Power | Volume 23

We get technical

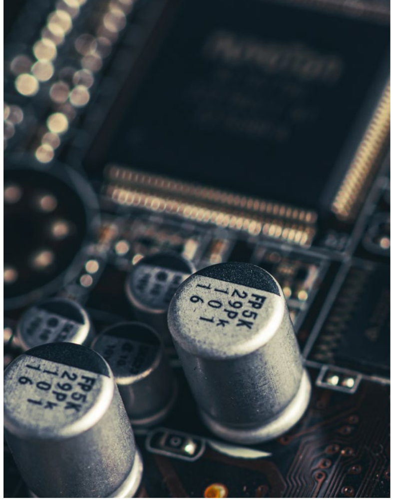
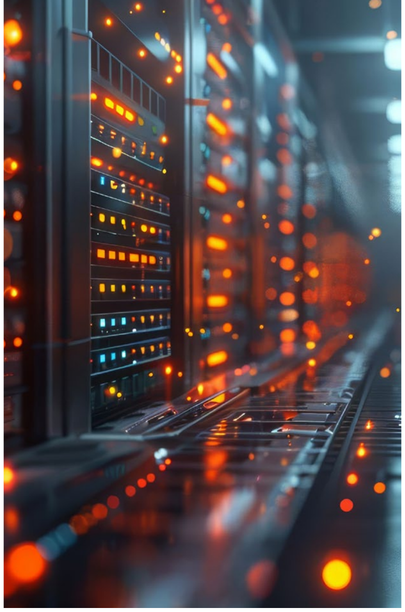
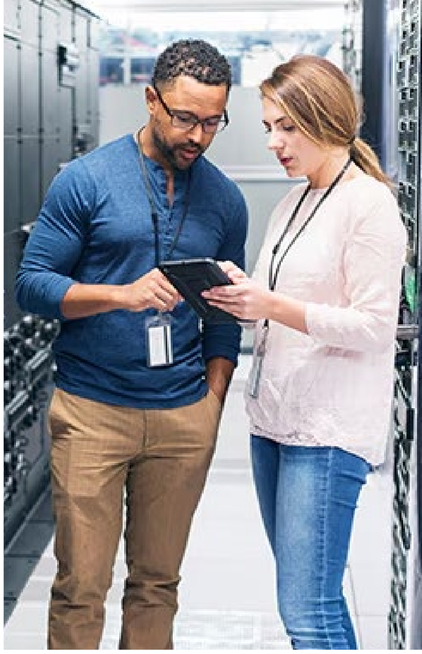
Use coupled inductors in multiphase buck converters to improve efficiency

Maximize power-device control efficiency with the right gate-driver power converter

Use transient voltage suppression diodes to ruggedize circuits and maintain electrical integrity

Exploring how silicon carbide is transforming energy systems

DigiKey

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Editor's note

Welcome to the DigiKey eMagazine Volume 23 – Power.

This issue delves into the evolving world of power electronics and innovative system design. As technology continues to push the boundaries of performance, efficiency, and reliability, engineers are met with both unprecedented challenges and opportunities.

In this issue, we spotlight groundbreaking advancements shaping the future of power systems. From the high-speed efficiency of GaN technologies to the versatility of configurable power solutions tailored for precision, our articles reflect the pulse of progress.

We also examine cutting-edge components like the DUSH960-1248 DC UPS DIN Rail and DCM3717 high-density converter modules, each offering compact and robust answers to today's power demands. For design engineers striving to optimize performance, our deep dives into multiphase buck converters, gate-driver power converters, and TVS diodes provide critical insights for achieving greater efficiency and protection.

Finally, we look toward the horizon with "Exploring How Silicon Carbide is Transforming Energy Systems", highlighting the materials revolution redefining what's possible in energy infrastructure.

Whether you're designing for industrial, automotive, or advanced computing systems, we hope this issue equips and inspires you with practical knowledge and forward-thinking solutions.

Leveraging configurable power solutions for mission-critical applications

By Abhishek Jadhav for DigiKey

Advanced Energy

For many engineers, powering complex industrial systems means stacking multiple single-output power supplies, from 24 V for displays, 12 V for logic, to 48 V for motors. Whether the design team chooses a standard part or a full custom unit, this one rail, one supply approach is common across industries.

But this approach comes at a price. Fragmented power architectures increase component count, complicate cabling, and drive up design time and cost. Furthermore, any late-stage changes in power requirements can trigger an expensive redesign or integration of an additional PSU (power supply unit). In the high-reliability applications of medical devices and industrial automation, adding a new PSU introduces more points of failure, which is a significant drawback.

To address these challenges, Advanced Energy offers a more flexible, multi-output power solution, moving away from the one-output-per-supply strategy. Customers can choose between:

- Configurable power supplies, which are modular hardware platforms that can integrate various DC output modules
- Fully programmable power supplies, which enable real-time software-based adjustments to the output using digital control protocols like PMBus or CAN bus

By leveraging these configurable power supplies, design teams can power all their loads from one integrated system that is customizable to the specific voltage needs. This results in a clearer design with fewer components and easy integration. Advanced Energy power supplies will suit the needs from a 600 W fanless unit for a surgical device to a 30 W rack system for a semiconductor fab.

Flexibility in power supply designs

Configurable power supply units consist of a standard AC/DC digitally controlled power conversion front end with power factor correction and several swappable DC output modules installed in slots. Design teams can choose appropriate modules that can be configured to provide the required set of output voltages.

This optimization is achieved without custom engineering, simply by slotting in the right module. For example, a single configurable unit can host several modules to yield multiple isolated outputs, each set to a different voltage and current limit, all powered from one AC input. This offers design flexibility because, as needs change, engineers can reconfigure by simply swapping a module rather than redesigning the entire power architecture.

But to further add more flexibility in the power supply designs, fully programmable power supplies incorporate digital control for real-time adjustments. This means they are not only hardware modular but also allow output settings to be fine-tuned through software commands on the fly. The internal architecture uses microprocessor control for both the front-end and each module, exposing interfaces like PMBus, CANBus, and Ethernet for external monitoring and control.

Engineering teams can not only change the output voltage, but can also adjust current limit, ramp rate, sequences, and even certain protection thresholds. This means that a single power system can adapt to different operating modes by software programming rather than physical changes.

In summary, the key distinction is that configurable units are flexible at build-time and upgrade time, whereas fully programmable units emphasize on-the-fly control. Both of these power supply architectures eliminate the one-supply, one-output approach that limits traditional PSU designs.

Configurable power supplies with CoolX and uMP

Advanced Energy offers a series of configurable power supply units for scenarios where multiple outputs and specialized performance are required. Still, design cycles and budgets won't allow full custom power units. In addition to a modular hardware platform, these configurable power supplies enable design teams to mix and match standard modules to create a composite supply that meets the voltage rail requirements.

The Advanced Energy CoolX modular power supplies, which target medical and precision lab systems, have a wide range of configurable AC/DC solutions that range from 600 W to 3000 W. The power units in this product line include both natural convection cooled, and variable speed fan cooled systems that are capable of delivering up to 24 outputs with series and parallel options.

Figure 1: Advanced Energy CoolX600 series is a convection-cooled, modular power supply platform, delivering 600 W from a compact 215.9 x 114.3 x 39.1 mm package. (Image source: Advanced Energy)

For example, the CoolX600 (Figure 1) can host up to four modules to provide as many as eight isolated DC outputs (1 - 58 V). For higher power, the CoolX1000 supports up to six modules and twelve outputs for a total of 1000 W. These units are designed with stringent medical safety standards, such as IEC 60601-1 certifications, ensuring the product meets low leakage current requirements.

For a medical diagnostic OEM, designing a biomedical analyzer requires a configurable multi-output PSU with medical safety certification and integration support. Advanced Energy CoolX1800 units enable customers to combine all power needs into one compact power supply, improving system integration.

Advanced Energy also offers a low-power range of configurable power supply units under the uMP series (Figure 2). . A single uMP power supply unit can pack up to 1200 W of output across multiple channels in a slim 1U-tall chassis, which is far smaller and lighter than using several individual PSUs of equivalent combined power.

For instance, a 6-slot uMP chassis can provide six different voltages, each isolated, or some outputs can be paralleled for higher current on a particular rail. This flexibility makes uMP an ideal solution for industrial automation, test and measurement, and laboratory systems where a variety of voltages are needed to power motors, sensors, controls, and test circuits.

Despite the small size of uMP supplies, they are built for robust performance and carry industrial EN 60950/62368-1 safety approval and even meet military-standard shock and vibration specifications with options for conformal coating. These features make sure the units are ideal for deployment in harsh industrial environments.

However, when industries demand a power supply that can adjust to changing power requirements on the fly, they also want more control over optimizing output power in real-time. Advanced Energy offers fully programmable PSUs for teams where output requirements may change during operation.

Software-driven programmable power supplies

These power supplies offer software-defined intelligence where the output parameters can be adjusted in real-time through firmware commands and remote interfaces. Advanced Energy's NeoPower (Figure 3) is a configurable AC/DC power supply that provides high power density as either a programmable voltage or current source.

The NeoPower NP08 is the latest programmable AC/DC power system in the 4 kW class, targeting medical and industrial markets. At its core, NeoPower provides up to 4,000 W of output power in a modular design with eight output slots. These slots can be fitted with various modules to achieve the required mix of output voltages and currents.

The key technology that makes programmable power supplies more adaptable is a digital platform that supports multiple communication protocols for control and monitoring. For example, out of the box, the NP08 can be controlled via Modbus RTU to configure output setpoints, read back telemetry, and manage faults.

Figure 2: Advanced Energy uMP Gen I digitally configurable power supply is housed in a 1U case with 4 or 6 slot card options and power ratings from 400 W to 1200 W. (Image source: Advanced Energy)

Figure 3: Advanced Energy NeoPower NP08 AC-DC configurable power supply with power density of 18 W/in³. (Image source: Advanced Energy)

Figure 4: Advanced Energy iHP Air-Cooled Series accepts 3000 W single slot modules for up to eight different outputs for a total output power of 24 kW. (Image source: Advanced Energy)

For example, in an automation system, the NeoPower can change an output from 24 V to 28 V on the fly to speed up a motor, or a test system can sweep the voltage to a device under test via software commands. Use cases for NeoPower include advanced manufacturing and automation scenarios where one power system might drive PLC I/O racks, sensors, and machine vision cameras (each with different voltage).

Another solution with high power programmability from Advanced Energy is the iHP (Intelligent High Power) Series, which is designed for mission-critical applications, demanding kilowatts of power, multiple outputs, and robust performance under harsh conditions. An iHP power system (Figure 4) is a scalable rack-mounted platform that can be configured from a few kW up to 30 kW output.

The system is digitally controlled with a high-speed internal communication bus that enables capabilities like user-programmable slew rates and voltage or current mode programming. The iHP series also supports redundancy and fault-tolerant configuration, with multiple modules that can be paralleled with OR-ing diodes for N+1 redundancy. This ensures that if one module fails, others can take over to maintain power continuity.

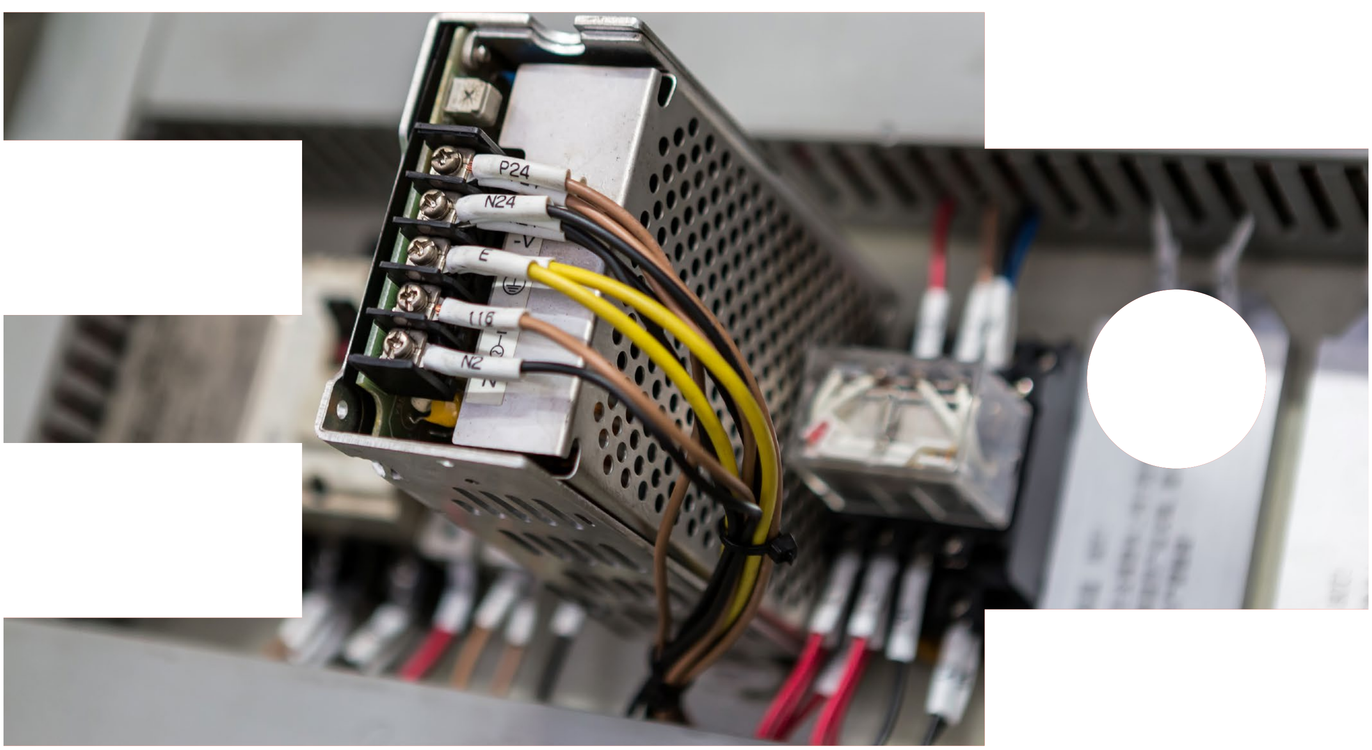
From mid-range configurable modular power supplies to high-power programmable systems, Advanced Energy delivers flexibility without complexity. Engineers can meet their specific power requirements with a solution that adapts to their changing needs, whether for a fanless 4-output medical supply or a smart 8-output industrial unit.

Conclusion

Building a power supply system is not easy. However, the move from a one-output-per-supply strategy to a multi-output power solution is key to adapting to the evolving needs of medical and industrial systems. Advanced Energy changes the mindset from "I need this PSU and that PSU to get all my voltages" to "I can get this-and-that in one package."

In conclusion, Advanced Energy's configurable and programmable power solutions allow engineers to remove the pain points of traditional complex power systems. The power supply is no longer a limitation or afterthought; it has become an enabling, adaptable part of innovation.

(CTA) To learn more, visit Configurable Power Supplies.



Maintaining continuous power in modern industrial environments

By Abhishek Jadhav for DigiKey

TDK·Lambda
Trusted • Innovative • Reliable

In modern industrial automation systems, maintaining continuous DC power to controllers, sensors, and actuators is crucial, as devices like Programmable logic controllers (PLCs), SCADA nodes, and drive electronics are sensitive to even short power interruptions. These interruptions can result in significant production downtime or require time-consuming system reboots.

Traditionally, engineers relied on backup batteries or supercapacitors with switchover circuits to bridge power losses, and often an AC UPS upstream for a critical environment. However, DC-side backup introduces key challenges, like the backup source voltage must match the load voltage, or additional converters are needed to charge batteries and supply loads at different levels.

For instance, a building automation panel might require a 24 V DC bus, but prefer a higher voltage battery bank for more energy storage. Implementing this using conventional components would require separate DC/DC converters for charging and discharging, along with control circuitry to manage the switchover.

To address these issues, TDK-Lambda offers its DUSH960-1248 DIN rail mount DC uninterruptible power supply (DC-UPS) that integrates backup power management with DC conversion in a single intelligent unit.

Technical details of the DUSH960-1248

The DUSH960-1248 is designed to perform two critical functions in one device. First, under normal conditions, it acts as a DC-UPS, routing power from an external AC/DC source to the DC load while simultaneously charging an attached battery. In the event of an input power loss, it seamlessly switches to the battery to maintain a regulated DC output, ensuring continuous power to downstream electronics during outages or voltage dips.

Second, the module serves as a bidirectional DC/DC buck-boost converter, decoupling the battery voltage from the load voltage. This means that the battery's nominal voltage can be higher or lower than the load's voltage; the DUSH960 dynamically steps the voltage up or down as required. Under normal power, it will buck or boost the input to the appropriate level to charge the battery, and under backup, it will buck or boost the battery output to sustain the load.

This dual-purpose approach eliminates the need for separate charger and regulator units. The internal design of the DUSH960-1248 uses a bi-directional DC-DC converter topology to manage power flow in both directions with high efficiency.

Efficiency is another important aspect of the module that operates at up to 96-98 percent efficiency depending on the mode. The module also imposes no minimum load requirement and maintains a low ripple (<690 mV) on the output, which prevents the introduction of noise that could interfere with sensitive control electronics.

The DUSH960-1248 operates in a wide voltage range on input from 10 V to 60 V DC and provides a programmable, regulated output between 10 V and 58 V DC. In practical terms, this single module can accommodate 12 V, 24 V, 48 V nominal systems and anything in between, whether the main supply or the battery.

For example, an integrator could use a 24 V AC/DC supply with a 48 V battery bank and 24 V loads, configurations that generally would be difficult without multiple converters. The module's maximum output power is 960 W at 48 V and 20 A, which is sufficient for large PLC racks, motors, and safety systems in industrial environments.

The DUSH960-1248 is available in two models, -0M and -1M, to suit different user needs and budgets. Both variants share the same core electrical specifications and performance, but the primary difference lies in the user interface and a minor power output feature. The -0M model provides a 5 A auxiliary output that is tied to the battery, which can be used to power small auxiliary loads that need

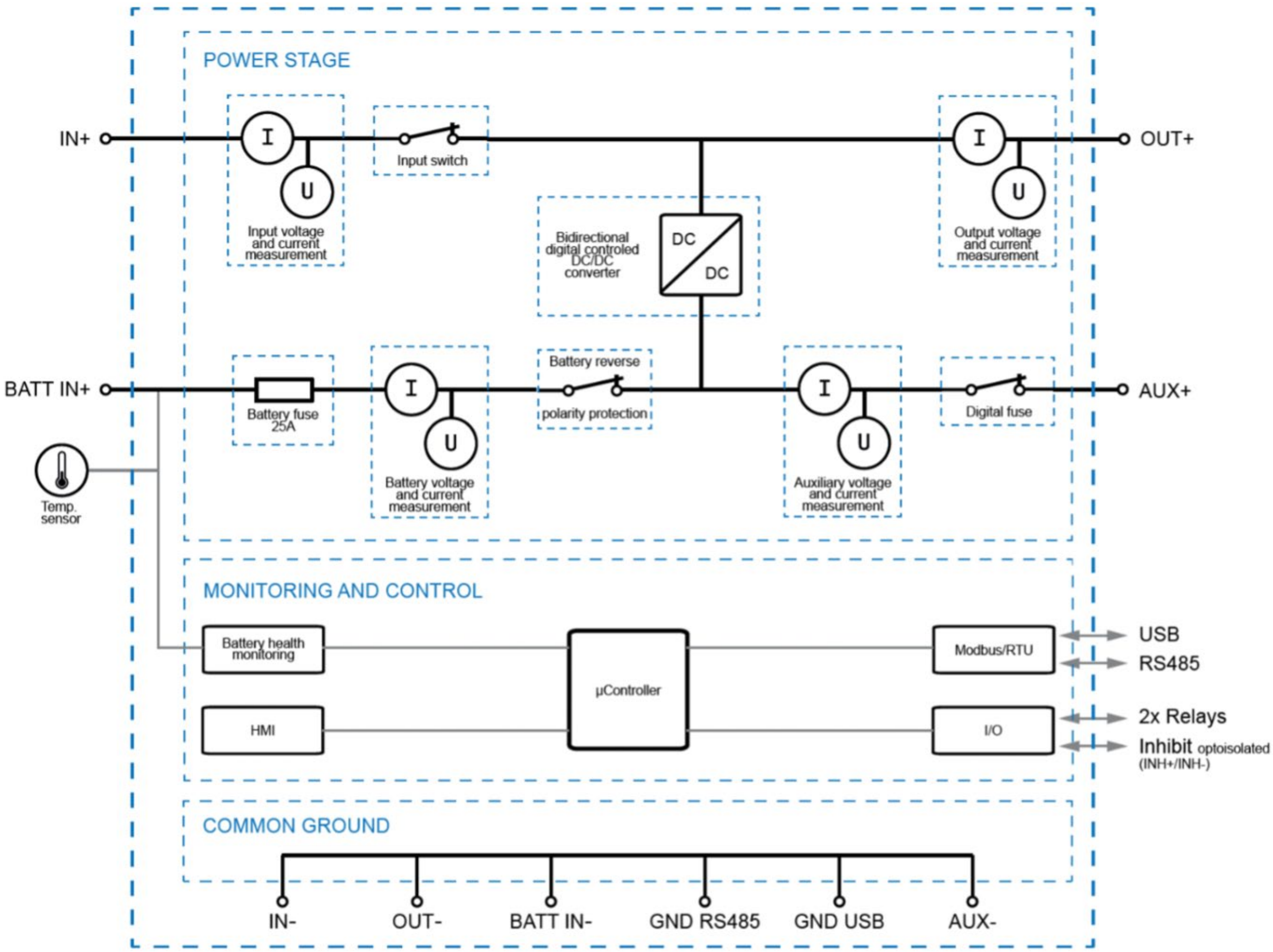


Figure 1: Block diagram of DUSH960-1248 showing power stage, control, and monitoring. (Image Source: TDK-Lambda)

battery voltage, for example, a lighting circuit or fan that should run off the battery during an outage. The other module does not include the auxiliary output.

In addition to the power hardware, the DUSH960-1248 includes robust monitoring and communication capabilities. The front panel features a 1.5-inch color LCD display with control buttons, allowing on-site human operators to view status information and adjust settings. The DUSH960 series supports remote monitoring through Modbus/RTU over RS-485 and a mini-USB port for direct connection to a PC.

