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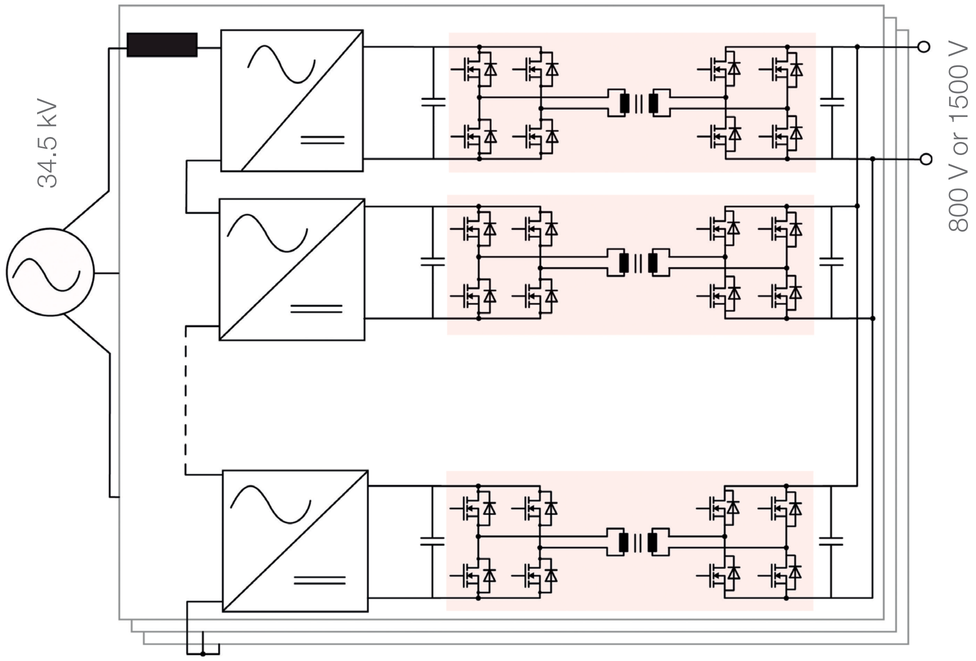
SiC Modules for High Power Data Centers



Built into the Future

From Grid to GPU: Enabling Multi-Megawatt SST Architectures with High-Current SiC Power Modules

AI-driven data centers require power-supplies with high efficiency, power density, and reliability. Solid-State-Transformer (SST) architectures based on SiC power modules enable direct conversion from 34.5 kV medium-voltage grids to 800 V and future 1500 V data center DC-infrastructures. This article highlights how high-power SSTs and high-current, highly reliable SiC modules can support multi-megawatt hyperscaler applications while improving efficiency and the key AI performance metric: "Tokens per Second per Megawatt."

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The electricity demand of datacenters is set to increase by at least two fold until 2030 [1]. Moreover, large scale data centers (Hyperscalers) will be a key driver for the overall electricity demand [2]. Today, 72% of the datacenters have a power demand of more than 50 MW [3] and blueprints for 100 MW installations are available [4]. Trends indicate that future Hyperscalers demand power in the GW range [5].

Today, electrical power and the connection to the electricity grid is considered to be the ultimate constraint for AI infrastructure [6]. Therefore, "performance per Watt" or "Tokens per Second per Megawatt" are considered key indices for evaluating AI throughput. AI infrastructure is power hungry, and any improvement in efficiency translates into "tokens" and finally into revenue. Considering the trajectory of power demand for AI infrastructure and the improvements to "Tokens per Second per Megawatt", it can be summarized that power supply for AI infrastructure will require solutions which can innovatively combine high power densities and high operational efficiency while maintaining a certain level of modularity to scale output power.

