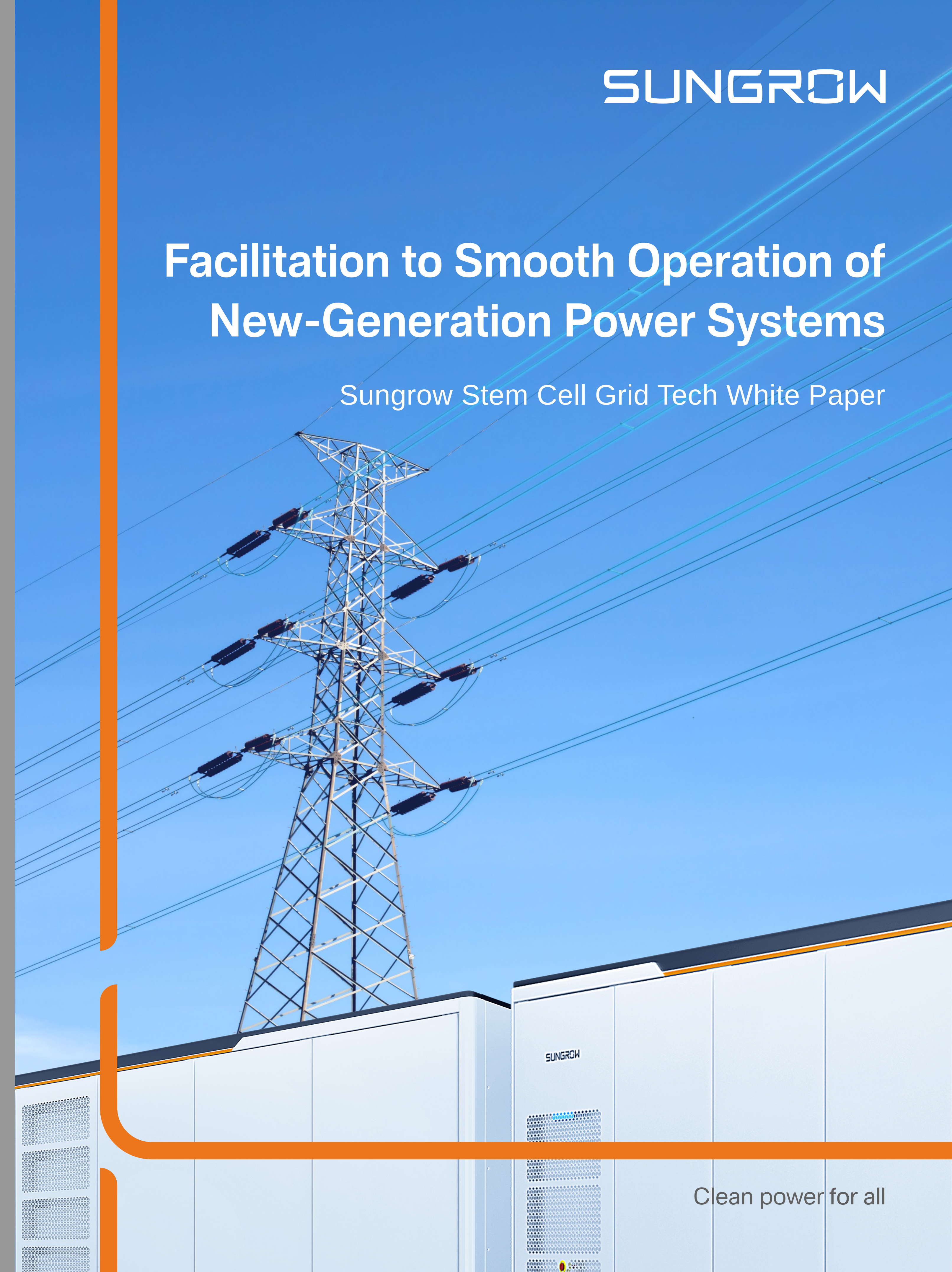
SUNGROW

Facilitation to Smooth Operation of New-Generation Power Systems

Sungrow Stem Cell Grid Tech White Paper



Clean power for all

Preface

In the context of achieving carbon neutrality, the integration of renewable energy power plants into the grid has witnessed a steady rise. In addition, the convergence of frequent extreme weather conditions and various unpredictable factors has contributed to the growing complexity of the new power system. Consequently, this intricate scenario presents novel challenges to maintaining system operational stability.

The energy storage system (ESS), a critical component of the new power system, plays an indispensable role in ensuring power grid stability. The continuous increase in new energy facilities in relation to conventional sources of electricity generation imposes new requirements on the ESS grid supporting capacity.

In an effort to stabilize grid operations, Sungrow Power Supply proposed the Stem Cell power grid technology to facilitate the smooth operation of the new power system. This White Paper contains thorough elaborations on relevant technical solutions for reference by market insiders.

Contents

Characteristics and Development Trends of New-Generation Power Systems

Substantial Application of Renewable Energy

In a bid to achieve the "dual carbon" target, efforts have been made to accelerate the structural energy transformation amid constant increases in renewable energy consumption relative to total energy consumption. As of 2022, the cumulative installed capacity of wind and solar power generation facilities worldwide reached 2,168 GW, accounting for 25% of the global total installed capacity. Wind and solar energy has become an important component of the energy structure. It is predicted that by 2030, the installed capacity of global wind and solar power generation plants will increase to 7,219 GW, accounting for 47% of the global total installed capacity, pointing to significant changes in the power grid landscape in the future.

