project stakeholders to interpret grid-code requirements of Chile and translate them into project-specific system design, control, modelling, and validation, with coordinated BESS, Power Converter System (PCS), and plant-level controls to support compliance and grid integration.

The Copiapó project in Chile adopts an advanced grid-forming control strategy, enabling the energy storage system to exhibit voltage-source characteristics. This allows the system to autonomously establish voltage and frequency without external grid support, and to provide services such as black start, synthetic inertia, damping oscillation suppression, and active RoCoF response. The system significantly enhances the grid's disturbance rejection capability, suppresses wide-band oscillations, and maintains reliable power supply to critical loads during grid faults or outages, which effectively improve the reliability of the regional power grid. In the event of a voltage fluctuation or power outage, the system exhibits stable operating performance, which effectively prevents fault propagation, and provides reliable support to Chile's national grid.

Latin America's Largest Grid-Forming PV-BESS Proiect: Atlas 250MW/1000MWh

Chile's National Electric System (SEN) is characterized by its ultra-long distance, low-inertia grid, high renewable penetration, and extensive weak-grid areas. Consequently, there is an urgent need for energy storage to provide critical frequency support, virtual inertia, and short-circuit capacity compensation.



Station Wide Grid-Forming Black Start

Self-synchronization of over 80 PCS units enables synchronous black start of the entire station.

Key Metric: Synchronous Black Start Time ≤180 seconds

Millisecond-level voltagesource stabilization

Providing high-quality power for the entire station.

Key Metric: Response Time ≤ 300 ms

Load Start

Virtual inertia supports large disturbances, enabling direct starting of heavy loads and transformers.

Key Metric: Withstanding ≥ 80% step-load impact

Automatic On-Grid/Off-Grid Transitio

Ensuring seamless integration on the high-voltage side.

Key Metric: Synchronization Error ≤ 1°

Strong Support for Weak Grids

Stable operation in extremely weak grids, providing short-circuit capacity and phase-stabilizing support.

Key Metric: Minimum Stable SCR ≥ 1.1

GFM/GFL Seamless Transfer

Seamless switching between grid-forming and grid-following modes.

Fig. 1.3 Overview of the Copiapó project

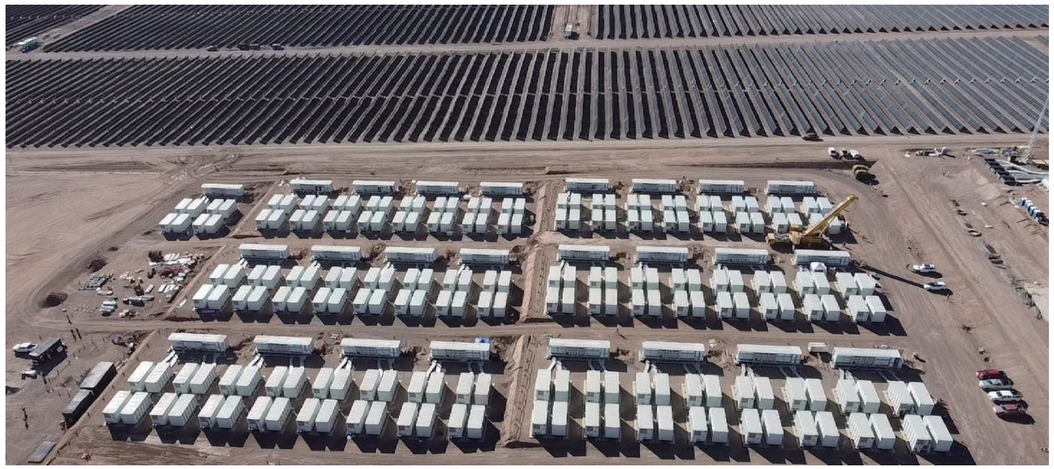


Fig. 1.4 A photo of the project site

1.3 Key insights from project practice

Challenges such as multi-mode switching, multi-time-scale frequency response, coordinated voltage support, and black start cannot be addressed through standalone converter functionality alone.

They require coordinated integration across battery systems, PCS, plant-level controls, system models, and grid interfaces, together with localized engineering and compliance expertise. Trina Storage brings these capabilities together to translate local grid requirements into validated, deliverable system-level solutions.

Part 2
Grid Stability Concepts and Grid-Forming Technologies

Grid stability refers to the ability of a power system (Fig. 2.1) to maintain key parameters such as frequency, voltage, and power angle within permissible ranges following a disturbance, and to restore equilibrium within a given period of time. If the grid becomes unstable, it may suffer from sudden frequency drops, voltage collapses, or even large-scale blackouts, leading to terrible consequences to power supply, industrial production, and social life. In 2021, persistent high temperatures in France triggered wildfires that caused cascading failures on cross-border transmission lines. The resulting decline in grid frequency activated Under Frequency Load Shedding (UFLS) schemes, leading to disconnections of a large amount of load and severely impacting local industrial operations and domestic daily life.



Fig. 2.1 A photo of a part of a power grid

2.1 Metrics for Measuring Grid Strength

Grid strength is an important metric for measuring a power system's ability to resist disturbances and maintain synchronism. A strong grid means the system has high inertia and high short circuit capacity, while a weak grid is the opposite. The common metrics for measuring grid strength are briefly introduced in the following subsections.

Short Circuit Ratio

Short Circuit Ratio (SCR) serves as a "pulse indicator" for measuring grid strength. It is defined as the ratio of the short circuit capacity of the system to the capacity of the connected power source. When the SCR is greater than 3, the grid is considered robust. At this level, the system has ample inertia and stable voltage support, responding to disturbances with composure and resilience. When the SCR falls below 2, the grid becomes fragile. In this condition, the system becomes exceptionally sensitive to external disturbances, where even minor fluctuations can trigger severe voltage and frequency oscillations, potentially leading to system instability and disconnections of grid-connected resources (generators, consumers and storage assets).

System Inertia

System inertia is the comprehensive manifestation of the rotating mass of all synchronous generators in a power system. When system inertia is abundant, frequency is very stable, with slow and gentle fluctuations, leaving enough time for frequency regulation response. When inertia is scarce, frequency becomes less stable, with steep and fast

variations, making frequency regulation significantly more challenging, and the system constantly faces the risk of losing its stability altogether.

Impedance Characteristics

System impedance ratio (X/R ratio) determines the grid's response characteristics to current variations and directly affects voltage stability. When the X/R ratio is high, the grid is strong, providing robust voltage support, with voltage and power changes less likely to interfere with each other. When the X/R ratio is low, the grid is weak, where voltage may collapse rapidly, potentially triggering cascading failures and endangering system security.

2.2 Key Factors Affecting Grid Stability

Grid stability is not only determined by the inherent strength of the grid itself, but is also affected by grid size, grid topology, compositions of power sources and loads.

Grid Size and Topology

Grid size can affect system inertia and stability. Large scale grids usually have a large system size, with more conventional generating units distributed across the network, resulting in high inertia, and the impact of disturbances is easily dispersed (Fig. 2.2). Small, isolated grids, on the other hand, are the opposite. They have limited regulation resources, experience larger fluctuations in frequency and voltage, and are prone to instability. Grid topology is also a relevant factor: radial/linear grids are usually weaker than more densely meshed grids.



Fig. 2.2 A photo of a part of a large-scale grid

Power Source Type

In a power system, different types of power sources contribute to grid stability in fundamentally distinct ways. Conventional synchronous units, such as thermal and hydroelectric plants, provide inherent inertia and short circuit current capability through their physical rotors, spontaneously supporting frequency and voltage. These units serve as the cornerstone of stable operation in traditional power grids. Grid-following power sources rely on phase-locked loops to track grid phase and require external provision of voltage and frequency references. They can operate normally in strong grids, but their stability performance degrades significantly in weak grids, making it difficult for them to actively support the system. Grid-forming power sources overcome these limitations. They are capable of autonomously establishing voltage and frequency, emulating the behavior of synchronous generators to actively provide synthetic inertia and support power system stability. Grid-forming sources (Fig. 2.3) are particularly suitable for weak grids, isolated operation, and scenarios with high penetration of renewable energy sources, which makes them a critical component for the stable operation of future power systems.

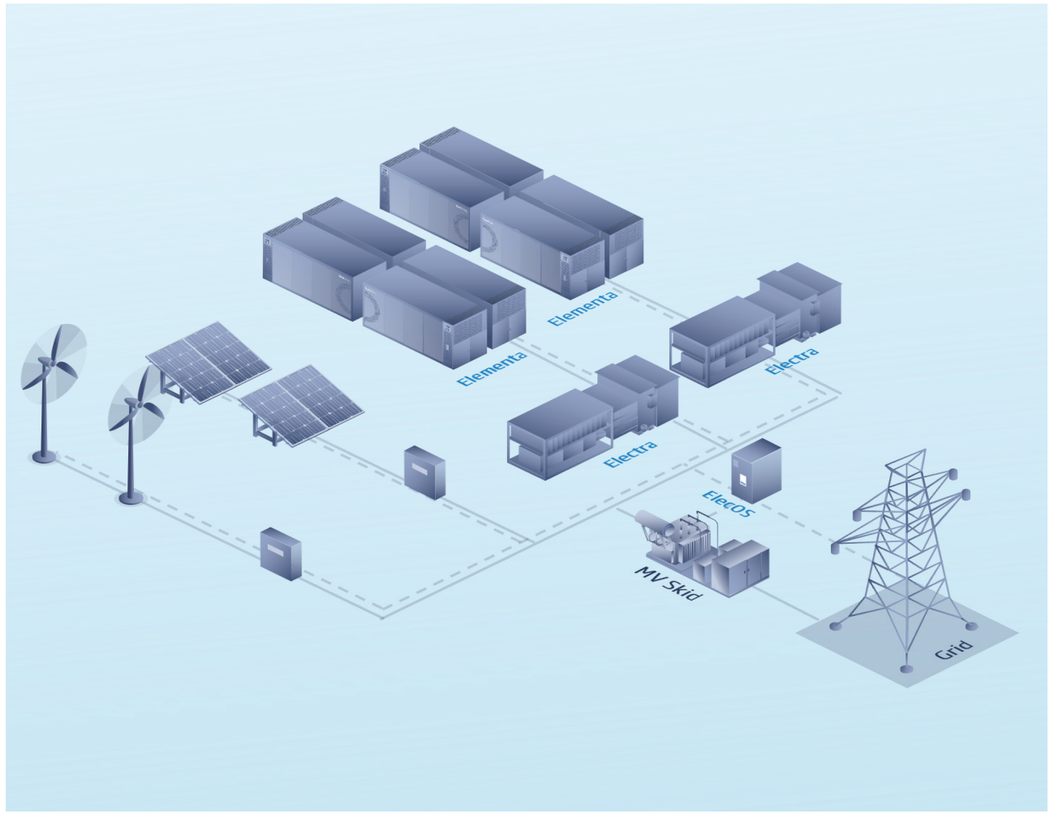


Fig. 2.3 An illustrative example of Trina Storage's solutions

Load Type

Stationary high loads, such as those found in urban clusters and industrial zones, are characterized by large power demand and high density. They act like a heavy object suspended at the center of a spider web, requiring the grid to possess enough strength and sustained support capability. Impactful loads, such as fast charging electric vehicles, exhibit irregular and sudden fluctuations in load demand, continuously challenging the grid's dynamic response and instantaneous regulation capability.

The current development of power grids is simultaneously facing the dual challenges of emerging structural weaknesses, marked by the high penetration of renewable energy integration, and increasing systemic shocks, driven by the growing prevalence of impact loads. These combined factors render the issue of grid stability to be more complex and urgent than ever before.

