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AC-Native Battery Systems

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Introduction

Battery systems in electric vehicles (EVs) and stationary energy storage have traditionally followed a direct-current (DC)-native architecture. The battery pack acts mainly as a passive DC energy source, while waveform synthesis, fast electrical dynamics, and grid interfacing are handled by external power-conversion hardware. Internal sensing and control are typically limited to monitoring and protection, with most high-bandwidth actuation occurring outside the pack.

Several emerging requirements are now challenging this separation between external functionality and internal controllability. Fast charging pushes cells into steep polarization regimes and amplifies module-level heterogeneity, while uneven aging reduces usable capacity, power capability, and pack lifetime. As pack size and cell count increase, outlier cells become more likely, complicating thermal management, balancing, and fault handling. Under these constraints, battery packs may require more sophisticated cell-level control and coordination to access their theoretical capacity.[1]

Vehicle-to-grid (V2G) and vehicle-to-home (V2H) functions add further system-level demands. In DC-native systems, bidirectional power exchange and grid interaction are well established but typically rely on centralized power-conversion hardware. This concentrates grid interfacing, protection, and control in a few conversion stages, limiting how flexibly these functions can be distributed under cell heterogeneity, fault conditions, or advanced grid-interactive operation. More broadly, fixed internal current paths and centralized conversion restrict pack-level current routing and localized actuation.

Recent technological progress now makes this architectural separation worth revisiting. Wide-bandgap semiconductors, including silicon carbide (SiC) and gallium nitride (GaN), are enabling efficient, compact power conversion at module or even cell scales.[2] Modular power-electronics integration is also becoming commercially viable, with control and conversion increasingly distributed rather than confined to centralized inverters. Industrial demonstrations, including Volvo's SmartCell,[3] Porsche's alternating current (AC) Battery,[4] and Stellantis's Intelligent Battery Integrated System,[5] illustrate that AC waveform synthesis inside the battery pack could be gradually technically feasible.

At the architectural level, AC-native battery systems differ from both conventional DC-native packs and converter-centric modular multilevel approaches. DC-native packs supply DC power to an external converter and retain a largely static internal topology. Modular multilevel converter (MMC)-based battery systems distribute switching across submodules but are typically framed as power-electronics hierarchies. AC-native architectures instead relocate controllable energy conversion inside the pack. By embedding switching and coordination within electrically controllable units, the pack can synthesize AC waveforms, dynamically route current paths, and participate in voltage- and frequency-related behavior through internal coordination.

This relocation changes where sensing, actuation, and control are implemented within the battery system. With power electronics integrated inside the pack, functions such as in-operation cell balancing, selective module bypass, and current redistribution can be achieved through active local actuation rather than external conversion alone. The pack can therefore sense, route, and regulate energy more flexibly, with dynamic responses governed by internal coordination rather than a peripheral device. Co-locating sensing, switching, and control at the module level makes the battery pack itself a site of real-time decision-making.

The focus of this Future Energy article is therefore architectural, not electrochemical. AC-native battery systems do not introduce new cell chemistries or bypass electrochemical constraints. Instead, they expand the degrees of freedom for pack-level sensing, actuation, and control, while actively redistributing complexity between internal battery with different states. Assessing their implications of performance, reliability, and cost requires careful consideration of mechanisms, evidence, and limitations of AC-native battery systems.

The architectural shift: from a passive DC source to an active energy-processing platform

Conventional DC battery packs operate as passive DC sources whose behavior is shaped mainly by the external inverter and charger stack (Figure 1A). Their static internal topology offers limited response to cell-to-cell inconsistencies, so heterogeneity directly curtails power, reduces usable capacity, or increases fault sensitivity. DC-reconfigurable designs extend this architecture through cell- or cluster-level switching for bypassing, selective routing, and fault handling (Figure 1B).[6] However, they remain DC systems that their switching flexibility does not provide AC synthesis or localized active voltage-frequency control, and the centralized inverter still governs system-level dynamics.

