NEXT-GENERATION MEDIUM-VOLTAGE ARCHITECTURE FOR AI DATA CENTERS

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EXECUTIVE SUMMARY

Artificial Intelligence (AI) data centers are entering an era of unprecedented power demand, emphasizing the critical need for innovative power solutions to meet the rapid expansion of large language models (LLMs), deep-learning clusters, and generative AI workloads. Facilities exceeding 200 MW are becoming common, underscoring the importance of evolving power architectures to support this growth.

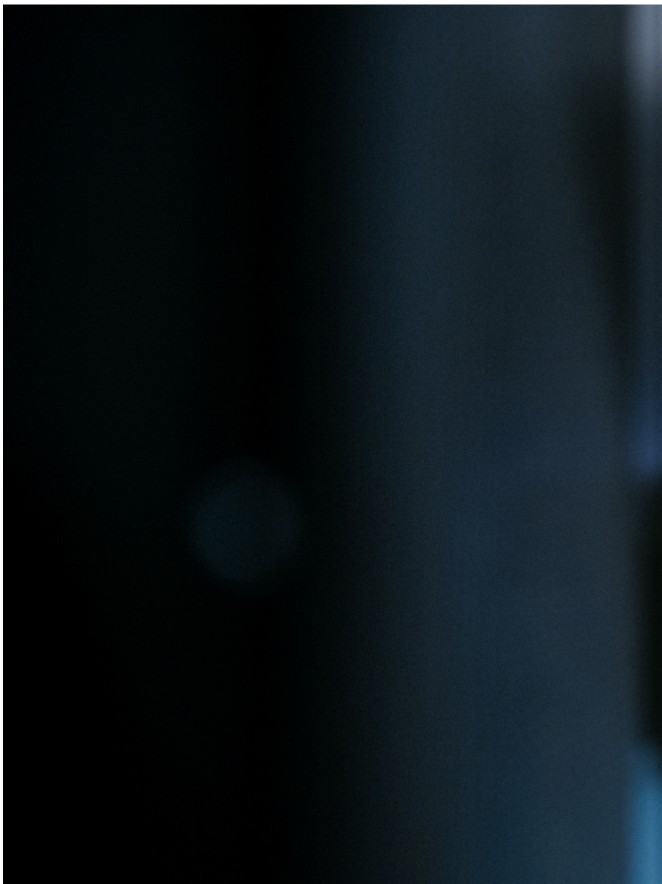
As grid codes continue to advance, they increasingly require stable, fault-tolerant operation with capabilities such as ride-through performance and frequency support. These evolving requirements are driving a fundamental rethinking of data-center power infrastructure and its potential impact on the power grid. Traditional low-voltage (LV) UPS topologies—long the standard for data-center protection—are becoming insufficient. They introduce avoidable conversion losses, limit scalability, and complicate compliance with stringent global grid-integration standards.

A piece of next-generation medium-voltage (MV) architecture—integrating ABB's HiPerGuard MV UPS, eStorage Battery Energy Storage Systems (BESS), intelligent switchgear, and advanced microgrid controls—offers a reliable and forward-looking alternative to conventional designs. This whitepaper outlines the technical rationale for this shift, describes how these components can provide stability and compliance, and explores use-case scenarios that demonstrate their effectiveness in AI data centers.

The combined deployment of MV UPS and BESS enables:

- State-of-the-art high-performance power protection with millisecond-level response
- Extended ride-through and enhanced energy flexibility, including peak shaving and ancillary services
- Full microgrid capability, including grid-forming capability and black-start functionality
- Significant reduction of diesel generator dependency, enabling significant CO_2 reductions
- Compliance with global grid codes, including LVRT, MLVRT, PFAPR, ROCOF, and reactive power mandates
- High scalable architecture, efficiently supporting hundreds of megawatts at >98% system efficiency
- A pathway to 100% renewable integration and 24/7 carbon-free operation

Together, these capabilities establish a future-proof platform that meets both the technical and sustainability demands of AI-driven digital infrastructure.



