Jointly released by Huawei Digital Power
and TÜV Rheinland

High-Precision SOC Algorithms for Energy Storage Systems Across Full Lifecycle

White Paper

Foreword

As global energy structure transitions toward clean, low-carbon sources, energy storage technology—serving as a critical enabler for large-scale renewable energy integration and flexible power system regulation—is experiencing rapid growth. Energy storage systems have demonstrated significant application value in grid frequency regulation, peak-valley arbitrage, and renewable energy grid integration. State of Charge (SOC), a core parameter of energy storage systems, has estimation accuracy and consistency that directly impact system operational efficiency, safety, and economics. Research indicates that for every 1% reduction in SOC estimation error, the available capacity of energy storage systems across different scenarios can increase by approximately 1%-2%, fully underscoring the strategic value of high-precision SOC algorithms.

Currently, energy storage commercial models are evolving from single applications to multi-scenario coordination, encompassing energy time-shifting, capacity leasing, and virtual power plants, placing higher demands on SOC estimation accuracy, reliability, and consistency. However, traditional SOC algorithms are limited by the nonlinear characteristics of Lithium Iron Phosphate ($LiFePO_4$) batteries, complex operating conditions, and aging factors, making it difficult to meet the requirements of emerging electricity markets for maximizing revenue through high-precision SOC control under rapid dynamic response conditions. Particularly when participating in electricity spot markets or ancillary services, SOC errors may cause charging and discharging strategies to fail, triggering penalty charges and reducing user economic returns.

To enhance industry awareness of the importance and necessity of high-precision SOC management for energy storage systems, Huawei and TÜV Rheinland jointly present this white paper, which systematically elaborates on the value characteristics of high-precision SOC algorithms, covering grid-side energy storage trading scenarios, Grid-Forming (GFM) service scenarios, and conventional peak-valley arbitrage scenarios. It provides in-depth analysis of technical challenges and development status in each scenario, and forward-looking proposes innovative algorithm technology directions for industry reference.

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01 Importance of High-Precision SOC Prediction and Equalization Technology

High-precision SOC prediction and equalization technology is the core technology enabling safe, efficient, and intelligent operation of energy storage systems, directly determining system economic returns and long-term reliability. Against the backdrop of electricity market reform, high-precision SOC has become the foundational technical cornerstone supporting multi-scenario business models.

1.1 High-Precision SOC Enhances Economic Returns in Mainstream Commercial Scenarios

1.1.1 Grid-Side Energy Storage Trading Scenarios

In electricity market trading, SOC estimation errors directly affect energy storage dispatch decisions, trading outcomes, and revenue potential: SOC overestimation may lead to overselling electricity and trigger penalty charges; SOC underestimation results in idle available capacity and revenue loss. To mitigate risks, operators typically set large safety margins, which directly reduce available capacity and trading income. [Quoted from ACCURE. 2025 Energy Storage System Health & Performance Report]

Table 1: SOC Error Risk Logic

Common Scenario Phenomenon	Impact on Trading Actions	Impact on System Revenue
Overestimated SOC value	Operator believes more energy is available for sale	Insufficient energy delivery; contract failure may result in fines
Underestimated SOC value	Operator believes available energy is inadequate	Available capacity remains idle, causing revenue loss
Persistent SOC error	Dispatch system avoids aggressive trading; conservative or erroneous operating strategies	Erroneous SOC estimation during bidding may prevent full utilization of high-price periods

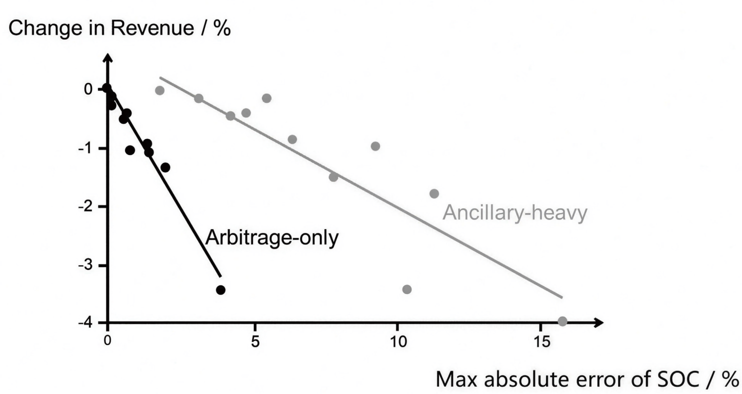


Figure 1: Impact of SOC Error Magnitude on Revenue Across Different Operating Strategies

For every 1% increase in SOC error, revenue from arbitrage-only operations decreases by 0.82%, while revenue from ancillary service-oriented operations decreases by 0.20%. This highlights the financial significance of accurate SOC estimation in multi-market $LiFePO_4$ battery systems. [Quoted from Powin & Tierra Climate. The Economic Value of SOC Accuracy: Quantifying Revenue Impacts of State-of-Charge Estimation in LFP Battery Systems. Whitepaper, March 2025]

SOC estimation accuracy has significant impact on the operational performance and economic benefits of Battery Energy Storage Systems (BESS), with the degree of impact varying by operating strategy. In arbitrage-oriented applications, every 1% increase in SOC estimation error reduces revenue by approximately 0.82%; in ancillary service-oriented operations, this figure is 0.20%. Meanwhile, every 1% increase in SOC estimation error is expected to reduce effective available energy capacity by 1.2%, directly impacting revenue potential and capital efficiency.

The financial impact of SOC accuracy is further amplified by market timing. Errors occurring during periods of high volatility or high electricity prices may disproportionately affect annual revenue performance, highlighting the importance of maintaining consistently accurate SOC estimation during high-value operating periods.

SOC errors in arbitrage scenarios can be described through a simplified framework where Day-Ahead (DA) dispatch represents the planned and committed energy position. First, the error manifests as a physical constraint, appearing as SOC jumps or deviations in estimated SOC values, where the battery reaches capacity limits and cannot fully follow the DA dispatch schedule. At this point, deviations are settled at the real-time balancing energy price (Ausgleichsenergiepreis, reBAP), using the German market as an example. This mechanism exposes the affected energy to highly volatile and unpredictable real-time pricing. From an economic perspective, this outcome is undesirable as it cannot be reliably predicted or hedged in advance, although it does not always lead to losses—imbalance prices may occasionally be more favorable than DA prices.

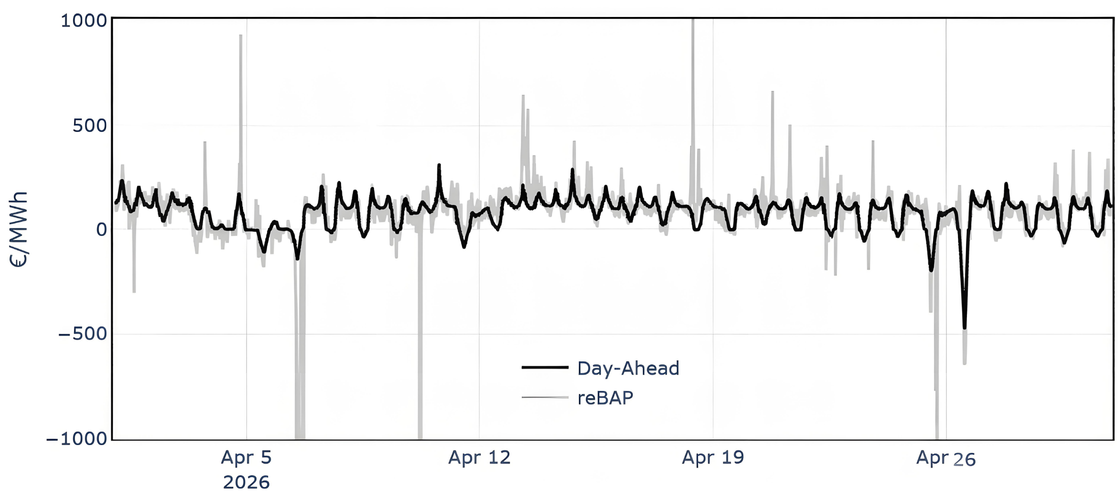


Figure 2: German Day-Ahead (DA) and Imbalance Price (reBAP) for April 2026

Figure 2 showing the spread between planned forward prices and real-time imbalance settlement prices. SOC errors may cause deviations from DA plans, with deviations settled at reBAP, exposing them to volatile real-time pricing. [www.netztransparenz.de]

Second, the SOC effect can be viewed as a missed trading opportunity, where with accurate SOC, a better DA dispatch plan could have been formulated and executed. This represents the arbitrage volume lost at DA prices that cannot be directly observed from actual execution results.