These interfaces allow engineers to read data such as input voltage, output load level, battery charge percentage, temperature, and other parameters. The power design engineers can configure the output set-points, charge current limits, and threshold alarms. TDK-Lambda provides a PowerCMC control and monitoring software to help engineers with maintenance, which can log alarms and display real-time status values.

Figure 2: TDK-Lambda's DUSH960-1248 DIN rail mount DC uninterruptible power supply is available in two variants -0M and –1M. (Image source: TDK-Lambda)

All of these communication features show that DUSH960-1248 is not a black box power supply, but rather an intelligent device that communicates with the larger control system. In a SCADA environment, for instance, the DUSH960 module can report its status over Modbus to the SCADA host, which can display backup system health.

A problem-solution analysis for integrators

Problem: In traditional DC power backup setups, achieving redundancy and high reliability often means adding more hardware. Each additional component, such as diodes and external relays, introduces points of failure and voltage drops. As the system becomes more complex, it becomes more challenging to ensure consistent operation, and the overall reliability can decrease despite having redundancy on paper.

Solution: The DUSH960-1248 can simplify system architecture by acting as a single coordination point for power flow. It connects the power supply, load, and battery in one unit, which allows it to inherently handle the redundancy function, which would otherwise require OR-ring circuits.

The module ensures that whichever source is available will power the load and prevent back feeding into the supply when on battery. For better system redundancy, the DUSH960 can be paired with a redundant primary supply as well, such as using a dual AC/DC supply configuration with a redundant module on the input. In such a case, the DUSH will draw from whichever supply is active and still manage the battery, which adds a second layer of redundancy by covering the case where both AC supplies fail by using the battery.

Problem: In an industrial environment, backup power systems need to be integrated with PLCs and SCADA systems and are not helpful if they operate in isolation. Plant operators need to know the status of the UPS, such as whether the system is on battery power, how much backup time is left, whether a battery fault has occurred, etc. With traditional DC UPS setups, monitoring relies on basic signals that indicate a mains failure but may not indicate a low battery.

Solution: The TDK-Lambda DUSH960-1248 module is designed with full integration into automated control networks. It provides both discrete signals and digital communication to interface with PLCs and SCADA.

For simple integration, the two configuration alarm relay contacts can be wired to the PLC inputs to signify events like AC Power Loss or Battery low. The Modbus/RTU interface via RS-485 allows a SCADA system or PLC with Modbus support to query dozens of parameters from the DUSH960, like input voltage, output voltage, current, battery charge percentage, battery temperature, etc.

Conclusion

The DUSH960-1248 DC UPS module combines power backup and conversion in a single unit. From an engineering perspective, it addresses multiple pain points, including voltage incompatibility, space constraints, complex wiring, and limited monitoring, with a single drop-in solution. By deploying the DUSH9601248, system integrators can ensure the uninterrupted operation of critical DC loads without changing the entire power architecture.

(CTA) To learn more, visit [DUSH960-1248]

A bridge to 48 V power architecture

By Abhishek Jadhav for DigiKey

VICOR

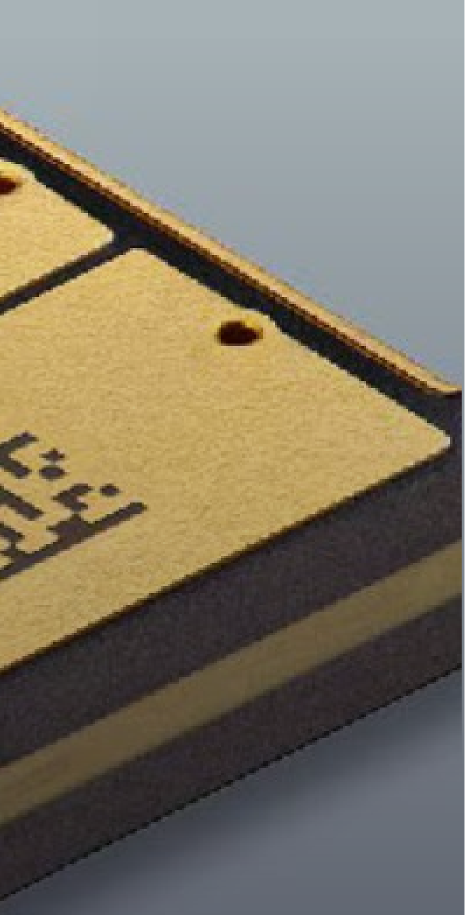


Figure 1. Vicor Corporation's DCM3717 48V DC/DC Converter Module. (Image Source: Vicor Corporation)

One of the most critical problems in the modern industrial infrastructure is the increasing power consumption. Although many high-power systems still run on 12 V distribution architectures, delivering large amounts of power at this voltage requires very high current. For example, 1 kW at 12 V necessitates about 83 A. This approach leads to bulky copper bus bars, thick cable harnesses, and high resistive losses.

To overcome these inefficiencies, the industry is shifting towards 48 V power delivery networks (PDNs). These higher-voltage systems reduce I^2R transmission losses and enable the use of lighter, more efficient cabling compared to 12 V distribution. However, a significant compatibility gap remains, as many existing subsystems still operate at 12 V and cannot be easily replaced.

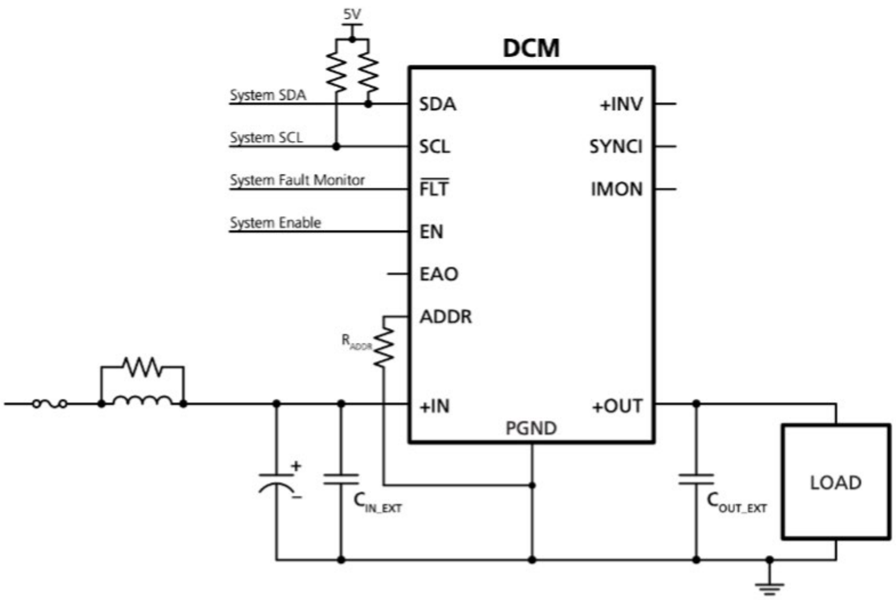
For example, delivering a given amount of power at 48 V requires only one-quarter of the current needed at 12 V, which in turn can cut distribution loss by up to ~75%. In the same example as above, 1 kW at 48 V would only require 20.82 A, which is four times less current, directly reducing cable thickness, weight, and resistive losses.

This creates a complex engineering challenge: how to adopt 48 V architecture without discarding legacy 12 V loads. This is where Vicor Corporation offers its DCM3717 (Figure 1), a high-density DC/DC converter module that is specifically designed to bridge the 48 V to 12 V divide. Vicor offers the module as an off-the-shelf converter that is ready to be integrated into high-power systems that will convert a 48 V bus to 12 V at the point of load.

Introducing the Vicor DCM3717 DC/DC converter module

The Vicor DCM3717 accepts a wide range of input voltage of 40 to 60 VDC and provides a regulated, adjusted output from 10 to 12.5 VDC. This single module replaces the traditional step-down converter or intermediate bus converter in a much smaller form factor. The DCM3717 comes in two power ratings: one model that delivers up to 750 W and another that delivers up to 1000 W.

Both models are packaged in a compact ChiP (Converter housed in Package) format, measuring only 36.7 x 17.3 x 5.2 mm. Despite its small footprint, the module achieves a high-power density of approximately 5 kW/in^3 by using smaller conductors and components for the same power transfer.



Typical application of DCM3717 to point-of-load. (Image Source: Vicor Corporation)

In practical terms, the dramatically smaller size is equivalent to a traditional DC/DC converter that allows engineers to add more features to the free space on the PCB or reduce the size of the overall system. This translates to weight saving, as large heatsinks or bulky magnetics are no longer needed to achieve the same power delivery.

Beyond size, the efficiency of the DCM3717 is high, peaking around 96 to 97 percent. This shows that little input power is lost as heat. The reduction in waste heat yield benefits, such as easing cooling requirements, allowing smaller heatsinks and less airflow to keep its temperature in check.

The module is also scalable. In the case of power systems that require more than 1 kW, up to four DCM3717 modules can be used in parallel for roughly 3 to 4 kW on a single 12 V rail. This allows power design engineers to adopt 48 V distribution incrementally and with low risk.

The DCM3717 module requires minimal external components, allowing the module to be integrated into an existing board, with minor layout adjustments.

The DCM3717 integrates numerous protective and control features, including built-in safeguards for over-current, short-circuit, and over-temperature conditions. For example, the module will automatically limit output current or shut down upon detecting a fault, such as a short or excessive temperature, thereby protecting both the module and the load.

Additionally, the DC/DC converter supports PMBus digital telemetry and control, which allows the system controller to monitor parameters like output voltage, current, and temperature in real-time. This ensures power design engineers can adjust the output setpoints and perform remote on/off via PMBus. The digital interface makes it easy to integrate the converter into smart power management schemes.

Functional working of the DCM3717

The converter uses a patented zero-voltage switching (ZVS) buck-boost regulator front-end, followed by the ZVS/ZCS Sine Amplitude Converter (SAC) current multiplier stage. This two-stage architecture allows efficient operation over a wide range of input voltages. ZVS reduces switching losses by ensuring the transistors switch when the voltage is near zero, while the resonant SAC stage transforms and filters the energy into a 12 V output.

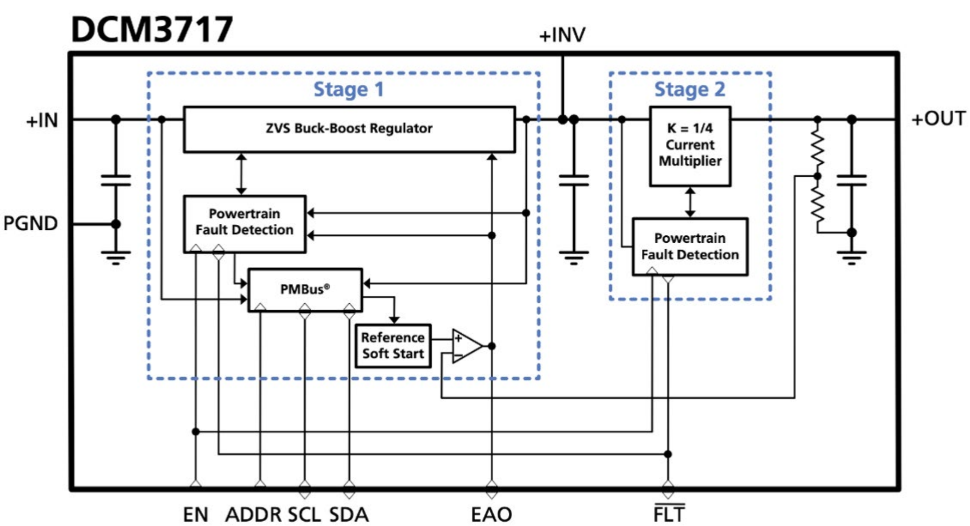
Stage 2 has a fixed ratio of 4:1 that quadruples both the voltage and the current. For example, if Stage 1 produces 48 V, Stage 2's output will be 12 V. Because the feedback is taken at the final V_{out} pins, the control loop automatically corrects for any variation introduced by the multiplier, such as those caused by temperature, load, and aging. This is how the DCM3717 module achieves tight regulation at the load terminals.

As the DCM3717 is designed to handle dynamic loads, the module can deliver peak current and power levels up to 20 percent higher than its continuous rating for up to 1 ms. This full peak capability is available for output voltages up to 12.2 V. Above this, the peak current limit is linearly reduced to prevent output-over-voltage events during fast load changes.

When the input voltage is applied, the module captures the PMBus address by sensing the resistor connected to the ADDR pin. This address remains fixed until the input power is removed. The start-up sequence begins once the input voltage is within its undervoltage and overvoltage thresholds. The FLT signal then goes high to indicate readiness, after which Stage 2 begins switching, and Stage 1 ramps its output reference to generate a smooth soft-start rise in the output stage.

However, if a fault is detected by the module, which can be input overvoltage, undervoltage, over-temperature, or load-related issues, the FLT pin is driven low, and power conversion stops within the specified fault-response time. The module does not restart while the fault condition persists.

The DCM3717 module combines an intelligent digital interface through PMBus with advanced power-train design, soft-switching efficiency, and robust fault handling, delivering a tightly regulated, high-density conversion stage that is straightforward to integrate into high-performance 48 V power delivery networks.



A functional block diagram of the Vicor Corporation DCM3717 high-density DC/DC converter module. (Image source: Vicor Corporation)

Conclusion

The shift to a 48 V power architecture is driving the need to achieve high efficiency in smaller and lighter weight converters for industrial and automotive systems. The Vicor Corporation DCM3717 high-density DC/DC module serves as a bridge between 48 V and 12 V loads, allowing power design engineers to modernize power delivery networks without compromising existing 12 V infrastructure.

To learn more, visit DCM3717 Converter Modules.

Gain advantages with GaN power devices

By Abhishek Jadhav for DigiKey

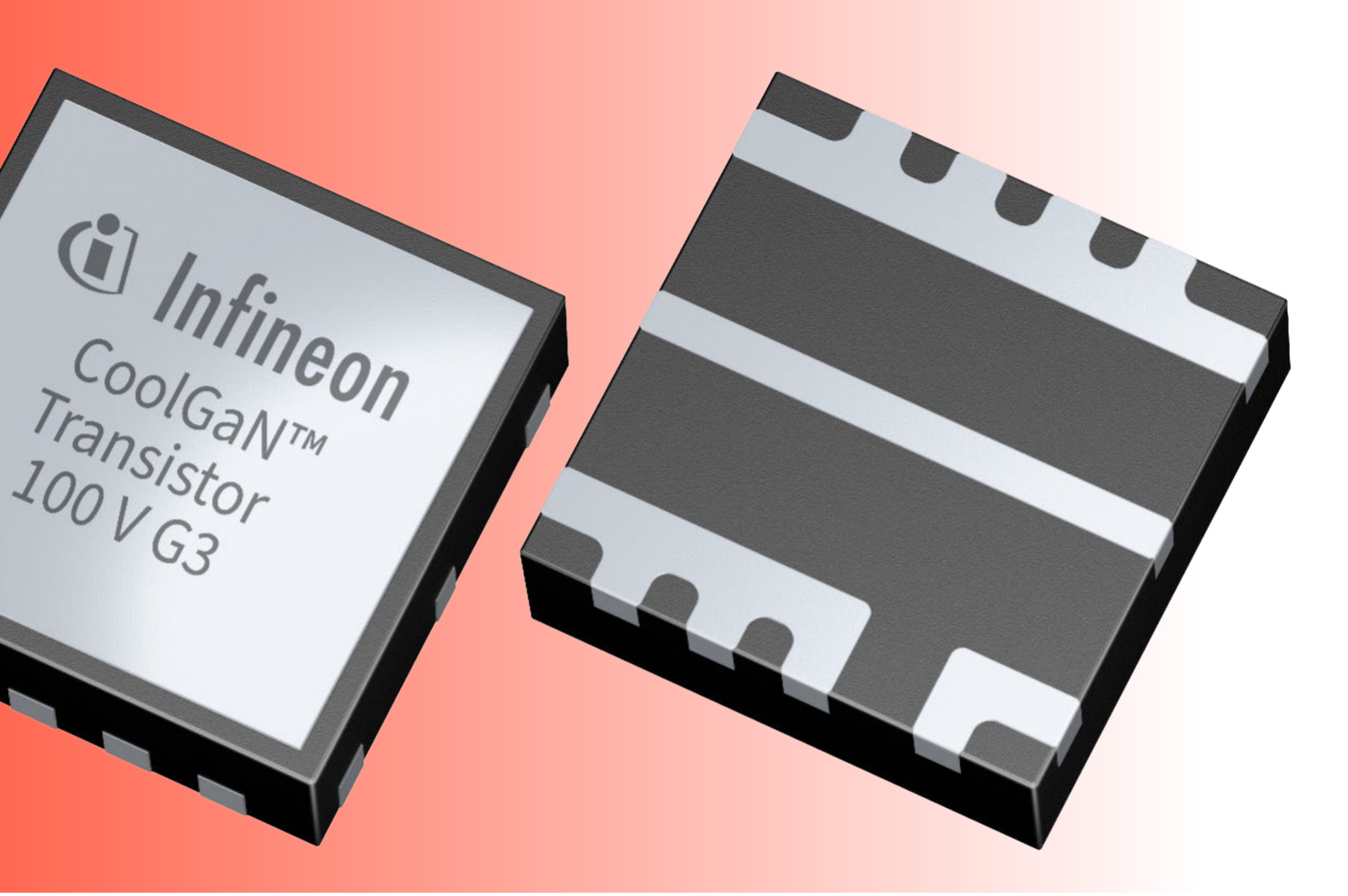
Silicon power devices such as MOSFETs and IGBTs have long been used in power electronics. However, they are increasingly constrained by fundamental performance limits in high-frequency and high-density designs. Design engineers often face trade-offs between conduction and switching losses, which restrict both efficiency and switching speed in silicon power converters.

Gallium Nitride (GaN), a wide bandgap semiconductor, offers a compelling alternative by overcoming many of silicon's inherent limitations. GaN transistors feature significantly lower output charge and gate charge, along with an almost negligible reverse-recovery charge for a given on-resistance.

These characteristics enable much faster switching and substantially reduced switching losses. Additionally, GaN's material advantages include high electron mobility, a high breakdown field, and low intrinsic capacitance, which allow performance levels well beyond those of traditional silicon MOSFETs.

Take, for example, 48 V PMSM motor drives, where switching losses at higher PWM frequencies often limit efficiency and torque control accuracy. GaN offers lower $R_{DS(on)}$, which reduces I^2R conduction losses, improving drive efficiency and extending motor runtime. Its near-zero reverse recovery charge Q_{rr} also enables tighter deadtime optimization, minimizing signal distortion.

In a conference, Infineon Technologies evaluated such a drive using GaN HEMTs and increased the switching frequency from 20 kHz to 100 kHz under field-oriented control. The higher frequency reduced motor phase current ripple and, together with FOC, improved overall system



Infineon IGB070S10S1 CoolGaN ™ transistor 100 V G3 with industrial grade 3 x 3 mm package. (Image source: Infineon Technologies)

efficiency by more than 5 percent, without impacting device temperature or loss.

Infineon offers a wide range of GaN power transistors that are available in voltage classes from 60 to 700 V and in a broad variety of packages. In particular, their medium voltage CoolGaN™ G3 discrete HEMT devices are high-performance transistors that are used for power conversion in a voltage range up to 200 V.

The CoolGaN™ G3 devices are enhancement-mode GaN HEMTs that are usually off for safe operations. They integrate a gate structure that turns on with a positive gate bias, similar to driving a MOSFET. This means standard driver ICs can often drive them and will fail-safe if gate drive power is lost.

Why Infineon GaN?

As GaN power devices transition from emerging technology to mainstream adoption, choosing the right supplier becomes critical for design engineers. Infineon leverages decades of expertise in power semiconductors and robust infrastructure to deliver key advantages. These include silicon compatibility, drop-in packaging, high thermal performance and reliability, broad voltage coverage, and strong field application engineering (FAE) support.

1. Drop-in compatibility

Infineon GaN discretes are designed in industry-standard packages, making it easier for integrators to replace the silicon

MOSFETs with GaN devices. The medium-voltage CoolGaN™ G3 series is available in compact PQFN packages with dual-side cooling metal pads, aligned with standard MOSFET layouts for true pin-to-pin compatibility.

This allows engineers to reuse the existing PCB footprint and socket, enabling multi-sourcing strategies and accelerating time to market. In addition to standard QFN packages, the G3 series includes options such as 3 x 3 mm 4-pin VSON for lower current devices and a larger 3 x 5 mm 6-pin package with exposed top cooling for higher power levels.

Infineon IGC019S06S CoolGaN™ transistor 60 V G3 in PQFN 3 x 5 mm package. (Image source: Infineon Technologies)

2. Thermal performance

Infineon's GaN devices are built with quality for reliable operation over a long period and in harsh conditions. GaN transistors inherently offer higher thermal conductivity than silicon devices, and when combined with Infineon package engineering, result in better heat dissipation and lower junction temperatures during operations.

For high-power designs, the CoolGaN™ G3 is also offered in packages with exposed die attach for enhanced cooling. For example, the 3 x 5 mm PG-TSON-6 package exposes the GaN die on the top side, enabling direct heat sinking and extremely low junction-to-case thermal resistance. This top-side cooling heat spreads over a larger area into the heatsink, minimizing temperature rise and allowing the device to handle high power levels.

3. Manufacturing scale

Infineon has made significant investments in GaN manufacturing capacity. The CoolGaN™ G3 family is manufactured on high-volume 8-inch silicon wafer process lines. Moving GaN to 200 mm wafers drives down cost and ensures the scalability of supply. Infineon has also demonstrated GaN growth on 12-inch wafers, further strengthening its long-term production capacity.

4. Broad voltage portfolio

The CoolGaN™ G3 covers a wide range of medium voltages, including 60 V, 80 V, 100 V, 120 V, and 200 V classes. This allows designers to choose the most suitable device rating for their system, minimizing $R_{DS(on)}$ and Q_G by not using over-rated devices. For example, a 48 V application can use an 80 V device instead of a 150 V device with better performance.