1. INTRODUCTION: AI DATA CENTERS AND THE NEW POWER PARADIGM

AI workloads are fundamentally reshaping the energy profile of data centers. Training a single frontier-scale model can be similar to those of traditional cloud deployments. Dense clusters of GPUs and tensor processing units (TPUs) generate rapidly fluctuating, non-linear, and unpredictable load patterns that require fast-responding, ultra-stable power architectures.

At the same time, sustainability requirements are intensifying. The Climate Neutral Data Centre Pact sets aggressive targets, including 75% renewable energy by 2025 and carbon neutrality by 2030. Leading hyperscale operators are already committing to 24/7 carbon-free operation and hybrid on-site generation. Power Purchase Agreements (PPAs), while valuable, cannot mitigate renewable intermittency or guarantee availability during disturbances on their own.

As AI data centers scale to 200–500 MW, transitioning to medium-voltage distribution becomes essential for efficiency, scalability, and reliability.

Medium-voltage distribution (typically 6–35 kV) offers clear advantages:

- Reduced copper requirements and lower resistive losses
- Improved scalability for large campuses
- Higher reliability enabled by simplified architecture
- Improved integration with utility-scale renewables and on-site energy storage
- Reduced dependence on extensive LV switchgear and transformer cascades

The transition to MV is not merely an engineering optimization; it is an essential foundation for the next decade of AI-driven digital infrastructure.

2. GLOBAL GRID COMPLIANCE REQUIREMENTS FOR LARGE AI CAMPUSES

The global grid landscape is undergoing rapid transformation in response to rising renewable penetration, increased system volatility, and the emergence of large, highly dynamic electrical loads, and often suffers from a lack of stable power generation. Transmission System Operators (TSOs) now require data centers and industrial loads to operate as grid-supportive assets rather than passive consumers.

01

Key Global Compliance Drivers

Collectively, these capabilities position MV-based architectures as the compliance-ready foundation for next-generation AI data centers.

Across Europe, North America, Asia, and the Middle East, regulatory bodies are implementing stringent technical mandates, including:

- Low Voltage Ride Through (LVRT): remain connected during voltage dips down to 0% for 200–300 ms
- Multiple LVRT (MLVRT): withstand multiple sequential faults (e.g., up to 10 voltage dips within 90 seconds)
- Frequency tolerance: typically, 47.5–52 Hz in Europe; ±2 Hz in Asia
- Rate of Change of Frequency (ROCOF): withstands up to 3 Hz/s in advanced grid systems
- Phase-angle jump tolerance: up to ±30°
- Post-Fault Active Power Recovery (PFAPR): restore at least 90% of active power within 0.5 seconds
- Reactive power capability: dynamic VAR support and power factor ≥ 0.99
- Validated simulation models: PSCAD or PSS/E models required for facilities exceeding 30 MW

These requirements are intended to prevent cascading outages, support rapid system stabilization, and ensure resilience during grid disturbances with fast system recovery.

Traditional LV UPS systems were never meant to provide these kinds of grid interaction or ride-through capabilities. Conversely, MV UPS and BESS systems—especially those designed for bidirectional operation and advanced grid management—are better suited to meet these needs.

An integrated MV UPS and BESS delivers:

- Instantaneous protection of critical loads
- Long-duration grid-support functions, including frequency and voltage
- Stable re-synchronization following disturbances
- Optimized battery control during disturbances or islanded conditions
- Full compliance with LVRT, MVRT, and PFAPR requirements without generator intervention

3. COMPONENTS OF THE MV ARCHITECTURE

ABB has conducted extensive field testing and lab simulations using real AI load profiles to ensure that UPS systems are truly AI-ready. These tests, which validate compliance with international standards and long-term reliability under the stress of dynamic and peak loads, underscore ABB's commitment to delivering a reliable product.