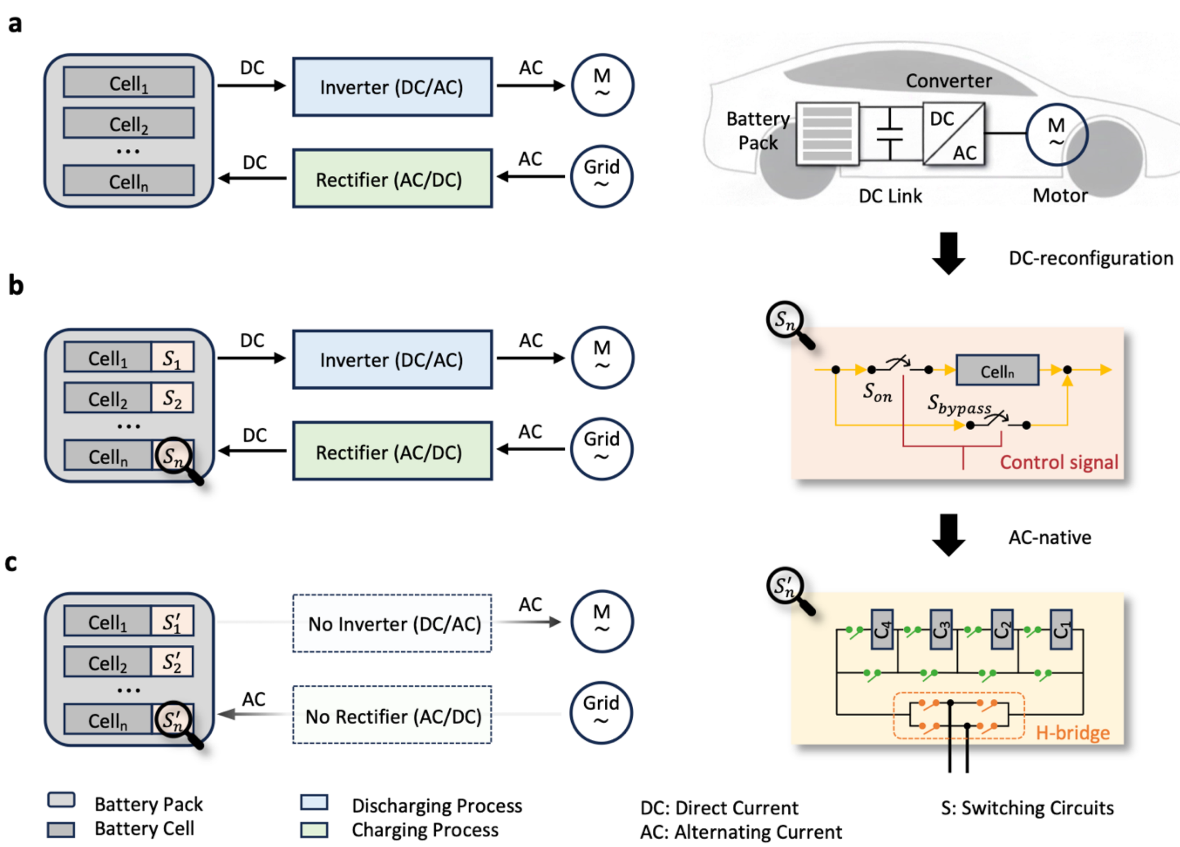

Figure 1: Representative examples of (A) conventional DC architecture, (B) reconfigurable DC architecture, and (C) AC-native architecture for battery systems.