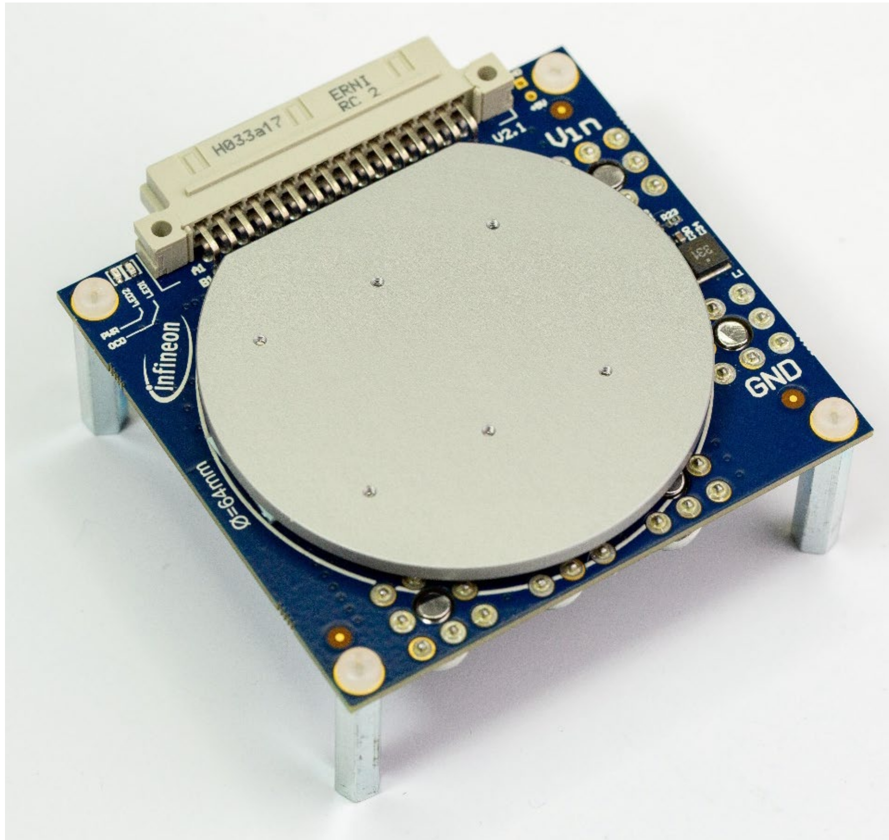
5. Application support

Beyond hardware, Infineon backs its GaN portfolio with extensive application resources. Its global network of field application engineers, trained in GaN applications, provides hands-on guidance for design-in, PCB layout, gate driving, and troubleshooting. In addition, the company complements this with detailed application notes, reference designs, and a wide range of evaluation boards that help engineers reduce development cycles and optimize performance.

How to implement GaN?

After choosing the right GaN supplier, it is important to be able to successfully design power converters. Infineon offers evaluation kits such as the EVALMTR48V20AGAN for low-voltage motor drives, the REFIBC1600WGAN board for scalable 48 to 12 V regulated intermediate bus converters, and the EVAL7126G100VGANC half-bridge evaluation board, among others.

These boards provide proven layouts and schematics using CoolGaN™ G3 devices. By testing on these devices, designers can familiarize themselves with GaN behavior, such as fast switching waveforms and thermal performance, and adapt the design patterns to their specific projects. Infineon also sometimes provides user guides and design files for reference designs.



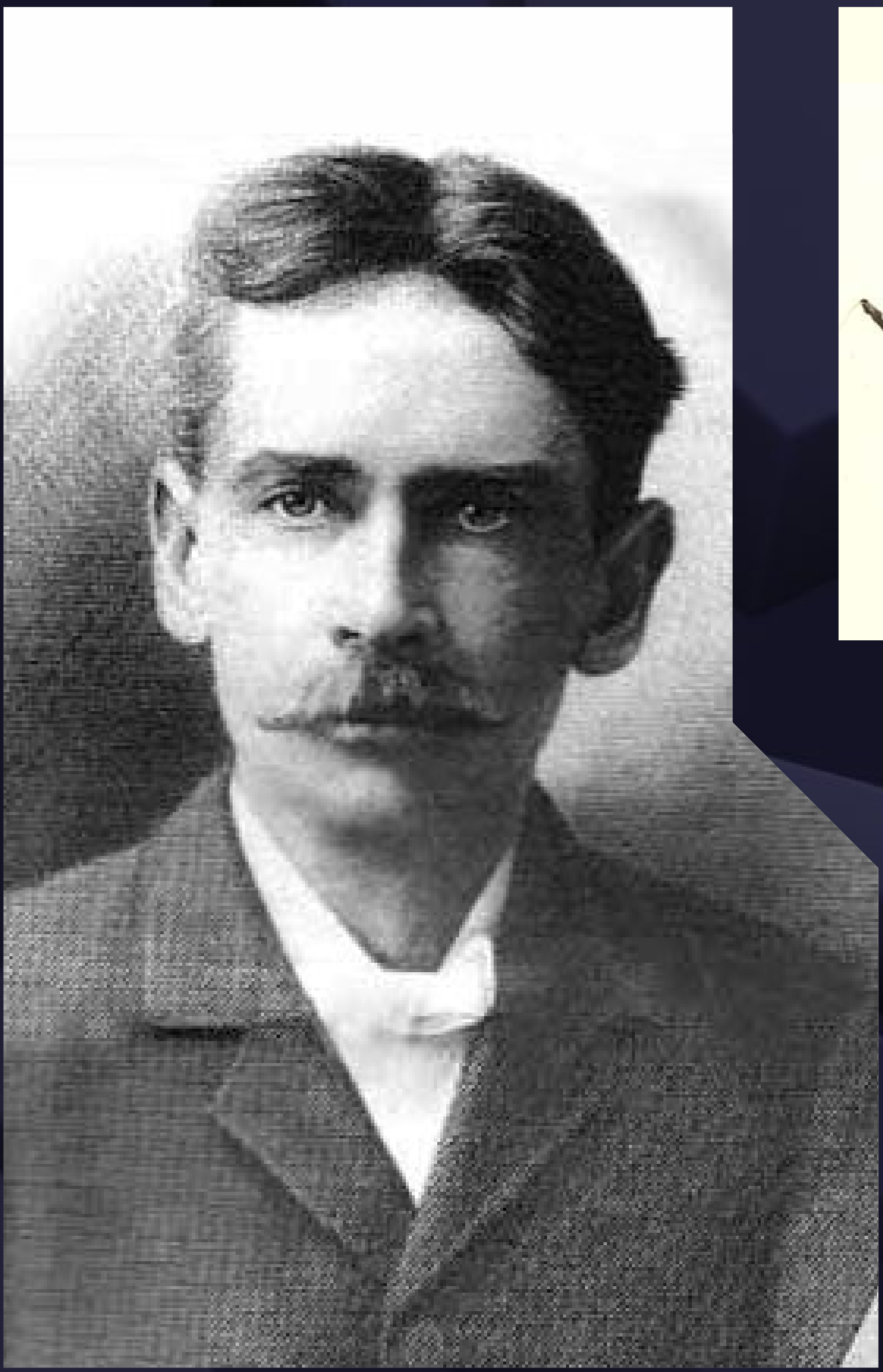
Infineon EVALMTR48V20AGAN for low-voltage motor drives with CoolGaN™ Transistor 100 V G3 and TDI EiceDRIVER™ 1EDN7126U. (Image source: Infineon Technologies)

Conclusion

GaN transistors have changed the power electronics landscape by addressing the limitations of silicon-based power devices. It allows engineers to design power converters and inverters with better efficiency, speed, and power density.

Infineon's CoolGaN™ discrete portfolio amplifies these advantages by providing high-quality, application-specific GaN devices backed by strong engineering support. Design engineers can push the performance limits while reducing risks, benefitting from silicon-compatible packaging, broad device selection, and reliability.

To learn more, visit CoolGaN™.



Painting of Williston Academy from the late 1870s.

Forgotten genius: William Stanley Jr.'s legacy in electrical engineering

By David Ray
Cyber City Circuits

William Stanley Jr.

In the history of invention, many names have been lost to time or overshadowed by the 'giants of industry.' Stanley is one of the names that haven't been lost from the public's mind, but not for the reasons many might think. In his lifetime, he was granted one hundred twenty-nine patents covering a wide range of devices, many related to the electrical field, some not. While the reader may recognize his name from the side of their all-metal, vacuum-sealed coffee cup, his most notable contribution is the AC power transformer that brought AC power transmission to civilization. Stanley's patent #349,611 changed everything and became the prototype for all future power transformers.

Childhood

William Stanley Jr. was born in Brooklyn, New York, in 1858, but soon moved to his ancestral home, being raised in Great Barrington, Massachusetts. Stanley's father, William Stanley Sr, was a successful Yale-educated New York lawyer, and his mother was the daughter of a wealthy New York importer. At a very young age, Stanley showed a talent for mechanical things. It is said that at age ten, he took a pocket watch apart and reassembled it, and it kept perfect time afterward.

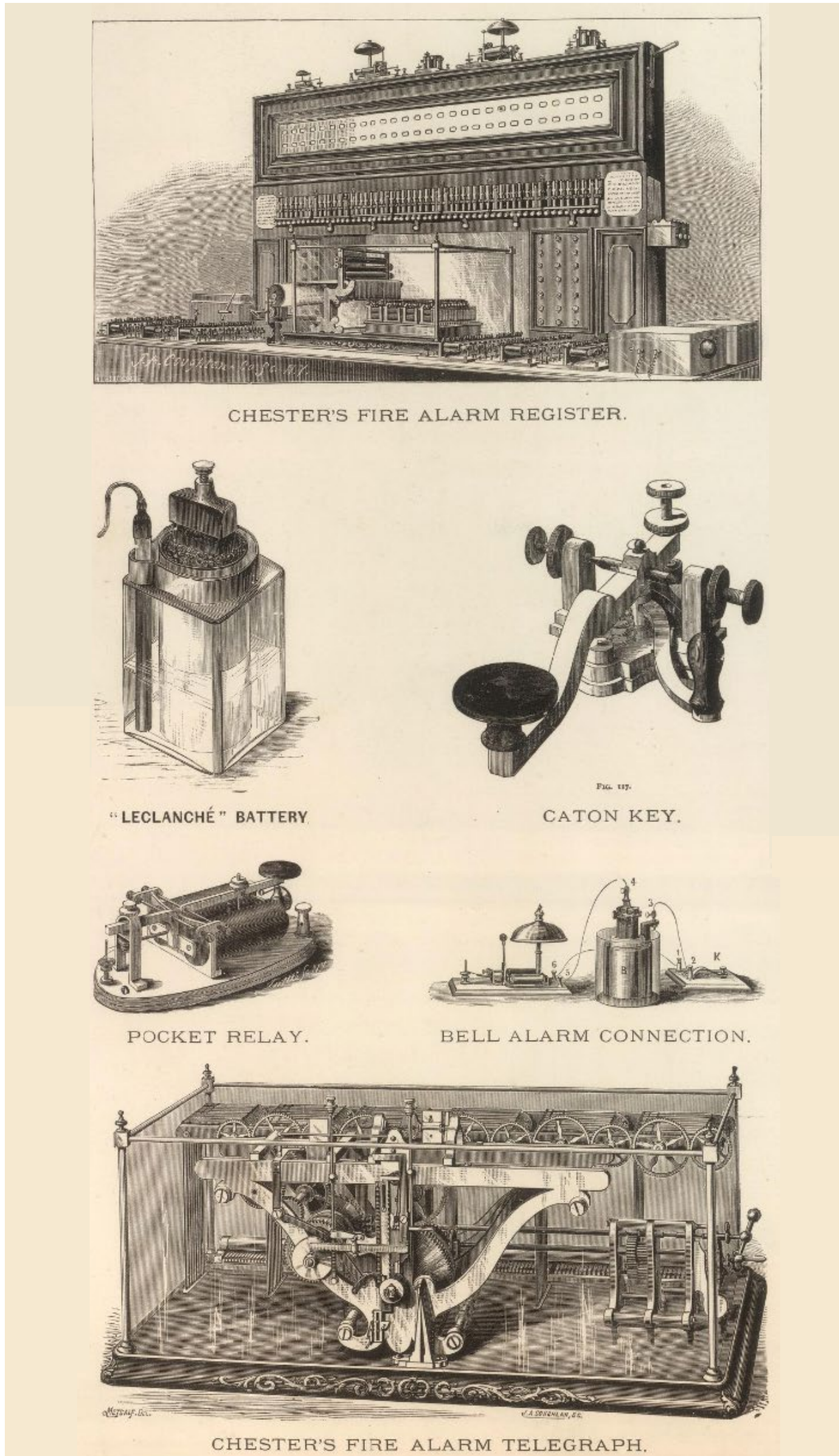
Stanley attended Williston Academy (also known as Williston Seminary) in Easthampton, MA, and graduated in 1877. Afterwards, his father sent him to Yale to study law, but by

Christmas break, he had become disenchanted with school in general and dropped out. He would comment many years later, “I am afraid there is a good deal of stuff taught in school that clogs instead of clears the brain.”

Retro Electro Fun Fact: During this era, Massachusetts was a hotbed for innovation. Along with many important inventions, one of the most essential tools of the period originated in Boston: the Stillson Wrench. Learn more in the Retro Electro article, Steel and Steam. (Link: https://emedia.digikey.com/eMagazine-Vol-20-Test-Tools-and-Measurement/28-29/)

Early career

After leaving school, he took no time getting to work and fell into the electrical industry. With his strong mechanical mind, he began working for a telegraph equipment manufacturer in 1877 named Charles T Chester.



Images from a period Chester catalog of equipment that Stanley would have been working on during his time there.

Retro Electro Fun Fact: In 1877, the US Patent Office's model archive caught fire and destroyed many of the original patent models submitted by their inventors, including the Elisha Gray and Alexander Graham Bell models. This event brought fire suppression systems to the front of mind for many inventors and engineers.

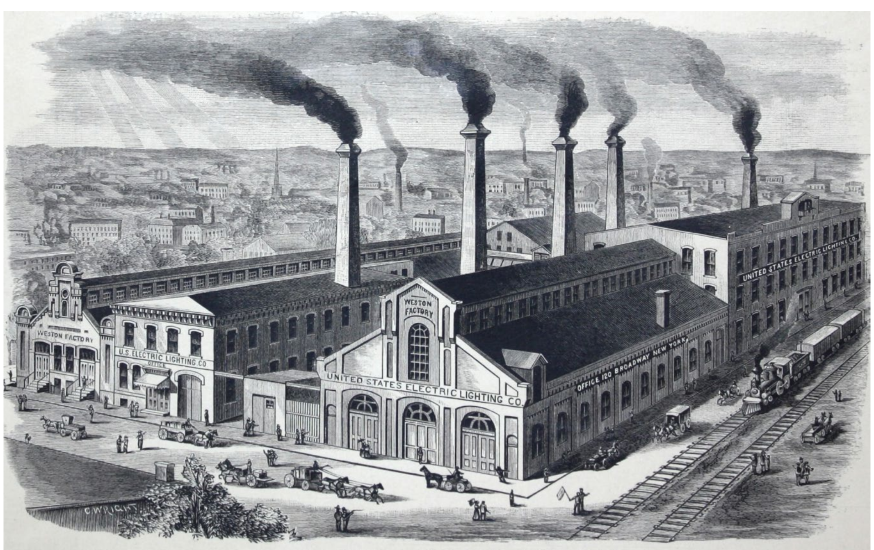
Chester developed many fire alarm and suppression systems that integrated with the telegraph systems of the day.

While working for Chester, he saved up money and, with a loan from his father, bought into a nickel-plating shop. While working there, he developed new methods for electroplating, speeding up the process, which became very successful within his first year of involvement.

Soon he found that the day-to-day routine at the shop no longer could keep his interest, and in 1880 he went to work for a British inventor named Hiram Maxim at the United States Electric Lighting Company. Stanley's salary was cut significantly, but he was satisfied being able to work on new problems every day.

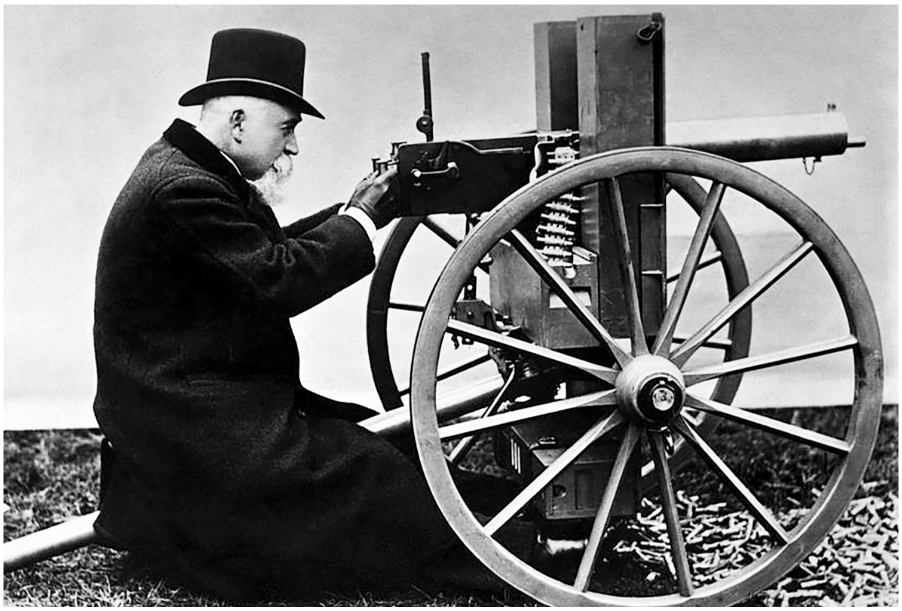
The best description the writer can find of young Stanley comes from Maxim as a "very tall and thin, but what he lacked in bulk he made up in activity. He was boiling over with enthusiasm. Nothing went fast enough for him. I believe he preferred that each week should contain about 10 days and that the days should be about 48 hours long. Whatever was given to him to do he laid himself out to do in the most thorough manner. He would spare no trouble or expense to accomplish the task which was given him to do, after laying out his own money in order to obtain material which he thought might be better than what was available in the works."

Eventually, Stanley was made the first assistant in charge of research and development for Maxim, where he worked on developing new incandescent light bulbs. While Thomas Edison was working on the light bulb, many others in the New England area were also working on similar projects. The following year, 1881, Maxim would leave and return to England, selling his interest in the United States Electric Light Company to the American Electric Company, which would then rebrand as the Thomson-Houston Electric Company. This company would later be merged with Edison's company to create the General Electric company.



Drawing of Maxim's United States Electric Lighting Co.

Retro Electro Fun Fact: Sir Hiram Maxim was one of the members present at the 1881 International Electrical Congress when the units of measure, like Ohm and Volt, were standardized for the first time. Read more about that event in the Retro Electro article 'Ohm's Day.' (Link: https://emedia.digikey.com/view/639112496/21/)



Hiram Maxim with his magnum opus, the Maxim Machine Gun.

After Maxim left the country, Stanley went to work for the Swan Electric Lamp Company in Boston. While working at the Swan Electric Lamp Company, Stanley was responsible for numerous patents related to improvements in incandescent lamps. For the next few years, he worked for Swan in a private lab in New Jersey. It was here that he met his wife, Lila Courtney Wetmore, with whom he would have six sons and three daughters.

One of the major innovations from Stanley during this period was a 'lamp regulator.' Prior to this, a lamp's brightness would fluctuate constantly depending on the generator's load. This invention would help keep a steady current through the bulb's filament, allowing for a consistent brightness. This caught the attention of railway industrialist George Westinghouse. Soon after, Swan Electric Lamp Company was sold to Brush Electric Light in 1884.

George Westinghouse and the air brake

George Westinghouse Jr. was born in 1846 in New York. His father owned a successful machine shop and Westinghouse was quick to learn the trade. Following his naval service in the Civil War at age nineteen, he received his first patent for a rotary steam engine. His first groundbreaking invention was the air brake for trains, which he patented in 1869 at the age of twenty-two.

George Westinghouse

During the mid-19th century, with the start of the Second Industrial Revolution, trains were the primary way to carry goods and people long distances. The number of trains on the railway increased in size, quantity, and speed more than ever before. Horrific train crashes were regularly reported in newspapers across the country. At that time, the best way to slow down or stop a train was by having a 'brakeman' riding on top of the train cars. When the engineer sounded the whistle, the brakeman would jump up and turn the wheel to engage the brakes, then move to the next car to do the same for each following car. A speeding train could take up to two miles to come to a complete stop, and that was only if the brakeman survived the trip. It was not uncommon for a brakeman to fall to his death while trying to perform his job, and if that happened, there was no better way to stop the train and prevent a catastrophic crash. It was said that during this period, up to five thousand brakemen would die in a year.

Brakemen would run up and down a train to operate the brakes on the train cars as the train moved.

Deadly train crashes were not uncommon during this time.

Westinghouse, reportedly personally affected by a disastrous crash, turned his attention to the new field of industrial pneumatics, creating the air brake. The new invention enabled trains to stop in a fraction of the distance, allowing them to become longer and heavier, thereby carrying more goods and more people.

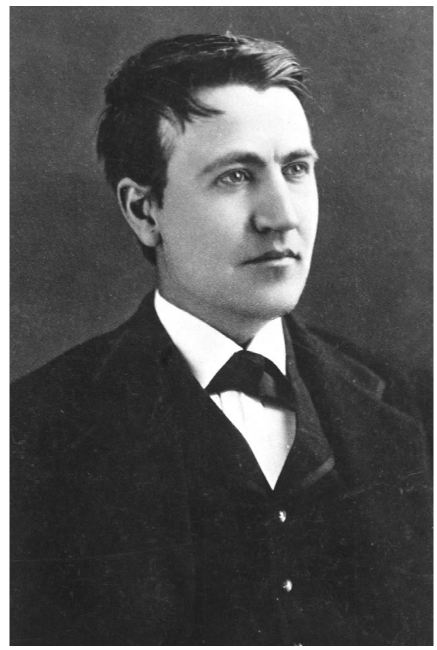
In 1869, he formed the Westinghouse Air Brake Company and started demonstrations of his new system across the country, selling thousands of units a year. By 1877, most passenger trains were equipped with Westinghouse Air Brakes, making Westinghouse very wealthy. He used this wealth to invest in many inventions and innovations.

Solving the problem with Edison's DC power

Up to this point in electrical history, direct current (DC) was the dominant system of power transmission, but it presented significant limitations. DC power could only be transmitted effectively over very short distances (up to one and half miles) due to the voltage drops of the power lines. To resolve this, the number of power stations increased, generating more pollution, while the power lines became thicker and more expensive. It was obvious that widespread urban electrification would never be practical and would be difficult and expensive to maintain. As Stanley himself said, "It was the common saying of the day that, if one should attempt to light Fifth Avenue from Fourteenth Street to Fifty-Ninth Street, the (DC) conductors required would be as large as a man's leg."