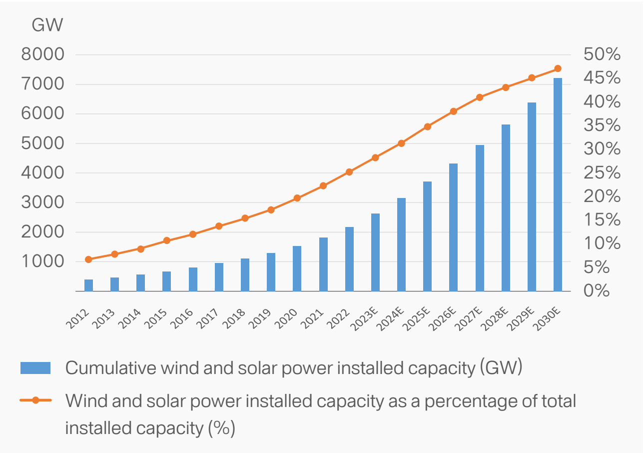


Figure 1: Forecast of global wind and solar power installed capacity (source: BloombergNEF)

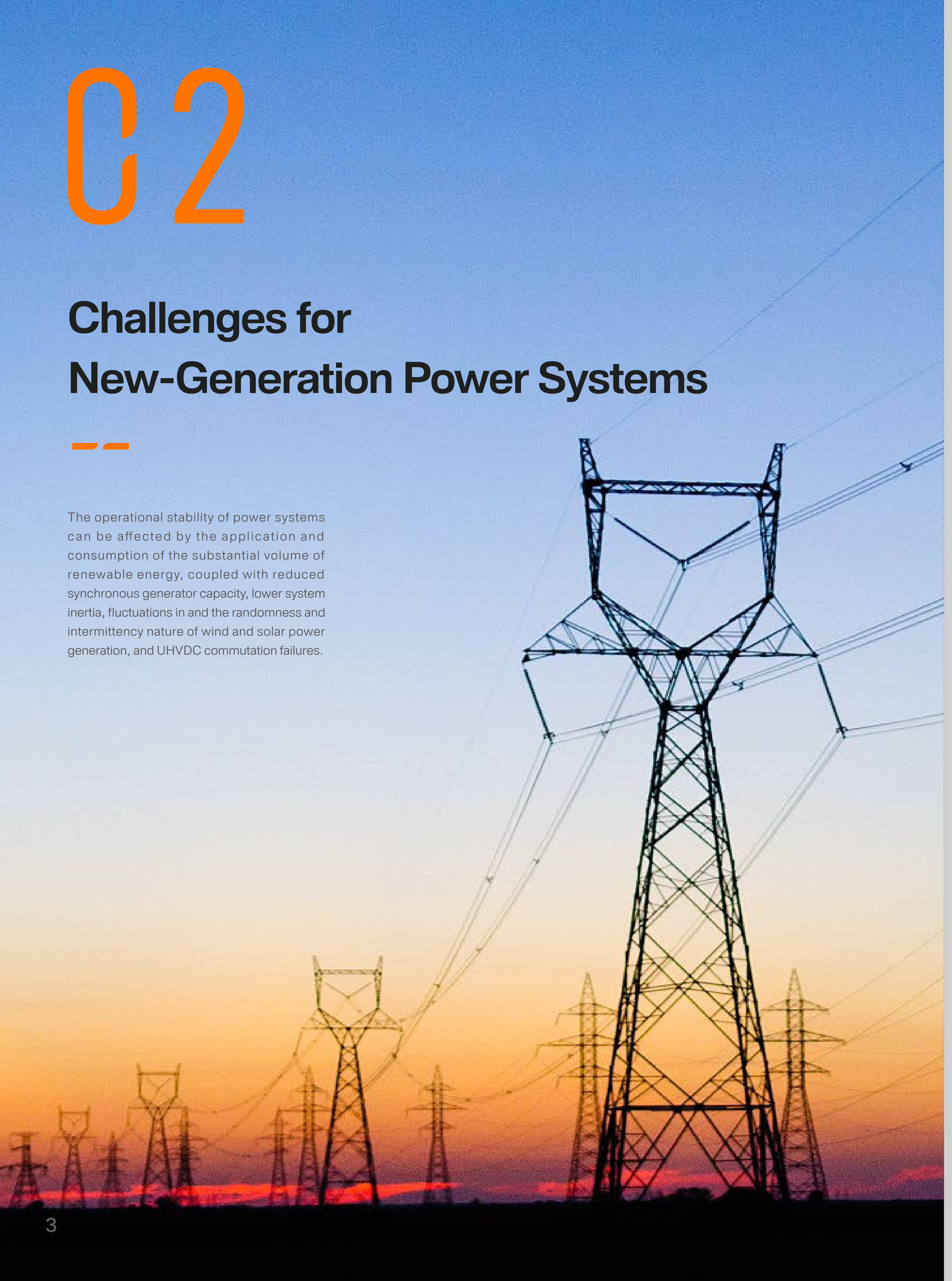
Substantial Application of Power Electronic Equipment

Along with the extensive application of renewable energy sources such as wind and solar, power electronic generation equipment has gained traction among electric power systems. Due to the differences in control features between renewable energy generation facilities and traditional synchronous generators, and the different control schemes adopted for different grid-connected power electronic devices, low inertia, low damping, and low voltage support have become prominent characteristics of new-generation power systems. Furthermore, the large-scale application of power electronic devices such as HVDC converter stations and power flow controllers (such as Unified Power Flow Controller and Static Synchronous Series Compensator) on the transmission side, and the adoption of a substantial number of power electronic devices in charging piles and other power consumption equipment, have made power grids increasingly complex, posing new challenges to power grid stability.

Substantial Adoption of UHVDC Transmission

Given the long distances between energy production and consumption areas, the construction of large-capacity and long-distance energy transmission channels, with ultra-high voltage (UHV) transmission serving as the backbone network, is accelerating on a comprehensive scale. In China, for example, intensive development of wind and solar energy, hydropower, and nuclear power facilities are mostly concentrated in the southwestern, northwestern, northeastern and northern regions, while power consumption centers are primarily found in the central and eastern regions. In the case of high-capacity long-distance energy transmission channels, a partial power grid disconnection caused by a severe malfunction may lead to extensive power redistribution throughout the power grid. Currently, the voltage of UHV direct current (UHVDC) bus is up to ±1100 kV. In the event of a commutation failure or DC blocking, it increases the risk of system frequency and voltage instability, as well as instantaneous overvoltage, thereby placing more stringent requirements on the performance of the converter equipment in terms of, for example, inertial support, frequency support and voltage support.

Figure 2: UHV power transmission



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Challenges for New-Generation Power Systems

The operational stability of power systems can be affected by the application and consumption of the substantial volume of renewable energy, coupled with reduced synchronous generator capacity, lower system inertia, fluctuations in and the randomness and intermittency nature of wind and solar power generation, and UHVDC commutation failures.

1 Unstable voltage

Given the limited capacity of the regional power grids, the large-scale application of renewable energy power plants may cause voltage fluctuations due to natural factors such as wind and sunlight, thus affecting voltage stability. In the event of series compensation of transmission lines using shunt capacitors or reactors or a UHVDC commutation failure, the resulting increase in steady-state and transient voltage fluctuations on the system will demand higher dynamic voltage regulation capability on the power system. In engineering applications, there is a need for support for multiple consecutive faults crossing high and low voltage levels, as shown in Figure 3.

