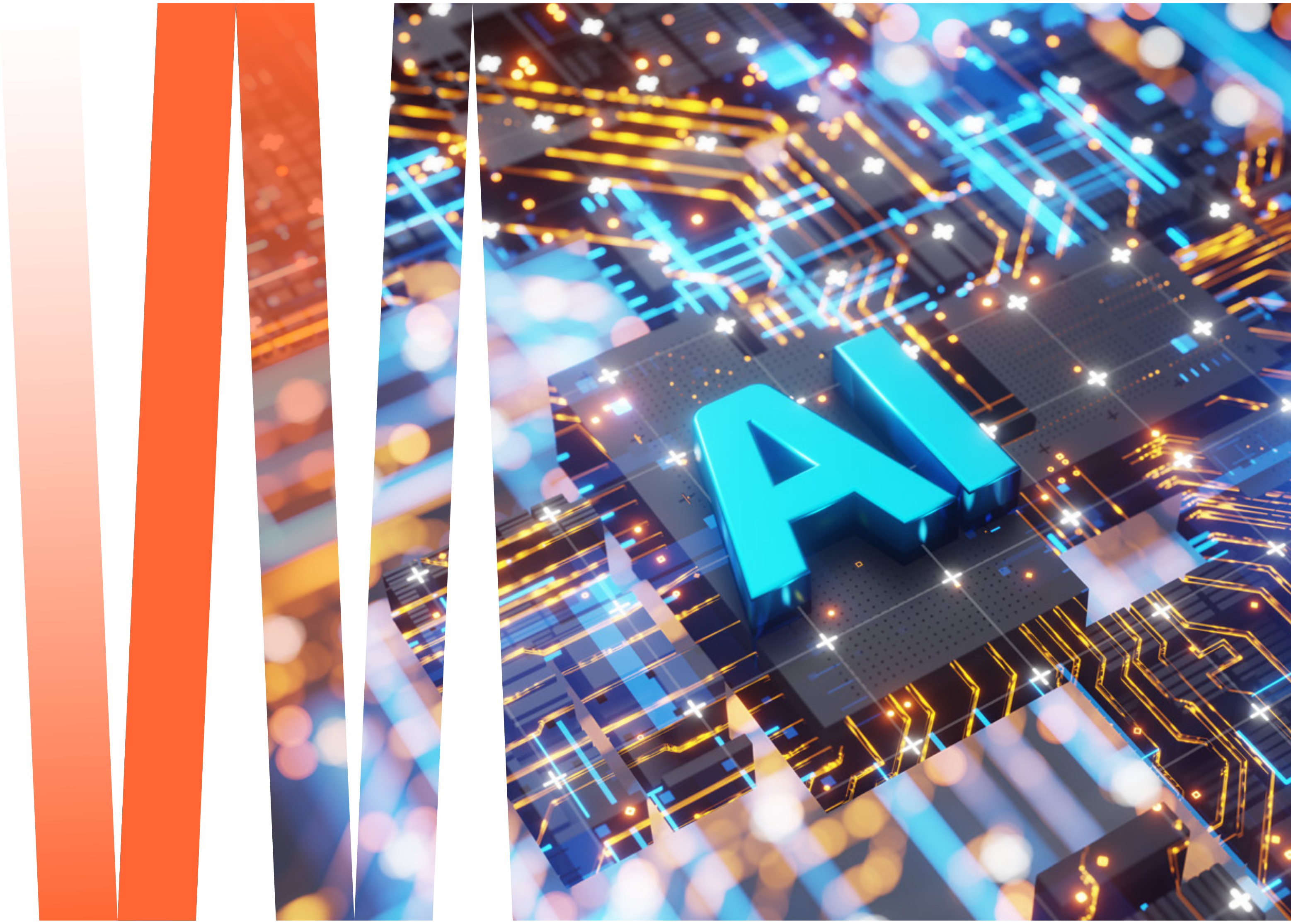
White paper

Advanced UPS controls for AI workloads management

Enabling stable power protection in high-performance computing environments



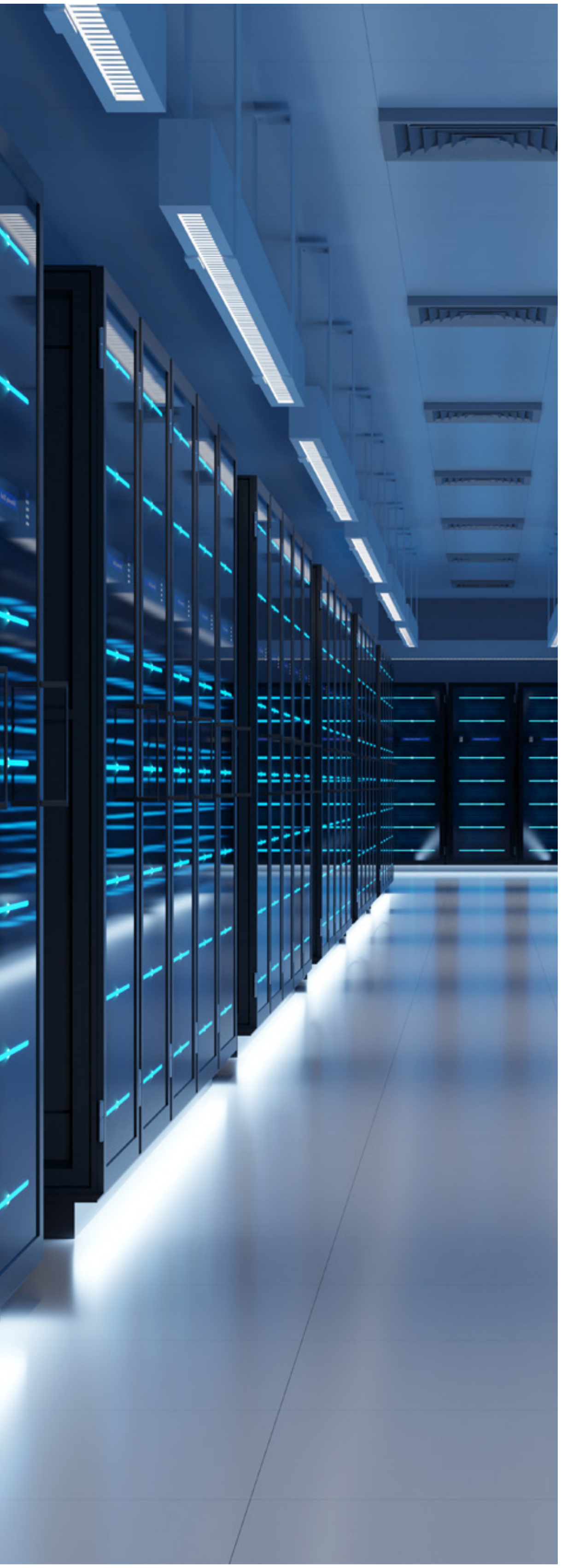


Table of contents

Introduction

As artificial intelligence (AI) applications become more complex and compute-intensive, the data centers' power train must be equipped to respond to increasingly fast-changing and unpredictable load patterns.[1] Modern AI computing workloads generate power consumption profiles that are both highly dynamic and impulsive

