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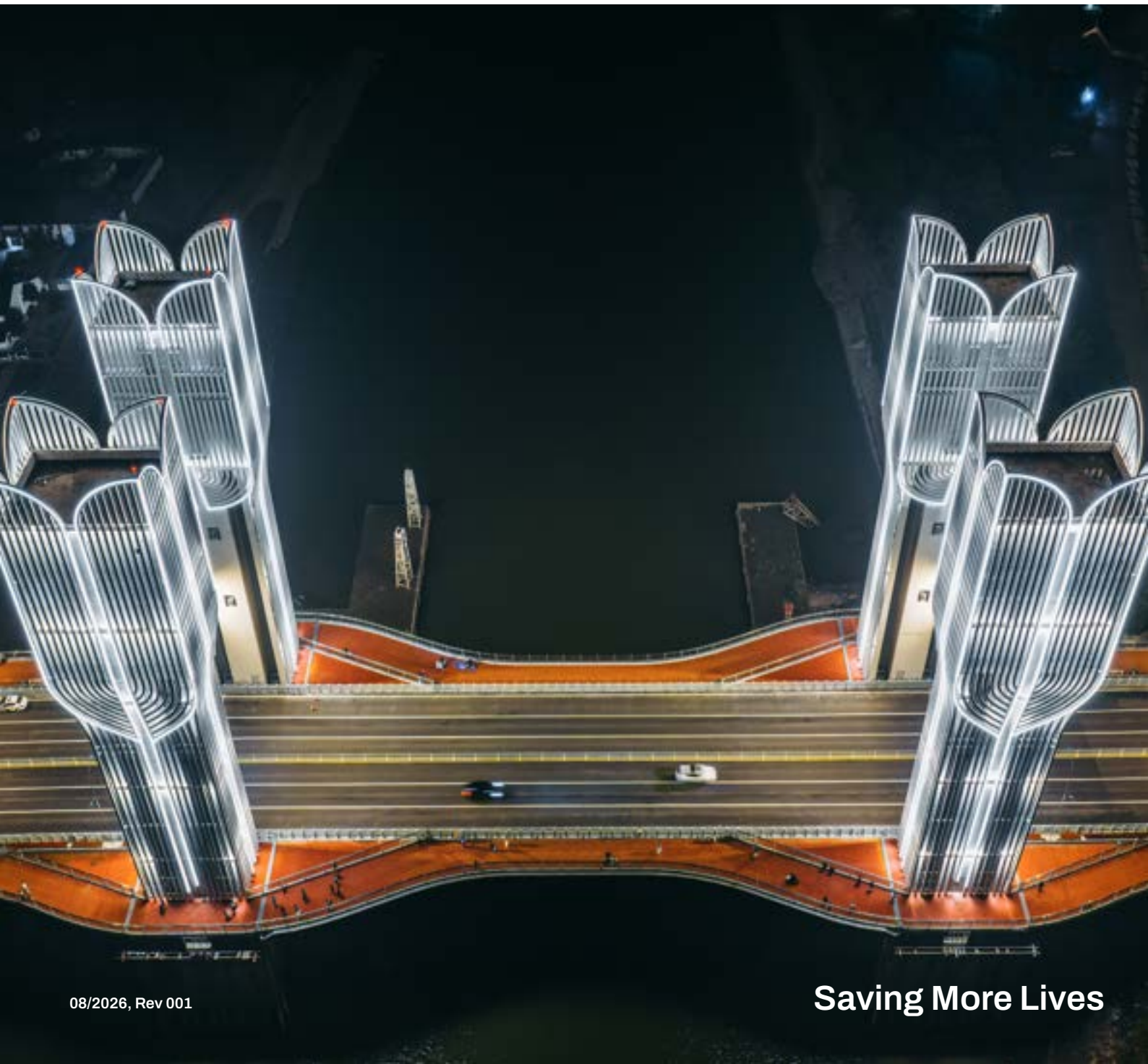
WHITE PAPER: PYRO SAFETY SWITCH

Enhancing Electrical Safety in Battery Energy Storage Systems (BESS)



