Stem-cell Grid-forming Tech 2.0 White Paper

Grid-Specific Security and Stability Solutions

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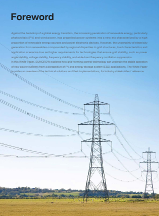
Foreword

Against the backdrop of a global energy transition, the increasing penetration of renewable energy, particularly photovoltaic (PV) and wind power, has propelled power systems into a new era characterized by a high proportion of renewable energy sources and power electronic devices. However, the uncertainty of electricity generation from renewables-compounded by regional disparities in grid structures, load characteristics and application scenarios-has set higher requirements for technologies that ensure grid stability, such as power angle stability, voltage stability, frequency stability, and wide-band frequency oscillation suppression.

In this White Paper, SUNGROW explores how grid-forming control technology can underpin the stable operation of new power systems from a perspective of PV and energy storage system (ESS) applications. The White Paper provides an overview of the technical solutions and their implementations, for industry stakeholders' reference.



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01

Characteristics of New Power Systems

1.1

Continuous Rise of Installed Capacity of Renewable Energy

The global energy transition is accelerating. BloombergNEF’ s latest data (see Figure 1) show that the installed capacity of renewable energy has surged since 2020, reaching a total of 3260 GW by 2024. It is estimated that the installed capacity will grow by 9932 GW by 2030.

Figure 1: Annual Cumulative Installed Capacity of Global Wind and Solar Power (BNEF 2024)

1.2

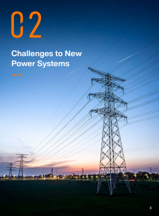
Low Inertia and Damping Capability of Power Systems

Renewable energy sources inherently exhibit intermittency and volatility. Moreover, most generation facilities connect to the grid through power electronic devices, which lack the rotational inertia and damping properties as conventional generators. Consequently, overall system inertia and damping are reduced.

These "low inertia and damping capability" conditions make power systems vulnerable to disturbances from power fluctuations and faults, increasing the risk of frequency fluctuations, voltage instability, and even widespread power outages. For example, a sudden drop in wind or PV output may lead to a rapid frequency decline because the system lacks sufficient inertia to buffer the frequency change, which may activate underfrequency load shedding and, subsequently, cause power outages.

02

Challenges to New Power Systems



2.1

Power Angle Stability Challenges

In conventional power systems, synchronous generators maintain synchronized operation through electromechanical coupling to ensure power angle stability. However, with the increasing integration of renewable energy sources, power electronic devices have largely replaced synchronous generators, resulting in reduced system inertia and weakened synchronization capability. When subjected to disturbances such as sudden load changes or grid faults, renewable energy-based generation units without sufficient inertia cannot provide adequate synchronous power support. This can lead to larger power angle differences between power generation units, increasing the risk of loss of synchronism and, in severe cases, system separation.

On January 8, 2021, a busbar coupler at a 400 kV substation in Ernestinovo, Croatia, tripped due to an overload from rising power flows. This incident tripped multiple lines between the northwestern and southeastern grids within 20 seconds, forming different coherent groups operating against each other. Ultimately, the Continental Europe grid was separated into two areas—northwest and southeast—resulting in significant frequency fluctuations and power angle instability. In the graph below, event #1 is the trip of the busbar coupler in Ernestinovo and event #2 is the Serbian line trip. The Phasor Measurement Unit (PMU) recordings included in Figure 2 explain how the separation occurred. The first three substations (blue) are in the western area and the second three (red / orange / yellow) are in the eastern area. Another example of a power incident caused by power angle instability is the Continental Europe grid separation event on July 24, 2021.

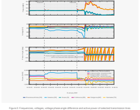


Figure 2: Frequencies, voltages, voltage phase angle difference and active power of selected transmission lines (reference for voltage phase angle difference is Lavorgo [CH] substation)

2.2

Voltage Stability Challenges

Voltage stability in power-electronics-dominated power systems faces new challenges. On the one hand, commutation failures in high-voltage direct current transmission can lead to continuous voltage fluctuations. On the other hand, a sudden drop in PV power generation at night—without sufficient reactive power compensation—may trigger voltage instability. Furthermore, renewable energy-based generation units typically exhibit insufficient reactive current supply capability and inferior voltage regulation performance compared to conventional generators, which can supply reactive current several times their rated current for voltage support.

On September 28, 2016, severe weather conditions, including typhoons and heavy rains, struck the grid in South Australia (SA). Six transmission line faults triggered multiple voltage drops and disconnected numerous wind turbines. After the Heywood interconnector tripped, the power system became islanded and ultimately collapsed, leading to a 50-hour statewide blackout in SA. Figure 3 shows voltages measured at a number of key 275 kV points across the SA networks, as well as the 275 kV voltage measured at Heywood in Victoria, for the period immediately before loss of the Heywood Interconnector. The graph shows a rapid decline in voltages across the SA network following final loss of the Davenport–Mt Lock 275 kV line. Voltage instability also occurred during the blackout at Rio de Janeiro International Airport in Brazil in May 2023 and the major power outage in Texas, USA, in February 2021.

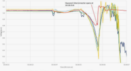


Figure 3: 275 kV voltage decline across South Australia prior to separation on September 28, 2016

2.3

Frequency Stability Challenges

In new power systems, the declining system inertia has made frequency stability an increasingly prominent issue. On August 9, 2019, a lightning strike hit a transmission line in northern London, causing the Hornsea One wind farm to drop offline. Shortly afterward, a steam unit at the Little Barford power plant in Bedfordshire shut down automatically. This resulted in a cumulative generation loss of over 1130 MW within one second. The system's rate of change of frequency (ROCOF) exceeded 0.125 Hz/s, tripping the distributed generators. The frequency ultimately dropped to 48.8 Hz, activating underfrequency load-shedding measures and causing widespread power outages across the UK. Figure 4 shows annotated frequency trace of the event of August 9, 2019. Similarly, on December 23, 2023, the sudden trip of a high-voltage transmission line between the UK and France caused an instantaneous power loss of 1 GW in the UK grid. The system frequency plunged from 50 Hz to 49.3 Hz.