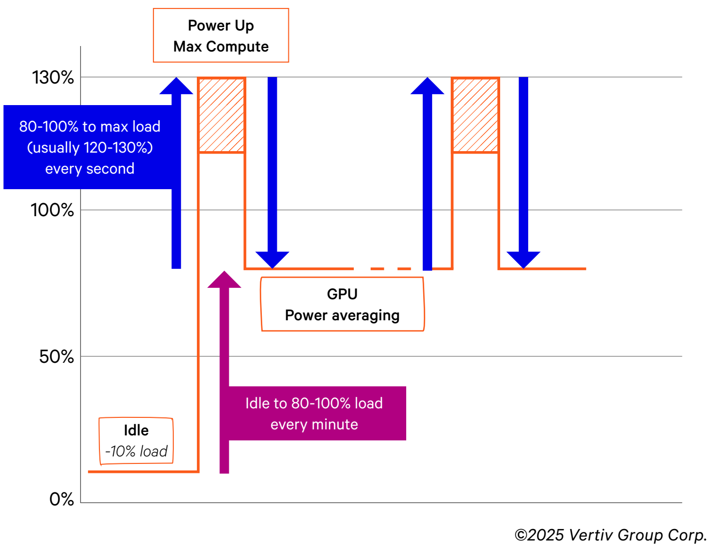


Figure 1. AI workloads' power consumption profiles fluctuate in milliseconds.
Source: Vertiv

The diagram illustrates a representative AI load pattern. System cycles rapidly power up to maximum compute levels, often exceeding 100% nominal load, then quickly drop to a graphics processing unit's (GPU's) lower-averaged power state. This behavior repeats frequently, creating power patterns that are both sharp and regular.

Laboratory testing and field observations indicate that these rapid fluctuations can have wide-ranging impacts, including:

- **Power quality and grid stability:** Introducing power fluctuations that may cause frequency deviations and harmonic distortions that can challenge upstream electrical systems.
- **Critical equipment performance:** Creating sudden thermal and electrical stress on racks, power supply units, power electronics, and distribution components.

To mitigate these effects, a set of advanced features can enable the uninterruptible power supply (UPS) to **actively manage the extreme variability of AI-driven loads.**[2] Rather than treating the batteries as passive backup devices, these features implement smart control strategies that optimize the UPS's interaction with both the batteries and the upstream infrastructure.

Two complementary UPS control features are introduced in this technical note:

- **Battery Shield:** A control feature that prevents unnecessary battery involvement during fast transients. This maintains that backup energy reserves are reserved exclusively for outage events, while extending battery life and reliability through AI-assisted loads.
- **Input Power Smoothing (IPS):** A dynamic load averaging algorithm leverages the battery system as a short-term buffer to smooth the power peaks on the UPS output. By filtering fast AI load fluctuations, it stabilizes the UPS input power, reducing stress on utility sources, generators, transformers, and switchgears.

Together, these features provide a comprehensive approach to managing the dynamic and impulsive nature of AI workloads.

[1,2] Raggi, T., 2025. Vertiv.

"Battery Shield" mode of operation

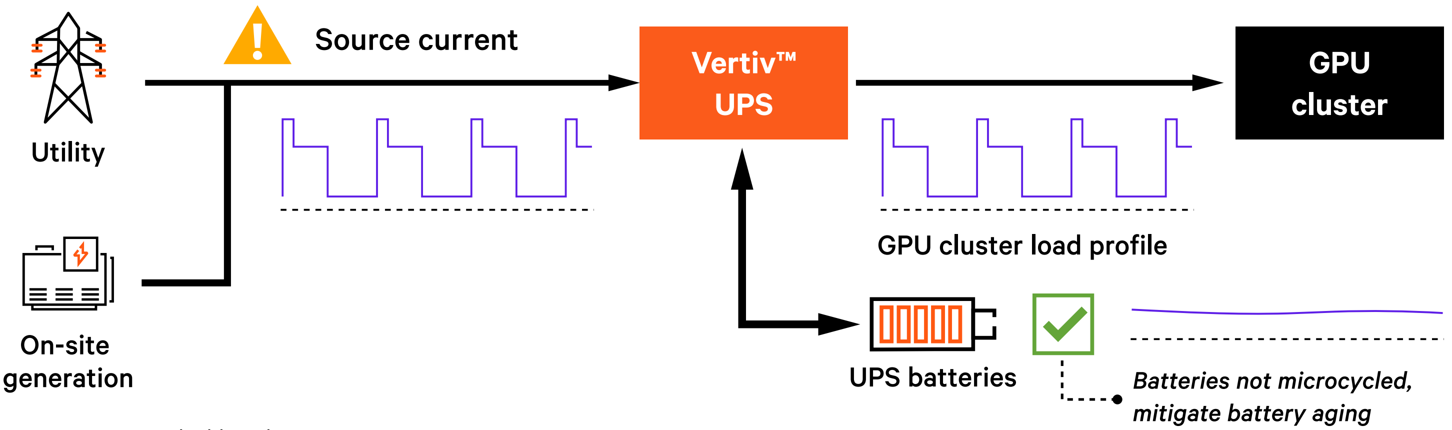


Figure 2. Battery Shield mode overview. Source: Vertiv

Capabilities and benefits

Modern AI workloads introduce highly dynamic and impulsive load profiles with GPUs, driving power steps that can swing from idle to full load in milliseconds. For some UPS – depending on the AI load profile and other system conditions – these fast transitions could be partially absorbed by the batteries, resulting in frequent **micro-discharges** that accelerate **battery aging** and reduce overall battery lifetime.

The **"Battery Shield"** feature mitigates this issue by **managing these power steps internally** in the UPS without engaging the batteries. This allows the UPS to absorb 0–100% power steps directly, protecting the energy storage system from unnecessary stress. When power demand exceeds rated 100% thresholds, Battery Shield mitigates battery exposure. The feature supports multiple chemistries, including Lithium-ion (Li-ion), valve regulated lead acid (VRLA), and nickel zinc (NiZn).

By preserving batteries from unnecessary cycling, Battery Shield keeps backup energy always available when it truly matters, such as grid outages, reduces battery aging, and reduces maintenance needs.

Technical operations and overview

The Battery Shield function relies on dynamically controlling the **DC link voltage** to provide sufficient stored energy for transferring upstream fast and repetitive load steps without engaging the battery system. By increasing the voltage reference, the UPS maintains an energy buffer that shields the batteries from unnecessary cycling.

- **Load below partial threshold:** When the inverter load is below the defined partial-load threshold, the rectifier increases the DC link voltage at an equal or higher value of the maximum setpoint. This raises the stored energy in the DC capacitors, enabling the **UPS to avoid microcycling** the energy storage source.
  - This control mode applies only when the DC link is supplied by the rectifier. It does not apply when the booster is the active source.
- **Load above high threshold:** When the inverter load exceeds the high-load threshold, the DC link voltage is returned to its nominal setpoint. This maintains stability at higher operating points while **preventing overstress on the DC capacitors.**
  - This adjustment applies when the rectifier is supplying the DC link.
- **Dynamic response:** The DC link reference auto-adjusts, maintaining fast convergence and allowing the UPS to follow repetitive load transients occurring multiple times per second.