1.1.2 Grid-Side Energy Storage Grid-Forming Service Scenarios

In Grid-Forming (GFM) energy storage scenarios, the importance of SOC/SOE accuracy is higher than that of ordinary Grid-Following (GFL) energy storage. GFM energy storage must actively establish voltage and frequency, and provide continuous rapid power response during frequency disturbances, islanded operation, Black Start, and weak grid support. Therefore, SOC error not only affects electricity market trading revenue, but also impacts grid-forming reserve capacity, sustainable support duration, and system stability. Assuming improvement of GFM energy storage project SOC accuracy from ±5% to ±2.5%:

Table 2: Grid-Forming Energy Storage SOC Upper/Lower Limit Margins

Item	SOC Accuracy ±5%	SOC Accuracy ±2.5%
Rated Capacity	100 MWh	100 MWh
Single-Side SOC Uncertainty	5 MWh	2.5 MWh
Single-Side Safety Margin Reduction	—	2.5 MWh
Dual-Side Available Window Improvement	—	5 MWh

With SOC accuracy improved from ±5% to ±2.5%, a 100 MWh energy storage station can theoretically release approximately 5 MWh of additional dispatchable capacity.

Based on the additional 5 MWh of released capacity, the revenue at different annual cycle counts is as follows:

Table 3: Revenue from Released Available Capacity in Grid-Forming Energy Storage

Annual Equivalent Cycle Counts	Net Revenue 0.044 USD/kWh	Net Revenue 0.074 USD/kWh	Net Revenue 0.118 USD/kWh
250 cycles/year	55,147 USD/year	91,912 USD/year	147,059 USD/year
300 cycles/year	66,176 USD/year	110,294 USD/year	176,471 USD/year
330 cycles/year	72,794 USD/year	121,324 USD/year	194,118 USD/year

Although SOC accuracy improvement does not increase the physical capacity of batteries, it reduces conservative margins and converts more capacity into "dispatchable capacity." For a 100 MWh station, this is equivalent to gaining 5 MWh of additional available energy storage capacity. Based on preliminary estimates of energy storage system investment costs ($118–$176/kWh), the equivalent capacity investment value corresponding to 5 MWh is: 5,000 kWh × 118 = $590k. That is, the available capacity released through SOC accuracy improvement is equivalent to reducing redundant capacity investment by approximately $590k to $880k.

1.1.3 Renewable-Plus-Storage PPA and Electricity Trading Scenarios

Renewable-plus-storage Power Purchase Agreement (PPA) energy storage systems are primarily used to smooth photovoltaic power generation fluctuations and achieve energy time-shifting (e.g., storing excess midday solar power for nighttime use), converting volatile solar power into stably available "green electricity" and reducing user electricity costs. Energy storage charges and discharges regularly on a daily basis, balancing generation and load, and SOC charging/discharging accuracy affects charge/discharge duration. Insufficient charge/discharge quantities may result in penalty assessments. Taking a 100 MWh energy storage station as an example, with 1% SOC algorithm optimization, the annual arbitrage capacity can increase by 360 MWh (based on one charge-discharge cycle per day).

1.2 High-Precision SOC Improves System Performance and Stability

High-precision SOC is not only the foundation of economic returns but also a key technology ensuring safe and stable operation of energy storage systems. SOC errors and inconsistency may lead to reduced system efficiency and insufficient charge/discharge capacity, while affecting grid dynamic response capability. Especially in Grid-Forming (GFM) energy storage and long-duration energy storage systems, SOC estimation accuracy directly determines system reliability and grid compatibility.

1.2.1 Grid-Forming/Microgrid Energy Storage System Stability

Grid-forming energy storage stability relies on rapid power control, which must be built upon accurate SOC boundaries. The more precise the SOC estimation, the more stably, continuously, and reliably grid-forming energy storage can undertake grid support tasks.

High-Precision SOC Capability	Impact on GFM Stability
Accurate assessment of available energy	Improves reliability of frequency support and islanded support
Accurate assessment of charge/discharge margin	Maintains upward and downward regulation capability, avoids saturation, enhances black start, islanded operation, and reserve capabilities
Supports SOC high/low point identification	Enables more robust control parameters, prevents microgrid system instability, avoids sudden power limiting or tripping during support
Wide-SOC-range grid forming	Reduces conservative margins while ensuring stability, maximizing available capacity release

In Grid-Forming (GFM) energy storage systems, high-precision SOC is a critical prerequisite for safety protection. GFM energy storage must actively establish voltage and frequency, and provide continuous rapid power response during frequency disturbances, islanded operation, black start, and weak grid support. SOC errors directly affect charge/discharge control boundary protection, power limiting, and grid-forming exit risks.

Safety Protection Target	Risk of Insufficient SOC Accuracy	Role of High-Precision SOC
Discharge control boundary protection	Continued discharge at low SOC triggers undervoltage protection	Preemptive derating to preserve critical support capability
Charge control boundary protection	Continued charge at high SOC triggers overvoltage protection	Preemptive derating to limit charging power
Frequency support protection	Unable to sustain output during under-frequency	Accurately determines sustainable discharge duration
High-frequency absorption protection	Unable to absorb excess power	Accurately determines sustainable charge duration
Black start protection	Insufficient energy during startup	Accurately determines startup conditions
Islanded protection	Insufficient off-grid reserve power, erroneous support duration estimation	Proactively sheds load or activates backup resources (e.g., diesel generators)

1.2.2 Energy Storage System Performance Enhancement

Individual batteries may have different operating boundaries in different SOC ranges; reaching these boundaries requires derating operation, otherwise it may lead to out-of-specification battery usage, affecting performance or even accelerating aging. High-precision SOC ensures battery cells operate within reasonable specification ranges, reduces the safety margin that must be reserved, and overall improves system available capacity and extends battery life.

Furthermore, when inconsistency occurs in series-architecture energy storage systems, due to the "weakest link effect," the system may trigger premature charge/discharge end cutoff due to the weakest battery cell. In parallel battery Racks, SOC inconsistency causes current imbalance, reducing system efficiency. Multi-level SOC equalization can effectively reduce capacity differences between Battery Packs and between Battery Racks, maximizing system availability.

1.3 Automatic SOC Equalization Reduces O&M Costs

As energy storage system scale expands and deployment scenarios become more complex, traditional manual O&M models face severe challenges. Automatic SOC calibration combined with automatic equalization technology can significantly reduce full-lifecycle O&M costs. According to industry research data, energy storage systems adopting automated SOC management can reduce O&M manpower investment by approximately 30% to 50%, while improving system annual availability by over 6%.

1.3.1 Automatic SOC Calibration

Long-term lack of calibration leads to SOC integration drift, affecting estimation accuracy and consequently impacting energy storage charge/discharge quantities and revenue. Under certain non-deep charge/discharge operating conditions, traditional SOC/SOH calibration typically relies on manual or semi-manual methods, such as periodic full charge/discharge and capacity calibration testing. These operations incur the following costs:

Cost Type	Specific Description
Labor cost	O&M personnel on-site operations, data analysis, test records
Downtime cost	Energy storage system unable to participate in electricity trading or provide ancillary services during calibration
Dispatch cost	Temporary adjustment of trading plans and available capacity declarations required

Huawei enables automatic calibration functionality that automatically identifies operating conditions without requiring shutdown, manual site visits, or user intervention, achieving SOC and SOH calibration for battery Racks during battery subsystem operation, maintaining long-term high-precision system operation and reducing manual O&M investment.

1.3.2 Multi-Level Automatic Equalization

Automatic equalization is a key means to improve energy storage system available capacity, safety, and O&M efficiency. The inter-Pack inconsistency in BESS directly reduces available energy capacity and revenue potential; inter-Pack inconsistency exceeding 10% requires corrective measures to restore capacity and revenue and reduce accelerated degradation risk.

Energy storage systems experience approximately 5% to 6% SOC divergence annually due to self-discharge differences, typically requiring professional engineers to visit sites for O&M, using external charge/discharge equipment for supplementary charging, involving repeated disassembly and assembly of batteries or cables, with charge/discharge equipment having narrow operating temperature ranges, low current, and long duration.

- Onsite SOC calibration by professional engineers is required.
- In manual calibration, the precision depends on experience.
- Connecting to an external charger requires repeatedly removing and installing the battery packs and cables.
- Manual SOC calibration is required during pack replacement.
- Old and new battery packs are used together and connected in series, causing high overcharge risks.

High costs

CNY 2000/time of professional manual site visit

Low precision

Precision depending on experience, high error

Economic loss

Discharge loss due to shutdown for 2-3 days

Safety risks

Mis operations causing short circuits and reverse polarity prone to occur, unreliable electrical connection

Figure 3: Pain Points of Traditional Manual SOC Equalization

Huawei's "one pack, one optimization; one Rack, one management" capability supports passive equalization between battery cells, eliminating SOC differences at all levels during operation without requiring annual manual equalization O&M. This includes battery pack replacement scenarios where pack-level optimization can rapidly restore consistency to optimal status, maximizing system available capacity.