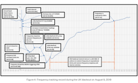


Figure 4: Frequency tracking record during the UK blackout on August 9, 2019

2.4

Wide-Band Frequency Oscillations

Renewable energy sources are connected to the grid via power converters, which introduce complex control dynamics and fast responses, increasing the risk of oscillations across a wide frequency range. Additionally, the low damping level of new power systems makes wide-band frequency oscillation more likely to occur and harder to be suppressed, posing a challenge to the secure and stable operation of the grid.

On July 1, 2015, a sub-synchronous oscillation occurred in a wind farm in Northwest China, triggering torsional vibration protection in a thermal power unit located more than 300 kilometers away and causing the unit to shut down. This was a typical power oscillation event caused by the propagation of sub-synchronous oscillation component across multi-level grids. In recent years, sub-synchronous and super-synchronous oscillations in wind farms in this region have caused over 100 wind power disconnection events. Statistics on the system-side sub-synchronous oscillation incidents in the first half of 2016 are presented in Figure 5.

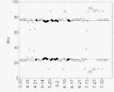


Figure 5: Statistics on sub-synchronous oscillation frequencies in Northwest China, 1H2016

2.5

Grid-Specific Solutions for Diverse Power System Needs

The causes of the grid incidents discussed above are classified into power angle instability, voltage instability, frequency instability, and wide-band frequency oscillations. In fact, grid incidents involve multiple interacting instability factors. For instance, the continental Europe synchronous area separation phenomena on January 8, 2021, mentioned above were characterized by a voltage collapse at all substations close to the line of separation, an increase of the voltage phase angle difference between the two areas, and a difference in the frequencies of the two areas—the frequency was increasing in the South-East area and decreasing in the North-West area.

Currently, the industry advocates for solutions that power inverters utilize grid-forming technologies to ensure grid stability. However, significant differences in renewable energy penetration rate, grid structures, load characteristics and application scenarios across regions suggest that a one-size-fits-all grid-forming solution is inadequate. Moreover, current approaches often overlook the impact of DC-side energy on the realization of grid-forming technology. Also, relying solely on the grid-forming capability of individual inverters, rather than plant-level capabilities, poses potential risks for the large-scale implementation of grid-forming technologies.

In the face of these challenges, technology solution providers must develop "grid-specific" solutions from a system-level perspective, fully considering the unique characteristics of grids in different regions, such as renewable energy penetration rate, grid structures, load characteristics and application scenarios.

03

Stem-cell Grid-forming Tech 2.0

SUNGROW's innovative Stem-cell Grid-forming Tech 2.0, a "grid-specific" security and stability solution, is developed to address the need for stable energy scheduling on the AC side. Departing from conventional grid-forming solutions that concentrate solely on AC-side control of power converters, this technology systematically integrates DC-side battery management with AC-side grid-forming control. Leveraging a GW-scale, full-link simulation platform for electrical, thermal, and noise analysis, it pioneers a three-tier "battery-power converter-plant" synergy architecture that instills system-level stability in renewable energy plants (Figure 6). This technology ensures safe and efficient battery charging and discharging on the DC side, providing stable energy support for the AC side, under varying grid conditions, environmental factors, and application requirements. It enables faster frequency and voltage regulation and more robust black-start capability, maximizing the benefits of renewable energy plants.

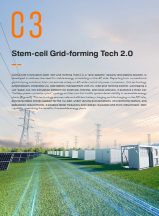


Figure 6: Architecture of Stem-cell Grid-forming Tech 2.0

3.1

Comprehensive Grid Support on the AC Side

1 Power Angle Stability Support

A Asymmetric & wide-range phase angle jump ride-through technology

① Challenges

In power systems, the occurrence and clearance of short-circuit faults can lead to changes in the external network topology, causing voltage phase jumps at the point of connection (POC). These changes can significantly impact the stability of the virtual power angle. Similar to synchronous generators, grid-forming inverters automatically provide active phase jump power during phase jumps. However, in the event of wide-range phase jumps, the active phase jump power output of the grid-forming inverters may exceed the limits. Without timely intervention, this may cause the grid-forming inverters to trip, resulting in a loss of grid support and potentially exacerbating the fault.

② Technical solution

As shown in Figure 7, SUNGROW's adaptive phase angle jump ride-through technology proactively captures grid phase information from state variables. During wide-range phase angle jumps, the technology employs feedforward control to rapidly adjust the internal frequency of voltage, accelerating the virtual rotor swing and enabling swift changes in the grid-forming inverter's internal voltage phase angle, thereby ensuring power angle stability. Moreover, through adaptive regulation, this function is gradually diminished during minor phase jumps, allowing grid-forming inverters to maximize their frequency support capabilities.

When asymmetric phase angle jumps occur in the grid, an appropriate amount of negative sequence voltage is generated based on the fault severity to support the faulty phase voltage. This enables a transition from passively adapting to grid unbalance to actively supporting grid voltage.

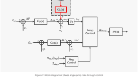


Figure 7: Block diagram of phase angle jump ride-through control

③ Technical solution effectiveness

Figures 8 to 9 depict the changes in current and active power waveforms of the DC/AC power converter unit when a 90° phase angle jump occurs in a three-phase grid voltage. Without implementing any optimization strategy, the peak current significantly exceeds the overcurrent threshold, and the regulation process is prolonged. However, when the proposed optimization is applied, the current transition becomes smooth.

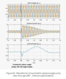


Figure 8: Waveforms of symmetric phase angle jump ride-through (90°, without optimization)

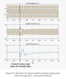


Figure 9: Waveforms of symmetric phase angle jump ride-through (90°, with optimization)

Figures 10 to 11 depict the changes in current and active power waveforms of the DC/AC power converter unit when a 90 ° phase angle jump occurs in a two-phase grid voltage. Without implementing any optimization strategy, the peak current is high and the regulation process is prolonged. However, when the proposed optimization is applied, the current transition becomes smooth.