Internal impact on UPS architecture:

- **DC link control loop** is modified to include load-dependent reference shifting.
- **Energy storage** is effectively protected by the DC capacitors due to their contribution to transient handling.
- **The battery interface remains idle** during normal dynamic events, reducing unnecessary micro-cycling and maintaining energy reserves fully available for backup conditions.

“Input Power Smoothing” (IPS) mode of operation

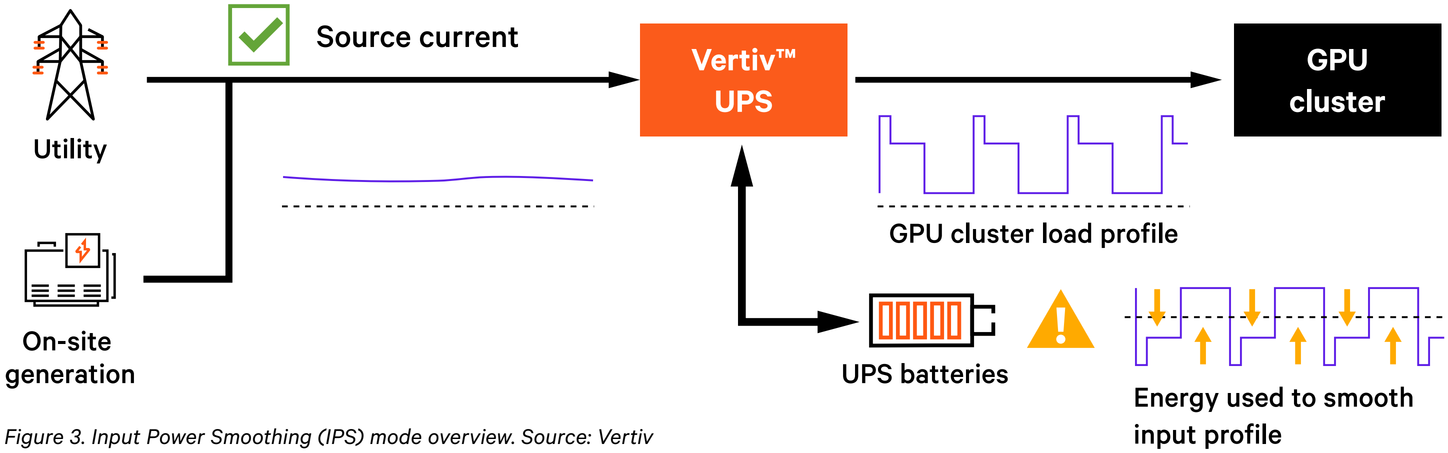


Figure 3. Input Power Smoothing (IPS) mode overview. Source: Vertiv

Capabilities and benefits

AI workloads propagate impulsive and repetitive fluctuations across the power electrical infrastructure. Without mitigation, these fluctuations can result in sudden power spikes, increasing stress on generators, transformers, switchgear, and the utility grid.

The “Input Power Smoothing” (IPS) feature addresses this challenge by **leveraging the UPS battery system** as an active power buffer. Instead of reflecting the fast and irregular GPU-driven load steps to the input, the UPS dynamically absorbs or injects power from the batteries, maintaining that the input side sees a stable and smoothed power demand.

The level of **smoothing is configurable** based on actual load behavior. Users can define limits such as the maximum smoothing percentage or the maximum time window for battery engagement, allowing the feature to be tuned according to both the specific AI workload profile and the battery chemistry in use.

By shaping the power profile on the UPS input, IPS **protects upstream infrastructure** from short-term load transients, reduces thermal and electrical stress on critical components, and helps facilities comply with grid operator constraints. For installations supported by generators, it improves stable operation and minimizes the impact of sudden load variations that could otherwise cause generator instability or load rejection.

Algorithm

The Input Power Smoothing algorithm regulates the input power fluctuations of the UPS system based on the average output power while respecting the operational limits of the rectifier, inverter, generator, and battery system.

The algorithm works as follows:

- **Average output power calculation:** The system continuously calculates the average output power using a digital filter over a defined time window. This average output power also serves as a **reference point** for determining the input power fluctuation range.

- **Target fluctuation range setting:** A target fluctuation range percentage (FR%) is a user-defined parameter that determines the allowable variation in input power around the system's average output power.

FR% ≥ 0% - The input power is permitted to fluctuate within the specified target FR% range relative to the average output power. The lower limit of this fluctuation is automatically determined by the battery's charging capability.

Example:

If the average output power is 90% of a 1000 kW UPS (i.e., 900 kW), and FR% is set to 20%, then the input power may vary between 720 kW and 1080 kW.

In practical applications, even with an FR=0%, the input power cannot remain perfectly constant. Small residual variations are normal and originate from component tolerances, calibration accuracy, and the natural response of the control loops, particularly under fast-changing AI/GPU workloads. This constraint becomes even more critical under **unbalanced AI workloads,** where power demands can vary unpredictably, making zero fluctuation tolerance impractical.

Moreover, an FR value close to zero can be selected to achieve behavior very close to a fixed input power condition.

Note: *The achievable FR% may be limited by the converter hardware due to tolerance on the components and the calibrations. Each UPS has its own topology and sizing, which define the allowable FR range. Choosing a UPS with a suitable hardware design, such as those in the Vertiv portfolio, facilitates proper FR capability.*

Operational constraints

The algorithm enforces **upper and lower power limits** based on:

- **Rectifier capacity** (maximum input current)
- **Generator capability** (maximum capability of the generator to handle load swings)
- **Battery charge/discharge capability** (maximum charge/discharge current and state of charge, or SOC).
- **Utility THDv** (utility tolerance to step loads, impacting utility THDv) If the selected target FR% conflicts with the above-mentioned limits, the system will automatically **increase the fluctuation range** to remain within safe battery operating conditions, or **decrease the fluctuation range** when rectifier capacity or generator capability are constrained (achievable only when battery conditions allow for this).

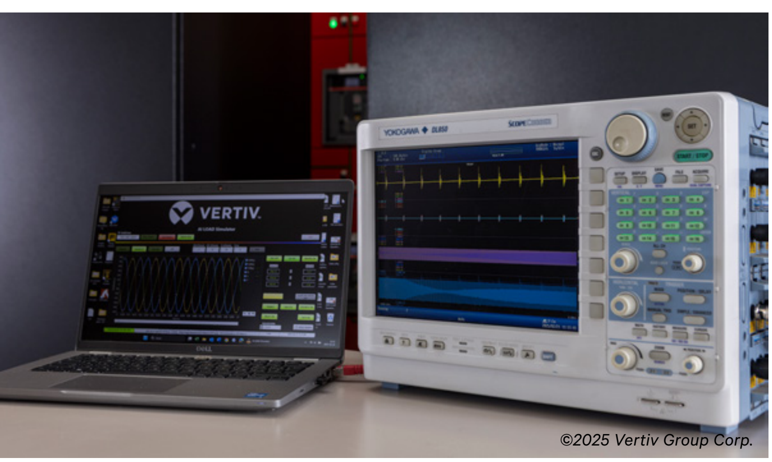


Figure 4. The Vertiv™ AI Load Simulator replicates the electrical behavior of variable AI loads, enabling engineering teams to test UPS systems and full power train under AI-driven conditions. Source: Vertiv

Dynamic adaptation

When the **average output power changes,** the fluctuation band automatically updates based on the new average power value. The rectifier should always provide the average power, plus or minus some variation allowed by the FR%, and just enough charging power to prevent the state of charge (SOC) from decreasing.