AC-native architectures move beyond these DC-native limitations by distributing power-processing capability across electrically controllable battery units. Each unit combines one or more cells with local switching circuitry, implemented through switch-based full-bridge stages or MMC submodules (Figure 1C).[7] This enables voltage synthesis, impedance shaping, and controlled AC generation where cell dynamics originate. With actuation embedded throughout the string, modules can contribute signed voltages, participate selectively in waveform formation, and generate internal excitations that reveal frequency-dependent impedance features largely hidden under DC operation. Centralized conversion is thus complemented by coordinated unit-level actuation, turning the battery pack from a passive DC source into an actively actuated system.

Capabilities enabled by AC-native architectures

Several capabilities frequently attributed to AC-native battery architectures arise from architectural mechanisms that have been studied previously in related systems, including reconfigurable battery packs and MMC-based battery systems. Rather than treating AC-native batteries as a fundamentally new electrochemical technology, it is more precise to interpret them as an architectural framework that integrates and extends these mechanisms. Table 1 organizes these mechanisms into four categories, including enhanced diagnostic observability, topology-aware energy routing, stress steering, and active fault isolation, and summarizes the current evidentiary basis supporting each capability. This evidence also highlights the type of scientific supports available in the literature and the limitations that remain.

Mechanism	Role of AC-native architecture	Representative evidence	Evidence type and baseline	Limits
Enhanced diagnostic observability [6-9]	Internal switching enables controlled perturbations for active probing, improving identifiability of impedance and state variables	-Active-perturbation diagnostics review highlights designed excitation for scalable diagnostics -BI-MMC experiments use converter switching currents for impedance inference -Reconfigurable pack models support interpretation of distributed measurements	-Experimental demonstration and modeling framework -Baseline: passive DC monitoring	-Limited by excitation design, sensor bandwidth, electromagnetic interference management, and safety constraints
Topology-aware and actuation-centric energy routing [3, 4, 5, 9, 12]	Flexible pack voltage/current formation and integrated inverter-charger architectures allow better matching to charger constraints and reduce conversion stages Embedded multilevel conversion shifts conduction/switching losses and enables module-level ripple shaping	-Ripple-mitigating scheduling suppresses low-frequency ripple and shifts the spectrum to 5kHz, reducing up to 20% relative battery losses; -BI-MMC efficiency depends on operating regime -Multilevel "AC battery" concepts distribute conversion for propulsion and supply -Battery-integrated MMC (BI-MMC) charging analysis shows charging capability depends on submodule design and constraints -IBIS prototype reports ~15% faster charging and ~10% efficiency improvement via integrated inverter-battery architecture	-Modeling and lab validation -Baseline: central inverter and fixed DC pack -Architectural analysis and prototype comparisons -Baseline: conventional EV architecture (separate inverter and charger)	-Efficiency gains are operating-point dependent -Higher component count impacts reliability and cost -Gains depend on charger voltage limits, pack dispersion, and semiconductor losses -Increased switching hardware adds complexity
Spatial and temporal stress steering [9,10]	Pack-embedded switching and modularization redistribute current, bypass duty, thus heat across cells/modules, enabling heterogeneity-aware dispatch and thermal homogenization	-Reconfigurable-BMS literature identifies topology control as a lever for managing cell heterogeneity and lifetime -Thermal reconfiguration by current redistribution demonstrates shaping cell heat generation to homogenize temperature fields, with defined temperature "state of inhomogeneity" decreasing from over 6% to less than 1%.	-System-level concepts and validated thermal models with no current redistribution functions -Baseline: static series and parallel packs	-Depends on SOC and SOH estimation accuracy, sensing limits, and control policy -Does not modify electrochemical aging mechanisms
Active fault isolation through modular switching [3, 4, 6, 9, 12]	Local switching enables cell/submodule bypass and continued operation through topology reconfiguration	-Reconfigurable-BMS literature emphasizes fault tolerance via cell isolation -Modular converter architectures provide redundancy -BI-MMC and SmartCell concepts highlight inherent fault isolation and redundancy	-Architecture-level evidence and prototype concepts -Baseline: static series pack	-Often requires derating -Effectiveness depends on fault detection latency and system topology -Increased component count affects reliability

Table 1. Architectural mechanisms underlying AC-native battery systems, the current evidentiary basis supporting them, and key limitations reported in the literature.