2.3 Grid Fluctuation Types

Grid fluctuations are mainly classified into three types: frequency fluctuations, voltage fluctuations, and power angle disturbances. These three types of fluctuations reflect different aspects of system stability.

Frequency Fluctuation

Frequency directly reflects the real time balance of active power across the entire grid. In traditional power grids, where synchronous generators serve as the cornerstone and system inertia is abundant, frequency fluctuations are gentler, and frequency regulation margins are relatively large. In the era of high penetration of renewable energy, however, system inertia is significantly reduced, and the rate of change of frequency increases dramatically (Fig. 2.4). This leads to a significant rise in frequency regulation pressure, posing severe challenges to grid frequency stability.

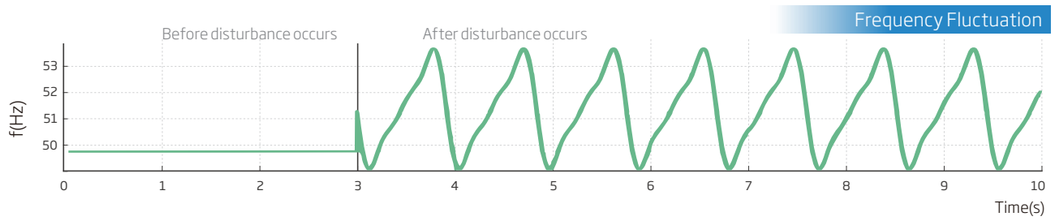


Fig. 2.4 An illustrative example of frequency fluctuation

Voltage Fluctuation

In power grids with high X/R ratios (e.g., transmission systems), voltage stability is primarily determined by the reactive power balance of the system. When reactive power supply is insufficient, voltage support becomes inadequate, leading to voltage drops. This phenomenon of voltage fluctuations (Fig. 2.5) is particularly pronounced at the far end of long-distance transmission lines, for example, during the startup of large motors. In weak power grids, where the system lacks sufficient voltage strength, even minor disturbances can trigger significant voltage fluctuations. Without timely intervention, such conditions can easily lead to voltage collapse incidents.

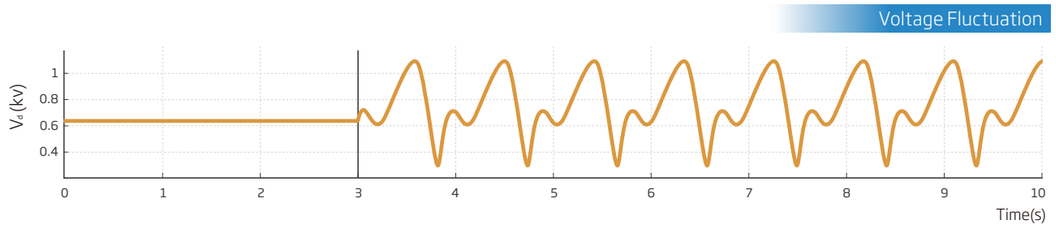


Fig. 2.5 An illustrative example of voltage fluctuation

Power Angle Disturbance

Power angle refers to the relative electrical angle (referring to the reference machine) between generator rotors. When a disturbance occurs, the power angle oscillates. If such an oscillation continues to grow, it will lead to loss of synchronism in the system. Synchronous machines naturally provide power angle stability. In power systems with high renewable penetration levels, however, the lack of inertia and synchronous support can easily trigger low frequency oscillations, which may subsequently result in loss of synchronism (Fig. 2.6).

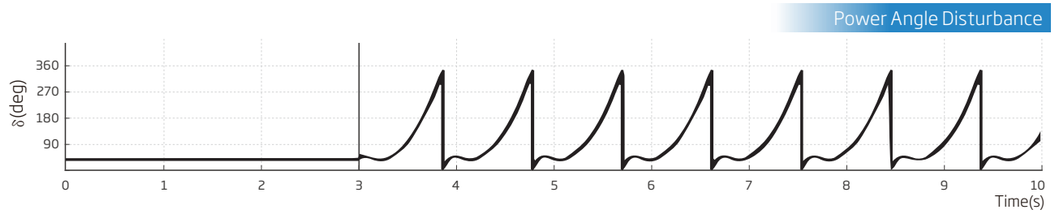


Fig. 2.6 An illustrative example of power angle disturbance

In summary, the current power grid is undergoing a systemic "genetic transformation": the cornerstone of stability, namely synchronous power sources, is being extensively replaced by new components that respond quickly but heavily dependent on external signal references, namely conventional power electronic sources. This is not a simple "component replacement" but a profound systemic transformation. The consequence is not instability per se, but rather a paradigm shift in grid stability. The "free" stability services inherently provided by the physical characteristics of synchronous power sources, including inertia, voltage support, and short circuit capability, are diminishing, creating a significant "stability deficit". Bridging this deficit cannot be achieved by reverting renewable energy sources to behave like synchronous machines. Instead, it requires the adoption of new technologies that equip renewable energy sources with active support capabilities, namely grid-forming technology, within the latest generation power electronics converter products.

2.4 Introductions of Common Grid-Forming Technologies

To address weak grid issues, the common grid-forming support solutions currently available in the industry mainly include small synchronous condensers, grid-forming static VAr generators (SVG), grid-forming static synchronous condensers (SSC), and grid-forming energy storage systems (with grid-forming control in their PCS).

Small Synchronous Condenser

A small synchronous condenser is essentially a synchronous machine operating without mechanical load （Fig. 2.7）. Its stability capability derives from physical characteristics rather than control algorithms. By virtue of its actual rotating mass, a synchronous condenser provides physical inertia, short circuit current support, reactive power support, and power angle synchronization capability. It can participate in grid support immediately upon disturbance without requiring control intervention, exhibiting natural and reliable support performance. During fault conditions, it can deliver large short circuit current, which facilitates protective relay operation and voltage recovery. As a mature technology validated over a century, its operating behavior is highly predictable. However, its limitations are also evident, i.e., the equipment is large in size, requiring high investment and maintenance costs. Furthermore, it cannot participate in active power regulation, its response speed is constrained by mechanical limitations, and it lacks flexible deployment capabilities, making it difficult to adapt to distributed scenarios.



Fig. 2.7 A photo of a synchronous condenser

Grid-Forming Static VAr Generator (SVG)

A grid-forming SVG (Fig. 2.8) is essentially a fast reactive power compensator based on power electronic-based control. It provides voltage support by regulating reactive current on a millisecond timescale. Its advantages include fast response speed, compact structure, and lower cost compared to synchronous condensers, which makes it suitable for deployment at substations and plant sites. However, its limitations are also evident. SVG does not provide true physical inertia and cannot mitigate the rate of change of frequency. Its short circuit current capability is limited, resulting in insufficient support during severe faults. Furthermore, it can only address voltage related issues and cannot participate in frequency and power angle stability regulation at the system level.



Fig. 2.8 A photo of SVG

Grid-Forming Static Synchronous Condenser (SSC)

A SSC (Fig. 2.9) emulates the characteristics of a synchronous machine through control algorithms. It can actively establish voltage, provide synthetic inertia, and possess droop control capability. However, its energy source (available energy for providing grid support services) is limited, resulting in constrained inertia support capability.



Fig. 2.9 A photo of SSC

Grid-Forming Energy Storage

Grid-forming energy storage (Fig. 2.10) is not simply "energy storage + converter". Its essence lies in enabling the energy storage system to act as a "voltage source" for the grid through the PCS control system, rather than operating as a grid dependent "current source". It possesses capabilities to support frequency stability, voltage stability, and power angle stability.

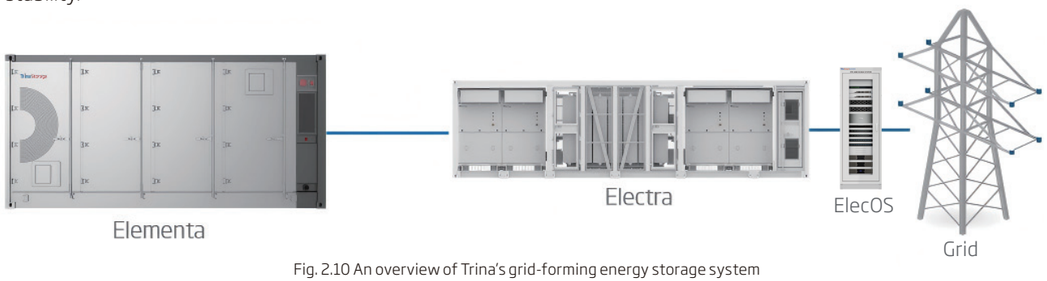


Fig. 2.10 An overview of Trina's grid-forming energy storage system

Part 3
Concepts and Challenges of Grid-Forming Energy Storage System

3.1 Fundamental Concept of Grid-Forming Energy Storage System: The "Intelligent Anchor" of the Grid

In modern power grids, a grid-forming energy storage system is not merely an energy storage device, but rather a new type of power support unit that actively participates in grid stability regulation. Through high-performance power electronic converters and sophisticated real time monitoring and control algorithms, a grid-forming energy storage system is capable of autonomously establishing stable voltage and frequency references, effectively serving as an "intelligent anchor" within a complex, dynamic, and potentially unstable grid environment and providing a reference point and stability support for the surrounding system. Furthermore, under completely de-energized conditions, it can act as the "first spark" of the grid to initiate the entire system black start procedure.

3.1.1 Comparison with Grid-Following Energy Storage System

The main difference between grid-forming and grid-following energy storage systems essentially lies in their distinct output control modes and interaction logic with the grid (Fig. 3.1). Conventional grid-following energy storage devices operate in current source mode, relying on the external grid to provide voltage and frequency signals. They achieve synchronization through a phase locked loop (PLL) and then inject controlled current into the system based on previous set active and reactive power commands. Their control objectives focus on stable power output and good grid adaptability. Such devices typically perform well under conditions where the grid structure is robust and voltage and frequency signals are clear, making them the mainstream technology adopted by most grid connected renewable energy sources and energy storage systems today.

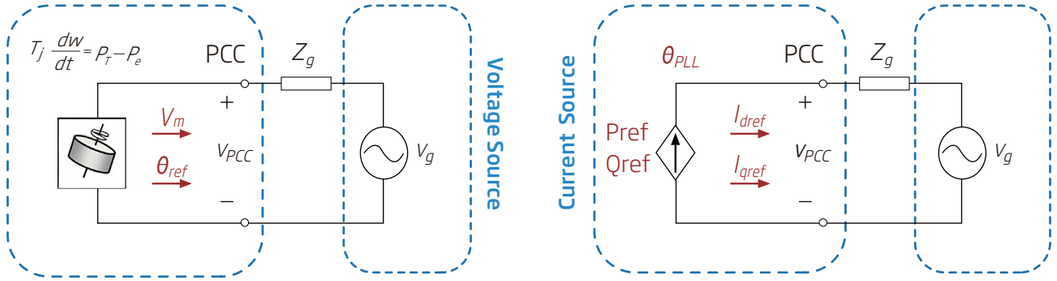


Fig. 3.1 Representations of a voltage source (left) and a current source (right)

3.1.2 Voltage and Frequency Source Characteristics: Actively Establishing the "Rhythm and Tension" of the Grid

Grid-forming energy storage system is capable of directly generating stable voltage waveforms. It can autonomously generate a steady state voltage at the point of interconnection. A grid-forming energy storage system, while operating within its operational limits, can stabilize and support the local grid voltage through precise reactive power control, allowing the local system to operate without waiting for the external grid to recover (Fig. 3.2). As for frequency, grid-forming energy storage system generates and maintains a stable system frequency through active power control, automatically guiding surrounding distributed energy generation resources and loads to synchronize with it, thereby avoiding frequency disorder (Fig. 3.3).