The algorithm continuously enforces SOC constraints:

- **Power smoothing stops** if SOC falls below a minimum threshold (configurable).
- In generator mode, smoothing may temporarily continue even with SOC as low as 10%, specifically during initial AI load startup conditions and only if allowed by the end user minimum SOC pre-settings.

Asymmetric fluctuation handling

The algorithm may allow positive fluctuation (input power increase) up to the defined FR%, but negative fluctuation (input power decrease) depends on the battery's charge acceptance capability.

If insufficient battery charging power is available, the smoothing function automatically exits to avoid batteries reaching end-of-discharge (EOD).

SOC management with input power smoothing

Managing the battery state of charge (SOC) properly is essential to maintain that the Input Power Smoothing (IPS) function operates reliably while preserving the battery's primary role as a backup energy source. The IPS algorithm dynamically regulates charging and discharging cycles within a controlled SOC window, maintaining optimal performance and preventing overuse or depletion of the battery system.

The control has a configurable nominal SOC value (e.g., 85%) and applies a configurable minimum value (e.g., 50%) to create a working SOC range, the maximum SOC value can be configurable or fixed depending on the UPS model (e.g. 97%). Within this window (e.g., 50–97%), the battery can freely charge and discharge in response to short-term load fluctuations caused by AI power transients.

This SOC range is bound by two key values:

- **Maximum SOC for IPS:** The upper limit of the SOC window. The battery should not operate near 100%, as this region exhibits low charge acceptance and leaves no headroom for recharging in the event of subsequent power drops. The maximum SOC maintains that a portion of the battery capacity remains available for charge recovery events, maintaining optimal system responsiveness.
- **Minimum SOC threshold parameter for IPS:** The lower limit of the SOC window. This value maintains that sufficient stored energy remains reserved for backup operations in case of a mains failure. Energy below this threshold is considered **reserved backup energy** and is not used for power smoothing. Maintaining this minimum level guarantees that the UPS continues to meet its core mission of providing uninterrupted power.

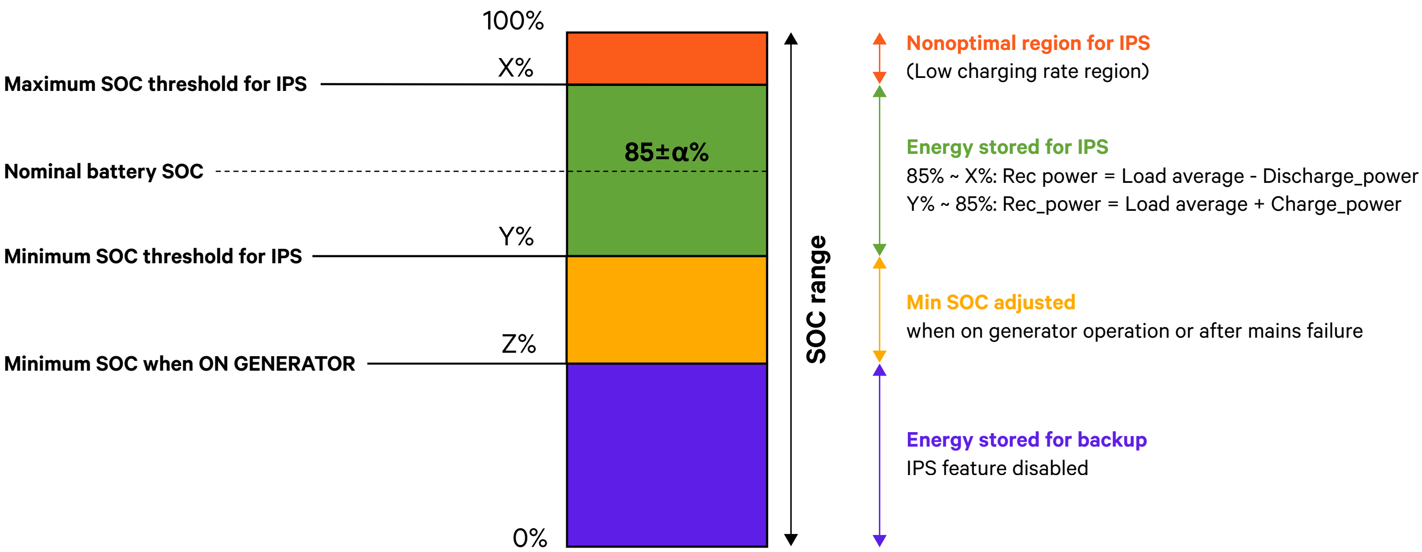


Figure 5. State of charge (SOC) management. Source: Vertiv

Adaptive behavior during generator operation and operational considerations

When the system operates in **generator mode** (ON GEN contact active), the algorithm lowers the minimum SOC threshold to a new lower SOC value. This allows the IPS function to remain active even when the batteries have partially discharged following a mains outage. Since the SOC level may already be below the normal IPS operating range, this adaptive adjustment facilitates continuity of input power smoothing during generator-supported operation while still maintaining adequate battery protection.

Because **battery discharge rates** are typically higher than their **charge rates,** effective operation of IPS requires sufficient battery capacity connected to the UPS. For installations requiring intensive power smoothing, high-charging-rate battery chemistries such as lithium-ion are recommended.

By maintaining SOC within a well-defined dynamic range and adapting thresholds based on operating conditions, the IPS algorithm facilitates a stable balance between power quality optimization and backup reliability.

Battery sizing and IPS effectiveness

Laboratory simulations further confirm that the extent of input power smoothing is strongly dependent on both the battery sizing and the charging/discharging capabilities of the UPS system.

As shown in the simulations below:

- With limited battery capacity, the system exhibits partial power smoothing because the battery discharging rate exceeds the available recharging power. This results in a **gradual decrease in battery SOC,** restricting the smoothing effect to short durations.
- With increased battery capacity, the charging and discharging power reach equilibrium, allowing the system to sustain **full power smoothing** indefinitely under the same load profile.

Key takeaway: To achieve **100% power smoothing,** sufficient battery energy must be available. Otherwise, the fluctuation range (FR) on the input side will be limited, and power smoothing can only be maintained for a limited period.

IPS with different energy storage configurations

The purpose of the simulations below is to show that additional batteries may be required depending on the AI load profile, the desired smoothing percentage, and the duration.