The mechanisms summarized in Table 1 can be grouped into four functional layers that together define the control stack of AC-native battery systems: (i) enhanced observability enabled by controllable excitation, (ii) topology-aware and actuation-centric energy routing enabled by embedded switching, (iii) spatial and temporal stress steering enabled by active current redistribution, and (iv active fault isolation enabled by modular protection and distributed power conversion.

Together, these mechanisms redistribute sensing, actuation, and protection within the battery pack. Controllable excitation improves observability of internal electrochemical states, providing a stronger basis for topology-aware and actuation-centric energy routing. When routing is treated as a control input, the system can modulate coupled stress profiles across cells to accelerate balancing and moderate degradation. These interactions collectively form the functional stack illustrated in **Figure 2,** which maps the architectural mechanisms in **Table 1** onto four operational layers: observability, topology-aware energy routing, stress steering, and active fault isolation.

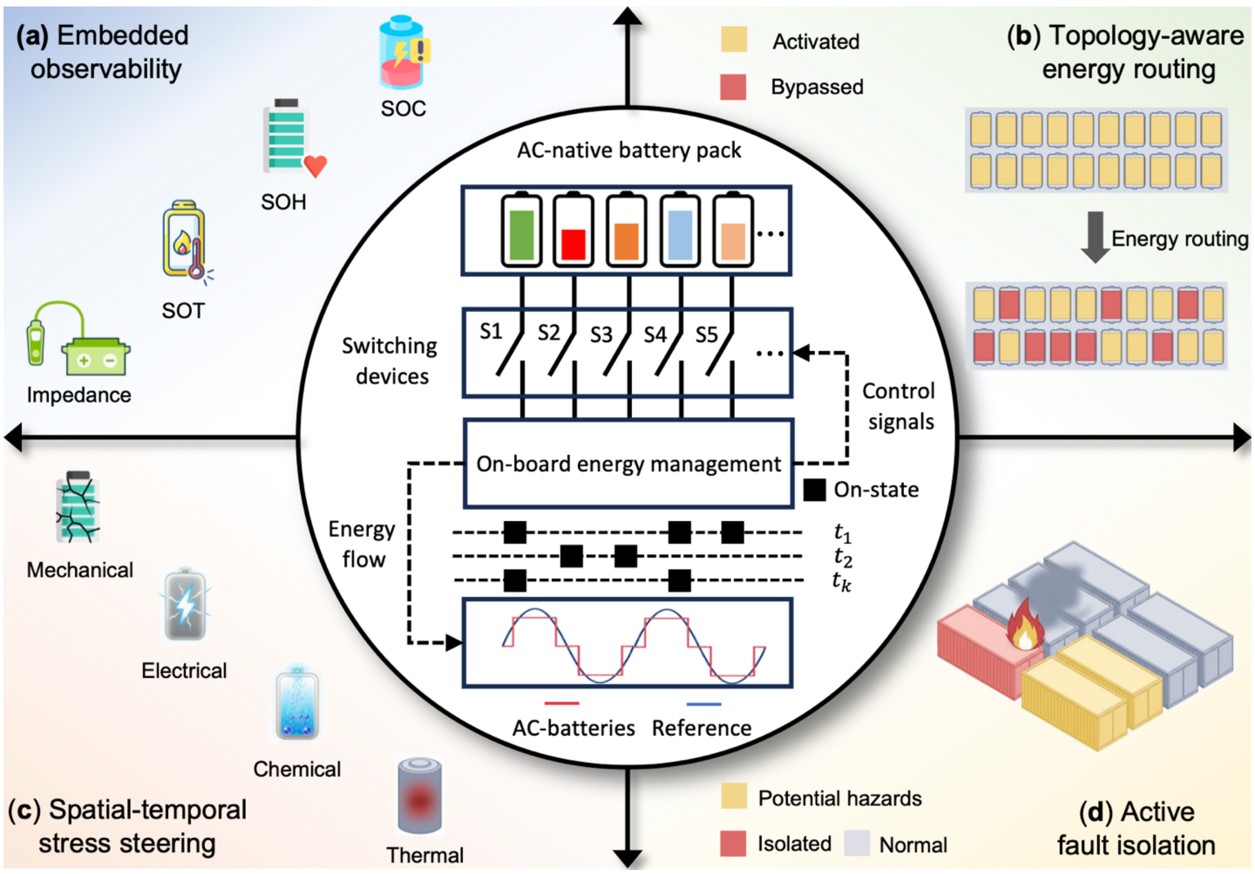

Figure 2: Intelligence and control stack of AC-native battery systems. (A) AC battery architecture-enabled observability through controllable diagnostic excitation, (B) topology-aware and actuation-centric energy routing, (C) spatial and temporal steering of electrical and thermal stresses, with mechanical stress evolving as a coupled downstream consequence, and (D) AC battery architecture-enabled protection with localized active fault isolation.

The first capability summarized in **Table 1,** enhanced diagnostic observability, arises from the ability of AC-native architectures to generate controlled internal excitation (**Figure 2A**). In DC-native operation, batteries are stimulated mainly by external load profiles, which occupy a narrow, application-dependent frequency spectrum. Consequently, internal processes such as charge-transfer kinetics, solid-phase diffusion, and interfacial resistance evolution remain weakly excited or difficult to distinguish from routine measurements. Embedded switching instead allows the pack to inject perturbations with specified frequency, amplitude, and phase, using them as designed probes of internal mechanisms. High-frequency components mainly reflect ohmic and charge-transfer processes, whereas lower-frequency excitation reveals diffusion-related dynamics.