1.4 Industry Status and the Necessity of Standard Development

Currently, SOC characteristics in the industry are covered by only a few standards such as GB/T 34131, whose test conditions for SOC accuracy and equalization capability are relatively simple and cannot fully reflect real-world SOC performance under various stringent scenarios. Traditional energy storage products claiming SOC accuracy capabilities lack effective verification methods, and other standards typically provide only range requirements or general statements such as "meets design requirements."

Table 4: Quantitative Classification of SOC Capability Levels

Level	Capability	Core Value
Level 0 (Basic)	Basic capability (single-stage conversion)	Achieves SOC precision through cooperation with cell manufacturers; lacks core differentiated competitiveness; cannot meet domestic and international premium energy storage project requirements; being gradually phased out
Level 1 (Enhanced)	Differentiated capability (single-stage conversion)	Expands some charge/discharge scenarios; optimizes thermal management design for certain scenarios; possesses certain SOC accuracy but cannot meet full-scenario safety requirements; some customers bear additional risk
Level 2 (Advanced)	Differentiated capability (dual-stage conversion)	Meets full-scenario charge/discharge and grid-forming requirements; achieves true productization; enables customers to realize full-scenario value; possesses strong competitive advantages and higher profit margins while helping customers avoid potential risks

Given that SOC has become a key competitiveness indicator for grid-forming energy storage and its measurement methods lack unified standards, Huawei has partnered with internationally authoritative third-party certification body TÜV Rheinland to conduct third-party certification of grid-forming energy storage SOC characteristics. The certification content is divided into four sections—accuracy, calibration, equalization, and grid-forming—to support the achievement of "reliable accuracy, controllable errors, whole-station multi-level equalization, and stable grid-forming."

Table 5: SOC Capability Level Classification — Specific Indicators

Level	Lv1 (Manual Calibration Assisted)	Lv2 (Conditionally Constrained Automatic Calibration)	Lv3 (High-Precision Automatic Calibration)
General characteristics	SOC serves as reference only; meets industry standards only; supports deep charge/discharge conditions	SOC can be used for dispatch; customers must reserve adequate margins; supports deep charge/discharge; partially supports shallow charge/discharge conditions	What-you-see-is-what-you-get SOC; supports both deep and shallow charge/discharge conditions
SOC accuracy (error)	5%	3%	2.5%
SOC calibration range	High-precision calibration convergence in 0–15% and 95–100% SOC; low-precision calibration convergence in 15–95% SOC	High-precision calibration convergence in 0–15% and 95–100% SOC; medium-precision calibration convergence in 15–95% SOC	High-precision calibration convergence in 0–15% and 95–100% SOC; high-precision calibration convergence in 15–95% SOC
Worst-case SOC available capacity after error convergence	≥90%	≥92%	≥95%
Grid-forming SOC upper limit (grid-connected VSG)	≥90% SOC	≥95% SOC	≥98% SOC
Grid-forming SOC lower limit (grid-connected VSG)	≤10% SOC	≤5% SOC	≤2% SOC
Grid-forming SOC upper limit (off-grid VSG)	≥90% SOC	≥95% SOC	≥98% SOC
Grid-forming SOC lower limit (off-grid VSG)	≤10% SOC	≤7% SOC	≤5% SOC
System SOC equalization capability	Supports cell-level equalization	Supports cell-level equalization and Rack-level management	Supports cell-level equalization, pack-level optimization, and Rack-level management

02 Challenges in High-Precision SOC Algorithm Design

Traditional SOC algorithms face fundamental challenges arising from the nonlinear electrochemical characteristics of lithium iron phosphate ($LiFePO_4$) batteries, highly variable operating conditions, and sensor sampling noise.

2.1 Nonlinear Electrochemical Characteristics of $LiFePO_4$ Batteries

Lithium Iron Phosphate ($LiFePO_4$) batteries offer significant advantages including high safety, long cycle life, environmental friendliness, and low material cost, establishing them as the dominant technology route in electrochemical energy storage. However, their unique electrochemical properties present inherent challenges for State of Charge (SOC) estimation.

First, $LiFePO_4$ batteries exhibit a highly nonlinear mapping between voltage and SOC. Compared to ternary lithium-ion batteries, their Open Circuit Voltage (OCV)-SOC curve demonstrates a pronounced plateau in the 20%–80% range, with voltage variations of only 20–30 mV. This Voltage Plateau causes even minute voltage measurement errors to translate into substantial SOC estimation deviations.