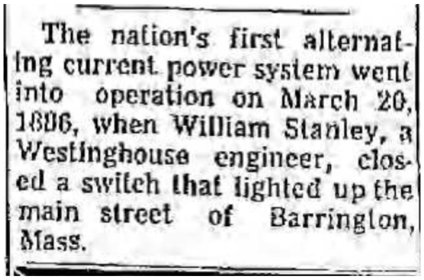
Edison was heavily invested in DC power transmission. He would negotiate deals with cities and municipalities to install numerous power stations throughout their areas, in exchange for the profits from those stations. With little to no upfront cost, towns were eager to grant him anything he wanted in exchange for streetlights and lit storefronts. The problem was that if anything emerged to threaten all the investment he had already made into DC systems, he would suffer significant losses.

Alternating current (AC) was the solution to this distance problem, but unfortunately for Edison, he was already waist-deep in DC power by the time he realized he could not pivot to AC easily. AC was superior to DC for power transmission because it could travel much farther with less loss. This was because AC voltage could be increased (stepped up) using a transformer, which reduced the current in the wires and thus minimized energy lost through heat from resistance. Once it reached its destination, the voltage could be safely stepped down again for use in homes and businesses. AC required fewer power stations and smaller transmission lines, making it overall much more cost-effective than anything Edison was doing.



Thomas Edison as he looked during this time.

Retro Electro Fun Fact: Around this time, Edison enlisted the help of a former Navy Officer named Frank J Sprague to try to solve his power transmission issues. Sprague found Edison to be insufferable and left to start his own company, developing the first practical electric motor for trolleys and railways. Read more about his story in the Retro Electro article 'Frank J Sprague and the Richmond Union Passenger Railway.' (Link: https://emedia.digikey.com/view/251481832/16-17/)


The nation's first alternating current power system went into operation on March 20, 1886, when William Stanley, a Westinghouse engineer, closed a switch that lighted up the main street of Barrington, Mass.

Newspaper clipping from 1886.

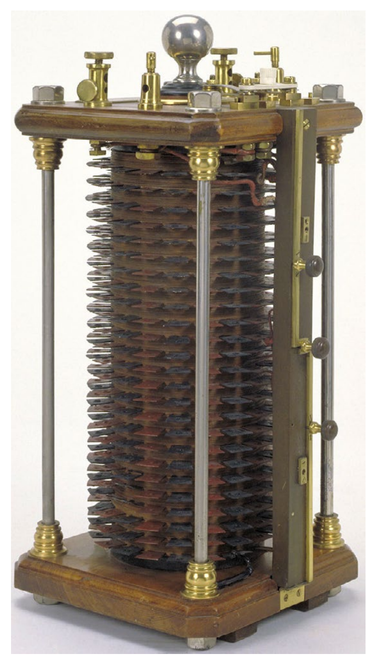
The electrification of Great Barrington

In 1884, when George Westinghouse discovered Stanley's lamp regulator, he sought out Stanley to work for him. Stanley was glad to work for Westinghouse in Pittsburgh, developing new inventions, but he became deathly ill with tuberculosis in 1885. It was determined that the harsh Pittsburgh industrial environment worsened his condition, and his doctor recommended that he move out of the city. He moved back to his childhood home in Great Barrington, MA, and rented a defunct rubber mill in November of the same year. The mill was in operation for many years until the Housatonic River's water level dropped eleven inches, making it impossible to run the necessary machinery.

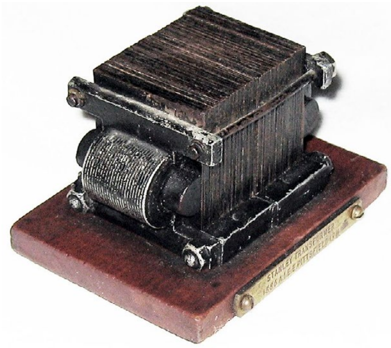
During his 'recovery retreat,' Stanley's drive for invention remained strong. He aimed to tackle one of the most pressing electrical engineering challenges of his time. Having firsthand experience with the limitations of direct current in his lighting projects, Stanley was committed to demonstrating that alternating current could be a safe, scalable, and efficient solution. When illness compelled him to leave Pittsburgh, Great Barrington offered a convenient testing ground. Its layout and small size made it perfect for trialing a new, ambitious system.

The first primitive transformer was designed by European inventors, Lucien Gaulard and John Dixon Gibbs. At the time, the term transformer had not been coined yet, instead calling it the 'secondary generator.' Soon after, in 1885, Stanley would have Westinghouse purchase the patent rights to Gaulard and Gibbs' invention.

The Horace Day Rubber Mill that Stanley worked out of in Great Barrington.



The Gaulard and Gibbs Secondary Generator



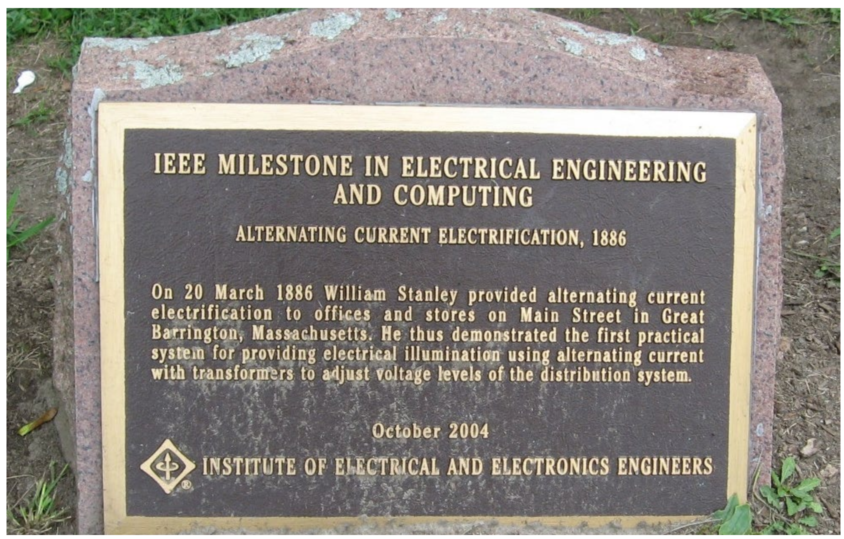
An 1886 Stanley Transformer

Stanley had a critical but constructive view of the secondary generator—the early transformer concept developed by Gaulard and Gibbs. He saw its promise, but also its shortcomings. He appreciated the underlying principle: magnetic induction could transfer electrical energy between circuits, but he criticized its efficiency and instability. The open-core design leaked magnetic flux, struggled to handle varying loads, and resulted in unpredictable voltage drops.

After studying its construction, Stanley experienced a 'Eureka' moment. Stanley's key insight was that using a closed magnetic path (a looped iron core instead of an open air core) and improved insulation would resolve these issues. His improvements made the transformer more reliable, easier to manufacture, and scalable, turning it from an experimental novelty into the backbone of his new AC system.

In early 1886, Stanley had a twenty-five horsepower Westinghouse automatic steam engine installed in his laboratory, which energized a five-hundred-volt Siemens alternator. He hand-built several of his new transformers (called 'exhorters' at the time) to study.

Starting in February through the first half of March, he hung over 4,000 feet of No. 6 wire along elm trees to Main Street. He used a large transformer in the rubber mill to step up the voltage to three thousand volts and he placed six of his transformers (dropping



Plaque placed near the location of the original rubber mill in 2004.

"On 20 March 1886 William Stanley provided alternating current electrification to offices and stores on Main Street in Great Barrington, Massachusetts. He thus demonstrated the first practical system for providing electrical illumination using alternating current with transformers to adjust voltage levels of the distribution system."

– A dedication plaque located on the corner of Cottage and Mill streets in Great Barrington, MA, close to where the original rubber mill power station was located.

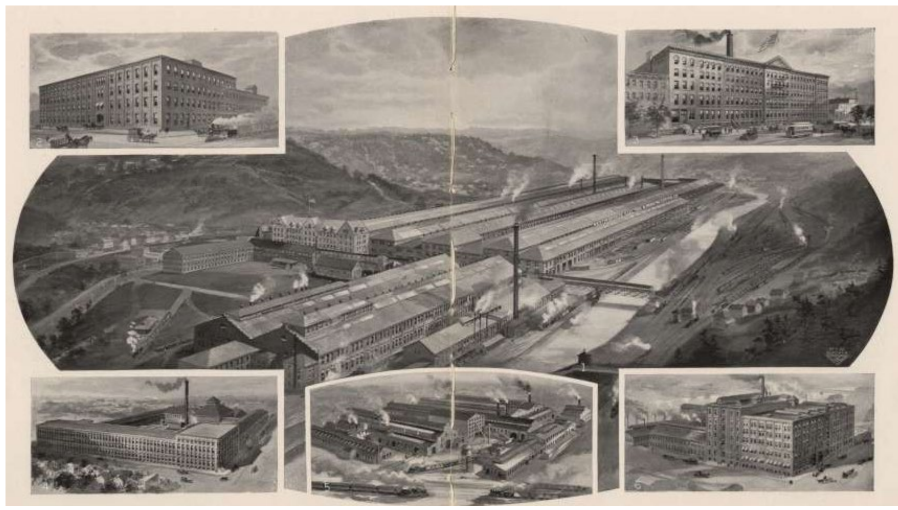
the power to 100 volts) in the basements of buildings along the route. His AC system supplied power to twenty-six businesses and four hundred incandescent lamps along Main Street.

Westinghouse Electric & Manufacturing Company

The noteworthy success in Great Barrington directly led to the founding of the Westinghouse Electric and Manufacturing Company in Pittsburgh, Pennsylvania, later in 1886. Along with William Stanley Jr he enlisted the help of engineers named Oliver B. Shallenberger, Nikola Tesla, and others to refine and commercialize the components needed for full-scale AC distribution, including generators, transformers, and motors. The company quickly began rolling out systems for municipal lighting and industrial use, leveraging the ability to transmit power at high voltages over long distances—something DC could not do. This demonstration lasted a short time before the engine and alternator started to fail, but it was solid evidence that his plan for electrification would work.

Westinghouse Electric became a powerhouse of innovation, filing hundreds of patents and installing dozens of AC systems across the United States and Europe within its first few years. Its greatest strength

Retro Electro Fun Fact: The story of the electrical industry at this time has been called the **'War of the Currents.'** That story is more complex than the scope of this article, but the reader can look forward to this story in a future Retro Electro article.



The Westinghouse Electric Manufacturing Company

lay in the synergy between Stanley's mind and Westinghouse's pockets. Westinghouse provided the business drive and capital, Stanley had already cracked the transformer problem, and soon Tesla would supply the missing piece—a practical AC motor. By building an integrated AC ecosystem, Westinghouse Electric not only challenged Edison's dominance but also laid the foundation for the modern electrical grid.

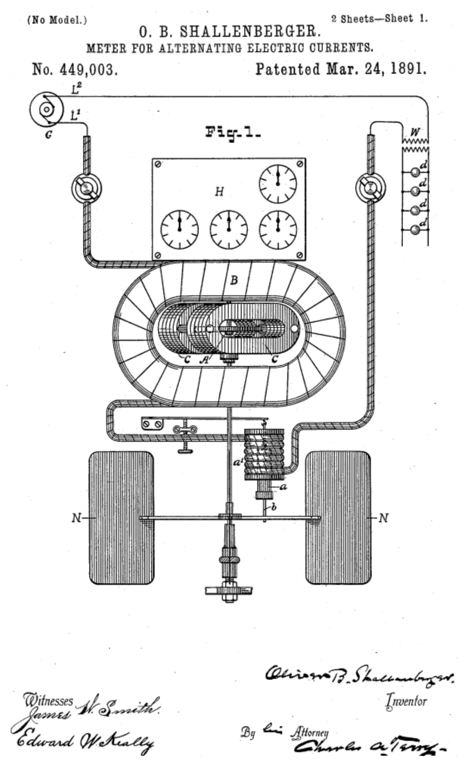
Stanley continued to work with Westinghouse until 1888. While many sources indicate that they had an amicable relationship, letters between Stanley and his father reveal that he felt he was repeatedly tricked and cheated by Westinghouse. Stanley felt that what he did "for the alternating system was what practically introduced it" to the market, while Westinghouse gave him little to no credit or notoriety, taking all of the accolades for himself.

He accused Westinghouse of creating "onerous conditions" while he derived all the benefits. He accused Westinghouse of taking his work, giving it to someone else for the to file the patent before Stanley could. He even said that

Westinghouse went as far as to break into his private laboratory to steal his work, documents, etc. Nikola Tesla also accused Westinghouse of many of the same things, offering large amounts of cash for his polyphase motor patents, but never receiving the full amount. Eventually, out of what seems to be frustration, he sold all of his patents, up to that point, to Westinghouse for a large cash amount and left the company in 1888.

Meter for alternating electric currents

The same year that Stanley left Westinghouse to work on his own, Oliver Shallenberger, another Westinghouse engineer, invented a meter that could be used for measuring a subscriber's usage by measuring the amps traveling through the meter. It used a rotating coil that moved in proportion to the current consumed, triggering a mechanical register that tracked the number of revolutions the coil had made. This was great for Westinghouse because they could track usage and bill accordingly, but it had several flaws. It was sensitive to voltage fluctuations, resulting in inaccurate readings regularly when the system was loaded down.



The Shallenberger Meter was revolutionary at the time.

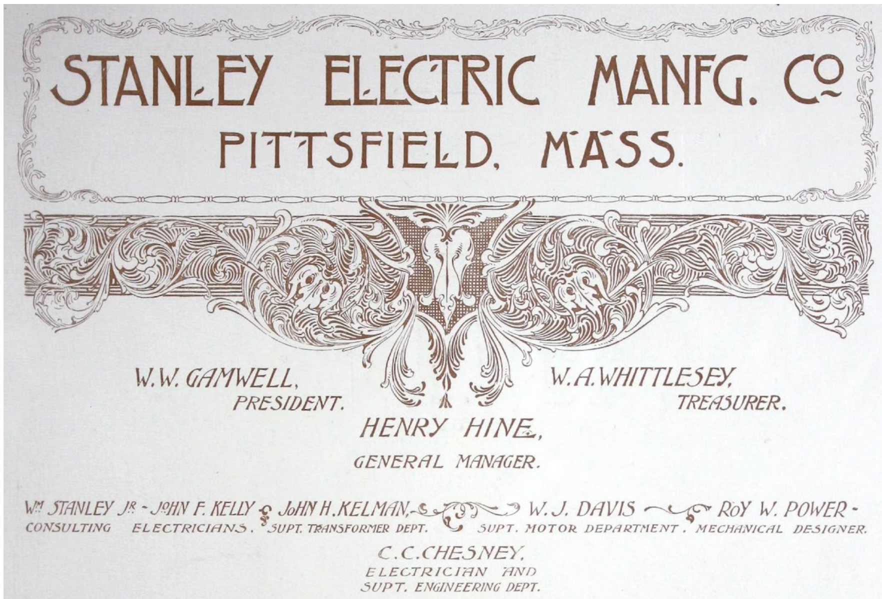
Stanley Electric Manufacturing Company and the Pittsfield Illuminating Company

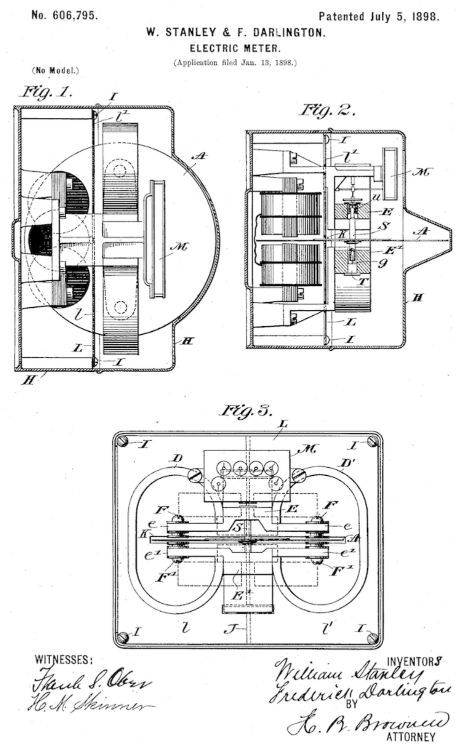
After Stanley left in 1888, he took a short sabbatical and soon after started a new business in Pittsfield, MA, the Stanley Electric Manufacturing Company in 1890. However, much of this work started the year before. He partnered with another former Westinghouse engineer, Frederick P. Darlington, who left around the same time.

Combined with another business venture of his, the Pittsfield Illuminating Company (later the Pittsfield Electric Company), his companies were the first to use a hundred-light transformer in this country, and by 1893, they had built a 4,000 kilowatt (4 megawatt) transformer, the largest in the world at the time. In 1899, the Stanley Electric Manufacturing Company had up to twelve hundred active employees, but it eventually merged with the General Incandescent Arc Light Company and changed its name to the Stanley G.I. Electric Manufacturing Company, before ultimately merging into General Electric.

"I honestly think we did pretty well. While the other fellows were writing articles to prove that efficient transformers must be limited in size, we were building them larger and larger and constantly increasing their efficiency."

– Stanley on the Stanley Electric Manufacturing Company





The watt-hour meter patent used two coils. One for measuring current and the other for measuring voltage.

The wattmeter

After the businesses in Pittsfield started falling through, he pulled back to Great Barrington, where his work on transformers started. He began the Stanley Instrument Company, selling transformers and measuring equipment, and they developed a new invention, the watt-hour meter. This meter was able to consider both the voltage at any given time, along with the current, giving a precise measurement of power usage in watt-hours. Another key to this innovation was found when the bearings used for the rotating disc used to measure power would fail, eventually realizing he could remove the bearing altogether and use magnets to suspend the coil and disc for the most precise usage measurements available, culminating with an 1898 patent no. 606,795 and this is what Westinghouse needed to form a case for patent infringement of their earlier Shallenberger AC meter.

After eight years of litigation, Westinghouse and his army of lawyers won the final judgement, exhausting what limited resources Stanley had left in 1907, putting his company out of business while Westinghouse assumed control of the numerous patents Stanley was granted while developing the watt-hour meter.

He would spend the next several years as a consulting engineer for companies like General Electric while also working on his own projects.

Stanley Bottle Company

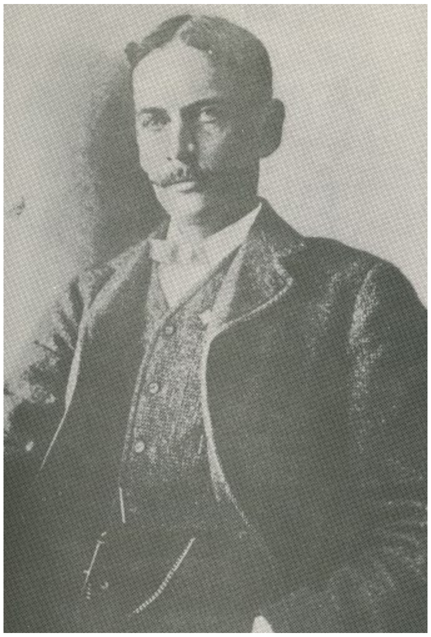
In 1913, William Stanley invented the all-steel, double-wall vacuum bottle and named it after himself. Pulling from his earlier experience with nickle plating and pulling a vacuum from light bulbs. The brilliance is that if you remove the air between two conductors of heat, the energy from one side, doesn't travel through the vacuum in the middle, insulating the material on the inside from the ambient environment outside.

The first vacuum-insulated container was call the Dewar Flask, invented by Sir James Dewar in 1885, but used glass as a core insulator and sold under the brand Thermos. Instead of glass, Stanley's version was all metal and sold them under the name SuperVac and could keep coffee hot all day.

The Stanley Bottle Company made a wide assortment of containers.

Legacy

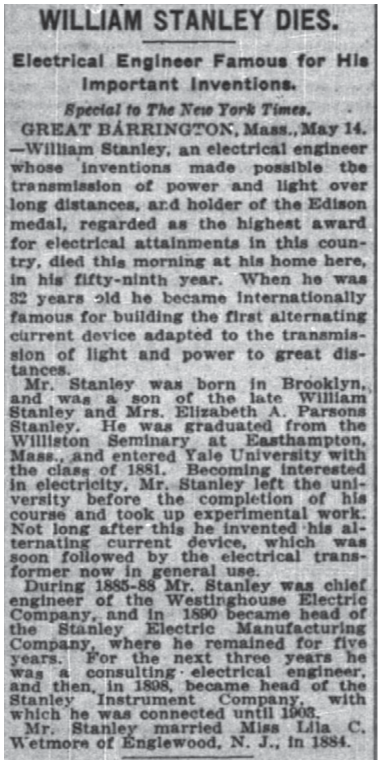
William Stanley Jr.'s contributions fundamentally reshaped how humanity harnessed and distributed electrical energy. While history often spotlights Edison and Westinghouse as the titans of electricity's early days, Stanley's innovations were critical in establishing the practical foundation for alternating current, an essential pillar of the modern electrical grid. His pioneering improvements to transformers and visionary system designs demonstrated that AC power could reliably and economically travel vast distances, enabling



William Stanley Jr

widespread electrification and altering the landscape of industry and daily life. Stanley's later innovations, including the watt-hour meter and his vacuum-insulated bottle, further illustrate a lifetime characterized by a relentless pursuit of ingenuity and practical solutions.

Though Stanley's story includes moments of frustration and overshadowing by more famous contemporaries, his enduring legacy lives on, not just in historical records and commemorative plaques, but in the everyday convenience and safety we experience every time we flip a switch or pour a hot drink. William Stanley Jr. may not always receive the acclaim he deserves, yet the lasting impact of his vision and determination continues to resonate across generations.



WILLIAM STANLEY DIES.

Electrical Engineer Famous for His Important Inventions.

Special to The New York Times.

GREAT BARRINGTON, Mass., May 14. —William Stanley, an electrical engineer whose inventions made possible the transmission of power and light over long distances, and holder of the Edison medal, regarded as the highest award for electrical attainments in this country, died this morning at his home here, in his fifty-ninth year. When he was 32 years old he became internationally famous for building the first alternating current device adapted to the transmission of light and power to great distances.

Mr. Stanley was born in Brooklyn, and was a son of the late William Stanley and Mrs. Elizabeth A. Parsons Stanley. He was graduated from the Williston Seminary at Easthampton, Mass., and entered Yale University with the class of 1881. Becoming interested in electricity, Mr. Stanley left the university before the completion of his course and took up experimental work. Not long after this he invented his alternating current device, which was soon followed by the electrical transformer now in general use.