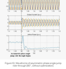


Figure 10: Waveforms of asymmetric phase angle jump ride-through (90°, without optimization)

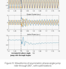


Figure 11: Waveforms of asymmetric phase angle jump ride-through (90°, with optimization)

2. Voltage Stability Support

A Adaptation to wide-range instantaneous SCR change

① Challenges

Industrialized renewable energy plants are typically located in remote areas far from load centers. The electricity must be transmitted through long-distance power lines, multiple transformers, and sometimes series compensation devices, resulting in complex grid impedance characteristics at the point of common coupling. Fault-induced changes in the grid structure, coupled with the high randomness and volatility of renewable energy generation, cause frequent changes in grid-connected power. This further leads to significant fluctuations in grid impedance, resulting in sudden changes in grid strength.

② Technical solution

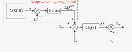


Figure 12: Adaptive voltage regulation control strategy

The virtual synchronous generator (VSG) control adds a reactive power control loop following the adaptive regulation of inverter terminal voltage (Figure 12). This enables the grid-forming DC/AC power converter unit to instantly adjust reactive power during sudden changes in grid strength. The VSG's reactive power–voltage control emulates the excitation regulation process of synchronous generators, characterizing the reactive power–voltage droop. By implementing real-time closed-loop control of the terminal voltage, reactive power is provided to support the terminal voltage during changes in grid strength.

③ Technical solution effectiveness

As demonstrated in Figure 13, when there is a sudden change in grid strength, the short-circuit ratio (SCR) drops from 40 to 1. In response to this situation, the DC/AC power converter unit quickly adjusts its power output to compensate for the power imbalance caused by the change in grid strength. It can also effectively suppress voltage fluctuations, restoring system voltage stability within hundreds of milliseconds.

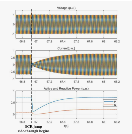


Figure 13: DC/AC power converter unit response to grid-side SCR drop from 40 to 1

B Enhanced continuous high/low-voltage ride-through technology

① Challenges

Thyristor-based line-commutated converter-based high-voltage direct current (LCC-HVDC) systems are widely used in long-distance, high-capacity power transmission. However, an HVDC commutation failure can lead to a sudden drop in AC bus voltage, followed by a sudden voltage rise caused by excess reactive power, resulting in continuous voltage fluctuations. Long-distance power transmission requires series compensation devices. The resonance between series compensation capacitors and line inductance can lead to transient overvoltage, which exacerbates voltage fluctuations. Furthermore, under weak grid conditions, conventional grid-following DC/AC power converters may induce transient overvoltage due to delayed reactive power withdrawal during voltage recovery. Therefore, the DC/AC power converter unit must be equipped with continuous ride-through capabilities to withstand prolonged, frequent, and severe voltage faults.

Technical solution

Drawing from in-depth research on the dynamic evolution mechanism of synchronous generators under significant voltage disturbances, SUNGROW has developed fast voltage regulation and incremental virtual impedance technologies based on the roles of the excitation system and transient reactance of synchronous motors during faults. As shown in Figure 14, by adjusting the amplitude of internal voltage and virtual impedance, the DC/AC power converter unit can inject more reactive current into the grid within its tolerance range during voltage sags or surges. This shortens the reactive response time to several milliseconds and enables quick recovery of the voltage at POC.

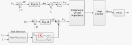


Figure 14: Block diagram of continuous high/low-voltage ride-through control

Technical solution effectiveness

To validate the DC/AC power converter unit's continuous high/low-voltage ride-through (HVRT/LVRT) capability, tests were conducted where the grid voltage was first dropped to 0.05 times the nominal voltage (Un) for 1.5 seconds, then raised to 1.3 times Un for 500 milliseconds. Throughout six consecutive voltage sag-surge cycles, the converter unit stayed connected to the grid. Through rapid and precise reactive power regulation, the converter unit quickly injected reactive power to support voltage recovery during voltage sags and promptly absorbed excess reactive power to suppress overvoltage during voltage surges, effectively mitigating the impact of voltage fluctuations on the grid (see Figure 15). During LVRT, the converter unit can withstand momentary overloads (e.g., 1.5 to 3 times the rated current) and maintains continuous and stable operation during faults, thereby supporting grid stability.

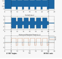


Figure 15: Waveforms of fault ride-through during six consecutive grid voltage sag-surge cycles

3. Frequency Stability Support

A Flexible inertia support

① Challenges

Synchronous generators have great inherent rotational inertia, and power electronics-based ESSs must possess inertia support capabilities. Grid-following power converters exhibit delays in frequency response, as control can only be performed after detection, and hence cannot meet the inertia requirements of new power systems.

② Technical solution

- Implement VSG control in grid-forming technology, integrating primary frequency regulation into the active power control loop to support frequency. The block diagram is shown in Figure 16.
- During system disturbances, parameters such as the VSG's moment of inertia and damping factor are used to reduce the ROCOF, thereby enhancing frequency stability and power angle stability.

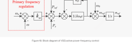


Figure 16: Block diagram of VSG active power-frequency control

③ Technical solution effectiveness

To validate the frequency support capability of the DC/AC power converter unit, tests were conducted involving controlled frequency changes at the POC of the ESS: Initially, the frequency was dropped from 50 Hz to 47 Hz, held for one second, and then restored to 50 Hz. Subsequently, the frequency was raised from 50 Hz to 53 Hz, held for one second, and then restored to 50 Hz. As shown in Figure 17, during significant grid frequency fluctuations, the converter unit effectively emulates the rotor inertia of a synchronous generator, with its active power output responding to the change of system frequency. The converter unit can provide active current support up to 1.5 to 3 times the rated active current and enable inertia responses within milliseconds. This rapid and precise frequency regulation compensates for the reduced inertia in new power systems due to gradually retired synchronous generators, significantly enhancing grid frequency stability.

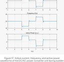


Figure 17: Active current, frequency, and active power waveforms of the DC/AC power converter unit during sudden frequency changes at POC

DC-coupled PV-ESS grid-forming control technology

① Challenges

Conventional PV systems typically operate at the maximum power point (MPP). Due to solar irradiance fluctuations, these systems lack active power reserves on the DC side, leading to insufficient transient stability of the DC bus voltage, and cannot provide reliable active power support in grid-forming mode. On the other hand, operating in reserved power mode can reduce PV plant revenue, and it is difficult to accurately and dynamically project the required power reserve at the operating point. These conditions limit the application of grid-forming technologies.