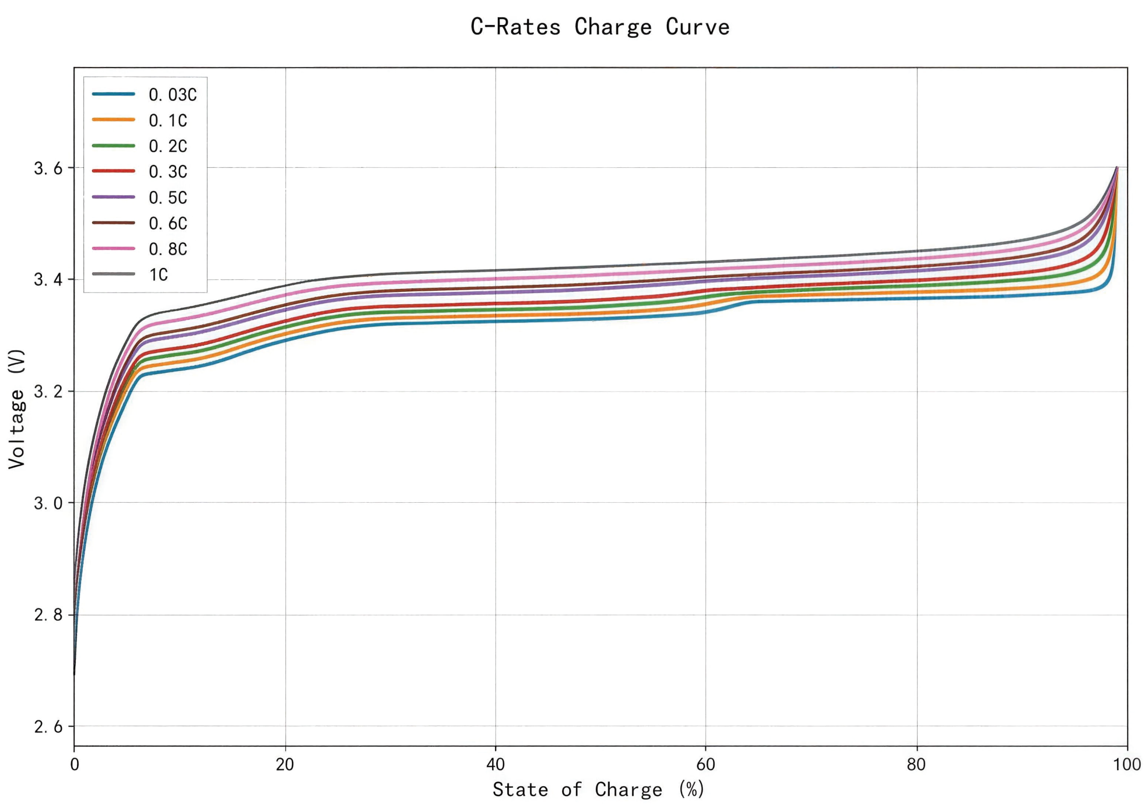


Figure 4: Charge Voltage-SOC Curves at Various C-Rates

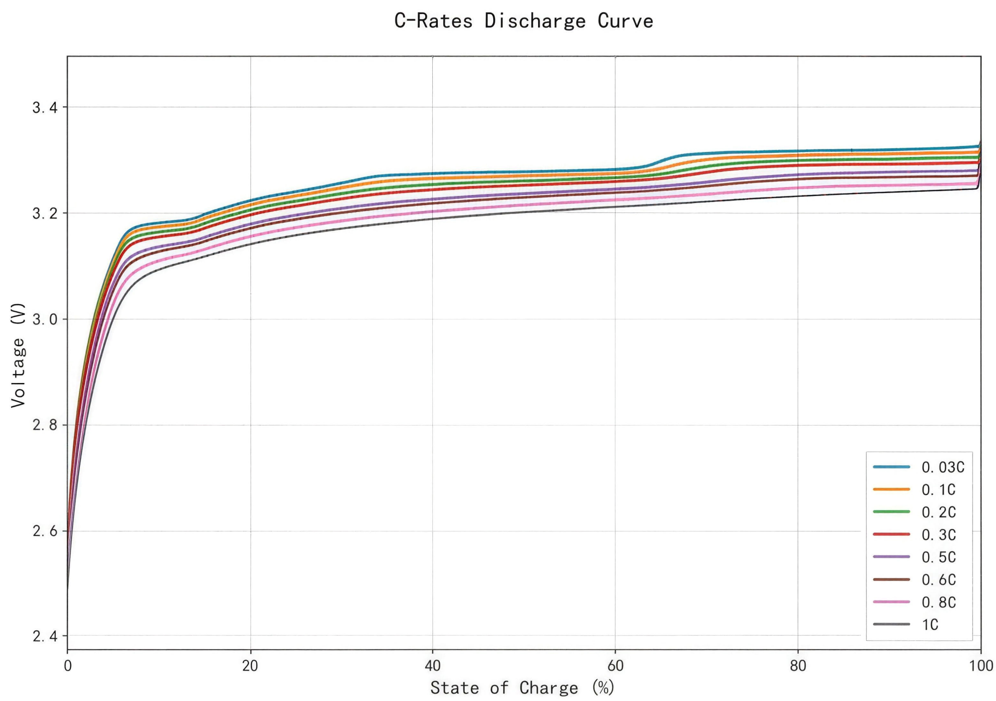


Figure 5: Discharge Voltage-SOC Curves at Various C-Rates

Second, $LiFePO_4$ battery OCV characteristics exhibit significant path dependency, known as the Hysteresis Effect. The OCV curves during charge and discharge diverge, with the hysteresis magnitude varying dynamically with temperature, C-Rate, and cyclic aging. This nonlinear time-varying characteristic makes it difficult for equivalent circuit model-based SOC estimation methods to achieve the required accuracy.

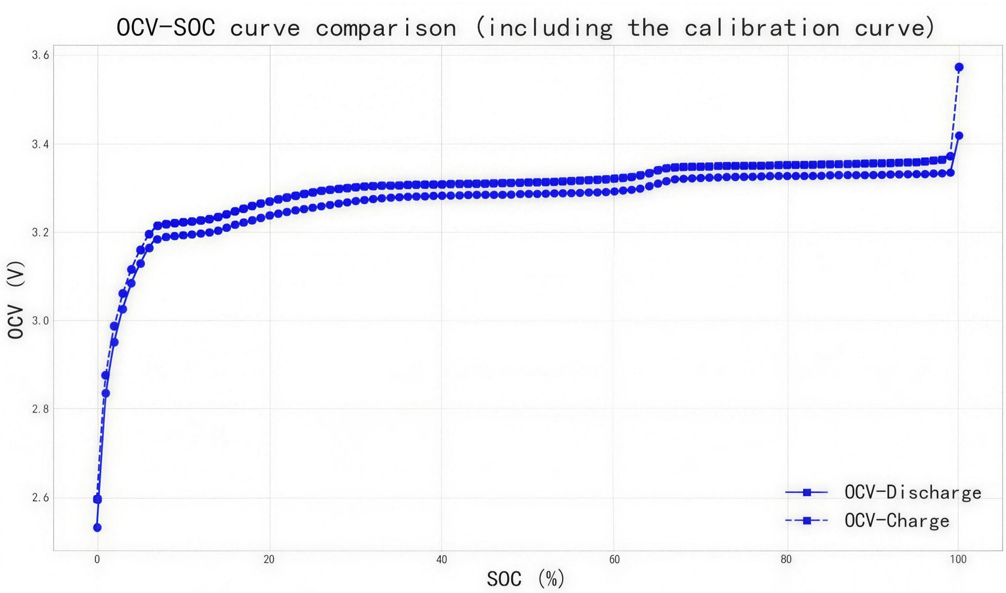


Figure 6: OCV-SOC Curve Comparison

Furthermore, $LiFePO_4$ batteries exhibit pronounced nonlinear polarization behavior. Ohmic polarization, electrochemical polarization, and concentration polarization follow distinct patterns across different SOC ranges and temperature conditions, further increasing the complexity of SOC estimation. Consequently, constructing electrochemical models capable of accurately describing the nonlinear characteristics of $LiFePO_4$ batteries and designing robust SOC estimation algorithms represent critical scientific challenges in Battery Management System (BMS) development.

2.2 Highly Variable Energy Storage Operating Conditions

Energy storage system operating conditions are considerably more complex and diverse than those of electric vehicles, encompassing grid frequency regulation, peak shaving and valley filling, renewable energy integration, and electricity market trading. Such variable operating environments cause battery operating states to exhibit significant dynamic, time-varying characteristics, substantially increasing the difficulty of SOC estimation.

Certain scenarios involve drastic fluctuations in charge/discharge C-Rate. In frequency regulation applications, energy storage systems must perform high-frequency, small-amplitude charge/discharge switching on a second-level timescale, where battery polarization voltage has not yet stabilized and terminal voltage cannot reflect the true OCV, rendering voltage-correction-based SOC algorithms ineffective. In microgrid and Grid-Forming (GFM) scenarios, systems operate for extended periods at low C-Rate or without deep cycling: prolonged low-C-Rate operation exacerbates cumulative errors in Coulomb Counting; extended non-full cycling reduces the voltage discrimination capability for SOC, making in-operation calibration difficult to achieve

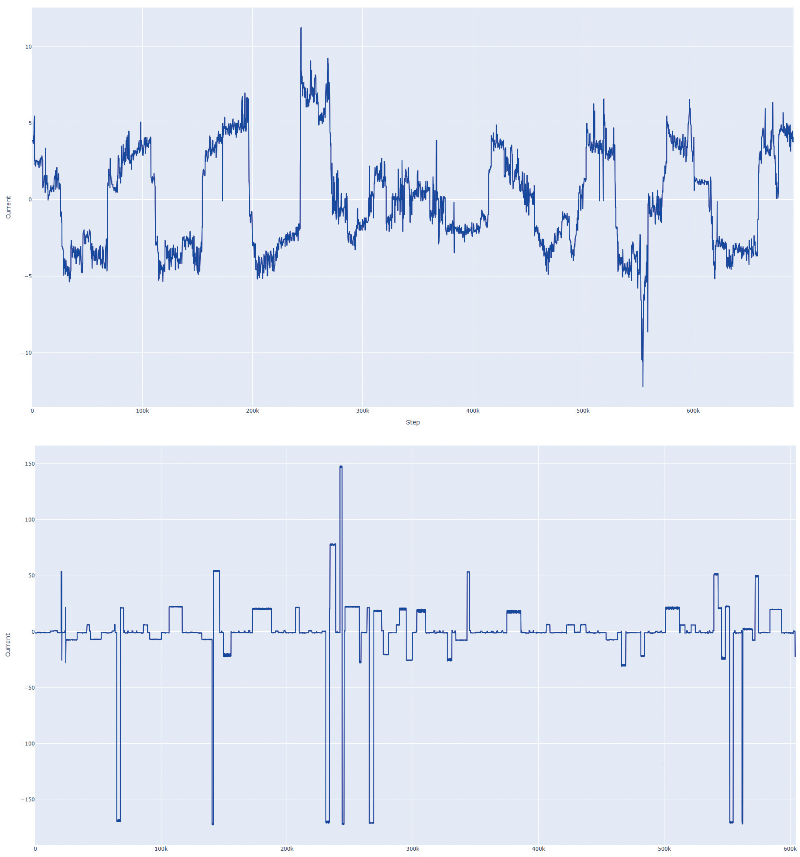


Figure 7: Current Waveform in Different Scenario

2.3 Sensor Sampling Noise Interference

Cumulative Drift from Current Sampling Error: Coulomb Counting serves as the fundamental SOC estimation method, with its accuracy directly dependent on current sensor precision. Hall Sensors or Shunt Resistors exhibit zero-point drift and gain errors, which are significantly affected by temperature. Over the long-term operation of energy storage systems, even a current measurement deviation of merely 0.5% can lead to cumulative SOC errors exceeding 10% without high-precision calibration. Under low-current standby or micro-cycling conditions, signal amplitudes approach the sensor noise floor, reducing the Signal-to-Noise Ratio (SNR) and making it difficult to distinguish true current from noise.

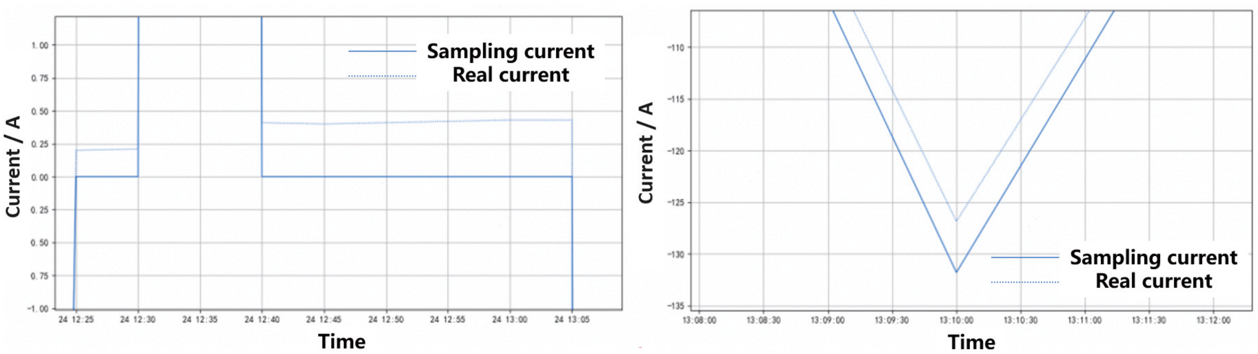


Figure 8: Current sampling error diagram

Voltage Sampling Quantization Error and Noise: $LiFePO_4$ batteries exhibit extremely small OCV variations within the voltage plateau (a 65% SOC change corresponds to only 70 mV voltage change). If BMS voltage sampling accuracy is insufficient, a 10 mV deviation can introduce up to 25% SOC error, while a 6 mV deviation can introduce up to 15% SOC error. Coupled with the hysteresis between charge and discharge OCV curves and the susceptibility of terminal voltage to polarization effects, $LiFePO_4$ battery OCV demonstrates high sensitivity to current disturbances.