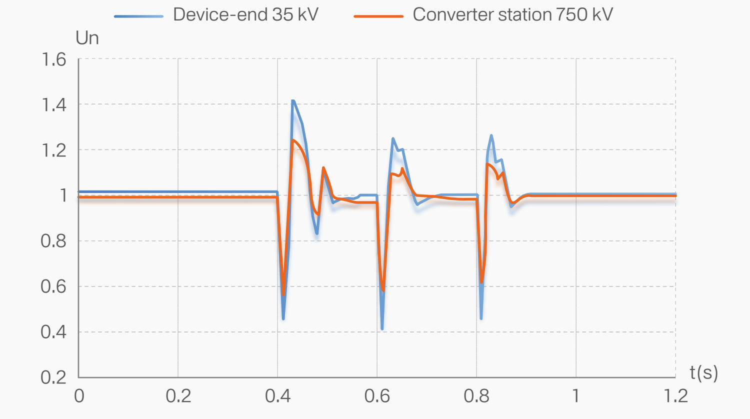


Figure 3: An example of grid requirements for continuous voltage FRT

2 Wideband oscillation

Power system oscillations caused by the inherent properties of power electronic devices have spilled over from the traditional power frequency range to the medium and high frequency range. New-generation power systems demonstrate complex features related to mode coupling instability. In recent years, the world has witnessed multiple incidents of grid disconnection caused by oscillation resulting from large-scale application of renewable energy sources. Wideband oscillation has become a pressing issue that needs to be tackled for new-generation power systems.

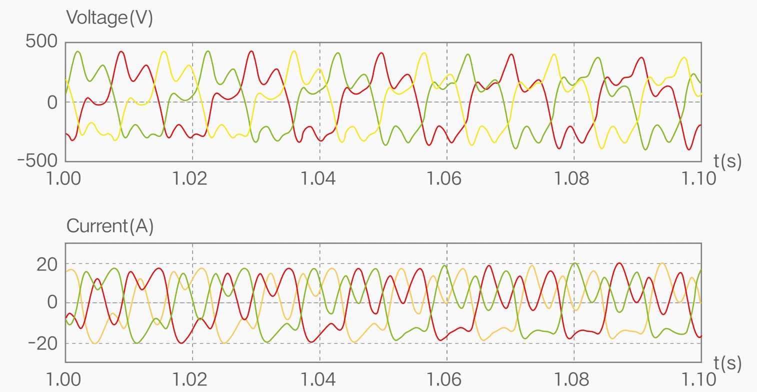


Figure 4: Power oscillations in a power electronic device

3 Low inertia, unstable frequency

The application of substantial renewable energy sources has led to a transformation of the power systems away from "controllable power generation tracking uncontrollable load flow" toward "bidirectional matching of uncontrollable power generation and uncontrollable load flow". Large-scale application of renewable energy sources such as wind and solar power can reduce inertia in the system and cause frequency instability, affecting the performance of motors and other electrical equipment. In severe cases, it can lead to systemic frequency breakdown, causing widespread power outages.

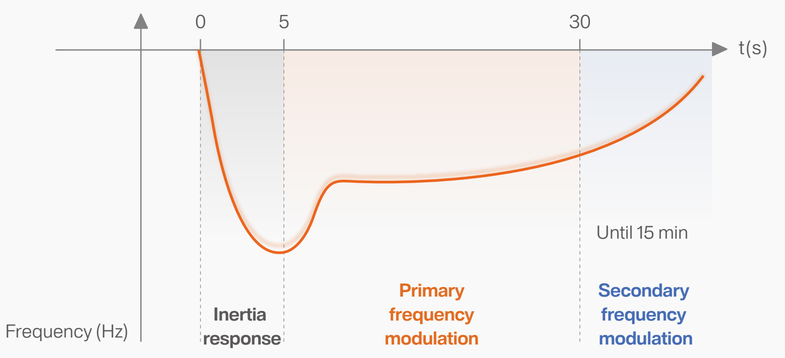


Figure 5: Power system frequency modulation process

03

Stem Cell Grid Tech

Amid the increasing market penetration of renewable energy, the ESS grid connection technology has evolved from the stage of adaptation to the power grid to one that focuses on supporting the grid, ushering in the new phase of "grid reconstruction".
Based on a profound understanding of the power grid network, Sungrow has innovatively proposed the Stem Cell Grid Tech to ensure the smooth operation of new-generation power systems, with grid-forming control technology serving as one of its important components.
ESSs help to stabilize power grids through frequency modulation, voltage regulation, harmonic suppression, black start, or other ways, similar to the functions of stem cells in repairing, purifying and making blood for human tissues.

1 Enhanced HVRT & LVRT

When the voltage at the POC drops due to a short circuit or other reasons, or when overvoltage occurs due to substantial load disturbances, the ESS needs to remain connected to the grid and provide reactive power support to help the grid recover and "ride through" the fault location. Grid-connection standards such as GB/T 34120 and GB/T 36547 require the reactive power response time during voltage FRT to be 30ms. Against the backdrop of "high carbon emissions, high energy consumption and high pollution", ESSs should be capable of performing continuous HVRT and LVRT for multiple times, and this is also a general requirement for the next-generation grid connection standards.

Solution

① **Fast positive and negative sequence decoupling:**
Fast fault detection of grid voltage fault (in excess of 0.9 p.u. to 1.1 p.u.) is performed by the ESS. Based on real-time positive and negative sequence decoupling algorithms, the positive and negative sequence components of the grid voltage are extracted, and a rapid power control algorithm is used to achieve 10 millisecond-level reactive power response, supporting voltage fault recovery.