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Saving More Lives

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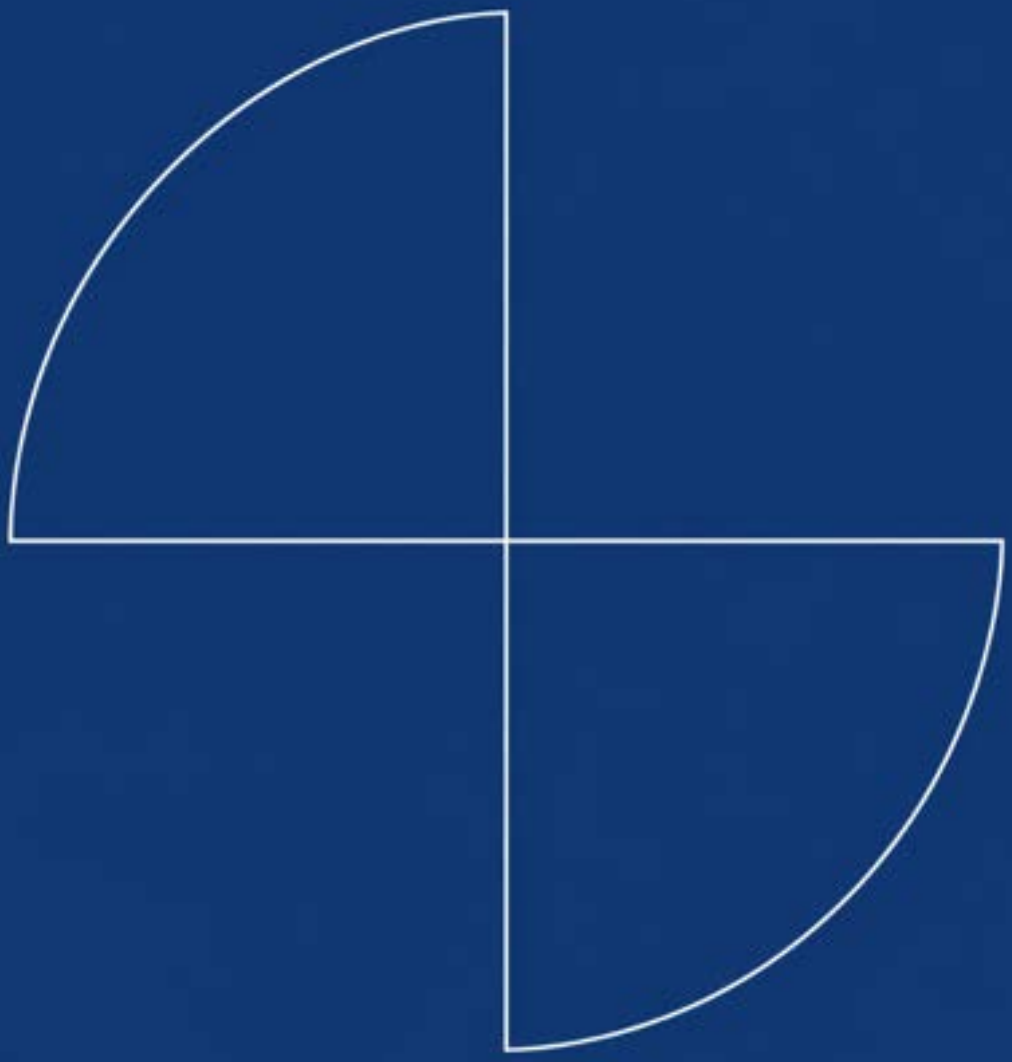
Deterministic Isolation as a System Level Safety Capability

Battery Energy Storage Systems (BESS) are rapidly increasing in voltage level, energy capacity, and architectural complexity. As a result, they are no longer peripheral assets but integral parts of critical power infrastructure. This transformation fundamentally changes electrical fault behaviour and exposes limitations in conventional Direct Current (DC) protection concepts.

This white paper outlines why established protection methods reach their limits in modern BESS architectures and introduces deterministic isolation as a system level safety capability. By enabling predictable behaviour under worst case electrical conditions, deterministic isolation supports safe scaling, architectural replication, and regulatory confidence in high energy DC systems.



