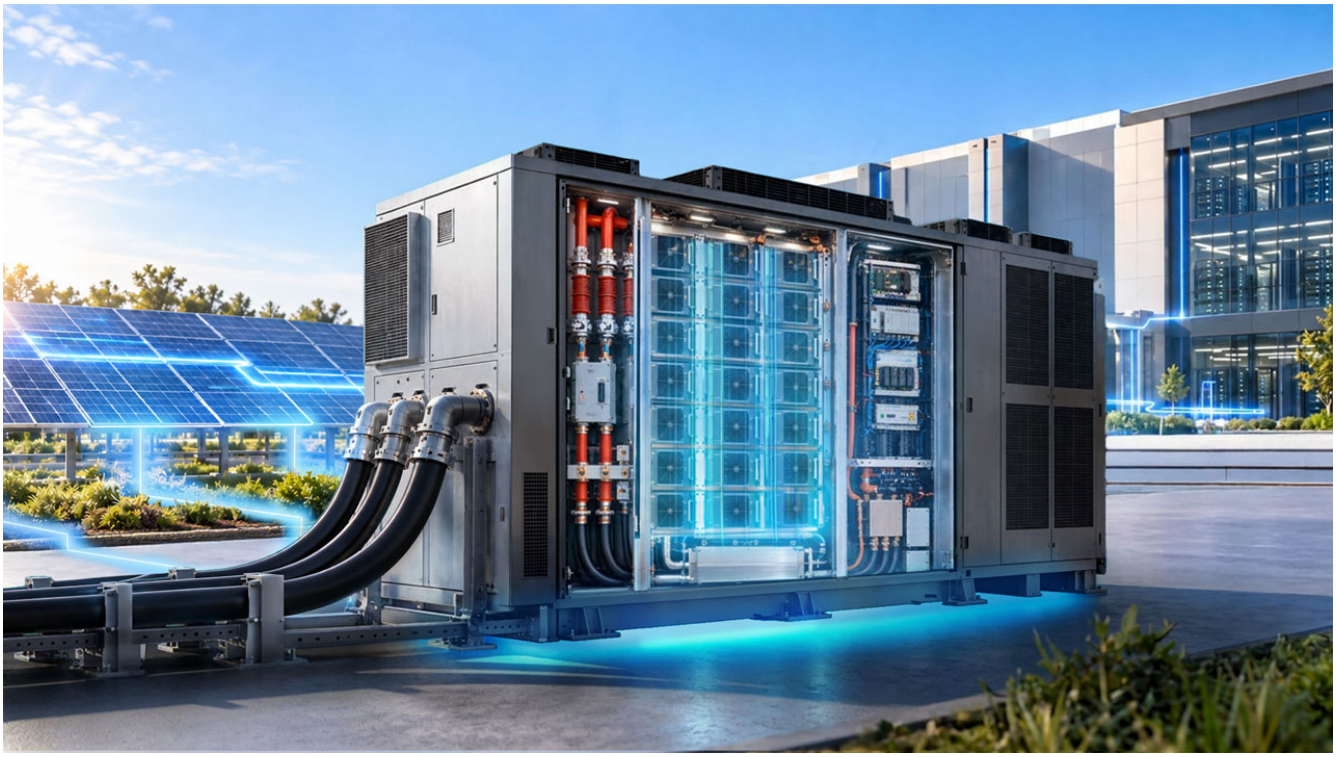
Technical Article

Solid-state transformers are ready to reshape grid-scale power delivery

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- Solid-state transformers (SSTs) enable efficient, compact power delivery that scales to 35kV and 6MW.
- Silicon carbide (SiC) technology advancements are accelerating SST adoption in data center, electric vehicle (EV) charging, and energy storage applications.



SSTs have long offered the potential to improve power-conversion efficiency, reduce system size, and enable flexible power architectures. Until recently, technical and economic limitations restricted their widespread adoption, but advanced SiC power devices with voltage ratings as high as 3.3kV are overcoming these barriers. These devices enable higher switching frequencies, higher DC-link voltages and fewer converter cells, supporting more compact architectures. As SST developments target power levels of 2MW to 6MW and grid voltages as high as 35kV, engineers must prioritize advanced converter topologies, high-voltage isolation, real-time control, and reliable communications.

