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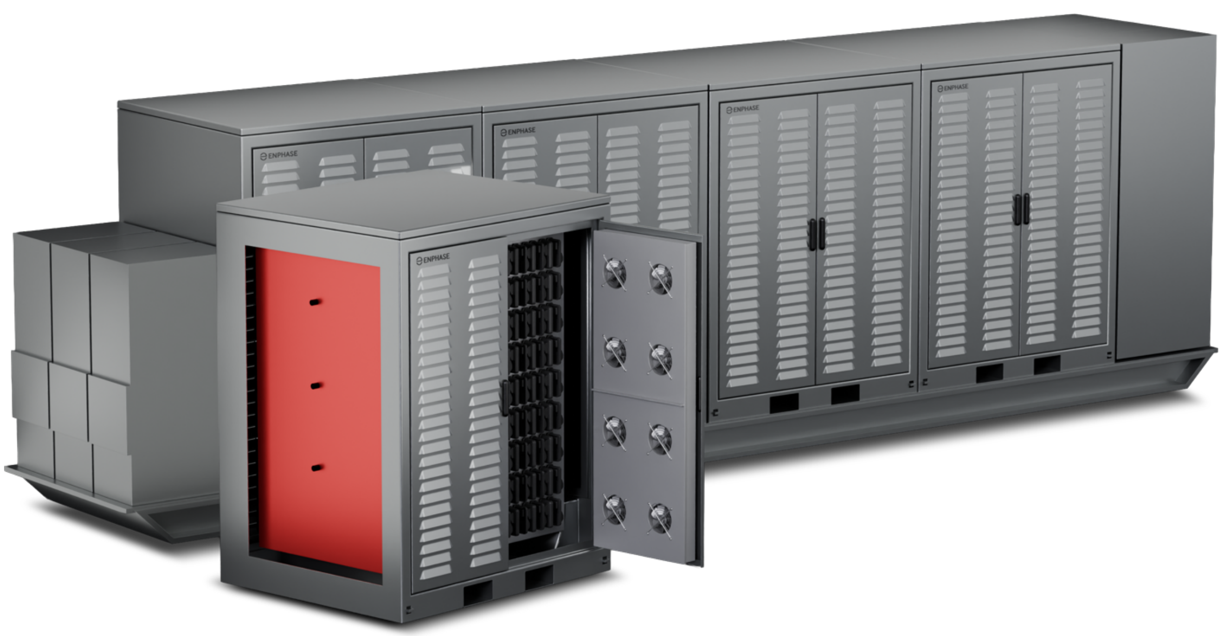
IQ SOLID-STATE TRANSFORMER

Intelligent power for AI.



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ABSTRACT

Intelligent power for AI

The rapid growth of AI data center capacity is increasingly constrained by available electrical infrastructure. Capacity is now discussed in terms of electrical power consumed (MW or GW) rather than computing output, a clear sign that electrical energy availability has become the primary design constraint. Several solutions are being pursued as part of a holistic design approach that includes 800 VDC (±400 VDC) power architecture, Battery Energy Storage Systems (BESS), and Solid-State Transformer (SST) technology.

Enphase Energy is developing the IQ Solid-State Transformer (IQ SST) to serve the needs for the next generation of 800 VDC (±400 VDC) architecture slated for adoption in AI data centers starting mid-2027. The IQ SST takes a fundamentally different approach from competing designs: a larger number of smaller, lower-power modules that deliver the high switching frequency and control bandwidth needed for fast, precise load management.

This design choice yields four distinct advantages: sub-millisecond control response that eliminates the need for local energy buffering; high availability through parallel redundancy with hot-swap serviceability; lower system cost through reliance on widely available, lower-voltage components; and a proven, scalable U.S.-based manufacturing capability built on Enphase's existing high-volume production infrastructure.

1.25 MW	99.999%	<1 ms	342
PER RACK · SCALES TO 5 MW	SYSTEM AVAILABILITY	TRANSIENT RESPONSE	POWER MODULES PER RACK

01 What is an SST?

The concept of a Solid-State Transformer (SST) dates back over 100 years, predating the advent of solid-state (semiconductor) power switches. Over the years, this concept has been referred to by many different names. However, in recent decades there has been an industry and academia convergence towards adoption of the SST moniker. Further nomenclature confusion stems from the SST name being used to describe a wider range of devices than inferred by the now commonly agreed upon SST definition.

The commonly used definition for an SST that aligns with the AI data center usage is a device that replaces the traditional *passive* 'iron and copper' ubiquitous electrical utility transformer with an *active* device that uses solid-state semiconductor switches to transform energy at a synthesized frequency hundreds to thousands of times higher than the utility grid frequency.

The advantages of an SST over a traditional 'iron and copper' transformer chiefly relate to the vastly superior control functionality afforded through an actively controlled solution. Other advantages relate to extended functional capabilities such as Direct Current (DC) output as well as reducing the amount of expensive copper that is used in traditional 'iron and copper' utility transformers.