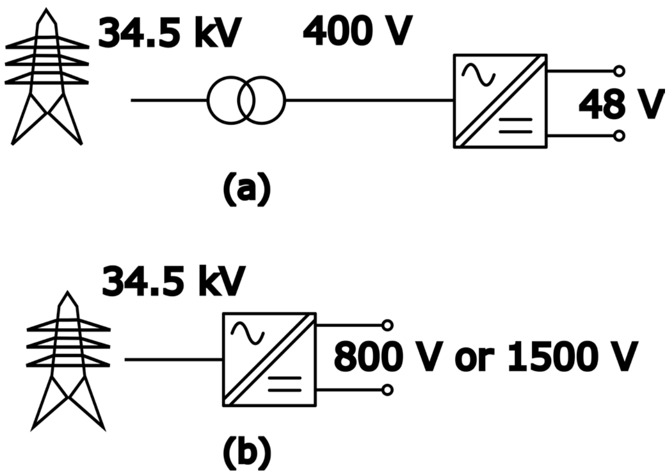


Figure 1: (a) Conventional approach with Low Frequency Transformer (LFT) and multi-stage AC to DC conversion at low voltage with isolation. (b) SST based power delivery to datacenter at DC-voltages of 800 V or 1500 V.

From LFT to SST

As illustrated in Figure 1, the power architecture to supply the server racks has transitioned from a 48 V DC-bus to 800 V. Referring to Figure 1 (b), an AC-to-DC conversion stage is employed with galvanic isolation to energize the 800 V DC-bus directly from the 34.5 kV distribution network. Such a power-conversion system is commonly referred to as Solid-State-Transformers (SST). Replacing the conventional system, based on low frequency transformers (LFT), with an SST offers several advantages especially including higher efficiency, increased power density, and enhanced design flexibility and modularity [7]. Particularly, modular SST architectures are considered attractive for Hyperscalers due to their scalability and suitability for multi-megawatt power levels [8]. The power supply architecture can be developed using multiple AC/DC and isolated DC/DC conversion cells (refer to Figure 2).

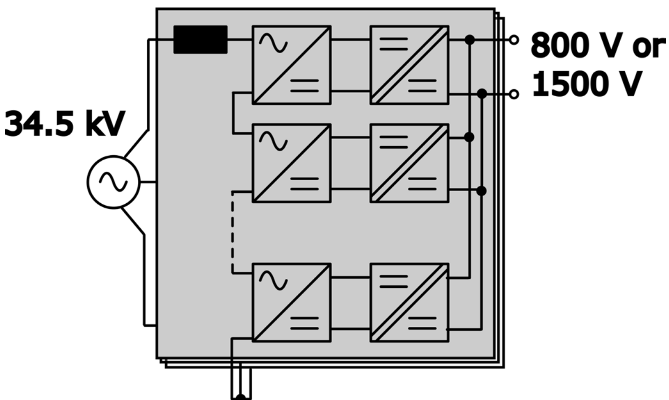


Figure 2: Simplified SST architecture with multiple cells being connected in series at their input.

Topologies and Solutions

Today 800 V DC-bus systems are state-of-the-art for server-rack supply. However, motivated by the significant increase in power demand, higher system voltages like 1500 V are being discussed [9]. For PV inverters and battery-energy-storage systems, 1500 V is the widely accepted DC-voltage level as it represents the upper-limit of the European Low Voltage Directive (IEC). In the following, both, the 800 V and 1500 V use cases shall be analyzed in more details.

The focus of the evaluation is limited to the isolated DC-to-DC conversion stage inside each cell of the SST. In this example, a dual-active bridge topology is considered as depicted in Figure 3. At the input side, which is connected via an AC/DC converter to the medium-voltage distribution network, 1800 V DC-link voltage is considered. Due to the comparable high operating voltage, grid voltages like 34.5 kV can be achieved with a reasonable number of cells, which limits system complexity.