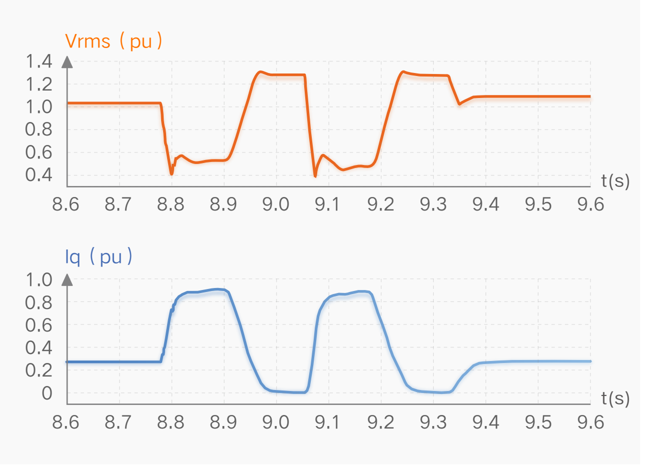


Figure 6: An example of the reactive power response process for continuous grid FRT

② **Dynamic virtual impedance:**
In a normally operating system, the Power Conditioning System (PCS) is connected to the grid with the regular virtual impedance enabled, enhancing automatic sharing of active power and reactive power.
In the event of a short circuit or overload in the system, the PCS generates overcurrent. If the output current is greater than the preset value and the port voltage is lower than the preset voltage, the PCS automatically switches to the virtual impedance adaptive mode, changes the virtual impedance value, and adjusts the voltage setting and the point of connection (POC) voltage of the closed-loop control equipment in real time. The PCS is involved in real-time voltage building of the power grid, automatically outputs reactive power, and smoothly performs continuous voltage fault ride through (FRT), making it the fundamental FRT technology for distributed power grid applications.

2 Adaptive wideband oscillation suppression

In a new-generation power system equipped with power electronics, factors such as equivalent impedance mismatch, incorrect control parameters and system delay increase the risk of power frequency and high frequency oscillation. For example, inconsistent coordination and response differences in power scheduling strategies between different regions, as well as resonance between power electronic devices and grid impedance, may lead to wideband oscillations of the system.

Solution

Based on fast frequency-domain/time-domain resonance analysis of voltage and current at Points of Common Coupling (PCCs) of high-performance digital controllers, intelligent perception with multi-dimensional wideband oscillations is used to extract information on main characteristics and detect oscillations. Voltage source grid-forming is employed to redefine grid impedance and eliminate oscillations, enabling the system to adapt to complex grid conditions.
As shown in the simulation example in Figure 7, PV and energy storage POCs are connected to the main network through 2 back transmission lines, of which line 1has rated voltage of 275 kV and line 2 of 132 kV; PV grid-connected capacity is 100 MW, and energy storage grid-connected capacity is20 MW/20 MWh. Simulation operating condition: When a short circuit occurs in line 1, the relay action removes the fault point.

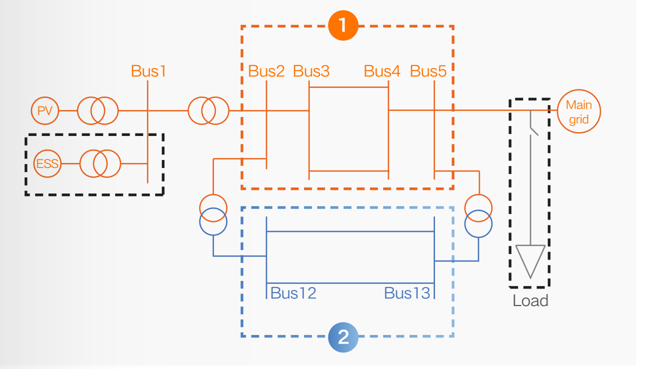


Figure 7: Simulation topology for reliable grid connection of ESSs paired with a PV power generation system.

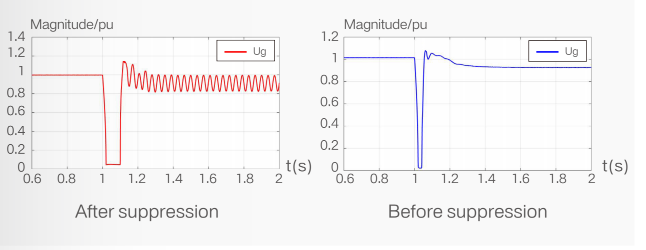


Figure 8: Energy storage uses voltage source to suppress wideband oscillations

As shown in Figure 8, in the case of energy storage without wideband oscillation suppression, the voltage at Bus 1, the PV storage POC, oscillates continuously, and the oscillation frequency is around 30 Hz. When the wideband oscillation suppression strategy and voltage source control are adopted, the oscillation can be quickly eliminated within the power cycle to stabilize the power grid.

3 POD

In some countries, power grid specifications require ESSs to be equipped with the power oscillation damping (POD) technology to detect and suppress active oscillations within the 0.3-2 Hz low frequency range. Such requirements tend to be more stringent in regions with relatively high penetration of renewable energy.

Solution

The Sungrow ESS adopts the station-level scheduling and group control technology, and the POD controller of the Energy Management System (EMS) collects PCC power and frequency information. When the frequency detected exceeds the threshold, proportionate adjustments are made based on the calculated power differential, and compensatory corrections are made for communication and response latency. With the damping power outputted, the ESS responds to the damping power command, and suppresses low-frequency power oscillations of 0.15-2.5 Hz within 3-5 cycles. The control mechanism is shown in Figure 9.

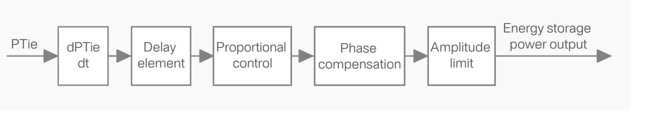


Figure 9: Working principle of POD control

As shown in Figure 10, a system configuration containing energy storage is established in the PSCAD simulation system, where SG1 and SG2 stand for power generation units with the same capacity (200 MW), and each has a local load of 100 MW at the near end. The ESS is on the side near SG2. Simulation of load disturbance, with LOAD3 active power of 10 MW.