[8] This frequency-mechanism correspondence improves state observability by decoupling otherwise entangled responses. The diagnostic value therefore lies in turning switching capability into an active perturbation framework for internal observability. By co-optimizing active perturbation design and feature extraction, such excitation can yield rapid, interpretable diagnostics under practical operating conditions.

Taking embedded observability as data source support, the second mechanism identified in **Table 1**, topology-aware and actuation-centric energy routing, emerges once observability is paired with embedded actuation (**Figure 2B**). In conventional DC designs, the entire string is constrained to follow a single current trajectory determined at the inverter. Even DC-reconfigurable approaches provide only coarse routing through bypass or selective engagement.[9] AC-native systems operate differently. Actuation occurs at the electrical units themselves, which makes sub-millisecond changes to current direction possible and allows selective participation of specific cells or strings. Routing decisions can depend on waveform objectives. Different groups of modules can supply traction loads, auxiliary systems, or grid interfaces independently. Internal AC synthesis from AC-native battery architecture makes routing a continuous control action, enabling the battery pack to shape power delivery in real time, allocate cells by load and health, and interface with multiple domains, all without dedicated DC/DC converters.

Building on controllable routing, the third mechanism in **Table 1**, stress steering, enables spatial and temporal steering of electrical and thermal stress across heterogeneous cells through active current redistribution (**Figure 2C**), with mechanical stress evolving as a coupled downstream consequence. At cell level, controlled current profiles can redistribute local strain and suppress the buildup of stress concentrations. At the pack level, stronger cells are loaded more heavily while weaker cells are relieved, and thermal hotspots are moderated through coordinated switching.[10] Together, these capabilities elevate battery balancing from a slow corrective procedure into high-bandwidth control, enabling state trajectories across cells (e.g., state of charge and state of health) to converge quickly on their timescales.