② Technical solution

As shown in Figure 18, through block-level integration of control signals from PV inverters and battery containers, combined with a control strategy based on real-time bus voltage control arbitration, an integrated, virtual DC-coupled PV-ESS system is created. This solution decouples the MPPT (MPP tracking) control of PV output power, the SOC management of the energy storage units, and the requirements for inverter power scheduling and grid-forming control.

- PV side:
  MPP tracking calculations are performed based on the sampled voltage and current data from the PV array. The calculation results are used as control information to be communicated with the system.

- ESS side:
  Based on local battery SOC management strategies, control information required for PV MPP tracking is obtained. The DC/DC converter employs a bus voltage control arbitration algorithm at the DC coupling point, facilitating effective PV MPP tracking while maintaining voltage stability at the coupling point.

- Inverter side:
  Based on battery pack SOC management strategies and grid scheduling requirements, MPPT control and grid-forming algorithms are integrated to support various application scenarios, including MPPT-grid-forming and scheduling-grid-forming operations. This maximizes PV power generation and also provides real-time grid-forming responses to aid transient and steady-state grid voltage and frequency regulations.

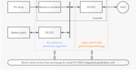


Figure 18: Block diagram of DC-coupled PV-ESS solution

③ Technical solution effectiveness

To validate the system' s technical reliability, tests were performed on the DC-coupled PV-ESS grid-forming inverter under frequency fluctuation conditions. As shown in Figure 19, the inverter operates in grid-forming mode. When the frequency drops, the inverter injects active power into the power grid, which is drawn from the DC link. By applying the bus arbitration stabilization algorithm, stored energy is delivered to the DC link, which thereby stabilizes the DC voltage.

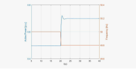


Figure 19: Active power waveforms of the DC-coupled PV-ESS grid-forming inverter under frequency fluctuations

4. Wide-Band Frequency Oscillation Suppression

A Power oscillation damping

① Challenges

Low-frequency power oscillations in power systems are primarily caused by the relative rotor swings of generators. Such oscillations can be triggered by system disturbances, load fluctuations, and other factors. If left unattended, they can lead to system instability and even widespread power outages. With the increasing penetration of renewable energy sources and a higher level of grid interconnection, the damping characteristic of power systems is weakened, and low-frequency oscillations become a more pronounced challenge.

② Technical solution

As shown in Figure 20, power oscillation damping (POD) controllers are composed of low-pass filters, high-pass filters, lead/lag compensators, as well as gain control and saturation parameters. They not only filter out the DC component and high-frequency noise in the frequency but also ensure the damping capability for low-frequency oscillations in the 0.1–10 Hz range.

Figure 20: Block diagram of POD control

③ Technical solution effectiveness

The effectiveness of the low-frequency oscillation suppression function is demonstrated in Figure 21. After injecting a 1 Hz oscillation component into the system frequency, it is observed that the active power exhibits a corresponding oscillation component. Notably, the phase of the active power oscillation is nearly opposite to that of the frequency oscillation component, providing positive damping. The results show that when the amplitude of grid frequency oscillation exceeds a set value, the converter unit can reduce the amplitude through active power regulation.

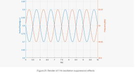


Figure 21: Render of 1 Hz oscillation suppression effects

B Multi-band frequency oscillation suppression

① Challenges

In new power systems, the interactions among renewable energy-based generation units, flexible AC/DC equipment, and their diverse control algorithms, coupled by complex grid conditions, give rise to the issue of multi-band frequency oscillations covering sub-synchronous, super-synchronous, medium-to-high frequency, and high frequency bands.

② Technical solution

To address multi-band frequency oscillation issues, smart sensing technology for multi-dimensional wide-band frequency oscillations is utilized, based on real-time dynamic response data, to extract key characteristic information to accurately identify the oscillation modes. VSG grid-forming technology is employed to dynamically reshape the grid-connected impedance characteristic. Moreover, through optimization controller or introducing virtual impedance in the control loop of the DC/AC power converter unit, the amplitude-frequency and phase-frequency characteristics of the converter unit's output impedance are reshaped, so that the system can remain stable in the sub-synchronous, super-synchronous, medium-to-high frequency and high frequency bands (≤ 2.4 kHz) to avoid oscillation.

3.2

Dynamic Energy Optimization on the DC Side

1. Precise SOC Calibration Technology

① **Challenges**

In grid-forming mode, the DC/AC power converter unit actively responds to grid ancillary services (e.g., primary frequency regulation, inertia support), generating power that is not controlled by the Local Controller (LC) or Energy Management System (EMS). This power is random in nature, with unclear charging and discharging directions. Such uncontrolled active power can lead to issues such as SOC unbalance within the battery system, low battery level, or overcharge.

② **Technical solution and effectiveness**

As shown in Figure 22, based on an AC storage system architecture, SUNGROW addresses SOC inconsistency, low battery, and overcharge issues during the charging and discharging process through fine-grained, self-optimizing rack-level management:

- SOC balancing:
  The LC acquires real-time data on uncontrolled power resulting from the DC/AC power converter unit' s ancillary services. By applying an inter-rack power balancing algorithm, it assigns different charging/discharging power levels to different string converter units, addressing SOC unbalance and improving overall charge/discharge capacity by up to 8%.

- Low battery and overcharge protection:
  When any cell triggers a Level 2 overvoltage or undervoltage alarm, the LC and the string converter unit collaborate in real time to disable charging or discharging for the affected rack, thus preventing low battery or overcharge. This minimizes battery risks while continuing to allow grid-forming ancillary services.

- Automatic recharging:
  In the event of low battery, the LC can automatically initiate low-power recharging during system standby. This enables intelligent online operation and maintenance (O&M) and eliminates the need for manual recharging operations, improving the overall economic performance of the power plant.

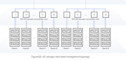


Figure 22: AC storage-rack-level management topology

2. AI-Driven Bionic Full Liquid Cooling Technology

① Challenges

Grid-forming ESSs are characterized by high charging and discharging frequencies, rapid power fluctuations, and instantaneous high-ratio overloads. Under extreme conditions, the output current can surge from 0 to 3×In within milliseconds, causing significant fluctuations in system heat load. This generates substantial heat in both the batteries and power electronic components (such as inverters). Applying traditional cooling designs from grid-following ESS to these scenarios can result in high auxiliary power consumption and potential overheating of components, thereby affecting system performance and lifespan.