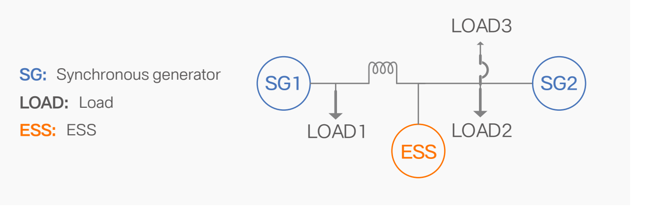


Figure 10: PSCAD simulation system resource configuration

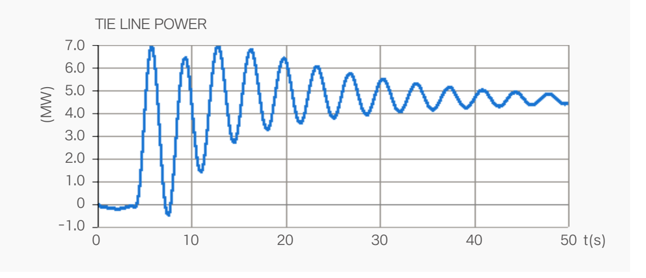


Figure 11: Wideband oscillations generated in a system without POD

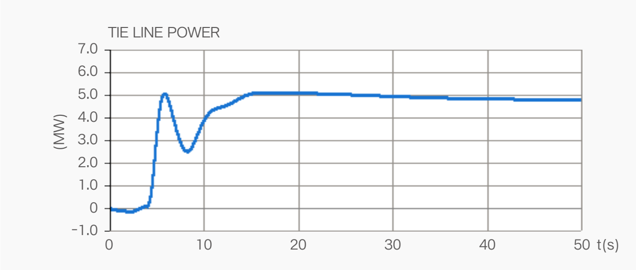


Figure 12: POD's suppression effect on wideband oscillations

As shown in Figure 11, the circuit breaker connecting to LOAD3 is initially open. At this time, SG1 and SG2 respectively supply power to the near-end load, and the power of the tie line is 0. At the fourth second, the circuit breaker of LOAD3 is closed, and the power of the tie line oscillates at a frequency of 0.3 Hz. As shown in Figure 12, after the POD controller is installed, the ESS responds to the POD output power command, and oscillations are quickly suppressed in the system.

4 Microsecond-level voltage construction

Characteristics of synchronous generators include self-balancing, droop and large inertia, which are conducive to the stable operation of power systems and the reasonable allocation of load power. In new-generation power systems where renewable energy makes up a high portion of electricity generation, ESSs are needed to simulate the functions of synchronous generators. That is, under normal operating conditions, the ESSs act as low-impedance voltage sources, to control the voltage magnitude and phase angle of the output, which inherently suppress rapid changes and improve the stability of the power system, as shown in Figure 13.

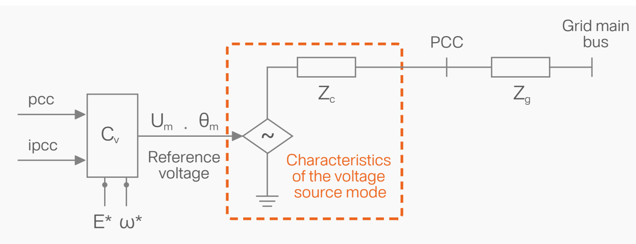


Figure 13: Diagram of the equivalent voltage source principle

Solution

ESSs simulate the voltage regulation function of synchronous generators to provide reactive power support to the power grid, as shown in Figure14 .

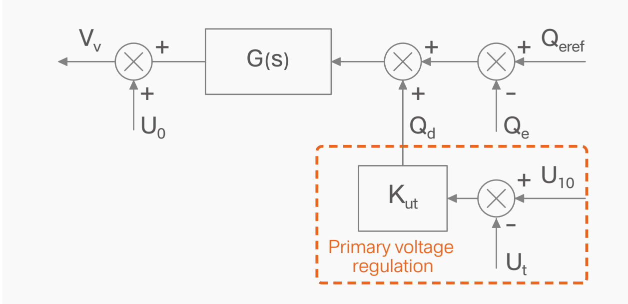


Figure 14: Voltage regulation control block diagram

① As regards VSG control, the undervoltage regulation of the terminal voltage Ut (primary voltage regulation function) is added to the reactive power control circuit, effectively supporting the amplitude of the terminal voltage Ut; the reactive power-voltage control of VSG simulates the excitation regulation process of a synchronous generator, and is used to manifest the undervoltage droop characteristics of reactive power and voltage.
② Real-time closed-loop control is applied to the terminal voltage Ut, and under operating conditions that may cause voltage transients such as weak grids or FRT, the reactive power output is adjusted to support the terminal voltage Ut.
Control in the current source mode under weak grid conditions is shown in Figure 15. During full-load power scheduling, the grid voltage fluctuation range is 12% Un, which can easily lead to local grid instability and system oscillation. Control in the voltage source mode under weak grid conditions is shown in Figure 16. During grid-connected full-load power scheduling, microsecond-level reactive power response is achieved, and the grid voltage fluctuation is less than 2% Un. Furthermore, the terminal voltage Ut is automatically stabilized without affecting active power scheduling.

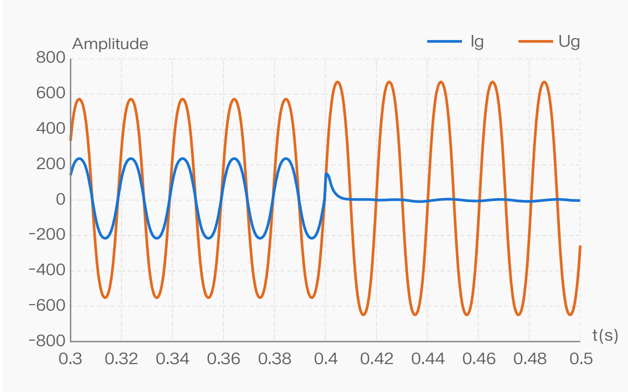


Figure 15: Autonomous voltage regulation in the current source mode under weak grid conditions

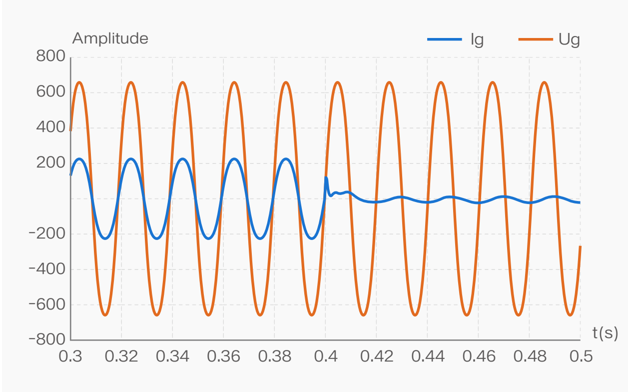


Figure 16: Autonomous voltage regulation in the voltage source mode under weak grid conditions

5 Flexible inertial support

Synchronous generators are characterized by substantial rotational inertia, and power electronics-driven ESSs should be able to provide inertial support accordingly. The ESS operating in the current source mode should be detected before controlled when performing frequency response, and the resulting second-level delay makes it difficult to meet the inertia response requirements of new-generation power systems. Therefore, ESSs should operate from voltage source, and provide millisecond-level inertial response functionality to stabilize frequency on the power grid.