These capabilities are popularizing the adoption of SSTs in data centers, megawatt-class EV charging, and grid-connected energy storage. In data centers, an SST-based power architecture can improve overall grid-to-graphics processing unit power delivery efficiency by more than one percentage point. Given that a single artificial intelligence (AI) compute rack consumes approximately 1MW, this marginal gain translates into meaningful energy savings across large-scale data center facilities.

Figure 1 shows the architectural changes from the traditional approach with low-frequency transformers and multistage AC/DC and DC/DC conversion, to direct conversion from the mid-voltage grid through high-frequency transformer down to $800V_{DC}$ or $1.5kV_{DC}$.

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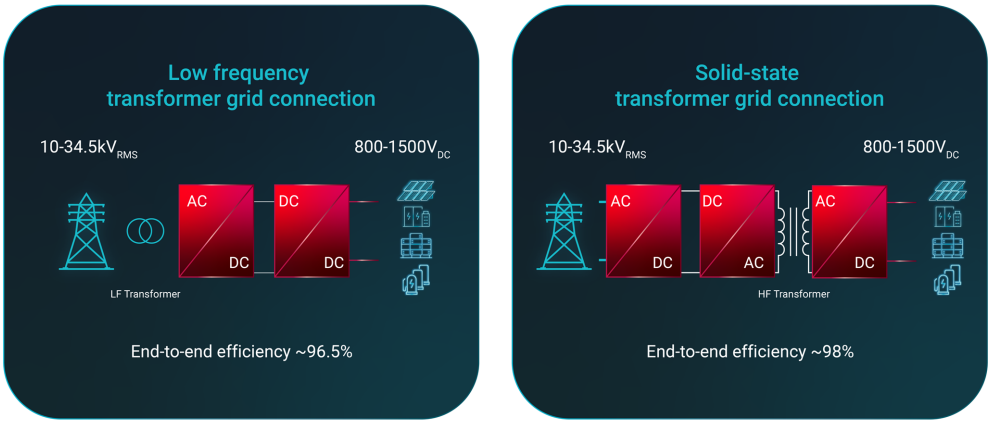


Figure 1. Efficiency savings with a low-frequency transformer-based grid connection vs an SST implementation

Changes that make SSTs a viable alternative to low-frequency transformers

Modern SiC devices support higher switching frequencies while reducing power losses, which improves overall system efficiency. These higher operating frequencies also enable smaller passive components, resulting in more compact designs and lower material costs. Texas Instruments (TI) supports these systems with isolated gate drivers, isolation technologies, sensing solutions, and real-time control capabilities to make large-scale SST deployment increasingly practical.

A typical SST implementation uses stacked AC/DC converters on the medium-voltage side (AC_{MV}) with parallel-connected DC/DC outputs on the low-voltage side (Figure 2).

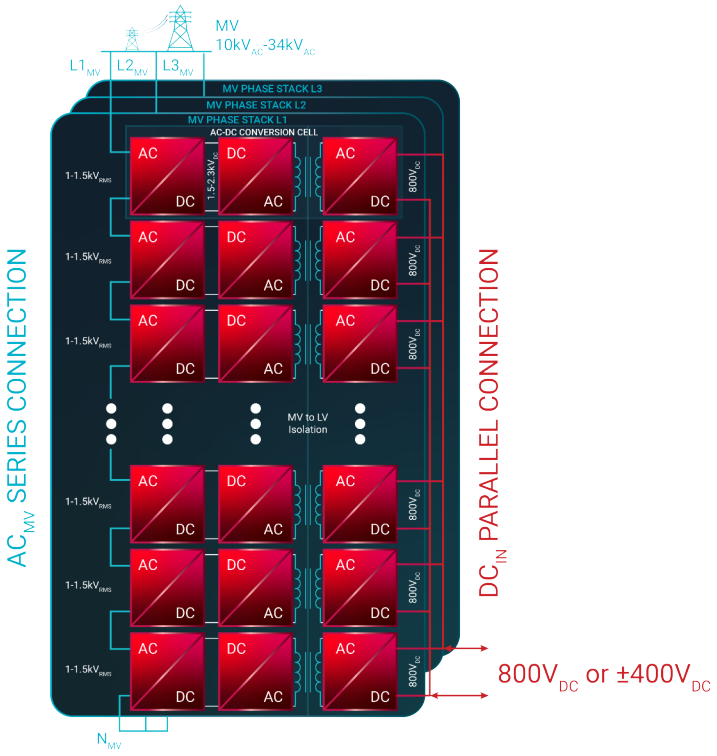


Figure 2. A typical SST implementation, with stacked air conditioning and mechanical ventilation converters and parallel low-voltage outputs