02 AI Data Center Adoption of SST Technology

AI compute rack power density is increasing at an unprecedented rate. As an example, the state of the art (mid-2026) NVIDIA Vera Rubin NVL72 rack consumes >200 kW of power and will be the last generation of hardware to be powered from a 50 VDC rack level bus. The NVIDIA Rubin Ultra NVL576 rack is expected to be available by mid-2027 and will use the new Kyber rack architecture that is based on an 800 VDC rack level bus consuming >600 kW of power. The current NVIDIA technology roadmap extends out to 2028 with the Feynman rack which will also be based on the 800 VDC architecture and is slated to consume >1 MW of power. [1]

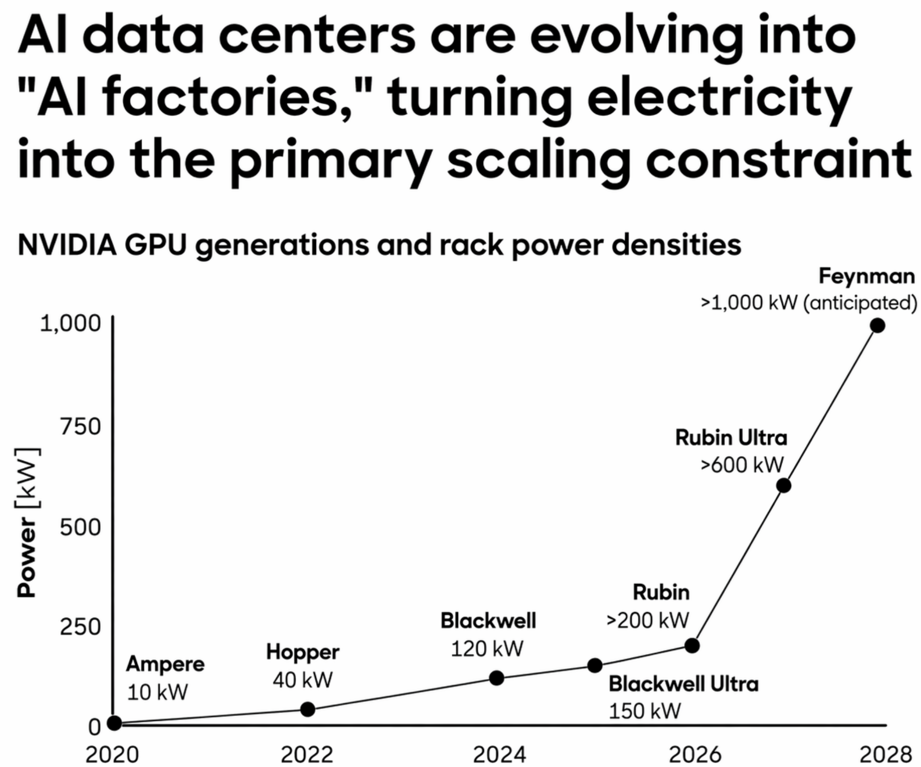

Figure 1: NVIDIA AI data center GPU rack technology roadmap. [1]

In addition to NVIDIA's technology roadmap, Open Compute Project (OCP), the industry standards group, has defined a slightly different path forward, outlined in their Mt. Diablo standard [2] that is based on a ±400 VDC architecture. Because there is sufficient overlap between the NVIDIA 800 VDC and the OCP Mt. Diablo ±400 VDC architectures, Enphase has designed a solution that can support either architecture with its IQ SST solution.

Conventional data center rack designs have accommodated 'front-end' AC:DC Power Supply Units (PSU), which have traditionally only occupied a small percentage (<10%) of the total compute rack space. However, as the power density of the compute rack has grown, the amount of rack space required to accommodate the front-end PSUs has also grown.

The OCP Mt. Diablo and NVIDIA specifications for accommodating the ±400 VDC and 800 VDC architectures have defined a sidecar power rack concept. Each compute rack that will accommodate NVIDIA Rubin Ultra NVL576, consuming >600 kW of power, will be paired with a sidecar rack that is placed to the immediate side of the compute rack. With the >1 MW anticipated power consumption of the NVIDIA Feynman compute rack, the sidecar power rack will be fully populated with PSUs and power supply support hardware, such as Battery Backup Units (BBU) and Capacitor Backup Units (CBU).

The value proposition for the adoption of SST technology in AI data centers relates to the ability to reduce or eliminate the sidecar power rack which can effectively free up half of the premium value white space in the data center where the AI compute racks are located. This allows the amount of AI compute capacity to be doubled for a given AI server room footprint. However, eliminating local energy storage in the form of BBUs and CBUs from the sidecar power rack depends on the SST having a fast enough control response.