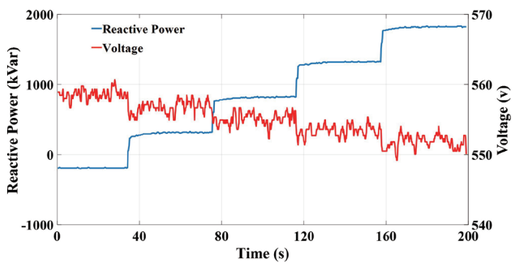


Fig. 3.2 An illustrative example of reactive power response of a grid-forming energy storage system during a low voltage transient (1.0p.u.-0.98p.u.-0.96p.u.-0.94p.u.-0.92p.u.)

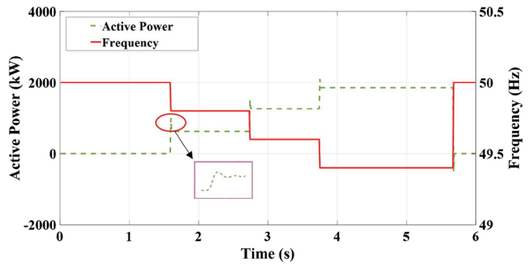


Fig. 3.3 An illustrative example of active power response of a grid-forming energy storage system during a frequency variation (50Hz-49.8Hz-49.6Hz-49.4Hz-50Hz)

3.1.3 Synthetic Inertia and Damping Emulation: Injecting "Physical Memory and Stabilizer" into the Grid

The rotating part of a synchronous generator inherently possesses inertia, which provides a buffer during frequency fluctuations and reduces the magnitude of those fluctuations. In grid-forming energy storage systems, the output active power is naturally driven by the phase angle difference between the internal electromotive force and the grid voltage, enabling a fast and spontaneous response that opposes frequency changes (Fig. 3.4). This mechanism perfectly replicates the physical inertia of a synchronous generator rotor, endowing the grid with self-buffering capability during disturbances (Fig. 3.4).

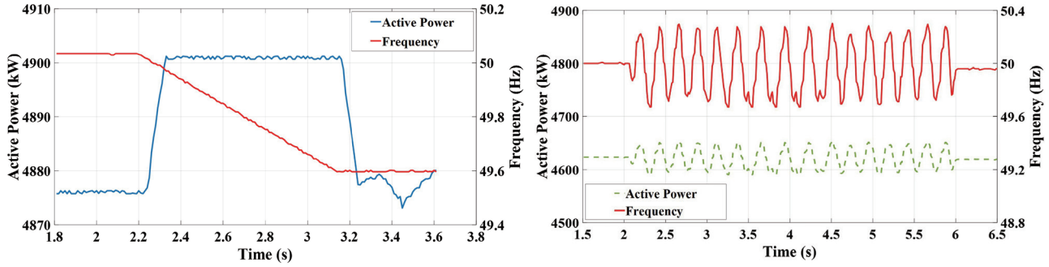


Fig. 3.4 Illustrative examples of frequency (RoCoF) response (left) and damping response (right) of a grid-forming energy storage system

3.1.4 High Overcurrent and Short Circuit Support Capability: Providing Much Needed "Grid Strength"

In weak grid scenarios, insufficient short circuit capacity is a major cause of protection device malfunction and frequent system collapse. Grid-forming energy storage systems, by enhancing its controllable overcurrent capability, can "hold up" the grid at critical moments. Unlike the overcurrent protection logic of conventional power electronic devices, grid-forming energy storage systems can deliver current several times above its rated value for a limited duration while maintaining controllability,thereby achieving fault ride through and voltage support objectives (Fig. 3.5)

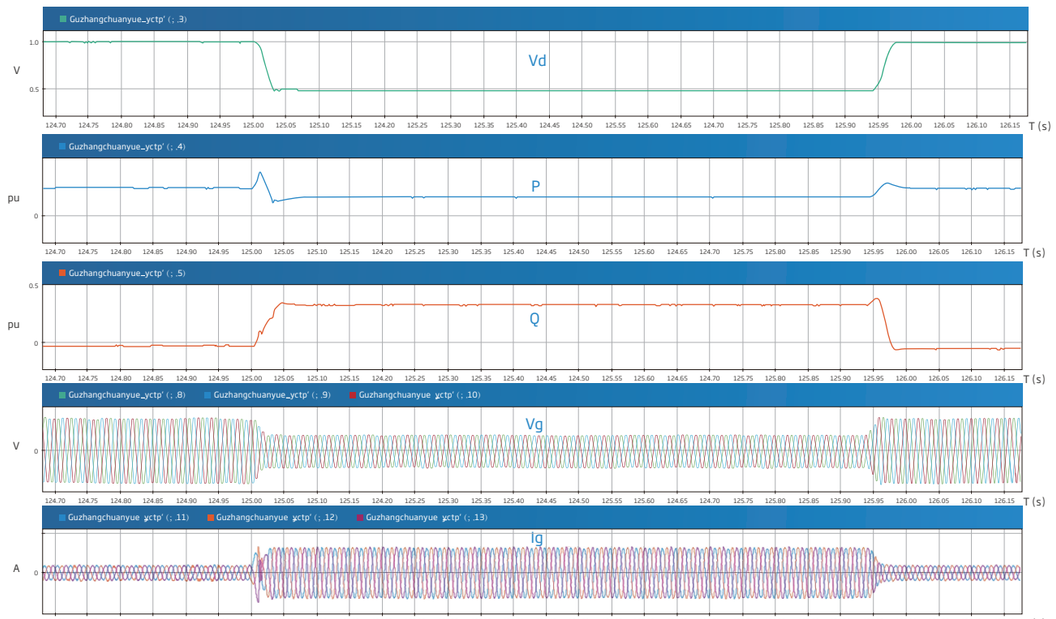


Fig. 3.5 Measurements of a grid-forming energy storage system during a grid voltage sag event

3.1.5 Black Start Capability: The "Spark of Life" for the Grid

Black start refers to the process of restoring a grid after a complete blackout by using a device that requires no external power supply to start up and recover the grid. Under completely de-energized conditions, grid-forming energy storage system establishes voltage and frequency reference without relying on any external power supply (Fig. 3.6). It then progressively re-connects generators and critical facilities (loads) according to a strategy that prioritizes essential loads, preventing transient surges and subsequent collapse (i.e., rapidly establishing a small-scale grid with stable voltage and frequency, and then gradually expands it).

This is like a spider on a damaged and motionless web. The spider first weaves a small, stable patch of new web with rhythmic vibration, and then continuously expands it from that foundation until the entire system is restored.

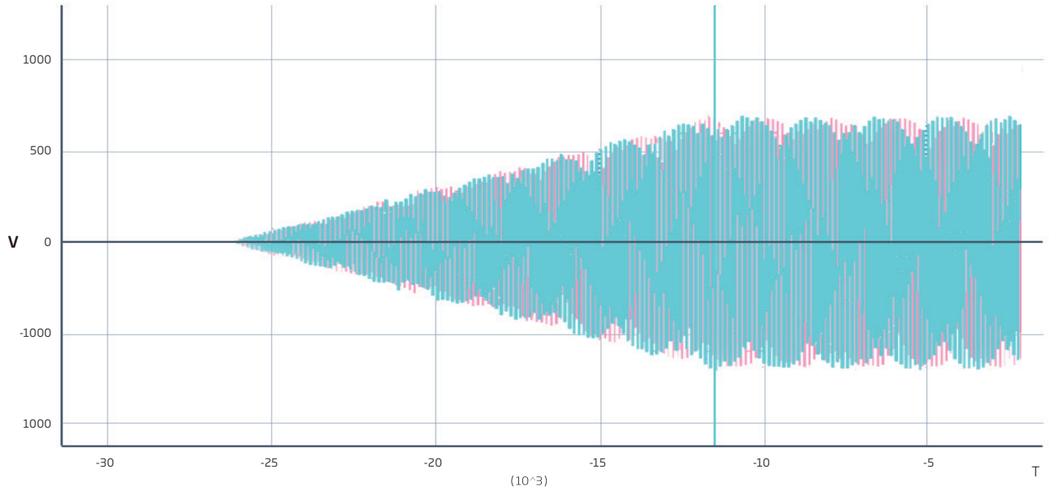


Fig 3.6 Voltage measurements of a grid-forming energy storage system during black start

3.2 Current Technical Challenges

3.2.1 Seamless Multi-Mode Switching and Stability

With respect to seamless multi-mode switching and stable operation, the core technical challenge lies in achieving smooth transitions between grid connected and islanded modes. The control objectives, reference benchmarks, and dynamic response characteristics of the two modes are fundamentally different. How to ensure that the switching process (between grid connected and islanded modes) is free of deteriorating transient and does not trigger unstable system oscillations has become the critical challenge in control algorithm design. Insufficient synchronization accuracy in voltage phase and amplitude during such transitions can easily generate inrush currents, leading to equipment damage or even system instability. Furthermore, inappropriate control actions may also cause the SCR to drop instantaneously from a very strong grid condition (e.g., SCR = 100) to an extremely weak grid condition (SCR= 1.0). The drastic change in grid impedance further exacerbates the complexity of the switching process. Changes of grid topology or faults may also cause instantaneous phase jumps in voltage, making conventional PPL-based control architectures highly susceptible to loss of synchronism and disconnection under such disturbances. Achieving smooth PCS control mode switching and stable operation under various complex operating conditions, including wide range fluctuations in grid strength, abrupt impedance changes, and phase angle jumps, are critical bottlenecks that grid-forming energy storage systems must overcome.

3.2.2 Coupling of Frequency Response in Multiple Time Scales

Within the frequency response framework, the three core functions, namely synthetic inertia support, primary frequency regulation, and secondary frequency regulation, cover regulation requirements ranging from several milliseconds to several seconds. The control objectives at different time scales exhibit inherent coupling and potential conflicts. Synthetic inertia support within several milliseconds suppresses the rate of change of frequency (RoCoF) through rapid injection or absorption of active power. However, excessive frequency response may superimpose with the droop control of primary frequency regulation, leading to frequency overshoot. Meanwhile, primary frequency regulation relies on droop control to achieve power frequency response. If the frequency response mismatches the command update cadence of second level secondary frequency regulation (i.e., Automatic Generation Control (AGC)), it can easily cause frequency oscillations or regulation lag. Conventional solutions struggle to achieve optimal response across different disturbance scenarios, further highlighting the coupling conflicts in multi-time scale frequency controls. Achieving smooth transitions among the above-mentioned frequency controls during dynamic processes represents a critical technical bottleneck that the frequency response function of grid-forming energy storage systems must overcome (Fig. 3.7).

