Elektro-Automatik

WHITE PAPER:
THE BENEFITS OF USING SIC TECHNOLOGY IN NEXT GENERATION PROGRAMMABLE POWER SUPPLIES

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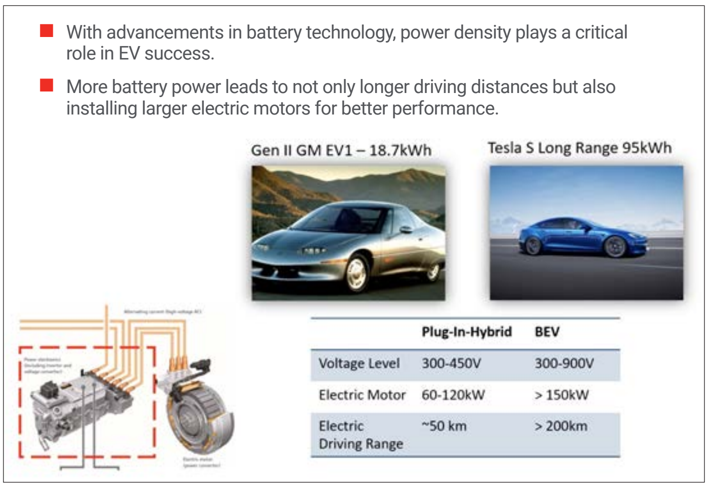
With the worldwide effort to increase energy conservation and reduce fossil fuel use, electrification is occurring at a rapid pace. The electrification of automobiles, airplanes and other transport vehicles is stretching the limits of power consumption across the globe.

With the increasing demand for levels in electrical energy, continual advances in renewable energy solutions are required. This paper will review the trend in increased power and the challenges faced by manufacturers of power instrumentation required to test new products. Furthermore, this paper will present how EA Elektro-Automatik (EA) addressed the challenges with the use of silicon carbide (SiC) transistor technology to create a new line of power supplies that:

- Improved efficiency
- Increased DC output voltage to 2000 V
- Reduced volume with increased power density
- Reduced the $/W cost

MARKET TRENDS — HIGHER POWER WITH HIGHER VOLTAGE AND CURRENT

Market Trends — Higher Power with Higher Voltage and Current
The electric vehicle (EV) market is growing rapidly and EVs require substantial power. The battery pack of the first commercially available model had a 300 to 450 VDC output to power a 120 kW electric motor (**Figure 1**). The Tesla Model S has motors exceeding 150 kW and uses a 95 kWh battery pack operating at greater than 900 VDC. To support fast charging for greater market acceptance, EV chargers are exceeding 240 kW. See **Figure 2**.



	Plug-In-Hybrid	BEV
Voltage Level	300-450V	300-900V
Electric Motor	60-120kW	> 150kW
Electric Driving Range	~50 km	> 200km

Figure 1. Evolution of battery voltage and power for EVs

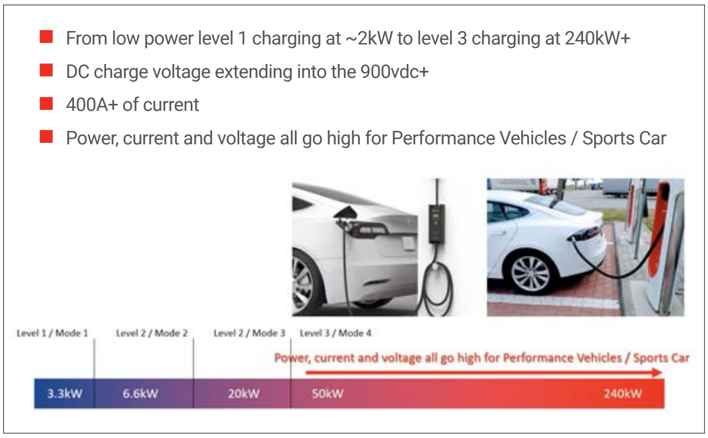


Figure 2. Power requirements for the various levels of automobile battery charging

Hydrogen fuel cells are becoming a viable method for powering vehicles. Cell stacks can contain over 500 kW and supply current up to 1000 A.

Energy storage systems can supply MW for server farms, as illustrated in **Figure 3**. Server farms are transitioning from AC to DC distribution at a voltage around 360 VDC and a current capacity of 2000 A. Emerging technologies are pushing voltages into the 1800 VDC range.