During 1885-88 Mr. Stanley was chief engineer of the Westinghouse Electric Company, and in 1890 became head of the Stanley Electric Manufacturing Company, where he remained for five years. For the next three years he was a consulting electrical engineer, and then, in 1898, became head of the Stanley Instrument Company, with which he was connected until 1903.

Mr. Stanley married Miss Lila C. Wetmore of Englewood, N. J., in 1884.

Stanley's obituary from 1916.

Suggested reading

"Apparatus for Transmission of Light and Power by Two Phase Alternating Current"

"A Frictionless Wattmeter" by Wallace D White (Electrical World June 17, 1899)

"Distribution of Power by Alternating Currents" by William Stanley Jr and John F Kelly

"William Stanley: Lighted a Town and Powered an Industry" by Bernard Drew and Gerard Chapman

"The Great Barrington Electrification, 1886" by Edison Tech Center

"William Stanley" on the Engineering and Technology History Wiki

"Alternating Current Electrification 1886" on the Historical Marker Database

Patent US449003A: 'Meter for alternating electric currents' by Oliver Shallenberger

1858

Born in Brooklyn, New York; raised in Great Barrington, Massachusetts.

1877

Graduated from Williston Academy; briefly attended Yale University.

Began work with telegraph equipment manufacturer Charles T Chester.

1880

Joined Hiram Maxim at the United States Electric Lighting Company.

1881

Worked on incandescent lamps; Maxim sold company, later part of General Electric.

1884

Joined Swan Electric Lamp Company; developed lamp regulator innovation.

1885

Recruited by George Westinghouse to refine AC power distribution systems.

1885-1886

Developed practical AC transformer and distribution system in Great Barrington, MA.

March 20, 1886

Demonstrated first practical AC electrification in Great Barrington.

1886

Westinghouse Electric and Manufacturing Company founded, incorporating Stanley's innovations.

1888

Left Westinghouse amid disputes; sold AC patents to Westinghouse.

1890

Founded Stanley Electric Manufacturing Company in Pittsfield, MA.

1893

Produced the world's largest transformer (4,000 kilowatt) at Stanley Electric Manufacturing.

1898

Developed advanced watt-hour meter with magnetic bearings (patent no. 606,795).

1907

Lost the watt-hour meter patent lawsuit to Westinghouse; Stanley's company closed.

1913

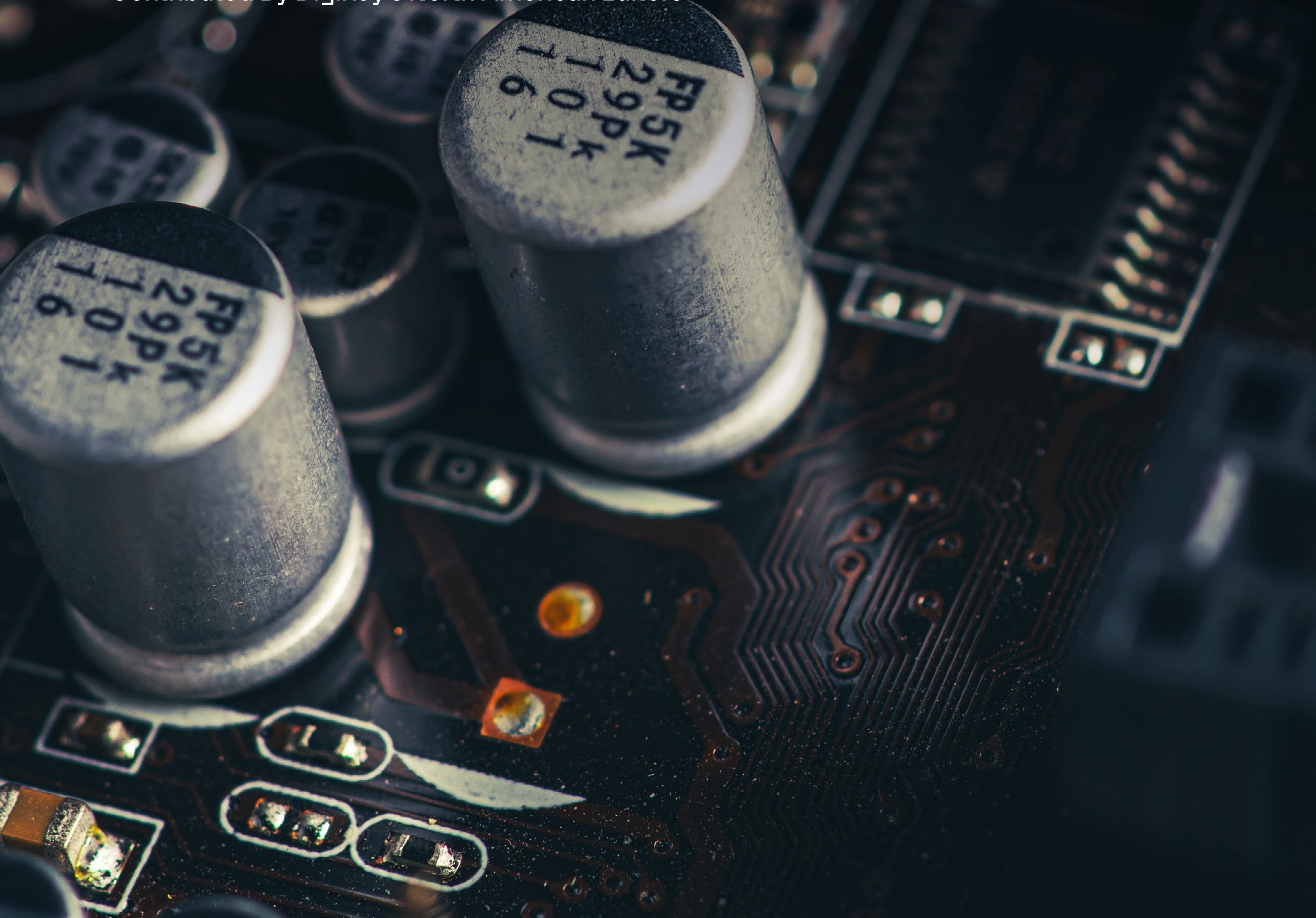
Invented the all-steel, double-wall vacuum-insulated Stanley bottle ("SuperVac").

1916

Passed away, leaving a profound legacy in electrical engineering and everyday technology.

Use coupled inductors in multiphase buck converters to improve efficiency

By Kenton Williston
Contributed By DigiKey's North American Editors



Multiphase buck converters are widely used in 12 V applications such as datacenters, artificial intelligence (AI) systems, and communications infrastructure. A common theme across these use cases is the need for improved efficiency without compromising performance or increasing the physical footprint.

One promising approach involves coupled inductors (CLs). By using mutual inductance between phases, CLs enable superior current ripple cancellation, resulting in significant efficiency improvements while preserving compatibility with conventional layouts.

This article briefly outlines the efficiency and layout challenges facing designers of multiphase buck converters. It then introduces CLs, presents experimental results validating the efficiency improvements, and shows how they are applied in converters from Analog Devices.

Conventional multiphase buck converter efficiency challenge

In high-performance computing and communications systems, efficiency losses in power delivery can have outsized impacts on system cost, reliability, and thermal management. Designers of conventional multiphase buck designs often face challenges in this regard, particularly under light-load conditions where switching and AC losses become more pronounced.

At the same time, power-stage layout and mechanical constraints limit the options available for improving performance. In many systems, there is little room to increase component size, and changes to the printed circuit board (pc board) layout may not be feasible in the face of common footprint strategies.

As a result, there is strong interest in approaches that can deliver higher efficiency without requiring substantial changes to the power architecture. Ideally, such solutions would retain the same footprint, allow the use of existing output capacitance (C_O), and maintain transient performance across a wide range of load conditions.

CLs address these demands by enabling ripple reduction and switching loss improvements, all within the same physical footprint as conventional designs.

How CLs improve power conversion

CLs offer an effective way to improve efficiency in multiphase buck converters without altering the layout. Unlike conventional designs that treat each phase as electrically independent, CLs share a standard magnetic structure that enables interaction between phases.

Two key parameters govern this interaction: leakage inductance (L_k) and mutual inductance (L_m). The leakage inductance behaves like the phase inductance (L) in traditional designs, while the mutual inductance introduces magnetic coupling across phases. As current increases in one phase, it induces a voltage in the others that opposes their current change, resulting in significant ripple current cancellation.

Equations 1 and 2 define the expected ripple current for conventional discrete inductor (DL) designs (dIL_{DL}) and CL designs (dIL_{CL}). These currents depend on the input and output voltages (V_{IN}, V_O), inductances L, L_k, and L_m, switching frequency (F_S), and a “figure of merit” (FOM).

Equation 1:

$$dIL_{DL} = \frac{V_{IN} - V_o}{L} \times \frac{D}{F_S}$$

Equation 2:

$$dIL_{CL} = \frac{V_{IN} - V_o}{L_k} \times \frac{D}{F_S} \times \frac{1}{FOM\,(D, N_{ph}, p, k)}$$

Where:

ρ = the coupling coefficient = L_m/L

D = duty cycle

N_{ph} = the number of coupled phases

Equation 3 lays out the calculations for the FOM. This equation captures the extent of ripple cancellation as a function of various parameters. Specifically, the FOM depends on ρ, N_{ph}, and D.

Equation 3:

$$FOM = \frac{\left(1 + \frac{\rho}{\rho + 1} \times \frac{1}{N_{ph} - 1}\right)}{1 - \left[(N_{ph} - 2 \times j - 2) + \frac{j \times (j+1)}{N_{ph} \times D} + \frac{N_{ph} \times D \times (N_{ph} - 2 \times j - 1) + j \times (j+1)}{N_{ph} \times (1 - D)}\right] \times \frac{\frac{\rho}{\rho + 1}}{N_{ph} - 1}}$$

Where:
j = floor (D × N_{ph})

While the FOM depends on many factors, the coupling coefficient ρ plays a significant role. To illustrate this point, it is helpful to consider a practical example.

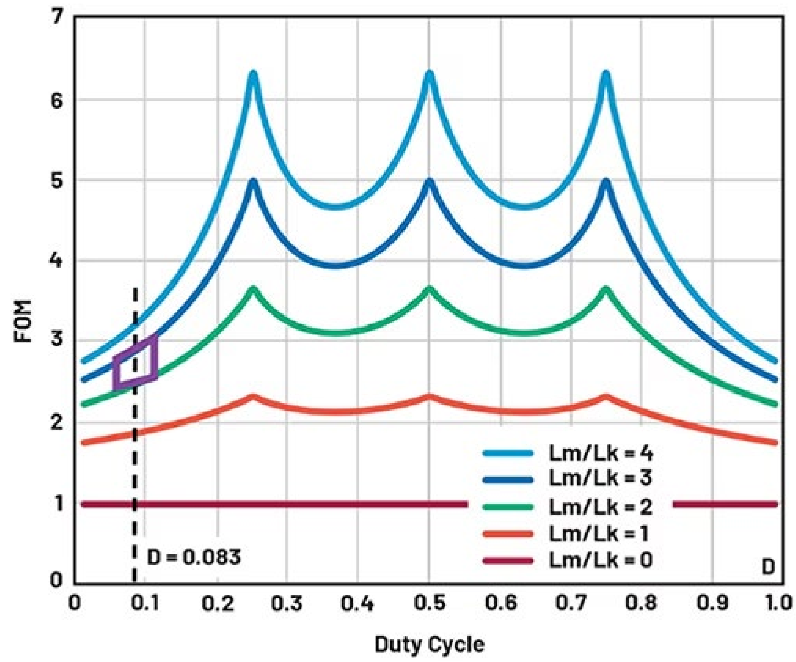


Figure 1: Shown are the FOM values for a 4-phase CL for various L_m/L_k values as a function of D; the region of interest is highlighted. (Image source: Analog Devices, Inc.)

Evaluating ripple current for coupled inductors

Figure 1 illustrates FOM values for an application with a V_{IN} of 12 V and a V_O of 1 V, with a D of ~0.083 and conventional DL values of 100 nanohenries (nH). To upgrade this design to a CL while maintaining the transient performance with the same C_O tank, the L_k for the CL must be 100 nH. This leaves L_m as the design variable. Higher values of L_m lead to lower ripple, but a conservative L_m of 260 nH is sufficient to achieve most of the desired benefits.

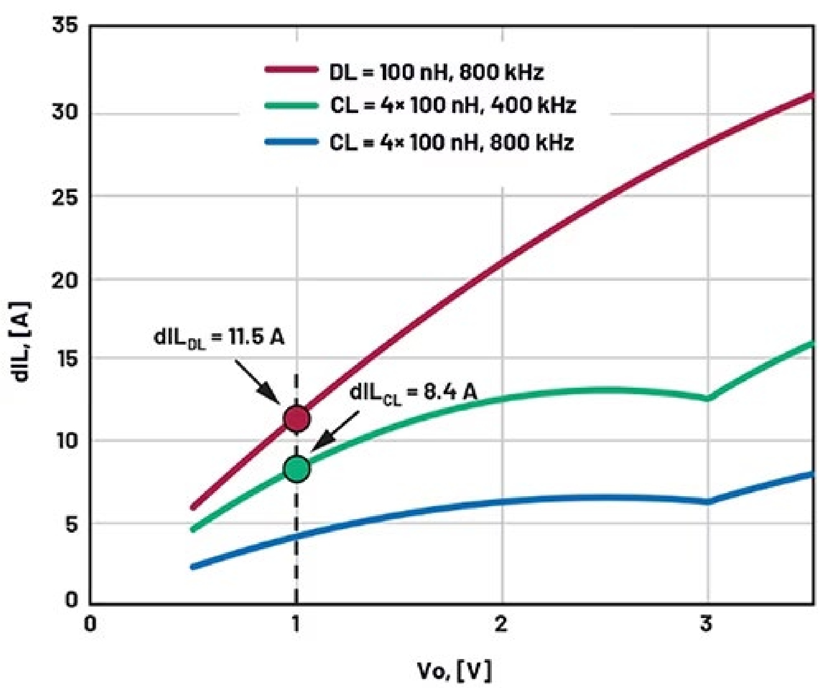


Figure 2: Current ripple for DL = 100 nH (800 kHz) and CL = 4 × 100 nH (800 kHz, 400 kHz) for V_{IN} = 12 V as a function of V_O. (Image source: Analog Devices, Inc.)

Even with this fairly conservative design, the ripple reduction is sufficient to enable lower switching frequencies. This is illustrated in Figure 2, which compares the current ripple for different inductor configurations and switching frequencies. The graph demonstrates that a CL operating at 400 kilohertz (kHz) maintains lower ripple than a conventional design at 800 kHz.

The reduced switching frequency directly translates to lower switching losses, which include transistor switching losses, dead-time losses in MOSFET body diodes, reverse recovery losses, and gate drive losses. These frequency-dependent losses decrease proportionally as the switching frequency is reduced, resulting in substantial efficiency improvements.

Efficiency gains are most visible at light loads, where AC losses are more prominent due to their fixed nature regardless of output current. However, the benefits extend across the entire load range. Figure 3 shows experimental results comparing an 8-phase system with coupled inductors at 400 kHz against a conventional design at 600 kHz, demonstrating approximately 1% improvement at peak efficiency and 0.5% improvement at full load.

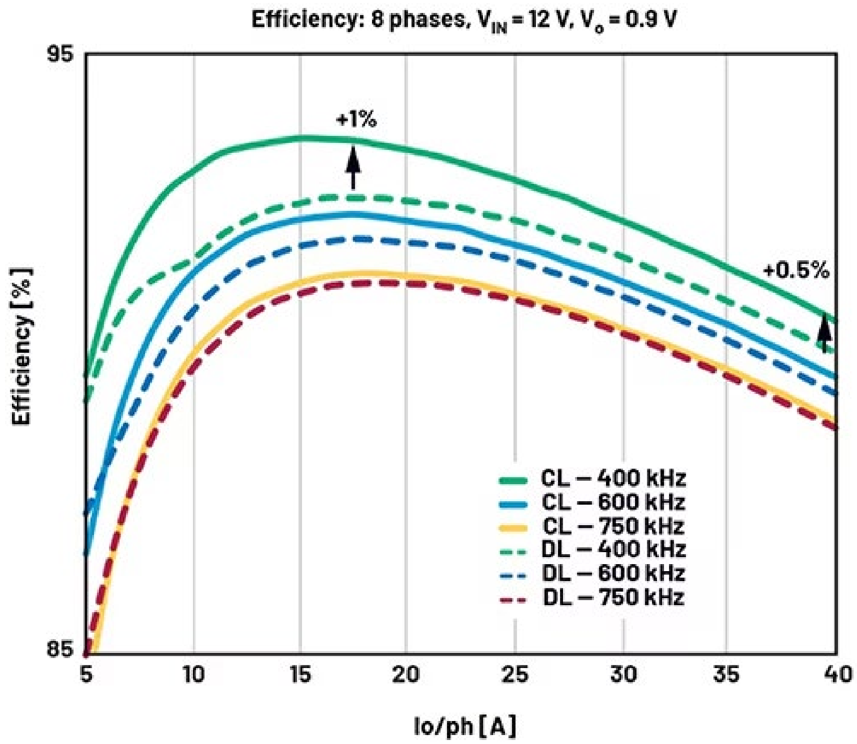


Figure 3: Shown is a measured efficiency comparison of the 8-phase DL = 100 nH (dashed curves) and 2 × CL = 4 × 100 nH (solid curves) designs with a common footprint. (Image source: Analog Devices, Inc.)

Improving efficiency without sacrificing transient response

Notably, these efficiency improvements are achieved without compromising transient performance. Figure 4 illustrates the transient behavior of a 4-phase buck converter, comparing waveforms from an 8-phase design with discrete inductors (DL = 100 nH at 600 kHz) and a configuration using two CLs, each serving 4 phases (2 × CL = 4 × 100 nH at 400 kHz) with V_{IN} = 12 V, V_O = 0.9 V for 135 A load steps. Using the same current slew rate and C_O results in comparable transient responses.

While the lower switching frequency of the CL might typically reduce feedback bandwidth, two factors counteract this limitation: the inherent advantages of the multiphase architecture and the enhanced phase margin provided by the coupled design. This phase margin improvement occurs because all coupled phase currents respond simultaneously when the duty cycle changes in response to a transient event in one phase.

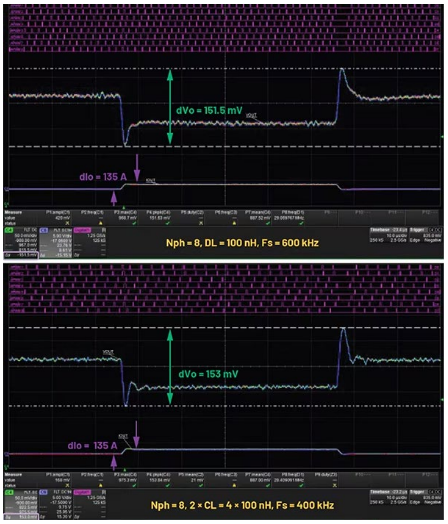


Figure 4: Shown is the transient for 8-phase DL = 100 nH (600 kHz) and 2 × CL = 4 × 100 nH (400 kHz) for V_{IN} = 12 V, V_O = 0.9 V for 135 A load steps; same board, same C_O, same conditions. (Image source: Analog Devices, Inc.)

Lower losses lead to better thermal performance, which can, in turn, enhance long-term reliability and potentially reduce cooling requirements in thermally constrained systems. All these benefits are achieved while maintaining compatibility with existing layouts.

Selecting components for multiphase buck converters

To implement an efficient multiphase buck converter, attention can be focused on three key components: the voltage regulator controller, the power stage integrated circuit (IC), and the CL. The controller manages phase timing and synchronization, the power stage handles high-current switching, and the CL enables ripple cancellation, driving improved efficiency.

For the controller, the Analog Devices' [MAX16602GGN+T](MAX16602GGN+T) (Figure 5) is a solid pick. Offered in a 56-QFN (7 mm × 7 mm) package, this device supports an 8-phase rail and a separate single-phase rail. Notable features include autonomous phase shedding, telemetry via PMBus, integrated fault protection and logging, and an internal 1.8 V bias regulator. These features enable precise control, reduced component count, and enhanced transient response in multiphase voltage regulator systems.

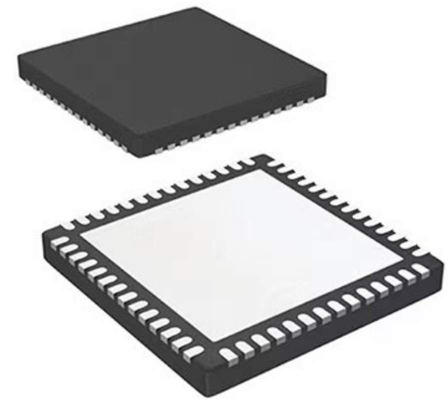


Figure 5: The MAX16602GGN+T voltage regulator controller supports up to 8 phases. (Image source: Analog Devices, Inc.)

The power stage can be implemented using Analog Devices' [MAX20790GFC+T](MAX20790GFC+T) (Figure 6). This smart power stage integrates MOSFETs, gate drivers, and current sensing into a single 12-FC2QFN

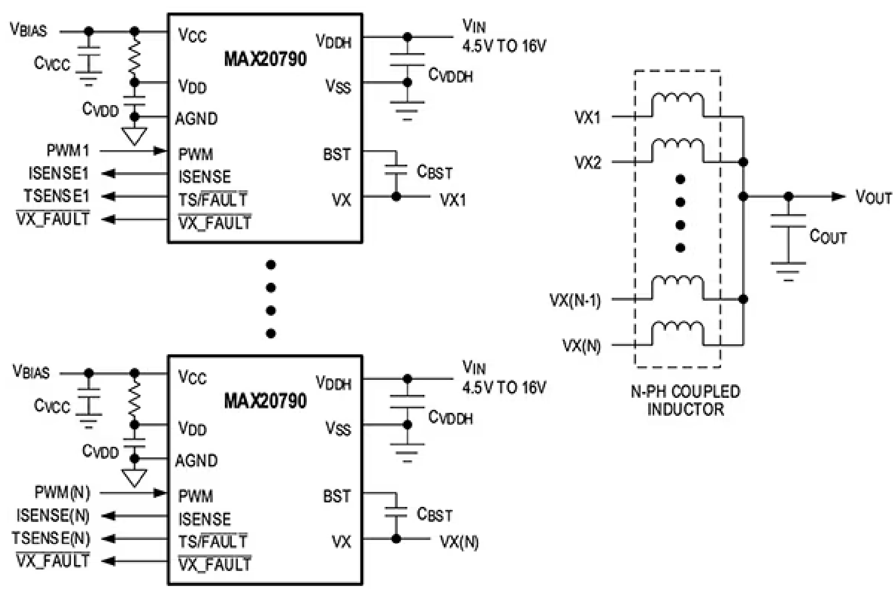


Figure 6: The MAX20790GFC+T smart power stage integrates MOSFETs, gate drivers, and current sensing into a single device. (Image source: Analog Devices, Inc.)