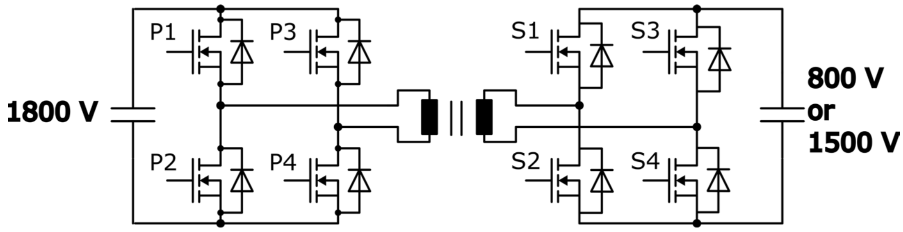


Figure 3: SST solution based on a Dual-Active-Bridge topology.

In the following analysis, 16 cells are considered per phase.

800 V DC-voltage output system

For the isolated DC/DC converter from 1800 V to 800 V, the considered Mitsubishi Electric SiC MOSFET power modules are for the primary side the FMF800DC-66BEW (3.3 kV / 800 A) in the LV100 housing, and for the secondary side the FMF600DXE-24BN (1.2 kV / 600 A) in the NX housing with 2 devices in parallel. The operating conditions are listed in Table 1. The virtual junction temperature is estimated on the devices based on liquid cooling with the thermal resistances from heatsink to water of around 16 K/kW and 30 K/kW for LV100 and NX packages, respectively. The remaining parameters are taken from datasheets.

Switching frequency f_C	10	kHz
Output power P_{out}	550	kW
DC input voltage V_{in}	1800	V
DC output voltage V_{out}	800	V
Turns ratio N	2.25	
Stray inductance L_σ	25	µH
Water temperature T_W	40	°C
Primary side power module	FMF800DC-66BEW	
Secondary side power module	FMF600DXE-24BN	

Table 1: Simulation conditions for a power supply system with a DC voltage output of 800 V.

As shown in Figure 4, for the operating conditions in Table 1, the maximum virtual junction temperature of the primary side and secondary side power modules reaches 127 °C and 150 °C, respectively.

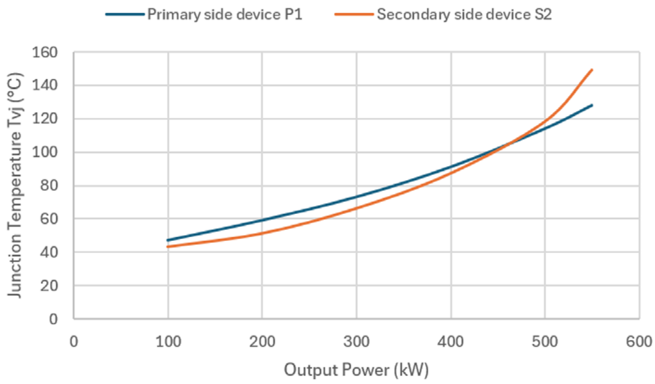


Figure 4: Simulation results showing maximum output power versus maximum junction temperature of the power module for DC-output = 800 V.

1500 V DC-voltage output system

For the isolated DC/DC converter from 1800 V to 1500 V, the considered Mitsubishi Electric SiC MOSFET power modules are, for the primary side the 2 FMF800DC-66BEW in parallel, and for the secondary side the 2 FMF1600DC-50CW (2.5 kV / 1600 A) in parallel. Both devices use the LV100 housing. Table 2 shows the operating conditions. The virtual junction temperature is estimated on the devices based on liquid cooling with the thermal resistances from heatsink to water as around 16 K/kW for the LV100 devices. The remaining parameters are taken from datasheets.

Switching frequency f_C	10	kHz
Output power P_{out}	1.3	MW
DC input voltage V_{in}	1800	V
DC output voltage V_{out}	1500	V
Turns ratio N	1.2	
Stray inductance L_σ	5	µH
Water temperature T_W	40	°C
Primary side power module	FMF800DC-66BEW	
Secondary side power module	FMF1600DC-50CW	

Table 2: Simulation conditions for a power supply system with 1500 V_{DC} output.