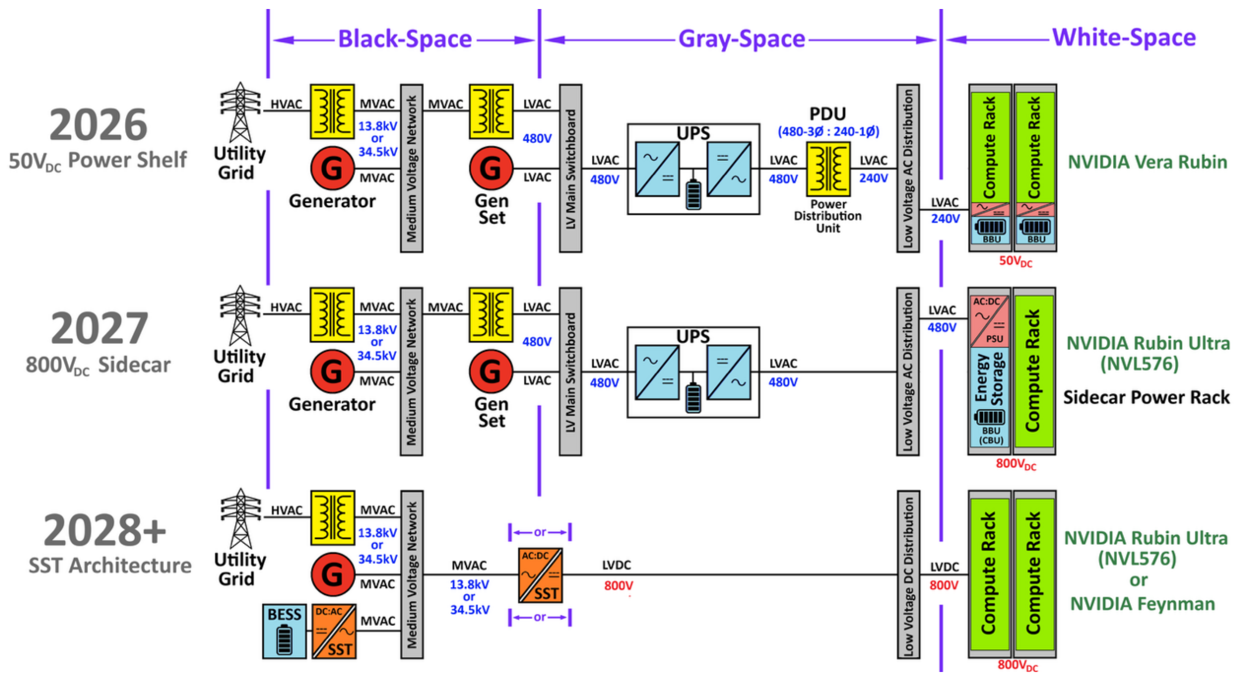

Figure 2: Line diagrams depicting typical AI data center system configurations: 1) Today, 2) Mid-2027, and 3) 2028+

Further value is associated with the ability to eliminate the Uninterruptible Power Supply (UPS) that occupies an increasingly large part of the data center gray space and fulfilling its backup functionality using a Battery Energy Storage System (BESS) located in the black space outside and far away from the data center building. Again, the ability to locate BESS backup remotely depends on the SST having a fast enough control response to enable the remote location of the BESS backup.

Adopting SST technology enables the power supply related hardware to be moved from occupying premium data center white space. The SST can effectively replace the function of the sidecar power rack and be in the less contested data center gray space or alternatively located in the black space completely outside the data center building.

The urgency of this transition is compounded by a separate but related constraint: conventional medium-voltage utility transformers are facing severe supply chain pressure. Surging demand from data center buildout, renewable energy, and grid modernization, combined with limited global manufacturing capacity, has pushed lead times for large power transformers to two to four years in many cases. For data center operators trying to bring capacity online quickly, this bottleneck is as significant as the power density challenge itself. SST technology, built from widely available components and compatible with high-volume manufacturing, offers a path around this constraint.

03 Crossing the Chasm for SST Technology

Geoffrey A. Moore's book from 1991 titled "Crossing the Chasm" [3] outlines a central tenet relating to the existence of a chasm that separates the early adopter market from the early majority market. According to this definition, we believe that SST technology is currently sitting in this chasm flanked by electric locomotive applications as the early adopters and the AI data center application as the early majority market.