01

HiPerGuard MV UPS

The HiPerGuard MV UPS offers cutting-edge power protection at medium voltage, delivering the performance and stability needed for large-scale AI data centers and for state-of-the-art power protection of critical loads. Key attributes include:

- <2 ms response time during grid power quality events
- Voltage conditioning with tight regulation tolerances
- Operation in both power conditioning and independent modes
- 98%+ system efficiency, minimizing electrical losses
- High overload capability, ensuring resilience against transient events
- Full compliance with global grid codes, enabling ride-through performance without reliance on bypass operation
- Simplified distribution design, thanks to MV-level deployment that reduces downstream switchgear requirements

HiPerGuard offers:

- Lower total cost of ownership
- Smaller footprint
- Minimal mechanical wear
- Superior dynamic response

HiPerGuard’s primary function is to provide continuous power conditioning and instant protection for critical IT loads, serving as the backbone of a resilient, compliance-ready MV energy platform.

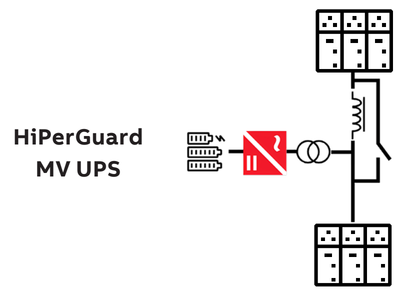


Figure 1
ABB´s HiPerGuard simplified block diagram.

02

Battery-Energy Storage System (BESS)

A BESS complements the UPS by delivering long-duration energy storage and advanced grid-interactive capabilities. It extends system resilience, enables flexible energy management, and supports the full suite of modern grid-stability functions required by a large AI data center. The fundamental application of the BESS in a given environment is to help the facility's ride-through on the power grid during disturbances, as stipulated by some modern grid codes.

Key functions include:

- Peak shaving and load shifting, optimizing grid draw and reducing demand charges
- Fast Frequency Response (FFR) for rapid stabilization during frequency excursions
- Renewable firming and smoothing, mitigating intermittency from on-site or contracted renewables
- Support for microgrid islanding, maintaining stable operation
- Black-start capability, enabling recovery of loads and re-energization sequences
- Virtual inertia and grid-forming capability, enhancing overall system stability
- Bidirectional power flow, enabling participation in ancillary service markets

ABB's eStorage portfolio spans 0.6 MW to 21.6 MW per block, enabling modular deployment and scaling to hundreds of MW through:

- 1-hour, 2-hour, and 4-hour configurations
- Modular feeder architecture for flexible site design
- Active thermal management for improved lifecycle performance
- Advanced EMS-based control to coordinate UPS-BESS operation

While UPS batteries usually provide only minutes of run time, sufficient to bridge the transition to backup generators, BESS delivers hours of energy support, with continuous cycling optimized for long-term operational efficiency.

03

Medium-Voltage Switchgear

MV switchgear forms the structural backbone of the MV architecture, providing protection, routing flexibility, and operational control required for AI data centers. Its core functions enable:

- Segregation of UPS battery strings from BESS, ensuring safe and optimized operation of each subsystem
- Fast isolation during abnormal or fault conditions to protect both IT and the electrical infrastructure
- Flexible routing of power flows, enabling adaptive system configurations as loads evolve
- Controlled islanding and seamless re-synchronization, supporting microgrid and resilience functions
- Safe detachment of sensitive IT loads, maintaining power quality during disturbances
- Support for redundant power paths, including complete 2N configurations, as well as shared-redundant and distributed-redundant architectures

An intelligent automation layer orchestrates real-time command of the switches, UPS modules, and BESS to maintain seamless power quality and enable grid-support capabilities across the entire MV system.

04

On-Site Generators

While backup generators (diesel, gas, or other technologies) remain a component of most large data center designs, their operational role changes significantly within an MV architecture augmented by UPS and BESS. Key shifts include:

- No requirement for immediate startup during grid outages, reducing mechanical stress
- BESS provides continuity of supply until state-of-charge (SoC) reaches defined thresholds.
- Substantially reduced generator run time, improving sustainability metrics.
- Lower fuel consumption, particularly during short interruptions that previously triggered generator operation.