As shown in Figure 5, for the operating conditions in Table 2, the maximum virtual junction temperature of the primary side and secondary side power modules reaches 136 °C and 150 °C, respectively.

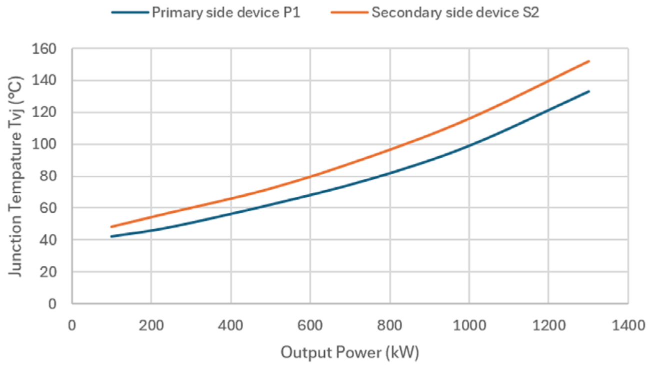


Figure 5: Simulation results showing maximum output power versus maximum junction temperature of the power module for DC-output = 1500 V.

The simulation results show that 550 kW and 1.3 MW are realistic targets for a 800 V and 1500 V system. As stated above, for the connection to the 34.5 kV distribution network, 16 cells are considered per phase, resulting in 48 cells for the three phases. Delivering 1.3 MW per cell using Mitsubishi Electric SiC power modules results in a system output power of 62 MW. It becomes evident that high-power SST and high-current SiC power modules are the crucial components to current data center power requirements of 50 MW and higher. At the same time they are providing a scalable path to support future growth and improving "Tokens per Second per Megawatt".

Power modules considered in this analysis
The primary side requires power modules with 3.3 kV SiC MOSFETs while the secondary side power modules are either 1.2 kV SiC MOSFETs for 800 V output or 2.5 kV SiC MOSFETs for the 1500 V output. Each power module is a half-bridge consisting of 2 switches in a package. While the 1.2 kV power module is available in the NX housing, the 2.5 kV and 3.3 kV power modules are available in the LV100 housing.

1.2 kV SiC MOSFETs
Power module package compatibility is a key aspect which system designers need to consider when new solutions are being developed. Widely utilized conventional packages have been developed based on Si IGBT devices, and incorporating SiC devices in these conventional (but widely accepted) packages are challenging. SiC MOSFETs switch faster than Si IGBTs and require special power module design consideration with regards to internal current balancing of parallel connected MOSFET dies and overall internal parasitic inductance. The NX package is a widely adopted power module housing for several applications including uninterruptable power supplies, photovoltaic, battery storage systems and motor drives for output power in the range of several hundred kilowatts. A usual disadvantage of a conventional NX package is its high internal parasitic inductance in the range of 15 to 20 nH. The reason for this is the layout of the chips and the internal busbar design. High internal inductance presents a challenge for SiC adoption as it prevents the user from taking advantage of high switching speeds.

The special NX module for SiC adoption
This problem was solved by introducing a special NX module (Figure 6) designed for SiC adoption [10]; its internal busbars are organized in a laminated structure (Figure 7). The SiC MOSFET dies were internally placed for optimum current sharing. The overall parasitic inductance of the NX SiC module is about 9 nH. The package utilizes an AlN ceramic substrate and offers 4 kV of isolation between the terminals and the baseplate.

Figure 6: SiC MOSFET power module FMF600DXE-24BN in the NX package.

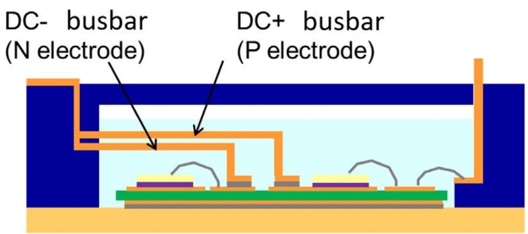


Figure 7: Cross-section of the NX SiC power module showing laminated busbar design.