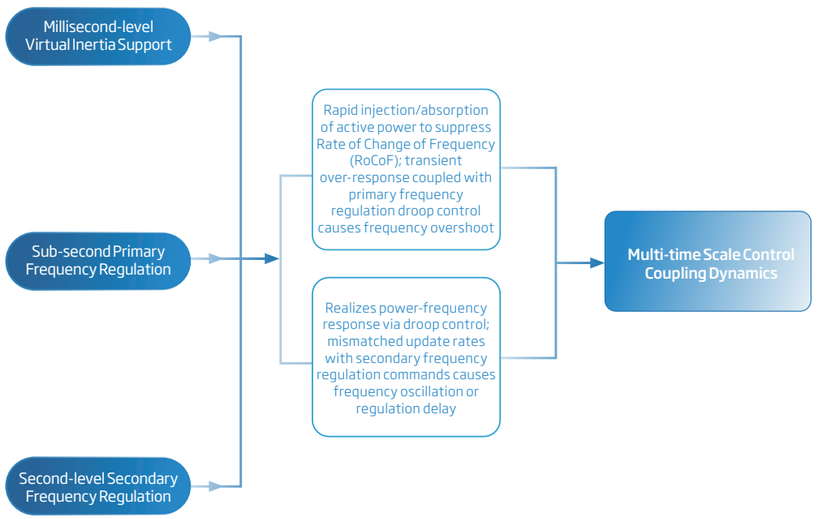


Fig. 3.7 Structure of Multi-time scale coupling of frequency response

3.2.3 Dynamic Coordination of Voltage Support and Reactive Power Management

The coordination among transient fault ride through, steady state primary voltage regulation, and regional secondary voltage regulation (i.e., Automatic Voltage Control (AVC)) also presents significant challenges of grid-forming energy storage systems. Fast reactive power injection during fault ride through must prioritize system voltage stability, but this may conflict with the reactive power allocation objectives of steady state voltage regulation. The difference in response speed between regional AVC commands and local primary voltage regulation droop control can easily lead to voltage regulation lag or overregulation. Achieving natural layering of the above-mentioned voltage controls based on physical mechanisms, smooth transition during dynamic processes, and intelligent trade-offs in cases of control objectives conflict represents a critical technical bottleneck that the voltage support function of grid-forming energy storage systems must overcome (Fig. 3.8).

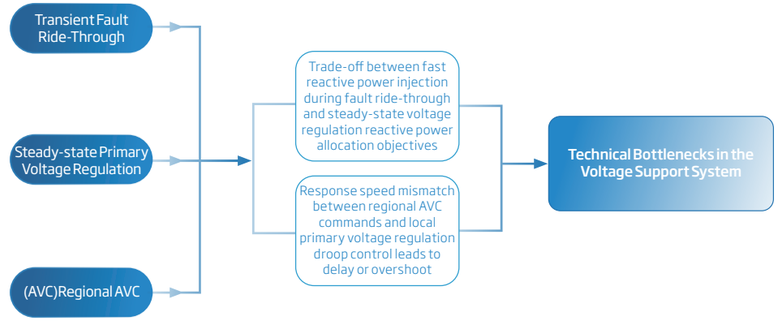


Fig. 3.8 Structure of dynamic coordination of voltage support and reactive power management

3.2.4 Technical Bottlenecks in Black Start Scenarios

In a black start scenario, the grid-forming energy storage system contributes to several necessary processes, including building up a voltage reference from scratch, multi-machine parallel operation, source-load balancing, and grid synchronization. When building up the voltage reference from scratch, improper control of the voltage ramp up curve can easily cause a high inrush current in transformers due to sudden voltage changes, leading to startup failure. In the multi-machine parallel operation phase, each PCS must synchronously establish its voltage reference. Conventional approaches relying on top-level communication are susceptible to communication delays, resulting in inconsistent startup timing, and large circulating currents due to different voltage amplitude and phase. In the source-load balancing phase, if the impact of load connection (such as large induction motors) cannot be effectively mitigated, the established voltage may collapse again. During the grid synchronization phase, insufficient synchronization accuracy in voltage phase and frequency can produce a massive inrush current upon direct closing of the circuit breaker. Achieving expected performance and functions in all above-mentioned black start processes represents a critical technical bottleneck that grid-forming energy storage system must overcome (Fig. 3.9).

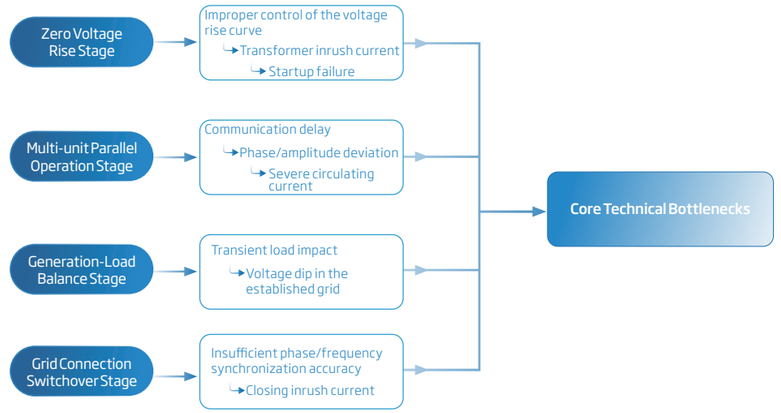


Fig. 3.9 Technical bottlenecks in black start scenario

Part 4
Trina Storage Grid-Forming Energy Storage System Solution

The Trina Storage grid-forming energy storage system is not merely a breakthrough in a single device, but rather a full stack technological reconfiguration ranging from cell to system and from hardware to software. In grid-forming scenarios, the three core units, which will be introduced and discussed later in this part, perform their distinct roles while achieving deep coordination.

4.1 Assurance: End-to-End System Integration Verification Capability

4.1.1 Trina Storage Vertically Integrated System Layout

The energy storage industry faces an excessively wide technology span, requiring the integration of multidisciplinary knowledge and experience to accurately match system capacity/power and perform validation. In the meantime, each project is highly customized, demanding clearly specified technical parameters, functional requirements, and performance indicators based on project characteristics and appropriately matched equipment. To address these challenges, Trina Storage has established an Advanced Energy Storage Integration Center (AEI) (Fig. 4.1), where a professional algorithm optimizes system coordination, enabling full life-cycle management and control, and ensuring safer, more stable, and longer-lasting operation of energy storage systems. Building on the AEI, Trina Storage has further established a System Solution Research Institution, focusing on in-depth research into grid-forming system technologies and covering areas such as simulation technology research and empirical grid-forming validation. Although most power electronics manufactures confine grid-forming technology to a single power electronic device, we believe that the essence of a grid-forming system lies in the coordination and interaction among multi-level equipment.

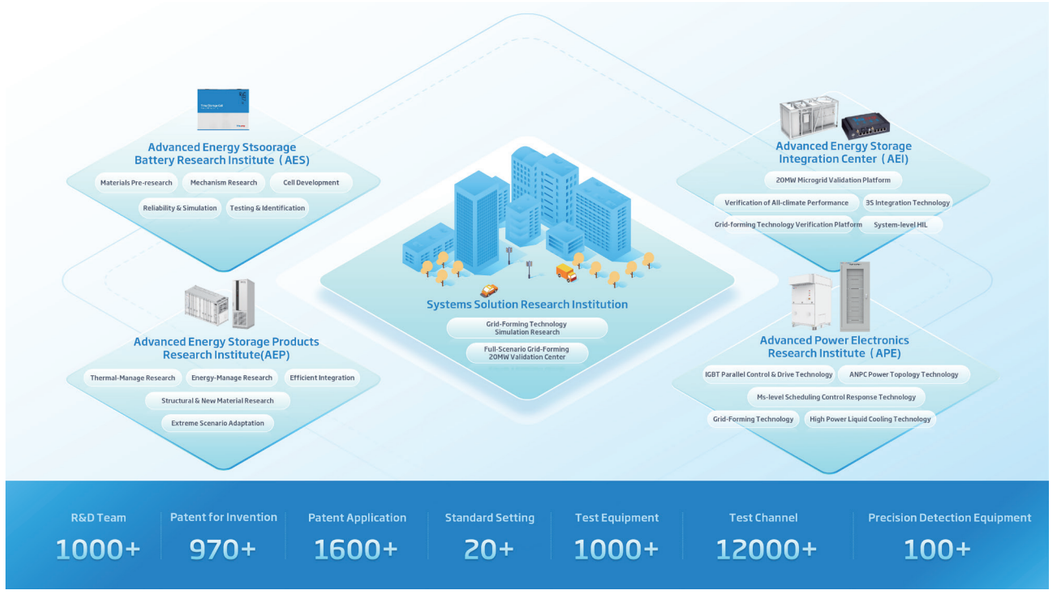


Fig. 4.1 Vertically integrated system portfolio developed by Trina Storage

Systems Solution Research Institution

The System Solution Research Institution comprises a Grid-Forming Technology Simulation Center and a 20MVA Validation Center (Fig. 4.2). The Grid-Forming Technology Simulation Center is primarily responsible for core functions such as system-level technical feasibility analysis, stability and compliance verification, and control strategy development and optimization. It ensures implement ability, safety, and compliance of energy storage projects and fully supports early-stage power grid planning, including system-level power flow calculations, plant-level system stability analysis, and high/low voltage ride-through verifications. The Grid-Forming Technology Simulation Center also integrates in-house Electromagnetic Transient (EMT) modelling, Hardware-in-the-loop (HIL) testing, and MW-level grid simulators, representing software-only, software-plus-hardware, and full-hardware verifications. Additionally, the simulation center supports steady-state analysis, power quality assessment, and control principal simulation, it also supports system optimization tests under complex operating conditions, covering grid-forming application scenario validation and iterative algorithm development.

On the basis of meeting the overall validation requirements for grid-forming PCS products and grid-forming energy storage systems, the Validation Center further expands its empirical testing capabilities for solar-storage-diesel microgrids, providing customers with grid-forming system solutions for diverse application scenarios.

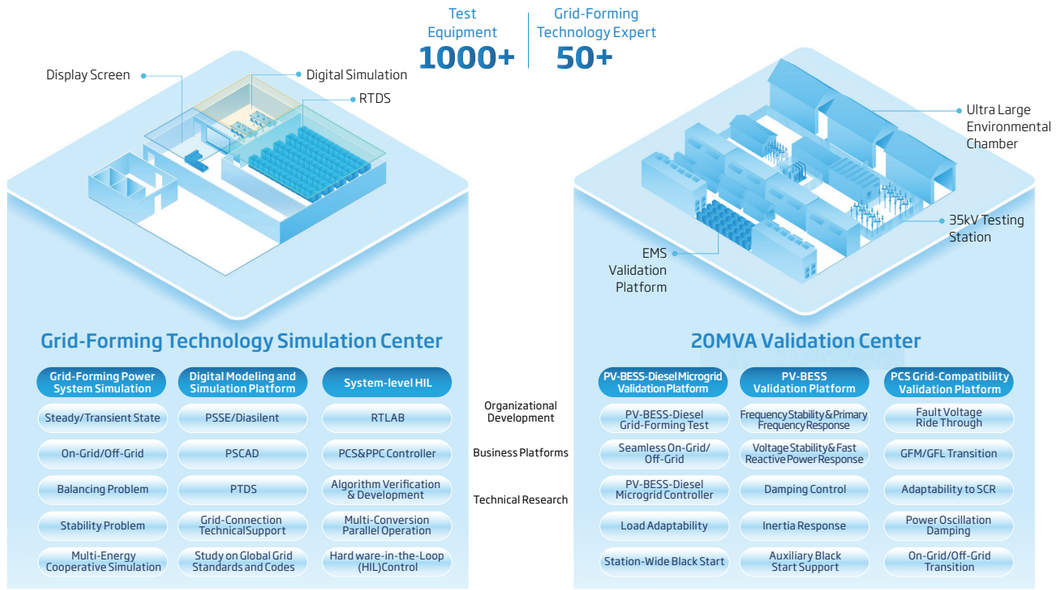


Fig. 4.2 Systems solution research institution in Trina Storage

4.1.2 20MVA Validation Center

Trina is building a grid-forming 20MVA back-to-back validation platform (Fig. 4.3). As a core grid-forming energy storage system integration platform, the validation center will comprehensively address the shortcomings of existing testing facilities and create a rare industry facility for medium- to high-voltage, large-capacity energy storage system integration verification. The platform covers two voltage levels, i.e., 22kV (±10%) and 35kV, with a core capacity of 20MVA. Leveraging the existing foundation from the first-phase renovation project in 2025, the validation center will be upgraded and completed with optimized high-voltage cable routing and well-planned equipment locations. The platform can perform a huge number of tests and studies, such as block-level grid-forming/black-start tests, system integration commissioning, grid-forming tests of large-capacity (e.g., 10/12.5/13.8MVA) medium-voltage integrated machines, prototype verification, type tests, as well as project integration commissioning test at the 22kV (±10%) medium-voltage side. It serves not only as a dedicated experimental platform for energy storage system coordination and energy management, but also as a platform for Factory Acceptance Testing (FAT) and customer witnessing for local and international projects, providing full-link technical verification support for the deployment of grid-forming energy storage system solutions.