Simulation 1: Partial power smoothing

Load profile: 30% to 100%, 0.5Hz, 50% duty cycle

Max power: 1200kW

Energy storage: 7x Lithium-ion battery cabinets (64A max recharge current for each cabinet)

Negative power balance: With this load profile, battery recharging can't keep up with battery discharge.

Outcome: Battery SOC will decrease and IPS can only be used for a limited amount of time, unless the input power FR is allowed to increase.

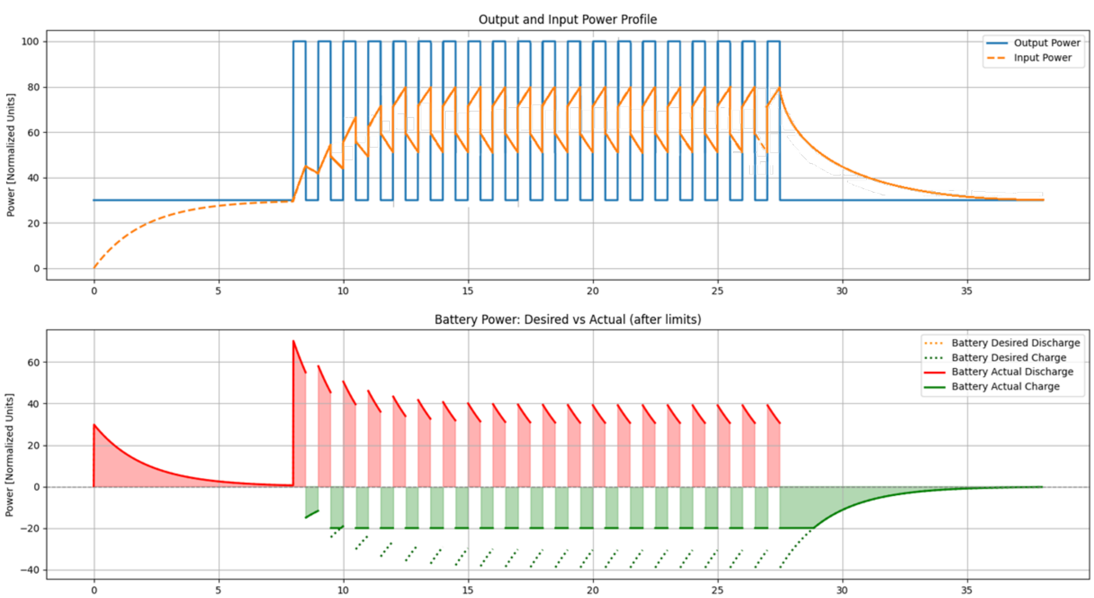


Figure 6. Partial power smoothing example. Source: Vertiv

Simulation 2: Full power smoothing

Load profile: 30% to 100%, 0.5Hz, 50% duty cycle (same as simulation 1)

Max Power: 1200kW (same as simulation 1)

Energy storage: 14x Lithium-ion battery cabinets (64A max recharge current for each cabinet)

Neutral power balance: With this load profile, battery recharge can keep up with battery discharge.

Outcome: UPS can perform power smoothing throughout the system's useful life.

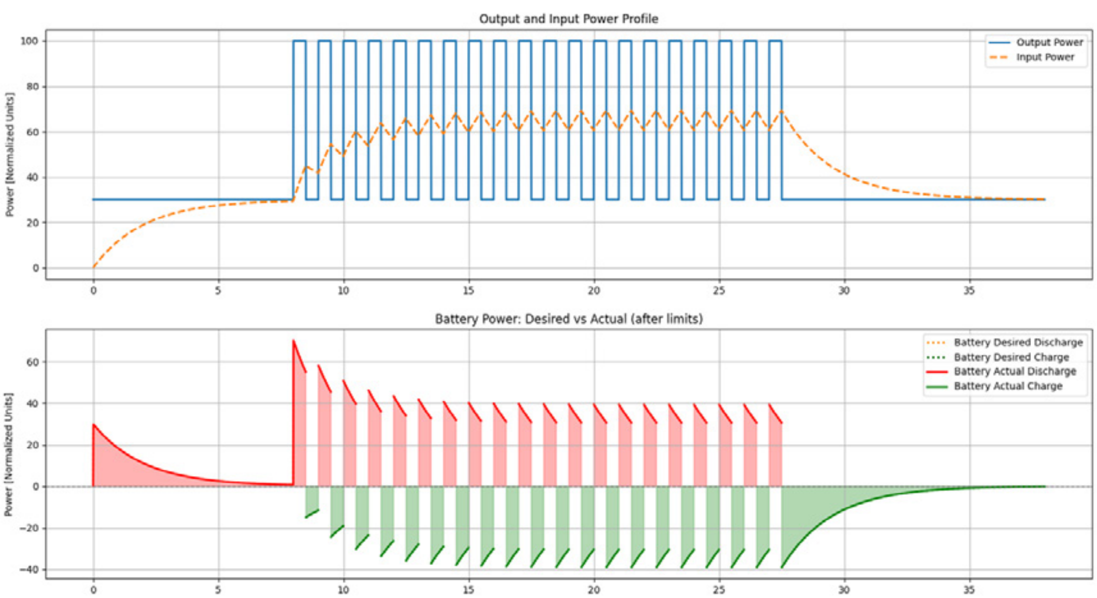


Figure 7. Full power smoothing example. Source: Vertiv

Input power ramp behavior

The rate at which input power varies is a critical parameter for power train stability. Generators and some grid operators can only tolerate a limited rate of power variation, typically expressed in kW per second. Exceeding this threshold may lead the generator to interpret the transient as a fault condition, triggering protection mechanisms that disconnect the load from the source.

To mitigate this phenomenon, Input Power Smoothing (IPS) implements a controlled input power ramp behavior, designed to smooth the power steps upstream of the UPS. Instead of mirroring the fast AI load profile directly at the UPS input with a lower amplitude, the system introduces a controlled ramp profile that gradually adjusts the input power to follow the load. This approach significantly reduces the load variation ramp perceived by the upstream source, keeping the power change within its acceptable limit.

From a control standpoint, this functionality is realized through the UPS firmware that generates an averaged representation of the output power. The filtering process determines the rate of change of the input power setpoint, effectively defining how fast the UPS will adjust its input power in response to output load steps.

A configurable parameter allows the operator to tune the behavior according to the characteristics of the upstream system. This parameter directly affects the internal filter time constant (**τ**), providing flexible control over the ramping rate. Increasing **τ** results in a slower input response and gentler transitions (suitable for generators or weak grids), while decreasing **τ** allows faster dynamics where the source can tolerate steeper variations.

This configurability enables the UPS to maintain compatibility across a wide range of installation scenarios, maintaining stable operation even in the presence of rapidly changing AI workloads, while respecting the dynamic constraints of the power source.