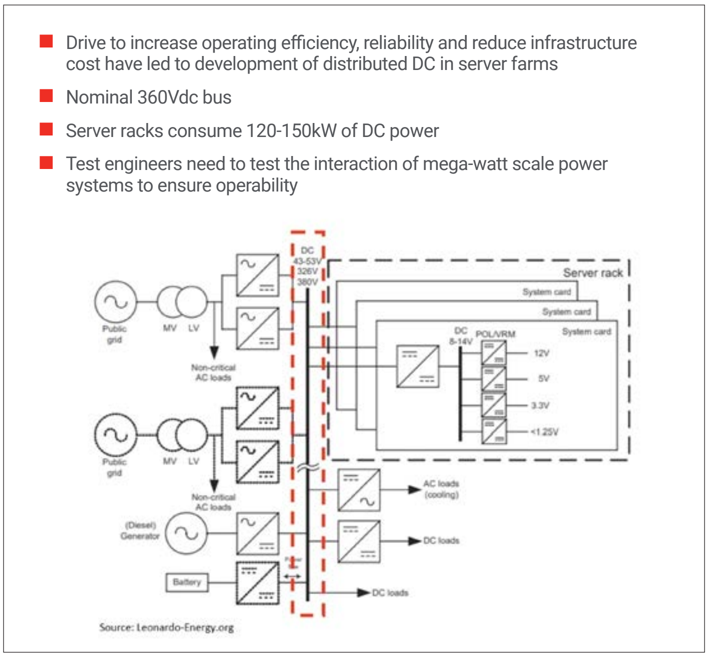


Figure 3. Server farm power requirements

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The increases in voltage and current create test challenges for design and compliance test engineers. Test systems must be capable of generating the required high-power levels. The systems can use traditional 15 kW silicon (Si) transistor-based power supplies housed in 3U high, full rack width enclosures. Generating 150 kW demands 10 of the 15 kW supplies in a single 42U high, 19-inch test rack. The test rack needs sufficient space for the 10 power supplies, paralleling infrastructure and adequate cooling capacity. Based on the power requirements from the examples presented, providing 450 kW would require three of the 150 kW test racks, as shown in **Figure 4**. This assembly consumes 18 square feet of rack space. If the supplies operate at a maximum efficiency of 93%, the assembly generates 31.5 kW of heat requiring removal.

- Existing commercially available power solutions are 15kW in a 3U chassis
- 30kW in a 6U chassis
- Cost usually linear to 3-5% savings with each additional chassis
- Paralleling to achieve high power requires cabinet infrastructure Limited to ~150kW in a single 42U rack.
- Footprint requirements
- Efficiency of 93% means a 450kW supply generates up to 31.5kW of heat
- Example of 450kW requires 18sqft. of floorspace

Figure 4. 450 kW test system requiring thirty 15 kW instruments and three test racks.

Traditional power supplies using Si semiconductor technology can have a maximum efficiency of 93% when using switch mode topologies operating at around 40 kHz. If these supplies use a 5 kW power module, the power density is 9.2 W/in^3. An Si-based MOSFET design needs three switching transistors to generate 5 kW. With a de-rating requirement for the MOSFETs of 30%, the 5 kW power module must use three 500 VDC modules in series to achieve 1500 VDC. **Figure 5** shows the schematic for the power module.

- Space requirements based on existing MOSFET devices. Three Si MOSFET's per 5kW
- Increasing power density while reducing heatsink requirements
- 30% voltage derating required on Si Fet for internal quality standards
- Somewhat limited ability of Si to reliability and accurately achieve >1500Vdc