Solution

On the condition that synchronous generator control is adopted in the ESS:
① Add primary frequency modulation to the active power control circuit to support grid frequency, as shown in Figure 17.

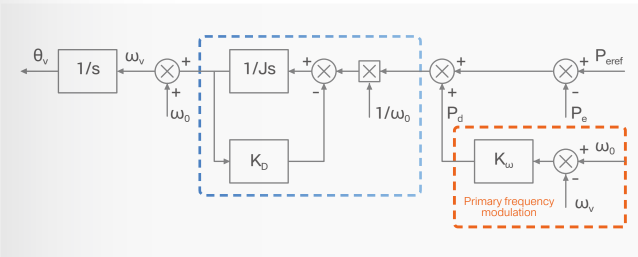


Figure 17: Frequency modulation control block diagram

② The rotational inertia J of the VSG is not significantly affected by hardware conditions and can be flexibly simulated and set. In the event of system disturbances, parameters such as rotational inertia J and damping coefficient KD slow down frequency changes in the system, thus improving the stability of the system frequency and power angle.

In both off-grid and grid-connected applications, the influence of inertia on frequency change is as follows:
Off-grid: Multiple inverters form a power grid jointly with diesel generators and other energy sources, and set the inertia time constant (T_J) to operate in the microgrid.
a. T_J = 0s, indicating that the system has zero inertia
b. T_J = 0.5s

When load is applied and cut off, frequency changes at two different time constants are shown in Figure 18.

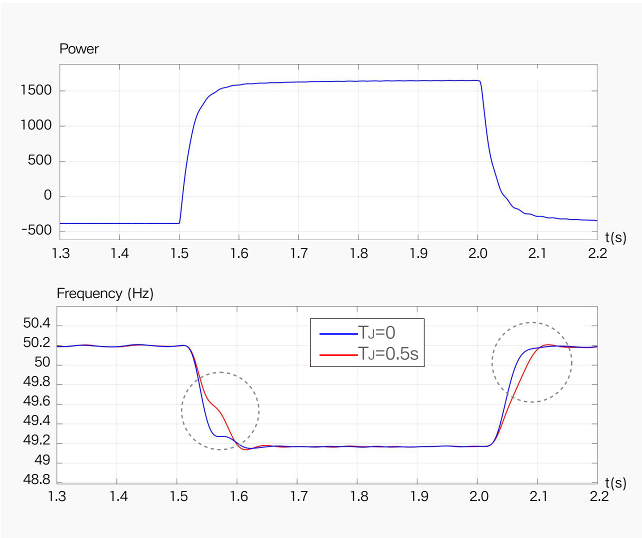


Figure 18: Impact of inertia on frequency changes

As shown in Figure 18, when the load is applied at 1.5 second and cut off at 2 second, the frequency decreases or increases faster in the inertia-free system. With the increase of virtual inertia, the system frequency change rate decreases significantly, and system frequency becomes more stable.

Grid-connected: Connect the inverter to the grid and set the inertia time constant (T_J) of the inverter.
a. T_J = 0s, i.e. system has zero inertia
b. T_J = 0.5s

The system power changes at two different time constants during frequency changes are shown in Figure 19.

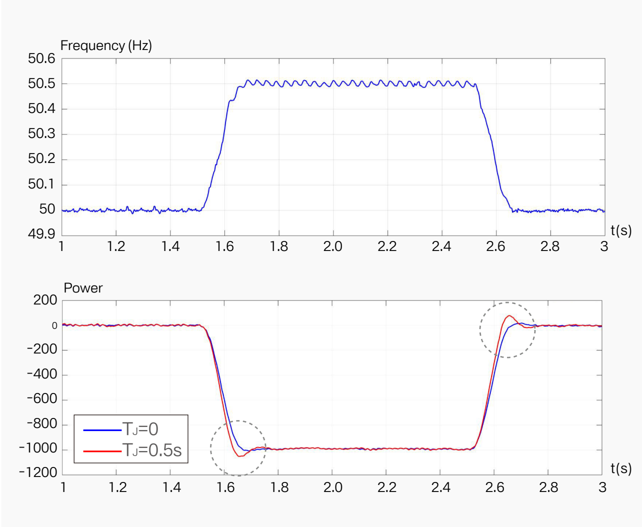


Figure 19: Impact of inertia grid-connected on frequency changes

As shown in Figure 19, when the inverter adds an inertia of T_J = 0.5s, during dynamic gridfrequency changes, active power is injected automatically at a faster pace compared to the inertia-free system, imitating the rotor characteristics of synchronous generators and suppressing fluctuations in the grid frequency.

6 Large-scale Black Start

Black start refers to a situation where synchronous generators are shut down unexpectedly due to grid power outage, and a certain capacity voltage source is built to assist in restarting the main synchronous generation unit. Traditional black start relies on diesel generators to excite synchronous generators, transformers and other equipment, resulting in high pollution and maintenance costs for backup over time. Black start of ESSs has become an urgent need, and black start has been scaled up in line with the increasing application of renewable energy resources and the rising popularity of distributed power sources. ESSs enable zero-voltage grid-forming by adopting the voltage source mode, coordinating multiple units to simultaneously start at zero voltage, and excite the main transformer. So storage systems should be capable of:

① **Providing sufficient storage capacity:**
The ability to guarantee power supply for partial power grids, and provide energy for auxiliary systems in the local grid in off-grid mode;

② **Withstanding high-current impulse:**
The ability to withstand short-term high current impact when the transformer or the synchronous generator is started;

③ **Soft starting:**
The ability to use a suitable slope output voltage to boost from zero to the nominal voltage, so as to prevent triggering protection when energized due the generation of excessive surge current.

Solution

Taking the ultra-large urban power supply system as an example, the power grid is divided into multiple power supply subunits, which are connected at a voltage of 110 kV or above to improve power supply reliability. Components of the power supply subunits mainly include PV, energy storage and gas turbines, as shown in Figure 20.