(3.25 × 7.4 mm) package device. Operating at a switching frequency range of 300 kHz to 1.3 megahertz (MHz), it enables designers to optimize the performance of CL designs. Key features include telemetry and fault reporting through the controller PMBus, as well as advanced self-protection features.

An example of a suitable CL is the Eaton CLB1108-4-50TR-R (Figure 7), which integrates four tightly coupled 50 nH phases into a single package. The component's construction supports high saturation current and thermal performance, making it well-suited to demanding AI and data center workloads.

In a typical configuration, the MAX16602 controller would drive up to eight MAX20790 power stages, with each output phase connected to the corresponding winding of a dual 4-phase CL. Compared to conventional designs, this architecture delivers measurable improvements in power efficiency while maintaining the same physical footprint and transient performance.

Figure 7: The CLB1108-4-50TR-R is a 4 x 50 nH coupled inductor. (Image source: Eaton)

Testing coupled inductor designs with evaluation hardware

For designers looking to explore CL solutions, Analog Devices' MAX16602CL8EVKIT# evaluation kit (Figure 8) provides a convenient platform for testing and development. This board is specifically designed to demonstrate the capabilities of the MAX16602 controller and MAX20790 power stage ICs in conjunction with coupled inductors.

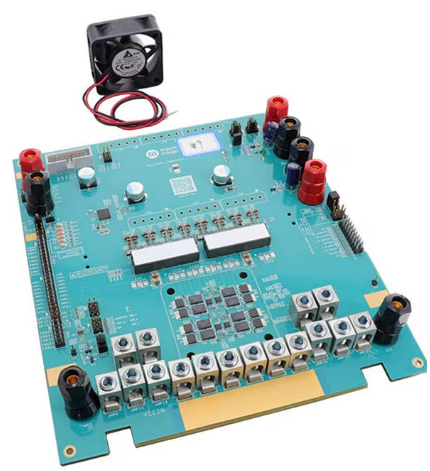


Figure 8: The MAX16602CL8EVKIT# can be used to explore multiphase buck converter designs. (Image source: Analog Devices, Inc.)

The evaluation kit is a practical reference design demonstrating how these components can be integrated effectively. It includes all the necessary circuitry to support an 8-phase power conversion solution and incorporates comprehensive measurement points that enable monitoring of key parameters such as transient response.

Conclusion

CLs offer significant advantages for multiphase buck converter designs. By introducing mutual inductance between phases, these components enable substantial ripple current cancellation, allowing for reduced switching frequency and improved overall efficiency. Importantly, these gains can be achieved without increasing the physical footprint or compromising transient performance. Combined with controller and power-stage chipsets, these solutions provide a practical path for designers transitioning from conventional topologies to more efficient, magnetically coupled alternatives.

Maximize power-device control efficiency with the right gate-driver power converter

By Bill Schweber
Contributed By DigiKey's North American Editors

From power supplies and motor drives to charging stations and myriad other applications, switching power semiconductors such as silicon (Si), silicon carbide (SiC), and gallium nitride (GaN) MOSFETs, as well insulated-gate bipolar transistors (IGBTs), are the key to efficient power-system designs. However, to achieve maximum performance from the power device, an appropriate gate driver is needed.

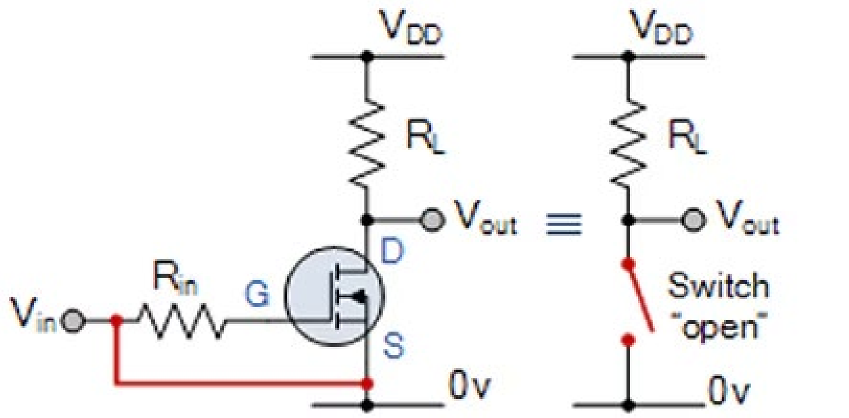


Figure 1: In cut-off mode, the MOSFET drain-source path looks like an open switch. (Image source: Quora)

As its name indicates, this component's role is to drive the power-device gate and so put it into, or pull it out of, conduction mode quickly and crisply. Doing so requires that the driver have the ability to source/sink sufficient current despite internal device and stray (parasitic) capacitance, inductance, and other issues at the load (gate). As a consequence, providing a properly sized gate driver with the suitable key attributes is critical to realizing the full potential and efficiency of the power device. However, to get the most out of the gate driver, the designer must pay special attention to the driver DC power supply, which is independent of the power-device DC rail. This supply is similar to a conventional supply but with some important differences. It can be a unipolar supply, but in many cases, it is a non-symmetrical bipolar supply, along with other functional and structural differences. Designers must also pay attention to form factor in terms of board footprint and low-profile requirements, and compatibility with a design's intended assembly and manufacturing processes.

This article will focus on power supplies for gate drivers, using surface mount device (SMD) DC/DC supplies in the Murata Power Solutions MGJ2 Series of 2-watt gate-drive DC/DC converters as examples.

Start with switching devices

An understanding of the role and desired attributes of the gate-driver DC/DC converter begins with the switching devices. For a MOSFET as switch device, the gate-source path is used to control the off or on state of the device (IGBTs are similar). When the gate-source voltage is less than the threshold voltage (VGS < VTH), the MOSFET is in its cut-off region, no drain current flows, ID = 0 amperes (A), and the MOSFET appears as an "open switch" (Figure 1).

Conversely, when the gate-source voltage is much greater than the threshold voltage ($V_{GS} > V_{TH}$), the MOSFET is in its saturation region, the maximum drain current flows ($I_D = V_{DD} / R_L$), and the MOSFET appears as a low resistance "closed switch" (Figure 2). For the ideal MOSFET, the drain-source voltage would be zero (V_{DS} = 0 volts), but in practice, V_{DS} is usually around 0.2 volts due to internal on-resistance $R_{DS(on)}$, which is typically under 0.1 Ohm (Ω) and can be as low as a few tens of milliohms.

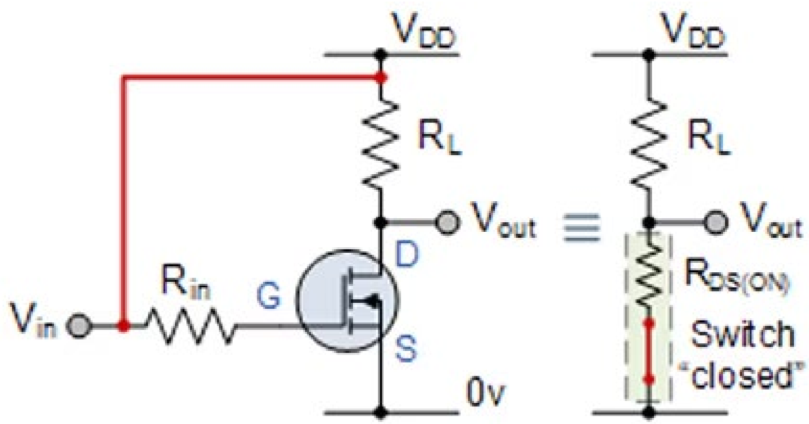


Figure 2: In saturation mode, the MOSFET drain-source path looks like a low-resistance switch. (Image source: Quora)

While schematic diagrams make it appear that the voltage applied to the gate turns the MOSFET on and off, that is only part of the story. This voltage drives current into the MOSFET until there is enough accumulated charge to turn it on. Depending on the size (current rating) and type of switching drive, the amount of current needed to quickly go into a fully on state may be just a few milliamperes (mA) to several amperes (A).

The function of the gate driver is to drive sufficient current into the gate quickly and crisply to turn the MOSFET on, and to pull that current out in a reverse manner to turn the MOSFET off. More formally, the gate needs to be driven from a low-impedance source capable of sourcing and sinking sufficient current to provide for fast insertion and extraction of the controlling charge.

If the MOSFET gate looked like a purely resistive load, sourcing and sinking this current would be relatively simple. However, a MOSFET has internal capacitive and inductive parasitic elements, and there are also parasitics from the interconnects between the driver and the power device (Figure 3).

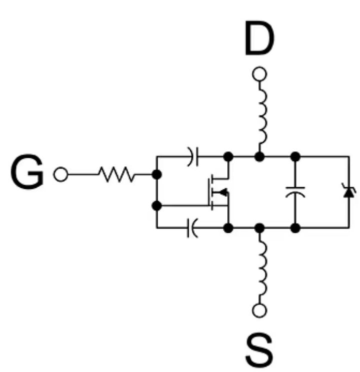


Figure 3: This model of a MOSFET shows the parasitic capacitance and inductance which affects driver performance. (Image source: Texas Instruments)

The result is ringing of the gate-drive signal around the threshold voltage, causing the device to turn on and off one or more times on its trajectory to being fully on or off; this is somewhat analogous to "switch bounce" of a mechanical switch (Figure 4).

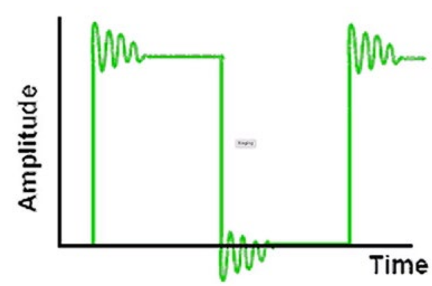


Figure 4: Ringing of the driver output due to parasitics in the MOSFET load can cause ringing and false triggering, similar to mechanical-switch bounce. (Image source: Learn About Electronics)

The consequences range from unnoticed or merely annoying in a casual application such as turning a light on or off, all the way to likely damage in the widely used pulse-width modulation (PWM) fast-switching circuits of power supplies, motor drives, and similar subsystems. It can cause short circuits and even permanent damage, in the standard half and full-bridge topologies where the load is placed between an upper and lower MOSFET pair if both MOSFETs on the same side of the bridge are turned on simultaneously even for an instant. This phenomenon is known as "shoot-through" (Figure 5).

Gate-drive details

In order to drive current into the gate, the positive rail's voltage should be high enough to ensure full saturation/enhancement of the power switch, but without exceeding the absolute maximum voltage for its gate. While this voltage value is a function of the specific device type and model, IGBTs and standard MOSFETS will generally be fully on with a 15-volt drive, while typical SiC MOSFETS may need closer to 20 volts for a full on-state.

The negative gate-drive voltage situation is a little more complicated. In principle, for the off-state, 0 volts on the gate is adequate. However, a negative voltage, typically between -5 and -10 volts, enables rapid switching controlled by a gate resistor. An appropriate negative drive ensures that the gate-emitter off-voltage is always actually zero or less.

This is critical because any emitter inductance (L) (at point 'x' in Figure 6) between a switch and the driver reference, causes an opposing gate-emitter voltage when the switch is turning off. While the inductance may be small, even a very small inductance of 5 nanohenries (nH) (a few millimeters of wired connection) will produce 5 volts at a di/dt slew rate of 1000 A per microsecond (A/µs).

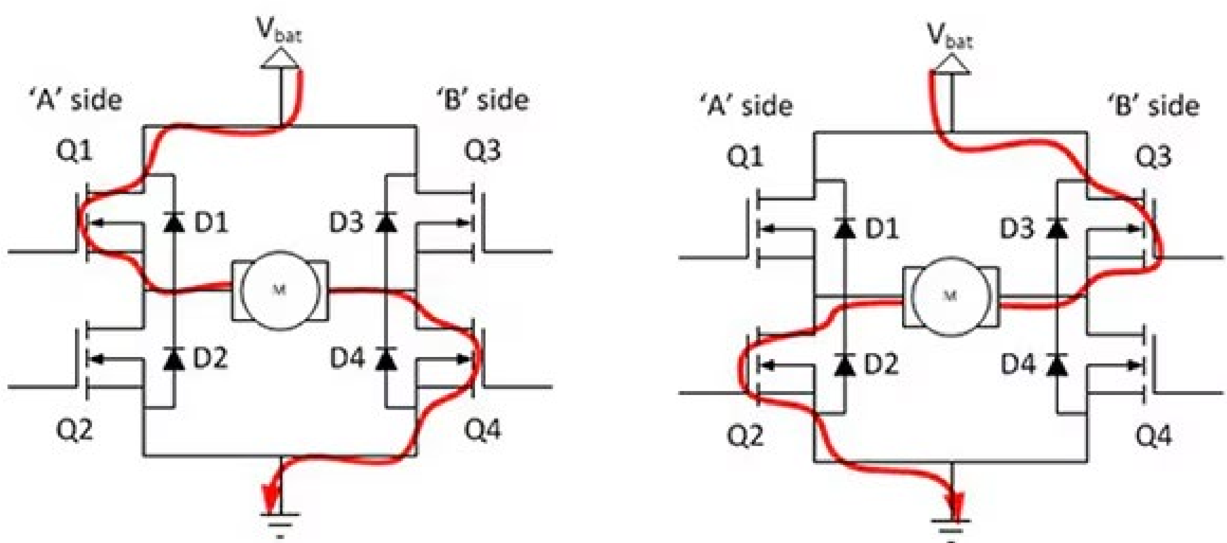


Figure 5: In contrast to the normal MOSFET turn on of Q1 and Q4 (left), or Q2 and Q3 (right), if Q1 and Q2, or Q3 and Q4 of the bridge are turned on simultaneously due to driver issues or other causes, an unacceptable and possibly damaging short-circuit condition called shoot through will occur between the power rail and ground. (Image source: Quora)

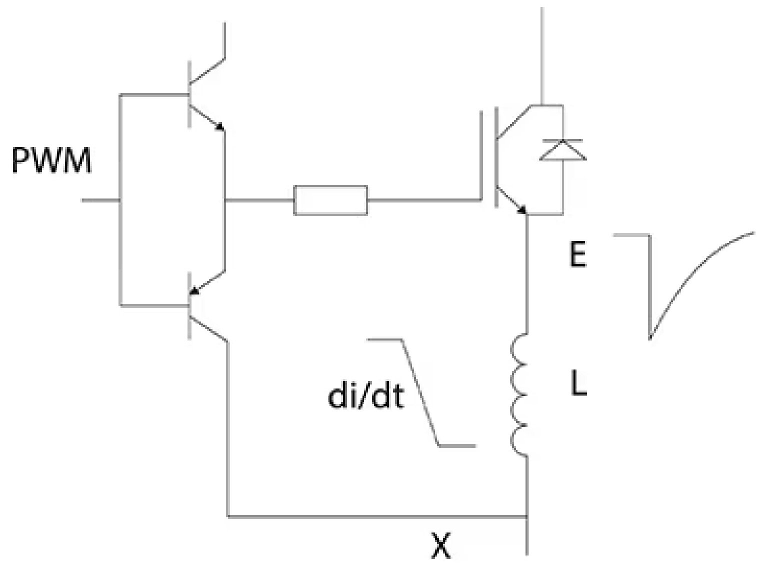


Figure 6: Even a small emitter inductance at point 'x' between a switch and the driver reference due to layout considerations can induce an opposing gate-emitter voltage when the switch is turning off, causing turn-on/off "jitter." (Image source: Murata Power Solutions)

A negative gate-drive voltage also helps to overcome the effect of collector/drain-to-gate Miller-effect capacitance C_m, which injects current into the gate drive circuit during device turn-off. When the device is driven off, the collector-gate voltage rises and a current of value $C_m \times dV_{ce}/dt$ flows through the Miller capacitance, into the gate to emitter/source capacitance C_{ge}, and through the gate resistor to the driver circuit. The resulting voltage V_{ge} on the gate can be sufficient enough to turn the device on again causing possible shoot-through and damage (Figure 7).

However, by driving the gate negative, this effect is minimized.

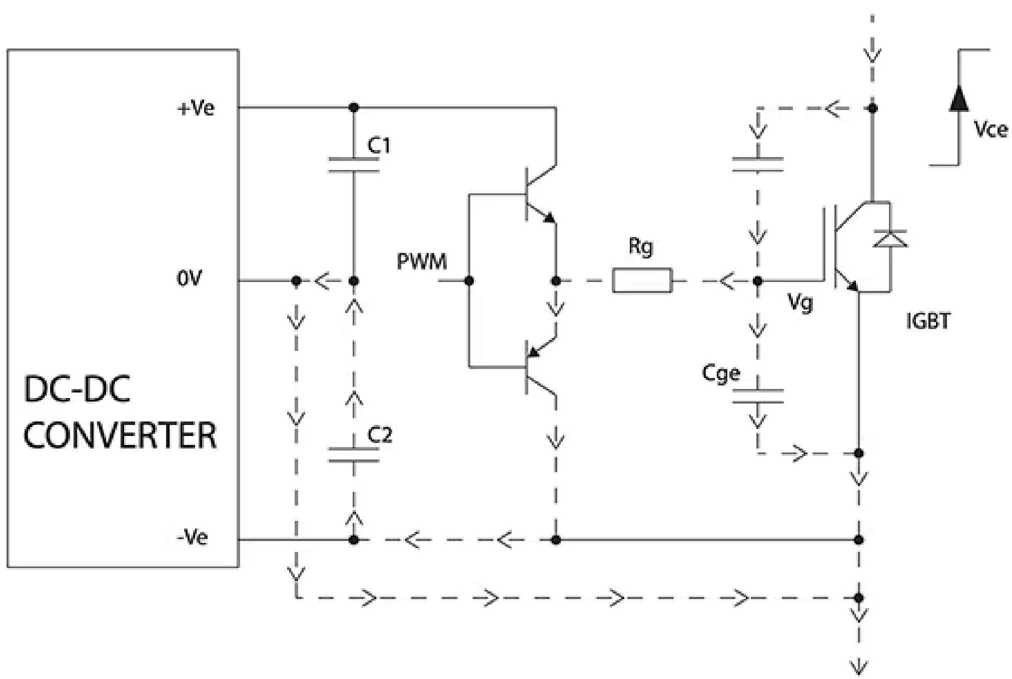


Figure 7: Using a negative gate-drive voltage can overcome the shortcomings which occur due to the presence of the Miller-effect capacitance within a MOSFET or IGBT. (Image source: Murata Power Solutions)

For this reason, an effective driver design requires both positive and negative voltage rails for the gate-drive function. However, unlike most bipolar DC/DC converters which have symmetrical outputs (such as +5 V and -5 V), the supply rails for the gate driver are usually asymmetrical with a positive voltage that is larger than the negative voltage.

Sizing the converter's power rating

A critical factor is how much current the gate-driver converter must provide, and thus its power rating. The basic calculation is fairly straightforward. In each switching cycle, the gate must be charged and discharged through the gate resistor R_g. The device's datasheet provides a curve for the gate charge Q_g value, where Q_g is the amount of charge that needs to be injected into the gate electrode to turn ON (drive) the *MOSFET* at specific gate voltages. The power which must be provided by the DC/DC converter is derived using the formula:

$$P = Q_g \times F \times V_s$$

Where Q_g is the gate charge for a chosen gate voltage swing (positive to negative), of value V_s and at frequency F. This power is dissipated in the internal gate resistance (R_{int}) of the device and external series resistance, R_g. Most gate drivers need a power supply below one to two watts.

Another consideration is the peak current (I_{pk}) required to charge and discharge the gate. This is a function of V_s, R_{int}, and R_g. It is calculated using the formula:

$$I_{pk} = V_s/(R_{int} + R_g)$$

In many cases, this peak current is more than the DC/DC converter can provide. Rather than go to a larger, more costly supply (that is operating at a low duty cycle), most designs instead supply the current using "bulk" capacitors on the driver supply rails, which are charged by the converter during low-current portions of the cycle.

Basic calculations determine how large these bulk capacitors should be. However, it is also important that they have low equivalent series resistance (ESR) and inductance (ESL) so as to not impede the transient current they are delivering.

Other gate-driver converter considerations

Gate-driver DC/DC converters have other unique issues. Among them are:

- *Regulation:* The load on the DC/DC converter is close to zero when the device is not switching. However, most conventional converters need a minimum load at all times; otherwise, their output voltage can dramatically increase, possibly up to the gate breakdown level.

What happens is that this high voltage is stored on the bulk capacitors, such that when the device starts to switch, it could see a gate overvoltage until the converter level drops under normal load. A DC/DC converter that has clamped output voltages or very low minimum load requirements should therefore be used.

- *Start-up and shutdown:* It is important that IGBTs and MOSFETs not be actively driven by the PWM control signals until the drive-circuit voltage rails are at their designated values. However, as the gate-drive converters are powered up or down, a transient condition may exist where devices could be driven on—even with the PWM signal inactive—leading to shoot-through and damage. Therefore, the DC/DC converter outputs should be well behaved on power-up and down with monotonic rise and fall (Figure 8).

- *Isolation and coupling capacitance:* At high power, power inverters or converters typically use a bridge configuration to generate line-frequency AC or to provide bi-directional PWM drive to motors, transformers, or other loads. For user safety and to meet regulatory mandates, the gate-drive PWM signal and associated drive power rails of the high side switches need galvanic isolation from ground with no ohmic path between them. Furthermore, the isolation barrier must be robust and show no significant degradation due to repeated partial discharge effects over the design lifetime.

In addition, there are issues due to capacitive coupling across the isolation barrier; this is analogous to leakage current between the primary and secondary windings of a fully insulated AC line transformer. This leads to requirements that the drive circuit and associated power rails should be immune to the high dV/dt of the switch node and have a very low coupling capacitance.

The mechanism of this problem is due to the very fast switching edges, typically 10 kilovolts per microsecond (kV/μs), and even as high as 100 kV/μs for the latest GaN devices. This fast-slewing dV/dt causes transient current flow through the capacitance of the DC/DC converter's isolation barrier.