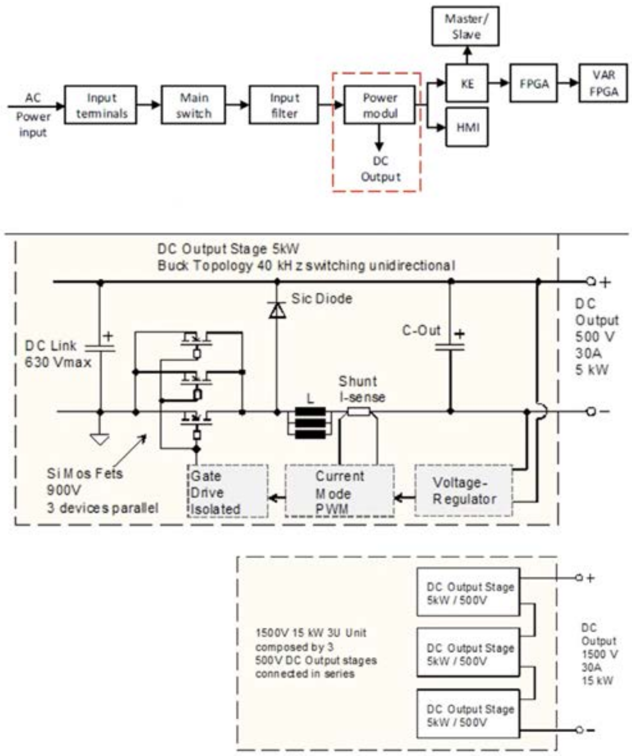

Figure 5. Si transistor-based 5 kW power module which uses three Si MOSFETs

BENEFITS OF SIC MOSFETS FOR HIGH POWER INSTRUMENTATION

To achieve their new power instrumentation design goals of higher voltage output, higher efficiency, higher power density and lower cost per W, EA needed new technology. The new technology is SiC transistors.

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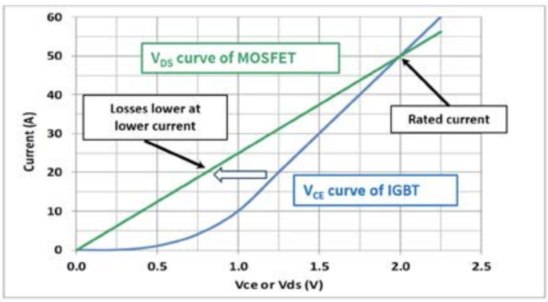
Higher Efficiency Due to Reduced Conduction and Switching Losses

Prior generations of three phase system-based power products utilized Si insulated gate bipolar transistors (IGBTs). IGBTs have the capacity to support 1200 V and supply high current. However, IGBT conduction and switching losses are high. In contrast, SiC MOSFETs, also high-power semiconductors, have much lower conduction and switching losses. As shown in **Figure 6**, SiC MOSFETs have a lower voltage drop than an equivalent IGBT when used as a switch. The RDS(on), the channel resistance of a saturated SiC MOSFET, is lower, particularly at low loads, than the pn junction resistance of a saturated IGBT. Thus, the conduction loss of a SIC MOSFET is lower than the IGBT's conduction loss. The switching loss difference, as shown on the right side of Figure 6, is much more significant. The Si IGBT has a higher capacitance than the SiC MOSFET, and it takes the IGBT more time to switch off. Figure 6 indicates that the SiC MOSFET reduces the switching energy loss by a factor of 10.

Conduction Loss

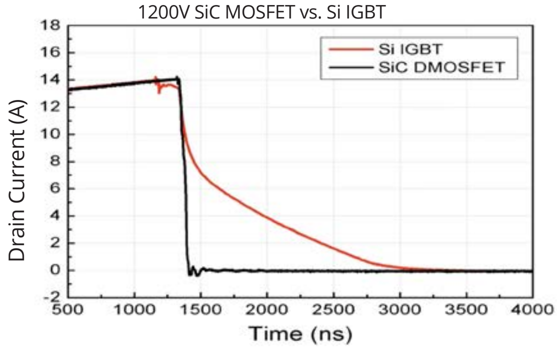
1200V SiC MOSFET vs. Si IGBT



- Under lower loads the SiC MOSFET conduction losses are as much as 1/2 the IGBT

Conduction Loss

1200V SiC MOSFET vs. Si IGBT



- IGBT tailing current eliminated
- SiC DMOSFET: 400mJ
- Si IGBT: 4490 mJ

Figure 6. Comparison of switching and conduction losses between a SiC MOSFET and a Si IGBT

Another factor in improved efficiency of SiC MOSFETS is the relative stability of $R_{DS(on)}$ over temperature as shown in **Figure 7**. Alternative semiconductor technologies such as GaN high electron mobility transistors and Si MOSFETs have $R_{DS(on)}$ magnitudes that can increase by a factor of three as the junction temperature rises from 25° C to 175° C. This is a significant increase in conduction power loss.