Executive Summary

Battery Energy Storage Systems are evolving from stand alone storage solutions into critical infrastructure components embedded in modern power systems. As systems scale in energy, voltage, and architectural replication, the consequences of electrical failures increase significantly. Events that were once localized can now escalate rapidly across racks, containers, or entire sites, with direct implications for personnel safety, asset integrity, availability, and liability.

This shift challenges long standing assumptions about DC electrical protection. Conventional devices such as fuses, circuit breakers, and contactors remain essential for operational control and fault interruption. However, under high energy DC fault conditions, their performance becomes increasingly dependent on fault development, timing, and arc behaviour. At elevated voltage and energy levels, milliseconds can determine the severity of damage and risk. In such scenarios, uncertainty in isolation behaviour becomes a safety concern.

This paper examines how BESS architecture and system scaling redefine electrical safety requirements. It explains why safety exposure is driven primarily by topology and replication rather than individual project size, and why emergency conditions must be addressed as a distinct safety domain, separate from normal operation.

Deterministic isolation is introduced as a complementary safety function, delivering a defined and predictable isolation outcome independent of fault evolution. Rather than replacing existing protection layers, it addresses scenarios where certainty and timing are critical to preventing escalation. Enabled by technologies such as pyrotechnic safety disconnects, it is emerging as a necessary layer for ensuring predictable safety performance in modern BESS systems.

BESS Evolution

From Storage Asset to Critical Infrastructure

BESS are no longer deployed as isolated or auxiliary systems. Over the past decade, their role has shifted toward supporting grid stability, power generation, and transmission resilience. As a result, their performance and safety are increasingly evaluated with the same expectations applied to other forms of critical infrastructure.

System scaling occurs along three dimensions simultaneously: stored energy, operating voltage, and architectural replication. Modern installations store significantly more energy, operate at higher DC voltages, and rely on modular, highly parallel system architectures. Individual components are no longer evaluated in isolation; instead, fleets of interconnected battery stacks operate as a single electrical system.

This evolution fundamentally changes the risk landscape. Electrical faults can propagate across shared DC structures and parallel energy sources within milliseconds. The resulting consequences extend beyond component damage to include personnel safety, system availability, regulatory exposure, and reputational risk. Electrical safety therefore becomes an architectural property that must be defined early and applied consistently across deployments.

Understanding BESS Architectures and Fault Behaviour

Modern BESS architectures differ fundamentally from traditional point to point electrical systems. Typical installations consist of multiple battery stacks connected in parallel through shared DC buses, cables, and busbars. Each stack represents an independent energy source capable of contributing power under both normal and abnormal conditions.

This distributed architecture supports scalability and redundancy, but it also defines fault behaviour. During an abnormal event, multiple energy sources can simultaneously feed the same fault through shared electrical paths. Fault current is therefore not limited to a single source, and escalation can occur rapidly.

At higher DC voltages, system inductance, arc energy, and transient overvoltages become dominant factors. Fault severity is often determined in the earliest phase of the event, before conventional protection devices fully operate. As a result, electrical safety must be assessed at the system level, based on worst case behaviour, rather than on individual component ratings alone.

Why Safety Exposure Scales with Architecture, Not Projects

In modern BESS platforms, safety exposure is primarily determined by architectural decisions. Voltage levels, DC bus structures, and protection philosophies are standardized and replicated across installations. Any limitation embedded in the architecture is therefore multiplied with each deployment.

A safety concept that is marginally acceptable in a single project may become unacceptable when replicated across dozens or hundreds of systems. As BESS increasingly support grid critical functions, tolerance for uncertainty narrows. Electrical safety must therefore be treated as a repeatable, architecture level attribute rather than a project specific adjustment.

Limits of Conventional DC Protection in Modern BESS

Conventional DC protection devices remain essential elements of BESS operation. However, as voltage, energy, and architectural complexity increase, these devices operate closer to their physical and functional limits.

High energy DC faults are characterized by rapid current rise and the absence of natural current zero crossings. Interrupting such faults requires active arc control under sustained electrical stress. Small variations in interruption time can lead to large differences in fault energy and damage.