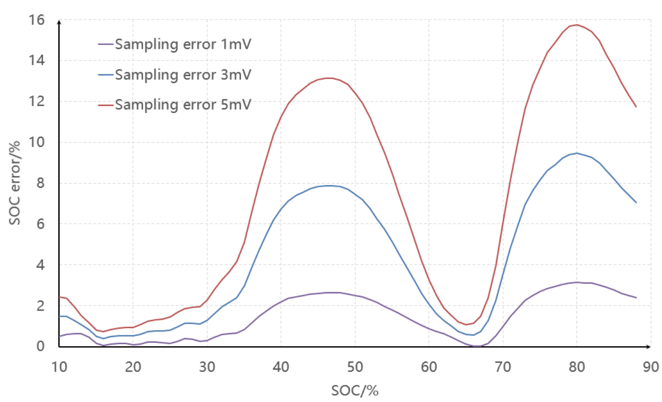


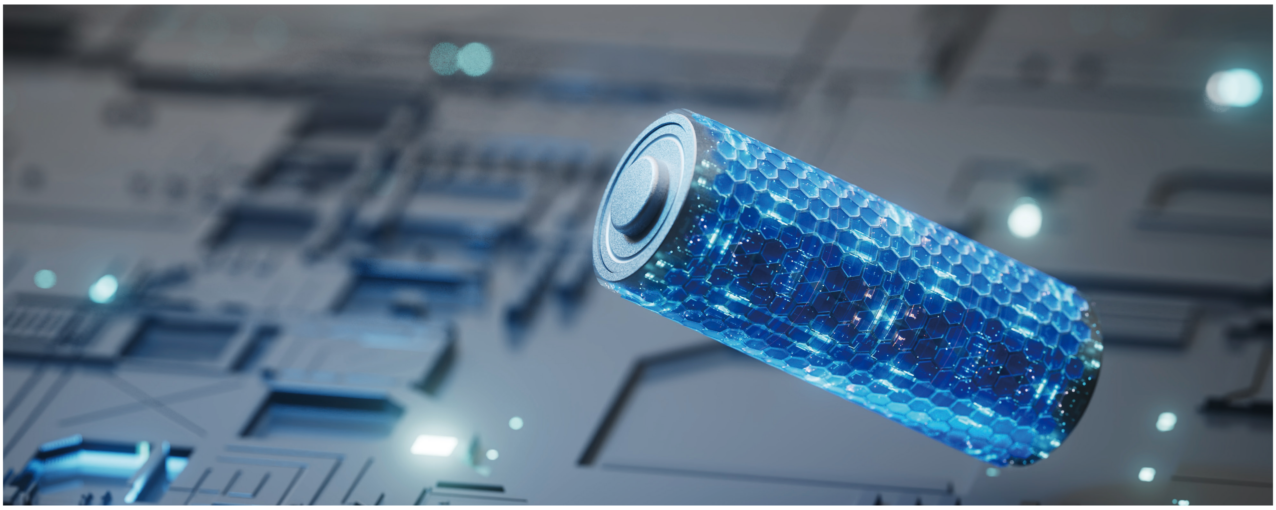
Figure 9: LFP Battery Voltage Plateau Characteristics

Additionally, sampled data must possess robust processing capabilities. Field operating conditions inevitably involve sensor transient faults, communication packet loss, and electromagnetic pulse interference; sampling algorithms must include outlier detection and rejection capabilities. If algorithms are overly sensitive to noise, they are susceptible to anomalous value interference; if filtering intensity is excessive, it leads to delayed sampling response, rendering the system unable to track true power changes.

03 Huawei Energy Storage High-Precision SOC Algorithm Design

3.1 Architecture and Design Philosophy

To address the core challenges posed by the nonlinear characteristics of lithium iron phosphate ($LiFePO_4$) batteries, variable operating conditions, and sensor noise interference, traditional single-dimension SOC estimation methods can no longer meet the requirements of high-precision energy storage systems. Drawing on its digital power technology philosophy, Huawei has conducted systematic testing and research on energy storage LFP battery characteristics, constructing a high-precision SOC algorithm framework. To address variable operating conditions, Huawei has established a systematic energy storage operating condition library and a corresponding Digital Twin platform. To address sensor sampling noise, Huawei has independently developed high-precision voltage and current sampling hardware chips, along with active/passive balancing hardware. Huawei proposes a high-precision SOC solution built upon a data foundation platform, featuring hardware-software synergy and multi-environment hierarchical testing — covering hardware sampling, edge computing, big data simulation training, and rigorous verification as a systems engineering endeavor.



3.1.1 Rich Scenario-Based Operating Condition Data Platform

SOX Optimization and Intelligent Laboratory: Data serves as the foundational resource for training and developing high-precision algorithms. Huawei has built a dedicated laboratory for Battery Management System (BMS) and SOX algorithm development, covering the complete testing chain from cells to Battery Packs to system-level environments. The laboratory continuously carries out multi-type calibration, operating condition, and characteristic tests, accumulating rich real-world application scenario data. Combined with digital capabilities, Huawei has constructed an industry-leading battery big data platform, providing solid support for SOC algorithm R&D and evolution.

Full-Scenario Operating Data Coverage: Through dedicated laboratory testing, a complete operating condition database has been built, covering cell calibration, characteristic testing, and scenario-based operation. Measured data covering multiple application scenarios — including electricity market trading, microgrid GFM, peak shaving and valley filling, and backup power — has been accumulated, encompassing real response characteristics of batteries at different State of Health (SOH) stages and under various C-rates, used for thorough pre-deployment simulation verification. Huawei's advanced AI data augmentation system can stratify, grade, and classify operating conditions, generating scenario-specific data in conjunction with high-precision electrochemical models, ensuring 100% scenario coverage.

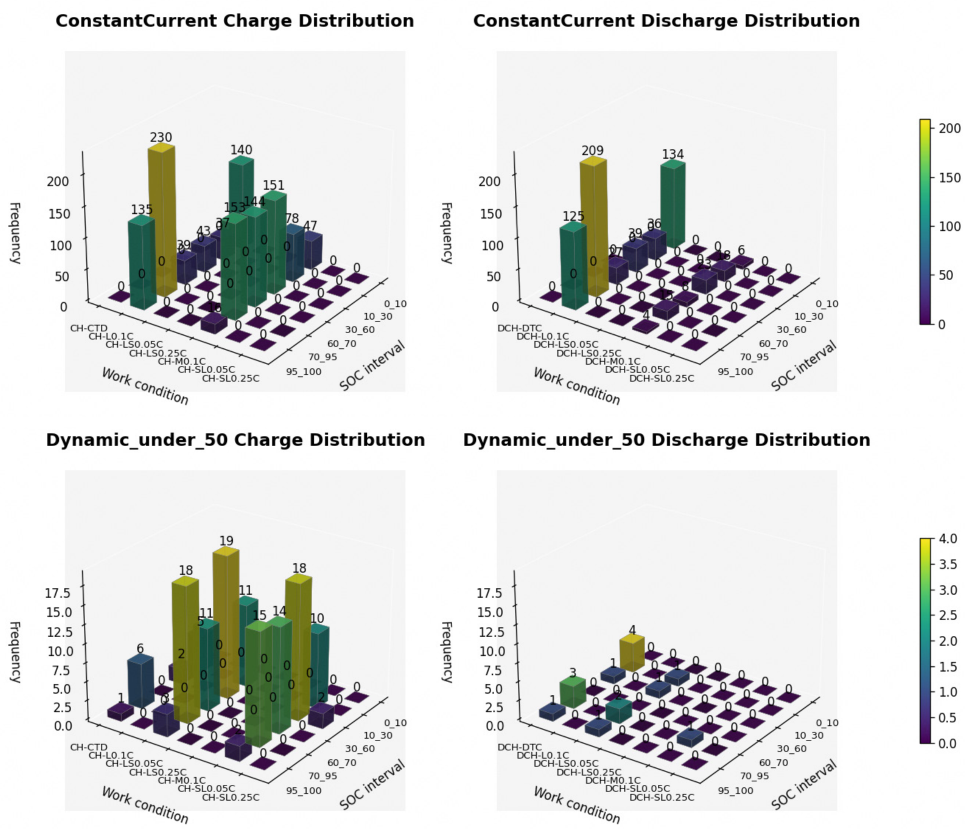


Figure 10: Full-Scenario Operating Condition Library

Full-Coverage Production Big Data: Huawei has established a production big data system covering the entire chain of cell manufacturing, module assembly, and system integration, achieving end-to-end data collection and closed-loop management from raw material incoming inspection, process parameter monitoring, critical quality inspection, to final product ex-factory. The system dynamically captures data from hundreds of thousands of production nodes in real time, encompassing key process parameters such as temperature, voltage, current, and internal resistance, forming a high-dimensional, high-precision production process profile. Based on this production big data platform, Huawei has realized full-lifecycle traceability for battery products — "a digital record from birth."