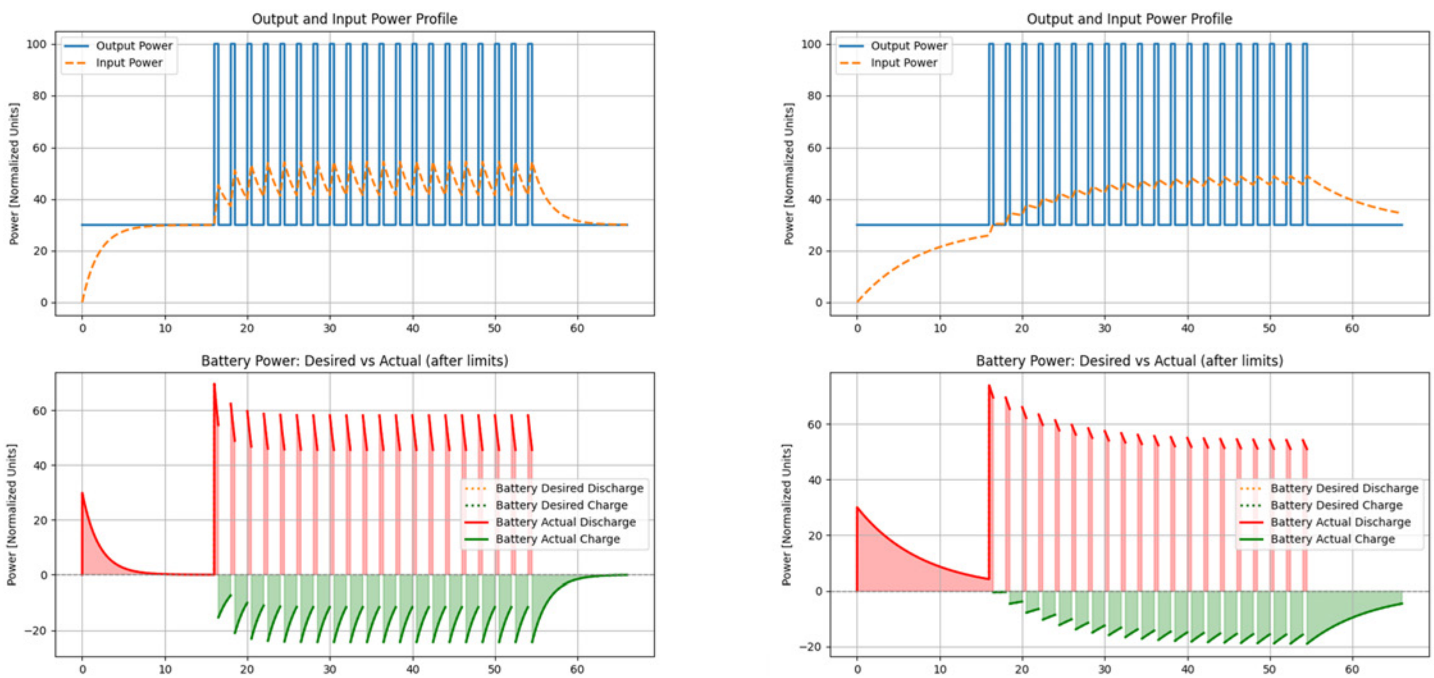


Figure 8. (Left) filter tau multiplier 1 with a ramp, which provides faster load change upstream of the UPS. (Right) filter tau multiplier 4, which provides a slower load change upstream of the UPS. Source: Vertiv

Importance of high C-rate charging current batteries for IPS with onsite generation equipment

Achieving effective input power smoothing in large-scale AI facilities is particularly critical when the primary power source is not the utility grid, but rather a site-generated system, such as gas generators or gas turbines. In these scenarios, maintaining a stable input power profile is essential to maintaining generator stability and preventing the occurrence of rapid load fluctuations that could exceed their dynamic response capability.

To reach this level of stability, batteries must be properly sized and be capable of sustaining very high charge rates. High C-rate batteries enable the UPS to absorb and inject large amounts of power within a fraction of a second, compensating for the sudden variations of AI workloads and maintaining a steady input demand from the generator.

The simulation shown below represents a graphic view where a gas generator supplies power to a NVIDIA GB300 rack installation (that contains components allowing partial power smoothing at rack-level).[3] Thanks to the selected battery configuration composed of battery modules rated at 6C charging capability, the system achieved 100% input power smoothing, with input power variation limited to approximately 1% per second.

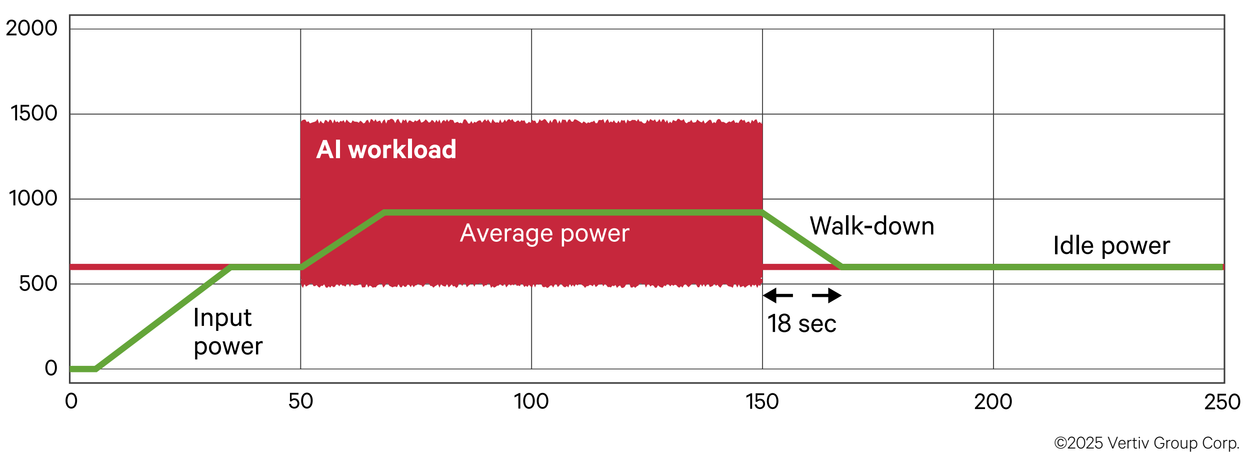


Figure 9. Gas generator supplies power to a rack installation. Source: Vertiv

High C-rate charging current capability is needed to maintain generator stability as on-site generation equipment is very sensitive to fast load changes. The high recharge rate is especially relevant during the walk-down phase, where a large amount of energy must be rapidly stored to balance the strong discharge occurring during the initial walk-in. Moreover, in the average power period, characterized by frequent and deep power oscillations, the high charging current capacity allows the batteries to continuously compensate for load swings without impacting the upstream generator.

[3] Vertiv, 2024.

IPS testing

To validate the performance of the IPS algorithm, a series of dynamic load tests was performed on a Vertiv™ large power UPS equipped with Li-ion batteries. The objective was to assess the system's ability to stabilize the input current under fast and repetitive load variations, which are typical conditions for AI and high-performance computing (HPC) clusters.