The NX SiC modules are currently available in the ratings of 1.7 kV / 600 A (FMF600DXE-34BN) and 1.2 kV / 600 A (FMF600DXE-24BN) and are provided with the second generation Mitsubishi SiC chip technology. The low inductance package design allows the user to extract maximum performance from the advanced second generation (G2A) SiC MOSFET chips.

The simulation results in Figure 4 indicate that the secondary side device FMF600DXE-24BN is the thermal bottleneck. By utilizing power modules with lower $R_{DS(on)}$ and higher current rating, it is possible to extend the overall output of the power stage.

Refering to Table 3, the NX SiC power module line-up is being extended towards higher current ratings. Additionally, a new chip generation (G2B) is also under development to further optimize overall electrical performance (refer to Figure 8).

Rating	$R_{DS(on)}$ [mΩ] at 150 °C	Status	Chip Technology
1.2 kV / 600 A	2.68	Mass production	G2A SiC
1.2 kV / 600 A	2.4	Under development	New G2B SiC
1.2 kV / 800 A	1.8		
1.2 kV / 1000 A	1.43		

Table 3: Line-up of the 1.2 kV NX SiC power modules currently under development.

Reliability of SiC power modules
While power density and efficiency play a direct role in determining the revenue generation capability of the installed AI infrastructure, reliability and preventing down-time due to failures is an often-overlooked aspect in the overall cost-benefit calculation. There are several known degradation modes for SiC MOSFETs. The stability of the $V_{GS(th)}$ is one key aspect, and Mitsubishi SiC power modules have demonstrated good $V_{GS(th)}$ stability (refer to Figure 9). Another topic which is important for long term is the so called "bipolar-current-degradation" [11]. Referring to Figure 10, it can be understood that, for 5 % increase in $V_{DS(on)}$, the estimated probability at the module level is about 100 ppm, indicating robustness towards bipolar current degradation.