3.1.2 Hardware-Software Algorithm Co-Design

Traditional SOC algorithm frameworks primarily rely on high-precision Coulomb counting, supplemented by end-of-charge/end-of-discharge voltage calibration correction and rest-state Open Circuit Voltage (OCV) correction. The sampling precision of voltage, current, and temperature has a critical impact on high-precision SOX algorithms.

High-Precision Voltage Sampling BMIC: Voltage sampling utilizes a self-developed high-precision Battery Management IC (BMIC) chip, paired with a low-drift precision reference, achieving ±1 mV-level voltage sampling accuracy

— effectively addressing the insensitivity of $LiFePO_4$ voltage changes within the voltage plateau region. This is complemented by a high-precision sampling filter algorithm with outlier rejection capability, enhancing the robustness and stability of the SOC algorithm, while enabling coordination between high-frequency sampling and balancing functions to ensure safe system operation.

High-Precision Current Sampling Rack Control Box: Multiple sets of high-precision reference power sources are designed to calibrate the reference sources against actual current sampling channels. Through arithmetic processing, the gain coefficient and offset voltage of the sampling circuit are eliminated, ensuring that sampling accuracy is essentially unaffected by circuit temperature drift under both high- and low-temperature conditions. The sampling circuit input stage adopts an instrumentation amplifier architecture with extremely high common-mode rejection ratio (CMRR), effectively eliminating common-mode signal interference. Low-offset operational amplifiers are selected to prevent secondary amplification circuit saturation. At the software level, a sampling offset compensation algorithm is integrated, enabling long-term recording and dynamic compensation of current sampling offset.

Temperature Sampling NTC: Temperature sampling employs Negative Temperature Coefficient (NTC) thermistor sensors. Through deep synergy with the SOC algorithm, battery temperature rise during charge and discharge can be identified and predicted, participating in real-time electrochemical model state estimation, polarization compensation, and OCV-SOC mapping update—significantly improving SOC estimation accuracy and dynamic response capability under complex conditions such as extreme temperature differentials and aggressive charge/discharge switching.

3.1.3 Multi-Environment Hierarchical Testing

BMS Digital Twin Simulation Platform: A BMS digital twin simulation platform has been constructed. By accessing the full-scenario operating condition database, batch rapid verification of algorithms is achieved, improving algorithm iteration efficiency and quality. The platform supports injection of errors and various abnormal operating conditions, enabling explicit assessment of algorithm capabilities and visualization of performance improvement after version iteration.

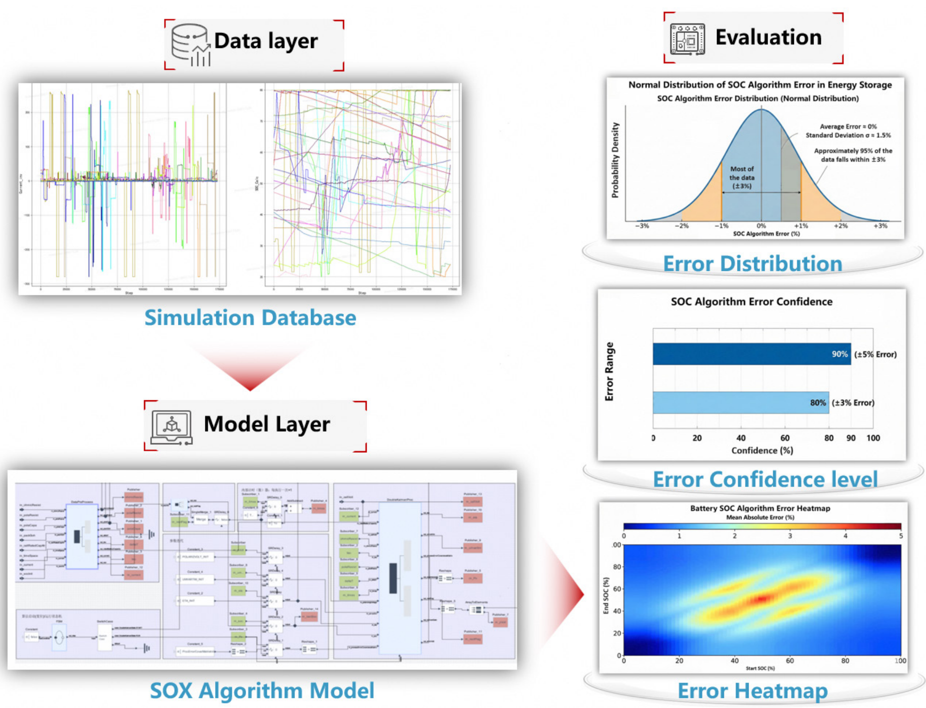


Figure 11: BMS Digital Twin Simulation Platform

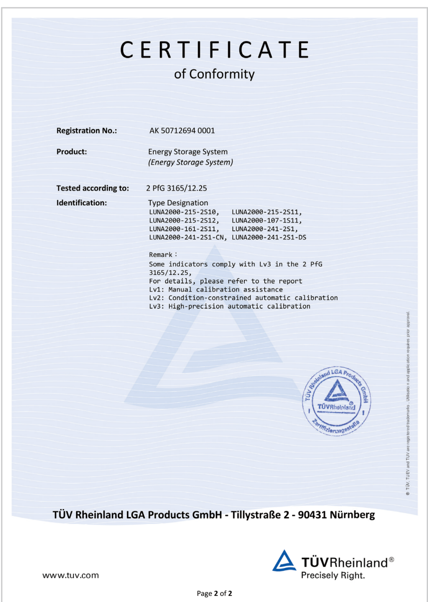
Hardware-in-the-Loop (HIL) Simulation Environment: Huawei operates a GW-class HIL simulation platform for PV-plus-storage solutions, capable of covering multi-scenario application testing and verification in an HIL environment. Test case sets built upon massive scenario data are used to conduct SOX, balancing, and other critical BMS algorithm characteristic tests in both HIL and physical environments, ensuring algorithm accuracy and stability.

Multi-Scenario System Algorithm Testing: Huawei maintains a systematic solution acceptance testing process and test case library. All testing is conducted on a unified test management platform, enabling version-controlled test case management, full traceability of execution processes, and automated data collection and structured storage of results. Critical algorithm characteristics including SOX and balancing are tested and verified in real-world environments to ensure algorithm accuracy and stability.

3.2 Innovation Breakthroughs

TÜV Rheinland conducted a third-party test assessment of Huawei's LUNA2000/LUTERRA2000 series energy storage systems based on 2 PfG 3165/12.25. The tests covered SOC accuracy, SOC auto-calibration, capacity availability, frequency regulation scenarios, Grid-Forming (GFM) capability, Black Start capability, and active/passive/inter-Rack balancing capabilities.

Test results showed that: under peak shaving and valley filling (deep charge/discharge) scenarios, tests were conducted with and without a 15% offset pull. In both cases, the system's maximum SOC error after convergence was ≤2.5%. In multiple frequency regulation (long-term shallow charge/discharge) scenarios, the system achieved automatic calibration convergence after 15% error injection. Furthermore, the system completed GFM grid-forming capability tests at 98% SOC and 2% SOC boundary conditions, and completed 70% R/C/L load Black Start tests at 5% SOC and 98% SOC conditions, with Black Start times all under 10 minutes. Balancing test results showed that 10% SOC differences between Battery Packs (PACKs) converged to 1% after two deep charge/discharge cycles, and maximum 30% SOC deviations between battery Racks ultimately converged to 1%.