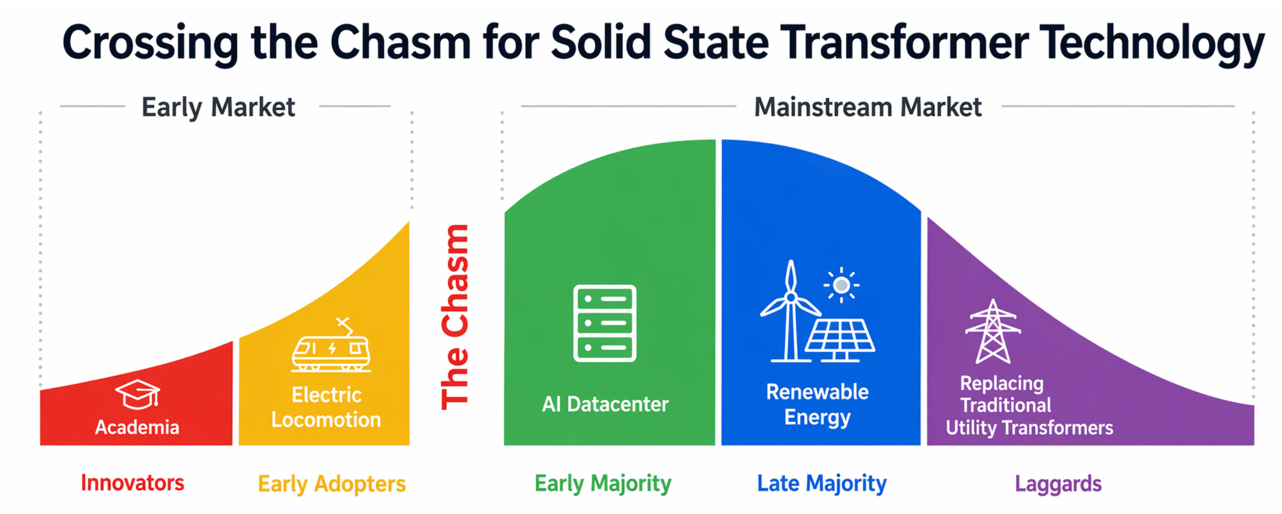

Figure 3: Crossing the Chasm [3]

It should be noted that the timescale for SST technology adoption is much longer than what is typically found with fast-evolving consumer-facing technology. The late majority market for SST technology will most likely be related to renewable energy applications that include:

- Electrical utility scale BESS
- Electrical utility scale Photo-Voltaic (PV) applications
- Electric Vehicle (EV) rapid charger infrastructure applications

However, the value proposition for these applications is compelling and easy to articulate. An SST combines two functions into a single device that consists of two separate components in these applications today:

- A conventional ‘iron and copper’ electrical utility distribution MVAC:LVAC transformer
- A conventional Low Voltage (LV) Inverter Based Resource (IBR) LVAC:LVDC converter

Combining these two functions allows for improved system level performance and reduced cost. These applications sit alongside Enphase’s residential and small commercial markets, extending 20 years of distributed power conversion expertise into new domains.

Ironically, it seems that the ‘laggards’ for SST technology are likely in the form of electrical utility companies’ adoption of SST technology to replace aging traditional ‘iron and copper’ MVAC:LVAC electrical distribution transformers. Although no higher level of integration is reached here, SSTs can all but eliminate the risk of cascading outages and the need for reactive power compensation and suppression of harmonics. It should also be appreciated that this potential electrical utility sector application currently dwarfs all potential near term early and late majority markets.

04 Modular Reliable Power is in Enphase’s DNA

Enphase Energy, a global energy technology company and the world’s leading supplier of microinverter-based solar and battery systems, was founded in 2006. Many of Enphase’s founders and employees came from the telecommunications and data center industries, where high reliability and high availability of infrastructure equipment are essential. That heritage continues to shape the company today, with system reliability remaining one of Enphase’s core market differentiators.

Enphase products are built around the microinverter, a distributed, redundant approach to power conversion. This architecture mirrors best practices in the data center industry, where distributed power systems have a proven track record of meeting demanding reliability and performance requirements.

The telecommunication industry created an infrastructure performance concept that is known as “five-nines” availability. In any given year of operation, the infrastructure should be fully operational and available for 99.999% of the time, a total down time of no more than 5 minutes per year. Modern data centers have adopted similar infrastructure availability requirements [4].

Data center power infrastructure achieves high system availability through parallel redundant equipment and hot-swap serviceability. The solar (PV) application is more demanding: because roof-mounted microinverters are costly to service, they must also deliver long service lifetimes, a requirement that goes beyond what typical data center equipment faces.

Over the past 20 years, Enphase has shipped approximately 87.8 million microinverters representing more than 30 GW of capacity, deployed in the company's solar and battery systems [5]. Enphase microinverters are built to an industry-leading reliability target of 500 DPPM (defective parts per million per year) and backed by a 25-year limited warranty.

05 The SST Competitive Landscape

The existing established electric locomotive application for SST technology is based on antiquated silicon-based thyristors (Silicon Controlled Rectifiers = SCR) and Insulated Gate Bipolar Transistors (IGBTs). These semiconductor power switches are inherently slow and result in slow control response time, which is not suitable for use in AI data center applications.

