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Fast-Response Frequency Regulation and Power Quality Without a Separate Power Bank

Frequency regulation and power-quality services demand storage that can reverse direction in a fraction of a second, hold high round-trip efficiency under constant shallow cycling, and survive years of that duty without the calendar fade that erodes revenue. The Hydrogen-Aluminum Energy Cell, disclosed in U.S. Provisional Application No. 64/055,649, describes a separator-free, bulk-equipotential architecture whose surface-bonded storage chemistry and internally conductive gel are structured for exactly this fast, high-rate, cycle-heavy service.

What This Application Specifies

Frequency regulation and power quality are among the most demanding jobs a storage asset can take on. The grid must hold its frequency inside a narrow band around its nominal value, and any instantaneous mismatch between generation and load pushes frequency away from that band. Ancillary-service markets pay storage to absorb and inject real power in near-real time, following an automated dispatch signal that can reverse polarity every few seconds. Power-quality service adds a second layer: smoothing voltage sags, damping flicker, and buffering the rapid ramps that inverter-based renewables inject into distribution feeders. This is not a bulk-energy duty. It is a fast, shallow, relentless cycling duty measured in charge reversals per minute.

The Hydrogen-Aluminum Energy Cell, disclosed in U.S. Provisional Application No. 64/055,649, is a sealed electrochemical cell with no internal separator. A continuous, dual-domain proton-conducting carbon gel fills the enclosure between two carbon current collectors, and a population of metal nanoflakes, aluminum in the preferred embodiment, is dispersed throughout that gel. Energy is stored as electron-stabilized metal-hydrogen surface bonds on the nanoflakes rather than by intercalation into a host lattice. Because the gel is simultaneously electronically and ionically conductive, the disclosure describes charge retention through bulk-equipotential saturation: with no external circuit closed, every flake sits at the same electrochemical potential and there is no internal driving force for the cell to discharge.

For this domain, three disclosed operating modes matter most. The specification describes a high-rate discharge mode supporting sustained currents in the range of approximately 10C to 100C for durations of approximately 1 to 60 seconds, a standard charge-discharge mode at bias in the range of approximately 1.8 to 2.5 volts and rates from roughly C/10 to 5C, and a distinct peak power mode for transient current draw substantially exceeding the nominal rating. Each of these is recited as an embodiment of the same physical cell.

Why It Matters

The economics of frequency regulation reward speed and durability, not raw stored energy. A resource that responds faster to a dispatch signal provides more useful regulation per megawatt of nameplate, which is why grid operators have moved toward performance-based accreditation that pays a premium for accuracy and responsiveness. But the same duty that earns that premium is corrosive to conventional cells. Continuous shallow cycling accumulates the intercalation-induced lattice strain and interfacial degradation the specification identifies as the use-driven failure modes of established chemistries, and those cells also lose capacity at rest through calendar fade whether or not they are dispatched.

The disclosure's architecture attacks both problems at the level of the storage mechanism. Because charge is held as surface-bonded hydrogen and reversed by proton-coupled electron transfer at the flake surface, the specification describes storage without the diffusion-limited intercalation kinetics that slow conventional cells at high rate. Because the gel carries no separator, there is no separator impedance to overcome and, per the disclosure, charge can be drawn from any region of the cell rather than from a localized electrode front. And because the cell is described as internally at rest in its equipotential condition, the disclosure projects calendar self-discharge rates well below one percent per year, with actual values to be determined empirically. For a regulation asset that spends its life following a signal around a mid-band state of charge, a mechanism whose cycle life is not eroded by that duty, and whose idle periods do not bleed away revenue, is directly aligned with how the service is paid.

How It Composes With the Domain

A frequency-regulation installation built on this cell would sit behind a bidirectional grid-tie inverter that follows the operator's regulation signal, exactly as a conventional battery does. The cell replaces the conventional pack, and its disclosed properties map onto the service in a few concrete ways.