Normalized $R_{DS(on)}$ vs. Temperature

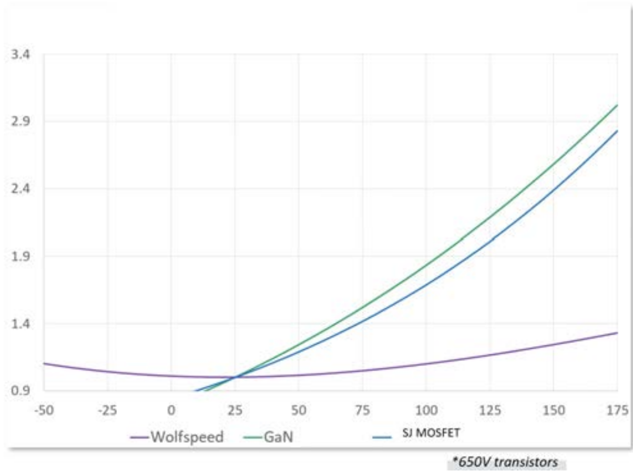


Figure 7. Comparison of $R_{DS(on)}$ as a function of temperature among a SiC MOSFET, a GaN MOSFET, and a SI MOSFET

Faster Switching Speeds

Since SiC MOSFETs take less time to switch, these transistors can operate at faster switching speeds. **Figure 8** shows that a SiC MOSFET has a dv/dt rate almost twice the rate of a Si MOSFET for both turn-on and turn off.

MOSFETs have an intrinsic body diode. For SiC MOSFETs, the body diode reverse recovery charge, Qrr, and the body diode reverse recovery time, Trr, are substantially smaller than a Si MOSFET's body diode. **Figure 9** shows the greater power loss and heat build-up of the Si body diode compared with the SiC body diode.

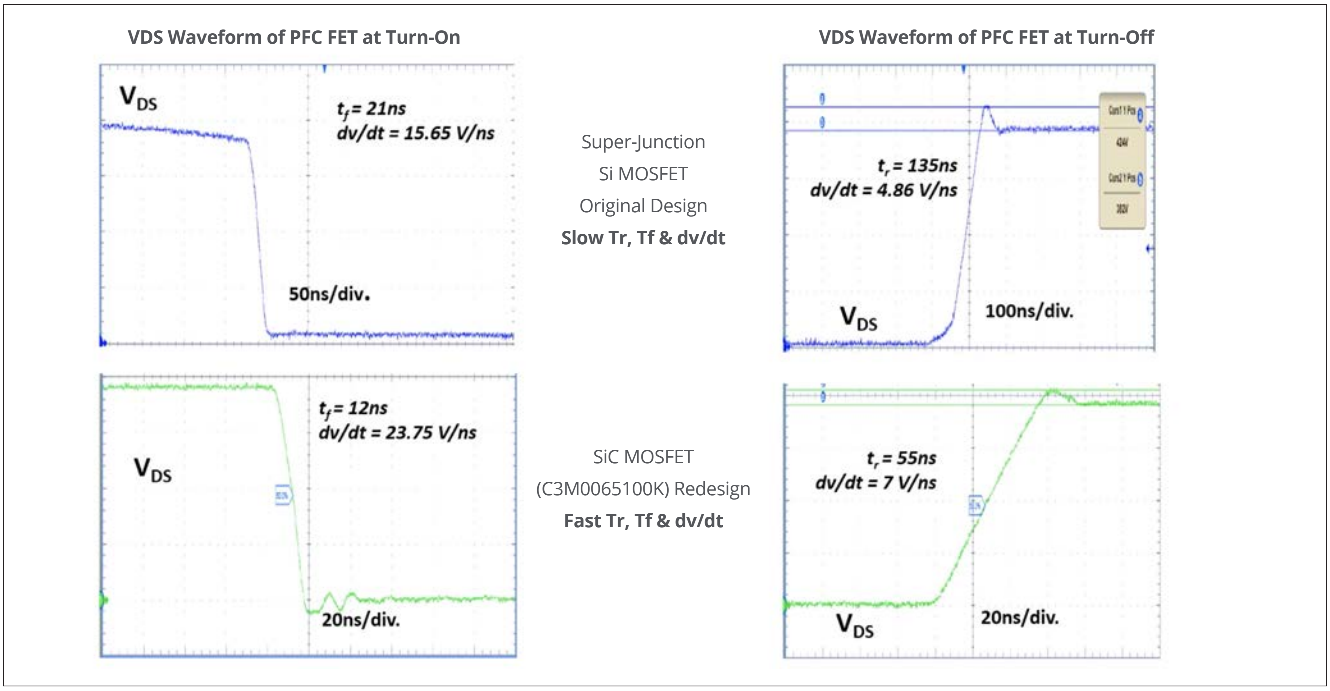


Figure 8. Comparison of turn-on and turn-off rates of a Si MOSFET (top plots) versus a SiC MOSFET (bottom plots)