These changes enable meaningful, quantifiable CO_2 reductions, particularly for high-reliability campuses that experience frequent but brief disturbances. Generators transition from primary backup sources to secondary resilience assets, activated only when truly needed.

4. MV ARCHITECTURE CONCEPT FOR AI DATA CENTERS

01

Baseline Power Architecture

A representative MV-based power architecture for an AI data center includes the following elements:

- HV switchgear receiving utility/grid input
- MV switchgear distributing power to redundant UPS branches
- HiPerGuard MV UPS providing continuous power conditioning to the critical distribution network
- UPS-protected MV or LV Power Distribution Boards (PDBs) feeding high-density AI IT racks
- Parallel BESS systems connected to MV buses for long-duration support and grid services
- A microgrid controller orchestrating real-time coordination of all assets
- On-site generators serving as tertiary backup resources

Power flows are dynamically optimized, with the microgrid controller determining dispatch based on real-time grid conditions, battery SoC, load prediction, and energy market pricing signals. This ensures a resilient, efficient, and grid-compliant power ecosystem suitable for large-scale AI workloads.

02

Redundancy Variants (2N, N+1, Distributed Redundant)

Designing and implementing the MV architecture with the large-scale critical facility allows for significant flexibility in design, buildout, and operation. This flexibility is reflected in the ability to accommodate different architectural styles, enabling varying levels of facility resilience.

Due to the ability to separate power protection and large energy storage systems, it is possible to allocate different capacity margins to optimize the TCO for facility owners.

Some of the examples of architectures may include (but are not limited to) the following:

1. Distributed redundant architecture; for example, a four-to-make-three arrangement
2. 2N structure, allowing for the active power protection from both radial power paths, and fulfilling the requirements of fault tolerance
3. N+1 structure, allowing for two-sided power supply and provisioning for the concurrent maintenance

Whilst the mentioned architectures are specific to power protection and the use of UPS technology, BESS is placed one level higher in the architecture, making a close connection to the grid. In that arrangement, the capacity and number of BESS systems can be determined solely based on the properties of energy and power requirements on both the facility and grid sides. They can achieve any time structure deemed required from the standpoint of TCO.