② Technical solution and effectiveness

SUNGROW has pioneered an AI-driven bionic full liquid cooling technology, as shown in Figure 23. It employs a liquid cooling method featuring high thermal conductivity and good temperature uniformity to maintain both batteries and inverters within appropriate temperature ranges under grid-forming conditions. Moreover, by incorporating an AI bionic algorithm that predicts charge and discharge behaviors for the next 24 hours, along with trends in battery and ambient temperature changes, it designs a dynamic thermal management control strategy. This approach maximizes the temperature stability for batteries and power electronics, reduces system auxiliary power consumption by 30.4%, and improves the system's overall economic performance.

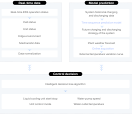


Figure 23: Control logic of AI-driven bionic full liquid cooling technology

3. Grid-Forming Electrical Hardware Design

① Challenges

Grid-forming operations involve frequency regulation, voltage support, and inertia response, characterized by rapid power fluctuations and momentary high-ratio overloads. These conditions place significant demands on the resilience of electrical hardware within ESSs. In grid-forming mode, the momentary current can reach up to 3 times the rated operating current (3 In), imposing a load impact on electrical hardware components. Hardware selection and design for conventional ESSs may not adequately address such impacts, which poses risks to system performance and safety.

② Technical solution and effectiveness

- Resilience design:
  To address grid-forming stress tolerance and hardware performance, SUNGROW increases the momentary withstand capacity margins for key components such as primary circuit fuses, contactors, circuit breakers, and connectors. The system integrates smart status monitoring and control mechanisms, complemented by an AI-driven bionic full liquid cooling technology, to provide comprehensive hardware protection.

- LVRT/HVRT design:
  To address momentary undervoltage in grid-forming scenarios and to ensure that the functional modules of electrical hardware can withstand momentary power reduction or even interruption without affecting fundamental operations, an intelligent and reliable fault ride-through design has been implemented. This design enables the ESS to maintain stable operation through grid oscillations.

- Auxiliary system design:
  In unstable grid conditions where grid-forming support is required, the connections of hardware components in the ESS could all experience electrical parameter changes caused by grid oscillations, or the transmission of high-frequency oscillations. Traditional low-impedance circuits may experience increased impedance due to overlapping oscillation frequencies, ultimately compromising the overall electrical connectivity. To address these challenges, SUNGROW has made specific optimizations on the electrical hardware at the plant level, block level, and container level to ensure reliable electrical connectivity under all operating conditions.

3.3

Autonomous Coordinated Control on the Plant Side

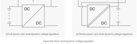
1. AC-DC Coordination at the Plant Level

① Challenges

As the penetration of renewable energy continues to increase, the grid' s dispatch requirement for ESS is rising, which directly affects the DC-side batteries. These requirements—such as ensuring reliable active power output on the AC side throughout the entire SOC range during grid HVRT, and the coordinated suppression of AC-side harmonic currents and DC-side ripple currents—will further drive the coordination between the AC and DC sides. In grid-forming scenarios, meeting the system' s threefold active power demand solely by oversizing or derating on the DC side increases initial investments and reduces the power plant' s economic performance.

② Technical solution

SUNGROW's Battery Management System (BMS) employs an integrated AC-DC management strategy, encompassing active monitoring, active storage, and active coordination. For example, to maintain reliable active power output on the AC side throughout the entire SOC range during grid HVRT: the conventional full-power rack-level two-stage dynamic voltage regulation architecture (a in Figure 24) can address the HVRT active power requirement for single-stage ESSs, but it suffers from high costs and low efficiency. In contrast, the partial-power rack-level dynamic voltage regulation scheme (b in Figure 24) significantly reduces costs, improves efficiency, and incorporates balancing functionality for parallel-connected racks to mitigate circulating current issues between racks.



a) Full-power rack-level dynamic voltage regulation

b) Partial-power rack-level dynamic voltage regulation

Figure 24: Rack-level dynamic voltage regulation

2. Large-Scale Black Start of the Plant

① Challenges

In the event of a blackout, a voltage source with appropriate capacity is required to help restart the main synchronous generation unit. Traditional black start methods use diesel generators to provide excitation for the synchronous generator, transformer, and other components. However, maintaining these diesel generators on long-term standby can lead to significant pollution and incur high operation and maintenance costs. As the share of renewable energy integrated into grids is rising and distributed power sources are widely used, there is an urgent need for black start capabilities and higher requirements on the scale of black start operations.

② Technical solution

As shown in Figure 25, SUNGROW' s PV inverter/energy storage system black start technology makes it easy to rebuild the grid voltage using on-site PV/energy storage systems, with no additional equipment needed. It offers multiple black start modes at the subarray level, collection line level, and plant level.

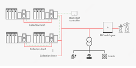


Figure 26: Application of PV/ESS black start technology

Through the voltage source mode, PV inverter/energy storage systems can perform grid-forming at zero voltage and coordinate multiple units to start at zero voltage simultaneously and excite the main transformer. The following functional requirements should be met:

- Sufficient stored energy:
  This ensures power supply to parts of the grid and loads and, in off-grid mode, provides energy for the auxiliary systems within the local grid.

- High current withstand capability:
  This refers to the ability to withstand inrush current upon transformer activation or synchronous generator start-up.

- Soft start function:
  This means ramping up the output voltage from zero to the nominal level at an appropriate slope, to avoid excessive inrush currents that could trigger the protection when powering on.

The key technologies for large-scale black start primarily involve synchronized start control and dynamic droop current-sharing control for multiple DC/AC power converter units. Upon receiving a black start signal, multiple converter units start up simultaneously with no inter-communication required, ensuring a smooth and continuous output voltage ramp-up. This smooth voltage ramping enhances the stability of the start-up process. After the converter units are networked and start normal operation, the system implements dynamic droop current-sharing control, enabling each converter unit to automatically adjust the droop coefficient based on real-time changes in output current and voltage. This ensures rapid and rational power and current distribution to satisfy system requirements. These key technologies significantly improve the voltage control consistency and minimize circulating currents.