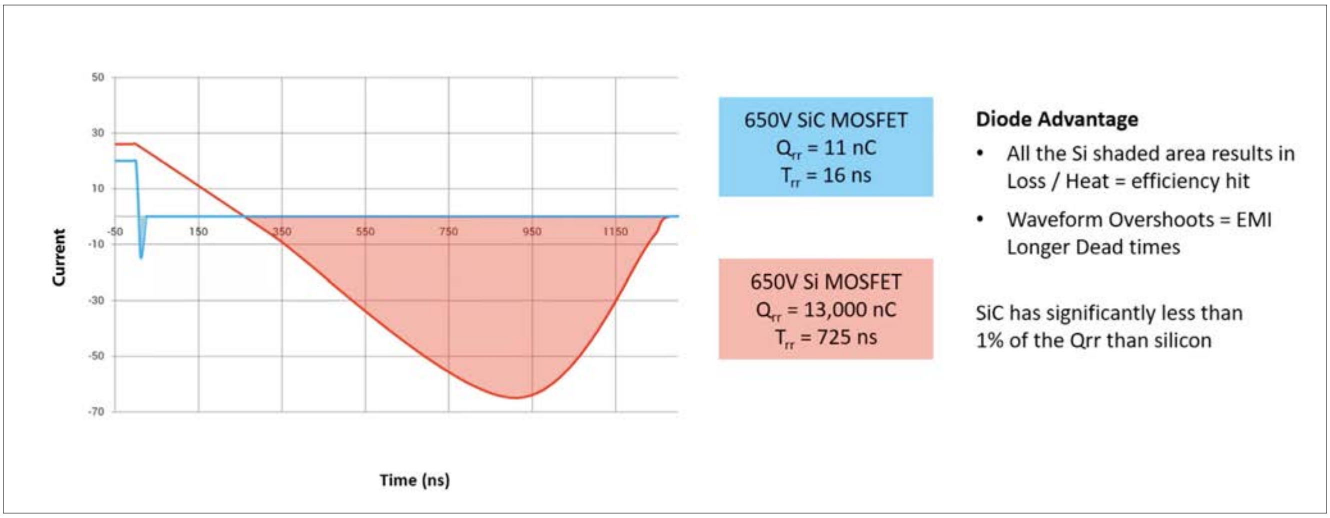


Figure 9. Comparison of power loss and heat build-up between an Si MOSFET and a SiC MOSFET

Enhanced Reliability

From a reliability standpoint, SiC MOSFETs have a higher breakdown voltage than their datasheet specification. **Figure 10** shows a batch of a 1200 V SiC MOSFET's breakdown voltages over their operating temperature range. At low temperatures, IGBT manufacturers do not guarantee breakdown voltages at low negative temperatures. For example, a 1200 V IGBT is not capable of supporting 1200 V at -30° C. The device must be de-rated at that temperature. The breakdown margin of the SiC MOSFET demonstrates how robust the component is to transient over-voltages.

Space-saving

The die size is another significant difference between SiC and Si power semiconductors. First, a SiC die is smaller than an equivalent power Si transistor die. Second, a Si component needs a back-biased diode to allow bi-directional current flow between collector and emitter. The SiC transistor source-drain channel can conduct current in either direction. In addition, the SiC transistor has a parasitic body diode as part of the transistor structure. Thus, the extra diode required for the Si transistor is not required for the SiC transistor. Using the example of a 1200 V transistor, the SiC transistor die area is about ¼ the die area of the Si transistor. Hence SiC component layouts in power circuits can exhibit lower stray inductance. Overall, the smaller SiC packages enable a higher power density in the end product.