Fast reversal. The regulation signal alternates between charge and discharge commands with little warning. The bulk-equipotential principle described in the specification means the cell holds charge by saturation rather than by insulation, and the equipotential condition is broken only by closure of the external circuit. In the limiting case of an open circuit the cell does not discharge at all, and it discharges only as fast as the load admits. That framing suits a duty in which the inverter, not the cell, sets the moment-to-moment power flow.

High instantaneous power. Fast frequency response and power-quality smoothing call for brief bursts well above the sustained rating. The disclosed high-rate mode covers 10C to 100C bursts of roughly 1 to 60 seconds, and the separately disclosed peak power mode extends this further through controlled, localized failure of the boron-doped carbon framework at strained sites, releasing bonding electrons into the gel's conduction band. The specification describes peak current limits of approximately 50 to 100 times the nominal sustained rating and peak-event capacity of roughly 5 to 15 percent of nominal storage capacity per event, for durations of approximately 0.1 to 60 seconds, with the damaged framework healed during subsequent recovery operation by carbon migrating from the auxiliary reservoir. In the disclosure's own terms this means a voltage sag or a synthetic-inertia response can be served from the same physical cell without over-sizing the pack or bolting on a separate supercapacitor bank.

State-of-charge tracking. Accurate regulation requires the controller to know the cell's state of charge in real time so it can keep headroom in both directions. The specification describes a smooth, gradually declining discharge voltage profile arising from a distribution of hydrogen-binding energies across a structurally non-uniform flake population, and states that this smooth profile admits state-of-charge estimation directly from open-circuit voltage with high accuracy across the capacity range. For a mid-band regulation duty, that maps cleanly onto the controller's need to hold a target set point.

Round-trip efficiency. Ancillary-service revenue is netted against the energy lost each cycle. The disclosure projects round-trip efficiency in the range of approximately 80 to 90 percent for normal-rate operation, with peak-power events carrying a lower projected range of approximately 60 to 80 percent because of the failure-and-heal step. A well-designed controller would reserve the peak mode for the rare deep transient and serve routine regulation in the higher-efficiency band.

What This Enables

Composed into a grid-tied system, the disclosed cell points toward regulation and power-quality assets that are sized for power and duration rather than over-sized to survive their own duty cycle. Because the specification describes peak capability drawn from the same cell rather than from a separate high-power device, a plant could consolidate what is often a two-device architecture, an energy battery plus a power-dense buffer, into a single storage medium. That consolidation reduces the balance-of-plant complexity that power-quality installations otherwise carry.

The disclosed cycling behavior is the other lever. The specification describes a mechanochemical healing process in which mobile carbon migrates to strained sites during cycling, projected to compensate for cycling-induced strain and to admit a stabilized cycle-life regime rather than monotonic capacity loss, until the auxiliary carbon reservoir approaches exhaustion. If borne out empirically, that behavior suits an asset whose value depends on staying in service through millions of shallow charge reversals a year. Combined with the projected low self-discharge at rest, it describes a resource that neither wears out from being used nor decays from sitting idle between market intervals, which is the exact combination a fast-response ancillary-service operator is trying to buy.

Boundary Conditions

Several honest limits apply. The provisional discloses an architecture and its operating mechanisms; nothing in it has been built, benchmarked, or field-validated, and the numerical ranges above are disclosed or projected values, not measured results. The specification repeatedly flags that calendar life, cycle life, self-discharge, and the stabilized-cycling regime are to be determined empirically through prototype and long-duration testing.

The peak power mode carries specific caveats. It operates through controlled framework failure and requires a recovery period of approximately 30 seconds to 60 minutes per event, during which the cell continues at its sustained rating while healing proceeds. Its efficiency is lower than normal-rate operation, and the disclosure describes external control circuitry that enforces maximum peak current, event duration, minimum recovery interval, and cumulative event count. A frequency-regulation controller would have to schedule around those limits rather than treat peak power as always available. More broadly, market participation depends on the accreditation rules, telemetry requirements, and interconnection standards of the relevant grid operator, none of which the cell itself changes.