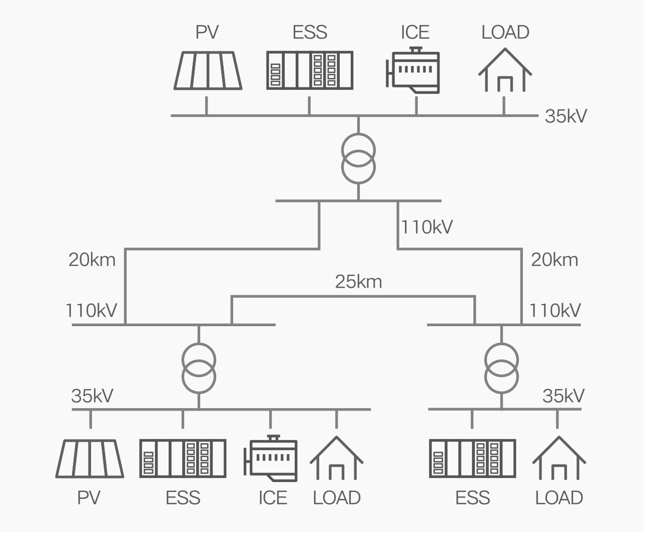


Figure 20: Diagram of multi-microgrid interconnection power supply system

Black start of large-scale distributed power grids adopts a zonal asynchronous approach, and the process is generally demonstrated as follows:

① **Zonal asynchronous start-up**
During black start of the internal microgrid system in each substation, a single ESS cannot drive the auxiliary load of the gas turbines, the EMS selects the minimum start-up capacity according to the start-up load in the microgrid, and assigns the corresponding capacity of the ESS to start up in parallel, with transformer excitation supported. 50 MW inverters in a certain project simultaneously start and build up voltage, and are parallelly connected with other ESS chains and solar chains to form a microgrid. The process is shown in Figure 21.

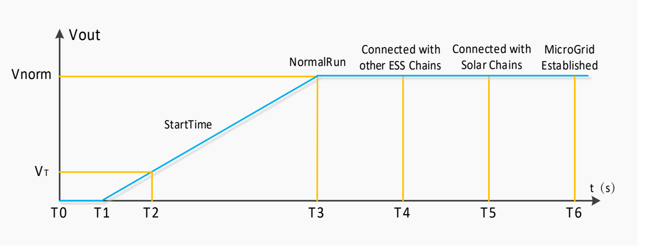


Figure 21: Start-up process of microgrid power supply subunits

The key points are as follows:
Synchronous start-up control of multiple inverters:
After receiving the black start signal, multiple inverters synchronously start without intercommunication, and the output voltage increases continuously and smoothly. The start-up process provides load bearing capacity, and the high-capacity main transformer is excited.
Dynamic droop control strategy:
Multiple networked inverters can withstand substantial current shocks caused by dragging the auxiliary starting motor of the gas turbine or the input of large-capacity isolation transformers.

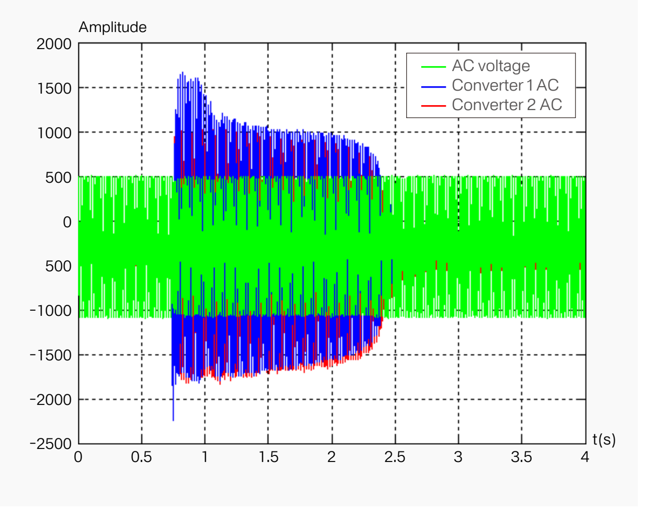


Figure 22: Example of the instantaneous impact resistance against post-networking high-capacity loads

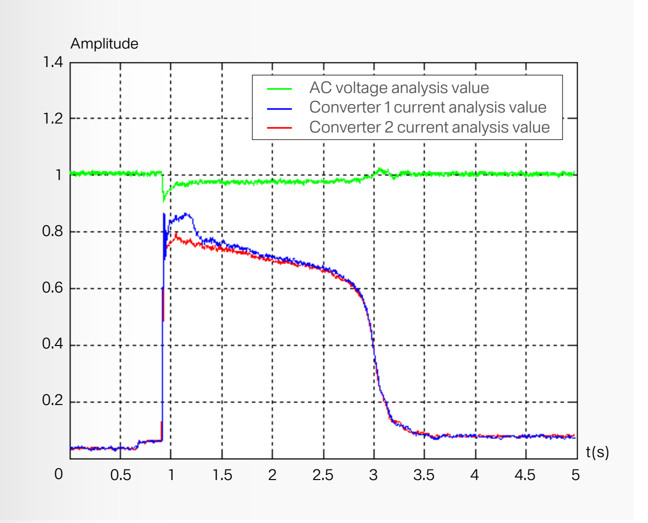


Figure 23: Example of transient steady-state current sharing among multiple inverters

② **Simultaneous and parallel connections of different divisions**
Different divisions support adjustable voltage and frequency. The EMS within each division retrieves external voltage and frequency information, and the synchronous mechanism is closed to complete the construction of the entire distributed power grid.

7 Virtual dual-source superposition control

The operation of the power system is complex and constantly changing. Benefits of voltage-source and grid-connected control include real-time voltage stabilization, inertial support, voltage building and enhanced grid strength. However, with exceptionally high grid strength, voltage-source grid-connected control may cause issues such as instability and slow scheduling response, so it can be applied in combination of the current-source grid-connected control approach for better performance.
The existing dual-mode control theory based on adaptive grid impedance requires real-time detection of grid impedance, which poses great challenges at the engineering stage. Sungrow proposed the virtual dual-source superposition control technology, which adopts a network control strategy that combines the features of the virtual current source and voltage source approaches, as shown in Figure 24.

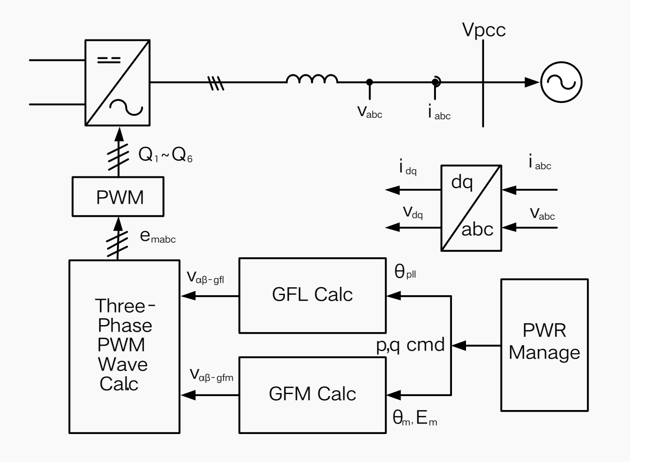


Figure 24: Control strategy of the virtual dual-source superposition control technology

Virtual dual-source superposition control is based on the superposition principle, which involves simultaneously performing voltage-source and current-source control operations, and conducting power distribution and management according to application requirements. It offers both voltage-source and current-source control advantages, provides real-time support for grid voltage and inertial support as well, improves grid strength, and ensures system stability covering a broad SCR range (0-100), hence the improved overall scheduling performance.