This antiquated silicon semiconductor switch technology has been recently displaced by the vastly superior Wide Bandgap (WBG) semiconductor switches based on Silicon-Carbide (SiC) and Gallium-Nitride (GaN) technology.

Recently, several SST start-up companies have been established embracing these new technologies. A key challenge for anyone in this space will be turning a promising concept into a volume-manufacturable product that meets the market's performance, cost, and reliability expectations.

06 Enphase's Modular Foundation

All solid-state transformers are inherently based on a modular design concept because of the high utility voltages involved for which no monolithic solid-state switches exist. Multiple small power modules are connected in an arrangement that creates a large power capacity SST product. The Alternating Current (AC) inputs of these small power modules are connected in series, while the outputs (DC or AC) are connected in parallel.

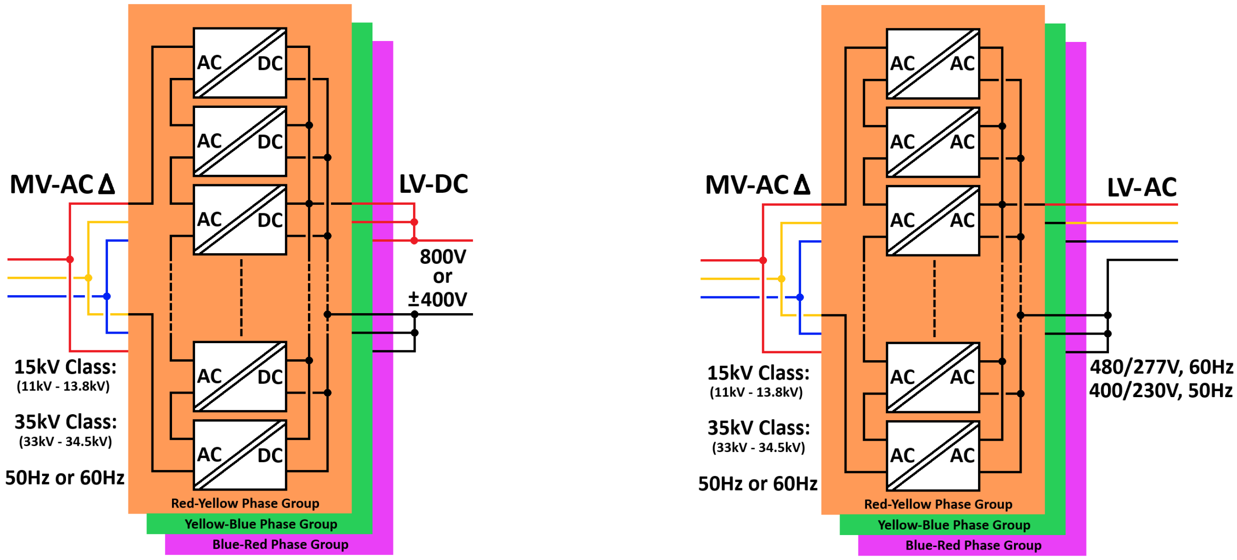

Figure 4: Modular SST Solutions: AC:DC (Left) and AC:AC (Right).

As such, the microinverter power conversion architecture developed by Enphase is well suited to a modular SST solution. The cornerstone attributes that Enphase has established as the foundation of its existing renewable energy product portfolio include:

- **Fast Control Response** — control bandwidth >10 kHz
- **High Conversion Efficiency** — industry-leading; maximizes system value
- **High Reliability** — industry-leading field reliability and product warranty with a 25-year life expectancy
- **Distributed Power Architecture** — easily scalable with no single point for system failure
- **Parallel Redundancy** — with 'hot-swap' serviceability
- **Established Manufacturing** — products supplied from U.S. manufacturing facilities, easily scalable using widely available high-volume components
- **Advanced Technology** — Custom 22 nm Control ASIC, GaN BDS
- **Advanced Grid Functions** — meets electrical grid operator requirements

These core pillars have established Enphase as a global leader in microinverter-based solar and battery systems and form the foundation for the IQ SST -- purpose-built to meet the demands of AI data center applications.

07 The Enphase Differentiation

The central challenge in SST design is achieving the control performance needed to manage dynamic grid-edge loads, without relying on batteries to compensate for slow system response. Enphase's approach addresses this directly: the IQ SST is built around a larger number of lower-power modules, which enables the high switching frequency and control bandwidth that fast load response requires.

Many competitors favor fewer, higher-power modules using high-voltage Silicon Carbide (SiC) switches. While this reduces module count, higher-power modules switch at lower frequencies, limiting control bandwidth and slowing system response. The result is a design that depends on batteries to handle transients that a faster system could manage directly.