The final mechanism summarized in **Table 1**, active fault isolation, follows naturally from the same embedded switching capability (Figure 2D). In DC-native battery packs, cells are hard-wired through welded interconnects, and protection relies on pack-level devices such as relays, fuses, and inverter-side monitoring. A single cell fault can propagate through the series chain, and remediation often requires battery pack disassembly and replacement of an entire module, which can be prohibitively expensive. AC-native architectures introduce an additional layer of protection and flexibility.[9] Building on the same diagnostic capability that reveals early impedance irregularities, local switching can isolate a problematic unit before its behavior affects neighboring cells. In cases where electrical instabilities emerge, coordinated switching can stabilize emerging oscillatory conditions. Battery safety thus shifts from a boundary enforced solely by external circuitry to an active property of the pack itself.

Taken together, the functioning mechanisms summarized in **Table 1** illustrate that AC-native architectures do not derive their capabilities from new electrochemical phenomena, but from an expanded actuation–sensing design space at the pack level. Specifically, embedded switching provides actuation authority, controlled excitation improves observability, and modular topology enables resilience and active fault isolation. These mechanisms are tightly coupled: improved observability informs routing decisions, which in turn influence degradation and reliability outcomes.

System-level implications for electric vehicle and stationary energy storage

AC-native architectures have system-level implications arising from how power conversion, sensing, and protection functions are distributed within the battery system. The relevance of these implications differs between EVs and stationary energy storage systems, where operating constraints, reliability requirements, and cost structures are distinct. In both cases, potential benefits must be weighed against increased internal complexity and qualification requirements.

For EVs, AC-native architectures can relax charging-time constraints caused by early voltage limits in individual cells by enabling controlled current redistribution, depending on cell heterogeneity and control strategy. By moving part of the power-conversion function into the pack, they may simplify external conversion stages in some designs, although at the cost of added internal switching losses and hardware complexity. Improved use of heterogeneous cells may also increase accessible capacity, but vehicle-level range gains depend on duty cycle, control policy, and system losses. Active local fault isolation can support degraded-operation modes and help avoid full-pack shutdown under defined faults. Current-routing control also offers additional freedom for managing thermal gradients and usage distribution, although safety and lifetime benefits depend on integration with thermal management, protection systems, ageing mechanisms, and control implementation.

In stationary energy storage, internal AC synthesis can shift part of the power-conversion function into the battery pack, reducing reliance on external power conversion system (PCS) hardware while increasing internal component count and qualification requirements. Although the same architectural mechanisms apply, their relevance differs in stationary settings, where availability, serviceability, and redundancy often outweigh peak efficiency. Module-level conversion can reduce single points of failure in centralized PCS designs and support continued operation under defined faults, depending on topology and control. Under long-duration, partial-state of charge (SOC) duty cycles, these traits may affect degradation, maintenance, and redundancy management, although lifecycle economics remain application- and deployment-dependent.

Integration with power grids and emerging grid-forming requirement

As grid-forming functions become increasingly important for distributed energy resources, battery architectures that support voltage-frequency interaction beyond centralized conversion stages are gaining interest. By enabling internal AC waveform synthesis, AC-native architectures could contribute to voltage-frequency interaction at the pack level, complementing rather than replacing conventional inverter-based grid interfaces.[6] Local actuation enables waveform generation and modulation at finer spatial scales, but response bandwidth remains limited by switching losses, thermal constraints, electromagnetic compatibility, and grid-code requirements. Controlled internal excitation can reveal impedance-related information to inform grid-interaction strategies, although robust integration of such information into real-time stability control remains an open research question.

These features expand the design space for batteries as grid-support assets. In stationary storage, they may enable alternative partitions between battery hardware and external power-conversion systems, particularly for microgrid or community-scale installations.[11] For EVs, similar architecture traits suggest pathways for controlled islanding or limited building support during V2G and V2H operation, subject to safety, certification, and grid-integration constraints. In remote or weak-grid settings, active fault isolation and distributed actuation may affect maintenance strategies and availability, although their cost impact remains context-dependent. As distribution networks evolve, a key question is how grid-interaction functions should be divided and coordinated between battery systems and external power-conversion hardware.