Disclosure Scope

The technology described here is disclosed in U.S. Provisional Application No. 64/055,649, "Bulk-Equipotential Electrochemical Energy Storage Cell with Hydrogen-Activated Metal Nanoflakes in a Dual-Domain Proton-Conducting Carbon Gel." All statements about what the cell does, including its bulk-equipotential charge retention, surface-bonded hydrogen storage chemistry, high-rate and peak power operating modes, smooth voltage profile, and projected efficiency and life figures, trace to that provisional disclosure and are presented as disclosed or projected, not as built or validated results. The novelty resides in the combination, architecture, and resulting new category of cell; the underlying materials science of metal-hydrogen surface bonding, proton-conducting carbon gels, and fractal nanoflake morphology is pre-existing and is not claimed as newly discovered basic science. The frequency-regulation, power-quality, and ancillary-service framing, including any references to market structures, dispatch signals, accreditation, and interconnection practice, is external domain and regulatory context provided to show an enabling application; it is not part of the disclosure and should not be read as a representation about any particular grid operator's rules or about commercially available products.

Hydrogen-Aluminum Energy Cell (/h-al-battery) All 40 steps → (/inventive-steps)

Sealed electrochemical cell storing energy as reversible covalent hydrogen bonds on carbon electrodes.

Provisional application

PRIMARY TECHNICAL DISCLOSURE

- A Hydrogen-Aluminum Surface-Bond Storage Cell with Bulk-Equipotential Charge Retention (/articles/a-hydrogen-aluminum-surface-bond-storage-cell-with-bulk-equipotential-charge-retention)

SECONDARY TECHNICAL

- Charge Retention by Bulk-Equipotential Saturation Without an Internal Separator (/articles/h-al-battery/bulk-equipotential-charge-retention)
- Storing Energy as Electron-Stabilized Metal-Hydrogen Surface Bonds Formed by Proton-Coupled Electron Transfer (/articles/h-al-battery/hydrogen-metal-surface-bond-storage)
- Electron-Mediated Bond Stability: The Kinetically Trapped Idle State Behind Indefinite Calendar Life (/articles/h-al-battery/electron-mediated-bond-stability)
- Hot-Proton Charging Versus Cold-Proton Discharge: The Bias-Gated Asymmetry That Blocks Self-Charge and Self-Discharge (/articles/h-al-battery/hot-cold-proton-asymmetry)
- Asymmetric Dual-Domain Proton Paths: Separate Ingress and Egress Routes in a Hydrogen-Aluminum Storage Gel (/articles/h-al-battery/asymmetric-dual-domain-paths)
- Hydrophobic Gating: Rejecting Neutral and Molecular Hydrogen While Admitting Only Biased Protons (/articles/h-al-battery/hydrophobic-gating)
- The Storage Gel as a Polarized Electrochemical Switch: Coherent Alignment, Equipotential Locking, and Load-Proportional Discharge (/articles/h-al-battery/gel-polarized-switch)
- Flake-Flake Electrostatic Isolation: DLVO Repulsion as a Self-Discharge Barrier in a Separator-Free Hydrogen-Aluminum Cell (/articles/h-al-battery/flake-electrostatic-isolation)
- Dynamic Flake Expansion: Carbon-Intercalation Wedging to Expose Buried Metal Surface Under Bias (/articles/h-al-battery/dynamic-flake-expansion)
- Hydrogen-Locked Expanded State: Surface-Energy Inversion as a Positive-Feedback Capacity Mechanism (/articles/h-al-battery/hydrogen-locked-expanded-state)
- Secondary Carbon-Hydrogen Storage on Transmuted Intercalated Carbon (/articles/h-al-battery/secondary-carbon-hydrogen-storage)
- Mechanochemical Strain Self-Healing and Use-Positive Aging in a Bulk-Equipotential Hydrogen-Aluminum Cell (/articles/h-al-battery/mechanochemical-self-healing)
- Boron Doping of the Carbon Framework as a Multi-Function Precision Multiplier (/articles/h-al-battery/boron-doping-precision-multiplier)
- The Floating Aluminum Equipotential Extension Layer: A Multifunctional Inner Case for the Bulk-Equipotential Cell (/articles/h-al-battery/aluminum-equipotential-extension-layer)