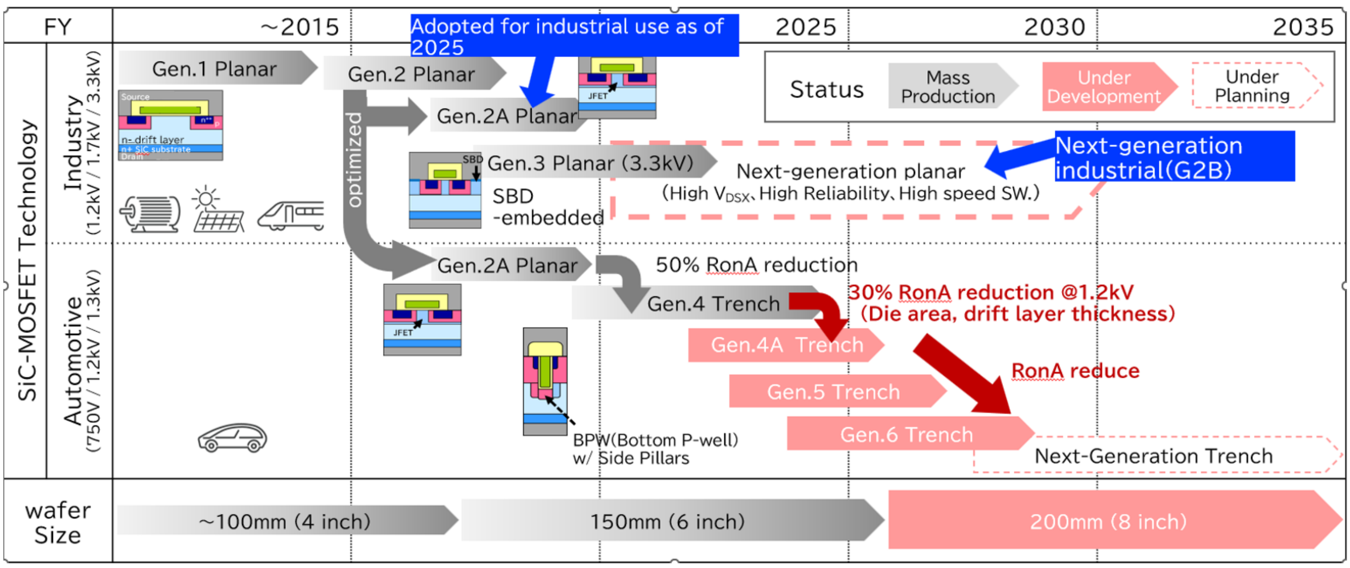


Figure 8: SiC Chip technology roadmap.

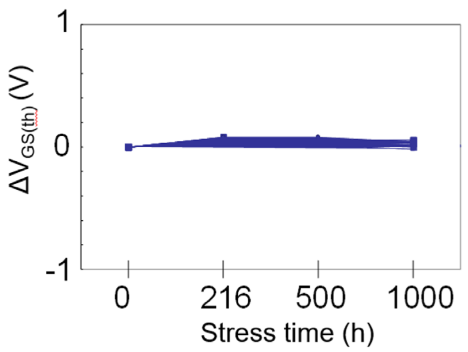


Figure 9: Delta $V_{GS(th)}$ vs stress time for T_{vj} = 150 °C, V_{GS} = +20 V, duration = 1000 hours. N = 22 pcs.

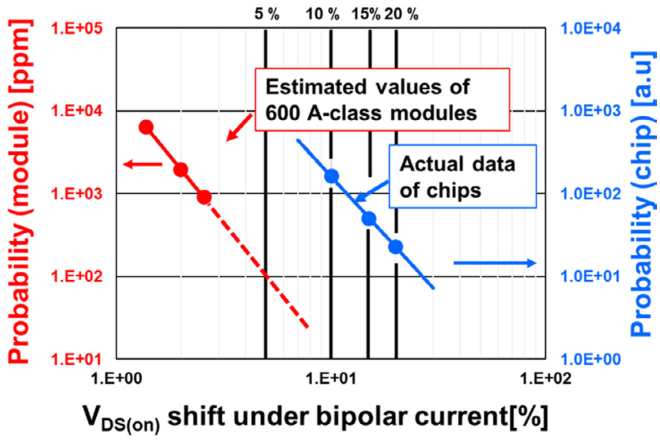


Figure 10: Probability of $V_{DS(on)}$ shift of SiC MOSFET chips due to bipolar current stress for a 1200 V SiC device.

2.5 kV and 3.3 kV SiC MOSFETs

Table 4 presents the line-up of the 2.5 kV and 3.3 kV SiC power modules which are applicable for the datacenter power supply application. The devices are available in the LV100 package (refer to Figure 11), which is accepted as the industry standard for high power applications. The LV100 modules are widely adopted in megawatt level PV, BESS applications as well as traction applications. The LV100 package was developed considering SiC adoption for high power applications and is therefore already optimized with regards to internal busbar layout and the internal chip placement. The LV100 module shown in Figure 11 utilizes an AlSiC baseplate for high thermal cycling capability and has an isolation voltage of 6 kV between terminals and baseplate. Table 4 shows the line-up of the available SiC LV100 modules.

Figure 11: The LV100 package for the FMF1600DC-50CW and FMF800DC-66BEW.