Industrial trajectories and barriers to adoption

Exploratory deployment of AC-native architectures may first be considered where certification hurdles are more manageable and integration can be evaluated without full high-voltage qualification. Low-voltage 12 or 48 V auxiliary systems offer such contexts, avoiding much of the burden associated with high-voltage safety requirements.[12] Stationary energy storage systems that rely on external power-conversion hardware also offer a testbed for alternative partitions between battery hardware and PCS functionality, especially where availability and redundancy are priorities. Heavy-duty vehicles and microgrid-connected storage may provide further evaluation opportunities once component maturity, reliability, and qualification pathways are clearer.

From an industrial perspective, AC-native architectures redistribute cost, reliability, and system responsibility rather than offering inherent economic advantages. For OEMs, internalized power electronics may affect wiring complexity, fault handling, and warranty exposure, with net value depending on reliability and service strategies. Cell manufacturers may benefit if reduced binning requirements outweigh added integration demands. In stationary storage, alternative partitions between battery systems and PCS hardware may improve availability and redundancy but not necessarily reduce cost. Overall adoption depends on system-level cost trade-offs, packaging maturity, qualification standards, and long-term reliability validation, which remain barriers rather than guaranteed enablers.

Real adoption of AC battery systems will be governed mainly by economics and reliability. The cost of additional SiC and GaN devices must be assessed together with potential savings from reduced or simplified external power-conversion hardware, passive components, wiring, cooling, and protection elements. The durability of embedded power electronics is equally critical, since switches must withstand vibration, moisture, thermal cycling, and high-current transients inside the pack. Packaging fatigue, solder-joint degradation, and gate-driver reliability therefore remain major engineering barriers. Safety and certification requirements, including ISO 26262 and grid-interactive compliance, will also shape early deployment. For OEMs, improved warranty outcomes are a key incentive; for stationary storage, reductions in PCS cost and levelized cost of energy are central. Adoption will begin where system-level cost trade-offs, reliability validation, and qualification frameworks align.

Beyond economics and certification, scalability introduces important architectural trade-offs. As electrically controllable units increase, so do switching elements and coordination layers. However, control and communication complexity need not scale linearly with cell count. Practical designs can use hierarchical coordination, with local controllers operating at module or cluster levels and exchanging aggregated state information rather than continuous cell-level signals. This structure limits communication bandwidth growth and distributes computation across local controllers, avoiding centralized bottlenecks.

Switching granularity introduces another trade-off. Finer electrical segmentation improves state observability, topology-aware energy routing, stress steering, and active fault isolation, but beyond a point it offers diminishing gains relative to added hardware, thermal-management demands, and synchronization overhead. A key feature of AC-native systems is that segmentation granularity can be tuned to application scale rather than maximized indiscriminately. Scalability therefore becomes a design variable, not an inherent limitation, supporting balanced deployment from small modules to vehicle-scale packs and large stationary storage systems.

Outlook

AC-native architectures offer an alternative way to organize how batteries interface with electrical energy systems. Their development will depend on how industry evaluates trade-offs among distributed actuation, internal switching, and pack-level coordination. Whether boundaries between battery systems and power-conversion hardware become more fluid will depend on semiconductor cost, packaging maturity, qualification standards, and long-term reliability. Capabilities such as embedded observability, topology-aware and actuation-centric energy routing, stress steering and fault isolation create new design options, but also add components, control complexity, and certification challenges. Whether such AC-native battery systems architectures deliver practical advantages remains application-dependent, shaped by control strategy, hardware maturity, and economic trade-offs. These factors define a broad design space for future research rather than a predetermined path for battery system architecture evolution.

RESOURCE AVAILABILITY

No original data and code have been used in this study.

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AUTHOR CONTRIBUTIONS

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DECLARATION OF INTERESTS

The authors declare no competing interests.

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