04

Value Proposition for Customers

Stem Cell Grid Tech allows for more stable and flexible power generation on the part of power generation facilities. It helps to stabilize the voltage and frequency of new-generation power systems, and accelerate recovery of off-grid wind and PV power generation.

Improve system strength

It provides millisecond-level inertial response when frequency fluctuations occur in the power grid, quickly suppress frequency fluctuations; when voltage transient changes in the grid, it enables synchronous adjustment of active power and terminal voltage, and keep the voltage fluctuation below 2% Un.

Restore grid power supply

It provides prompt assistance in restarting gas turbines and reconnecting new energy power plants when a partial power grid experiences a power outage, to create a regional or city-level distributed power grid and quickly restore power supply.

Increase additional revenue

Additional revenue is obtained through rapid and flexible participation in grid peak shifting, frequency modulation, backup power applications, and other ancillary services.

05 Case Study

Coqên (China)

1500 kW Microgrid Project

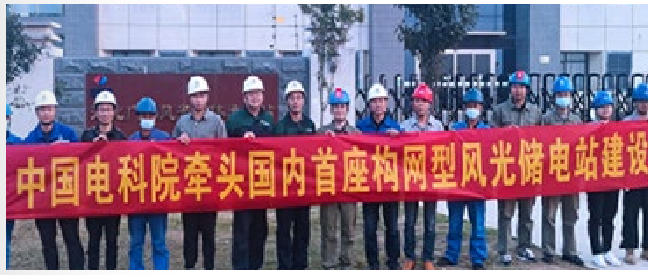
The average altitude of the Coqên County is over 4,700 meters, ranking it among the highest counties in the country. In the year, the local temperature varies from 25.0 ° C at the peak to -34.0 ° C in the winter, with abundant sunshine supplies. Both winter and spring are cold. The local energy structure is dominated by hydropower and supplemented by PV, meaning that power generation output is greatly affected by the climate. Located far away from Tibet's main power grid, Coqên's local grid structure is relatively weak, and it is difficult to control grid operation, hence the relatively low power supply reliability overall.

Sungrow integrates 5 parallel power sources - hydropower, PV, wind power, hybrid energy storage (lithium-ion and lead-acid) and diesel generators, and set up a 10 kV microgrid equipped with 3 power supply incoming lines and 4 load outgoing lines. Employing the virtual synchronous generator (VSG) control strategy, it brings to inverters new features such as rotor motion equation of synchronous generators, primary frequency modulation and reactive power voltage regulation, allowing to build grid voltage and improve the frequency stability and power supply quality of microgrid systems.
The power station is a typical renewable energy multi-energy complementary power supply system. By stably feeding load from multiple power sources and ensuring the voltage supporting capability, we substantially improved the system stability performance, ensuring reliable power supply for more than 4,000 urban, industrial and pastoral users in Coqên. It marked a real milestone in terms of applying the multi-energy complementarity strategy and the VSG technology in the field of microgrids and in high-altitude areas.

Suizhou (China)

32 MW New Power System Project

Suizhou is located in the northern part of Hubei Province, at the intersection of the Yangtze River and Huaihe River basin, where the local climate type is subtropical monsoon climate. Influenced by solar radiation and monsoonal circulation, Suizhou has a mild climate, abundant sunshine and rainfall, with distinct four seasons. Power transmission control at checkpoints poses additional challenges to new energy consumption, and conventional power sources are unable to cancel out fluctuations in new energy output, leading to difficulties in balancing power supply and demand. New energy is inertia-free and provides rather limited support for the power grid, leading to a decrease in system frequency modulation and voltage regulation capacity, and thereby affecting grid stability.



Sungrow adopts the multi-microgrid interconnection and decoupling technology based on energy routers to improve outbound transmission capacity; for certain wind power and PV generator sets, we carried out voltage source support transformation, and provided virtual inertia with real-time voltage support, as well as the voltage building capability under islanding conditions.
We succeeded in improving the power supply quality of the regional power grid, and reduced the fluctuation range of 10 kV bus voltage from 15% Un to10% Un; We reduced investment required for power systems, and improved new energy consumption capacity and system stability.

Indiana (North America)

15 MW/5.5 MWh Black Start Project

Indiana is located in the north central United States. The local industries mainly include advanced manufacturing, industrial machinery production, and logistics transportation. It is home to the second largest production plant of Toyota Motor in North America and the second largest FedEx center in the United States. As coal energy has been phased out in recent years, Indiana has embarked on the development of renewable energy, setting ESSs to integrate new intermittent renewable energy, and cope with emergency off-grid accidents.

Sungrow uses 15 MW/5.5 MWh ESSs, to promptly propel the gas turbine rotor to the preset speed based on the droop control and multi-PCS wireless parallel connection technologies, and excite and soft start the 100 MW power transmission transformer.
We succeeded in completing black start of two 110 MW gas turbines, swiftly restored the stable operation of the power grid, replaced diesel generators, and achieved the black start of gas power plants. The entire process is safe and economical with impressive quality attained.

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Overview and Outlook

Looking into the future, the construction of new-generation power systems will be a highly innovative undertaking of system engineering which involves deep-level collaboration and joint innovation among various entities such as power generation facilities, power grids and users to co-build a new coordinated development ecosystem integrating "generation-grid-load-storage".

As an important step in connecting renewable energy sources to the grid at an extensive scale, the Sungrow ESS is committed to continuously making innovations and breakthroughs to steadily support the smooth operation of new-generation power systems adhering to the principle of "building professional ESSs integrating power electronics, electrochemistry and grid support technologies", on the basis of effective applications of related technologies such as system strength and short-circuit capacity enhancement, inertial support, wideband oscillation suppression, FRT, and extensive-scale black start.

SUNGROW

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