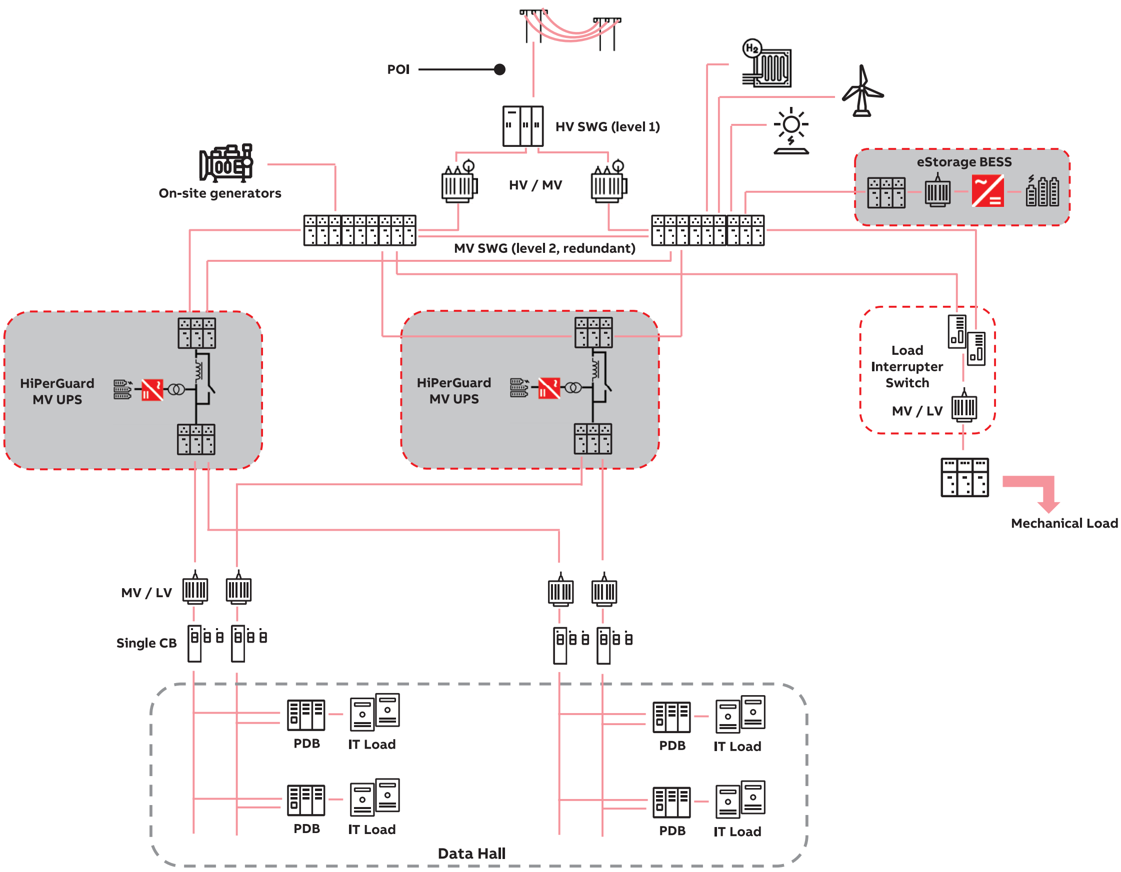


Figure 2
AI Data Center with BESS and MV UPS – 2N Electrical Scheme

Additionally, segregated battery strings allow the UPS and BESS to operate independently during disturbances.

The core architectural innovation is the strict functional separation of the UPS battery dedicated to IT protection, allowing the BESS battery to remain grid-connected when appropriate. This prevents unnecessary cycling of the UPS battery, preserves optimal SoC for protection, and maximizes overall system efficiency while maintaining high uptime for the critical facility and supporting the power grid.

03

Power-Flow Scenarios

Regular Operation (Grid-Tied):

- UPS operates in conditioning mode, ensuring voltage stability and protection.
- BESS runs in grid-following mode, providing services such as peak shaving, FFR, or demand reduction.
- Microgrid controller coordinates real-time dispatch for cost, efficiency, and emissions optimization.

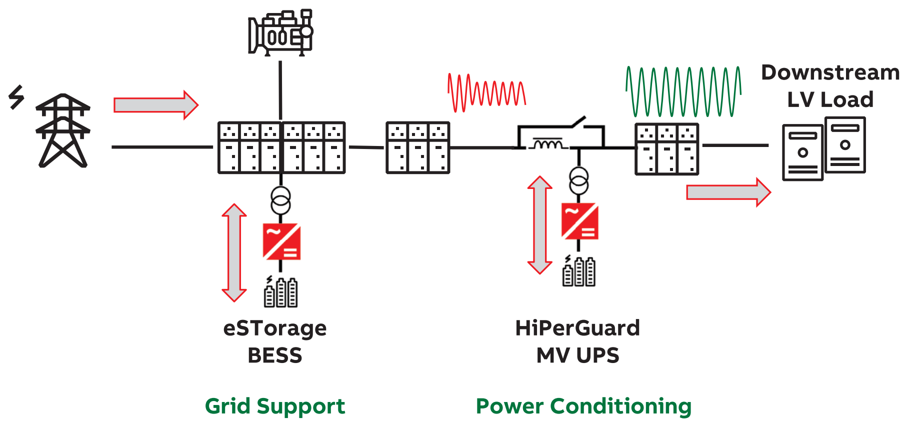


Figure 3
Power flow under regular operation

Grid Disturbance:

- UPS instantly supports critical loads (<2 ms).
- BESS provides fast frequency response over the next several seconds, contributing to grid stabilization.
- Generators are not required to activate, avoiding unnecessary run time and emissions.

