MarSum Solutions: Power Electronics for Utility-Scale Battery Storage Systems

Utility-scale battery energy storage systems (BESS) are becoming a core part of modern power infrastructure. As renewable generation expands, utilities and developers need storage systems that can absorb excess energy, discharge during high-value intervals, and provide fast grid services without sacrificing reliability. At megawatt scale, the battery cells are only one part of the engineering challenge. The power conversion system (PCS), plant controls, protection strategy, thermal design, and grid interface determine whether stored DC energy can be converted into reliable, compliant AC power at the point of interconnection.

This paper discusses the power electronics behind large BESS projects, with a focus on bidirectional inverter and converter architecture, power quality, fast-response grid services, renewable plant integration, and high-reliability design. The goal is to frame BESS not as a collection of battery containers, but as a coordinated grid-connected power conversion system where early architecture choices shape efficiency, availability, safety, and project bankability.

Why utility-scale storage is a power electronics problem

A BESS must move energy in two directions. During charging, the site converts grid or renewable AC power into controlled DC power for the battery array. During discharge, the system converts stored DC energy back into synchronized AC power while meeting voltage, frequency, reactive power, ramp-rate, and protection requirements. That bidirectional behavior makes the PCS one of the most important design elements in the project.

Unlike a passive load or a simple generator, a storage plant may operate across many modes in the same day: charging from solar oversupply, discharging during peak demand, responding to frequency events, providing voltage support, following market dispatch commands, or holding reserve energy for reliability. Each mode stresses the PCS, battery management system, thermal system, transformers, breakers, communications, and plant controller in different ways. Successful BESS design therefore requires a system-level view of power electronics, controls, protection, and operating strategy.

What is inside a utility-scale BESS

Most utility-scale storage projects can be described as a set of tightly coupled subsystems. The exact packaging differs across vendors, but the engineering functions are consistent.

Battery containers and DC blocks

Cells, modules, racks, and battery containers define the energy capacity of the system. String configuration, DC voltage range, state-of-charge windows, and degradation targets shape the allowable operating envelope for the PCS.

Power conversion system (PCS)

The PCS performs bidirectional conversion between the battery DC bus and the grid-side AC system. It must regulate active and reactive power, manage current limits, ride through disturbances, and maintain acceptable efficiency across many operating points.

Controls, EMS, and SCADA

The energy management system (EMS), plant controller, battery management system (BMS), and supervisory control and data acquisition (SCADA) interface coordinate dispatch, limits, alarms, and data flow between battery hardware, site controls, and external operators.

DC collection and protection

DC combiner hardware, contactors, fusing, isolation monitoring, precharge circuits, and disconnect strategy manage high-current DC paths. These choices influence fault containment, serviceability, and safe maintenance procedures.

Transformer and grid interface

Step-up transformers, switchgear, metering, grounding, and protection equipment connect the PCS to the point of interconnection. Utility requirements and grid studies often determine voltage class, grounding approach, fault behavior, and power quality limits.

Thermal and safety systems

Cooling, fire detection, ventilation, enclosure design, and emergency response interfaces protect equipment and personnel. These systems must support repeated cycling, hot-weather operation, and fault response without creating avoidable downtime.

Bidirectional PCS design: the center of the storage plant

The PCS is where battery chemistry becomes a grid asset. A well-designed PCS must operate efficiently during both charge and discharge, provide accurate power control, and remain stable across a wide DC voltage range as battery state of charge changes. It must also satisfy interconnection requirements for reactive power, power factor, frequency response, voltage ride-through, harmonic distortion, and communications.

At high power levels, efficiency is not just an energy-cost metric. Losses become heat that must be removed from semiconductors, magnetics, buswork, filters, and enclosures. Switching frequency, semiconductor selection, filter design, transformer selection, and cooling architecture are therefore coupled decisions. Pushing one target too far, such as power density or switching speed, can create new constraints in electromagnetic interference, thermal margin, acoustic behavior, or long-term reliability.