Additionally, the Trina Storage system integration validation platform is built upon four R&D laboratories, including the first self-built 35kV medium-voltage station, an Ultra-large Drive-in Environmental Chamber (ULDC), an AC-side system integration validation field, a 1:1 System-level HIL, EMS validation platform. All tests conducted on the platform follow a four-level verification framework, supporting customized energy storage solutions. The platform rigorously simulates system energy efficiency and stability experiments in a closed-loop manner. It performs block-level integration commissioning and pre-testing considering extreme operating conditions, communication consistency, etc., thereby mitigating grid-connection risks upfront and shortening delivery cycles.



Fig. 4.3 A photo of the 20MVA Validation Center

The first self-built megawatt-level 35kV station (Fig. 4.4) breaks through the environmental and resource constraints associated with third-party sites. Operating within a 35kV medium-voltage grid environment, the system simulates field station layouts to carry out block-level cascading pre-commissioning tests, verifying key indicators such as high-voltage grid connection performance, and accelerating on-site grid-connection acceptance. With advantages including 24*7 flexible test scheduling and end-to-end deep verification, the system provides strong support for the smooth delivery of energy storage system products.



Fig. 4.4 A photo of the 35kV medium-voltage substation

Within the Trina's west test site, two industry-leading environmental chambers have been built (Fig. 4.5), each offering an ultra-large single-chamber volume of 478 m³. These chambers can accommodate 40-foot subsystems, including DC container and MV skid, enabling full-environment simulation tests under extreme temperatures ranging from - 50°C to +90°C and humidity levels between 25% and 98% RH. Trina Storage is the first one to propose a temperature specification for the environmental chamber under full-load conditions in industrial area, ensuring that the temperature difference across the chamber is consistently maintained within ±4°C when the product operates at full power inside the chamber.



Fig. 4.5 A photo of an environmental chamber

4.2 Grid-Forming Foundation: DC container

As the core energy storage unit of an energy storage system, the DC container serves not only as the "energy warehouse", which ensures continuous energy supply, but also as the "power source", which supports stable system operation and rapid response. From battery cell to system, Trina Storage has achieved full-dimensional grid-forming adaptation. With quantified technical specifications and precise design optimization, Trina Storage has built a solid foundation that meets grid dispatch requirements and supports stable system operation.

"Trina Cell": A Long-Life, High-Consistency Battery Cell (Fig. 4.6). With a focus on material innovation and quality control upgrades, the Trina Cell delivers high reliability tailored grid-forming applications. By selecting highly stable active materials and integrating long-life technologies, it reduces lithium loss during cycling at the chemical level, significantly slows capacity fade and ensures long-term reliability for grid-forming scenarios from the outset. Furthermore, the cell is produced in a fully automated facility that enables high-precision control over key processes such as electrode coating, winding, and sealing. A full-process digital quality management system performs 100% inspection of critical parameters including capacity, voltage, and internal resistance, ensuring exceptional consistency within each batch. This lays the chemical and manufacturing foundation for long-term system stability and grid-friendly operation.

Premium 587 Design

Delivers a holistic enhancement in energy density, efficiency, and long lifecycle, overcoming the fundamental trade-offs.

Capacity	314Ah	587Ah	
Energy Density	391Wh/L	417Wh/L	6.6%+
RTE	95%	96%	1%+



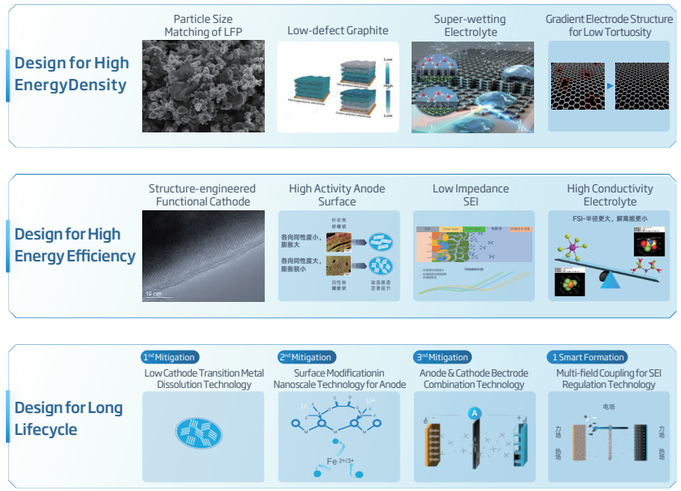


Fig. 4.6 Overview of the Trina Cell

"Elementa": A Grid-Forming Enhanced Battery System. Designed to meet the demands of high-power response, efficient energy utilization, and safe and controllable operation in grid-forming scenarios, the Trina cabinet achieves deep integration between the battery system and grid dispatch through targeted design (Fig. 4.7). In terms of energy reserve, the cabinet features a compact module and enclosure design that enables a highly integrated layout of components, delivering leading volumetric energy density. This provides a solid physical foundation for critical applications such as sustained power output during grid faults and long-duration frequency regulation.

Module Pro Design

Passed Standard Transportation Test
IEC/UL/GBT vibration test

Compact Design
Increased energy density by 12.8%



Module

Capacity	Grouping	Ingress Protection
195.354kWh	**26@4*module**	**IP67**

Fig. 4.7 Module design of the Elementa

In terms of intelligent management, the Battery Management System (BMS), acting as the 'brain' of the cabinet, employs high-precision cell state monitoring algorithms to accurately identify key parameters such as cell voltage and state of charge (SOC). It reports the maximum allowable charge/discharge power of the battery system to the PCS and Energy Management System (EMS) in real time. Through dynamic switching technology, the BMS enables the best-performing battery clusters to participate in energy output and promptly isolates faulty clusters to ensure system continuity in black-start scenarios.

4.3 Zero Awareness Adaptive Control Technology Under Grid Disturbances

In terms of EMS state perception, ElecOS dynamically adjusts the station operation mode in real time based on full dimensional real time collected data, grid strength level, and grid disturbance type. It collects multi-dimensional data from the grid side, including frequency, voltage, and power, with a data collection capability of millions of points per second. Combined with multiple types of intelligent diagnostic models, ElecOS provides early warning of potential risks to the grid, PCS, and battery blocks, thereby precisely supports the safe and stable operation of the grid.

At the control architecture level, Electra PCS abandons the conventional PPL dependent control approach and adopts a power synchronization control architecture (Fig. 4.8). In scenarios where a grid moves into island mode, Electra PCS enhances operational flexibility and achieves seamless transition with zero latency mode switching. Meanwhile, the PCS directly establishes the internal electromotive force based on the power balance equation, with a unified underlying control architecture that fundamentally eliminates the control reference discontinuity problem caused by mode switching. When the grid suffers a severe phase angle jump of up to ±60 degrees, the PCS instantaneously provides compensation by adjusting active power, rather than tripping in response to the erroneous phase jump (Figs. 4.9 and 4.10). The PCS can relock synchronization within 50 milliseconds, ensuring precise synchronization during grid connected operation.

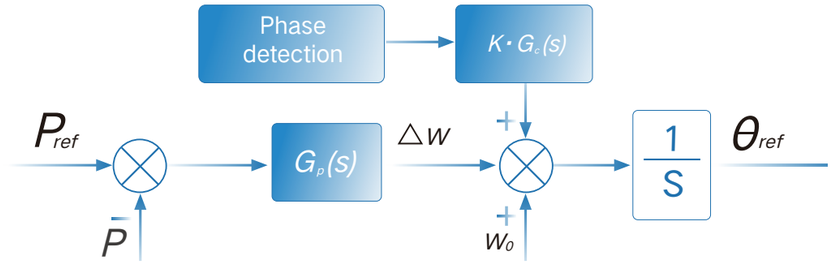


Fig. 4.8 Phase angle jump control block diagram

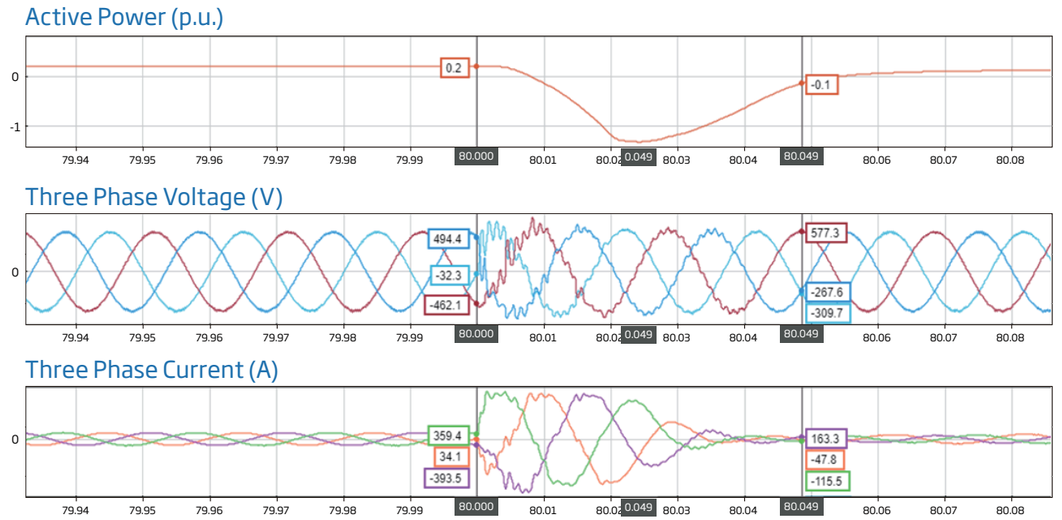


Fig. 4.9 Record of response during a phase angle jump of 60°

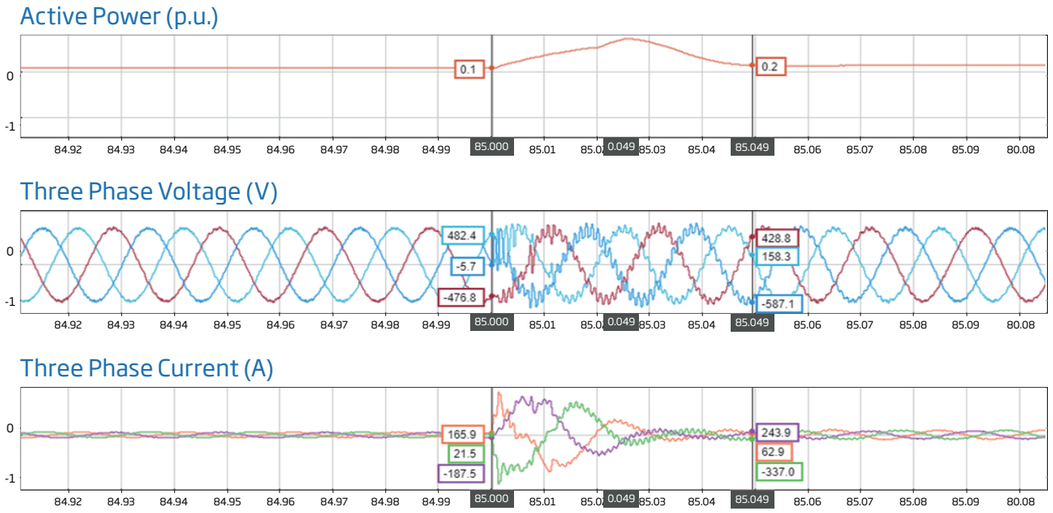


Fig. 4.10 Record of response during a phase angle jump of -60°

At the grid adaptation level, in order to address wide range fluctuations in grid strength from a very strong level (e.g., SCR = 50) to an extremely weak level (e.g., SCR = 1), Electra PCS abandons the conventional method of using a single fixed set of parameters for all scenarios and adopts a virtual impedance real time reconfiguration algorithm (Fig. 4.11). Through online impedance identification, the PCS can perceive the impedance characteristics at the point of common coupling (PCC) in real time and dynamically adjust the magnitude-frequency characteristics of its output impedance to actively adapt to the grid environment, fundamentally eliminating the risk of resonance. When the SCR drops instantaneously from 50 to 1, the algorithm identifies the sudden change of impedance within 10 milliseconds, and switch control parameters are updated seamlessly on a millisecond timescale. Throughout the whole process, the voltage waveform exhibits no divergence or oscillation, and the active power returns to its rated value within one second, achieving seamless transition from a very strong grid to an extremely weak grid (Fig. 4.12).