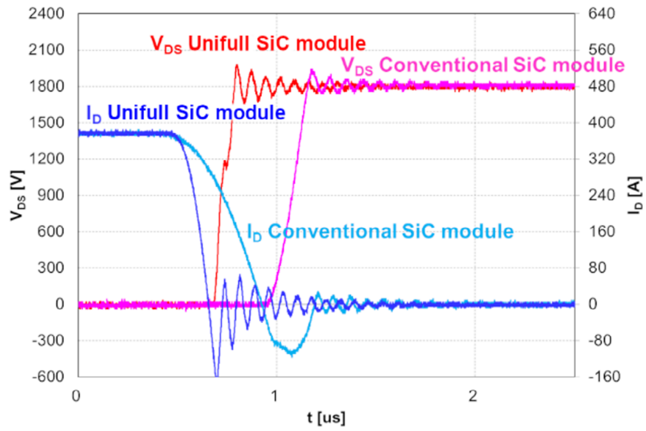
The 2.5 kV / 1600 A SiC LV100 (FMF1600DC-50CW) has been specifically developed for PV and BESS applications requiring 1.5 kV DC-link. For such applications, the best trade-off between cosmic ray FIT and electrical loss performance is required while maintaining sufficient margin for switching over voltages, which is relevant while utilizing SiC high switching speed operation. Since the module utilizes the latest G2B SiC chip technology, it is optimized for best electrical loss performance (Q_{rr} reduction using proton irradiation), and the module has a target FIT of less than 100 for 1500 V.

Type Name	Blocking Voltage [V]	Rated Current [A]	$R_{DS(on)}$ at 150 °C [mΩ]
FMF1600DC-50CW	2500	1600	1.75
FMF200DC-66BE	3300	200	17.25
FMF400DC-66BEW	3300	400	8.63
FMF800DC-66BEW	3300	800	4.31

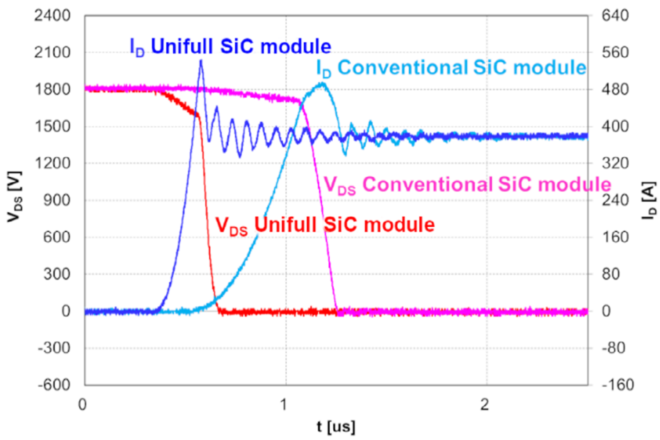
Table 4: The line-up of the 2.5 kV and 3.3 kV SiC LV100 modules.

3.3 kV SiC MOSFET

In 2024, Mitsubishi Electric has released the Unifull™ SiC power modules with embedded Schottky Barrier Diode (SBD) [12][13]. The embedded SBD effectively solves the issue of bipolar degradation by deactivating the internal body diode of the SiC MOSFET. Furthermore, as the body diode is deactivated, Unifull SiC power modules have no reverse recovery losses and reduced turn-on losses. Exemplary switching waveforms shown in Figure 12 demonstrate the absence of recovery charge and the higher switching speed of the Unifull power modules. Overall, switching losses of Unifull 3.3 kV SiC MOSFETs are reduced by 58 %, compared to the previous 3.3 kV SiC generation as shown in Figure 13.



(a) diode reverse recovery



(b) MOSFET turn on

Figure 12: Switching waveform comparison between conventional 3.3 kV SiC MOSFET (FMF375DC-66A) and Unifull™ 3.3 kV SiC MOSFET (FMF400DC-66BEW).

Mitsubishi Electric has specially developed Unifull 3.3 kV SiC power modules for high reliability applications like railway traction and grid applications. 6 kV isolation voltage and partial-discharge free design according to IEC 61287-1 make this device suitable for direct operation at the high-voltage electricity grid. In case of unforeseen events, surge current and I^2t values are specified with 5.9 kA and 180 kA^2s, respectively.