The PCS also defines how the storage plant behaves during grid disturbances. Current limits protect power semiconductors and DC-link hardware, but they also shape fault contribution, voltage support, and ride-through behavior. For large projects, the practical question is not only whether the inverter can reach a nameplate power rating. It is whether the system can deliver the right power, at the right time, while staying within electrical, thermal, battery, and utility limits.

Grid services and operating modes

The value of utility-scale BESS depends on the ability to move between operating modes predictably. The same battery plant may support market revenue, renewable integration, and reliability services, but each use case places different requirements on the PCS and controls.

Frequency regulation and fast response: Battery storage can change output rapidly, making it useful for frequency regulation and other ancillary services. The PCS must translate dispatch commands into stable active-power response while respecting battery state of charge, ramp limits, thermal constraints, and grid-code requirements.

Peak shaving and energy shifting: For utilities, commercial sites, and grid operators, storage can discharge during high-demand periods and recharge when energy is less constrained. Efficient cycling, accurate scheduling, and degradation-aware control are important because revenue depends on repeated operation over the life of the asset.

Voltage and reactive power support: Many interconnection agreements require reactive power capability and voltage support. The PCS and plant controller must coordinate reactive power response with active power dispatch, current limits, transformer capability, and local voltage behavior.

Ramp-rate control and renewable smoothing: Co-located storage can reduce sharp changes in solar or wind output and help a hybrid plant meet ramp-rate limits. This requires coordination between renewable generation, storage availability, plant-level forecasts, and point-of-interconnection limits.

Reserve and contingency support: Some projects hold stored energy for contingency response, outage support, or reliability events. In those cases, controls must preserve reserve capacity and prevent market dispatch from consuming energy that is required for reliability obligations.

Integration with solar, wind, and hybrid plants

Storage is often deployed with renewable generation because it changes the shape and usefulness of variable energy. Solar-plus-storage projects can shift midday production into evening peaks, reduce curtailment, and provide a more controllable interconnection profile. Wind-plus-storage projects can smooth output, support ramp management, and help capture value during periods when transmission capacity or market pricing would otherwise limit production.

The key architecture decision is whether the storage plant is AC-coupled, DC-coupled, or designed as a more integrated hybrid plant. AC-coupled systems connect the battery PCS and renewable inverter systems on the AC side, often simplifying retrofit and independent operation. DC-coupled systems connect storage behind a shared DC architecture, which can reduce conversion steps in some solar applications and capture clipped or curtailed energy more directly. Hybrid plant designs must define how the plant controller prioritizes energy shifting, grid services, state-of-charge management, renewable smoothing, and interconnection limits.

These choices are not only commercial. They affect fault behavior, control hierarchy, metering, protective relaying, model validation, equipment ratings, and commissioning. A hybrid plant that looks simple in a one-line diagram can become difficult to operate if the PCS, renewable inverters, EMS, and utility-facing plant controller are not coordinated from the beginning.

High-reliability design requirements

Utility-scale BESS frequently operates as critical infrastructure. Failures can affect market revenue, renewable project output, grid-service obligations, and public confidence. High availability therefore depends on more than selecting a reliable inverter. It requires architecture-level decisions that support fault isolation, graceful derating, maintainability, and validated controls.

Modularity and redundancy

PCS blocks, battery containers, auxiliary systems, and communications should be structured so that a localized failure does not disable the entire plant. N+1 or block-level redundancy can allow continued operation at reduced capacity during service events.

Thermal margin and cycling duty

Repeated charge-discharge cycles create heat in semiconductors, magnetics, buswork, and battery containers. Thermal design must reflect real duty cycles, ambient extremes, filter losses, cabinet airflow, coolant paths, and equipment aging.

Battery limits and degradation

The PCS cannot be optimized independently from battery state of charge, temperature, voltage limits, degradation models, and warranty constraints. Aggressive grid-service response must remain compatible with cell health and project revenue assumptions.

Fault handling and isolation

DC faults, ground faults, overtemperature events, communication loss, and abnormal grid conditions need defined detection and response behavior. Protection should isolate the fault while preserving safe equipment states and useful diagnostic data.

Power quality and EMI/EMC

Large PCS installations must control harmonics, flicker, power factor, switching noise, and conducted or radiated emissions. Filter design, grounding, shielding, transformer selection, and layout decisions all influence compliance and field reliability.