Since current I = C x (dV/dt), even a small barrier capacitance of just 20 picofarads (pF) with 10 kV/μs switching results in a current flow of 200 mA. This current finds an indeterminate return route through the controller circuitry back to the bridge, causing voltage spikes across connection resistances and inductances, which can have the potential to disrupt operation of the controller and the even DC/DC converter. Low coupling capacitance is therefore very desirable.

There's another aspect to basic isolation and associated insulation of the DC/DC converter. The isolation barrier is designed to withstand the rated voltage continuously, but because the voltage is switched, the barrier can potentially degrade more quickly over time. This is due to electrochemical and partial discharge effects in the barrier material that would occur solely as a result of a fixed DC voltage.

The DC/DC converter must therefore have robust insulation and generous creepage and clearance minimum distances. If the converter barrier also forms part of a safety isolation system, the relevant agency regulatory

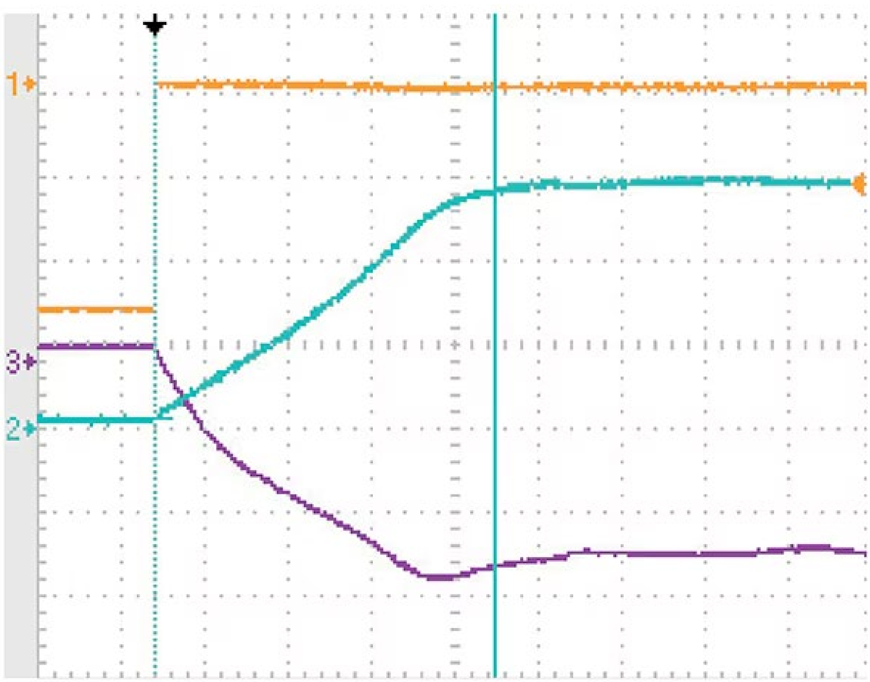


Figure 8: It is critical that the DC/DC converter outputs are well behaved during power-up and down sequences and not have voltage transients. (Image source: Murata Power Solutions)

mandates apply for the level of isolation required (basic, supplementary, reinforced), operating voltage, pollution degree, overvoltage category, and altitude.

For these reasons, only gate-drive DC/DC converters with suitable design and materials are recognized or are pending recognition to UL60950-1 for various basic and reinforced levels of protection (and which are generally equivalent to those in EN 62477-1:2012); more stringent recognition is also in place or pending to medical standard ANSI/AAMI ES60601-1 with 1 × Means of Patient Protection (MOPP) and 2 × Means of Operator Protection (MOOP) requirements.

- *Common-mode transient immunity:* CMTI is an important gate-driver parameter at higher switching frequencies where the gate driver has a differential voltage between two separate ground references, as is the case for isolated gate drivers. CMTI is defined as the maximum tolerable rate of rise or fall of the common-mode voltage applied between two isolated circuits and is specified in kV/μs or volts per nanosecond (V/ns).

Having a high CMTI means that the two sides of an isolated arrangement—the transmit side and receive side—exceed the datasheet specifications when "striking" the insulation barrier with a signal having a very high rise (positive) or fall (negative) slew rate. The DC/DC converter datasheet should have a specification value for this parameter, and designers need to match it to the specifics of the operating frequency and voltage of their circuit.

Figure 9: All units in the Murata MGJ2 series of DC/DC converters have the same outward appearance and size, but they are available with a variety of input voltage ratings and bipolar output voltage pairings. (Image source: Murata Power Solutions)

Meeting the gate-driver DC/DC converter requirements

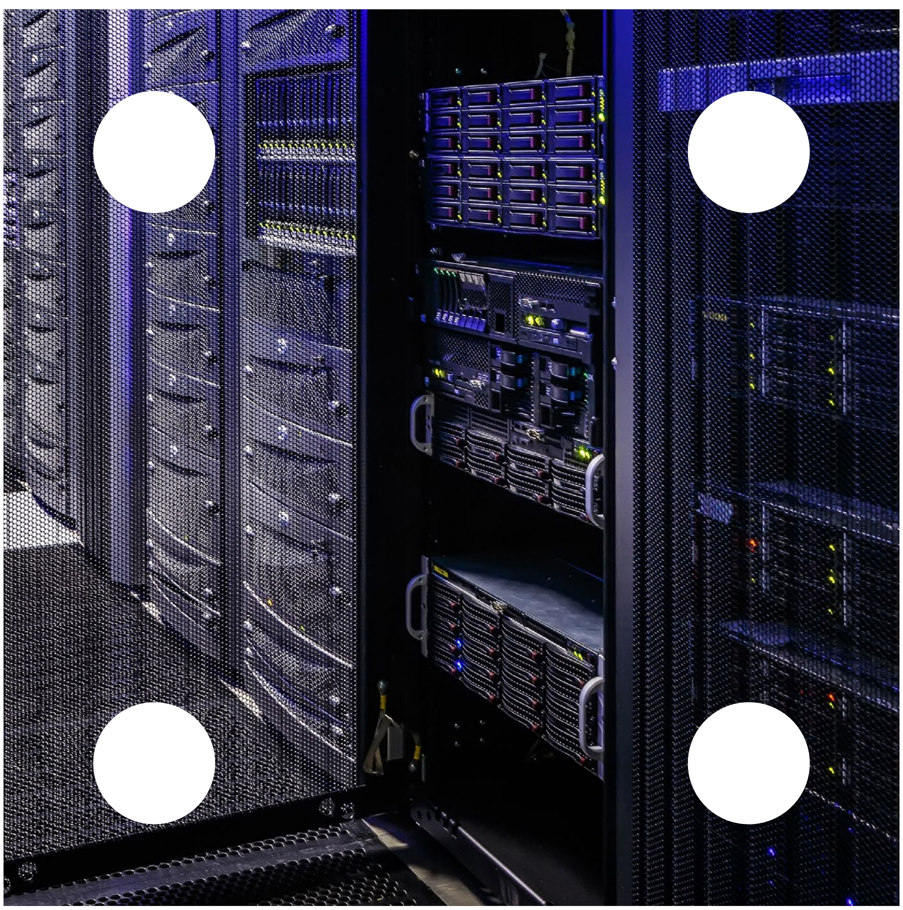
Recognizing the many challenging and often conflicting demands on gate-drive DC/DC converters, Murata has extended their MGJ2 series of through-hole DC/DC converters to include SMD DC/DC units. Their converters are well suited to powering the high-side and low-side gate-drive circuits of IGBTs and MOSFETs in space- and weight-constrained applications due to their performance, compact form factor and low profile (approximately 20 millimeters (mm) long × 15 mm wide × 4 mm high), and compatibility with SMD manufacturing processes (Figure 9).

The members of this family of 2-watt converters operate from nominal inputs of 5, 12, and 15 volts, and offer a choice of asymmetric output voltages

(+15 volt/-5 volt, +15 volt/-9 volt, and +20 volt/-5 volt outputs) to support optimum drive levels with the highest system efficiency and minimal electromagnetic interference (EMI). The surface-mount packaging eases physical integration with the gate drivers and enables closer placement, thus reducing wiring complexity while minimizing EMI or radio frequency interference (RFI) pickup.

The MGJ2series is specified for the high isolation and dV/dt requirements needed by bridge circuits used in motor drives and inverters, and the industrial-grade temperature rating and construction provides long service life and reliability. Other key attributes include:

- Reinforced insulation to UL62368 recognition (pending)
- ANSI/AAMI ES60601-1 recognition (pending)
- 5.7 kV DC isolation test voltage (per “hi pot” test)
- Ultra-low isolation capacitance
- Operation up to +105°C (with derating)
- Short-circuit protection
- Characterized common-mode transient immunity (CMTI) >200 kV/μs
- Continuous barrier-withstand voltage of 2.5 kV
- Characterized partial discharge performance



Two units show the range of performance available in the MGJ2 series:

- The MGJ2D152005MPC-R7 takes a nominal 15-volt input (13.5 to 16.5 volts) and delivers highly asymmetrical outputs of +20 volts and -5.0 volts at up to 80 mA each. Key specifications include 9% and 8% load regulation (maximum) for the two outputs (respectively), ripple and noise below 20/45 mV (typical/maximum), efficiency of 71/76% (minimum/typical), isolation capacitance of just 3 pF, and mean time to failure (MTTF) of approximately 1100 kilohours (kHrs) (determined using MIL-HDBK-217 FN2) and 43,500 kHrs (per Telecordia SR-332 calculation models).

- The MGJ2D121509MPC-R7 operates from a nominal 12-volt input (10.8 volts to 13.2 volts) and provides asymmetrical outputs of +15 volts and -9.0 volts, also at up to 80 mA. Other key specifications include 8%/13% load regulation (typical/maximum) for the +15-volt output and 7%/12% load regulation (typical/maximum) for the -9.0 volt output, ripple and noise below 20/45 mV (typical/maximum), efficiency of 72/77% (minimum/typical), isolation capacitance of 3 pF, and MTTF of approximately 1550 kHrs (using MIL-HDBK-217 FN2) and 47,800 kHrs (Telecordia models).

In addition to the expected listings and graphs detailing static and dynamic performance, the common datasheet for the members of this series calls out the many industry standards and regulatory mandates that these converters meet, along with comprehensive details of the associated test conditions used for determining these factors. This provides a higher level of confidence and speeds product certification in applications with strict conformance requirements.

Conclusion

Selecting the appropriate MOSFET or IGBT device for a switching power design is one step in the design process. There's also the associated gate driver which controls the switching device, flipping it between on and off states quickly and crisply. In turn, the driver needs a suitable DC/DC converter to provide its operating power. As shown, Murata's MGJ2 series of 2-watt surface-mount DC/DC converters offers the electrical performance needed and also meets the many complicated safety and regulatory mandates required in this function.

Use transient voltage suppression diodes to ruggedize circuits and maintain electrical integrity

By Bill Schweber
Contributed By DigiKey's North American Editors

Electrical fast transient (EFT) voltages are a reality that designers must account for to protect their circuits, systems, and system users. EFTs have many sources, including common electrostatic discharge (ESD) due to an simple actions like walking across a rug, starting a motor, or striking lightning causing a ripple effect. These transients can adversely affect every product class, from low-voltage battery-powered wearables to high-power motor systems.

The effects of EFTs range from temporary disruption and inability to function to long-term degradation in performance and outright permanent damage and failure. While designers can take steps to reduce voltage transients, such as using anti-static enclosures, filtering, clamping at the source, or implementing additional grounding, these measures often need to be revised or upgraded depending on the specific application scenario.

To reliably minimize or eliminate the detrimental consequences of transient voltages, designers can use two-terminal passive components called transient voltage suppression (TVS) diodes. Although generally viewed as an open circuit, these diodes react almost instantaneously and resemble a short circuit when the transient event occurs, thus diverting the transient overvoltage to ground. TVS diodes offer fast response, high voltage-withstand capability, long life, and low capacitance.

This article will examine the need, role, types, and application of TVS diodes, using various device families and devices from Eaton Corporation plc (Eaton) for examples.

Start with IEC standards

To mitigate the risks of EFTs, the International Electrotechnical Commission (IEC) has defined three internationally recognized standards for overvoltage protection within IEC 61000-4 ("Electromagnetic compatibility (EMC): Testing and measurement techniques"):

1) *IEC 61000-4-2* covers system-level ESD immunity, which applies to ESD caused by human contact (Figure 1). For this waveform, the rise time (tr) is short at 0.7 to 1 nanosecond (ns), with most of the energy dissipating within the first 30 ns, after which it rapidly decays. Therefore, very fast-acting overvoltage protection is required for a timely response to ESD events.

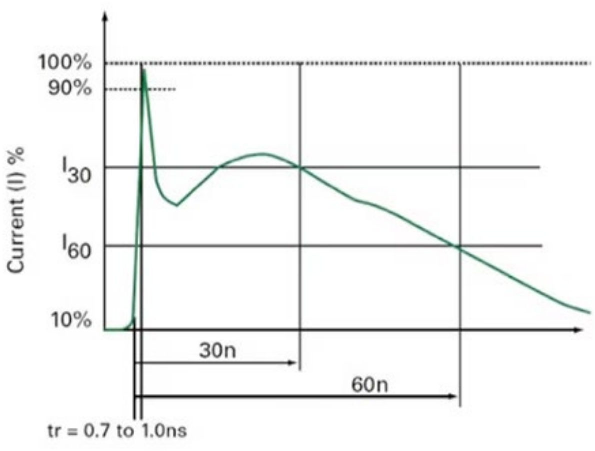
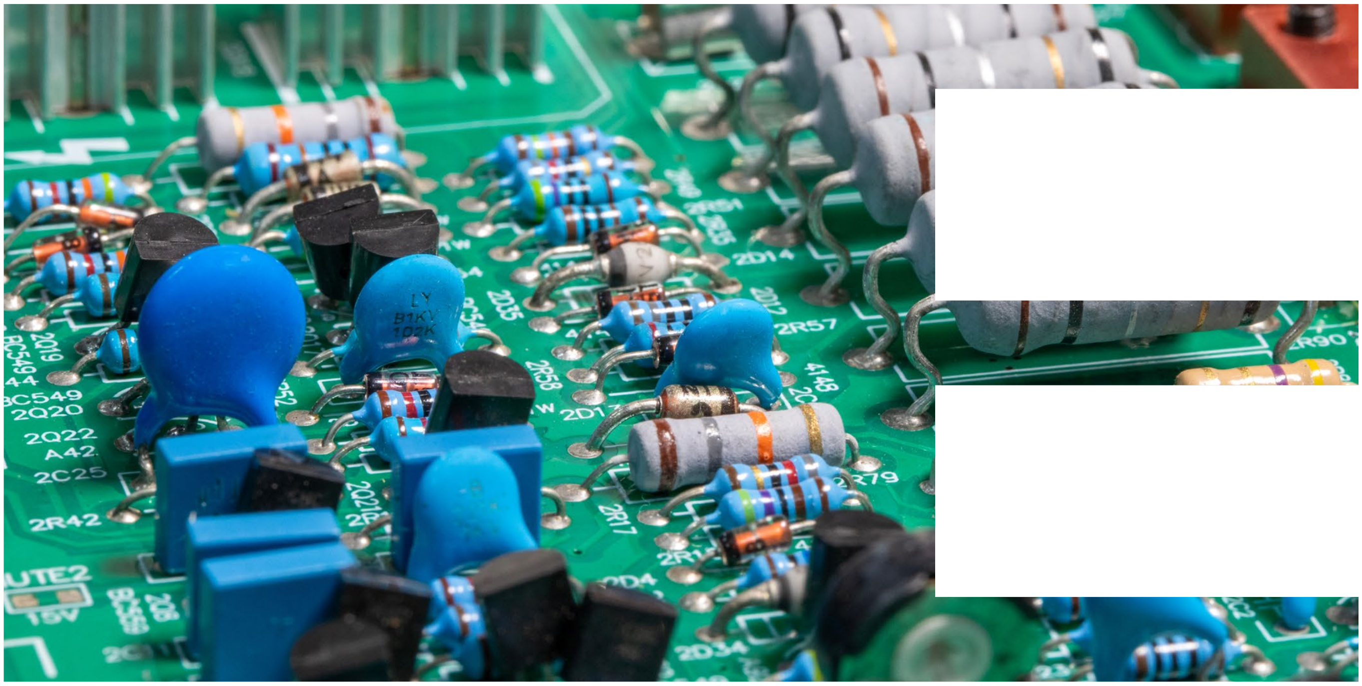


Figure 1: A typical ESD pulse waveform due to human contact, as characterized by IEC 61000-4-2, shows a very short rise time of less than a nanosecond, with most of the energy dissipating within the first 30 ns. (Image source: Eaton)



The waveform alone does not indicate the associated voltage levels. IEC 61000-4-2 specifies test voltages for system-level ESD immunity in various equipment for contact and air discharge (Figure 2).

IEC 61000-4-2 LEVEL	CONTACT DISCHARGE	AIR DISCHARGE
Level 1	2 kV	2 kV
Level 2	4 kV	4 kV
Level 3	6 kV	8 kV
Level 4	8 kV	15 kV

Figure 2: The IEC 61000-4-2 levels for air and contact discharge further define the human-contact specifics. (Image source: Eaton)

The appropriate choice of a TVS diode will depend on the level of ESD protection required in an application. Note that all of Eaton's TVS diodes offer Level 4 minimum performance when tested to IEC 61000-4-2. Other options are available with even higher ESD withstanding protection, providing up to 30 kilovolts (kV) for both air and contact discharging.

2) *IEC 61000-4-5* covers immunity against electrical surges, such as those from lightning or from switching power systems. Unlike relatively low-power static electricity, lightning strikes can contain up to 1 gigajoule (GJ) of energy and deliver up to 120 kV of surge voltage. Lightning-induced transients can occur due to direct lightning on outdoor electrical circuits producing surge voltages, indirect lightning strikes inducing surge voltages in conductors, or lightning ground current flows. Note that TVS ESD suppressors are not intended to protect against direct lightning strikes, but suppressors are still needed as these strikes can send transients throughout electrical distribution systems for distances of 1 mile or more.

IEC 61000-4-5 defines a typical lightning voltage waveform (Figure 3).

The IEC 61000-4-5 standard also specifies test voltage levels for surge immunity in classes of electrical/electronic equipment (Figure 4).

The levels are defined by the end application:

- Class 1: Partially protected environment
- Class 2: Electrical environment where cables are well-separated, even at short runs
- Class 3: Electrical environment where power and signal cables run parallel
- Class 4: Electrical environment having interconnections run as outdoor cables along with power cables, and the cables are used for both electronic and electric circuits

3) *IEC 61000-4-4* covers protection for EFTs (Figure 5). EFTs are caused by the operation of inductive loads, such as heavy-duty motors, relays, switching contactors in power distribution systems, and the switching in or out of power factor correction equipment.

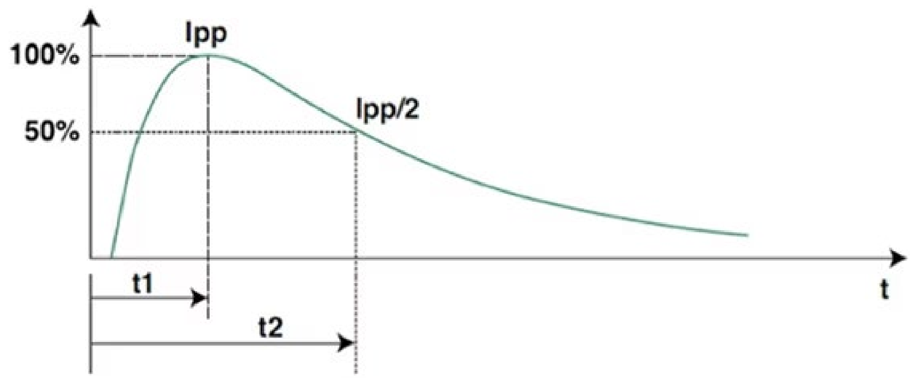


Figure 3: This is the lightning pulse waveform defined by IEC 61000-4-5 (IPP is peak current). (Image source: Eaton)

IEC 61000-4-5 SURGE TEST LEVELS		
Class	**Voltage leve (kV)**	**Maximum peak current at 2 Ω (A)**
1	0.5	250
2	1	500
3	2	1,000
4	4	2,000
X	Custom	Custom

Figure 4: IEC 61000-4-5 defines four classes of test levels for electrical surge immunity. (Image source: Eaton)

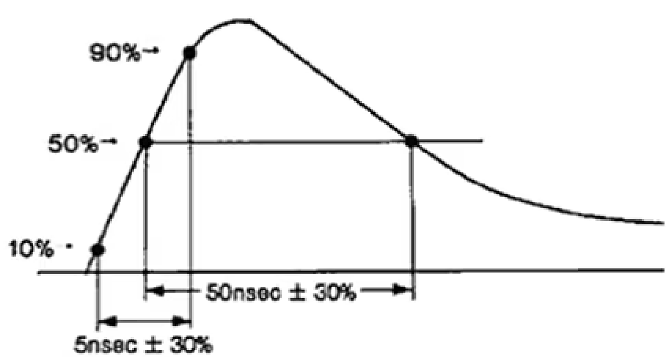


Figure 5: Shown is the EFT pulse waveform as characterized by IEC 61000-4-4. (Image source: Eaton)

CLASSIFICATION	SUCCESSFUL ESD PERFORMANCE
Class 1	0 V to 1,999 V
Class 2	4 2,000 V to 3,999 V
Class 3	4,000 V or greater

Figure 6: There are three levels of ESD sensitivity classifications per MIL-STD-883 Method Number 3015. (Image source: Eaton)

Note that EFTs are often characterized simply by two paired numbers: their rise time to peak value (t_1), and the pulse duration until the transient falls to 50% of peak value (t_2). The 8/20 microsecond (µs) transient is a common pulse in industrial applications.

The magnitude of transient-voltage ESD a circuit or system must withstand depends on the application. Three classes are defined by MIL-STD-883, which is widely used by the industry, as well as military and aerospace systems (Figure 6).

TVS devices solve the problem

To meet various requirements and protect their systems, designers can use TVS diodes. TVS diodes are silicon overvoltage protection devices that work based on the diode avalanche-breakdown principle. They are installed parallel with the normal circuit to protect internal components from short-duration (transient) and medium/high voltages (Figure 7).