CERTIFICATE
of Conformity

Registration No.: AK 50712694 0001
Product: Energy Storage System
(Energy Storage System)
Tested according to: 2 PfG 3165/12.25
Identification: Type Designation
LUNA2000-215-2S10, LUNA2000-215-2S11,
LUNA2000-215-2S12, LUNA2000-107-1S11,
LUNA2000-161-2S11, LUNA2000-241-2S1,
LUNA2000-241-2S1-CN, LUNA2000-241-2S1-DS

Remark：
Some indicators comply with Lv3 in the 2 PfG 3165/12.25,
For details, please refer to the report
Lv1: Manual calibration assistance
Lv2: Condition-constrained automatic calibration
Lv3: High-precision automatic calibration

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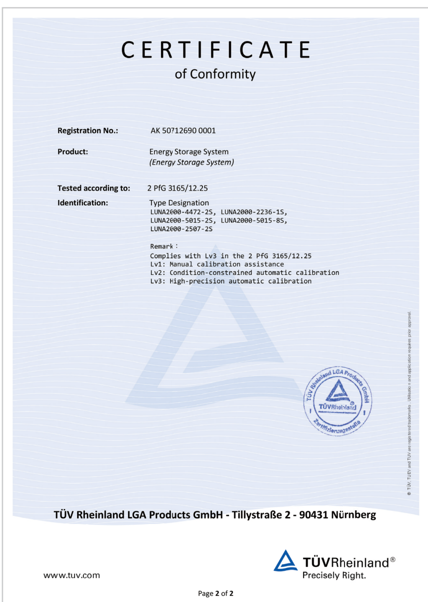

CERTIFICATE
of Conformity

Registration No.: AK 50712690 0001
Product: Energy Storage System
(Energy Storage System)
Tested according to: 2 PfG 3165/12.25
Identification: Type Designation
LUNA2000-4472-2S, LUNA2000-2236-1S,
LUNA2000-5015-2S, LUNA2000-5015-8S,
LUNA2000-2507-2S

Remark：
Complies with Lv3 in the 2 PfG 3165/12.25
Lv1: Manual calibration assistance
Lv2: Condition-constrained automatic calibration
Lv3: High-precision automatic calibration

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Figure 12: SOC LV3 Certification from TÜV Rheinland

These results demonstrate that high-precision SOC, auto-calibration, and auto-balancing capabilities can enhance the available capacity, dispatch credibility, grid-forming stability, and O&M efficiency of energy storage systems, providing key technical support for high-value applications such as grid-side energy storage participation in electricity market trading, frequency regulation, microgrid grid-forming, and Black Start.

3.2.1 SOC Calibration

Compared with traditional SOC algorithm frameworks, Huawei has built a unique SOX algorithm framework, forming an algorithm strategy centered on a confidence assessment model, coordinated by multiple calibration methods, and covering multiple typical scenarios.

Confidence Assessment Model: Building upon the traditional SOC algorithm framework, Huawei introduces a confidence assessment model based on hardware-layer synchronous sampling error identification and charge/discharge voltage feature recognition. This model dynamically calculates state estimation accuracy and the credible weight of multiple calibration sources according to current operating conditions (current magnitude, temperature, rest duration), serving as the core skeleton of the algorithm to identify appropriate calibration trigger timing.

Figure 13: Hardware-layer sampling error identification

Dynamic Polarization Compensation Technology: To address long-term plateau-region cycling conditions, the algorithm incorporates multiple sets of battery charge/discharge characteristic curves, capable of real-time separation of ohmic voltage drop, electrochemical polarization, and concentration polarization voltage components. Within constant current change windows, the true OCV is captured and reconstructed, enabling calibration and range positioning within the $LiFePO_4$ flat region.

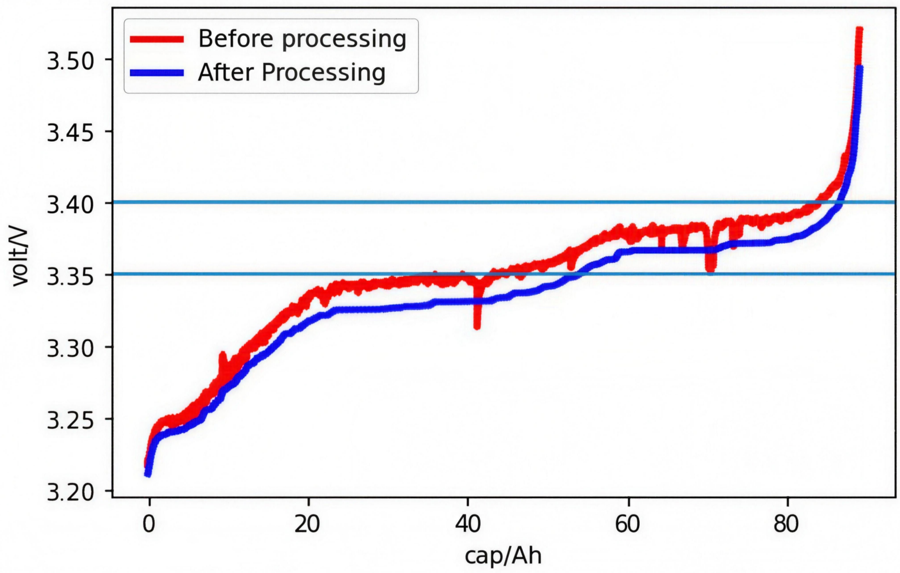

Figure 14: Dynamic polarization compensation technology

AI + Physics-Based Model Fusion Estimation Technology: To address the nonlinear dynamic characteristics of $LiFePO_4$ batteries under frequency regulation micro-cycling conditions, Huawei adopts a physics-based model fused with AI model modeling approach. Physical characteristics that are difficult to be directly described by AI-enhanced mechanistic models. which helps improving the generalization capability and stability of traditional battery model algorithms. A post-processing module is designed to perform intelligent arbitration based on the advantageous operating conditions of different algorithms, with an added filtering post-processing step. Even under conditions of frequent current fluctuations and unstable voltage, SOC range correction can be achieved, enhancing algorithm stability.

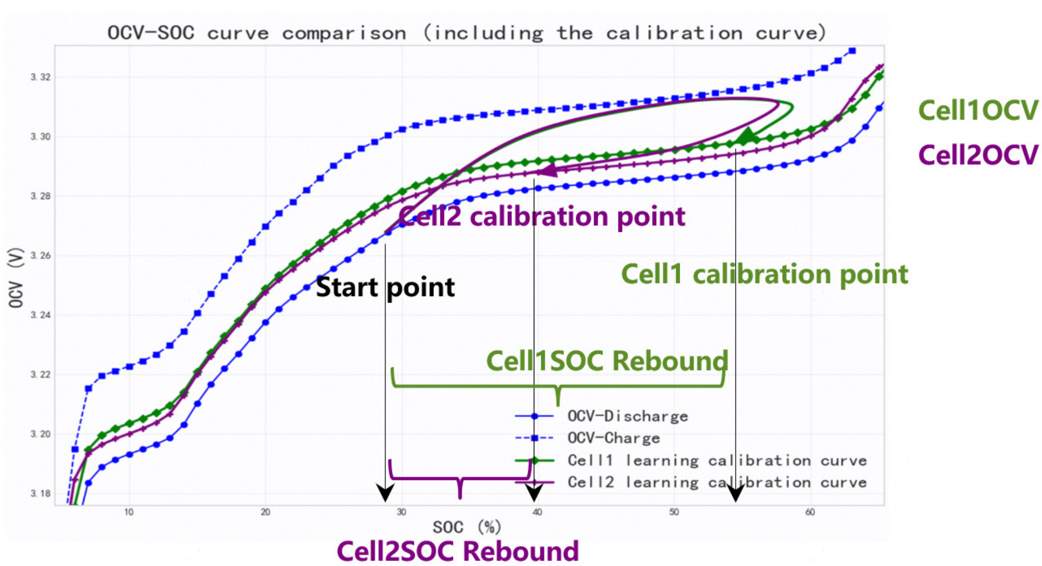

Figure 15: AI-enhanced description of battery hysteresis characteristics

3.2.2 SOC Balancing

3.2.2.1 Pack-Level Optimization

In energy storage systems, due to differences in battery manufacturing processes, operating environments, and long-term aging, SOC inconsistency among individual cells or Battery Packs is inevitable. This inconsistency leads to reduced system charge/discharge capacity and decreased system efficiency. Therefore, effective SOC balancing strategies are essential for improving the overall performance of energy storage systems.

"Pack-Level Optimization" is an SOC balancing strategy based on independent Battery Pack management, treating each Battery Pack in the energy storage system as an independent control unit with optimized charge and discharge management. Each Battery Pack is equipped with an independent DC/DC (Direct Current to Direct Current) converter. During operation, high-SOC Battery Packs transfer energy to low-SOC Battery Packs, achieving overall SOC balance and maximizing Depth of Discharge (DOD), avoiding overall system capacity limitation caused by individual Battery Packs.