Models, commissioning, and data

Validated models, staged commissioning tests, and reliable plant data are essential for utility approval and long-term operation. Model fidelity, controller settings, alarms, and acceptance tests should be aligned before field energization.

Markets moving toward larger BESS deployments

Utility-scale storage is growing because renewable penetration, grid congestion, peak demand, and reliability needs are increasing at the same time. Market forecasts point to rapid expansion, with one projection estimating the global BESS market growing from roughly $51 billion in 2025 to about $106 billion by 2030. The engineering implication is straightforward: more projects will need power electronics that can operate reliably as grid assets, not just as battery chargers.

United States: The U.S. market is shaped by solar-heavy regions, growing battery interconnection queues, capacity needs, and ancillary service opportunities. Large projects must satisfy utility study requirements, regional transmission organization rules, grid-code behavior, and increasingly detailed inverter-based resource expectations.

Europe: European storage deployment is tied closely to renewable integration, energy arbitrage, grid congestion, and system flexibility. BESS projects must often address grid-code compliance, market participation, power quality, and integration with wind and solar assets across diverse national requirements.

Asia-Pacific: Asia-Pacific markets include large renewable buildouts, industrial load growth, island systems, and aggressive grid modernization programs. Project needs vary widely, but high-density power conversion, safety, grid compliance, and cost-effective reliability remain central concerns.

Integration challenges that determine project success

The most difficult BESS problems usually appear between subsystems. A battery vendor may define cell limits, a PCS supplier may define inverter capability, an EMS may define dispatch behavior, and a utility may define interconnection requirements. The project succeeds when those boundaries are engineered together.

Control hierarchy

The EMS, BMS, PCS controller, plant controller, and utility interface need clear authority across charge, discharge, standby, alarm, and fault modes. Ambiguous command priority can create late-stage commissioning problems.

State-of-charge management

Grid services can be limited by available energy rather than nameplate power. Dispatch strategies must preserve the state of charge needed for committed services while limiting unnecessary battery degradation.

Communications and cybersecurity

Large storage plants depend on reliable data links between containers, PCS units, site controllers, market interfaces, and utility systems. Communications design must support secure command handling, alarms, data quality, and recovery from network failures.

Protection coordination

AC and DC protection must account for current-limited inverter behavior, transformer configuration, grounding, isolation monitoring, battery fault response, and utility relay expectations.

Grid model validation

Utilities increasingly expect validated models for inverter-based resources. BESS projects may require positive-sequence studies, electromagnetic transient studies, and hardware or controller validation depending on site strength and required services.

How MarSum supports utility-scale BESS programs

MarSum Solutions supports battery storage, renewable integration, and high-power conversion programs with an engineering-first approach focused on performance, robustness, and manufacturability. Utility-scale BESS projects sit at the intersection of power electronics, controls, protection, thermal design, and grid integration, which is where early engineering choices have the largest effect on project risk.

Our work can include PCS architecture review, bidirectional converter and inverter support, power-stage and filter design input, grid-code and power quality review, controls and EMS interface definition, fault-handling strategy, thermal and reliability assessment, and validation planning. We also help teams translate broad requirements such as frequency response, peak shaving, renewable firming, state-of-charge limits, and availability targets into testable engineering criteria.

For developers, equipment suppliers, and project teams deploying grid-scale storage, BESS power electronics should be treated as a core architecture decision rather than a procurement detail. A disciplined system-level approach can reduce commissioning risk, improve utility confidence, and support a faster path from project design to reliable operation.

Engagement models

We support customer teams through focused technical consulting, design reviews, model and controls support, and deeper co-development efforts depending on program phase. Typical engagements range from early feasibility and requirements definition to prototype validation, field-debug support, and production-readiness planning for grid-connected storage and hybrid renewable systems.

Selected sources: U.S. DOE energy storage and BESS materials; NERC inverter-based resource guidance; MarketsandMarkets Battery Energy Storage System market forecast.

Contact us today to scope your utility-scale battery storage, PCS design, or renewable-storage integration project!