APPLICATIONS · GENERAL

- Grid-Scale and Renewable-Firming Storage with the Hydrogen-Aluminum Energy Cell (/articles/h-al-battery/grid-scale-storage)
- Building-Integrated and Behind-the-Meter Storage: Putting Energy Cells Inside the Structure With the Hydrogen-Aluminum Energy Cell (/articles/h-al-battery/building-integrated-storage)
- Stationary Backup and UPS Reserve Power for Data Centers, Hospitals, and Telecom (/articles/h-al-battery/backup-and-ups)
- Storage for Microgrids, Islands, and Off-Grid Sites: A Stationary Cell Built From Abundant Materials (/articles/h-al-battery/microgrid-and-off-grid)
- Electric Mobility and Transport: How a Hydrogen-Aluminum Cell Architecture Maps to Vehicle Constraints, and Where It Does Not (/articles/h-al-battery/ev-and-mobility)
- Marine and Rail Energy Storage: A Bulk-Equipotential Hydrogen-Aluminum Cell for Mass-Tolerant Heavy Transport (/articles/h-al-battery/marine-and-rail)
- Supply-Chain-Resilient Field Power: An Abundant-Material Energy Cell for Defense and Expeditionary Operations (/articles/h-al-battery/defense-and-field-power)
- **Fast-Response Frequency Regulation and Power Quality Without a Separate Power Bank (/articles/h-al-battery/frequency-regulation-power-quality)**

APPLICATIONS · SPECIFIC

- CATL (Contemporary Amperex Technology Co. Limited) alternative: a hydrogen-aluminum cell architecture vs LFP, NMC, and sodium-ion at the chemistry-category and materials-sourcing level (/articles/h-al-battery/catl)
- LG Energy Solution NCM/NCMA lithium-ion cells vs the Hydrogen-Aluminum Energy Cell: an architectural comparison (/articles/h-al-battery/lg-energy-solution)
- Form Energy iron-air multi-day grid storage vs a sealed bulk-equipotential hydrogen-aluminum cell: an architectural comparison (/articles/h-al-battery/form-energy)
- ESS Inc, maker of long-duration iron flow batteries vs a sealed solid-state cell: comparing the flow architecture to the Hydrogen-Aluminum Energy Cell (/articles/h-al-battery/ess-inc)
- Ambri liquid-metal battery vs a solid-state hydrogen-aluminum energy cell: architectural comparison for stationary storage (/articles/h-al-battery/ambri)
- QuantumScape solid-state lithium-metal battery vs a bulk-equipotential hydrogen-aluminum surface-bond cell: an architecture comparison (/articles/h-al-battery/quantumscape)
- Natron Energy sodium-ion (Prussian-blue-electrode) batteries vs a hydrogen-aluminum surface-bond cell: an abundant-materials architecture comparison (/articles/h-al-battery/natron-energy)
- Eos Energy Enterprises Znyth zinc long-duration storage vs a hydrogen-aluminum equipotential cell: an abundant-materials architecture comparison (/articles/h-al-battery/eos-energy)

- EnerVenue nickel-hydrogen stationary cells vs a hydrogen-aluminum equipotential cell: two ways to store hydrogen in a battery (/articles/h-al-battery/enervenue)
- Skeleton Technologies supercapacitors vs the Hydrogen-Aluminum Energy Cell: pairing high power with bulk energy storage (/articles/h-al-battery/skeleton-technologies)

Hydrogen-Aluminum Energy Cell overview → (/h-al-battery)