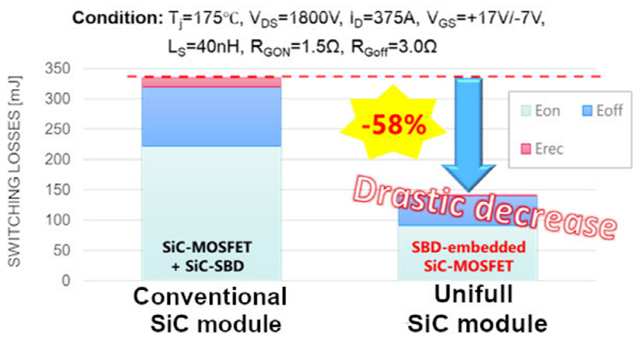


Figure 13: Swichting loss reduction of Unifull™ 3.3 kV SiC MOSFET (FMF400DC-66BEW) compared to conventional 3.3 kV SiC MOSFET (FMF375DC-66A).

Unifull power modules use sintering to attach the SiC dies to the substrates. This increases the power-cycling capabilities compared to conventional soldering technology. To provide even higher power-cycling capability for especially demanding applications, Unifull™ Plus technology has been developed [14] recently. As visualized in Figure 14, enhance bond-wire material and chip metallization is utilized for Unifull Plus. Measurements confirm that Al-alloy wire and enhanced metallization achieve approximately 5 times higher power-cycling capabilities than the original Unifull bond-wire material (refer to Figure 15).

High efficiency, fast switching speed and high ruggedness make Unifull Plus power modules especially suitable for SSTs with direct grid connection.

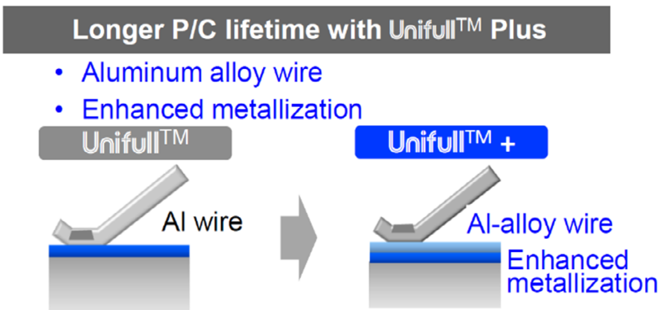


Figure 14: Unifull™ Plus uses enhanced bond wire and chip metallization to increase power-cycling capabilities.

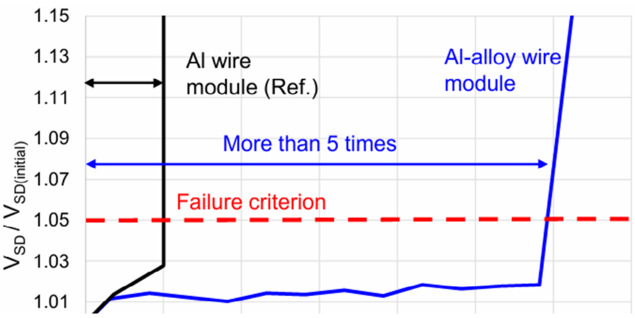


Figure 15: Al-alloy wire and chip metallization, as used in Unifull™ Plus technology, allow 5 times longer power-cycling-lifetimes.

Conclusion

AI-driven datacenters require power-supply solutions that combine high efficiency, power density, scalability, and reliability. SST architectures based on SiC power modules can achieve these requirements, while allowing direct conversion from the medium-voltage distribution network to 800 V and future 1500 V DC datacenter infrastructures while supporting these requirements.

The analysis shows that 550 kW and 1.3 MW are realistic targets for 800 V and 1500 V SST cells, respectively. For a 34.5 kV distribution network considered in this work, the resulting SST can achieve more than 60 MW of power capability. High-power SSTs utilizing high-current SiC power modules therefore represent a scalable solution for current and future hyperscale datacenters while improving the key AI efficiency metric: "Tokens per Second per Megawatt."

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