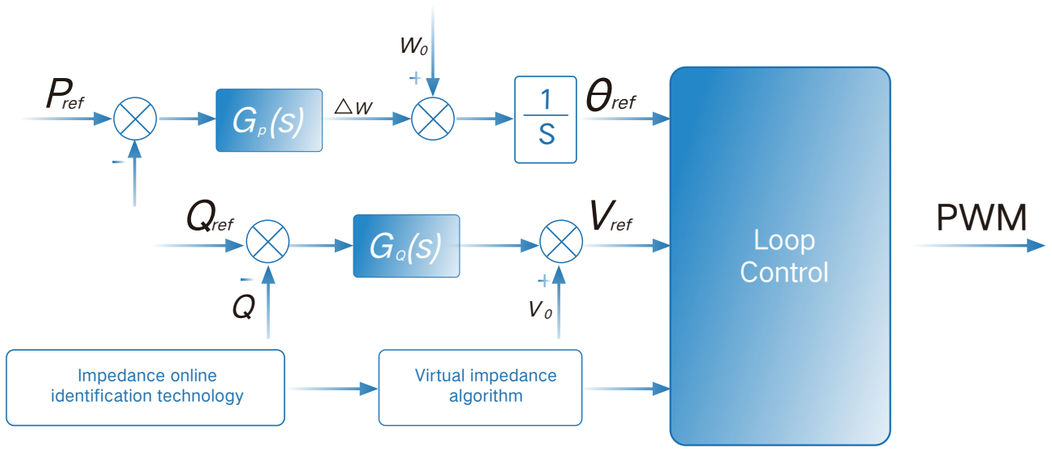


Fig. 4.11 Impedance reshaping control block diagram

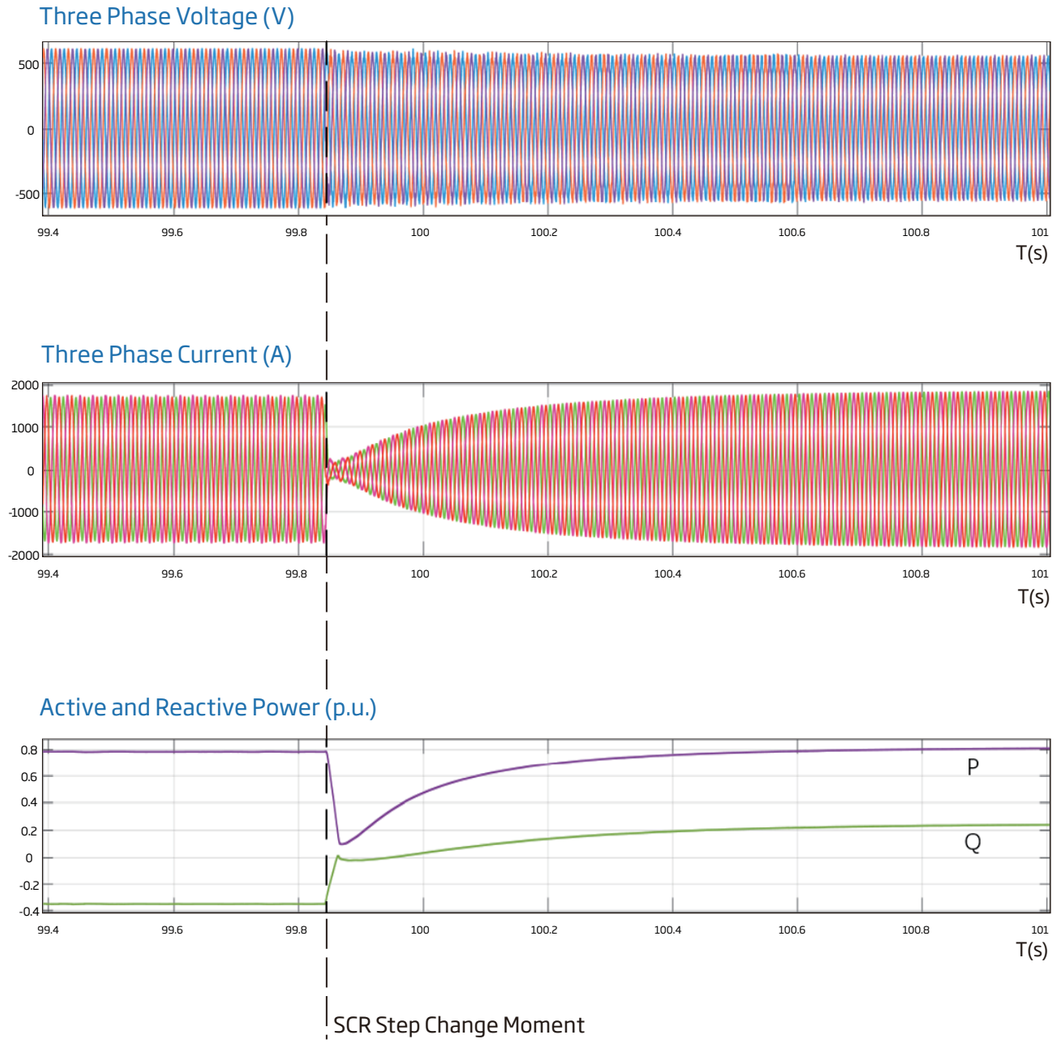


Fig. 4.12 PCS waveforms when grid SCR jumps from 50 to 1

At the stability assurance level, the Trina Storage solution achieves precise responses to differentiated risks under varying grid strengths. In strong grid conditions where SCR exceeds 20 or even reaches 100, the algorithm automatically adjusts the current loop bandwidth and introduces active damping to eliminate high frequency resonance ripples. In extremely weak grid conditions (e.g., SCR = 1), the power synchronization control architecture, combined with a virtual resistance injection algorithm, strongly enhances system damping. This acts like installing an "electronic-based shock absorber" for a highly unstable system, ensuring that the PCS operates stably without derating or tripping.

4.4 Multi-Scale Frequency Response Coordinated Control Technology

To address the multi-time scale coupling challenges in the frequency response framework, Trina Storage has proposed a physical model driven hierarchical decoupling solution (Fig. 4.13).

In the synthetic inertia support layer, Electra PCS incorporates a high speed RoCoF observer to achieve dynamic adaptive inertia support. It provides rigid support: when a rapid frequency change (high RoCoF) is detected, the algorithm automatically increases the synthetic inertia coefficient within milliseconds, delivering inertia comparable to that of a large physical rotor to firmly "hold back" the frequency. In the meantime, it also possesses flexible recovery capability: when the frequency enters the recovery zone (low RoCoF), the algorithm, as summarized in (4.1), automatically reduces the inertia compensation and introduces strong damping to quickly dampen power oscillations and shorten the regulation time. The Trina Storage adaptive algorithm reduces the active power response time to a 100-millisecond level and reduces the response time by 50% compared to conventional strategies. The adaptive inertia algorithm ensures both fast response during frequency changes and smoothness during the frequency recovery and stabilization phase (Fig. 4.14).

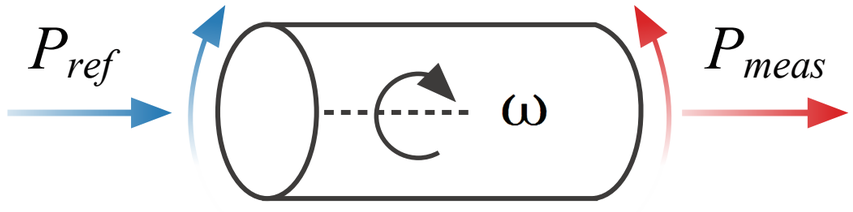


Fig. 4.13 Universal physical model of a rotating mass

$$J \cdot \omega_0 \cdot \frac{d\omega}{dt} = P_{ref} - P_{meas} - D \cdot (\omega - \omega_0)$$

(4.1)

Variable Description:

J: Virtual moment of inertia. It simulates the physical mass of a synchronous generator rotor and determines the "inertia strength" of the PCS in resisting frequency changes.

D: Damping coefficient. It simulates the damping winding characteristics of a generator and is used to suppress power oscillations.

ω, ω_0: Real time angular frequency and reference angular frequency.

$\frac{d\omega}{dt}$: Rate of change of angular frequency. It characterizes the speed of grid frequency fluctuations.

P_{ref}, P_{meas}: Measured active power and active power reference value.

By introducing the virtual moment of inertia *J*, the PCS simulates the kinetic energy release process of a physical rotor at the instant of a fault, limiting the magnitude of $\frac{d\omega}{dt}$ and preventing frequency collapse. The damping coefficient D is then used to suppress subsequent power oscillations.

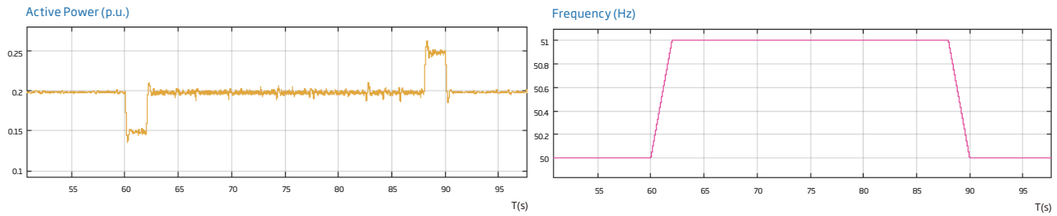


Fig. 4.14 Measured active power and frequency waveforms during frequency deviation events

In primary frequency regulation layer, Electra PCS follows the classical droop control formula (4.2), replicating the mechanical external characteristic of a physical generator, namely "the heavier the load, the slower the rotational speed". When load demand increases in the grid causes a frequency drop, the PCS automatically increases its active power output according to this physical model, impeding further frequency decline. Most importantly, this approach features autonomous synchronization capability requiring no communication interconnection. Each individual PCS can share load proportionally up to its capacity based solely on the local frequency change at its terminals, providing a physical foundation for stable operation in multi machine parallel scenarios (Fig. 4.15).

$$f - f_0 = - K_p \cdot (P - P_0)$$

(4.2)

Variable Description:

f, f_0: Real time frequency and rated frequency.