The IQ SST's modular architecture delivers advantages across four key dimensions:

- **Performance** — Small module power supports high switching frequency and wide control bandwidth, enabling near-instantaneous load response. This makes it possible to eliminate batteries from white and gray space applications -- a significant cost and complexity reduction.
- **Reliability** — Parallel redundancy combined with hot-swap serviceability achieves 99.999% system availability, meeting the most stringent data center uptime requirements.
- **Cost** — Lower-voltage components are widely available and cost-effective, reducing bill-of-materials cost relative to high-voltage alternatives.
- **Supply Chain** — Module manufacturing leverages Enphase's existing high-volume, U.S.-based automated production lines, reducing procurement risk.

08 The Enphase IQ SST Technology

The power module that will be used in the Enphase IQ SST is based on Enphase's existing IQ Microinverter design. The module design shares much in common with the latest IQ Microinverter used in Enphase's battery storage products.

Enphase microinverters use a unique single-stage converter topology that enables high power conversion efficiency, low Electro-Magnetic Interference (EMI), and excellent control response. Enphase's adoption of this topology since inception was made possible due to the proprietary custom control ASICs that Enphase developed for this purpose.

The latest Enphase IQ Series Microinverters are based on the fifth generation of custom control ASIC codenamed Kestrel. This ASIC is fabricated using a 22 nm CMOS process and integrates an advanced custom digital controller for the Enphase single-stage converter, along with additional capabilities including modern security and functional safety features, and a multi-core software architecture that enables high performance and system availability.

Kestrel also includes a dedicated tandem function developed specifically for IQ SST applications. This allows two Kestrel ASICs, separated by tens of thousands of volts, to operate as a single controller via a fiber-optic interface using industry-proven components designed specifically for this application. This enables each IQ SST power module to inherit Enphase's full microinverter control stack, including years of proven reliability in grid-connected deployments.

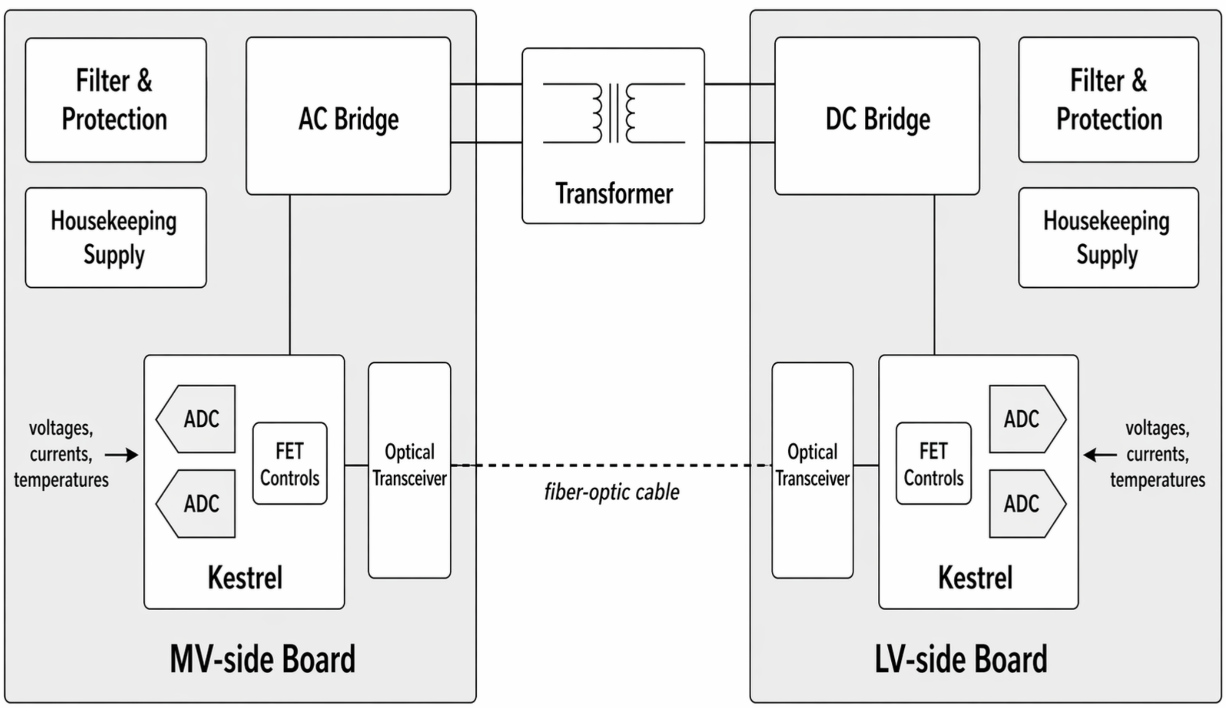

Figure 5: Enphase Kestrel control ASIC supports an IQ SST specific 'tandem' function that links two ASICs via a fiber-optic interface to function as a single control ASIC.