Under these conditions, conventional protection exhibits inherently non deterministic behaviour. While acceptable for many operational scenarios, this uncertainty becomes a safety concern in severe fault events where predictable outcomes are required to prevent escalation.

For example, in a parallel rack architecture, a fault in one string can be fed simultaneously by multiple adjacent strings through a shared DC bus. In such cases, fault current magnitude and duration depend on dynamic system interactions, making isolation timing difficult to predict with conventional devices.

Emergency Isolation as a Distinct Safety Function

Electrical systems must distinguish clearly between functions intended for normal operation and those required for emergency conditions. In large scale BESS, this distinction is critical.

Operational switching manages predictable events such as load changes and routine faults. Emergency scenarios follow a different logic. Their objective is immediate risk mitigation by rapidly bringing the system to a safe state, independent of operational continuity.

In high energy DC environments, delayed or uncertain isolation can result in rapid escalation. Emergency isolation performance must therefore be defined by behaviour under the most severe conditions, not by nominal operation.

Safety Standards and Regulatory Context

BESS safety is increasingly shaped by standards focusing on fault containment and thermal runaway mitigation.

Key frameworks include:

- **UL 9540 / UL 9540A** – system-level safety and test methods for thermal runaway propagation
- **NFPA 855 –** requirements for fire protection, explosion mitigation, and system-level risk assessment
- **IEC standards** (e.g. IEC 62619, IEC 62933) – battery and system integration safety

Across these, a clear direction is emerging:

Safety is defined by the system's ability to limit escalation and reach a safe state under worst-case conditions.

This shifts requirements toward predictable, fast, and controlled isolation, making deterministic isolation directly relevant for compliance, certification, and insurance acceptance.

In practice, this increasingly requires system designers to demonstrate controlled isolation mechanisms that prevent fault escalation rather than relying solely on passive fault interruption.

Deterministic Isolation: Concept and Principle

Deterministic isolation is a safety function defined by predictable and reproducible behaviour under specified emergency conditions. Once a trigger condition is met, the isolation outcome is known and independent of fault magnitude, current development, or arc behaviour.

By decoupling the isolation action from fault evolution, deterministic isolation eliminates uncertainty in the most critical phase of an electrical event. In replicated BESS platforms, this predictability supports consistent safety performance across installations and throughout the system lifecycle.

The Solution: Fast, Deterministic Safety Disconnects in BESS

Fast deterministic safety disconnects enable deterministic isolation at the system level. They form a dedicated emergency safety layer that complements existing protection and operational switching functions.

Isolation is explicitly commanded based on defined trigger criteria. Once activated, the disconnect operates independently of electrical fault characteristics, ensuring consistent and predictable behaviour. Architecturally, deterministic disconnects establish controlled isolation boundaries that limit fault propagation and support containment at rack, container, or system level.

In practice, achieving this level of deterministic isolation requires a fundamentally different type of device compared to conventional protection. One such implementation is the pyrotechnic safety switch (pyro fuse).

Pyro fuses are actively triggered, one-time mechanical disconnects that physically sever the conductor using a pyrotechnic actuator, creating a permanent and unambiguous isolation.

Key performance characteristics:

- Ultra-fast response: typically <1–2 ms
- High breaking capability: ~10–20 kA at up to 1500 V DC
- Trigger-based operation: independent of current level
- High post-isolation resistance: MΩ-range insulation
- Low on-state resistance: tens of μΩ
- Deterministic action: no risk of partial opening or contact failure