P,P_0: Real time output active power and rated active power reference value.

K_p: Active power droop coefficient. Its physical meaning is equivalent to the "speed regulation" of a generator, determining the sensitivity of the system frequency variation.

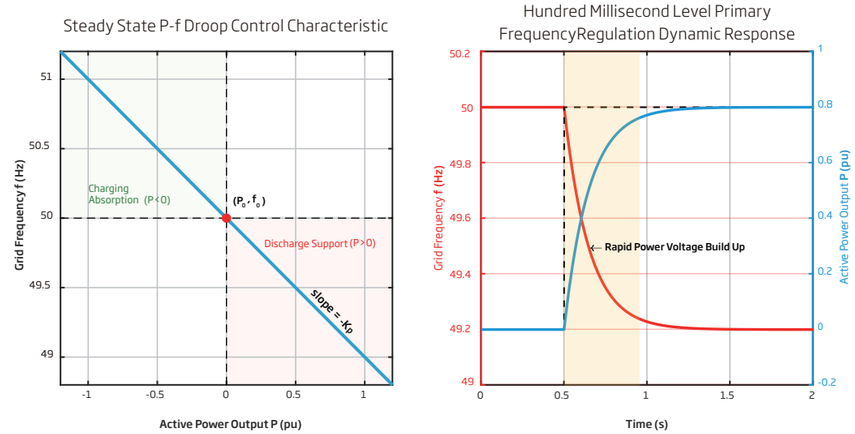


Fig. 4.15 Steady state P-f droop control characteristic (left) and primary frequency regulation dynamic response (right)

At the secondary frequency regulation layer, ElecOS relies on a high precision measurement algorithm to monitor the voltage frequency and amplitude at the point of interconnection in real time. Based on the charge and discharge characteristics of Trina Storage cells and the operating status of the PCS, ElecOS dynamically optimizes the allocation of active power commands, achieving an optimal balance between power output and SOC equalization. Particularly in complex scenarios involving PCS units with different rated powers, battery blocks with different rated capacities, or battery blocks with different degrees of aging, the system achieves excellent adaptability and stable operation.

The PCS responds to the AGC command issued by ElecOS and achieves zero error regulation through the integral equation (4.3). By leveraging the cumulative effect of the integral term on frequency deviation, the PCS automatically adjusts the active power reference point to compensate for the residual deviation remaining after primary frequency regulation. From a control essence perspective, AGC shifts the P-f droop characteristic curve upward or downward. ElecOS brings the operating point back to the rated frequency, ensuring that the fast response of primary frequency regulation and the precise adjustment of secondary frequency regulation operate without interference and in a coordinated and orderly manner, while maintaining the original droop slope (Fig. 4.16).

$$P_{ref}(t) = P_{set} - K_{if} \cdot \int (f - f_0) dt$$

(4.3)

Variable Description:

$P_{ref}(t)$: Dynamic active power re ference value. The active power command ultimately executed by the PCS internal control loop.

P_{set}: Base dispatch power. The initial power setpoint issued by the EMS.

K_{if}: Frequency integral gain coefficient. It determines the speed at which secondary frequency regulation eliminates frequency deviation, typically slow and measured in minutes.

$\int(f-f_0)dt$: Integral term of frequency deviation. As long as the frequency f is not equal to the rated value f_0, this term continues to accumulate, driving the change of P_{ref} until the deviation is eliminated.

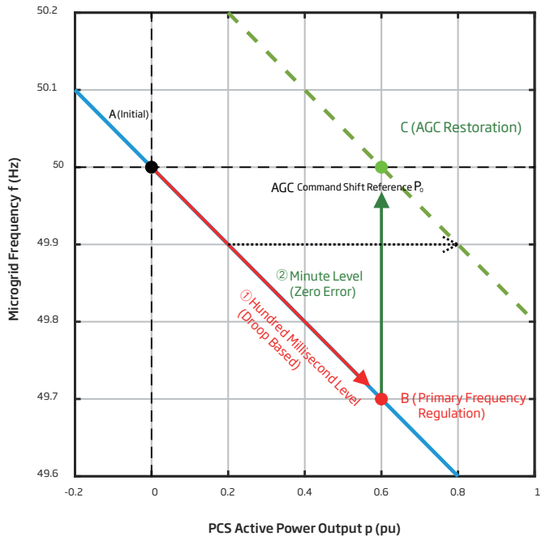


Fig. 4.16 PCS active power output under different system frequency

The three control equations (4.1,4.2,4.3) exhibit natural layering in terms of physical mechanism. The swing equation governs inertia response, the droop equation governs primary frequency regulation, and the integral equation governs secondary frequency regulation. The parameters at each level are optimized independently. Through real time RoCoF feedback, dynamic withdrawal of inertia and smooth engagement of damping are achieved, fundamentally avoiding the coupling conflicts inherent in multi-time scale control.

4.5 Full Range Voltage Reconstruction Technology

To address the multi-scale coordination challenges in the voltage support framework, which encompasses fault ride through (among milliseconds), primary voltage regulation (among hundreds of milliseconds), and secondary level secondary voltage regulation (among hundreds of milliseconds), Trina Storage has proposed a physical model driven, hierarchically decoupled, voltage support solution, which enables seamless, full dimensional coordination ranging from transient fault response to steady state regulation.

In the fault ride through layer, when a voltage sag or swell is detected at the point of interconnection, the PCS switches its control strategy within milliseconds, transitioning from voltage source mode to dynamic current injection mode. It strictly follows the physical model, as shown in (4.4), supporting up to 1.5p.u. overload capability depending on the depth of voltage drop. This "ultra-fast rigid support" mechanism ensures that at the instant of a fault, the voltage at the point of common coupling (PCC) is forcefully lifted to prevent voltage collapse. In the meantime, it maintains a sufficient short circuit current level, ensuring that grid side protection devices can operate accurately and rapidly to clear the fault (Fig. 4.17).

$$I_q = I_{q0} + K \cdot (U_0 - U) \tag{4.4}$$

Variable Description:

I_q, I_{q0}: Reactive current output during fault and reactive current immediately before fault.

U, U_0: Real time voltage at the point of interconnection and rated voltage.

K: Dynamic reactive current scaling factor. It determines the support intensity of the PCS in response to voltage fluctuations, typically taking a value between 1.5 and 3.0.

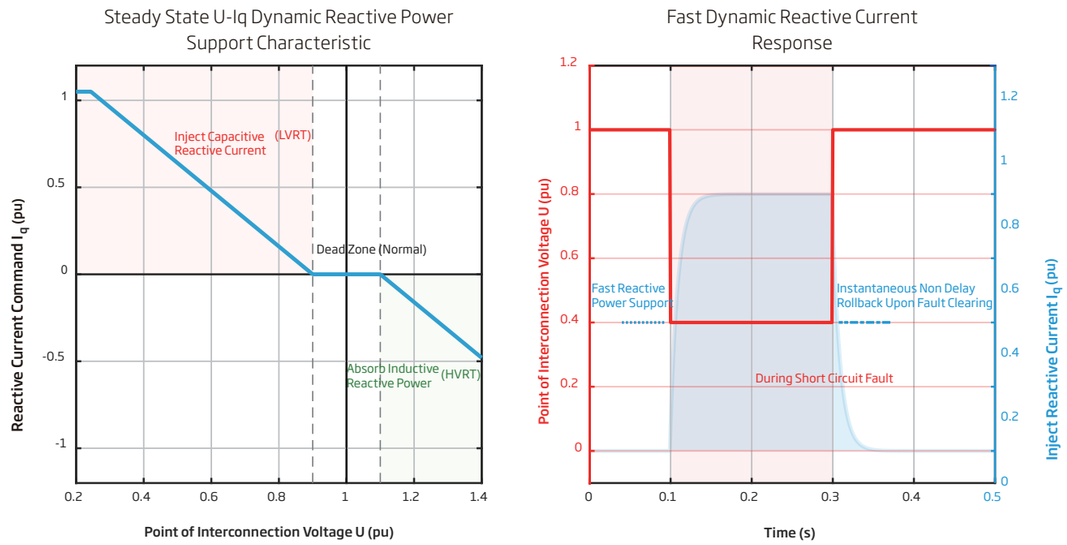


Fig. 4.17 Steady state U-Iq dynamic reactive power support characteristic(left) and fast dynamic reactive current response(right)

In the primary voltage regulation layer, Electra PCS adopts the classical reactive power to voltage droop control formula (4.5), precisely emulating the regulation characteristics of a synchronous generator excitation system. When a bus voltage drop occurs due to the startup of an inductive load, the PCS automatically increases its reactive power injection according to this physical model to compensate for the grid voltage drop. Most critically, the droop mechanism endows the system with autonomous load sharing capability. Without requiring communication interconnection, multiple PCS units can automatically share the system's reactive power demand in proportion to their respective capacities, which avoids reactive circulating current issues in parallel operation scenarios and establishes the foundation for stable operation in multi-machine parallel configurations (Fig. 4.18).

$$U - U_0 = - K_q \cdot (Q - Q_0)$$

(4.5)

Variable Description:

U, U_0: Real time voltage and rated voltage reference value.

Q, Q_0: Real time reactive power output and rated reactive power reference value.

K_q : Reactive power droop coefficient. Its physical meaning is equivalent to the voltage regulation coefficient of an excitation system, determining the linear relationship between voltage deviation and reactive power output.

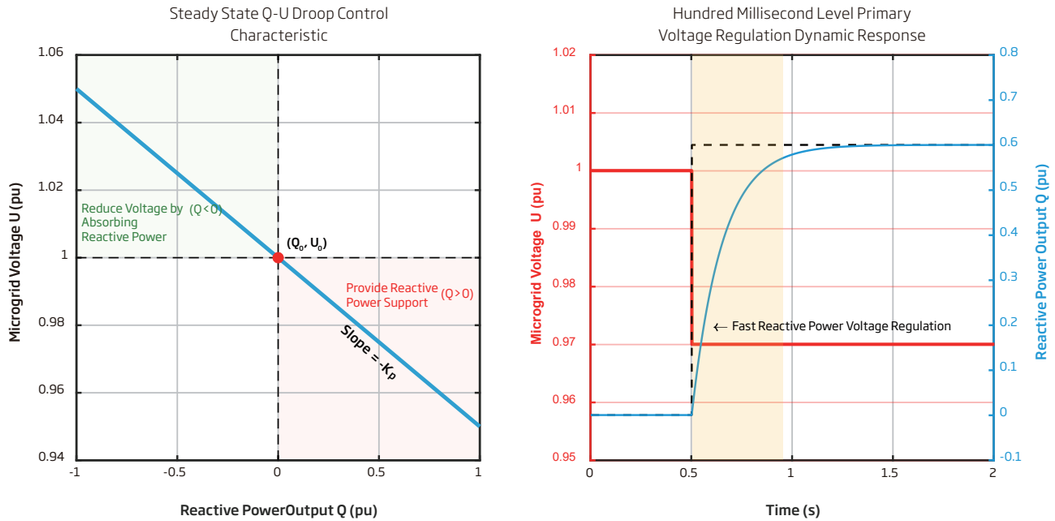


Fig. 4.18 Steady state Q-U Droop Control Characteristic(left) and primary voltage regulation dynamic response(right)

In the secondary voltage regulation layer, ElecOS detects steady state voltage deviations and issues secondary voltage regulation commands (AVC) to slowly and precisely restore the voltage to its rated value. The PCS responds to the AVC command issued by the EMS, performing regional level voltage correction through the integral equation. By leveraging the cumulative effect of the integral term on voltage deviation, as shown in (4.6), it smoothly adjusts the reactive power reference point of the PCS, bringing the critical bus voltage back to the target value with minimized error, thereby eliminating the inherent steady state deviation of primary voltage regulation. Based on a station-wide reactive power optimization algorithm, the EMS calculates the optimal reactive power allocation scheme, coordinates multiple PCS units to optimize the internal power flow distribution, reduces line losses, and reserves sufficient regulation margin for the next voltage fluctuation (Fig. 4.19).

$$Q_{ref}(t) = Q_{set} - K_{iU} \cdot \int (U - U_0)\, dt$$

(4.6)

Variable Description:

$Q_{ref}(t)$: Dynamic reactive power reference value. The reactive power command ultimately executed by the PCS internal control loop.