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The breakdown voltage of power semiconductors directly influences how designers implement the SST architecture. While early implementations primarily relied on 1.7kV power devices, the availability of SiC modules rated at 2.3kV and 3.3kV has significantly reshaped system design. Specifically, these devices allow for higher DC-link voltages, which enables a reduction in the total number of cells. For example, it is possible to reduce an SST requiring 100 converter cells with 1.2kV devices to approximately 50 cells using 3.3kV SiC devices. This reduction simplifies system design; decreases physical size; and reduces the complexity of the communication architecture, since every converter cell must communicate with a central controller. Figure 3 illustrates how cell counts scale down across different medium-voltage classes as SiC voltage ratings increase from 1.2kV to 3.3kV.

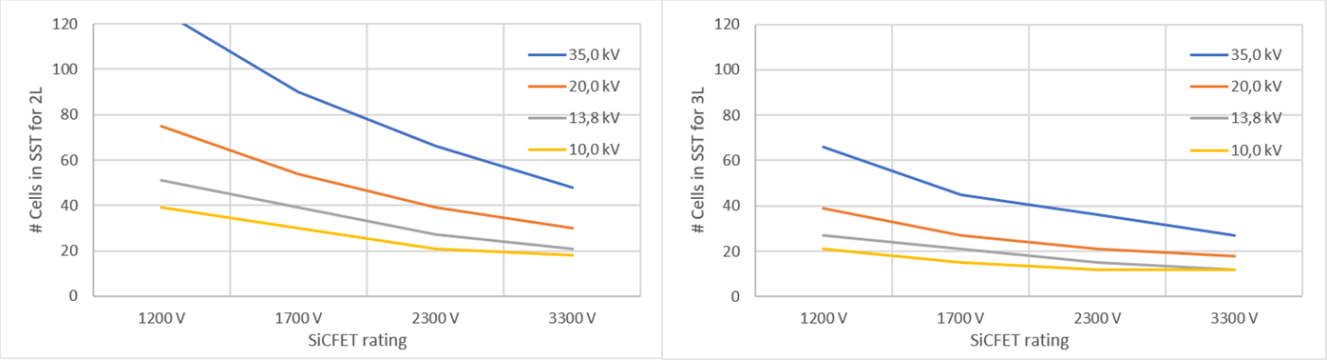


Figure 3. Cell scaling for 2L and 3L conversion cells based on SiC rating

At the same time, higher power density and faster switching speeds place greater demands on the supporting electronics. Gate drivers must provide advanced protection functions such as desaturation detection, support adjustable slew-rate control, supply sufficient gate-drive current for the power modules, and operate reliably under very high common-mode transient immunity conditions of up to 100V/ns. Additionally, when the operating voltage within an individual converter cell exceeds 2kV, isolated gate-driver implementations also require specific design techniques such as cascading isolation barriers to maintain reliable operation.

While devices in the 2.3kV to 3.3kV range provide a practical trade-off between architecture and cost, they also provide redundancy strategies. In N + 1 or N + 2 phase-stack configurations, each additional redundant cell represents a larger and more expensive increment in installed power capacity when using higher-voltage SiC devices. Phase-stack redundancy concepts commonly use N + 1 or N + 2 configurations so that the system can continue operating if an individual cell fails. Consequently, engineers must balance the reduction in cell count against the increased cost of each redundant unit.

Voltage requirements and power classes for SSTs

The relevant power and voltage classes for SSTs are also increasing. Early implementations were generally limited to approximately 1MW. Today, medium-voltage grid-connected solar and energy storage systems (ESSs) typically begin at around 2MW to 4MW, with some systems reaching 6MW. New SST developments must therefore support power levels in the 2MW to 6MW range, and several manufacturers have already announced systems within these power classes.

Grid-voltage requirements are evolving in parallel. Earlier SST designs primarily targeted medium-voltage grids at 10kV and approximately 13.8kV, while future generations are expected to support grid voltages of up to 35kV. These higher power and voltage levels introduce additional requirements for power density, insulation and high-voltage isolation. TI addresses these requirements with technologies for gate drive, isolation, sensing, and control designed to support efficient, grid-connected high-voltage power systems.