Role in Battery Energy Storage Systems

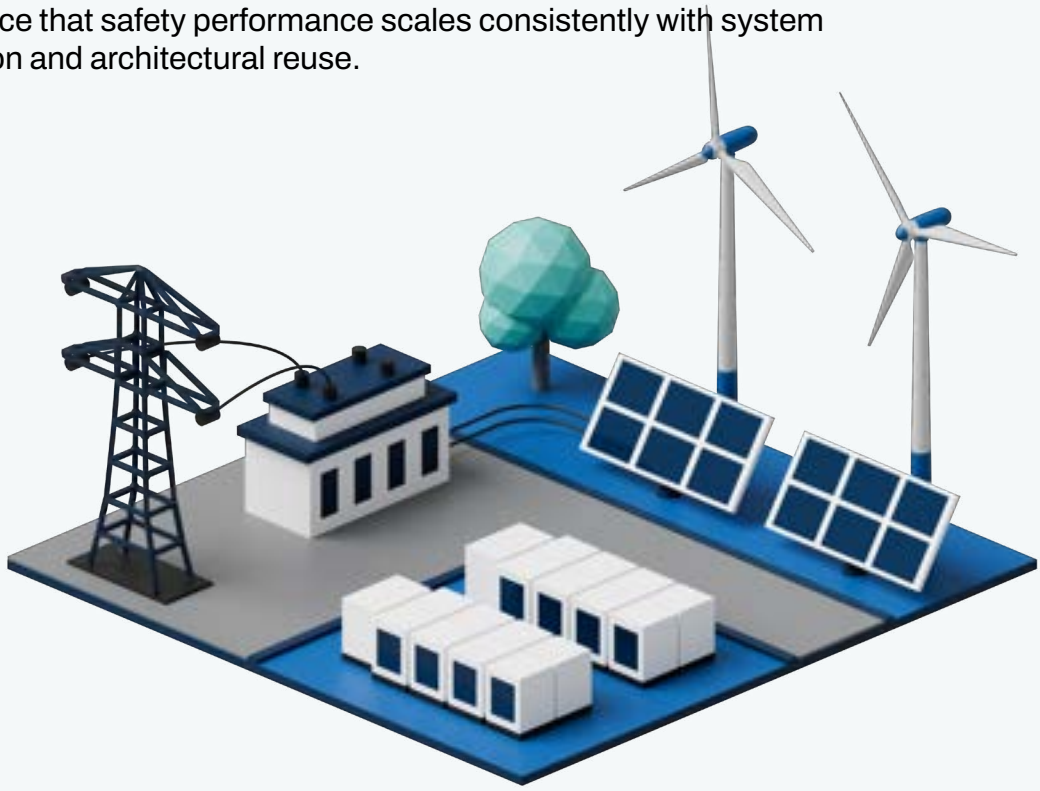
Pyro fuses act as a dedicated emergency safety layer, complementing conventional protection. They are placed at key isolation points (e.g. string, rack, or DC bus level) to ensure immediate, controlled disconnection in critical scenarios, limiting fault propagation and enabling predictable system behaviour.

Unlike conventional fuses or breakers, which depend on fault current and arc interruption dynamics, pyro fuses are trigger-based and independent of fault development. This eliminates variability in isolation timing and ensures a defined outcome across all fault scenarios.

Customer Value: Predictable Safety at Scale

The primary value of deterministic isolation lies in predictable system behaviour under extreme conditions. By reducing uncertainty, it limits fault escalation and supports effective containment of abnormal events.

Predictable behaviour strengthens safety cases for regulators, certifiers, insurers, and authorities. It reduces asset damage, limits downtime, and protects availability in infrastructure scale installations. Ultimately, deterministic isolation enables confidence that safety performance scales consistently with system replication and architectural reuse.



Who Benefits and When It Becomes Relevant

Deterministic isolation becomes relevant when worst case electrical behaviour, rather than nominal operation, determines safety outcomes. It provides value to system OEMs, integrators, and asset owners by enabling consistent, repeatable safety concepts across platforms.

It is particularly relevant in architectures with multiple parallel energy sources, increasing voltage levels, and large stored energy, where fault escalation potential is high and safety performance must be replicated across many installations.

Implications for Future BESS Design and Deployment

Future BESS platforms must treat electrical safety as a foundational architectural attribute, not a late stage verification activity. As systems scale, acceptable safety concepts will increasingly be defined by worst case behaviour and reproducibility rather than by component ratings alone.

Designing deterministic isolation into the architecture from the outset supports scalable, resilient, and future proof energy storage systems.

Conclusion and Key Takeaways

Pyro Safety Switch

The scaling of BESS fundamentally changes electrical fault behaviour and safety requirements. Architecture, topology, and replication now dominate risk exposure.

Deterministic isolation addresses safety gaps that arise when conventional DC protection reaches its limits. Designing for predictable behaviour under severe conditions is becoming a defining requirement for safe, scalable energy storage systems.