A critical design challenge for any SST module is the insulation system that bridges the medium-voltage and low-voltage domains. The IQ SST power module crosses this boundary at only two points: the fiber-optic link between the tandem Kestrel pair, and the main high-frequency power transformer. This transformer is a proprietary design that meets the insulation, long-term reliability, and performance requirements of the IQ SST application. The transformer, like those in all Enphase microinverters, uses custom magnetic cores and windings developed by Enphase's in-house magnetics team, drawing on two decades of experience designing high-frequency transformers for demanding, long-life applications.

The IQ SST power module also inherits the IQ Microinverter's low-EMI signature, which is a direct consequence of the single-stage resonant topology. This enables the use of low-cost plastic enclosures, a design choice that carries meaningful system-level benefits for the IQ SST rack by simplifying the implementation of electrical field grading across the medium-voltage and low-voltage domains.

Enphase's latest IQ9 Series Microinverters have adopted Gallium-Nitride (GaN) High Electron Mobility Transistor (HEMT) power semiconductor switches. These GaN HEMT devices are in the form of conventional Uni-Directional Switch (UDS) and new Bi-Directional Switch (BDS) technology. Enphase Energy has been deeply involved with the power semiconductor industry during the development of GaN HEMT BDS technology, and GaN BDS switches offer a cost advantage of up to 4x over conventional pairs of UDS devices [6]. GaN devices are now widely available and offer the optimal combination of performance and cost. They are ideally suited for use in Enphase's unique single-stage microinverter products and will also be used in the IQ SST.

09 The Enphase IQ SST Product

The first Enphase IQ SST product in development will support operation from both 35 kV-Class Medium Voltage (MV) utility connections (33 kV and 34.5 kV) as well as 15 kV-Class MV utility connections (11 kV, 13.2 kV, and 13.8 kV). The DC output voltage will support both the NVIDIA 800 VDC as well as the Open Compute Project (OCP) ±400 VDC standards. The IQ SST single-rack product will have a nominal power rating of 1.25 MW with the ability to connect multiple racks together on a skid to accommodate up to 5 MW with additional rack level redundancy, as required (N+1, N+2, 2N, etc.). This will be achieved through a rack of 342 power modules connected in a delta configuration of 3x114 modules for 34.5 kV operation.

The rack is designed for flexible deployment environments, supporting two cooling configurations. For outdoor applications located in the black space outside the data center, the IQ SST makes use of forced air cooling, drawing ambient air through the IP55 rated rack via serviceable air filters and directing it over the 342 individual IQ SST power modules. For indoor applications located in the gray space, the IQ SST product can support a liquid cooling option in the form of a liquid-to-air heat-exchanger 'top-hat' (a unit that sits directly on top of the rack and exchanges heat with the facility's liquid cooling loop).

Figure 6: The Enphase Energy 1.25 MW IQ SST rack

It is envisioned that AI data centers might transition away from the 800 VDC (±400 VDC) DC architecture sometime in the future and move to adopting 1.5 kVDC (±750 VDC). The IQ SST power module is already designed to support this higher DC voltage, also needed for utility-scale PV and BESS applications. As a result, an IQ SST product variant will be offered when these markets materialize.

10 Advantages of Enphase IQ SST

The unique architectural approach being adopted by Enphase for the IQ SST power module results in the IQ SST using a much higher number of lower-powered modules than those used by many competitors. The use of a high number of small power modules has many advantages.

Smaller power modules rely on using smaller circuit inductance values switched at much higher frequency than their larger counterparts. This combination of smaller circuit inductance operated at higher switching frequency results in a considerable improvement in control response time. The loads created by AI data centers are notoriously dynamic, resulting in load fluctuations between 10% and 100% several times per second [7].