③ Technical solution effectiveness

Figure 26 illustrates the dynamic characteristics of the black-start process. During the voltage soft-start phase, multiple DC/AC power converter units achieve stable and coordinated operation, with no abnormal circulating currents detected by the system. After the voltage is stably established, the system successfully connects to the rated load, exhibiting no overshoot or oscillation in voltage during the transient process, which demonstrates excellent dynamic performance.

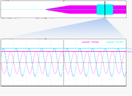


Figure 26. Black-start process

3. Seamless Switching Between On-Grid and Off-Grid Modes

① Challenges

In the on-grid mode, the DC/AC power converter unit operates in sync with the main grid, enabling bidirectional power flow. In the off-grid mode, the converter unit operates independently or supplies power to local loads, autonomously regulating voltage and frequency. With the rapid development of distributed energy, ESSs must be able to seamlessly switch between on-grid and off-grid modes to ensure reliable power supply and high power quality. Inappropriate switching strategies can lead to significant electrical transients at the point of common connection, causing disturbances to the power system and potential damage to sensitive equipment within microgrids.

② Technical solution

SUNGROW inverters emulate the operational characteristics of synchronous generators, thus delivering similar inertia and damping properties. During on/off-grid mode switching, the inertia and damping properties of the VSG are utilized to smoothly adjust output power and voltage, reducing voltage fluctuations and enhancing system stability and reliability. When transitioning from off-grid mode to on-grid mode, a pre-synchronization strategy is applied to align the VSG' s voltage magnitude and phase angle with those of the grid before grid connection to minimize impact, as shown in Figure 27.

Figure 27: Schematic diagram of VSG grid connection

③ Technical solution effectiveness

As shown in Figure 28, during the transition from the on-grid mode to the off-grid mode, the voltage and current waveforms remain stable and power output is continuous, with no significant impacts. This demonstrates that the system has the capability for seamless on/off-grid switching, ensuring the continuous and stable power supply.

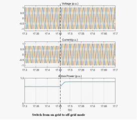


Figure 28: Seamless on-grid to off-grid mode switching

- Field testing:
  SUNGROW successfully completed the black start and grid synchronization tests at the 220 kV Dongtian energy storage plant (75.9 MW/151.8 MWh), initiated by Guangxi Hydropower Research Institute. The test results (Figure 29) show that the DC/AC power converter unit at the plant is capable of grid synchronization with a phase angle difference no greater than 10°.

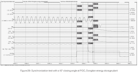


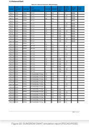
Figure 29: Synchronization test with a 10° closing angle at POC, Dongtian energy storage plant

3.4

End-to-End Simulation Capabilities

1. Electrical Simulation

SUNGROW operates the world' s largest simulation platform, backed by a team of over 100 electrical simulation experts and multiple Hardware-in-the-Loop (HIL) laboratories. The platform integrates simulation software, including PSCAD, PSSE, DigSILENT, and DSATool, with more than 20 HIL testbeds, including RT-LAB and RTDS. This comprehensive setup supports simulation testing for advanced technologies, including grid-forming technologies, across the globe and has a simulation capacity reaching gigawatt levels. In response to Australia' s specific grid code requirements, SUNGROW successfully passed Generator Performance Standards (GPS) certification and over 1000 model validation cases in the Detailed Model Acceptance Test (DMAT), as shown in Figure 30.



SUNGROW PPC DMAT ASSESSMENT REPORT

6.2 Balanced fault

Figure 30: SUNGROW DMAT simulation report (PSCAD/PSSE)

In an Australian grid-forming project, SUNGROW conducted a plant-level simulation of a 303 MW / 672 MWh ESS to verify its stable operation under grid conditions at the connection point and to ensure compliance with all grid-connection requirements. These include:

①Ensuring simulation accuracy and consistency by comparing the electromagnetic, electromechanical, and HIL models.

②Performing large grid simulations at the plant level to comprehensively assess the grid-forming power plant's impact on and contribution to the grid conditions at POC.

③Precisely modeling plant parameters and conducting over 1000 dynamic simulation tests to ensure compliance with the technical requirements of the Australian National Electricity Rules (NER) for renewable energy generators.

2. Noise Simulation

SUNGROW' s noise simulation laboratory is equipped with simulation software such as CadnaA, SoundPLAN, and Simcenter 3D, allowing it to perform noise simulations for renewable energy plants worldwide. All noise simulation and analysis works comply with internationally recognized standards, including ISO 9613 (Acoustics – Attenuation of sound during propagation outdoors) and HJ 2.4 (Technical Guidelines for Environmental Impact Assessment – Acoustic Environment).

Taking grid-forming products as an example, SUNGROW' s noise simulation capabilities address a wide range of scenarios involving disparate ambient temperatures (25° C, 35° C, 55° C, etc.), operating power (100%, 80%, 50%, etc.), plant layouts, and geographic locations. With a maximum simulation capacity exceeding 20 GW, these capabilities play a critical role in site selection and plant construction for renewable energy plants by:

① Evaluating whether plant-emitted noise complies with local environmental noise regulations.

② Designing noise mitigation solutions and evaluating their performance in a simulation.

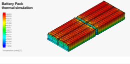
③ Recommending suitable plant locations (with respect to residential areas) that meet noise level requirements.

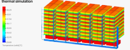
Figure 31 presents a sound pressure level map for a GWh-scale plant, illustrating the distribution of noise around the plant. This visualization is essential for ensuring environmental protection compliance, optimizing site selection, and designing noise mitigation measures.