Q_{set} : Base dispatch power. The initial reactive power setpoint issued by the EMS, typically calculated by the station wide reactive power optimization algorithm.

K_{iU} : Voltage integral gain coefficient. It determines the speed at which secondary voltage regulation eliminates voltage deviation.

$\int (U - U_0) dt$: Integral accumulation term of voltage deviation. As long as the bus voltage U deviates from the target value U_0, this term continuously accumulates, driving the change of Q_{ref} until the deviation is eliminated.

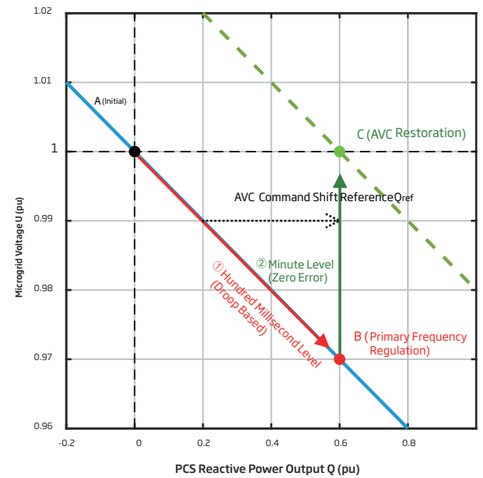


Fig. 4.19 PCS reactive power output Q under different voltage magnitudes

Through the above-mentioned hierarchical and coordinated control architecture, Trina Storage systematically resolves core challenges including the conflict between forced injection during fault ride through and steady state voltage regulation objectives, the rhythm matching between droop control and regional AVC, and reactive power equalization in multi-machine parallel operation. This provides grid-forming energy storage with multi-dimensional, highly reliable voltage support capability.

4.6 Black Start Technology (All Procedures)

To address the technical challenges of black start and grid synchronization among all procedures, Trina Storage leverages the deep coupling advantage of "ElecOS plus Electra integration" to establish a zero-impact black start technology system characterized by synchronous prediction and coordinated action.

On the EMS side, it serves as the global command center for black start and undertakes core responsibilities including strategy optimization, command issuance, and status monitoring. ElecOS continuously optimizes control models and

parameters based on extensive simulations and field measurement data, while refining communication and control strategies in conjunction with PCS characteristics to achieve a synergistic operational effect where the system delivers "1+1>2" (Fig. 4.20). By leveraging real time kernel technology and a high-speed multicast communication scheme, ElecOS and the PCS achieve a synchronous command reception delay of less than 1 millisecond, which effectively ensures high reliability of PCS phase synchronization. After issuing unified commands, all PCS units simultaneously establish voltage reference, including phase, amplitude, and frequency. Meanwhile, ElecOS dynamically monitors grid conditions, such as renewable energy output and load demand, directing the PCS to adjust grid-forming capacity accordingly, and eventually achieving a process of "starting, energizing loads, and charging simultaneously".

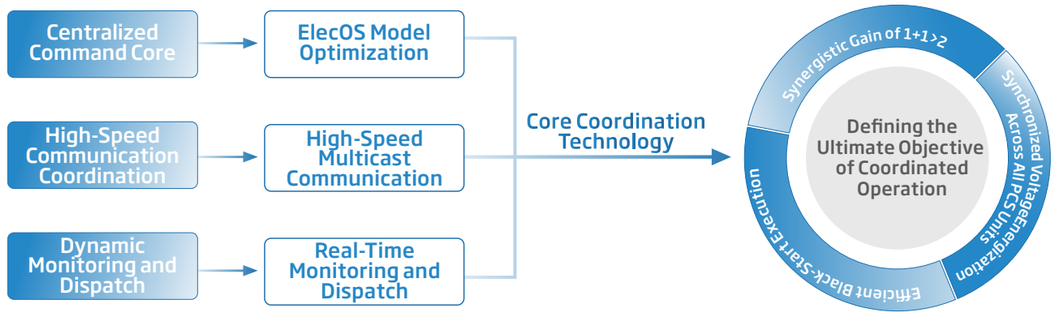


Fig. 4.20 Overview of the EMS coordination technology

On the PCS side, the solution abandons the direct closing mode and employs a dedicated inrush current suppression algorithm to physically prevent the generation of inrush current. Under complete blackout conditions, the grid-forming PCS, based on a self-excitation mechanism, achieves reconstruction from disorder to order through systematic evolution across four dimensions. By leveraging the high precision time synchronization protocol (PTP) of the self-developed system, all PCS units across the station achieve microsecond-level clock synchronization (Fig. 4.21).

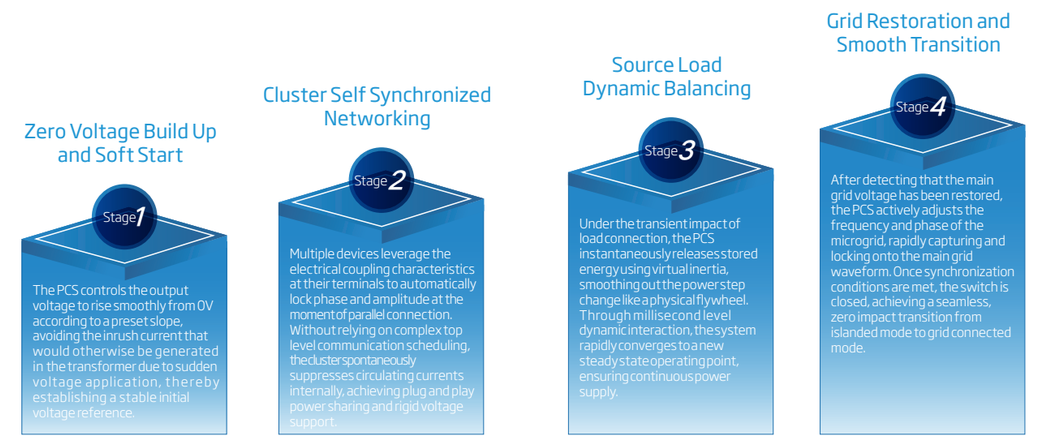


Fig. 4.21 Grid-Forming capability of the PCS

Stage 1: Zero Voltage Build Up and Soft Start

The PCS controls the output voltage to rise smoothly from 0V to the targeted value following a preset slope, avoiding the inrush current that would otherwise be generated in the transformer due to sudden voltage changes. Finally, it establishes a stable initial voltage reference.

Stage 2: Cluster Self-Synchronized Networking

Multiple devices leverage the electrical coupling characteristics at their terminals to automatically lock voltage phase and amplitude during parallel connection. The cluster spontaneously suppresses internal circulating currents and achieve plug and play power sharing and rigid voltage support without relying on complex top-level communication scheduling.

Stage 3: Source-Load Dynamic Balancing

Regarding the transient impact of load connection, the PCS instantaneously releases stored energy (synthetic inertia) to smooth the power step change, like a physical flywheel. Through millisecond-level dynamic interaction, the system rapidly converges to a new steady state operating point, ensuring continuous power supply.

Stage 4: Grid Restoration and Smooth Transition

After detecting that the voltage of main grid has been restored, the PCS actively adjusts the frequency and phase of the microgrid, rapidly capturing and following the main grid waveform. Once the synchronization condition is met, the switch is closed, achieving a seamless transition from islanded mode to grid connected mode.

On the other hand, the transformers are preferably made of high permeability magnetic materials and possess the capability to withstand transient overcurrent, tolerate wide frequency variations, resist voltage disturbances, and perform precise voltage regulation, to ensure continuous, stepless voltage ramp up during the black start process and improve success rates of grid restoration. In the meantime, the ring main unit switch requires strong closing and withstanding capabilities. The instrument transformer shall feature high bandwidth characteristics and insulation-based anti-interference capability, adapts to the instantaneous current variations during the voltage ramp up period in black start process, to ensure stable operation under complex operating conditions.

Through the above-mentioned collaborative architecture featuring global command by the EMS and local execution by the PCS, Trina Storage systematically resolves the core challenges of black start, including inrush current suppression, multi-machine synchronous voltage build up, load impact smoothing, and seamless grid transition.

This achieves high precision controls among all processes from zero voltage build up to grid synchronization, ensuring success of black start and seamless transition from islanded mode to grid connection mode.

Summary and Outlook

In response to the challenges of power systems with high renewable penetration and high power-electronics integration, Trina Storage delivers a comprehensive grid-forming solution that marks a fundamental leap from “device-level functions” to “system-level capabilities,” transforming energy storage systems from passive grid “followers” to active grid “supporters”.

Looking into the future, grid-forming technology is moving from an "optional add-on" to a "standard feature." As the penetration of renewable energy sources continues to rise, grid-forming capability will become a general requirement for power systems with very high shares of renewable energy generation. Trina Storage will continue to deepen the iterative upgrade of adaptive control algorithms, promote the deeper integration of wind power generation, solar power generation, and energy storage, and unlock the systemic value of grid-forming capability on a broader scale–standing as a steadfast pillar of support in the long race of energy transformation.

Appendix 1: Trina Storage PCS with Grid-forming Capabilities

Trina Storage aims to deliver high-quality and reliable energy storage systems with grid-forming capabilities to all clients to provide necessary support or services to local grids. The grid-forming capabilities of PCS (as one of the main components of an energy storage system) have been tested comprehensively, in close cooperation with third-party Testing, Inspection and Certification (TIC) service providers.

As an example, Trina Storage's PCS products (Type no. TSPCS3556-N2-E, TSPCS2782-N2-E and TSPCS2495-N2-E) have been tested (from 01/08/2026 to 01/09/2026) to verify its grid-forming capabilities. All tests have been performed in Trina Storage's laboratory and witnessed by professional engineers from a leading third-party international TIC service provider, TÜV Rheinland. The test items, which are summarized in Table I, are mainly based on National Grid ESO - Compliance Guidance Notes for NOA Stability Compensation Service Phase 3 (version 1, May 2022), while also taking into account the capability requirements for grid-forming generating units set out in GC0137 (published on 11 November 2021), Grid Forming Guidance Note - Issue 3 and Gird Forming Capability of Power Park Modules - Report on Technical Requirements - Final (03 October 2025). The test results illustrate and prove that the PCS under tests have satisfied the description of grid-forming capabilities defined in the above-mentioned documents.

Table I: Summary of Grid-forming Capability Tests

Clause	Test Items	Clause	Test Items
1	Active Phase Jump Power Test	6	Temporary Over Voltage Test
2	Power Oscillation Damping Test	7	Active RoCoF Response Power and Active Phase Jump Power under Extreme Conditions Test
3	Active RoCoF Response Power Test	8	Multiple Fault Ride Through Test
4	Primary Frequency Regulation Test	9	Short Circuit Test
5	Power Step Test		

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