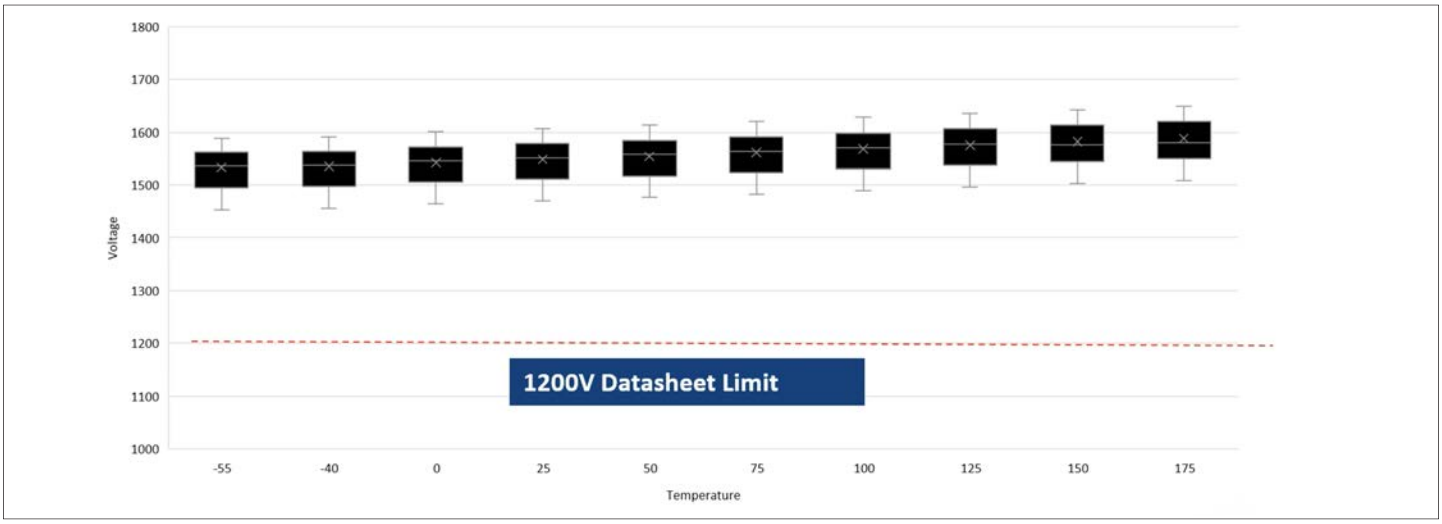


Figure 10. Actual breakdown voltage versus temperature of a SiC MOSFET. The plot represents measurements on sets of 15 components from three different production runs.

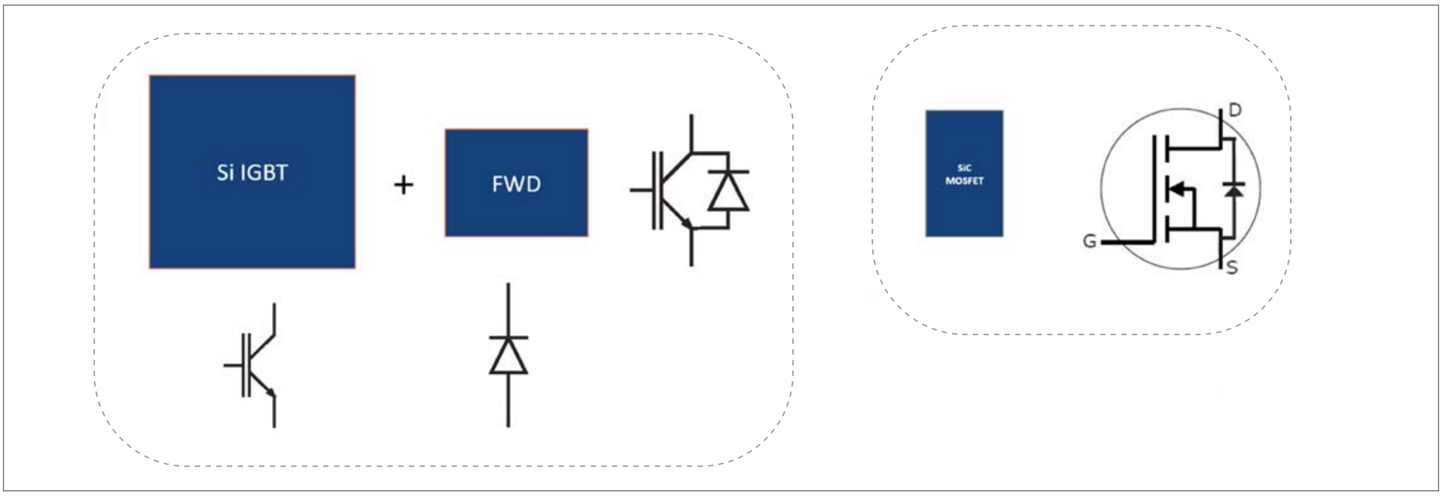


Figure 11. Si IGBT and diode pc board pad layout compared with the pad layout for a SiC MOSFET

EA ELEKTRO-AUTOMATIK'S GOALS FOR A NEW HIGH-POWER PROGRAMMABLE POWER SUPPLY SERIES

In response to the market demand for higher output voltage, smaller volume, and lower cost, EA Elektro-Automatik established the following goals for its new 10000-series programmable power supplies:

- 30 kW in a 4U high, 19-inch rack width enclosure
- Models with 2000 VDC output
- Autoranging output stage
- Unidirectional, bidirectional and regenerative DC power
- 10 – 15% cost reduction

The EA Elektro-Automatik design team was confident that the goals were achievable with SiC technology.