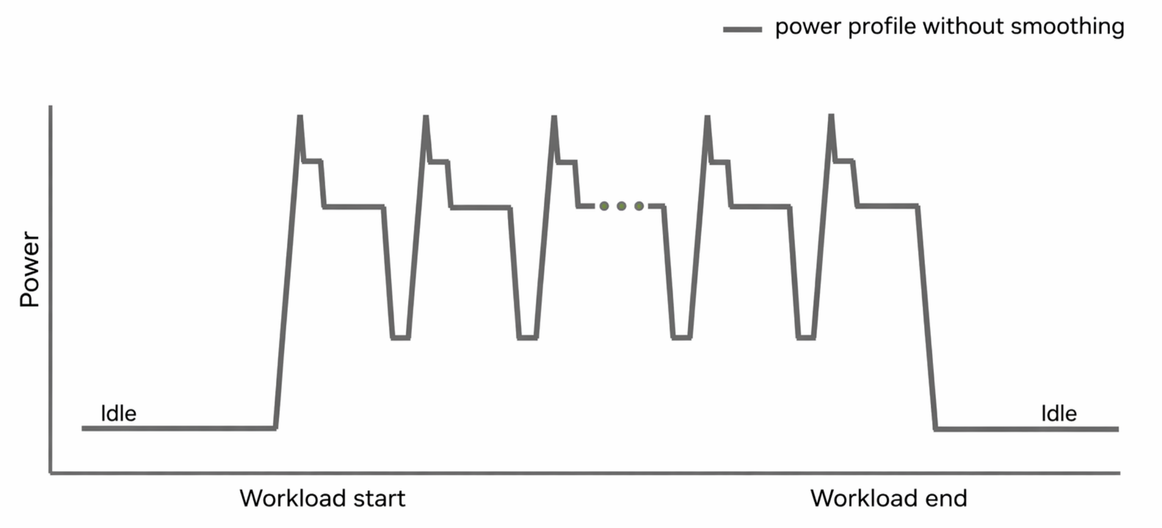

Figure 7: AI data center dynamic load details. [7]

Larger power modules, as used in competing SST products, take several AC line cycles to respond to a sudden load change. This necessitates significant super-capacitor buffering across the DC bus to maintain stable operation under typical AI data center dynamic loads. In contrast, the Enphase IQ SST is designed to respond to these sudden load changes in less than 1 ms.

The control response time for the Enphase IQ SST is approximately a thousand times faster than most conventional solutions. This directly translates to being able to reduce the required capacitor-based energy buffering that needs to be collocated in the AI compute racks by a factor of a thousand.

This vastly superior control response provided by the IQ SST solution will enable the bulk energy buffering solutions to be located farther away from the AI compute racks and moved outside the data center in the form of large-scale BESS.

The high number of power modules that will be used in the IQ SST also results in each individual power module using widely available lower-voltage rated components. The use of high-volume electronic components offers cost and availability benefits for IQ SST production. These components also have the benefit that high volume lifetime reliability data is commonly available.

The relatively small power rating of the IQ SST power module will be comparable to existing high production volume Enphase microinverters that are used in BESS products. Enphase has a proven track record of mass-producing high-reliability power modules based on the company's microinverter architecture. The IQ SST power module builds upon existing proven power conversion hardware and associated manufacturing capability.

Figure 8: Enphase Energy 4 kW IQ SST power module.

Included in the IQ SST power module is a comprehensive library of Advanced Grid Functions (AGFs) due to the reuse of Enphase's existing power conversion architecture. As penetration of Inverter Based Resources (IBR) has grown over recent decades, grid operators and utilities have introduced legislative standards requiring IBR assets to provide AGF capability to help stabilize the grid.

It is anticipated that this existing AGF capability that has been legislated for renewable energy IBR products will be adopted for electrical utility grid connected SSTs. If such legislation is enacted for SST products, then we expect that the Enphase solution will already be compliant with existing AGF capability as defined in the standards such as IEEE 1547 and UL 1741 [8, 9].

The Enphase IQ SST will also include a high level of parallel redundancy. As designed, up to 10% of the individual power modules can fail without impacting the performance of the IQ SST. Based on existing Enphase microinverter field reliability information, this level of inbuilt system redundancy is expected to be sufficient to last the IQ SSTs expected 10-year limited warranty life.

In addition to this inbuilt 10% parallel redundancy, the Enphase IQ SST will also support power module level hot-swap replacement. The small power module size used in the Enphase IQ SST will enable this hot-swap replacement to be performed by emergent robotic automation technology, increasingly used for white space maintenance in the data center. This simplifies the logistical and regulatory complexity of servicing the medium voltage (34.5 kV) connected IQ SST.

Systems based on IQ SST can also employ a second level of redundancy. In addition to power-module-level redundancy, product-level redundancy is supported at the 1.25 MW rack level.

The combination of industry-leading field reliability, high module count, inbuilt 10% parallel redundancy, module level hot-swap support, and dual-level redundancy provides a rich set of features that can support simple, effective maintenance of an installed fleet of IQ SST products.

11 Conclusion

Enphase Energy is developing the IQ Solid-State Transformer (IQ SST), targeted at the next generation of AI data centers adopting an 800 VDC (±400 VDC) power distribution architecture. The IQ SST will be built around a larger number of smaller power modules than conventional SST approaches, a design choice that prioritizes control performance, from which the system's other advantages will naturally follow.

This architecture will deliver four distinct competitive advantages:

- **Performance** — Sub-millisecond transient response, approximately one thousand times faster than conventional SST solutions, enabling remote BESS placement and eliminating the need for local energy buffering in the data center.
- **Reliability** — Inherent parallel redundancy with module-level hot-swap serviceability, providing the 99.999% system availability that modern AI data centers require.
- **Cost** — Reliance on widely available, lower-voltage components reduces bill-of-materials cost and avoids the supply constraints associated with high-voltage alternatives.
- **Supply Chain** — Direct compatibility with Enphase's existing high-volume, U.S.-based automated manufacturing infrastructure, providing a clear and proven path to reliable mass production.

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