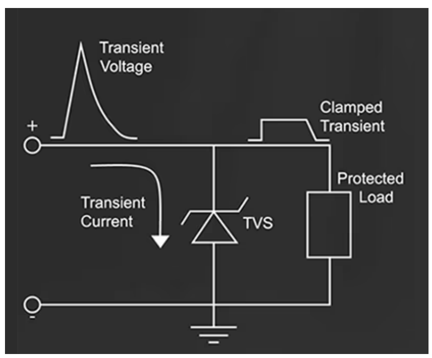


Figure 7: The TVS diode is placed across the input, between the line being protected and the system ground. (Image source: Eaton)

In normal, non-transient operation, TVS diodes maintain a high impedance and do not interfere with power or signal transmission through equipment. However, when a TVS diode experiences an instantaneous, high-energy shock across its terminals, it protects downstream circuit elements by rapidly entering a low-impedance state (called avalanche breakdown) to absorb the large current and clamp the voltage to a safe level.

TVS diodes are available as unidirectional or bidirectional P-N junction devices. Despite the names, most unidirectional TVS diodes suppress voltages in both polarities. The difference is that unidirectional types have asymmetrical voltage-current (V-I) properties, while bidirectional TVS diodes have symmetrical V-I properties (Figure 8). Bidirectional TVS diodes are well-suited for protecting electrical nodes with signals that are bidirectional or both above and below the ground voltage.

Top-tier parameters, packaging, and placement define TVS performance

TVS diodes are defined by many high-level specifications. Among them are:

- Nominal reverse working maximum voltage (V_{RWM}): Also called reverse standoff voltage, this is the maximum operating voltage of a TVS diode when it is "OFF"
- Breakdown voltage (V_{BR}): The voltage at which avalanche breakdown occurs in a TVS diode, resulting in low impedance

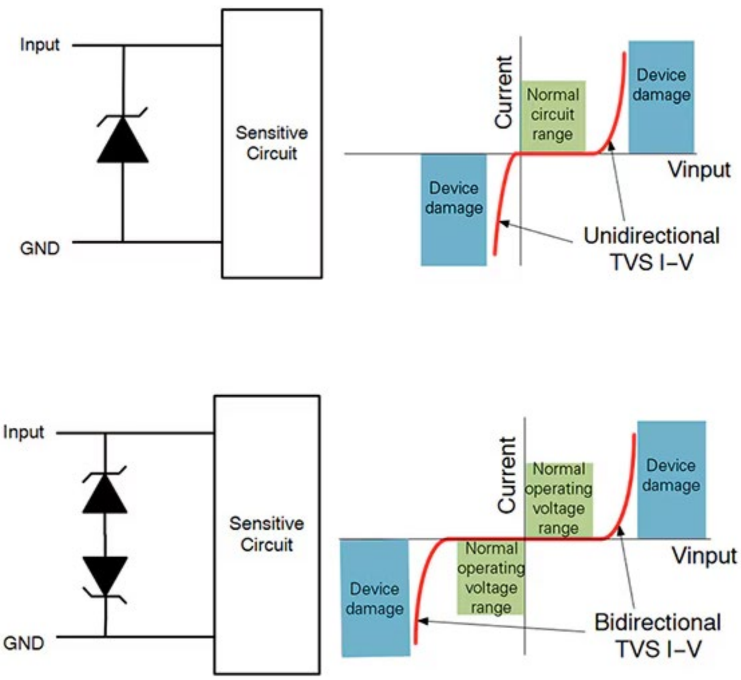


Figure 8: TVS diode names do not reflect any inherent directionality. Instead, unidirectional TVS diodes have asymmetrical voltage-current (V-I) properties, while bidirectional diodes have symmetrical V-I properties. (Image source: Eaton)

- Reverse leakage current (I_R): The current that flows through a TVS diode when it is reverse-biased
- Clamping voltage (Vc): The voltage across a TVS diode at its peak pulse current (I_{pp}) rating
- Capacitance: A measure of stored charge, generally in picofarads (pF), between the input pin and another reference point (often ground/earth), typically measured with a 1 megahertz (MHz) signal
- Peak current (I_{pp}): The difference between a current waveform's maximum positive and maximum negative amplitudes

Selecting a TVS diode is typically a four-step process:

1. Select a diode with a standoff voltage that is higher than the normal operating voltage
2. Verify that the specified peak current exceeds the expected peak current and ensure that the diode is specified to handle the required power during a transient event
3. Calculate the maximum clamping voltage (V_{CL}) of the selected diode
4. Confirm that the calculated V_{CL} is less than the specified absolute maximum rating for the protected pin

TVS device placement on the circuit board is critical to realizing the full performance capabilities of these devices. For the best surge protection, the diodes should be placed as close as possible to the point of voltage entry, such as the I/O ports, to minimize the impact of parasitics on the effective suppression of the fast transient surges.

Example TVSs illustrate the range of offerings

Eaton's TVS diodes are well-suited to overvoltage protection in I/O interfaces and high-speed digital and analog signal lines. They offer very low clamping voltages, high peak power, high current dissipation, and nanosecond response times.

TVS diode packaging is closely related to the specifications. Both surface-mount and through-hole packages are available, with the latter offering higher voltage/current performance.

TVS diodes must protect against a wide range of voltages and currents. Therefore, one value of voltage rating and other parameters cannot satisfy all EFT situations. Examples from four distinct families illustrate these points.

1) *The SMFE series* has a peak pulse power capability of 200 watts with a 10/1000 µs waveform. The devices are housed in an industry-standard low-profile SOD-123FL surface-mount package measuring 2 × 3 × 1.35 millimeters (mm) that optimizes board space for mobile and wearable devices.

One member of the series is the SMFE5-0A (Figure 9). It has a 9.2 V clamping voltage, a 21.7 ampere (A) I_{pp}, and supports unidirectional or bidirectional use cases. Reverse leakage current is under 1 µA above 10 V operation, and the response time is fast, typically less than 1.0 picosecond (ps) from 0 volts to V_{BR}.

2) *The ST series* protects one bidirectional I/O line, and targets USB and other data ports, touchpads, buttons, DC power, RJ-45 connectors, and RF antennas. Members of this family such as the 33 volt, 12 A I_{pp} STS321120B301 are housed in a tiny SOD-323 SMT package measuring 1.8 × 1.4 × 1.0 mm and are rated to 400 watts peak pulse power per line (tP = 8/20 µs). Diodes in this series support working voltages spanning 2.8 volts DC (V_{DC}) to 70 V_{DC} with ultra-low capacitance down to 0.15 pF. These diodes provide ESD protection up to 30 kV (per IEC 61000-4-2).

3) *The AK series* comprises high-power TVS diodes with up to 10,000 A protection and is designed to meet severe surge-test environments for AC and DC applications. These diodes feature low slope resistance as well as a superior clamping factor due to snapback technology. They meet UL1449 surge-protection device standards for applications such as consumer electronics, appliances, industrial automation, or AC line protection. (Note: slope or dynamic resistance is the resistance offered by the diode when an AC voltage is applied; snapback is a device process whereby conduction of large currents continues even at lower voltages.)

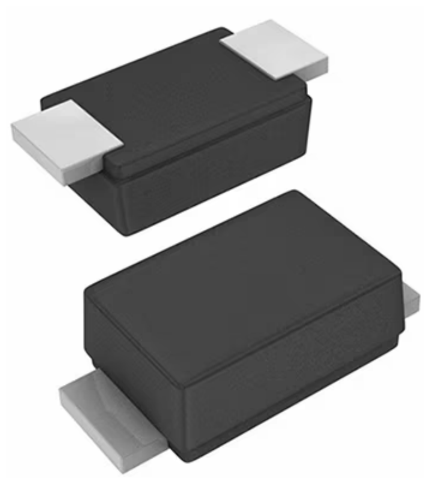


Figure 9: The SMFE5-0A 9.2 V TVS diode comes in a low-profile SOD-123FL surface-mount package and targets mobile and wearable applications. (Image source: Eaton)

To meet the amperage and UL requirements, devices in this series use through-hole axial-lead packaging as used with the AK6E-066C, a 120 V clamp, and 6000 A I_{pp} diode (Figure 10). This diode measures 25 mm along its leads, with a nearly square "central" body that measures approximately 13 × 15 mm.

Figure 10: The AK6E-066C high-power 120 V TVS diode offers up to 10,000 A protection and is housed in a through-hole axial-lead package. (Image source: Eaton)

4) *The SMAJExxH series* SMA-size TVS diodes are unique in that they are qualified to AEC-Q101 standards required for automotive applications. They provide 400 watt peak pulse power capability (with a 10/1000 µs waveform) and have a fast response time that is typically less than 1.0 ps from 0 V to V_{BR}, along with I_R less than under 1 µA above 10 volts.

Devices in this family span from 5 to 440 volts with unidirectional and bidirectional versions for each device and include the SMAJE22AH, which features a 35.5 V clamping voltage with 11.3 A I_{pp} (Figure 11). All devices in the series are housed in surface-mount plastic packages measuring 3.0 × 4.65 × 2.44 mm (maximum) and meeting the UL 94 V-0 flammability rating (Figure 11).

Conclusion

Electrical transients from static electricity, motor startup, or nearby lightning can damage electronic systems and their components. TVS diodes respond to these overvoltages almost instantaneously and divert the transient voltage and energy to ground, thus protecting the system. As shown, Eaton offers various series of TVS diodes, each series comprising numerous devices rated at different voltages to match the anticipated transient-voltage magnitude, end-product constraints, and regulatory mandates while requiring only a few square millimeters of circuit-board real estate.

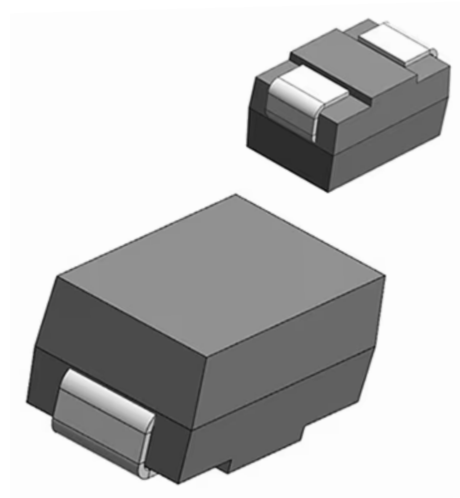
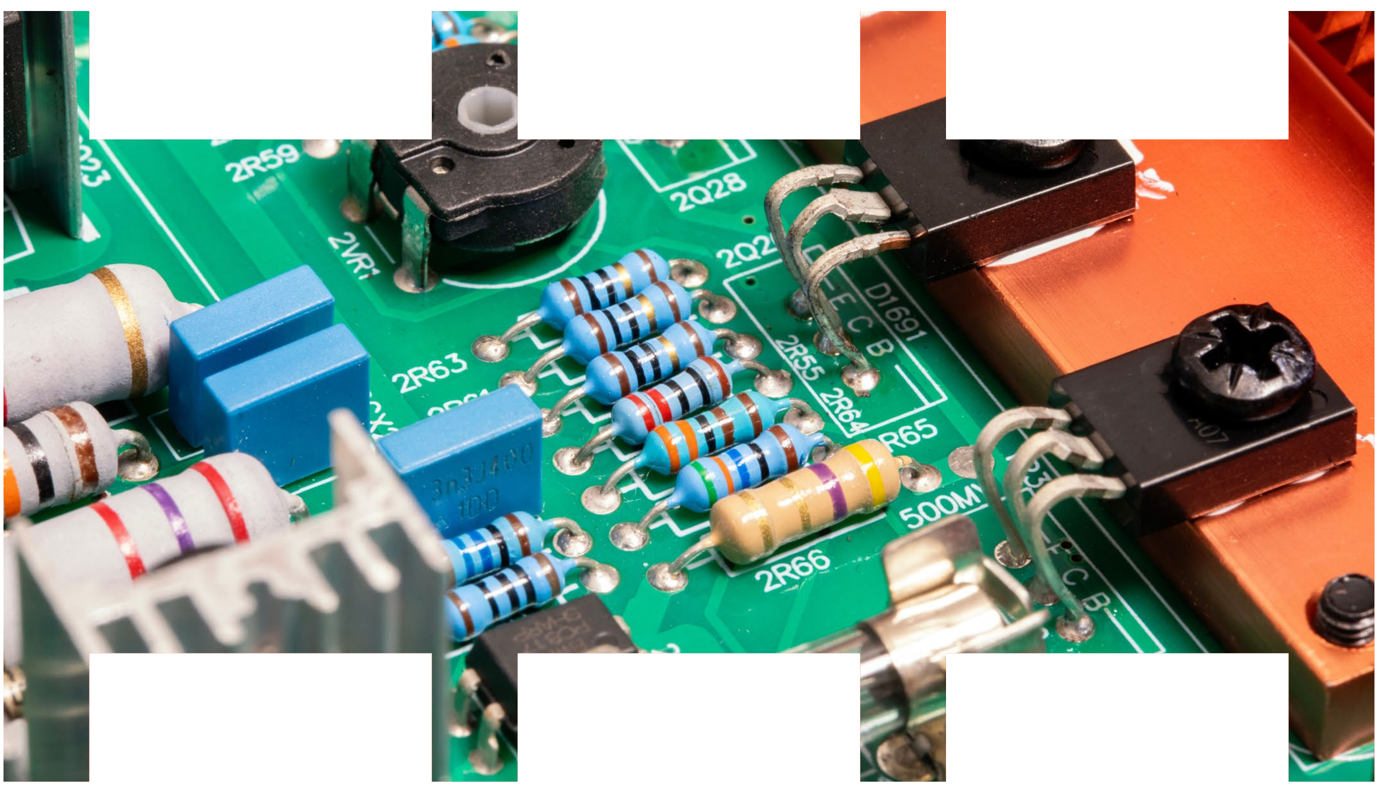
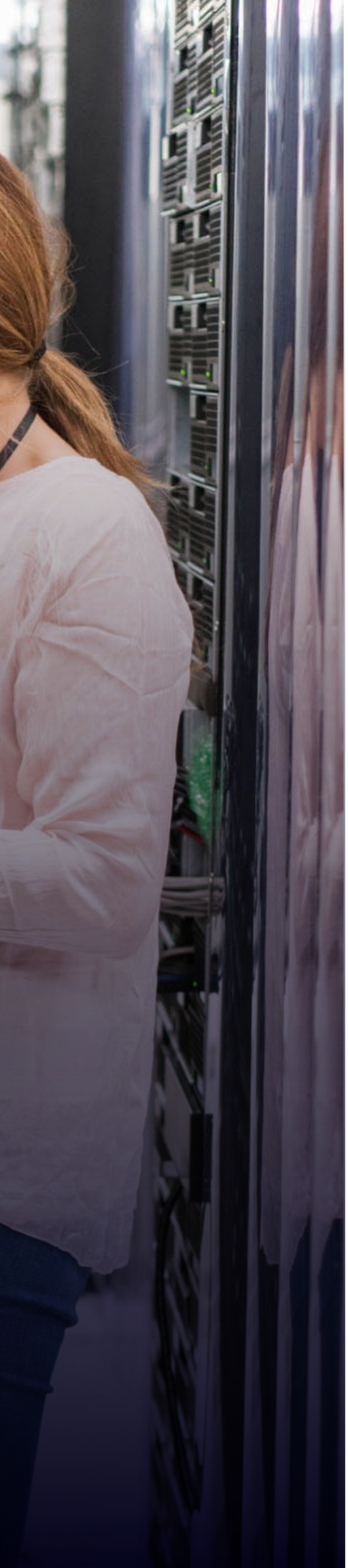


Figure 11: The SMAJE22AH 35.5 V TVS diode is qualified to automotive standards as called out by AEC-Q101; it also uses plastic packaging that meets the UL 94 V-0 flammability rating standard. (Image source: Eaton)



Exploring how silicon carbide is transforming energy systems



By Michael Williams, Shawn Luke

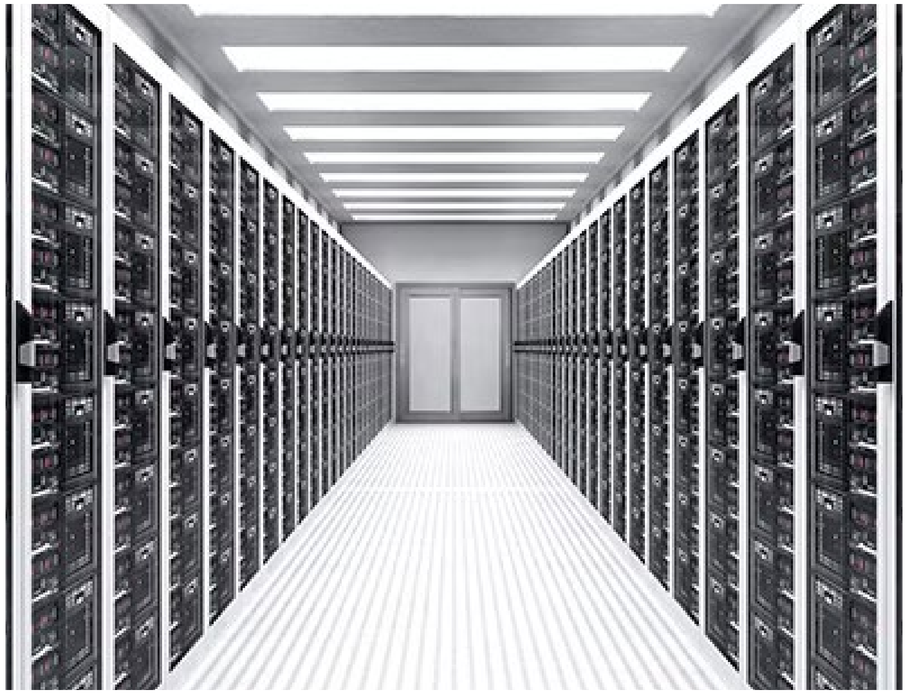
Silicon carbide (SiC) has become a cornerstone for enhancing efficiency and supporting decarbonization across industries. It's an enabler for advanced power systems, addressing growing global demands in renewable energy, electric vehicles (EVs), data centers and grid infrastructure. SiC technology has advantages over traditional silicon devices, especially in power conversion efficiency and thermally sensitive situations. Its overall impact in the electronics and power industries can lead to greater profitability and sustainability.

Experts from two industry-leading semiconductor companies – Michael Williams, director of marketing for industrial and infrastructure at Infineon Technologies and Shawn Luke, technical marketing engineer at DigiKey – share their thoughts on how SiC technology has impacted the market and what's next.

Shifting power consumption

"In the past, most power consumption was tied to some type of motor control such as industrial automation applications and factories, rail transportation, moving pumps for wastewater treatment or fluids like oil in pipelines," said Williams. "With the introduction of silicon carbide, there was a shift toward driving efficiency in the marketplace, enabling reductions in energy losses across multiple conversion stages, supporting high-demand applications."

This shift focused on decarbonization and the development of new generations of renewable technology, including renewable energy systems, EV infrastructure and data centers. It also improved power conversion efficiency from around 95% to 98.5%, a significant shift that has lowered energy losses, reduced heat generation and minimized cooling requirements.



Grid infrastructure

Simply transferring power from the grid or a high-voltage power line into a data center can result in a 5-6% loss in power as it travels through several layers of conversion. Data centers alone are estimated to account for 3% of global energy consumption today, projected to rise to 4% by 2030 (Data Centre Magazine, 2022), with no expectations of slowing down. SiC comes into play for datacenter power infrastructure, driving efficiency and system cost in grid-scale energy storage and solar central inverters. The combined solution enables future datacenters to work in a microgrid environment, reducing loading on the already strained U.S. grid.

“With the electrification of automobiles, we’re seeing many reference designs come out with bi-directional charging and advanced power electronics, meaning they’re charging during non-peak times and putting power back into the grid for peak times,” said Luke.

SiC, as a wide-bandgap technology, supports higher voltage handling and faster switching speeds in applications like EV charging. This has enabled a complete transformation of the global grid infrastructure while reducing system complexity and overall costs.

Designing with SiC technology

SiC technology addresses efficiency well, but there are times when a designer needs a small product, which is when wide bandgap (WBG) or silicon (Si) devices are used.

“Just as a designer has three technologies to choose from, they also have three fundamental design considerations. Do I make my product cost-effective; do I make my product compact; or do I make my product efficient?” explains Williams. “Choosing any two of these priorities allows a designer to choose Si solutions. However, designing for all three of these considerations requires wide bandgap devices. The key driver for compact products is increasing the switching frequency to reduce the size of the magnetics and capacitance in the system.”

Because of the WBG capability in SiC technology, voltage levels can be higher, which has enabled the next generation of technology implementation. The challenge is that SiC is a complex material to work with given it's a significantly stiffer base material than traditional silicon.

Power cycling is a key factor in package development, as it puts strain on the interconnection between the SiC die and its leadframe or substrate, potentially leading to premature device failure. Developing new interconnection technologies to improve the power cycling performance of future SiC devices is important in addressing the future requirements of a decarbonized grid.

"Applications now utilize much higher power cycling than the motor-drive applications of the past," said Williams. "Infineon has been focused on developing our .XT technology, an advanced interconnection technology proven to increase power cycling performance >22 times versus standard soft solder techniques. This technology development enables higher power density, improved thermal performance, and maximum system lifetime, enabling the shift to more renewable energy sources."

Power conversion market innovations

One area these experts are excited about is the decarbonization of the grid, which involves transitioning away from fossil fuel power plants (like coal and oil).

"Decarbonization can happen both at the macro level with changes power companies are making to switch to wind, solar and hydropower, but also at the consumer level through EVs and the like," said Luke. "Enablers like SiC are helping us get closer to microgrids more than ever before, localizing power sources for less conversion and loss, aiding in decarbonization."

Another innovation they see as having a strong impact on the power sector is the implementation of solid-state transformers. These can greatly enhance the infrastructure of the power grid, reducing the size, installation time and overall complexity of the utility site. Deploying solid-state transformers enables modular, high-voltage systems and microgrid solutions, leading to more sustainable power distribution.

What's next?

With new technology rolling out constantly, SiC is predicted to have a lasting presence.

"Infineon experts predict silicon power switching devices will continue to dominate the market for the remainder of the decade," said Williams. "We have a unique position in the market by offering all three switching technologies: silicon, silicon carbide and gallium nitride and see no threat from wide bandgap power devices reducing the total market size."

Companies like Infineon are investing in scaling manufacturing to increase capacity and developing solutions that improve power efficiency while reducing the cost of SiC technology. Innovations such as modular microgrids, distributed DC networks, and fusion reactors are on the horizon, with SiC at the core of these advancements.

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