Taking advantage of higher speed switching with SiC components, the new 10000-series switch mode AC-DC converters operate at approximately 60 kHz. That is 30% faster than the DC-DC converters of the industry-leading power supplies, which switch at around 30 – 40 kHz. The higher switching frequency in the 10000 series enabled the reduction in both the size of magnetic components and the size of the amplifiers. Not only did the magnetic components shrink by 30% in mass, but the design required one less inductive component saving valuable space and generating less heat.

The SiC power transistors allowed a three series amplifier configuration to output a bus voltage of 2700 VDC compared with 1500 VDC on the previous generation power supplies using Si technology transistors (**Figure 12**). Additionally, the new SiC-based power factor correction circuit enabled an expanded AC volt input range of 342 to 528 VAC. This saves on having multiple versions of a power supply with dedicated inputs of 380 VAC, 400 VAC or 480 VAC to cover worldwide requirements.

- SiC enables higher secondary DC link voltage to the DC-DC power module
- Higher secondary DC link voltage expanded DC output from 1,500Vdc to 2,000Vdc
- Higher PFC DC link voltage which expanded AC input range from 342-528VAC

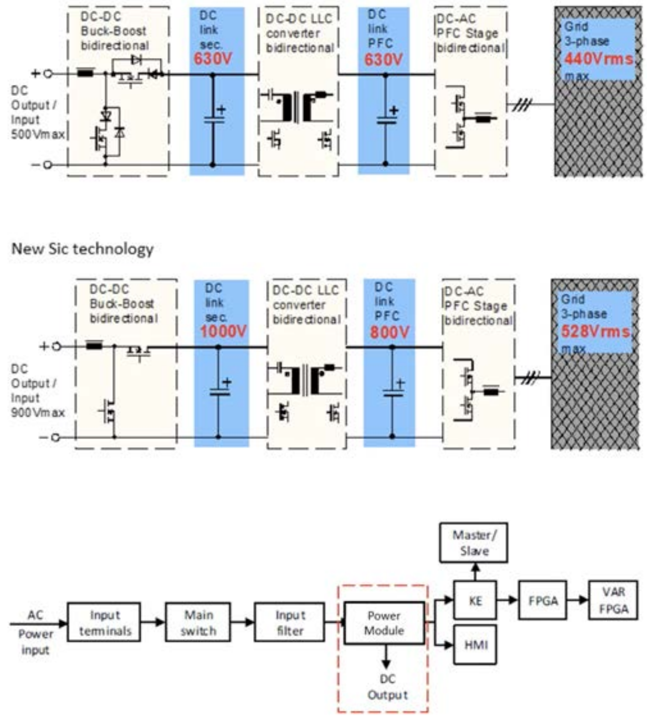


Figure 12. SiC MOSFETs permit higher output voltage and an expanded ACV input range.

Using SiC transistors, the DC-DC output stage required only one transistor switch compared with three Si transistor switches (**Figure 13**). Fewer components provide a 75% reduction in heat sink real estate and a cost savings. With less heat to remove, the designers were able to employ smaller cooling fans allowing the 10000-series power supplies to run more quietly.

Of most importance, the smaller inductors, the fewer filter capacitors and the smaller cooling fans allowed increasing the power density of a 10 kW power module to 13.3 W/cm^3 compared with earlier Si-based designs of 9.2 W/cm^3. SiC technology allowed a 45% increase in power density.

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- Single SiC MOSFET's per 5kW
- Heatsink size reduction
  - 75% space reduction per switch
- Cost savings per watt
  - Two less devices
- Smaller cooling fans. Less auditable noise and cost savings

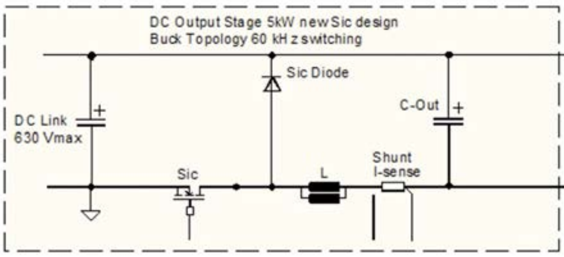

Figure 13. SiC transistor-based output stage enabled a 45% increase in power density.