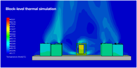
Figure 31: Sound pressure level cloud map near a GWh-scale power plant

3. Thermal Simulation

SUNGROW' s thermal simulation laboratory leverages advanced hardware facilities and a highly specialized team to meet simulation demands worldwide. Its computing infrastructure is built on a heterogeneous CPU+GPU cluster with thousands of cores, capable of processing simulations with hundreds of millions of mesh elements. The platform delivers more than twice the computational speed of traditional thermal simulation workstations, and integrates leading thermal simulation software such as Fluent, Icepak, and FloEFD to cater to a wide range of needs. Over 10% of the team hold doctoral degrees and more than 85% hold master' s degrees, fully qualified to provide end-to-end simulation services from modeling to results analysis. SUNGROW's thermal simulations cover grid-forming components, individual equipment, integrated systems, and plants and support steady-state, transient, and multiphysics-coupled simulations, adapting to various operating conditions including temperature, humidity, and altitude. The platform can solve complex problems involving hybrid cooling where air cooling, liquid cooling, and phase-change cooling are used together. SUNGROW has successfully validated complex simulation scenarios including for plants exceeding 20GWh and models with over 100 million mesh elements. This platform can support the long-term and stable thermal management of large-scale renewable plants (Figure 32).


Battery Pack thermal simulation


Battery system thermal simulation



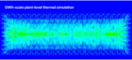


Figure 32: Thermal simulation cases (from component-level to plant-level)

① Improved system efficiency and reduced operating costs

By leveraging thermal simulation to optimize thermal and temperature control design, the energy consumption of cooling systems can be significantly reduced. For grid-forming projects, improved energy efficiency translates into lower long-term operating costs. For example, thermal simulation ensures that battery packs operate within their optimal temperature range, thereby extending battery life and improving overall system efficiency.

② Risk identification in complex operating conditions for enhanced design robustness

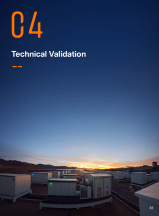
Grid-forming projects often face highly variable operating environments and load conditions. Thermal simulation enables the modeling of thermal performance under scenarios such as instantaneous overloads, ensuring the reliability of equipment throughout its lifecycle.

③ Intelligent thermal management for improved system performance

By leveraging simulation data to build digital models, cooling system operation strategies can be optimized. This enables dynamic adjustment of airflow and cooling capacity allocation, achieving intelligent thermal management and improving both system performance and operating efficiency.

04

Technical Validation



4.1 TÜV Rheinland Tests and Results

1. General

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TÜVRheinland®

1.1 Summary

The purpose of report is to evaluate the grid-forming performance of Sungrow's commercial ESS converters.

The evaluation process is as below:

Challenge: The voice was collected from market, customer and grid operator, to make clear the problem and challenge to the grid management caused by high amount of renewable energy.

Solution: Potential solutions by GFM were raised to solve the problem after a detail exchange and discussion with Sungrow from the view of technology.

Framework: The potential solutions were promoted to a detail feasible technical framework to specify the requirements on grid-forming.

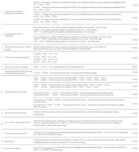
Test plan: To verify the products according to specified framework, a test plan was generated to instruct the test procedure. Both HIL simulation tests and on-site physical tests would be applied.

Verification: Measurement per test plan has been conducted to verify whether the product's output character fulfil the framework.

Decision: After a final review on evaluation process, framework and verification result, the decision would be made whether the product has got grid-forming performance and be able to improve the steady of grid.

During series of tests, the Sungrow's ESS converter SC2500UD-P3 / SC1250UD-FM / SC2500UD-US-P3 / SC210HX-US-FM / SC210HX-FM / SC125HX-FM showed outstanding performance on grid forming, includes the capability of phase jump withdraw, damping to voltage / frequency oscillation, resistance to excitation inrush current, wide SCR operation, VPRT, primary frequency control, black start and short-term overload, etc.

TÜV Rheinland LGA Products GmbH
Grid Code Compliance Service



No.	Test Item	Content	Result
1	Response to voltage phase jump	≤0.2Pn, ±90° Single-phase/Two-phase/Three-phase angle disturbance, each disturbance phase angle runs continuously for no less than 5s.	PASS
2	Damping to voltage / frequency disturbance	≤0.2Pn, Frequency disturbance amplitude 0.05Hz, the oscillation frequency of each disturbance amplitude 0.1Hz, 1Hz, 2.5Hz, 10Hz. ≤0.8Pn, Frequency disturbance amplitude 0.05Hz, the oscillation frequency of each disturbance amplitude 0.1Hz, 1Hz, 2.5Hz, 10Hz.	PASS
		≤0.2Pn, Voltage disturbance amplitude 5%Un, the oscillation frequency of each disturbance amplitude : 0.1Hz, 1Hz, 2.5Hz, 10Hz. ≤0.8Pn, Voltage disturbance amplitude 5%Un, the oscillation frequency of each disturbance amplitude : 0.1Hz, 1Hz, 2.5Hz, 10Hz.	PASS
3	Impedance at higher frequency	Zero output power, 1Hz~400Hz positive/negative impedance scanning, with 1Hz step. ≤0.5Pn, 1Hz~400Hz positive/negative impedance scanning, with 1Hz step. ≤1Pn, 1Hz~400Hz positive/negative impedance scanning, with 1Hz step.	PASS
		Zero output power, 410Hz~2400Hz positive/negative impedance scanning, with 10Hz step. ≤0.5Pn, 410Hz~2400Hz positive/negative impedance scanning, with 10Hz step. ≤1Pn, 410Hz~2400Hz positive/negative impedance scanning, with 10Hz step.	PASS
4	Resistance to excitation inrush current	Switch on the transformer with a capacity the same as the DC/AC power converter unit after the DC/AC power converter unit has stabilized in off-grid mode.	PASS
5	SCR rapid change withstand	≤0.26Pn, SCR: 10→1→10. ≤0.7Pn, SCR: 10→1→10. ≤0.26Pn, SCR: 40→1→10. ≤0.7Pn, SCR: 40→1→10.	PASS
6	Extra low SCR compatibility	SCR=1, ≤0.7Pn, the voltage drops to 0Un and holds for 10S.	PASS
7	Switching between grid-forming and grid-following mode	≤0.2Pn, ≤0.8Pn, Switching between grid-forming and grid-following mode.	PASS
8	Voltage fault ride through	LVRT: ≤0.2Pn, Three-phase/Two-phase 0.05Un, 0.2Un, 0.4Un, 0.6Un, 0.8Un. LVRT: ≤0.8Pn, Three-phase/Two-phase 0.05Un, 0.2Un, 0.4Un, 0.6Un, 0.8Un.	PASS
		HVRT: ≤0.2Pn, Three-phase/Two-phase/Two-phase 1.13Un, 1.17Un, 1.20Un, 1.3Un. HVRT: ≤0.8Pn, Three-phase/Two-phase 1.13Un, 1.17Un, 1.23Un, 1.3Un.	PASS
		Consecutive LVRT: ≤0.2Pn, Three-phase 0.05Un, time interval between the two drops is 2S. Consecutive LVRT: ≤0.8Pn, Three-phase 0.05Un, time interval between the two drops is 2S.	PASS
		Consecutive LV-HVRT: ≤0.2Pn, Three-phase 0.05Un-1.3Un, alternate six consecutive unpaused voltage drop-lift actions. Consecutive LV-HVRT: ≤0.8Pn, Three-phase 0.05Un-1.3Un, alternate six consecutive unpaused voltage drop-lift actions.	PASS
9	Synchronous condenser	Connect 4 GFM inverters under synchronous condenser mode, short circuit three-phase/single-phase with ground.	PASS
10	On- and off- grid mode switch	With the PCS operating at rated power output in grid-connected mode, disconnect from the grid, then connect resistive loads of Pn, 0.66Pn, and 0.33Pn. Record the time taken for the terminal voltage to stabilize within ±5% of the rated value.	PASS
11	Primary frequency control	With the PCS operating at rated output power at charging mode and discharge mode, set the power grid frequency from 50Hz to 47Hz/53Hz abruptly.	PASS
12	Black start	Two grid-forming converters are connected in parallel. First, a 0.2Pn resistive load is connected. After the bus voltage stabilizes, the load is increased to 1Pn one minute later.	PASS
13	Overload capacity	With the PCS operating at rated output power at charging mode and discharge mode, run the inverter with 120%In, 150%In and 200%In respectively.	PASS