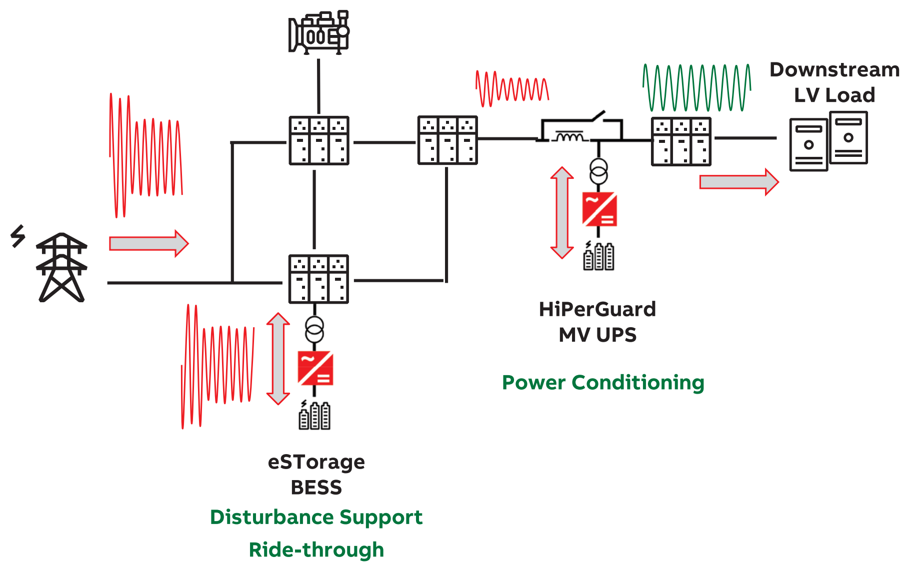


Figure 4
Power flow under grid disturbance

Power-Flow Scenarios (continued)

Island Mode:

- UPS maintains critical load power protection.
- BESS continues supporting the grid, acting either as a controllable load or as a source, depending on the nature of the disturbance profile.
- The generator's start-up is delayed, leveraging the inherent autonomy provided by the MV UPS and BESS combination.

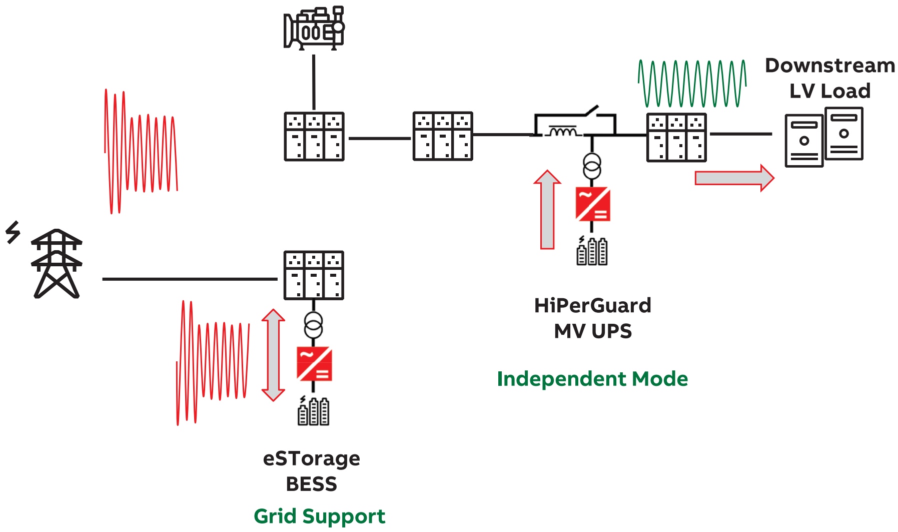


Figure 5
Power flow under islanded mode

Generator Engagement:

- Triggered only when the UPS SoC falls below the predefined threshold or when the BESS remains grid-connected while the rest of the data center infrastructure is decoupled from the grid.
- UPS maintains protection and voltage stability for IT loads.
- UPS stabilizes generator set points and smooths their output, minimizing partial-load inefficiencies.