The efficiency of programmable DC power supplies often rolls off as a function of power output. With SiC transistors and their low $R_{DS(on)}$ parameter, not only did overall power supply efficiency increase, but the efficiency at lower power output improved. The knee of the power curve at around 6 kilowatts gained over 2% in operating efficiency, as shown in **Figure 14**. That may not seem significant, but when providing 500 kilowatts of power, 2% makes a substantial power savings.

- SiC devices increased operating efficiency by:
  - Lower RDS(on) per T0247 package. SiC vs. Si reduction of ~factor of 5
  - SiC RDS(on) increase at high temperature is much lower than Si.
  - SiC switching losses are lower than Si.
  - SiC switching losses are very stable even at high temperatures.

EA SiC – 9000 Series 15 kW **EA SiC – 10000 Series 30 kW**

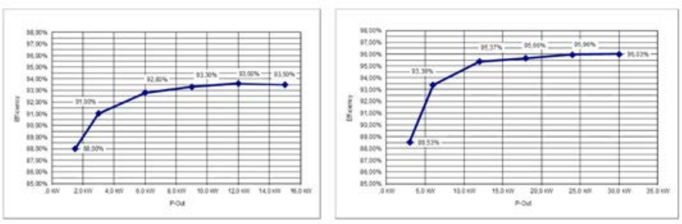

Figure 14. Improvement in efficiency over the power output range of the new 10000-series supplies compared with the older generation 9000-series supply.

All these improvements resulted in a 30 kW SiC-based programmable power supply in a 4U enclosure. Compared with the 450 kW system presented in Figure 4, eight paralleled, 30 kW 4U power supplies can generate 240 kW in a single 42 U high cabinet, providing an increase in power density of 37% (Figure 15). This represents approximately a 15 – 20% cost reduction in terms of $/W. There is further cost savings of about 15% in the cabinet infrastructure due to fewer instrumentation in the cabinet. One less cabinet reduces floor space from 18 ft^2 to 12 ft^2, representing a 33% savings in valuable manufacturing floor space.

The efficiency gains from 93% to 96% with the use of SiC transistors reduces the 450 kW power down to 18 kW of power lost as heat. The 18 kW of heat is a 42% reduction compared with Si transistor-based power supplies.

- 30kW in a 4U chassis including Autoranging output
- Up to 240kW in a single 42U cabinet. Increased power density of 37%
- End-User cost reduction of ~15-20% $/watt on power
- ~15% reduction in cabinet material infrastructure
- Floor space reduction from 18sqft to 12sqft. 33% savings!
- Efficiency gain from 93% to 96% means a 450kW reduces from 31.5kW of heat to 18kW. 42% less heat

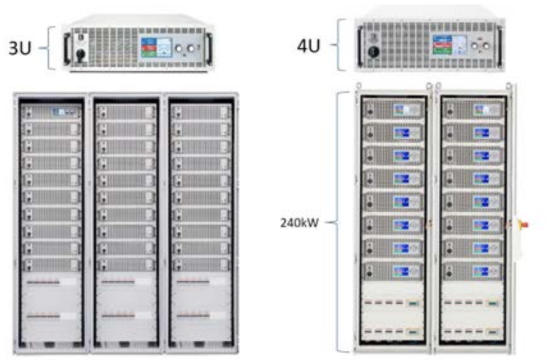

Figure 15. Space and cost savings with the new 10000-series compared with the older generation 9000-series power supplies

CONCLUSION — SIC TECHNOLOGY ALLOWED EA TO ACHIEVE ITS GOALS

SiC transistors can have a significant impact when used in programmable DC power supplies. They improve efficiency, increase power density, allow use of lower cost and smaller magnetic components and can be smaller than Si-based power supplies. EA Elektro-Automatik took advantage of SiC technology to achieve a 30 kW programmable power supply in a 4U high enclosure with models that can output 2000 V. The new supplies compared with Si models:

- Improve efficiency by 3%
- Increase power density by 37%
- Reduce floor space of a 240 W power supply system by 33%
- Reduce heat generation of a 240 W power supply system by 42%
- Reduce $/W by 15 – 20%

EA Elektro-Automatik's aggressive goals, which were achieved through the use of SiC technology, are the recommended technology for next-generation high power sources.

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