Architectural choices for SSTs

While earlier SST designs relied primarily on two-level H-bridge converters (see Figure 4), multilevel topologies, particularly the active neutral point clamped (ANPC) converter, are becoming more common in the AC/DC stages of next-generation SSTs. These topologies address the higher voltage stresses and efficiency requirements of modern systems.

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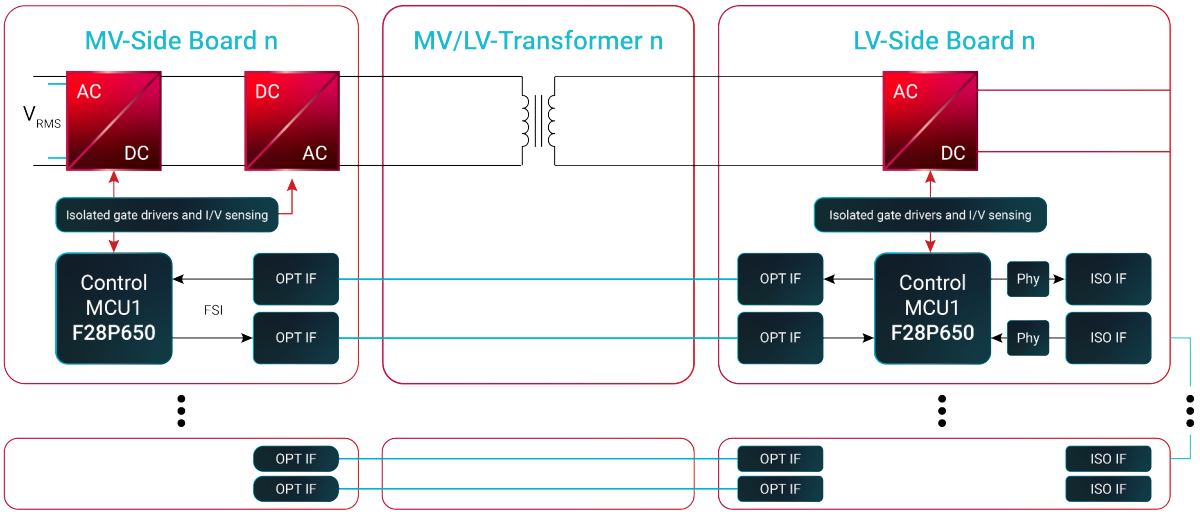


Figure 4. Conversion cell architecture with AC/DC and isolated DC/DC

For the isolated DC/DC stage, designers typically choose between a phase-shifted dual-active-bridge (DAB) converter and a resonant CLLLC DAB converter. Because multiple DC/DC converters connect in parallel within an SST, fixed-frequency topologies such as the phase-shifted DAB are often preferred for simpler synchronization. In contrast, a CLLLC DAB architecture can lead to slightly different switching frequencies, potentially creating audible beat frequencies or electrical interference that is difficult to filter.

To address diverse application requirements, TI provides a these device technologies:

- Real-time microcontrollers (MCUs) support established modulation techniques for two-level H-bridges and multilevel topologies, including ANPC, neutral point clamped, T-type and flying capacitor converters.
- High-voltage gate drivers and isolation specifically designed to meet the working-voltage requirements of 2.3kV and 3.3kV SiC power modules.
- Isolated sensing solutions provide precise current and voltage sensing optimized for high-voltage, high-frequency environments.

By connecting the control MCU's ground to the midpoint of the DC link – for example, with a real-time TI C2000™ MCU – designers can reduce the voltage stress across the isolation barrier and keep the relevant working voltages below 2kV.

As SST architectures continue to evolve toward supporting higher power levels, higher grid voltages, greater power density and more integrated control, the supporting technologies around the power semiconductors become increasingly important. High-voltage gate drivers, isolation, sensing, real-time control, and reliable system communication all play important roles to enable the next generation of SST systems.

Design-specific challenges to overcome

Beyond architectural choices, designers face a significant technical challenge in SST design: synchronization of the AC/DC stage and isolated DC/DC stage within each converter cell. These functions operate across two distinct voltage domains. The AC/DC stage and the primary side of the isolated DC/DC converter operate on the medium-voltage side, while the secondary side of the isolated DC/DC converter operates on the low-voltage side.

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The isolation barrier between these domains must withstand the full phase-to-neutral voltage of the SST. In a system rated at 35kV line-to-line, this voltage can reach approximately 20kV. Meeting this requirement demands substantial physical separation as well as appropriately dimensioned clearance and creepage distances, as shown in Figure 5, where the high-frequency transformer sits in the middle. On the medium-voltage printed circuit board (PCB) (Figure 5A) and the low-voltage PCB (Figure 5B), the isolation clearances must comply with the working voltages of the converter module, which typically do not exceed 2kV in new SST systems.