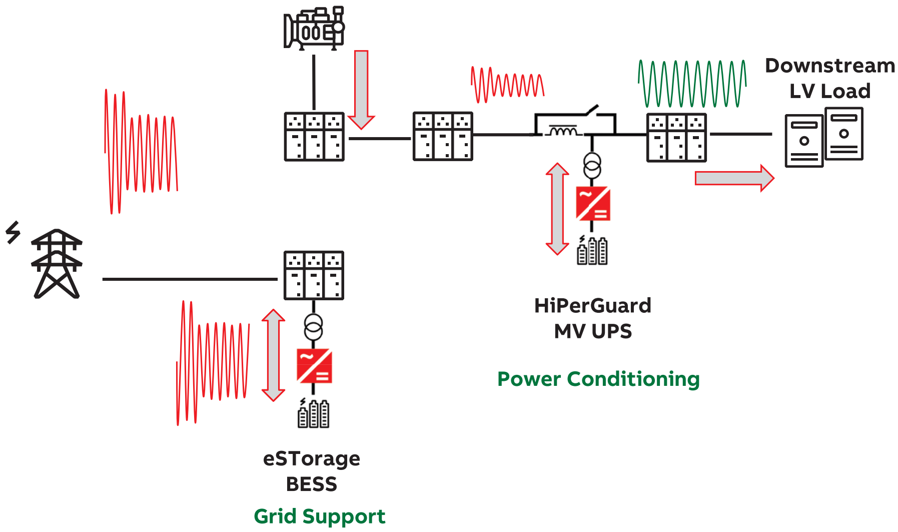


Figure 6
Power flow under islanded mode with generators engaged

Resynchronization:

- The microgrid controller aligns phase, frequency, and voltage automatically.
- Transition back to grid-tied mode occurs seamlessly, without impacting IT loads.
- This coordinated sequence ensures uninterrupted operation even during complex or prolonged grid events.

5. UPS VS BESS: COMPLEMENTARY ROLES

Although both systems leverage battery technology, the UPS and the BESS serve fundamentally different, and highly complementary roles within the MV architecture.

UPS (HiPerGuard):
- Primary purpose: instantaneous protection of critical IT loads
- Typical run time: minutes
- Response time: milliseconds
- Power flow: unidirectional, from source toward IT loads
- Control strategy: simple, protection-focused, with rapid deterministic responses
- Grid interaction: limited, primarily oriented toward load continuity

BESS (eStorage):
- Primary purpose: energy optimization and long-duration support
- Typical run time: hours
- Response time: tenths of milliseconds
- Power flow: fully bidirectional for charging, discharging, and grid services
- Control strategy: EMS-driven with predictive and economic dispatch algorithms
- Grid interaction: full participation, including grid-forming, virtual inertia, and ancillary services

“Together, these two systems form a layered protection and optimization system,” notes Domagoj Talapko, business development manager for ABB.

The UPS ensures uncompromised reliability for IT workloads, while the BESS delivers flexibility, sustainability, and grid-code compliance at scale.

6. MICROGRID CAPABILITIES AND ENERGY OPTIMIZATION

The MV architecture enables a full suite of microgrid operating modes, delivering resilience, efficiency, and economic benefits across a wide range of grid conditions.

Operating Modes

- **Grid-tied mode:**
  Provides peak shaving, time-of-use optimization, FFR, and reactive-power support through coordinated UPS-BESS operation.
- **Island mode:**
  The BESS forms or stabilizes the grid as needed, and the UPS ensures continuous protection of essential IT loads.
- **Black start:**
  The BESS energizes the MV bus, enabling the controlled restart of UPS and generators without a grid supply.
- **Transition modes:**
  Seamless transfers between operating states occur without any IT load interruption, ensuring continuous service availability.