Figure 33: TÜV Rheinland test results of SUNGROW Grid-forming DC/AC Power Converter Unit

05

Grid-Specific Project Cases

To date, SUNGROW has deployed over 12 GWh of grid-forming projects worldwide, with more than 30 projects spanning diverse scenarios across power generation, transmission, consumption, and microgrids. Aiming to offer grid-specific security and stability, SUNGROW delivers customized grid-forming solutions that support the stable operation of new power systems across different regions.

60MW / 120MWh Grid-Forming Project in Northwest China

This region in Northwest China has a high penetration of renewable energy, with PV power generation accounting for 88% of total installed capacity. However, as it is located at the end of the power grid, this region suffers from a weak grid structure and insufficient terminal voltage support. It also lacks regulating power sources, resulting in significant system stability issues such as low inertia and insufficient reactive power support.
SUNGROW delivered a 60 MW / 120 MWh grid-forming PowerTitan 2.0 solution to address these challenges. Through microsecond-level voltage formation, the system supports quick voltage recovery and enhances grid stability. Flexible inertia technology was applied to improve frequency stability, keeping grid frequency fluctuations within the normal range. In addition, large-scale off-grid black start capability enabled the creation of a microgrid, which is powered 100% by PV and other clean energy sources and supports stable operation around the clock. This solves the difficulties of resource development in remote areas far from large grids.
To cope with the region's high altitude and low temperatures, precise SOC management strategy and AI-driven bionic full liquid cooling technology are used to improve SOC accuracy, reduce auxiliary system losses, and extend the lifespan of both batteries and power electronic components. This allows for the stable and efficient application of grid-forming ESSs.

Saudi Arabia's NEOM:
Grid-Forming Project Integrating Wind, Solar, Battery, and Hydrogen for Multi-Energy Coordination

NEOM is a futuristic new city planned by the Saudi government, designed to be powered entirely by renewable energy and to host the world' s largest green hydrogen production base. To address the intermittency and volatility of renewable energy, the project is equipped with large-scale ESSs to ensure stable power supply during periods of low sunlight or minimal wind.

SUNGROW provided its 600 MW/600 MWh grid-forming PowerTitan ESS along with 2 GW 1+X modular inverters, enabling seamless switching between on-grid and off-grid modes in the PV-ESS system. In on-grid mode, the system exchanges energy with the grid based on adjustable setpoints. In off-grid mode, it instantly and seamlessly becomes the primary grid-forming resource. Through the coordinated control of PV-based and energy storage-based grid-forming technologies, the system maintains stable operation on the 380kV bus. It also supports the dynamic control of electrolyzers, ensuring the stable operation of hydrogen production equipment.

16MW / 88MWh Grid-Forming Project at the Dalia Power Plant in the MEA

The Dalia power plant in the MEA has a total generation capacity of approximately 900 MW, accounting for around 8% of the region' s total electricity supply. When plants undergo annual scheduled shutdowns for maintenance, restarts performed using traditional black start methods incur high costs and operational inefficiencies.

To address the challenges of restarting the Dalia power plant after routine maintenance, SUNGROW deployed a 16 MW / 88 MWh grid-forming PowerTitan 3.0. Using the voltage-source mode based on grid-forming algorithms, the system enables zero-voltage grid formation and supports simultaneous zero-voltage start-up of multiple units and excitation of the main transformer. This approach significantly reduces generation losses caused by long black start times and eliminates the pollution and maintenance costs associated with traditional diesel generator backups, ultimately improving the operational efficiency of the Dalia power plant.

06

Reflections and Path Forward

Grid-forming technology is evolving from device-level to system-level control. With Stem-cell Grid-forming Tech 2.0, security and stability are embedded as "genetic traits" within renewable energy plants, enabling a paradigm transition from passive grid-following to active grid-forming. Under the guiding principle of "grid-specific solutions", the three-tier coordinated architecture of Stem-cell Grid-forming Tech 2.0, which involves battery, power converter, and plant-level coordination, provides safe and efficient battery management, endows grid-forming converters with synchronous generator-like capabilities, and unlocks system-level grid-forming competence as well as multi-agent coordination capability. This marks a transformation of the business models of renewable energy plants, where security and stability translate to profitability.

Looking ahead, SUNGROW will actively promote collaboration across the industry, work to improve the grid connection standards and specifications for renewable energy plants, and continue investing in fundamental research and supporting technologies, aiming to contribute to the global energy transition.

Clean power for all

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