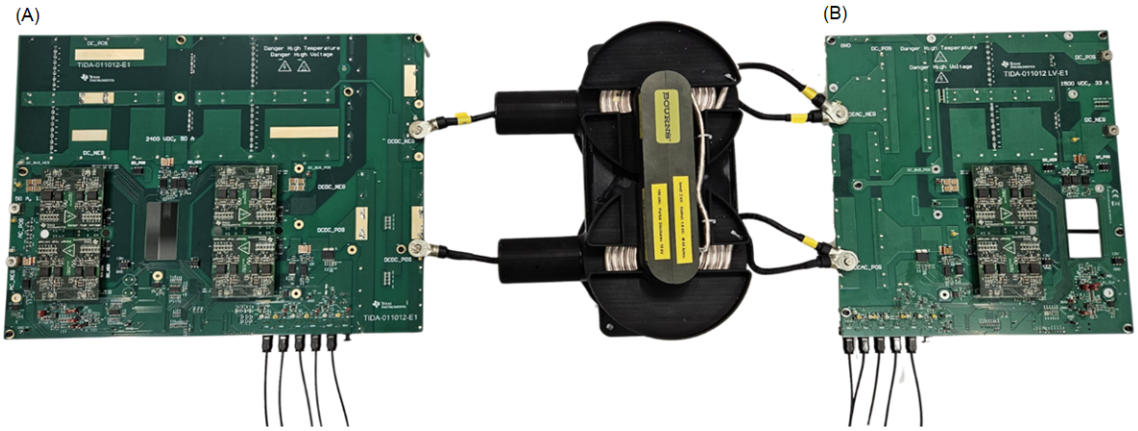


Figure 5. A 50kW SiC-based modular SST, with a plastic optical fiber interface between medium-voltage (A) and low-voltage (B) PCBs

Designers can implement communication across this high-voltage isolation barrier using optical links or radio-frequency technologies. Fiber-optic communication is currently the preferred approach because of its low latency, strong immunity to electromagnetic interference and high isolation capability. More cost-effective, high-speed optical transceivers will therefore play an important role in reducing overall SST system costs.

Additionally, designers must develop communication between the central controller and the individual converter cells within each phase stack. A standardized communication architecture based on a widely adopted and reliable protocol could simplify interoperability while making it easier to address evolving cybersecurity requirements, including regulatory frameworks such as the European Union's Cyber Resilience Act.

TI offers resources and reference designs to help designers accelerate time to market. For example, the 50kW SiC-Based Modular Solid-State Transformer for Medium-Voltage Applications Reference Design, shown earlier in Figure 5, is a good starting point.

Other applications that will benefit from SST adoption

SST development is also advancing rapidly in EV charging, particularly for megawatt-class charging infrastructures. Today, operators connect these systems to low-voltage grids operating at up to $690V_{AC}$ and interface them with the medium-voltage grid through conventional low-frequency transformers.

An SST enables a more direct connection to the medium-voltage grid and can improve energy efficiency by reducing the number of power-conversion stages between power generation and the EV battery. This architecture is particularly attractive for heavy-duty EVs and charging locations with multiple dispensers.

Medium-voltage grid-connected ESSs represent another compelling application. In combined solar and storage installations, connecting central solar inverters directly to the ESS on the DC side eliminates the need to convert solar power from DC to AC in the central inverter and then back from AC to DC for storage – a two-step conversion that wastes energy. A DC-coupled solar-plus-storage architecture connected to the medium-voltage grid through an SST simplifies the overall power-conversion chain, reduces conversion losses, and improves system efficiency.

Across these applications, SSTs enable architectures that are both simpler and more efficient in terms of energy conversion and power delivery.

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About the author

Harald Parzhuber manages the renewable energy systems team at Texas Instruments. He has over three decades of engineering experience, ranging from design and test engineering to product definition and system engineering. In addition to this, he holds four patents in the area of industrial automation. Parzhuber received his master's degree in electrical engineering from the University of Applied Sciences in Landshut, Germany.

Additional resources

- Check out a demonstration video of the 50kW SST design, "Replacing traditional transformers for AI data centers."

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Last updated 10/2025