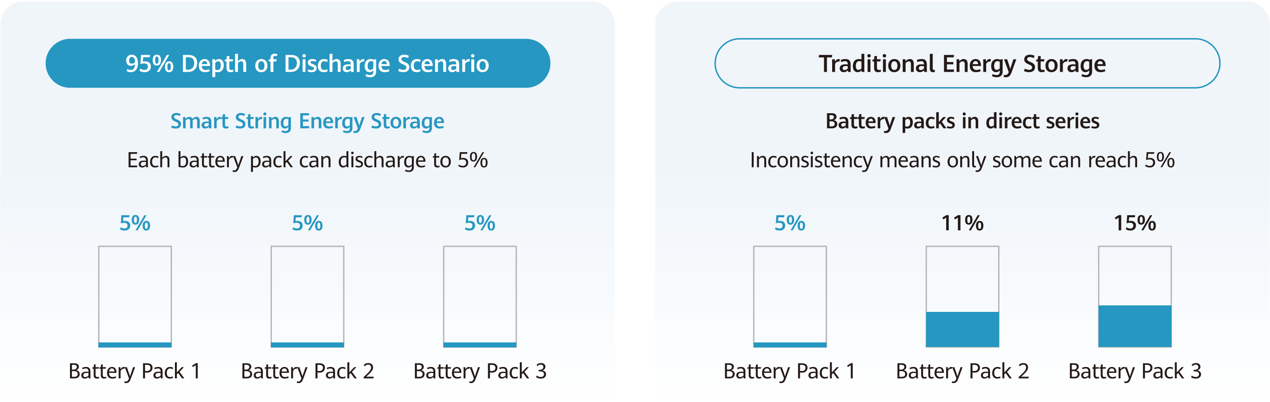

Figure 16: Pack-Level Optimization Architecture

3.2.2.2 Rack-Level Management

"Rack-Level Management" is a refined energy management strategy based on battery Racks. This strategy treats each Battery Rack (typically composed of multiple Battery Packs connected in series) as an independent control unit, using intelligent algorithms to achieve autonomous regulation of each Rack's SOC, ensuring that every Rack operates within its optimal SOC range.

Rack management dynamically adjusts charge and discharge power based on the SOC status of each Rack, overcoming the "bucket effect" (short-board effect) of traditional series architectures, improving system available capacity, and preventing some Racks from remaining in extreme SOC states for extended periods.

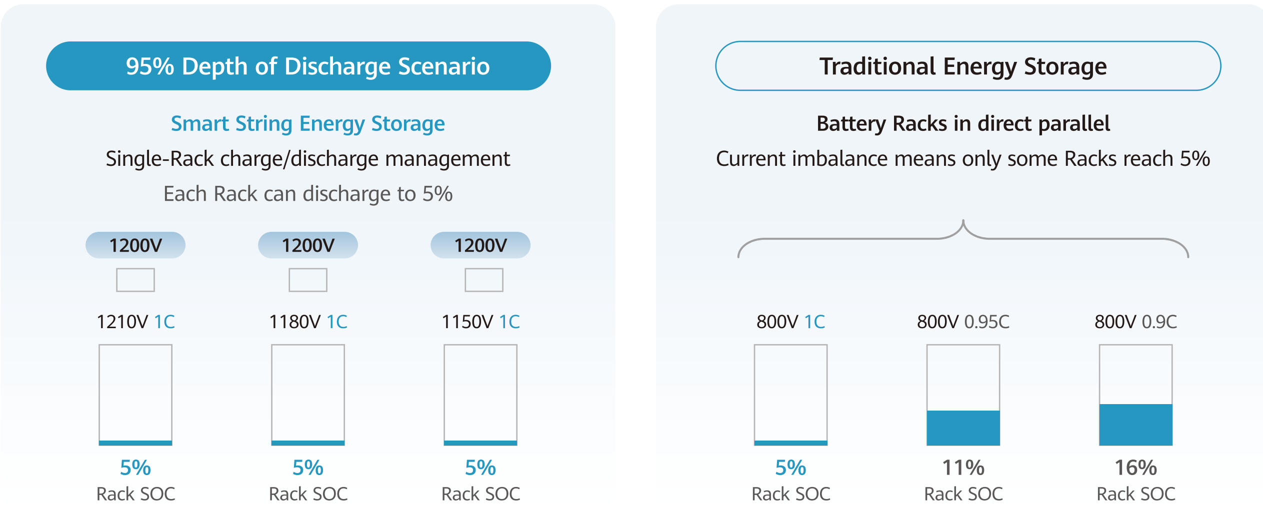

Figure 17: Rack-Level Management Architecture

3.2.3 SOX Auto-Calibration Strategy

As energy storage systems accumulate operating hours, estimation errors in battery state parameters (including SOC, SOH, and other SOX indicators) gradually increase. Long periods without calibration will lead to Coulomb counting drift, affecting SOC accuracy and consequently impacting energy storage charge/discharge capacity and revenue. Traditional fixed-period manual calibration requires additional O&M manpower and may affect system availability, incurring additional downtime costs.

Huawei enables the auto-calibration function to automatically identify operating conditions without requiring system shutdown, manual site visits, or user intervention. During battery subsystem operation, SOC and SOH calibration for battery Racks is achieved, maintaining long-term high-precision system operation while reducing manual O&M efforts and capacity test calibration operations.

04 Outlook and Summary

4.1 Next-Generation Technology Outlook

4.1.1 Expansion Force Sensor

$LiFePO_4$ batteries exhibit minimal voltage variation across the voltage plateau region, making traditional SOC calibration inherently difficult. Research indicates that the expansion force arising from material phase transitions exhibits characteristic changes across different SOC intervals, with its inflection points strongly correlated to charge/discharge capacity. This characteristic parameter is relatively insensitive to operating temperature, C-rate, and operating conditions. Integrating expansion force sensor data enables multi-physics collaborative calibration, significantly improving SOC estimation accuracy in the plateau region, and thereby enhancing the total dischargeable energy and economic returns of the energy storage system across its full lifecycle.

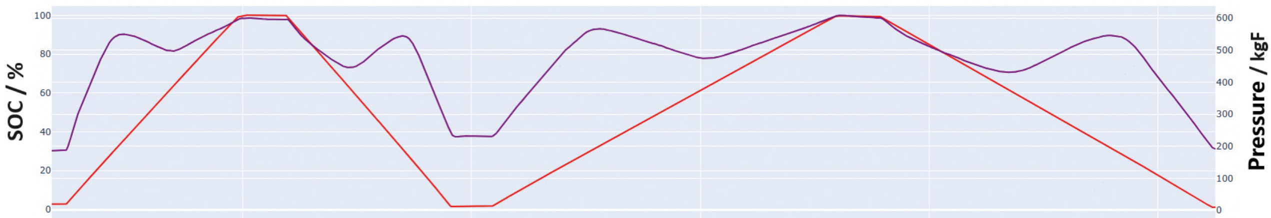

Figure 18: Comparison of Expansion Force and Voltage Curves

4.1.2 Edge-Cloud Collaborative Architecture

The edge-cloud collaborative architecture achieves high-precision real-time estimation of battery state parameters through hierarchical computing: terminal devices perform second-level real-time SOC estimation, edge nodes undertake multi-pack collaborative analysis and SOH calibration, and the cloud platform handles big data analytics and long-

term trend prediction. This architecture effectively extends the coverage of the algorithm, significantly improving state estimation accuracy and computational efficiency under complex operating conditions.

4.2 Summary

As the global energy transition toward clean and low-carbon sources accelerates, energy storage systems have become a core regulating resource for modern power systems, and their precise SOC management capability plays a pivotal role in enhancing system safety, reliability, and economics. The continued deployment of grid-forming energy storage represents a critical pathway toward carbon peaking and carbon neutrality goals, while high-precision SOC estimation and calibration technologies serve as the technical cornerstone for ensuring safe and efficient system operation and unlocking the full lifecycle value of energy storage plants.

Currently, precise SOC management faces multiple challenges: complex operating conditions demand higher state estimation accuracy, battery aging and temperature drift require more intelligent online calibration mechanisms, and grid-forming scenarios impose more stringent requirements on the real-time reliability of SOC for frequency support and power forecasting. To address these challenges, Huawei will continue to deepen innovations in precise SOC management, continuously improving SOX estimation accuracy, optimizing available capacity prediction, and ensuring state reliability under extreme operating conditions from the perspectives of core algorithm optimization, multi-physics fusion calibration, full-lifecycle data closed-loop management, and grid-forming SOC dispatch strategies— enabling state visibility, quantifiability, and dispatchability from cell to plant.

Going forward, intelligent, highly reliable, and intrinsically safe SOC management will continue to be the direction of advancement for energy storage systems. Huawei is committed to collaborating with industry partners to drive continuous expansion of SOC management performance boundaries, providing core technical support for building safer and more efficient energy storage systems, empowering green energy across all sectors, and jointly advancing the sustainable development of the energy industry.

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