The test setup consisted of the Vertiv™ large UPS operating in double conversion mode with the IPS mode enabled, coupled with the Vertiv™ AI Load Simulator, to generate load steps from 31% to 97% and from 63% to 97% of nominal power, with different frequencies. Below we are reporting two of the tests conducted as reference examples:

Test with load profile 1

Load step: 31% to 97% | **Frequency:** 1Hz with 50% duty cycle (Ton: 500ms - Toff: 500ms)

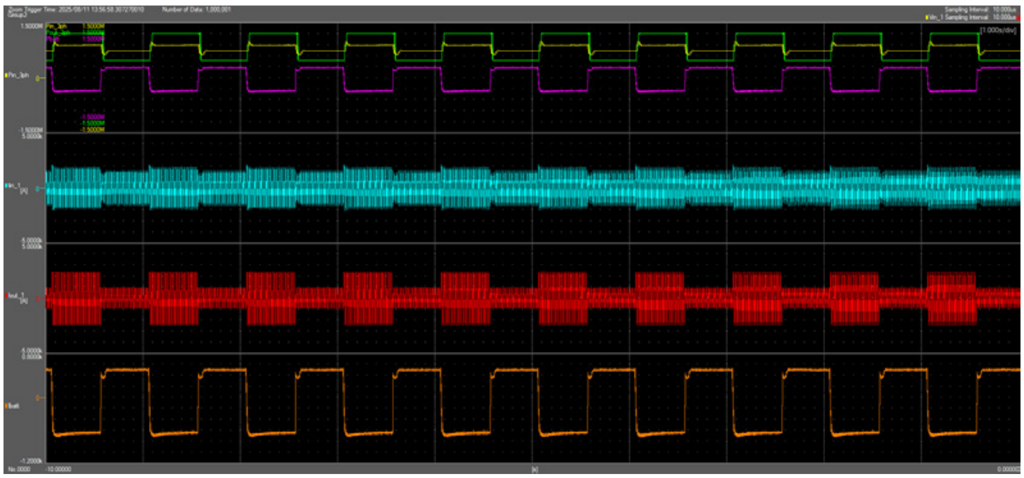


Figure 10. The first line reports input, output, and battery performance. A better detail of the waveform is visible from Line 2, where the input current is represented, while Lines 3 and 4 show the output (red) and batteries' (orange) views. Source: Vertiv

The above graph illustrates the input current behavior during cyclic load steps. On the first line, the green trace represents the output power delivered to the load, while the yellow trace shows the input current drawn from the grid. Without input power smoothing, such fast transitions would produce significant input current oscillations.

With input power smoothing active, however, the input current remains nearly constant, as the battery dynamically injects or absorbs the current to compensate for the power delta (bottom line orange trace). This demonstrates the algorithm's capability to maintain grid stability with a dynamic output load profile.

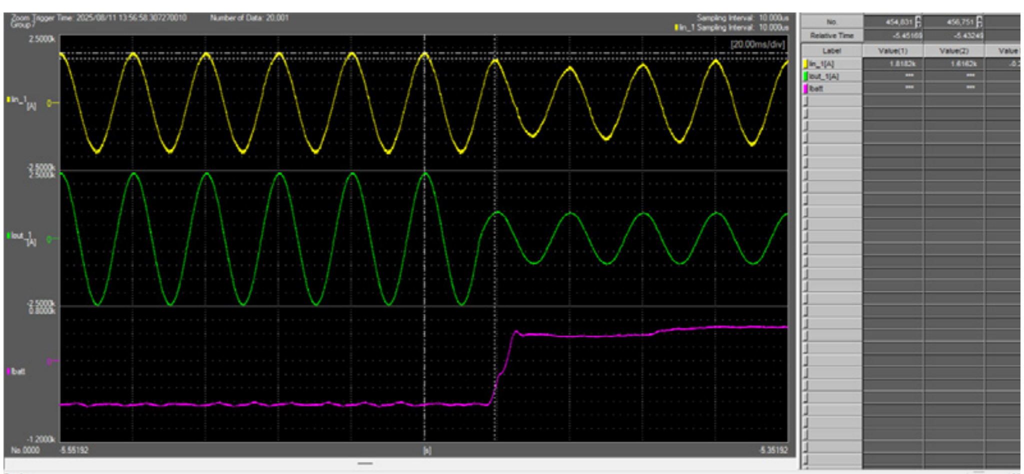


Figure 11. Load step down macro view, Line 1 (yellow) input current, Line 2 (green) output current, and Line 3 (purple) battery current. Source: Vertiv

This second plot (Figure 9) provides a zoomed-in view of the load step down current waveforms. The sinusoidal input current (yellow trace) remains almost constant despite a high decrease in the output current (green trace), confirming that input power smoothing effectively filters output load changes.

The violet trace represents the battery current: it alternates between positive and negative values, indicating charge and discharge cycles synchronized with load changes. This bidirectional response validates the correct dynamic coordination between the UPS and the battery system.

Test with load profile 2

Load step: 63% to 97% | **Frequency:** 1Hz with 50% duty cycle (Ton: 500ms - Toff: 500ms)

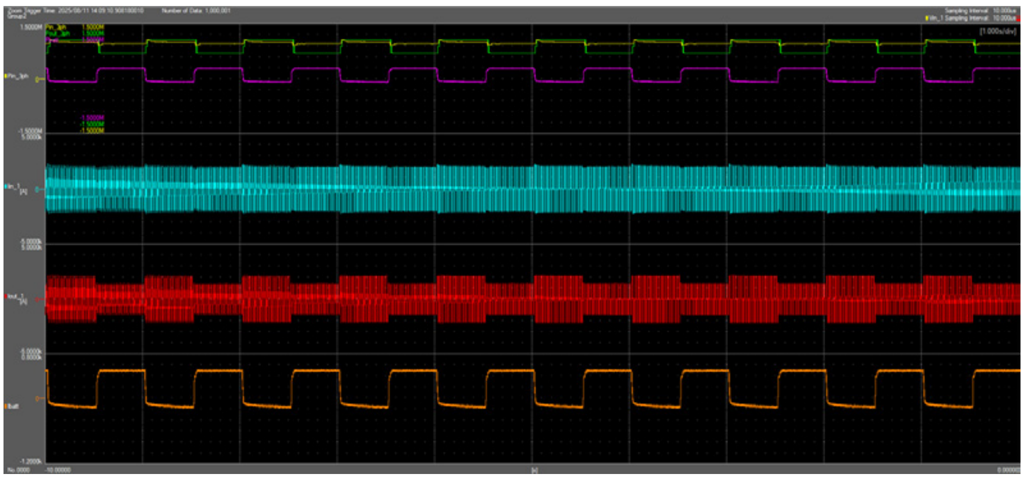


Figure 12. The first line reports input, output, and battery performance. A better detail of the waveforms is visible from Line 2, where the input current is represented, while Lines 3 and 4 show output (red) and batteries (orange) views. Source: Vertiv

The above graph illustrates the input current behavior with this second load profile, which has a lower amplitude. Input power smoothing can maintain a smooth input current (yellow trace) despite the decrease in output current (green trace). This is possible due to the dynamic injection and absorption of current in the batteries to compensate for the power delta (orange trace).