AI-Driven Predictive Control

Advanced EMS and AI-based algorithms support:

- Forecasting of high-density IT load patterns
- Optimized battery cycling strategies
- Predictive SoC management
- Anticipation and mitigation of grid disturbances
- Predictive maintenance scheduling

These capabilities maximize battery lifetime, system efficiency, and economic value, especially in large AI-focused campuses with highly dynamic load profiles.

Monetization and Grid Services

The MV microgrid platform unlocks multiple revenue-generating opportunities:

- Fast Frequency Response (FFR)
- Participation in primary and secondary reserve markets
- Demand-response programs
- Peak demand charge reduction
- Capacity aggregation via virtual power plants (VPPs)
- These capabilities transform the data center from a passive energy consumer into an active grid-support asset, improving return on investment (ROI) while supporting broader grid stability.

7. SUSTAINABILITY AND DECARBONIZATION PATHWAY

The MV architecture directly supports a broad set of sustainability and decarbonization objectives essential for next-generation AI data centers:

- Reduced generator runtime through delayed start events, lowering fuel consumption and emissions
- Simultaneous protection for both the grid and the data center during abnormal conditions, enhancing overall system stability
- Renewable energy firming, enabling higher on-site penetration and improved utilization
- Energy arbitrage and optimized dispatch, reducing the effective carbon intensity of imported grid electricity
- Battery-as-a-Service (BESSaaS) models, enabling large-scale storage deployment with minimal CAPEX
- Full microgrid capability, allowing grid-independent operation with a high renewable-rich generation

Collectively, these capabilities unlock a credible, scalable pathway to 24/7 carbon-free AI computation, aligning resilience with long-term sustainability goals.

"Microgrid-based MV architectures are redefining the future of AI infrastructure by turning energy resilience, renewable integration, and intelligent dispatch into a unified pathway toward truly 24/7 carbon-free operations," explains Carlos Nieto, global product line manager of energy storage for ABB.

8. FUTURE OUTLOOK

AI data centers will continue to redefine the limits of digital infrastructure, driving rapid innovation across power, cooling, and grid-interaction domains. Key trends shaping the coming years include:

- Agnostic and futureproof IT power supplies that eliminate traditional LV conversion and simplify distribution
- Gigawatt-scale campuses organized into distributed energy islands for resilience and scalability
- Gradual adoption of gas-based technologies and hydrogen-ready fuel cells, complementing or replacing conventional generators
- UPS systems with full grid-forming capabilities, providing advanced stability functions
- Greater alignment of global grid standards (IEC, IEEE, ENTSO-E), enabling a more consistent compliance framework
- Transition away from diesel, supported by long-duration storage, alternative fuels, and advanced microgrid controls
- Autonomous microgrids orchestrated by AI-driven control systems, optimizing resilience, cost, and carbon intensity in real time

The architecture outlined in this whitepaper provides the foundational platform for this evolution, enabling AI campuses to scale responsibly while meeting increasingly demanding reliability and sustainability requirements.

CONCLUSION

Next-generation MV architectures that integrate the HiPerGuard MV UPS with ABB's eStorage BESS provide a comprehensive solution to the emerging energy challenges of AI data centers. They provide unparalleled reliability, full regulatory compliance, advanced decarbonization capabilities, and scalability suitable for multi-hundred-megawatt to gigawatt campuses.

By reducing reliance on legacy LV distribution and diesel generation, and by integrating advanced microgrid functionality, these architectures enable:

- Resilient power protection for mission-critical AI workloads
- Power grid support and stabilization
- Sustainable, low-carbon operation aligned with global decarbonization goals
- Operational flexibility and new monetization opportunities through grid services
- Long-term scalability to support the accelerating growth of AI compute

In this era defined by AI-driven digital infrastructure, MV-based power architectures are not simply an improvement; they are an essential foundation for meeting the performance, reliability, and sustainability demands of the decade ahead.

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