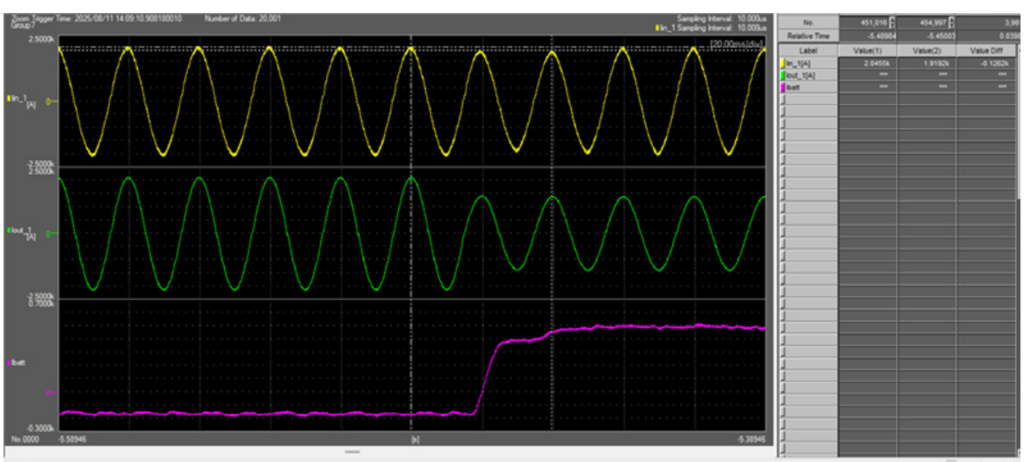


Figure 13. Load step down macro view, Line 1 (yellow) input current, Line 2 (green) output current, and Line 3 (purple) battery current. Source: Vertiv

This second plot (Figure 11) provides a zoomed-in view of a load step down current waveforms. The sinusoidal input current (yellow trace) remains constant, with no changes perceived on the input, despite the output current (green trace) suddenly decreasing.

The violet trace represents the battery current: it alternates between positive and negative values, indicating charge and discharge cycles synchronized with load changes.

Coordinated use of AI loads management features according to site constraints

The optimal strategy of AI workloads depends on the constraints and operational priorities of each site installation. Battery Shield and IPS are not mutually exclusive; they operate as complementary mechanisms that can be selectively activated depending on real-time conditions.[4] In normal operations, Battery Shield may be the preferred default feature to minimize battery stress.

However, under specific events, like a mains failure followed by generator operation, the strategy can shift, enabling IPS to protect the upstream source from AI workloads. For example, modern large-scale AI data centers (often operating with hundreds of MW) may also be supported by **on-site generation** devices such as gas or diesel generators, gas turbines, or fuel cell systems. These sources provide local, dispatchable power capacity that complements or relieves stress on the utility grid.

It is important to note that not all on-site generation systems exhibit the same load-step tolerance. High-performance on-site generation devices may be able to withstand large and rapid power transitions with minimal frequency or voltage deviation, whereas others have more limited dynamic capabilities. In this case, a higher smoothing level may be required to mitigate the power oscillations observed at the input. Conversely, when battery lifetime preservation is the main priority, smoothing can be reduced to limit cycling and energy throughput.

Increasing the smoothing level enhances grid-side stability, but proportionally increases battery usage.

- **High IPS:** Maximum mitigation of input fluctuations, higher battery cycling.
- **Moderate IPS:** partial mitigation while keeping throughput within acceptable limits.
- **Low IPS:** priority on battery longevity, limiting the UPS response to only the most critical fluctuations.

The optimal configuration often results from a calibrated balance: input power smoothing is set according to upstream constraints, while Battery Shield can be set during periods of where there are no upstream constraints and batteries needs to be protected.

Figure 14. Vertiv™ PowerUPS 9000 paired with the AI Load Simulator for advanced power testing. Source: Vertiv

[4] Vertiv, 2025.

Importance of UPS and battery sizing with AI workloads

The effectiveness of power stabilization features such as Battery Shield and Input Power Smoothing strongly depends on how the UPS and battery system are sized. In data center environments, sizing has historically focused on maintaining sufficient backup autonomy during mains outages. Modern AI clusters generate load profiles that are **fast-changing, repetitive, and thermally demanding,** requiring a new perspective on power infrastructure sizing.

For AI-driven data centers, UPS and battery sizing need to consider the workload behavior:

Load profile shape:
The amplitude of AI workload transitions.

Duty cycle and repetition rate:
The frequency of AI workload transitions.

High-amplitude and high-frequency load profiles increase both electrical and thermal stress, requiring an UPS and battery with a high response speed (higher charging current).

An **undersized system** limits the performance and compromises long-term reliability.[5] From an energy storage perspective, when the battery recharge rate is too low, the UPS **reduces its ability to sustain input power smoothing (IPS),** allowing load fluctuations to propagate upstream and placing additional stress on generators and the electrical grid.

Inadequate battery sizing also forces the battery to operate near its charge and discharge limits, accelerating **battery aging** and reducing its overall lifespan.

At the same time, from a UPS system perspective, AI workloads that repeatedly drive the UPS into overload can lead to significant **thermal stress on power electronics,** thereby increasing component temperatures.

A **correct sizing** approach starts with a detailed understanding of the AI load profile:

1. **Characterize the load pattern:** Measure or simulate the real power profile over time, identifying amplitude, frequency, and duty cycle of the load transients.
2. **Define the smoothing objectives:** Determine the percentage of fluctuation (FR%) to be filtered and the duration for which full smoothing should be maintained.
3. **Size the battery system accordingly:** Select battery capacity and chemistry that can sustain the target FR% without depleting SOC below the defined thresholds.
4. **Validate recharge equilibrium:** Monitor that the recharge rate matches the discharge rate over the defined smoothing window. This guarantees stable SOC and IPS availability.

By following this approach, the UPS system can achieve a **power balance,** maintaining input power stability for the useful life of the system under repetitive AI load cycles.

References

1. Vertiv. (2025). "The data center power train e-book."
https://www.vertiv.com/en-us/about/news-and-insights/articles/white-papers/the-data-center-power-train-managing-energy-from-grid-to-chip/

2. Raggi, T. (2025). Vertiv. "Understanding AI power demands: How standard Vertiv UPS systems support AI factory load dynamics."
https://www.vertiv.com/en-us/about/news-and-insights/articles/educational-articles/
understanding-ai-power-demands-how-standard-vertiv-ups-systems-support-ai-factory-load-dynamics/

3. Vertiv. (2025). "AI hub." https://www.vertiv.com/en-us/solutions/ai-hub/design/

4. Vertiv. (2025). "Optimized for AI: EdgeConneX's data centers leverage Vertiv's advanced power technology."
https://www.vertiv.com/en-us/about/news-and-insights/articles/case-studies/optimized-for-ai-edgeconnexs-data-centers-leverage-vertivs-advanced-power-technology/

5. Vertiv. (2025). "Enabling uninterrupted power: Design for reliability in UPS systems."
https://www.vertiv.com/en-us/about/news-and-insights/articles/white-papers/enabling-uninterrupted-power-design-for-reliability-in-ups-systems/

[5] Vertiv, 2025.

Vertiv.com

SL-80384 (12/25)